NATIONAL WATER SUMMARY 1986—
Hydrologic Events and Ground-Water Quality

United States Geological Survey
Water-Supply Paper 2325

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Hydrologic Events and Ground-Water Quality

By U.S. Geological Survey

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United States Geological Survey
Water-Supply Paper 2325

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FOREWORD

National Water Summary 1986—Hydrologic Events and Ground-Water Quality is the fourth in a series of annual reports that describe the conditions, trends, availability, quality, and use of the Nation's water resources. This year's report continues a discussion, begun in the 1984 *National Water Summary*, of principal aquifers in each State by assembling available information about the existing water quality of each aquifer, the location of major areas of known contamination and potential sources of contamination, and steps being taken by the States to manage their ground water. This subject is particularly timely because of the growing national awareness and concern that this important source of water supply is vulnerable to contamination by toxic industrial, domestic, and agricultural wastes.

The U.S. Geological Survey has been engaged in the study of the quantity and quality of ground-water resources of the United States for more than a century. Survey geologists early noted the importance of hydrogeologic information to the search for ground-water supplies in the plains country around Denver, Colo. S.F. Emmons, Geologist-in-Charge of the Division of the Rocky Mountains, included the following observation in his 1884 annual report to Director John Wesley Powell:

> The practical bearing of this study [of the Denver water supply] is not confined to Denver, but extends to the whole region of the great plains. While the existence of a synclinal basin has long been known to us from the hasty observations one makes in simply passing over the country, accurate and reliable maps and profiles are an indispensible basis for the observations which shall determine the true source of the water supply, the amount and quality that may be expected from different geologic horizons, and the most favorable points for sinking artesian wells; it is in large degree owing to the want of this accurate preliminary knowledge that the money already appropriated by Congress and spent in sinking artesian wells upon the plains of Colorado has been so barren of practical and definite results. (U.S. Geological Survey, 1885, Fifth Annual Report of the United States Geological Survey to the Secretary of the Interior 1883-1884, p. 45-46.)

More than 100 years later, information about the quantity, quality, and use of the Nation's ground-water resources continues to be the foundation of sound ground-water-management practices. Much of the U.S. Geological Survey's efforts have been devoted to characterizing the ground-water resources by assessing the amount and quality of water available for development. These efforts have been supported by research into the physical, chemical, and biological processes that control ground-water movement and the changes in water quality that take place naturally and as a result of human activities.

On an annual basis the U.S. Geological Survey is currently measuring ground-water levels at about 33,000 wells, determining chemical quality of water samples from about 9,000 of these wells, and conducting hundreds of ground-water investigations. Much of this work is carried out through the Survey's Federal-State Cooperative Program, a program of water-resources investigations and data-collection activities conducted on a cost-sharing basis with about 950 State, regional, and local water-management agencies.

Over the past decade, the major emphasis in U.S. Geological Survey ground-water programs has shifted significantly from determining availability of ground water to understanding the factors that affect the quality of ground water. Although we have learned much about the principles governing the movement of water through aquifers, much remains to be learned about the changes in inorganic and organic chemicals as they are transported through the subsurface environment by ground water. For example, a hydrologist, given knowledge of the aquifer medium, can easily predict water levels between two points of measurement. Unfortunately, we do not yet have a theoretical basis for predicting whether contamination occurs between two points where contamination has been detected. The only alternative is to obtain many point observations by drilling test wells—a very costly procedure.

For this reason, knowledge about the prevalence of toxic substances in ground water at the national scale is limited. Most information has come from the study of individual sites where contamination has been found. However, there are a number of reasons to believe that the extent of known ground-water contamination will increase in the next few years. First, the number of ground-water users will continue to increase. Second, society is now conscious of the problem, and water-management agencies, using sensitive analytical methods, will be looking harder at the water quality of ground-water supplies than they have in the past. Third, ground water moves relatively slowly, and chemicals from waste sites abandoned decades ago may begin to appear in water-supply wells miles away from the waste site. Thus, in the short run, the ground-water-contamination situation may appear to get worse despite increasing efforts devoted to ground-water protection by State and Federal regulatory and resource-management agencies and to the mitigation of ground-water contamination.

The proposed ground-water protection programs are based, of necessity, largely on existing knowledge that ranges widely in completeness across the Nation. In the future, more detailed information will be needed to design appropriate management and protection plans and to evaluate their effectiveness. The U.S. Geological Survey, through its Federal-State Cooperative Program of water-resources investigations, its hydrologic research programs, and other related programs, will continue to assist State and local agencies by providing hydrologic data, information on hydrologic processes, interpretation of investigation results, and training. In this way the Survey plans to continue to fulfill its century-old mission to help the Nation in the wise use and management of its vital ground-water resources.

Suggestions about themes for future *National Water Summary* reports and comments regarding the contents, style, and usefulness of this series of reports are welcome and encouraged. Remarks should be addressed to the Chief Hydrologist, U.S. Geological Survey, 409 National Center, Reston, Virginia 22092.

Dallas L. Peck

Director

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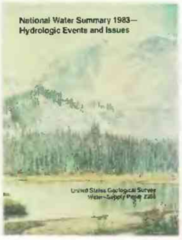
OVERVIEW AND INTRODUCTION

NATIONAL WATER SUMMARY—



1983 — Hydrologic Events and Issues (U.S. Geological Survey Water-Supply Paper 2250)

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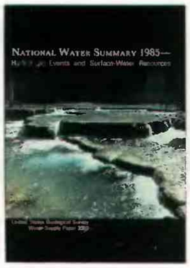

1985 — Hydrologic Events and Surface-Water Resources (U.S. Geological Survey Water-Supply Paper 2300)

COVER

Tiny ice particles coat the huge cottonweed trees in Carson City, Nevada, following a midwinter ice fog that is called "pogonip" by the Shoshone people of western North America. This rural setting, which is only 1.2 miles east of the Nevada State Capitol building, persists in 1987 partly because urban growth in the small valley is limited by the available water supply. The shallow stock well, driven by the windmill, draws water from unconsolidated alluvial deposits of Pleistocene age; these deposits also are tapped by deeper public-supply wells. (Photograph by A. S. Van Denburgh, U.S. Geological Survey.)

OVERVIEW

Ground water is one of the most important natural resources of the United States and degradation of its quality could have a major effect on the welfare of the Nation. Currently (1985), ground water is the source of drinking water for 53 percent of the Nation's population and for more than 97 percent of its rural population. It is the source of about 40 percent of the Nation's public water supply, 33 percent of water for irrigation, and 17 percent of freshwater for self-supplied industries.

Ground water also is the source of about 40 percent of the average annual streamflow in the United States, although during long periods of little or no precipitation, ground-water discharges provide nearly all of the base streamflow. This hydraulic connection between aquifers and streams implies that if a persistent pollutant gets into an aquifer, it eventually could discharge into a stream.

Information presented in the 1986 *National Water Summary* clearly shows that the United States has very large amounts of potable ground water available for use. Although naturally occurring constituents, such as nitrate, and human-induced substances, such as synthetic organic chemicals, frequently are detected in ground water, their concentrations usually do not exceed existing Federal or State standards or guidelines for maximum concentrations in drinking water.

Troublesome contamination of ground water falls into two basic categories related to the source or sources of the contamination. Locally, high concentrations of a variety of toxic metals, organic chemicals, and petroleum products have been detected in ground water associated with point sources such as waste-disposal sites, storage-tank leaks, and hazardous chemical spills. These types of local problems commonly occur in densely populated urban areas and industrialized areas. Larger, multicounty areas also have been identified where contamination frequently is found in shallow wells. These areas generally are associated with broad-scale, or nonpoint, sources of contamination such as agricultural activities or high-density domestic waste disposal (septic systems) in urban centers. At present, only a very small percentage of the total volume of potable ground water in the United States is contaminated from both point and nonpoint sources; however, available data, especially data about the occurrence of synthetic organic and toxic substances, generally are inadequate to determine the full extent of ground-water contamination in the Nation's aquifers or to define trends in ground-water quality. Most information about the occurrence of these substances has come from the study of individual sites or areas where contamination had already been detected or suspected.

Management and protection of ground water present a major challenge to the Nation. Current and projected costs of detection and cleanup of existing ground-water contamination are staggering and, even so, complete removal of pollutants from ground water in the vicinity of some waste sites might not be technically feasible. At all levels of government, the task of protecting the resource for its most beneficial uses is difficult and controversial.

Despite increasing awareness that some of the Nation's ground water is contaminated with a variety of toxic metals, synthetic organic chemicals, radionuclides, pesticides, and other contaminants that might present a long-term risk to human health, public policy towards ground-water protection is still in the formative stages. Despite increasing efforts devoted to ground-water protection by State and Federal regulatory and resource-management agencies, the extent of ground-water contamination is likely to appear to increase over the next few years because more agencies will be searching for evidence of contamination, and they will be using increasingly sensitive analytical procedures. Increased technology and expanded monitoring activities probably will detect the effects of past contamination and land uses on water quality. The significant time lag between a water-quality change in one part of an aquifer system and the effects of that change at a downgradient site, such as a well, results from the generally slow movement of ground water. This lag between cause and observed effect needs to be considered in evaluating the effectiveness of current and future ground-water policies and remedial measures.

Conclusive answers to questions about the location, extent, and severity of ground-water contamination, and about trends in ground-water quality, must await further collection and analysis of data from the Nation's aquifers. Generalizations, however, can be made, and the 1986 *National Water Summary*, which describes the natural quality of ground-water resources in each State and the major contamination problems that have been identified as of 1986, provides a national perspective of the ground-water-quality situation.

The 1986 *National Water Summary* follows the format of previous volumes. It contains three parts, and the contents of each of these parts are highlighted below.

HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS, WATER YEAR 1986

The 1986 *National Water Summary* documents a selection of 91 water-related events and conditions during the water year. Weather-related events caused more than $10.5 billion in economic losses nationwide. Of this amount, flood damages were more than $6 billion—the highest incurred since such records began—and 3 times the yearly average during 1976-85. Flood-related fatalities totaled 208, just above the national average of 200 lives per year. Flash floods accounted for 80 percent of the deaths.

Intense regional extremes of wetness and dryness characterized the 1986 water year. Most noteworthy was the drought that dominated much of Southeastern United States. The drought resulted from a weak and variable flow in the subtropical jet stream over the Southeastern United States and the absence of low-pressure troughs over the lower and middle Mississippi River valley, which brought fewer than normal large-scale cyclonic storms from the Gulf of Mexico. Persistent rainfall deficiencies (as little as 65 percent of normal) during 1985, followed by very low rainfall in the winter and spring of 1986, led to severe drought during the summer months over much of the region.

Initially, the drought was limited to small areas in eastern Tennessee and the western Carolinas, but by mid-July 1986, extreme dry conditions were present through most of Georgia, the Carolinas, Virginia, Maryland, eastern Alabama, eastern Tennessee, and southeastern Kentucky. During July and August, many streams in northern Georgia and the eastern Carolinas had their lowest seasonal flows of record. The cumulative streamflow from October 1985 to August 1986 was less then 40 percent of normal in a band extending from Mississippi to North Carolina. Many reservoirs were at below-normal summer levels. Low-flow conditions resulted in increased water temperatures and lowered dissolved-oxygen concentrations and pH in many streams. Several States reported fishkills, water-odor problems, and excessive aquatic weeds. Ground-water levels in the drought-affected areas generally were below normal, especially in parts of southwest Georgia where new record low levels were set during August. The drought severely affected agriculture and resulted in estimated economic losses in the Southeast exceeding $1 billion. Communities in Georgia and the Carolinas experienced water-supply shortages. As a result, most Southeastern States established a variety of drought contingency plans. By late August and early September 1986, however, sufficient precipitation fell to effectively end the drought.

In contrast to the dry Southeast, wet conditions in a region encompassing the northern Great Plains and upper Mississippi River valley continued with unusual persistence. Above-normal streamflow has prevailed across this region for 5 consecutive years. Historically, several 6-year sequences of above-normal streamflow and one 12-year drought (around the 1930's) have occurred in this area. In the western Rocky Mountains, mainly in Utah and in western Colorado, 5 consecutive years of above-normal streamflow occurred, which led to a record-high elevation for the Great Salt Lake—4,211.80 feet above sea level on June 1, 1986. The lake has risen 12.15 feet in less than 4 years resulting in extensive flooding.

In addition to the Southeast drought, water year 1986 included a number of other significant hydrologic events. In November 1985, the remnants of Hurricane Juan mingled with a low-pressure area moving in from the west and the entire system stalled over the Appalachian Mountains. From November 1 through 6, this unusual combination of weather systems caused rainfall in excess of 18 inches over the western areas of Virginia and 12 inches in West Virginia. The worst of the resultant flooding occurred in West Virginia, where the 100-year recurrence interval was exceeded in many areas. On August 6, 1986, a severe thunderstorm, focused in a narrow band 1 to 4 miles wide and 12 miles long, caused record flooding in Milwaukee, Wis. More than 5 inches of rainfall fell in 2 hours, inundating Milwaukee County Stadium (home of the Milwaukee Brewers baseball team) up to the fourth row of box seats. Torrential thunderstorms that began on September 10, 1986, dumped more than 10 inches of rain over a 3,500-square-mile area of the Lower Peninsula of Michigan, causing more than $400 million in damages. Crop damage was severe, and abnormally high precipitation for the remainder of September prolonged inundation of some agricultural land and prevented the salvage of many crops.

One of the most dramatic hydrologic events in the United States during this century occurred on May 29, 1986, when the Hubbard Glacier, which had been advancing across the mouth of Russell Fiord, completely sealed the entrance to the fiord, in the Tongass National Forest near Yakutat, Alaska. Russell Fiord (transformed by the ice dam into Russell Lake) filled rapidly, giving rise to the possibility that by 1987 the elevation of the lake would be so high that it would discharge into the neighboring Situk River basin with serious ecological and economic consequences. On October 8, 1986, before this could occur, the Hubbard Glacier ice dam failed and produced what was perhaps the greatest short-lived discharge of water in North America since glacial-lake outburst floods occurred at the end of the Pleistocene Epoch (about 10,000 years ago). Continued glacier advance, repeated damming of Russell Fiord, overflow from the impoundment into the Situk River, and eventual glacier advance into Disenchantment Bay and Russell Lake, are highly likely future occurrences.

Natural radioactivity and its effects on human health recently have become a major environmental concern because of the discovery of widespread occurrence, especially in Eastern United States, of the radioactive gas radon in the air of homes at concentrations that exceed the U.S. Environmental Protection Agency's recommended maximum levels. A less publicized but also important health hazard is the presence in ground water of naturally occurring radioactive substances. In addition to radon, large concentrations of dissolved radionuclides have been detected in some ground-water supplies throughout the United States. Although much is known about the theoretical geochemistry of radionuclides in ground water, predicting the amount of radionuclides in a particular ground-water supply is very difficult because of the strong influence of local geologic, geochemical, and hydrogeologic conditions. More data are needed particularly in rural areas where individual wells or springs are the usual sources of household water. Fortunately, conventional methods for treating raw water for some other contaminants also are effective in removing radionuclides found in ground water.

Water year 1986 marked both an anniversary and a beginning in the history of western water development. Hoover Dam, the Nation's highest and third-largest concrete dam, began its second 50 years of operation. The structure—identified by the American Society of Civil Engineers as one of the Nation's seven modern civil engineering wonders—dams the Colorado River between Nevada and Arizona near Las Vegas, Nev., forming 100-mile-long Lake Mead and impounding a volume of water nearly equal to 2 years of normal Colorado River flow. Now a National Historic Landmark, Hoover Dam continues to meet vital water-supply, power-production, and flood-control needs in the southwestern United States.

The Central Arizona Project delivered its first water to the Phoenix area on November 15, 1985, marking the completion of the first section of this major interbasin diversion from the Colorado River. The project, under construction by the U.S. Bureau of Reclamation and the State of Arizona, consists of three sections: the now-completed 190-mile-long Granite Reef Aqueduct; the partly completed Salt—Gila Aqueduct; and the Tucson Aqueduct, which is projected to be completed in 1991. When the entire aqueduct system is in operation, it will provide 60 percent of Arizona's surface-water supply, which will replace about two-thirds of the present ground-water withdrawal in the State.

HYDROLOGIC PERSPECTIVES ON WATER ISSUES

The hydrologic perspectives part of the 1986 *National Water Summary* provides an introduction to some of the technical and institutional issues that must be considered in developing ground-water-management programs. It also provides background information for the "State Summaries of Ground-Water Quality."

WATER-QUALITY ISSUES

The natural chemical quality of ground water is determined largely by the types of rock through which the water moves. Thus, the water chemistry observed in aquifers can be attributed to one or more combinations of these natural processes—dissolution and precipitation, oxidation-reduction reactions, ion exchange, biological activity within an aquifer, and mixing of ground waters of different compositions.

The vulnerability of an aquifer to contamination from land-surface or near-surface sources mainly depends upon the extent and location of recharge areas in relation to contamination sources, depth to the ground-water body, the composition of the soil and rocks overlying the aquifer, the recharge rate, and the potential for biodegradation of contaminants. Most dissolved contaminants move with the ground-water flow. Therefore, the ground-water flow system must be defined in order to determine the flow path of the solutes. Aquifers that have solution openings permit relatively rapid transport of pollutants from the surface and, thus, are very susceptible to contamination. Where soil mantles are thin or nonexistent and where ground water is relatively close to the surface, recharge rates can be rapid with little or no opportunity for pollutants to degrade or to be adsorbed on the rock materials. Once in the ground water, contaminants can move away from their source at the rate of ground-water flow with little alteration. Karst terrain, for example, which occupies nearly half of Kentucky, permits surface flows to enter ground-water systems directly through sinkholes and solution openings in subsurface limestone. In the past, sinkholes have been used as local waste dumps or for drainage sumps to carry away storm-water runoff from urban and agricultural areas, which resulted in the contamination of springs and wells by bacteria, nutrients, and whatever other contaminants were in the wastes. Similar conditions are found in many other parts of the United States including Alabama, Arkansas, Florida, Georgia, Missouri, and Tennessee.

Florida's hydrogeologic features, which are typical of many areas, include a thin soil layer, thick permeable sand overlying porous limestone aquifers, high water table, and large amounts of rainfall. These features make Florida's ground water particularly vulnerable to contamination from land-use activities associated with its rapidly expanding population. Aquifers in alluvial and terrace deposits in Oklahoma and valley-fill aquifers in New Mexico are other examples of ground water vulnerable to contamination because soils are thin or highly permeable and water tables are shallow.

Glacial-drift aquifers, which underlie much of the north-central and Northeastern United States, are very susceptible to contamination from surface activities. The same hydrologic characteristics that cause these aquifers to be sources of relatively large supplies of ground water facilitate the entry and migration of contaminants. The combination of relatively large transmissivity, shallow water table, absence of confining beds, thin and pervious soils, and their hydraulic connection with surface-water bodies significantly increases the potential for glacial-drift aquifers to become contaminated.

Deep, confined aquifers generally are much less vulnerable to contamination than are unconfined, shallow aquifers because the deep zones are more protected and isolated from pollution sources by the rock materials that constitute the confining beds. However, confined aquifers can be contaminated by sources located in their recharge areas or by sources that originate in the deep subsurface, such as leaking well casings, or features, such as permeable fault zones, that bypass natural geologic barriers. Aquifer recharge areas are extremely important because dumps and leaking storage tanks in these areas could release contaminants directly into the aquifer. The location of recharge areas, however, may be not be static; existing discharge areas can be converted into "new" recharge areas as a result of large withdrawals from wells that alter local or regional hydraulic gradients and flow directions.

Once contaminated, ground water is very difficult and expensive to cleanup. The selection of the best cleanup technology can be assisted by computer-based models that predict the movement of contaminants in ground water, although more research is needed to improve the existing understanding of solute-transport processes. The lack of relevant hydrologic, geologic, and chemical data at many sites unfortunately can severely limit the ability of scientists to use these predictive models effectively.

At some sites where contamination is a serious problem, contaminants have spread through the aquifer beyond any practical capability for intercepting or removing them. At such sites, the most practical strategy from a technological point of view might be to cleanup the source of contamination, monitor and track the location of the contaminated water, and await the slow natural flushing of the aquifer system while protecting it from further degradation. At other sites, the aquifer conditions and the type of contamination may allow contaminants to be removed at acceptable costs. The least costly strategy for the future will be to protect valuable aquifers from contamination rather than attempting to clean them up after they are contaminated. Whatever approach to ground-water contamination is used, the keys to a successful strategy are reliable data and an adequate understanding of the ground-water-flow system.

Six studies from the U.S. Geological Survey's Toxic Waste—Ground-Water Contamination Program are used to illustrate some of the complexities in finding and controlling ground-water contamination. One article describes a plume of contaminated ground water more than 2 miles long that has been created by 50 years of disposal of effluent from a sewage-treatment plant on Otis Air Base, Cape Cod, Mass. About 2.6 billion cubic feet of the Cape Cod sole-source aquifer has been affected by the disposed sewage. Low transverse dispersion in the aquifer has restricted the contaminants to a narrow, thin plume. This limited mixing has resulted in high contaminant concentrations in the core of the plume as far as 1 mile downgradient of the disposal site and in steep chemical gradients between the contaminant plume and surrounding uncontaminated water. This plume is an example of the contamination that can occur in a shallow, permeable, unconfined aquifer—the type of aquifer contaminated at many sites in Northeastern United States.

The complexities of investigating and delineating the extent of organic contaminants in ground-water systems contribute to making aquifer cleanup and restoration an interdisciplinary and long-term task. The complexities presented by organic contaminants are exemplified by five studies in diverse geographic locations. In Pensacola, Fla., at an abandoned wood-preserving plant, creosote wastes containing numerous organic compounds have infiltrated into the subsurface from surface impoundments. The organic compounds are abundant in the ground water, although some are being selectively degraded by microbial activity, possibly sorbed into aquifer sediments, and thus removed from the aqueous phase. Contamination extends to a depth of 110 feet below land surface and about 1,200 feet downgradient from the impoundments. The waste plumes are much less extensive, both areally and vertically, than would be expected from estimates of ground-water velocity.

In St. Louis Park, Minn., a suburb of Minneapolis, the site of a coal-tar distillation and wood-preserving plant provides a clear illustration of the interaction between ground-water pumping and contamination. Between 1918 and 1972, creosote-like coal-tar compound fluids accumulated in the glacial-drift aquifer, and by 1978, trace amounts of coal-tar compounds, including suspected carcinogens, were detected in public-supply wells completed in the deeper Prairie du Chien—Jordan aquifer. Coal-tar derivatives had migrated into the Prairie du Chien—Jordan aquifer because of local reversals in the regional hydraulic gradient caused by ground-water withdrawals and because of the flow of water through wells that tap several other aquifers in which contamination was present. A management plan, aided by computer simulations of ground-water flow, has been devised to accomplish two objectives—to control the hydraulic gradients and, thereby, alter the direction of contaminant transport in the Prairie du Chien—Jordan aquifer, and to treat contaminated water from the public-supply wells for subsequent use.

Agricultural productivity on lands overlying the High Plains aquifer system depends heavily on the use of fertilizers and organic pesticides and herbicides. These chemicals, however, pose a threat to ground-water quality of the region. In a study of six areas of the High Plains aquifer in Nebraska, the statistical relation of nitrogen and triazine (a herbicide) in ground-water samples to land use and hydrogeologic variables was examined. Three independent variables—well depth, irrigation-well density, and nitrogen-fertilizer use—explained 51 percent of the total variation in the nitrate concentrations. When correlated with triazine-herbicide concentration, nitrate concentration alone explained in a statistical sense 61 percent of the variation in the herbicide concentrations, suggesting that nitrate concentration might be an inexpensive test to identify areas with similar potential for triazine-herbicide concentrations in ground water.

In the New Jersey Coastal Plain, the most extensively used aquifer for water supply is the Potomac-Raritan-Magothy aquifer system. The recharge area of the aquifer, which parallels the Delaware River, is heavily industrialized with numerous landfills, surface impoundments, petrochemical storage tanks, and industrial facilities. Specific groups of contaminants detected in the aquifer appear to be associated with land uses in the outcrop area. For example, between Perth Amboy and Trenton, N.J., volatile organic compounds (mostly industrial solvents, degreasers, or fuels) were associated most closely with urban land, whereas pesticides (3 organochlorine insecticides and 2 triazine herbicides) were found more frequently in agricultural areas. The presence of the organochlorine insecticides reflects their long-term persistence in the environment even though the use of these insecticides has declined significantly during the past 20 years.

A similar study of the Upper Glacial aquifer on Long Island, N.Y., also demonstrated strong associations between land uses and ground-water contamination. Ground water from undeveloped areas had the lowest concentrations of inorganic chemical and volatile organic compounds. Trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane were the most common volatile organic compounds associated with industrial, commercial, institutional, and high-density residential areas. High-density residential areas also had the highest median concentration of chloride and dissolved solids, whereas agricultural areas had the highest median concentrations of nitrate and sulfate. The relation of the occurrence of volatile organic compounds in ground water to land use and population density suggests that refinement of land-use and water-quality relations in specific geographic areas could assist ground-water-management agencies to identify potential areas of contamination.

INSTITUTIONAL AND MANAGEMENT ISSUES

For a variety of reasons, ground-water quality is more difficult to manage and protect than the quality of surface-water resources. Thus, the problem of ground-water contamination has challenged the ingenuity and institutional capacity of government at all levels in the United States. Ground water moves slowly and rates of mixing and dilution of contaminants generally are very small. As a result, pollutant concentrations in ground water tend to be more persistent than they are in surface-water systems. The range of pollutants to be addressed is enormous and data are limited. Also, from a regulatory point of view, protecting ground-water quality implies controlling millions of discharges from waste dumps, surface impoundments, underground storage tanks, and a variety of activities of small businesses, farmers, and even individuals. Although prevention of contamination is complex and difficult, the alternative—cleanup of contaminated ground-water—is extremely costly and not always effective.

Federal agencies such as the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey recognize ground-water contamination as an important and controversial issue. EPA's "Ground-Water Protection Strategy," issued in 1984, reflects the principal role of the States in protecting ground water, and the Federal Government's responsibility for controlling certain contaminants and activities affecting ground water, such as the use of pesticides and the control of hazardous-waste sites. The Federal Government also conducts research, sets drinking-water standards, characterizes the resource, gathers information, and provides technical and financial assistance to the States.

A major issue facing Federal, State, and local government is how to prevent contamination of ground water. The U.S. Office of Technology Assessment has defined 33 major source categories of contamination. Existing Federal legislation that affects ground water deals with controlling sources of contamination and the use of certain chemicals. The Safe Drinking Water Act Amendments of 1986 encourages States to initiate ground-water-protection programs and to focus protection efforts on high-risk areas such as around public water wells. The aforementioned "Ground-Water Protection Strategy" fosters the creation of State ground-water protection strategies, which EPA supports through the Clean Water Act, Section-106 grants. Nearly all the States have or are developing protection strategies.

Another issue being debated is "how clean is clean," that is, what kind of protection should be afforded to ground water. In general, a nondegradation policy for ground water is technically infeasible, although such a goal has strong public support. In recognition of this issue, EPA's strategy adopts a differential protection policy, which stresses the need for greater protection and cleanup efforts for high-risk, high-use areas. As is clearly illustrated by the "State Summaries of Ground-Water Quality" in this volume, some ground water is not potable because of natural quality impairments and does not need the same level of protection that is needed, for example, by ground water that is used for drinking water. Similarly, the differential protection policy reflects the recognition that protection actions can be varied, depending upon the degree to which an aquifer is vulnerable to contamination. EPA developed a ground-water classification system as a framework and guide for applying a differential protection policy in EPA programs. A similar approach also has been adopted by about half the States.

Generally, EPA and State agencies have used drinking-water standards or maximum contaminant levels or equivalents as the basic standard for protection and cleanup of ground water. A major related question is whether or not the same standards should be used in restoring the ground water around a Superfund site as are used to protect a source of public water supply. Distinguishing between standards for cleanup and prevention and designing ground-water programs that provide for greater balance between prevention, restoration, and distribution, may achieve a greater level of water-supply protection than can be provided with existing levels of funding for ground-water programs. Another complex question that remains to be resolved is: Who pays for the cleanup of contaminated ground water and for the damages caused by contamination?

The National Research Council, Committee on Ground-Water Quality Protection, reviewed selected State ground-water-protection plans and programs and identified many promising program elements. Although no single program covered all desirable aspects of a model ground-water-protection program collectively the program elements described by the committee offer a wide array of presently used approaches to ground-water-quality management. A significant conclusion that can be drawn from the committee's review is that the differences in the States' physical, social, and political conditions are such that no single strategy for dealing with ground-water problems can be recommended for all States or localities. The committee recommended eight criteria for a comprehensive ground-water-protection program: (1) clearly stated goals and objectives; (2) a good information base about the resource and the problems; (3) a sound technical basis for strategies; (4) actions to eliminate or reduce sources of contamination; (5) mechanisms to coordinate actions at different governmental levels; (6) adequate legal authority and funding; (7) a process for evaluating economic, social, political, and environmental impacts; and (8) credibility with the public.

STATE SUMMARIES OF GROUND-WATER QUALITY

The State summaries of ground-water quality, which constitute the final part of the 1986 *National Water Summary*, illustrate the great variety of conditions that can exist at the State and local levels. As mentioned previously, these State summaries clearly show that the Nation has very large amounts of potable ground water. In their discussion of the contamination problem some State summaries concentrate on local problems associated with hazardous waste sites, some on contamination from urban areas, and others on statewide problems of agricultural chemicals. These differences of emphasis reflect the wide variety in hydrogeology, economics, and contamination threats to be found among the States. An important lesson to be learned from the State summaries is that any national policy on ground-water protection will need to be sufficiently flexible to address a large number of situations and concerns, to take advantage of and build upon existing institutions and laws, and to gain the support of the public while recognizing the limitations imposed by our currently incomplete understanding of ground-water resources.

INTRODUCTION

National Water Summary 1986—Hydrologic Events and Ground-Water Quality is a continuation of aquifer descriptions presented in the 1984 *National Water Summary* (U.S. Geological Survey, 1985). This year's report on ground-water quality is organized into three parts. The first part, "Hydrologic Conditions and Water-Related Events, Water Year 1986," provides a synopsis of the hydrologic conditions and water-related events that occurred during the 1986 water year (October 1, 1985–September 30, 1986). Streamflow variations are compared to precipitation, temperature, and upper-air atmospheric pressure patterns for the four seasons of the year to demonstrate the relation between seasonal climatic regimes and streamflows. Selected events described in this part include the blockage of Russell Fiord, Alaska, by Hubbard Glacier, and the subsequent breakout of the lake that formed behind an ice dam; floods in Michigan, Wisconsin, and West Virginia; a severe drought in the Southeastern United States; the emergence of major concerns about radon as a health hazard in the home; and two engineering milestones—the 50th anniversary of Hoover Dam and the opening of the Central Arizona Project.

The second part of the report, "Hydrologic Perspectives on Water Issues," contains two sections. The first, "Water-Quality Issues," describes the major factors controlling ground-water quality and illustrates, by six examples, the many ways in which ground water can become contaminated from point and nonpoint sources and the water-quality changes that take place as the contaminants move through the flow system. The second, "Institutional and Management Issues," reports on current thinking by the U.S. Environmental Protection Agency (EPA) about the Federal Government's role in ground-water protection and also describes the results of a recent study of State and local ground-water protection strategies conducted by the National Research Council.

The third and final part of the report, "State Summaries of Ground-Water Quality," summarizes the ambient quality of ground water in the principal water-supply aquifers and describes the nature and extent of contamination in each State, the District of Columbia (combined with Maryland), Puerto Rico, the U.S. Virgin Islands, the Trust Territories of the Pacific Islands, Saipan, Guam, and American Samoa. Information about the dissolved minerals in ground water generally is available for major aquifers. The distribution of synthetic contaminants, however, especially organic compounds, is much less well known, and the amount of information varies greatly from State to State. Each of the State summaries has multicolor maps that show the location of selected waste sites and areas of ground-water-quality concerns. The contents of the State summaries are discussed in the article "Synopsis of the State Summaries."

To supplement the information provided, bibliographic references are given at the end of each article and State summary. Most technical terms used in this volume are defined in the glossary. Since numerous text references are made to the national drinking-water regulations, these regulations are listed following the glossary. A conversion table of water measurements, a geologic-age chart, and a list of the chemical and common names of organic compounds mentioned in this volume also are provided for the reader's convenience.

The 1986 *National Water Summary* complements other reports, both Federal and non-Federal, that address the complex issue of ground-water contamination. A frequently cited report is *The Report to Congress, Waste Disposal Practices and Their Effects on Ground Water*. This EPA report, which describes the results of a survey of the disposal of wastes that might endanger water supplies and the means by which such disposal could be controlled, was submitted to Congress in fulfillment of the requirements of Sec. 1442(a)(4) of the Safe Drinking Water Act of 1974 (Public Law 93-523). Subsequently, the report was published in book form (Miller, 1980).

Another overview of ground-water quality was prepared by staff at the Philadelphia Academy of Sciences (Pye and others, 1983). Subsequently, the Office of Technology Assessment (OTA) noted that ground-water contamination had become the focus of public attention nationwide. The OTA was asked by the Congress to assess the current status of the Nation's knowledge about ground-water contamination and the ability of Federal and State programs to deal with the contamination problem. The resulting report (Office of Technology Assessment, 1984) concluded that Federal and State programs generally were concerned with managing selected point sources of contamination, regulating specific sets of contaminants, and protecting public drinking-water supplies. The OTA recommended that in order to protect the Nation's ground water from further contamination, the focus of those programs needed to be broadened.

A review of the state of scientific understanding of transport of ground-water contaminants by the National Research Council's Panel on Ground-water Contamination concluded that the capability to predict the behavior of chemical contaminants in ground water is necessary to assess risks associated with contamination problems and to design effective techniques to mitigate the problems (National Research Council, 1984). The study called for research on transport processes, a more thorough search for disposal sites that safely isolate toxic wastes from the biosphere, the segregation and disposal of wastes according to their hazards and chemical affinities, and decisions by governmental and industrial organizations on the location of repositories in which to dispose of various classes of wastes. At the request of EPA, the National Research Council established a Committee on Ground-Water-Quality Protection to examine various State and local ground-water-protection strategies. The committee concluded that no single program reviewed addressed all aspects of ground-water protection inasmuch as the State approaches to ground-water protection differ from State to State because of their physical, social, and political makeup (National Research Council, 1986). (See "State and Local Strategies for Protection of Ground-Water Quality—A Synopsis" in this volume.) The EPA reports providing information about ground-water protection activities included an *Overview of State Ground-Water Summaries* (U.S. Environmental Protection Agency, 1985) and a *Survey of State Ground-Water-Quality Protection Legislation, 1985* (U.S. Environmental Protection Agency, 1987).

Finally, the Conservation Foundation issued the final report of the National Groundwater Policy Forum and a guide to ground-water pollution problems, causes, and government responses (Conservation Foundation, 1986). The forum concluded, as did previous studies, that the variability of ground-water resources requires local flexibility in the approach to contamination problems. In particular, the forum recommended Federal legislation that would cite ground-water-quality protection as a national goal. This theme was repeated by the Environmental and Energy Study Institute's examination of ground-water quality and protection needs (Environmental and Energy Study Institute, 1986). The institute recommended that the Congress adopt the protection of ground water as a national goal and also improve the coordination of existing ground-water information and technical-assistance activities.

Acknowledgments

The 1986 *National Water Summary* is the fourth in a series of U.S. Geological Survey Water-Supply Papers prepared under the direction of Philip Cohen, Chief Hydrologist, U.S. Geological Survey. A goal of the *National Water Summary* series of reports is to organize in abbreviated form factual information about water conditions in the United States. The scope of this task requires information to be assembled from many individuals within the U.S. Geological Survey and from various Federal and State agencies. The report compilers gratefully acknowledge the assistance of water-resources agencies in each State in preparing and reviewing the State summaries of ground-water quality. In addition, the following Federal agencies provided data, advice, and review of parts of this report:

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U.S. DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION
U.S. DEPARTMENT OF TRANSPORTATION, COAST GUARD, NATIONAL RESPONSE CENTER
U.S. ENVIRONMENTAL PROTECTION AGENCY

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HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS, WATER YEAR 1986

REVIEW OF WATER YEAR 1986 HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS

By Harry F. Lins, John C. Kammerer, and Edith B. Chase

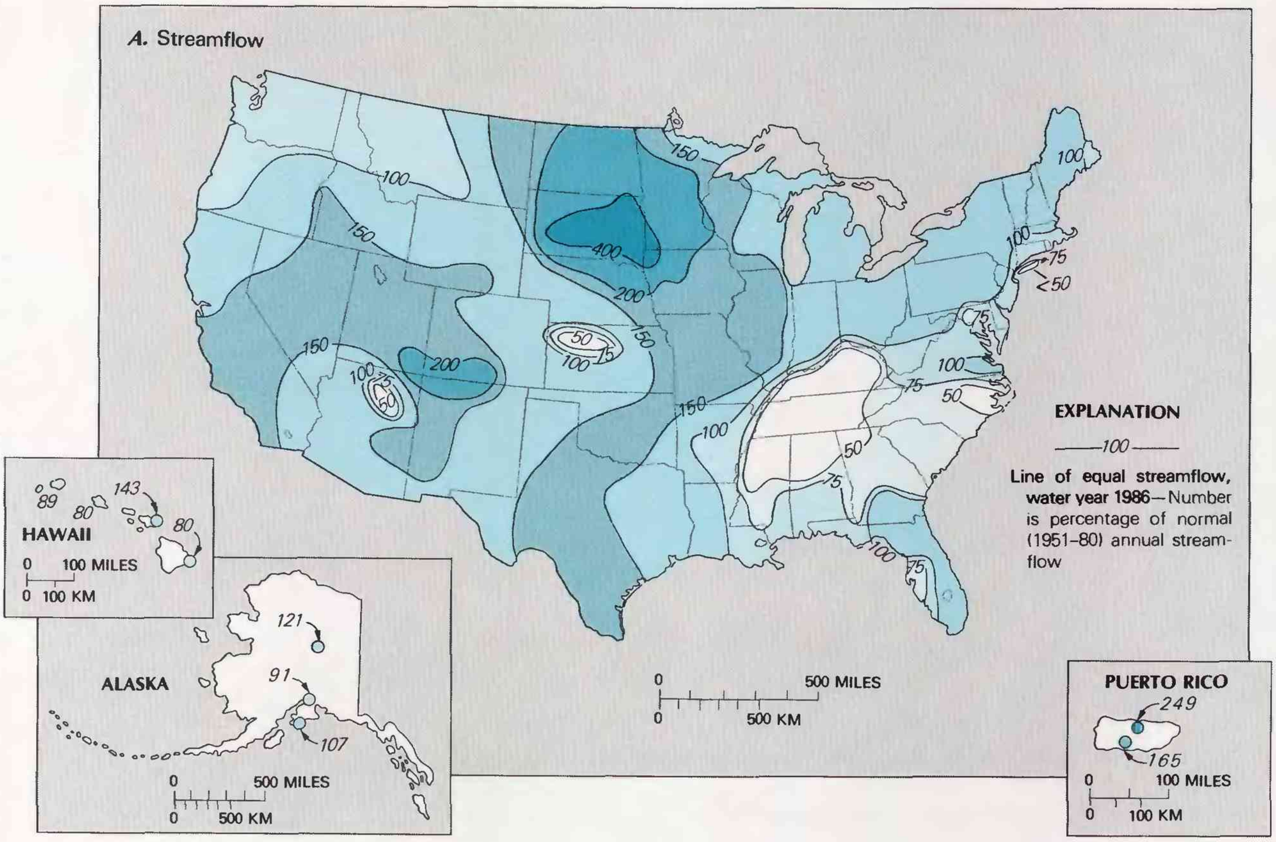
Surface-water hydrologic conditions and many water-related events are controlled primarily by meteorologic and climatic factors. The following annual and seasonal summaries of hydrologic conditions for water year 1986 are, therefore, described in a climatic context. Streamflow and precipitation, expressed as departures from long-term mean or normal conditions, are depicted on maps for a water-year overview. These quantities also are presented on a quarterly basis in seasonal summaries, accompanied by maps showing temperature as a departure from average conditions and mean atmospheric pressure conditions near 10,000 feet. The distribution of high- and low-pressure areas across the United States at about 10,000 feet, recorded in terms of the 700-millibar pressure surface, or height field, influences the distribution of surface temperature, precipitation, and, thus, streamflow. Usually, excessive precipitation and droughts that persist throughout a season will be observed in conjunction with persistent high- or low-pressure conditions in the upper atmosphere. Inasmuch as these maps depict conditions averaged over a 3-month period, ephemeral events, such as a single flood resulting from an individual storm, may not be associated easily with the general upper-level circulation.

The data used in preparing these summaries were taken from the following publications: the National Oceanic and Atmospheric Administration's *Climate Impact Assessment, United States*; *Daily Weather Maps, Weekly Series*; *Monthly and Seasonal Weather Outlook*; *Storm Data*; and *Weekly Weather and Crop Bulletin* (the last publication is prepared and published jointly with the U.S. Department of Agriculture); and the U.S. Geological Survey's monthly *National Water Conditions* reports. Geographic designations in this article generally conform to those used in the *Weekly Weather and Crop Bulletin* (see map).

Hydrologic conditions across the United States during water year 1986 were characterized by intense regional extremes of both wetness and dryness. The most notable features included a severe and prolonged drought in the Southeast, a broad area of very high streamflows in the northern Great Plains and upper Mississippi Valley, and a band of much-above-normal streamflows in the Four Corners area (fig. 1*A*). Regionally there were many similarities in streamflow conditions between water years 1985 and 1986. Both years had below-normal flows in the Southeast and mid-Atlantic States, Pacific Northwest, and parts of Kansas. Above-normal flows dominated both years in the northern Great Plains and upper Mississippi Valley and in parts of the Southwest. Significantly, however, the magnitude of the departures from normal increased dramatically in 1986, especially in the north-central part of the country and in the Southeast.

By far the most significant aspect of the 1986 water year was the prolonged and severe drought in the Southeastern United States (see article in this volume "Drought in the Southeastern United States, 1985–86"). The drought developed during the winter and spring seasons when the subtropical jet stream, normally overlying the Southeast in winter and spring, turned out to be both weaker and more meandering than normal. During winter, cyclonic storms, which typically form in and move through the Gulf and southeast Atlantic States, were displaced farther north and west. This effectively deprived much of the Southeast of its usual abundant winter moisture. During spring, when the track of the jet stream and surface storm systems seasonally migrate northward in response to the weakened temperature gradients across the mid-latitudes of the northern hemisphere, the pattern of frequent northward displacement persisted. Thus, upon entering the season of increasing water demand due to evapotranspiration and agricultural and domestic uses, the moisture problem was exacerbated as relatively weak atmospheric flow over the eastern United States produced very little precipitation (fig. 1*B*).

It is possible to see how more localized hydrologic conditions fit into the broader regional patterns by reviewing the graphs of monthly discharges for selected rivers and month-end storage of selected reservoirs (figs. 2, 3). Notice, for example, the contents of the Clinch River Projects reservoir in Tennessee and Lake Sidney Lanier in Georgia, both of which are located in the core drought area in the Southeast. In each instance, storage remained below the long-term median end-of-month value during most of the year. At the other extreme, the abundant moisture conditions in the northern and central Great Plains and upper and middle Mississippi Valley are reflected in the graph of monthly flows on the Mississippi River at Keokuk, Iowa, and on the Missouri River at Hermann, Mo. At both sites, flows exceeded



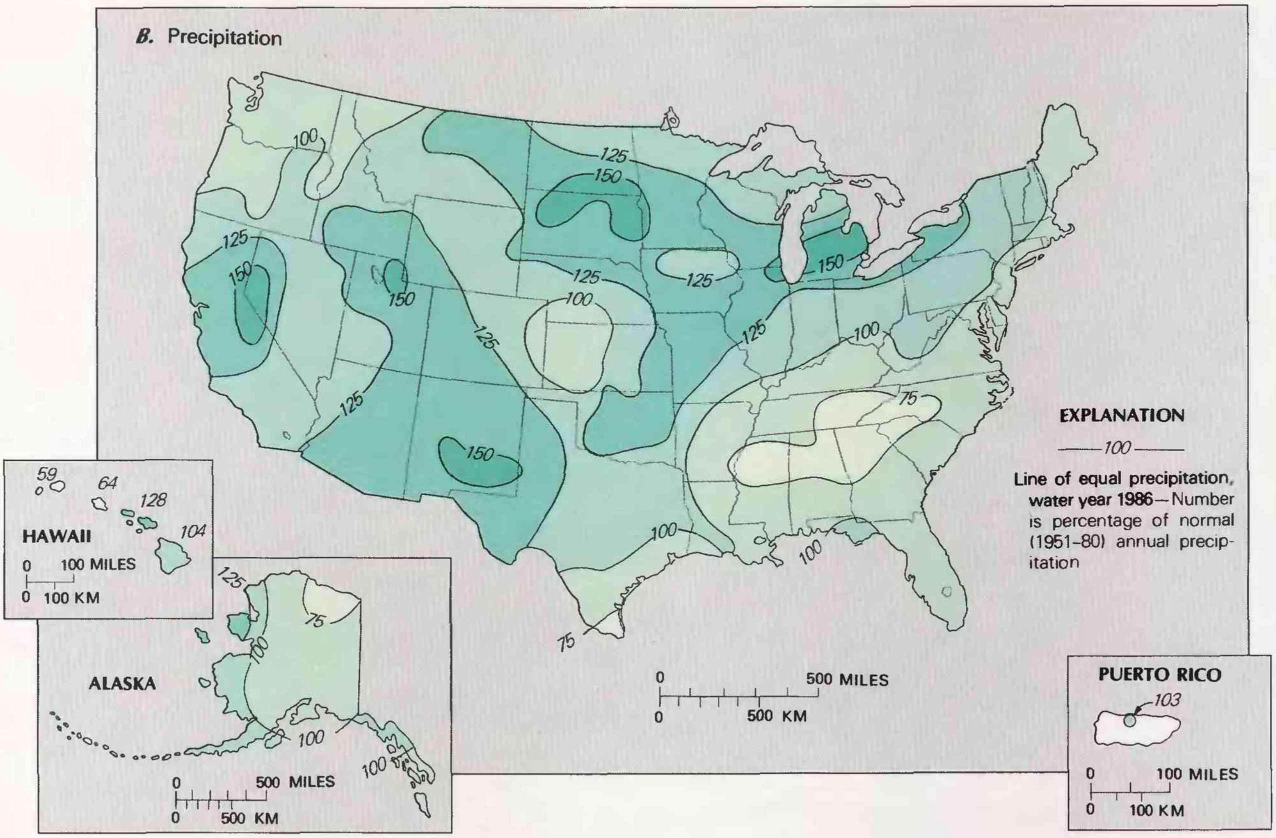


Figure 1. Streamflow (*A*) and precipitation (*B*) in the United States and Puerto Rico in water year 1986. Data are shown as a percentage of normal. (Sources: *A*, Data from U.S. Geological Survey; *B*, Data from National Oceanic and Atmospheric Administration, National Climatic Data Center.)

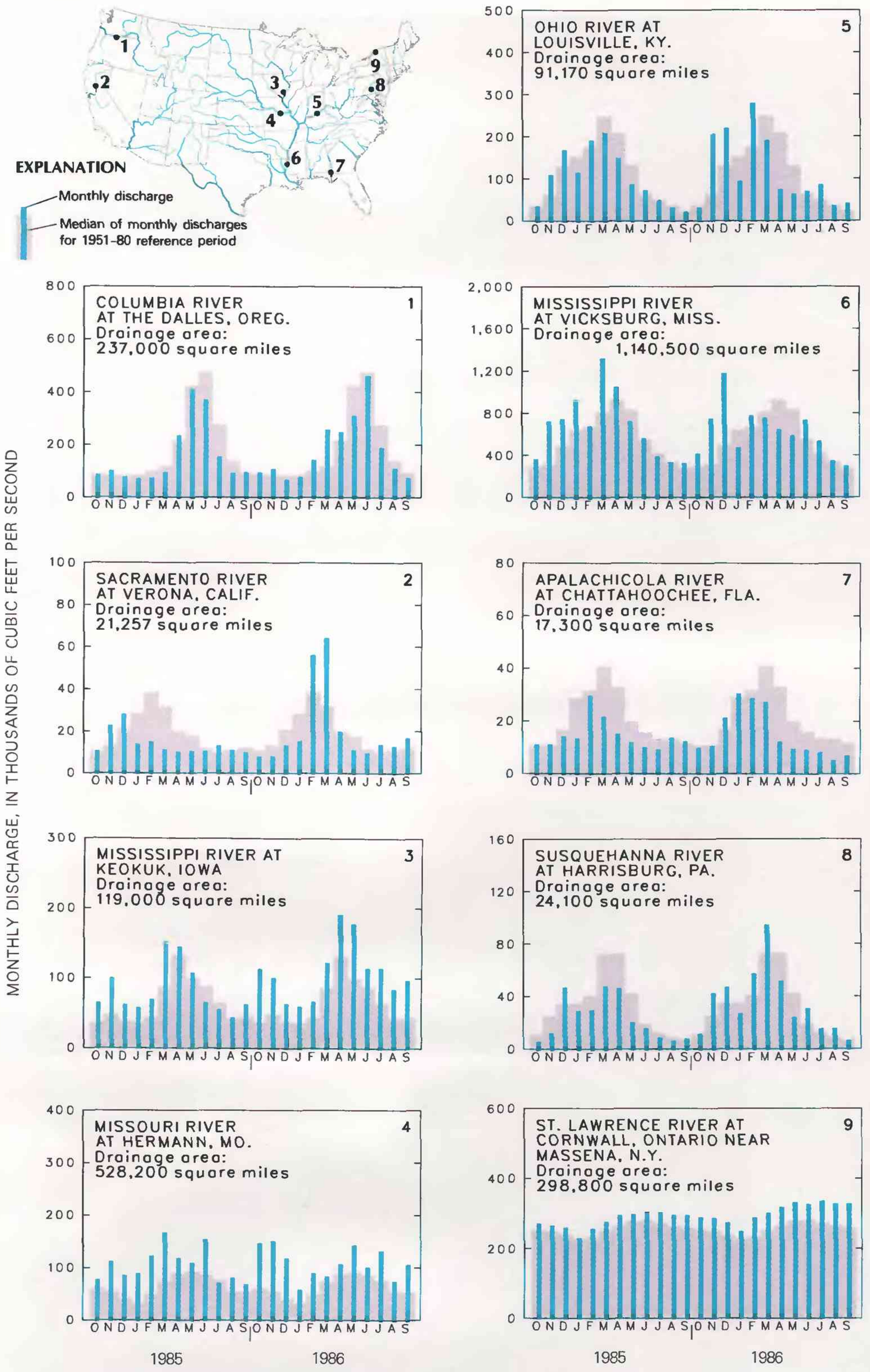


Figure 2. Monthly discharges for selected major rivers of the United States for water years 1985 and 1986 compared with monthly median discharges for the reference period water years 1951 to 1980. (Source: Data from U.S. Geological Survey.)

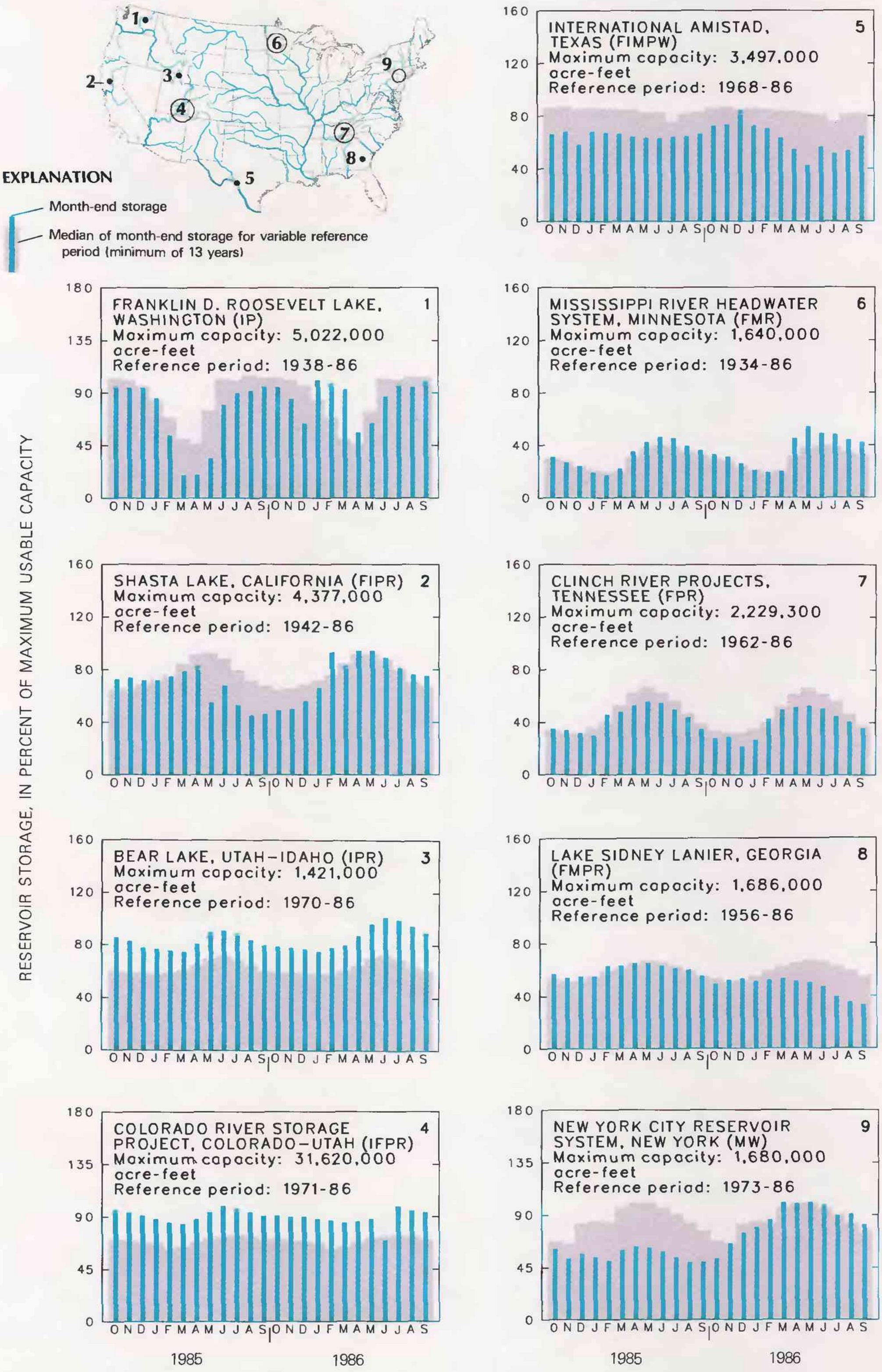


Figure 3. **Month-end storage of selected reservoirs in the United States for water years 1985 and 1986 compared with median of month-end storage for reference period.** Reference period varies but is a minimum of 13 water years. The reference period for each reservoir or reservoir system is shown on the graph; the beginning year for the reservoir system is the year records began for the last reservoir in the system. The location of individual reservoirs is shown on the map by a black dot; the general location of reservoir systems (multi-reservoirs) is shown by an open circle. Principal reservoir and water uses: F, flood control; I, irrigation; M, municipal; P, power; R, recreation; and W, industrial. (Source: Data from U.S. Geological Survey.)

the long-term monthly median in all months of the water year. Similarly, storage in Minnesota's Mississippi River Headwater Reservoir System either met or exceeded its median value in all months of the year.

The wet conditions in the region encompassing the northern Great Plains and upper Mississippi Valley are particularly noteworthy for their marked persistence. Above-normal streamflow has prevailed across this region for 5 consecutive years. More significant, however, is the fact that this area has shown pronounced persistence of both wet and dry conditions over the past 6 decades. For example, a 6-year sequence of above-normal streamflow dominated this region between 1947 and 1952, and it was closely followed by another 6-year period, between 1954 and 1959, when below-normal flows prevailed. These 6-year sequences are short in comparison to the 12-year period of drought that existed in this area between 1930 and 1941. Studies show that this region exhibits strong spatial and temporal coherence in annual streamflow anomalies. Indeed, nearly 10 percent of the total variance in long-term nationwide streamflow is explained by a regional pattern of wetness or dryness centered on the northern Great Plains and upper Mississippi Valley.

A far more unusual condition of persistent wetness has been experienced in the western Rocky Mountains, primarily in Utah and in western Colorado. That region also has completed 5 consecutive years of above normal annual streamflow. Unlike the north-central part of the Nation, however, Utah and western Colorado are not part of a region typified by spatially and temporally coherent flow patterns. In fact, this area appears to be a transition or boundary region both climatologically and hydrologically. Thus, such persistence is very difficult to understand; however, the effects are not hard to understand. Consider what this prolonged wetness has done to the Great Salt Lake. On September 15, 1982, the surface of the Great Salt Lake stood at 4,199.65 feet above sea level. By June 1, 1986, the surface stood at a record 4,211.80 feet, a rise of 12.15 feet in less than 4 years, exceeding both the magnitude and the rapidity of the 12-foot rise from 4,199.60 in 1861 to 4,211.60 feet in 1873. The total increase in lake volume from the 1982 seasonal low to June 1, 1986 was 9,486,140 acre-feet (3,092 billion gallons)—enough water to cover the State of Rhode Island (area 1,214 square miles) with 12.21 feet of water.

Highlighting the broad pattern of surface-water conditions nationwide were a number of specific significant events. A chronological listing and description of these occurrences appears in table 1, and their geographic locations are plotted in figure 4. Table 1 represents a culling of some hundreds of hydrologic happenings, generally omitting, for example, floods where the recurrence interval is less than 10 years, toxic spills that involve less than 2,500 gallons of oil, and fishkills of less than 5,000 fish. The selection of events for inclusion in table 1 was affected to some extent by the degree of media coverage, including National Weather Service and U.S. Geological Survey periodicals, as well as by communications from U.S. Geological Survey field offices alerting the national office that significant hydrologic events had occurred. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data are based on information provided to the U.S. Geological Survey by the U.S. Environmental Protection Agency. The reporting of fishkills by the States to the Environmental Protection Agency is voluntary, and not all States presently report such data.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986

[The events described are representative examples of hydrologic and water-related events that occurred during water year 1986. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data were provided by the U.S. Environmental Protection Agency on the basis of reports transmitted by State agencies. Meteorological data mostly are from reports of the National Oceanic and Atmospheric Administration. Abbreviations used: Mgal/d = million gallons per day; ft^3/s = cubic feet per second; mi^2 = square miles]

No. (fig. 4)	EVENT
	OCTOBER 1985
1	From October 4 to 7, a tropical depression (upgraded to tropical storm Isabel on October 8) moved northward across Puerto Rico producing record-setting rains of as much as 22.3 inches in 24 hours. The heaviest rains fell on the southern mountain slopes in the Ponce area near the southern coast and created severe flooding and numerous landslides that claimed at least 182 lives; 55 of the deaths were the direct result of flooding, and the remainder occurred as a result of landslides on a hill on Ponce's northwestern outskirts on October 7. Highways were cut, utilities were disrupted, and thousands had to seek temporary shelter; 25 towns were declared disaster areas by the Governor of Puerto Rico in the wake of reportedly the worst natural disaster ever to occur in Puerto Rico. Estimated damages to private and public property were more than $65 million. Rainfall frequencies exceeded the 100-year recurrence interval at several recording sites, and peak discharge for at least one stream-gaging site also exceeded the 100-year recurrence interval. The Toa Vaca Reservoir (design capacity 44,000 acre-feet) filled completely for only the second time since it was built in 1970, reducing flood peaks and damages in the lower valley of the Rio Jacaguas west of Ponce. On the north coast, Rio Grande de Manati flooded Barceloneta for the second time in 5 months, and Rio de La Plata caused extensive flooding at Toa Alta, about 10 miles southwest of San Juan.
2	In southwestern Pennsylvania near Beallsville, Washington County, about 25 miles south of Pittsburgh, some 21,000 fish died (including trout and bass) on October 5, along 4 miles of an unnamed tributary of Pike Run. The cause was silt, mine drainage, and other matter entering the stream. Pike Run is a tributary of the Monongahela River.
3	The southern one-third of New Mexico received as much as 7 inches of rain on October 8 and 9 from remnants of Pacific Hurricane Waldo, resulting in flash floods in some areas.
4	From October 9 to 11, remnants of Hurricane Waldo brought 2 to 6 inches of rain to the Texas plains and its eastern and central panhandle as well as to western Oklahoma,

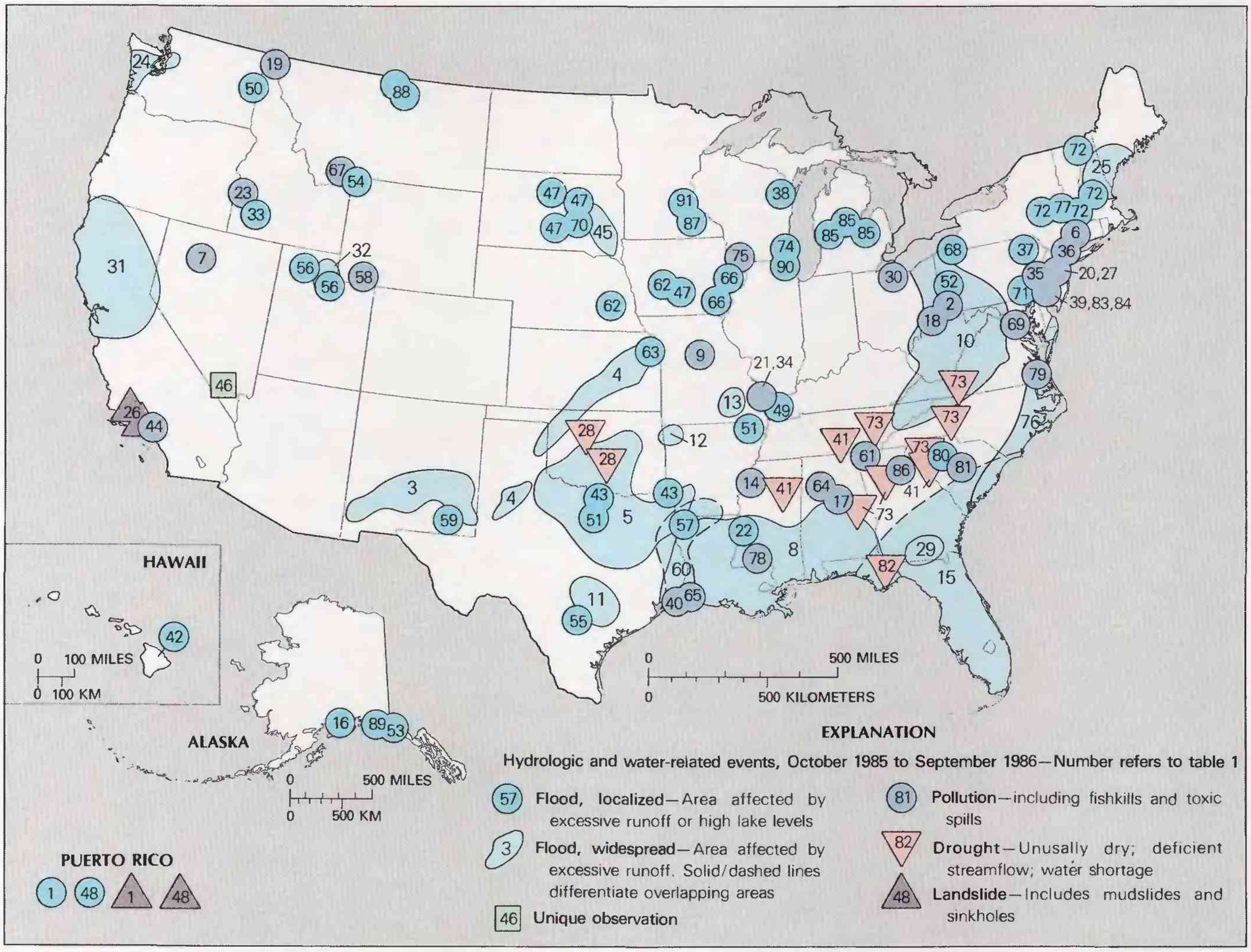


Figure 4. Location or extent of significant hydrologic and water-related events in the United States and Puerto Rico, October 1985 through September 1986.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986

No. (fig. 4)	EVENT
	OCTOBER 1985 (con.)
4 (con.)	central and northeastern Kansas, and south-central Iowa, causing localized flooding and moderate damage. In dry areas of Texas the rains were welcome and flash flooding was minimal because the rains were spread over a 2-day period. In central and northeastern Kansas the rain fell upon an area already wet from rains of the previous few days. Runoff sent streams several feet above flood stage for as many as 3 days. Major flooding occurred along the Marais des Cygnes, the Cottonwood, the Neosho, the lower Arkansas, the Little Arkansas, the Walnut, the Whitewater, the Ninnescah, and the Chikaskia Rivers.
5	Northeastern and north-central Texas received more than 7 inches of rain from repeated downpours on October 17 to 19, which resulted in 2 deaths, evacuation of more than 100 people from their homes, and lowland flooding of virtually all of northeastern Texas. On October 19 and 20, rains of 4 to more than 11 inches fell on southern Texas, with consequent floods and flash floods. Principal counties in the most severely flooded areas were Gillespie and Kerr Counties, Blanco and Burnet Counties, and Frio, La Salle, McMullen, Uvalde, and Zavala Counties. Flooding rivers included the Guadalupe, the Perdanales, the Nueces, the Frio, and the Atascosa Rivers.
6	On October 22 near Watertown about 4 miles northwest of Waterbury, Conn., 75,000 gallons of oil drained from a storage tank valve into a reservoir behind a containment dike. The valve had been opened after its lock had been cut. About one-third of the escaping oil breached the dike and entered Steele Brook, a tributary of the Naugatuck River at Waterbury. Cleanup operations were completed within a week.
7	Along 6 miles of the Humboldt River near Winnemucca (170 miles northeast of Carson City), Humboldt County, in northwestern Nevada, 15,000 fish (including catfish and bass) were killed on October 24 to 25 by methoxychlor used for flying-insect control.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	OCTOBER 1985
8	Hurricane Juan, the fifth North Atlantic hurricane of the season, lashed the central Gulf Coast October 26 to 31. It meandered along the central Louisiana coast and then moved east and north and inland at about the Alabama-Florida border, resulting in nearly 18 inches of rainfall in 5 days at the mouth of the Mississippi River in Louisiana. Rainfall totals of 7 to 13 inches were common along a 100-mile wide band of coast that included parts of five States. Louisiana's bayou country had severe flooding and damages accentuated by a 5- to 8-foot storm surge. At least 12 lives were lost, 9 associated with toppled oil rigs and boats lost at sea. On land, tens of thousands of residents were evacuated. Property damages, especially in Louisiana, but also including southern Mississippi and Alabama and the extreme western part of Florida's panhandle and extreme southeastern Texas, were about $1 billion. More than 50,000 homes were damaged in Louisiana alone. In Alabama major agricultural losses occurred to the soybean and pecan crops.
9	In Boone County in central Missouri, during the last week in October, urea ammonium nitrate fertilizer killed more than 17,000 fish (including bass and sunfish) along 7½ miles of Gans and Little Bonne Femme Creeks. These creeks flow into the Missouri River 9 miles south of Columbia, 110 miles west of St. Louis.
	NOVEMBER 1985
10	Hurricane Juan dissipated in the Ohio River valley November 1 and 2; a blocking high-pressure system off the east coast caused unusual amounts of moisture to move northward resulting in heavy rains from North Carolina to New York November 2 to 5. Rainfall totals exceeding 10 inches were common in the Appalachians in Virginia (more than 18 inches in two places) and West Virginia. The rains caused major floods November 3 to 7 in eastern West Virginia, western Virginia, and the Maryland panhandle and along the Monongahela River in Pennsylvania as flood magnitudes equaled or exceeded those for the 100-year recurrence interval at about 45 gaging stations in an 11,000-mi^2 area across the four States. Flash floods claimed 63 lives and damages were about $1 billion; the President declared 121 counties eligible for Federal disaster assistance. Officials evacuated tens of thousands of residents from flooded homes. The most severe flooding occurred along the flanks of the Appalachians in West Virginia and Virginia. For example, Cheat River near Parsons, West Va. (drainage area 718 mi^2), peaked at 200,000 ft^3/s, about 3.5 times the 100-year flood and about 3.8 times the former flood of record. In the Cheat River town of Albright, only 22 of the town's 132 houses were left standing. Flood frequencies were less than 100 years at gaging stations on the mainstem Potomac River downstream from Paw Paw, West Va. (See article in this volume, "The Ruinous West Virginia Flood of November 1985.") Roanoke River at Roanoke, Va. (drainage area 395 mi^2), peaked at a record high of 32,300 ft^3/s causing severe damages in that city as flood stages rose about 3.7 feet higher than those of the June 21, 1972, flood associated with Hurricane Agnes. On the Monongahela River in southwestern Pennsylvania, 62 barges broke loose from their moorings, hit other barges, and became caught in locks and dams.
11	Intense rains of 5 to 21 inches (21 at Garwood, Colorado County) on November 11 and 12 in southeastern Texas caused widespread flooding in a 10-county area bordering and west of Houston, especially along the San Bernard River and the lower Colorado River (of Texas). The bridge on U.S. Highway 59 over the San Bernard River near Hungerford, Fort Bend County, was under 4 feet of water, and 10 miles to the southeast near Boling the river reached a near-record crest of 41.5 feet. The most severely flooded areas were in Colorado County from south of Eagle Lake to the communities of Garwood and Lissie. In Rosenberg (Fort Bend County), 52 residents had to be evacuated from a nursing home. Damages in Wharton County alone (south of Colorado County) reportedly exceeded $1 million.
12	Flash flooding occurred in the five northwesternmost counties of Arkansas and adjacent Adair County, Okla., on November 18, as a result of 4- to 6-inch rainfall in 24 hours. War Eagle Creek (tributary to the White River), Benton County, rose about 20 feet. In Crawford County, a bridge along U.S. highway 71 was washed out. Barren Fork (tributary to the Arkansas River via the Illinois River) at Baron, Okla., crested at its highest level since 1944.
13	Severe local flooding on November 19 and 20 from rains in southern Missouri's White River basin drowned one person at Potosi, Washington County, and caused extensive damage to parkland facilities along the Ozark Scenic Riverways. The flooding near the head of the Current River (a tributary of the White River via the Black River) was reportedly the worst in 80 years. Peak flood flows at several stream gaging sites in southeastern Missouri had recurrence intervals exceeding 100 years.
14	From November 19 to 22, south of Clarksdale (Coahoma County) in northwestern Mississippi, contamination by an herbicide killed about 15,000 fish (including shad) along 25 miles of the Big Sunflower River. The river flows south into the Yazoo River, an eastern tributary of the Mississippi River.
15	Hurricane Kate, a rare late-season hurricane spawned November 16 and 17 north of Puerto Rico, moved west, northwest, and north and made landfall at Panama City on Florida's panhandle on the 21st. It was the first November hurricane to hit the United States in 50 years and had rainfall totals on the mainland of 5 to 10 inches. Some flash flooding occurred in parts of Florida, Georgia, and South Carolina, but high winds and tidal storm surges were by far the principal causes of death (at least six in the United States) and destruction—reportedly more than $200 million in total damages. Power lines were downed and 100,000 residents were evacuated from coastal areas.
	DECEMBER 1985
16	A breakout of a glacier-dammed lake on Alaska's Kenai Peninsula south of Anchorage affected flow of the Snow River over the period November 26 through December 6. The resulting maximum flow of the river was 12,000 ft^3/s on December 2. A breakout flood occurs here every 3 to 4 years, usually in September or October, but it sometimes has occurred more frequently and in other months.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	DECEMBER 1985 (con.)
17	On December 3 and 4 at Bessemer, Ala. (in Jefferson County, adjoining Birmingham), a spill of 5,000 gallons of diesel fuel at a rail-truck terminal drained into Valley Creek and killed nearly 9,000 fish along 8 miles of the creek. Valley Creek is a tributary of the Tombigbee River via the Black Warrior River.
18	In Tyler County in northwestern Ohio on December 5 and 6, chemical pollution from industrial operations killed about 11,000 fish along one-quarter mile of Sugarcamp Run. The small stream flows into the Ohio River about 30 miles northeast of Parkersburg, West Va.
19	On December 6 in northern Idaho 20 miles south of the Canadian border, an old railroad bridge at Bonners Ferry collapsed, causing eight hopper cars loaded with crushed phosphate rock to fall into the Kootenai River, an International Boundary waterway. Frequency of water-quality sampling of the river was increased to monitor levels of contamination possibly attributable to the phosphate rock. However, the situation did not become critical during the week of more frequent monitoring, and so the normal schedule of periodic monitoring was resumed.
20	In the Township of East Brunswick in east-central New Jersey, southeast of New Brunswick, Middlesex County, on December 13, two overfilled underground storage tanks containing septic waste and organic solvents discharged about 10,000 gallons of mixed waste materials onto the wetlands of Lawrence Brook. Operations were suspended at the waste-storage facility to reduce the threat of environmental damage while the contaminated materials were removed. Lawrence Brook is a tributary of the Raritan River.
21	On the Mississippi River along the southern Illinois border with Missouri, a towboat with nine barges in tow collided on December 17 with the railroad bridge at Thebes, Ill. (Alexander County). One barge lost about 200,000 gallons of the crude oil it contained, and the spill affected about 30 miles of the river. By mid-March, cleanup crews had removed all cleanable oil from the river and adjacent shorelines, and all contaminated floating debris had been collected and buried.
(not shown)	Drought emergency regulations in the Delaware River basin since May 1985 were terminated effective December 18 by a resolution of the Delaware River Basin Commission. Reservoir storage, ground-water levels, and stream discharge have returned to approximate average conditions for this time of year.
22	During December, the mean flow of the Mississippi River at Vicksburg, Miss., was 1,180,300 ft^3/s, the highest monthly mean flow for any December in the entire 59 years that continuous measurements have been made at that site. The flow is the drainage from 1,140,500 mi^2, about 38 percent of the total area of the 48 conterminous States and 99 percent of the drainage of the entire Mississippi River basin.
	JANUARY 1986
23	On January 3 in southwestern Idaho near Nampa (Canyon County), about 20 miles west of Boise, discharge from a waste pond at a meat processing plant killed several thousand fish in Indian Creek, including about 1,000 rainbow trout. Indian Creek is tributary to the Snake River via the Boise River.
	JANUARY 1986 (con.)
24	A Pacific storm producing nearly continuous rains of 3 to 9 inches in 36 hours caused severe flooding and mudslides in the Puget Sound area of western Washington on January 17 and 18. Severe land erosion caused roads to wash away and homes to fall down hillsides. Mudslides pushed debris into homes, stacked cars on top of each other, and moved buildings. There were about 30 mudslides around Seattle alone. A period of strong winds late in the day on the 18th forced the closure of floating bridges in the storm-affected area. Land under a railroad track south of Seattle gave way, derailing an Amtrak train, injuring at least 28 people. The largest amounts of rain, 6 to 9 inches, fell on a 900-mi^2 area centered 50 miles west of Seattle in Jefferson, Grays Harbor, and Mason Counties. Damages in the entire storm-ravaged area were reported to be between $15 and $20 million. The recurrence interval of precipitation in some parts of the area was greater than 100 years, according to the National Weather Service.
25	Between January 25 and 27, a combination of snow accumulation, rain, suddenly thawing temperatures (but still-frozen ground), and consequent rapid runoff caused extensive ice-jam flooding in New Hampshire and western Maine. Snowfall on January 25 was between 3 and 14 inches, followed the next 2 days by rainfall of 2 to 7 inches and sharp rises in temperature. Major ice-jam problem areas in New Hampshire included Peterborough (Hillsborough County) where the Contoocook River destroyed the town's only motel, Milford (Hillsborough County) on the Souhegan River, Shelbourne (Coos County) on the Androscoggin River, and several towns along the Pemigewasset and the Ammonoosuc Rivers in Grafton County. About 230 people had to be evacuated in various parts of the State. In western Maine, the Kennebec and Androscoggin Rivers were the two largest rivers with major ice-jam flooding. Damages in the two States exceeded $2 million. No deaths were reported.
26	A 5-inch rainfall on January 30 and 31 in southern California triggered mudslides, principally in Matilija and Decker Canyons of Ventura County, where a forest fire had denuded over 100,000 acres in 1985, and in Malibu in Los Angeles County. Four major slides occurred in Matilija Canyon between 4 and 7 miles west of Ojai. The slides ripped one canyon home from its foundation, caused another home to collapse, and seriously damaged a third. Debris and mud were 6 to 8 feet deep in some places. Twenty-one residents were evacuated by helicopter. Several slides blocked highways in Ventura and Los Angeles Counties.
27	On January 31 in the Township of West Windsor (Mercer County) southeast of Princeton in west-central New Jersey, a 14-inch petroleum transmission line ruptured. The line spilled about 10,000 gallons of gasoline onto the soil and into the Delaware and Raritan Canal, which parallels parts of Stony Brook and Millstone River. The canal is used for recreation and public water supply. Fire broke out from the gasoline vapors at the rupture and some residents were temporarily evacuated from their homes. The fire was soon extinguished and cleanup operations begun, including draining the transmission line. The canal was pumped down and flushed to dilute contaminants. By mid-March the contaminated soil had been removed and the pipeline repaired.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	JANUARY 1986 (con.)
28	In most of Oklahoma during January, unseasonably warm temperatures and no precipitation created drought conditions, which damaged winter wheat and exacerbated many grassland and forest fires.
	FEBRUARY 1986
29	Rains of 6 to 8 inches in 6 hours on February 10 and 11 in 9 counties in southern Georgia, capping a 5-day wet period, caused many flash floods. More than 50 washouts occurred on primary and secondary roads, affecting more than 15 bridges, and there was widespread flooding of croplands. Several streams in the Suwannee and the Ochlockonee River basins in north Florida had peak discharges equal to or exceeding those for the 100-year recurrence interval.
30	On February 14 near the center of Ohio's northern border along Lake Erie (near Huron, Erie County), a break in a 16-inch steel pipeline discharged 360,000 gallons of diesel oil in the vicinity of a pipeline facility. Approximately 40,000 gallons of the oil entered the Huron River about 3 miles south of where the river enters Lake Erie. About 200 to 300 gallons per day continued to discharge into the river via bedrock (shale) after February 14. Cleanup operations during February and March recovered about 200,000 gallons of the total oil spill.
31	Between February 11 and 22, persistent rain and snow in northern and central California and the adjacent Reno-Carson City area of western Nevada led to widespread flooding and mudslides. The excessive precipitation was triggered by a series of Pacific storms. The associated high winds, wave erosion, floods, mudslides, and dam and levee breaks caused at least 13 deaths, evacuation of more than 40,000 people, and an estimated $400 million in property damage. Thirty-nine counties were declared disaster areas. The largest total of precipitation, 49.6 inches, was at Bucks Lake, Plumas County, in the central Sierra mountains of northwestern California. Precipitation totals from 10 to 30 inches were common in most of northern California and in the upland areas of central California. In some mountainous areas, accumulations of up to 9 feet of heavy, wet snow closed ski areas and caused avalanches. The most severe flooding took place in north-central California from February 17 to 20 when peak discharges on many streams equaled or exceeded recurrence intervals of 20 to 80 years. North of San Francisco, the entire Napa Valley suffered damages, and the resort town of Guerneville, Sonoma County, inundated by the Russian River, was isolated for several days. Levee breaks on the Yuba River near Marysville, 40 miles north of Sacramento, forced the evacuation of about 21,000 people on February 20 to 21 and flooded about 30 mi^2. About 6,800 people were evacuated from flood- and landslide-affected areas in Napa, Sonoma, Solano, Marin, and Santa Cruz Counties. The American River (a tributary of the Sacramento River) at Fair Oaks, northwest of Sacramento, reached 130,000 ft^3/s, its highest flow since Folsom Dam was completed in 1953; the leveed channel of the river contained the flow with no breaks. Total inflow to the Sacramento-San Joaquin delta (San Francisco Bay) was a record-high 725,000 ft^3/s on February 20, according to the California Department of Water Resources. In western Nevada, including parts of Douglas, Lyon, Storey, Carson City, and Washoe Counties, flooding occurred along both the Carson and Truckee Rivers from February 17 to 21. Severe flooding in both Reno and Carson City on the evenings of February 17 and 18 occurred as heavy rains fell and were accompanied by snowmelt runoff at altitudes below 6,500 feet. On February 20, the peak discharge of the Carson River near Fort Churchill, Lyon County, exceeded the 100-year recurrence interval and was the highest flow in the 75 years of record at that site. The region experienced its worst flooding in 20 years and property damages were estimated to exceed $17 million. One death was reported.
32	Storm systems, associated with those just described for California and Nevada, also brought persistent and extensive precipitation (exceeding 10 inches of rain in some places) to northeastern Utah. The rainfall along the east slope of the Wasatch Range during February 15 to 19 was almost one-half the average annual precipitation at some sites and melted most of the snowpack below an altitude of 7,000 feet. The storms caused major flooding in many parts of the Cache Valley, Wasatch Front, and northern mountains during February 15 to 19. Avalanches blocked some roads, and three deaths were associated with the storm. The Weber River at Gateway (drainage area, 1,620 mi^2), 25 miles north of Salt Lake City, reached a peak discharge on February 17, which has been exceeded only four times since measurements began at that site in 1890. The counties of Cache, Morgan, Wasatch, and Weber were declared national disaster areas. The Governor of Utah estimated damages to public and private property, including agricultural lands, of nearly $4 million.
33	Heavy rainfall from storms previously described for California, Nevada, and Utah caused rapid snowmelt and the failure of an earth-filled dam on Frazier Reservoir near Mountain Home, Idaho. Flow in Canyon Creek resulting from this dam failure was calculated as 4,890 ft^3/s for February 23. Parts of State Highway 67 were washed out.
	MARCH 1986
34	On March 7, near mile 43 on the Mississippi River south of Thebes, Ill., and about 4 miles southeast of Cape Girardeau, Mo., two tank barges under tow ran aground on a rocky ledge. Two tanks were damaged on one of the barges, and some 378,000 gallons of fuel spilled into the river. Cleanup operations were completed by the end of the month.
35	Near Skippack in Montgomery County in southeastern Pennsylvania, chlorine from a municipal sewerage system killed about 17,500 fish (including more than 2,000 trout) on March 9 and 10 along 4 miles of Towamencin Creek. The creek is a tributary of Skippack Creek (a stocked stream), which in turn is tributary to the Schuylkill River via Perkiomen Creek.
36	On March 12 near Ossining, Westchester County, about 20 miles north of New York City, a tank truck overturned on March 12, and of 6,500 gallons of fuel oil discharged, about 2,000 gallons entered the Croton River via storm drains. The Croton River is tributary to the Hudson River. Cleanup operations included removal of contaminated soil and removal of oil from the Croton River.
37	In Pennsylvania on March 14, rains of up to nearly 3.5 inches (following lighter rains on March 12 and 13) combined with snowmelt caused small-stream flooding in much of

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	MARCH 1986 (con.)
37 (con.)	the Susquehanna valley and the northeastern part of the State. The most severe effects occurred along Tunkhannock Creek (a tributary of the Susquehanna River) in Wyoming County and the Lackawanna River and some of its tributaries in Lackawanna County. In these areas roads were washed out and more than 100 families were evacuated from their homes. A record high stage was recorded at the gaging station on Tunkhannock Creek near Tunkhannock and the corresponding peak discharge equaled the 25-year flood.
38	On March 20 and 21 in Oconto County in northeastern Wisconsin, very large ice jams along the Oconto River from Oconto to the mouth of the river at Green Bay, combined with near-record high water levels of the bay, caused widespread flash flooding in downtown Oconto. Damages were estimated to exceed $500,000, mainly in the business and industrial districts. Sixty-five homes were evacuated.
39	On the Delaware River in southeastern Pennsylvania on March 21, a tanker lost steering and struck a dock at Marcus Hook, Delaware County. About 100,000 gallons of crude oil spilled into the river from a hole in a cargo tank of the ship. More than half the oil was kept from spreading by booms deployed around the damaged tanker. Scattered patches of free oil affected about 2 miles of the New Jersey shoreline. By March 24, cleanup operations had recovered nearly 84,000 gallons of the oil spilled, but additional cleanup work was necessary for at least 2 more months.
40	On March 30 near Port Arthur (Jefferson County) in southeastern Texas, several cargo tanks of a tank barge were ruptured by underwater pilings as the barge was being pushed onto the bank of Taylor Bayou. More than 15,000 gallons of light oil discharged into the bayou from the ruptured tanks. By April 1, cleanup operations had recovered most of the oil from the bayou. The bayou flows into the Gulf of Mexico via the Port Arthur Canal and the Sabine River Pass.
41	During the 6-month period ending March 31, precipitation was below normal in most of Delaware, Maryland, Virginia, and the Southeast (other than Florida), and less than 50 percent of normal in parts of most of the Southeastern States, including large areas in the Carolinas, Tennessee, Georgia, Alabama, and Mississippi. In March, the dry conditions, especially unusual for this time of year, were reflected in part by forest fires in West Virginia, Tennessee, Kentucky, and North Carolina.
	APRIL 1986
42	On April 3, thundershowers caused scattered flash flooding in the Hamakua, Hilo, and Puna districts in northeastern parts of the island of Hawaii. Many rock slides occurred along the highway north of Hilo, particularly where as much as 15 inches of rain fell in a few hours. Five days later, additional rains (lasting 48 to 72 hours in some areas) along the Hamakua coast and extending westward into the Kohala area and southward into the Puna and Kau districts caused further flooding and rock slides. Rainfall in some areas was measured in feet.
43	In northeastern Texas from April 3 to 5, intense rains in scattered areas caused flash floods and temporary closing of many highways and other roads. In Grayson County, 5 to 7 inches of rain in less than 2 hours caused severe flooding, especially in the vicinity of Sherman where damages were estimated to be $1.3 million, and many
	ARIL 1986 (con.)
43 (con.)	people were evacuated from homes and apartments near Sand and Post Oak Creeks. Others were rescued from roofs, autos, and tree tops. Bowie, Hunt, and Smith Counties were among the counties that experienced flash floods from rains of as much as 7 inches on April 5. In the western part of Hunt County the high water washed out a railroad bed, causing a train derailment. Neighboring southwestern Arkansas and southern Oklahoma had some flash flooding from rains on April 4. At DeQueen in Sevier County, Ark., a 6.5-inch rainfall caused widespread flooding in the city, and two bridges were washed out.
44	Near Granada Hills in northwestern Los Angeles, Calif., a broken pipeline resulted in discharge of nearly 30,000 gallons of crude oil, of which 21,000 gallons reached nearby storm drains and Bull Creek. Most of the oil was removed from the drains and the creek, but an unknown amount of oil flowed into Los Angeles River, to which the creek is tributary. The banks and affected vegetation along Bull Creek were cleaned with high-pressure water and the oil-water mixture was recovered for recycling.
45	In eastern South Dakota during much of the spring and especially in April, unusually persistent and severe lowland and lake flooding occurred on flat and poorly drained areas. The remnant wet conditions from above-normal precipitation during 3 of the past 4 years were augmented by another spring of high runoff, including snowmelt from the Northern Plains blizzard of April 13 to 14 (6 to 15 inches of snow). Lake elevations rose more than 6 feet above normal, flooding hundreds of recreation homes, submerging sections of roads and railroads, and causing serious structural and erosional damage when winds generated lake waves. Estimated damage by the end of the month was nearly $4 million, and 8 counties were declared disaster areas in late April by the President. The James, the Vermilion, and the Big Sioux River basins were the basins principally affected by the floods of April 14 to 18 resulting from 2 to 4 inches of rain and the snowmelt runoff generated from the blizzard snowfall of April 13 and 14. The area hardest hit by flooding during April was in the Big Sioux River basin between Watertown (Codington County) and Madison (Lake County). Madison is 60 miles south of Watertown and 35 miles north-northwest of Sioux Falls. Lake Thompson in Kingsbury County (45 miles south of Watertown) increased from a 6,000-acre slough to a 16,000-acre, 20-foot-deep lake, flooded adjacent farmland and roads, and discharged into the Vermilion River for the first time in at least the past century.
	MAY 1986
46	A hydrologic occurrence unique in its coincidence of documentation was recorded on May 8 at Devils Hole about 60 miles northwest of Las Vegas, Nev. U.S. Geological Survey hydrologists completing some measurements in an air-filled subterranean chamber (reached only by scuba diving through a flooded cavern) suddenly were aware of low, moaning sounds in the naturally dark and normally silent chamber, followed by noises mimicking the draining of a bathtub. Then fluctuations of 8 to 12 inches in the water level occurred in the chamber at 2- to 3-second intervals. These effects lasted about an hour. They apparently were hydraulic pulsations related to the May 7 earthquake in the Aleutian Island of Alaska. The epicenter of the earthquake

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	MAY 1986 (con.)
46 (con.)	was nearly 3,000 miles away from the subsurface site in Nevada where this hydrologic phenomenon was observed.
47	Thunderstorms in central and eastern South Dakota on May 8 and 9 and in central Iowa on May 9 and 10 caused flash flooding in scattered areas. The largest reported rainfall in South Dakota was 7.5 inches west of Redfield in Spink County. In Walworth and Potter Counties most roads were under water and several bridges were washed out. In Lyman County the rain washed out the dam on Lake Byre, thereby removing the sole source of water for the city of Kennebec. In central Iowa, rains of 4 to 7 inches in Polk and Dallas Counties in the Walnut Creek basin caused a record crest of 18.3 feet in West Des Moines early on the morning of May 10. Damages to homes and businesses in the area of the creek reportedly were in millions of dollars. Walnut Creek is tributary to the Des Moines River via Raccoon River.
48	In Puerto Rico on May 15 to 16, 2 days of intense thunderstorms following nearly 2 weeks of scattered thunderstorms caused flooding in many parts of the island. Most of the intense rains were concentrated in the central interior. Numerous landslides blocked most of the higher interior roads, especially in the area of San Sebastian in northwestern Puerto Rico. As much as 11 inches of rain in 48 hours was reported in the central regions and nearly 6 inches along the northern coastal sections. One death was reported. The Rio de la Plata, Rio Grande de Manati, and Rio Grande des Arecibo were at bankfull stage. The Guayanilla River destroyed a bridge at Macana (near the western part of the southern coastline) that had been built to replace provisionally the bridge destroyed 7 months ago.
49	On May 15 and 16 in extreme southern Illinois (Johnson, Pulaski, Union and Alexander Counties) and adjacent Missouri (Cape Girardeau and Scott Counties), rains of 4 to 16 inches produced severe and widespread flash flooding. In Illinois several miles of secondary roads were washed out and about 15 bridges were severely damaged. Substantial damage occurred to 29 houses along Mill and Duck Creeks (tributary to the Ohio River via the Cache River). In Missouri, many homes and roads were damaged, and bridges were washed away. Cape Girardeau officials estimated damage of nearly $50 million. There were two deaths.
50	In eastern Washington the upriver dam on the Spokane River, 1 mile east of Spokane, was breached on May 20 by rising waters after a power failure during a thunderstorm. With the dam gates closed, the spillway could not convey the 9,000 ft^3/s flow. After the breach, peak discharge at the Spokane River gaging station 4.5 miles downstream was 16,200 ft^3/s, which is 10,200 ft^3/s less than the 1985 peak flow at that site. The Spokane River is a tributary to the Columbia River.
51	On May 24 in northeastern Arkansas and north-central Texas, severe storms caused localized damages in Piggott (80 miles north of Memphis, Tenn.) and Fort Worth, respectively. At Piggott, Ark. (Clay County), a downpour estimated at 5 to 6 inches in less than an hour inundated the town. About 50 families were evacuated from their homes. Nineteen city or county bridges were damaged or washed out. Estimated damages exceeded $1.5 million for structures (including bridges) in addition to crop damage of about $1.5 million. In the Fort Worth, Tex., area, a southeastward-moving storm traversed the downtown and east side of the metropolitan area, producing damaging downburst winds of up to 95 miles per hour, hail as much as 3 inches in diameter, and about 4 inches of rain in an hour. Wind, rain, and flood damages were estimated to be nearly $2 million, and 2 persons drowned when swept from their car after driving into a flooded underpass.
52	Between 3 and 5 p.m. on May 30, as much as 8 inches of rain fell on the northern suburbs—North Hills section—of Pittsburgh, Pa. (Allegheny County), and caused severe flash flooding along Pine Creek and its tributary Little Pine Creek. Pine Creek is a small tributary of the Allegheny River. The cone shape of the 6-mi^2 drainage area of the headwaters of these creeks concentrated the runoff, and the severity of the flood was aggravated further by the paved surfaces covering much of the natural drainage area. Also, flooding occurred as homebound commuters were on the roads. Nine lives were lost as a result of motorists being caught in their cars as waters rose and vehicles were washed off roadways that crossed or bordered the creeks. Numerous homes and businesses were damaged or destroyed, as were a sewage-treatment plant and a newly completed flood-control project. Damage was estimated at $23 million, and on June 5 the President declared the area a national disaster. The peak flow of Little Pine Creek near Etna (drainage area 5.78 mi^2) was about 7,400 ft^3/s, with a recurrence interval greater than 100 years. This is more than three times the previous peak ,discharge in the 25 years of stream measurements at that site.
	JUNE 1986
53	Near the southern coast of Alaska, about 170 miles northwest of Juneau, the advancing ice of Hubbard Glacier on May 29 reached the western shore of Russell Fiord, blocking the fiord and transforming it into a lake. The entrance of the fiord is off Disenchantment Bay, which forms a narrow inner arm of the larger Yakutat Bay. Hubbard Glacier is one of about 20 glaciers advancing rapidly (as much as 130 feet a day) in the area where the southeastern Alaskan Panhandle joins the main part of the State. The cause of rapid forward movement of these particular glaciers is not fully understood. However, Hubbard Glacier, which has been advancing since about 1900, began moving forward more rapidly in the winter of 1985–86, in part associated with the concurrent accelerated advance, or surge, of a main tributary, Valerie Glacier. Formation of the lake by advancing glaciers has occurred at least once before in the last 1,000 years, since the terminus of Hubbard Glacier was at the entrance of Yakutat Bay in the 12th century. [Note: The Hubbard Glacier ice dam failed in early October, and the lake drained within 2 days. During a 4-hour period of maximum lowering of the water level, average discharge from the lake was estimated to be about 3.7 million ft^3/s. See article in this volume "Hubbard Glacier Near Yakutat, Alaska—The Damming and Breakout of Russell Fiord/Lake, 1986."]
54	On June 2 in southwestern Montana, flooding in the upper reaches of the Madison River occurred as a result of record-breaking snowmelt runoff. The maximum discharge of the river near West Yellowstone, Mont., (drainage area, 420 mi^2), was 2,340 ft^3/s, highest since records began in 1913 with a recurrence interval of 100 years. The Madison River ultimately joins the Gallatin and Jefferson Rivers to become the Mississippi River.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	JUNE 1986 (con.)
55	In the southern Texas counties of Bexar (including San Antonio), Atascosa, Frio, Guadalupe, and Medina, widespread flash flooding resulted from rains of 4 to 11 inches on June 4. The San Antonio River and its tributary, the Medina River, remained above flood stage for several days. The San Antonio River near Elmendorf (10 miles south of San Antonio) crested at 53 feet on June 5, the second highest level at that site in the past 25 years. Flooding of lowlands occurred along many smaller streams. The 6.5-inch rainfall that occurred in the area of the San Antonio office of the National Weather Service was the highest 24-hour total of record, but it was exceeded in some other parts of the city and in many nearby areas to the west and southwest. In Medina County, as much as 11.5 inches of rain fell in and around the town of Yancy. In San Antonio itself, flooding was so severe that several of the main freeways were closed and more than 100 low-water crossings were barricaded. Although the storm caused no deaths, many rescues and evacuations were necessary and local damages were estimated to total nearly $3 million.
56	Between June 3 and 8, the level of Great Salt Lake reached 4,211.85 feet above sea level, the highest level in nearly 140 years of recorded and estimated levels of the lake, and 0.25 foot higher than the previous high in 1873. The slow seasonal rise of the lake was interrupted on June 8 when a 13-mile-long dike protecting the mineral recovery ponds of the AMAX Magnesium Corporation was breached during a severe windstorm. Estimated damage to the ponds, dike system, and potential economic impact to AMAX Magnesium Corporation was about $300 million. Maximum level of the lake would have been about 4,211.95 (perhaps on June 20) if the breach had not occurred. High waves damaged the 27-mile Southern Pacific Railroad causeway, putting that facility out of service for several weeks. Also in northern Utah, a combination of snowmelt and failures of small upland dams caused flash flooding along the Duchesne, the Weber, and the Provo Rivers during June 5 to 7. The flow of Provo River (a tributary of the Jordan River) near Woodland, Summit County, was the highest since 1963, with a recurrence interval greater than 100 years.
57	In northwestern Louisiana (Caddo, Bossier, Webster, and DeSoto Parishes) and adjacent east Texas, rains of 3 to 7 inches from June 9 to 11 caused major rises in Cross and Wallace Lakes west and south of Shreveport, La., widespread flash flooding, and washout of four bridges. Damage was estimated to be $4 million to bridges and roads and nearly $1 million to homes and businesses.
58	In mid-June in southwestern Wyoming (Sweetwater County), about 60,000 fish—almost entirely white suckers and Utah chubs—died from unknown cause in a 3- to 5-day period in Flaming Gorge Reservoir 15 to 30 miles north of the Wyoming-Utah border. The reservoir, created by damming the Green River in northeastern Utah, occupies many miles of the valley of the Green River in Utah and Wyoming and of its major Wyoming tributary Blacks Fork. The fishkill affected 11,000 acres of surface area of the main stem part of the reservoir and 7 miles along the Blacks Fork part of the reservoir.
	JUNE 1986 (con.)
59	In southeastern New Mexico a series of rains between June 17 and 27 in the Pecos River basin caused extensive flooding along the river in Lincoln, Chaves, and Eddy Counties. Total rainfall during the period generally was between 3 and 5 inches but reached a maximum of 15.72 inches at Carlsbad Caverns southwest of Carlsbad, Eddy County. Estimate of storm damage was at least $2 million.
60	Bonnie, the second Atlantic tropical cyclone of June 1986, was the 11th hurricane of this century to make landfall on the United States coast during the month of June. Spawned in the central Gulf of Mexico, Bonnie was classified a tropical storm on June 24 and a hurricane on June 25, moving northwestward and making landfall on the southeastern Texas coast that day. Then the center of the storm track moved northward, parallel to Louisiana's western border, and entered southwestern Arkansas on June 27 and southeastern Missouri on the 28th. More than 23,000 people evacuated the Texas–Louisiana coastal area, which sustained wind and water damages of at least $1.5 million from the initial onslaught of the storm. Torrential rains of 6 inches or more caused widespread flooding, including about 150 miles along the downstream half of the Neches River. Rainfall of 13 inches occurred at Ace in southern Polk County, Tex. From June 26 to 29 in adjoining areas of Louisiana, Arkansas, and Texas, downpours of 4 to 10 inches associated with the dissipating hurricane caused estimated flood damages of $10 million, centered on Shreveport, La. Cross and Wallace Lakes west and south of the city rose to their highest levels of record. Flow of Paw Paw Bayou (tributary to Cross Lake from the west) near Greenwood (drainage area, 80.5 mi^2) on June 27 was 19,100 ft^3/s, with a recurrence interval greater than 100 years. Remarkably there was but one death resulting directly from the floods of Hurricane Bonnie—a drowning from an overturned boat on Cross Lake near Shreveport.
61	In northwestern Georgia, municipal sewage killed more than 12,000 fish (70 percent game-fish) along 9 miles of West Chickamauga Creek near and northeast of Chickamauga, Walker County, during 5 days, June 24 to 28. Chickamauga is 15 miles south of Chattanooga, Tenn. West Chickamauga flows into South Chickamauga Creek (a tributary of the Tennessee River) near the southeastern boundary of Chattanooga.
62	Extremely intense thunderstorms traversed Iowa on June 29, dropping as much as 8 inches of rain, which caused flash flooding, especially in the Raccoon River (tributary to the Des Moines River) basin in Carroll, Dallas, Greene, and Guthrie Counties west and northwest of Des Moines in the west-central part of the State. Flooding and concurrent tornadoes and strong winds caused an estimated $30 million damage, including about $20 million to crops. One death was reported. One house adjacent to an artificial lake was lifted up and carried 3 miles away by the floodwaters. To the west, in eastern Nebraska, rainfall of 3 to 6 inches on June 29 and 30 in Polk, Butler, Hamilton, York, Seward, and Saline Counties caused flash flooding of farmlands, roads, and urban areas, especially along the Big Blue River and some of its tributaries. On 70 miles of the Big Blue River (a tributary of the Kansas River) from Seward (Seward County) to Barneston (Gage County) near the Kansas State line, the water level crested 5 to 12 feet above flood stage and did not drop below flood stage for about a week.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	JULY 1986
63	In northeastern Kansas northwest of Kansas City, two periods of intense rainfall on July 5 and 6 resulted in localized but major flash flooding in the city of Leavenworth. Total rainfall was more than 10 inches. The flooding was concentrated along 3 Mile and 5 Mile Creeks (small tributaries of the Missouri River) in and near the city, damaging at least 15 businesses and 50 homes.
64	On July 7 in north-central Alabama, nearly 50,000 fish (including 18 percent game-fish) died along 24 miles of Mulberry Fork where it borders or flows through Blount, Cullman, and Walker Counties near Sloan (Blount County), 25 miles northwest of Birmingham, Ala. The specific contaminant was not determined, but the kill apparently resulted from a heavy nutrient load and a subsequently low content of dissolved oxygen. Mulberry Fork is a tributary to the Mobile River via the Black Warrior and Tombigbee Rivers.
65	In southwestern Louisiana on July 7, a well blowout at a strategic oil reserve cavern spilled more than 300,000 gallons of crude oil into the lake and marsh area of Black Lake, Cameron Parish, about 20 miles southwest of Lake Charles, La., and 15 miles north of the Gulf of Mexico. By July 23, most of the oil had been recovered, partly from a containment area and partly from the lake and marsh area.
66	In eastern Iowa, rains of 4 to 8 inches on July 8 caused flash flooding, especially in the Wapsipinicon River (a Mississippi River tributary) basin, in Cedar, southern Clinton, and northern Scott Counties and in the Skunk River basin in Henry County. About 1,000 families were affected and 50 of these had to evacuate their homes because of the high waters.
67	In mid-July, toxic blooms of blue-green algae occurred in Hebgen Lake, which is in Gallatin County in the southwestern part of Montana west of Yellowstone National Park. Four cattle died as a result of algal poisoning, according to the Gallatin County Health Officer, and the lake was posted with signs warning people not to swim in areas where the algae, which looked like pea soup, were growing. Hebgen Lake has had toxic blooms of these algae in 1977 and 1985, also. This is only the fifth time toxic concentrations of blue-green algae have been documented in Montana. The 1985 blue-green algal blooms on Lake Hebgen caused the death of 17 cattle.
68	Late in the evening on July 18 and in the early morning of the next day, as much as 6 inches of rain (5 inches in 4 hours) fell on south-central Chautauqua County in southwestern New York State and adjacent parts of Warren County in northwestern Pennsylvania, causing flash floods along several small tributaries of the Allegheny River. In New York the Panama-Ashville area (west of Jamestown) received the most intense thunderstorm rainfall, overtopping Panama Dam and flooding Little Brokenstraw Creek. Goose Creek washed out a bridge and several homes in Ashville. In Chautauqua County as a whole, 51 bridges, 189 homes, and 39 businesses were among the structures flooded, and damages were estimated to exceed $5 million. Severe flood damages also occurred immediately to the south in Pennsylvania along Little Brokenstraw Creek (Lottsville, Wrightsville, and Pittsfield, Pa.) and Stillwater Creek (Sugar Grove, Pa.). Damage in just the town of Sugar Grove was estimated to be $1 million.
69	On July 20 and 21, near the southernmost part of Washington, D.C., close to the Maryland State boundary, about 50,000 fish (nearly all menhaden) died along 5 miles of the Potomac River as a result of toxic conditions generated by discharge of a combined sewer overflow.
	JULY 1986 (con.)
70	In eastern South Dakota on July 25 and 26, thunderstorm rains of 5 to 10 inches caused widespread lowland flooding, with water 5 feet deep in some areas. Beadle, Brookings, and Kingsbury Counties were among those affected by the storm. The most severe damages from the storm system resulted from associated hail and high winds.
71	On July 26 in Lancaster County in eastern Pennsylvania, thunderstorm rains of 5 to 10 inches caused flash floods on many local streams including Little Chickies Creek and Little Conestoga Creek, tributaries to the Susquehanna River via Chickies Creek and Conestoga Creek respectively. Many roads were damaged, at least one bridge was washed out, and dozens of people had to be rescued as rapidly rising water trapped them in buildings and automobiles.
72	Thunderstorm rains of 3 to 8 inches on July 29 caused flash flooding in several parts of the Northeast, including east-central New York, western Massachusetts, southwestern New Hampshire, and northern Vermont.
73	Drought conditions, especially with respect to agriculture, continued to prevail in most of the Coastal Plain in Delaware, Maryland, and Virginia and the Southeastern States except Florida. Flows of some streams were extremely low in eastern Alabama, eastern Tennessee, Georgia, and the Carolinas—conditions more typical of September and October than of mid-summer. Water-use restrictions were in effect in parts of Alabama, Georgia, Kentucky, North Carolina, and South Carolina.
	AUGUST 1986
74	On August 6, thunderstorm rainfall of nearly 7 inches (5.24 inches in 2 hours) caused widespread flooding in the Milwaukee metropolitan area of southeastern Wisconsin. (See article in this volume, "Flood of August 6, 1986, in the Milwaukee Metropolitan Area, Wisconsin.")
75	In southwestern Wisconsin on August 14 and 15, about 10,000 fish (including 3,100 smallmouth bass) died along 5 miles of Sinsinawa Creek about 4 miles northwest of Hazel Green, Grant County, and 15 miles east-northeast of Dubuque, Iowa. The pollutant was thought to be from pig manure from animal feedlot and waste operations. Sinsinawa River is tributary to the Mississippi River in northwestern Illinois.
76	From August 16 to 18, Hurricane/tropical storm Charley caused coastal and small-stream flooding from South Carolina to Virginia as the storm moved northward along the coast. Hurricane damages were estimated to exceed $10 million.
77	Unusually heavy midsummer rainfall in the Mohawk River basin of east-central New York State resulted in an August mean monthly discharge of the Mohawk River at Cohoes (Albany County) (drainage area 3,456 mi^2) more than twice the previous high discharge for August (1976) in the 68 years of record.
78	In southern Mississippi, a fishkill of about 40,000 fish (70 percent game-fish) occurred from August 16 to 18 along 50 miles of Bogue Chitto (river) south of Brookhaven, Lincoln County, 60 to 100 miles south of Jackson, Miss. The pollutant was a wood-preservative phenol—pentachlorophenol. Bogue Chitto is a tributary of the Pearl River.

Table 1. Chronology of significant hydrologic and water-related events, October 1985 through September 1986—continued

No. (fig. 4)	EVENT
	AUGUST 1986 (con.)
79	On August 18 in southeastern Virginia, nearly 61,000 gallons of sodium bisulfite discharged from a storage tank into the Western Branch Elizabeth River at Portsmouth. A valve of the tank had inadvertently been left open during plant shutdown procedures in preparation for Hurricane Charley. The chemical, in anhydrous solution, rapidly dissipated, and no adverse environmental effects were reported to the Coast Guard office responding to the hazard incident. The Elizabeth River enters the lower Chesapeake Bay by way of the Hampton Roads channel.
80	In central South Carolina northwest of Columbia, locally intense rains caused flooding and two deaths near Newberry (Newberry County) on August 18 and one death near Lexington (Lexington County) on August 21. At Newberry, about 10.2 inches of rain fell in 7 hours, causing $800,000 in damage to homes, bridges, and culverts. Flooding at Newberry was estimated to have had a recurrence interval of more than 100 years.
81	An extensive fishkill in the headwaters of Lake Marion in central South Carolina, southeast of Columbia, was first reported to State officials on August 23. The kill appears to have resulted from dissolved oxygen depletion caused by natural hydrologic events. Runoff from storms that caused flooding on tributaries in the upper part of the basin on August 18 and 21 apparently flushed organic debris from Sparkleberry Swamp at the headwaters of the lake into the lake. However, these materials were concentrated in the upper part of the lake because the total water discharged was small and did not flush these materials through the lake. A conservative estimate of the size of the kill is 100,000 fish, but the number of fish killed could well exceed that number.
82	Drought conditions persisted in parts of the Southeast but were eased at least temporarily in many areas by August rains. An example of prevalent much-drier-than-normal conditions was the Apalachicola River in Florida. The August flow of the river at Chattahoochee (Gadsden County) (drainage area, 17,300 mi^2), northwest of Tallahassee near the Georgia State line, was at an all-time monthly low in 58 years of record at that site. The river was closed to barge transportation early in the month and there was concern about possible adverse effects of low river flows on the Apalachicola Bay oyster industry because of predation by saltwater species associated with increasing salinity of bay waters.
	SEPTEMBER 1986
83	On September 2 in New Jersey south of Philadelphia, Pa., about 9,500 pounds of phenol from a reaction kettle at a chemical plant was discharged from a coolant water system into Matthews Branch at Woodbury, Gloucester County. Matthews Branch is tributary to the Delaware River via Woodbury Creek. Several thousand fish died from the toxic chemical. No cleanup was possible and local authorities posted signs prohibiting fishing in Matthews Branch.
84	Along the Delaware River near Paulsboro, N.J., and Philadelphia, Pa., a tanker ran aground on September 10, spilling 295,000 gallons of crude oil into the river near an oil refinery. Some oil came ashore on both sides of the river. Cleanup was completed by October 22, using booms, vacuum trucks, and high-pressure water to remove the oil and contaminated debris from along the banks of the river.
85	Severe flooding began on September 11 in the central part of Michigan's Lower Peninsula (between Lakes Huron and Michigan), caused by runoff from as much as 13 inches of rainfall during 48 hours. Peak discharges on many rivers equaled or exceeded both the peak of record and the 100-year flood. (See article in this volume "Flood of September 10 to 15, 1986, Across the Central Lower Peninsular of Michigan.")
86	On September 14 in northeastern Georgia, farm drainage of manure killed more than 16,000 fish (mostly non-game fish) along 7 miles of Barber Creek south of Bogart, Oconee County, southeast of Athens, Georgia. Barber Creek is a tributary of Altamaha River via NcNutt Creek and Oconee River.
87	Heavy thunderstorms on the evening of September 20 and early morning of the 21st forced the evacuation of more than 60 homes in Rochester, Minn. Continuing heavy thundershowers and flash floods over 17 counties in the southern part of the State resulted in one drowning on the 21st and another on the 22d. Maximum rainfall amounts in the 3 days totaled from 4 to 6 inches and followed 3 to 4 inches received in the previous week. Property damage in Rochester was estimated at nearly $100,000 with losses to agricultural crops estimated in the millions of dollars.
88	In north-central Montana, flooding occurred in the latter part of the month along the Milk River (a major tributary of the Missouri River) and its tributaries, especially when torrential rains of as much as 6 inches occurred within a 12-hour period on September 24. For example, peak discharge of Battle Creek of 9,780 ft^3/s at International Boundary (about 25 miles east of the Montana-Saskatchewan-Alberta tri-boundary point) (drainage area, 997 mi^2) was the highest flow in the 69 years of record at that site and was estimated to have a greater than 100-year recurrence interval.
89	During September, a breakout of Berg Lake, dammed by Steller Glacier, flooded about 50 mi^2 along the Bering River in southern Alaska.
90	During the last 7 days of September, rainfall totals of 10 to 12 inches in northeastern Illinois, especially in heavily populated northern Lake County north of Chicago, caused severe flooding on the Des Plaines and Fox Rivers (tributaries of the Illinois River). Peak flows in the Des Plaines River basin at various times between September 27 and October 1, included some with recurrence intervals of 75 years. Four deaths were attributed to the flooding, and damage estimates of $30 million in the Chicago area and $70 million in the outlying suburbs were reported.
91	In September 1986, the average flow of the Mississippi River at St. Paul, Minn., was the highest September flow in the entire 95 years of continuous record at the site—35,390 ft^3/s. The flow is from a drainage area of 36,800 mi^2, about 45 percent of the total area of Minnesota. In addition to the September flow, the greatest average annual flow in the 88-year period of record also occurred at this site during the 1986 water year—29,285 ft^3/s. This is almost three times (11,230 ft^3/s) the average annual flow for the 88-year period, and 34 percent greater than the previous high of 21,780 ft^3/s, which occurred in 1983. (See also article in this volume, "Unusual Hydrologic Events in Minnesota—*When it Rains. . . .*")

Seasonal Summaries of Hydrologic Conditions, Water Year 1986

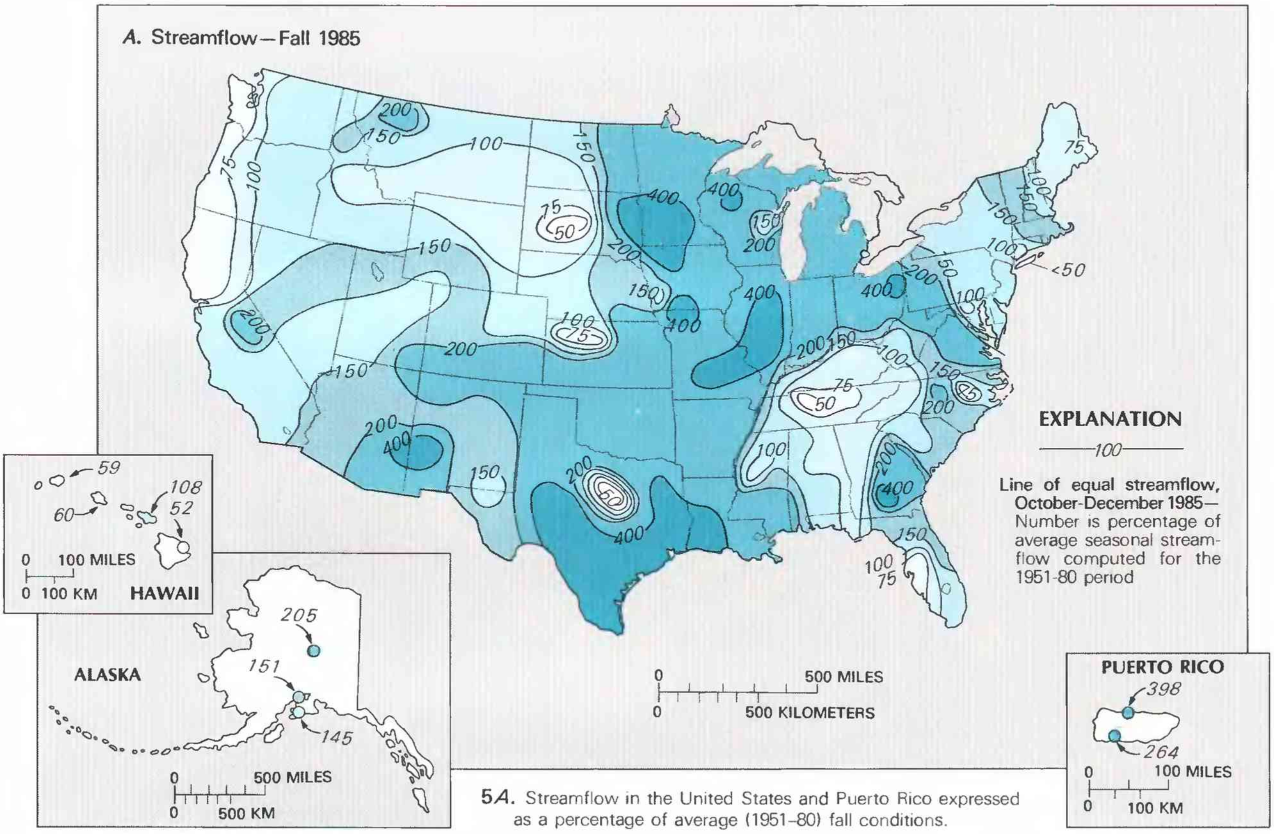
By Thomas R. Karl[1] and Harry F. Lins[2]

FALL 1985

The fall (October–December 1985) of water year 1986 saw a marked increase in streamflows from the preceding summer in many parts of the Nation. Substantial increases occurred in Arizona, New Mexico, the central Great Plains, the middle Mississippi Valley, the middle Atlantic region, and southeastern Georgia. Low flows, although less acute than during the summer, persisted from the Dakotas into the northern Rocky Mountains, in central Texas, in much of the Southeast, and along the Pacific Coast from San Francisco Bay to Puget Sound. (See figure 5*A*.) For the Nation as a whole, however, the general condition as characterized by the combined flow of the three largest rivers in the conterminous United States—the Mississippi, the St. Lawrence, and the Columbia—was one of abundant streamflow. The combined mean discharge of the "Big Three" for the season was 1,161,600 ft^3/s (cubic feet per second), up 51 percent from the previous season and 42 percent above the fall season median flow.

The above-median flows throughout much of the Nation continued a series of recent wet autumns. National precipitation data indicate that six of the wettest fall seasons of the 20th century have occurred since 1972. The fall of 1985 was the sixth wettest of this century. The heavy precipitation (fig. 5*B*) was associated with record cold temperatures (fig. 5*C*), which were the coldest of the century in much of the Pacific Northwest and the upper and middle Mississippi Valleys. As a result of the cold temperatures considerable precipitation fell as snow and, during November especially, record snows were reported in many areas of the Northwest. This early cold-season precipitation kept streamflows lower than they might have been if the weather had been milder.

The circulation feature that was responsible for the anomalously wet and cold weather in the Northwest was a Pacific/North American (PNA) teleconnection. In this instance, positive anomalies of the 700-millibar height field in the North Pacific centered around lat 50° N., long 150° W. were associated with negative 700-millibar heights downstream in the Western United States and positive heights in the Southeast (fig. 5*D*). Such a pattern is conducive to an uninterrupted path of cyclonic activity that starts on the west coast, moves over the Rockies, and stalls or decelerates in the Midwest. These storms draw warm air into their southeast sector and produce very wet and cold conditions to the north and west of their tracks.



EXPLANATION

—100— Line of equal streamflow, October-December 1985—Number is percentage of average seasonal streamflow computed for the 1951-80 period

5*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) fall conditions.

Figure 5. Hydrologic conditions during the fall (October-December 1985) of water year 1986. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

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[1] National Oceanic and Atmospheric Administration, National Climatic Data Center. [2] U.S. Geological Survey.

Precipitation from tropical storm systems was responsible for considerable flooding throughout much of the season. In October, for example, tropical storm Isabel generated rain that produced record discharges in 11 river basins in Puerto Rico. Flows on the Rio Descalabrado, Rio Inabon, and Rio Cerillos met or exceeded the 100-year recurrence interval. The flooding was directly responsible for 55 deaths and damage in excess of $65 million (table 1, event 1). Several days later, the remnants of Pacific Hurricane Waldo caused localized flooding in New Mexico and from western Texas to Kansas (table 1, events 3, 4). At the end of October, Hurricane Juan caused severe flooding in the bayous of Louisiana and erosion along the coasts of Louisiana and Mississippi and, to a lesser extent, along coastal reaches in Texas, Alabama, and extreme western Florida (table 1, event 8). Property damage was estimated at about $1 billion. In the first days of November, Juan moved into the Ohio River valley, stalled, and was fed additional moisture by a blocking high-pressure system over the Canadian Maritime Provinces. As the storm gradually drifted eastward it produced severe flooding in eastern West Virginia, western Virginia, and the Maryland panhandle and along the Monongahela River in Pennsylvania. Flood records were broken at 40 gaging stations and flood magnitudes equaled or exceeded the 100-year recurrence interval at 45 gaging stations in the region (table 1, event 10; see article in this volume "The Ruinous West Virginia Flood of November 1985"). By the end of November this storm, along with the remnants of Hurricane Kate, produced sufficient precipitation to raise the levels of reservoirs of the New York City system up to or above average and put an end to the mandatory restrictions imposed on water use during the drought of the previous water year (table 1, event 15 and unnumbered event between events 21 and 22). The drought emergency declared by the Delaware River Basin Commission on May 13, 1985, was officially terminated on December 18 as reservoir storage, ground-water levels, and streamflows throughout the basin rose to the normal range. (For details on the Delaware River basin drought, see Harkness and others, 1986, p. 29–34.)

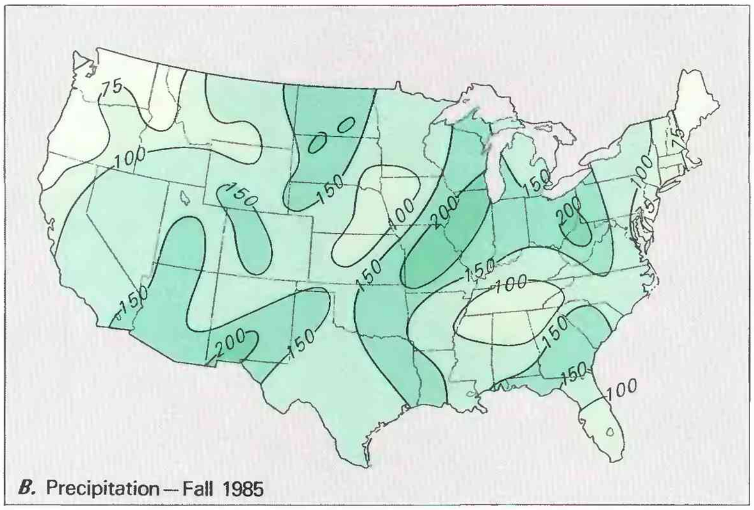
REFERENCE CITED

Harkness, W.E., Lins, H.F., and Alley, W.M., 1986, Drought in the Delaware River Basin, 1984–85, *in* U.S. Geological Survey, National water summary 1985—Hydrologic events and surface-water resources: U.S. Geological Survey Water-Supply Paper 2300, 506 p.

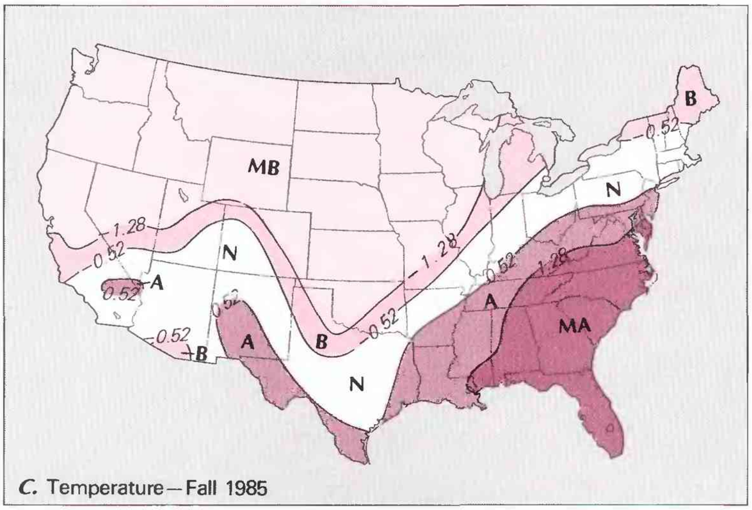
5*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) fall total precipitation.

5*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) fall conditions. (MA = much above, at least 1.28 standard deviations above the mean; A = above, between 0.52 and 1.28 standard deviations above the mean; N = near normal, between −0.52 and 0.52 standard deviations from the mean; B = below, between 0.52 and 1.28 standard deviations below the mean, MB = much below, at least 1.28 standard deviations below the mean.)

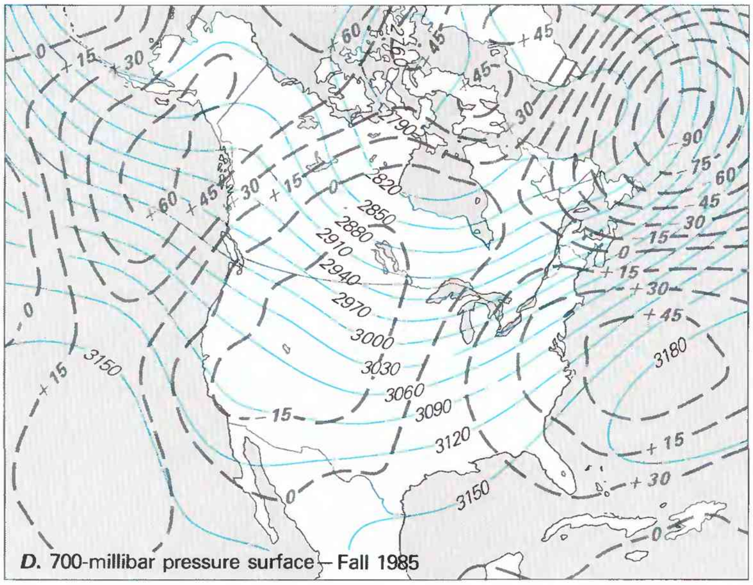
5*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) fall conditions (black dashed line). Data in meters.



B. Precipitation—Fall 1985



C. Temperature—Fall 1985



D. 700-millibar pressure surface—Fall 1985

Figure 5. Continued

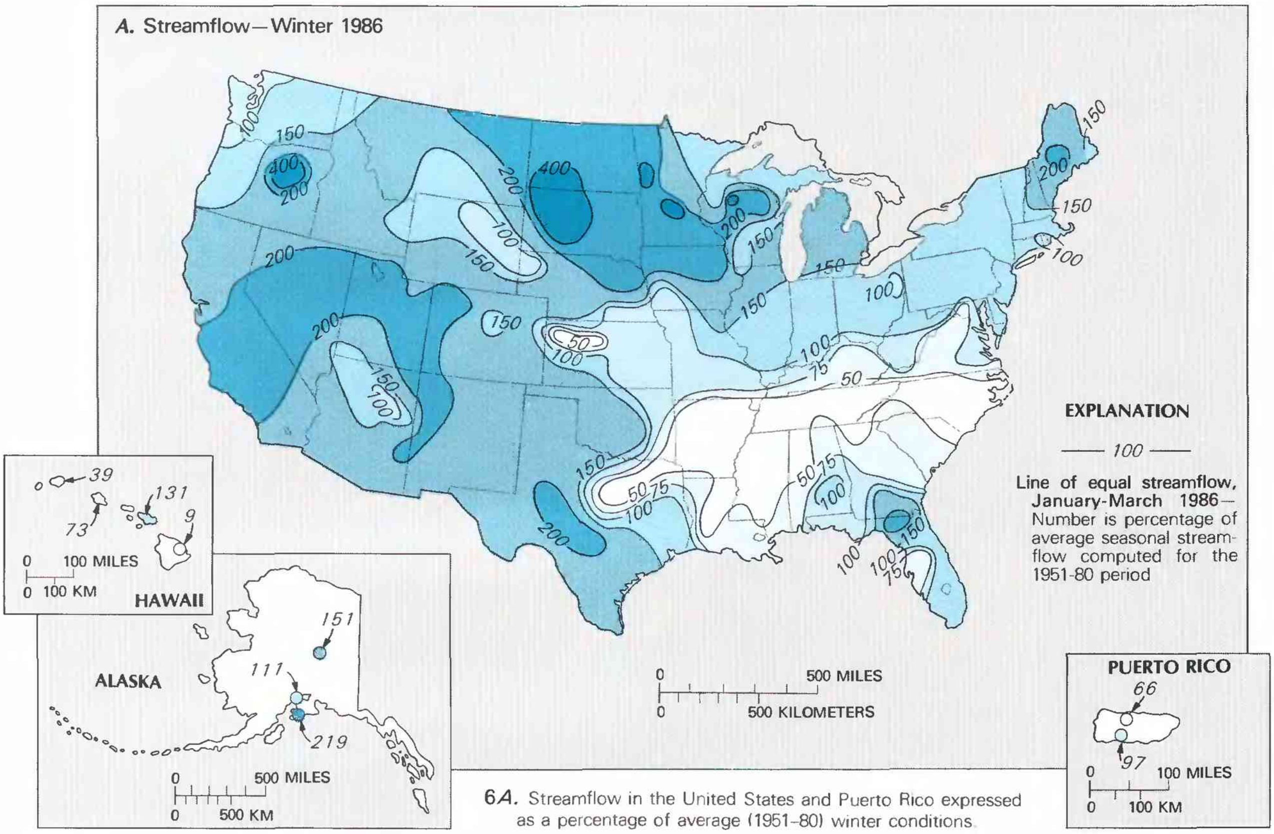
WINTER 1986

The largest change in the distribution of streamflow anomalies during the winter (January–March 1986) season was related to the dramatic increase in the area and magnitude of below-normal flows across much of the Southeast (fig. 6*A*). Record low flows for the month of March were recorded on the Etowah River at Canton, Ga., and the Cahaba River at Centerville, Ala. Typically, flows in the Southeastern States increase during the winter, but reduced precipitation during the winter of 1986 (fig. 6*B*) reversed this characteristic pattern. These dry conditions were reflected in the combined flow of the Nation's "Big Three" rivers during January, which, at 803,500 ft³/s, was a 47-percent reduction from the December flow. By contrast, the dryness that had prevailed in coastal areas of the Northwest during the fall season had been replaced by mostly above-normal flows. Throughout most of the West, the upper Mississippi Valley, and in the Great Lakes States, streamflows persisted in the above-normal range through March.

The winter precipitation pattern across the Nation was nearly a complete reversal from the fall pattern (fig. 6*B*). Much of the central part of the country during these winter months had below-normal precipitation, and areas in the Northeast and Northwest that had been relatively dry during the fall were now wet. January was particularly dry in the southern and central Plains with no precipitation recorded in Texas, Oklahoma, and Kansas (table 1, event 28). The Southeast was consistently dry each month through the winter, continuing the pattern that began during December.

In the West heavy rains began in mid-season. During the third week in February a complex grouping of relatively weak low-pressure systems brought heavy precipitation to the Pacific coast. Flood peaks associated with this storm system equaled or exceeded record peaks at more than a dozen sites in California, Nevada, and Oregon (table 1, event 31). Farther east this same storm system produced heavy rains along the east slopes of the Wasatch Mountains in Utah (table 1, event 32). Between February 15 and 19 several sites received nearly one-half the average annual precipitation, essentially melting the snowpack below an altitude of 7,000 feet. Also, the Great Salt Lake rose 0.75 feet during February to an elevation of 4,209.9 feet above sea level. In March the lake rose another 0.6 feet to close the season at 4,210.5 feet above sea level.

Temperature patterns (fig. 6*C*) during the winter also were reversed from their fall pattern. The intense cold in the West was replaced by much- above-normal temperatures, with many areas west of the Mississippi River having the warmest January and (or) March of the century. In the East, however, temperatures were much closer to normal during this period. The extremely warm temperatures in the

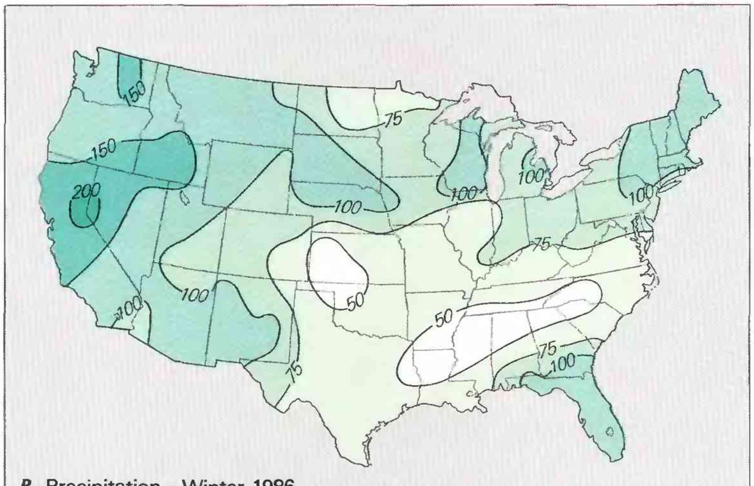


6*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) winter conditions.

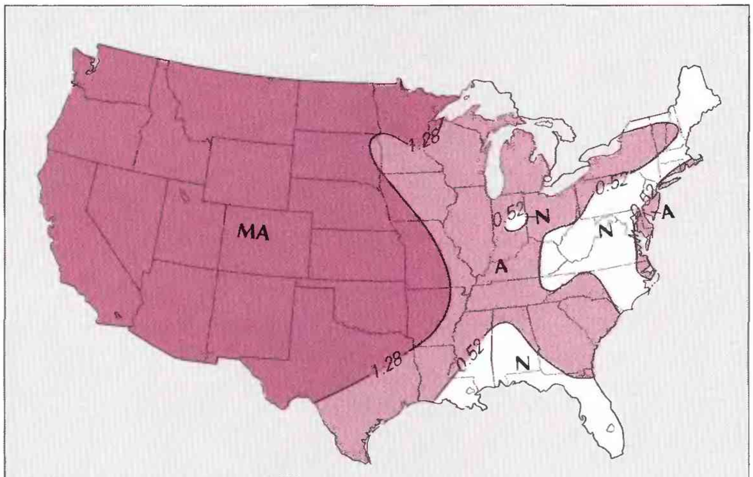
Figure 6. Hydrologic conditions during the winter (January–March 1986) of water year 1986. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

northern Great Plains during March undoubtedly contributed to rapid snowmelt and thawing, which caused streams to flow higher than expected given the precipitation pattern in this area during the winter. Much of the moisture in this area had fallen as snow during the previous season.

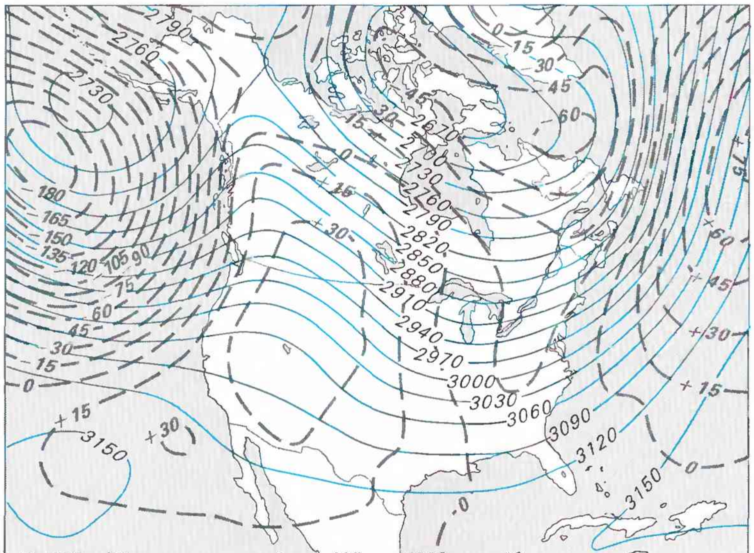
The circulation features that produced the remarkable reversal of temperature and precipitation patterns, which directly affected the streamflow, resulted from an opposite phase of the Pacific/North American teleconnection pattern that existed during the previous season. During the winter months large negative 700-millibar height anomalies, centered around lat 45° N., long 155° W., replaced the positive 700-millibar height anomalies that had existed in that region (fig. 6*D*). The downstream North American height field reacted accordingly with positive anomalies over the Rocky Mountains and somewhat below normal heights in the East. The anticyclonic flow, or ridge, over the Rocky Mountain States discouraged the development or movement of storms from the Pacific or Gulf of Mexico as a dry northwesterly flow prevailed in the Southeast. During much of the season storms from the Pacific Ocean were only able to penetrate the western periphery of the upper-level ridge in the Rockies. This ridge helped produce the anomalous warmth in the West, and the downstream trough in the East helped keep temperatures there more seasonable.



B. Precipitation—Winter 1986



C. Temperature—Winter 1986



D. 700-millibar pressure surface—Winter 1986

6*B*. Precipitation in the conterminous United Stated expressed as a percentage of average (1951–80) winter total precipitation.

6*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) winter conditions. (MA = much above, at least 1.28 standard deviations above the mean; A = above, between 0.52 and 1.28 standard deviations above the mean; N = near normal, between −0.52 and 0.52 standard deviations from the mean; B = below, between 0.52 and 1.28 standard deviations below the mean; MB = much below, at least 1.28 standard deviations below the mean.)

6*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) winter conditions (black dashed line). Data in meters.

Figure 6. Continued

SPRING 1986

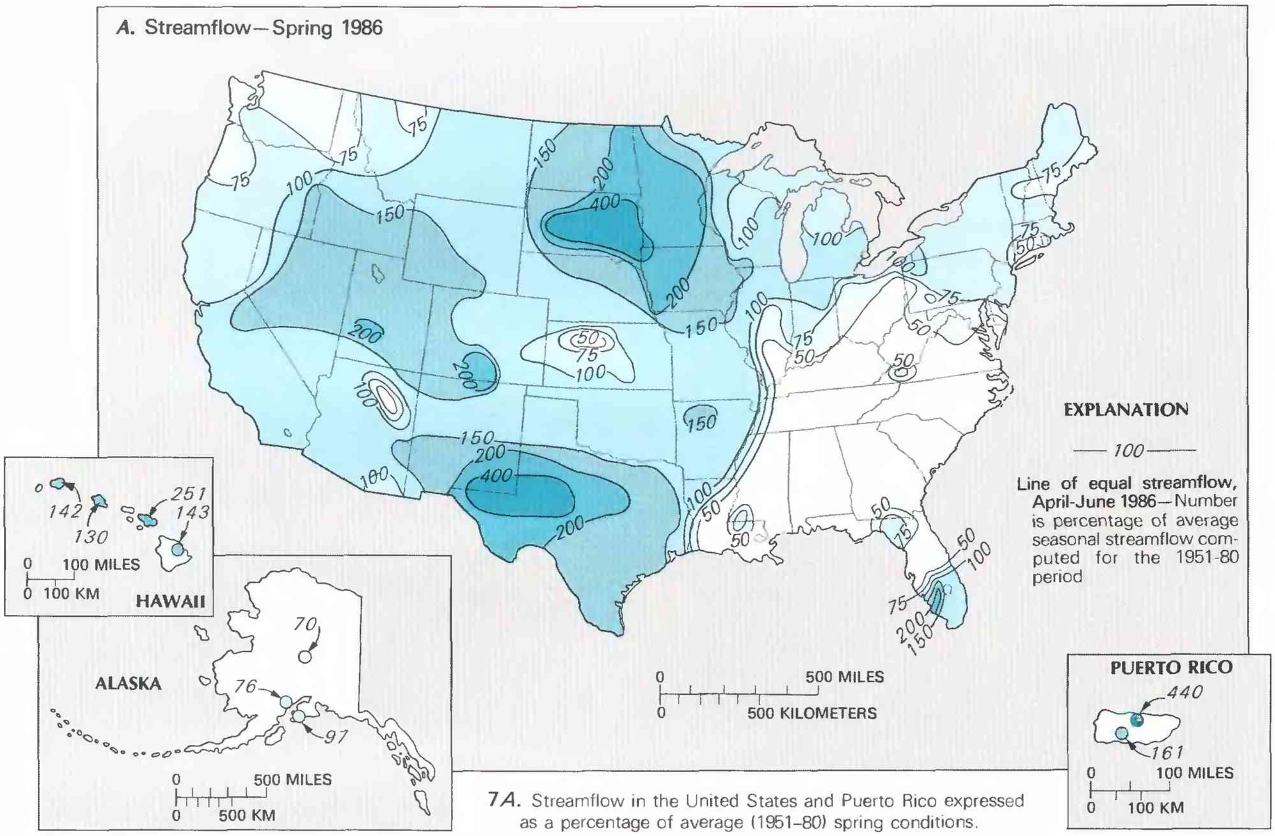
With the spring season (April–June 1986) came a progressively dramatic intensification of low streamflow conditions in the eastern third of the Nation. From the Ohio River valley and mid-Atlantic States south to the Gulf of Mexico, flows in most areas were less than half their normal value throughout the season (fig. 7*A*). In contrast, abundant streamflows persisted from the winter in the northern Great Plains, west-central Texas, and across the Great Basin into the central and southern Rockies.

The season began with below-normal flow conditions expanding to encompass most of the area east of the Mississippi River, including those areas where flows had been above normal in March. In those areas of the Southeast where dry conditions prevailed during the winter, flows continued to decrease dramatically.

During April, record monthly low flows occurred at 16 of the 38 index gaging stations in the Southeast. Although flows increased slightly in some parts of the East in May, they continued declining in most areas of Kentucky, Tennessee, Alabama, Georgia, and the Carolinas. By season's end, all river basins in Georgia, North Carolina, and South Carolina had experienced three consecutive months of below-normal streamflow. The sixth consecutive month of below-normal flows occurred at 10 index stations—five in North Carolina, two in South Carolina, and one each in Tennessee, Alabama, and Georgia. Record low flows for each month of the season were recorded on Contentnea Creek at Hookerton, N.C., on South Yadkin River near Mocksville, N.C., and on Pee Dee River at Peedee, S.C. In addition, the usable contents of most reservoirs in the Southeast declined to below normal levels by the end of the spring. The most significant declines occurred in the Tennessee Valley where the contents of selected reservoirs by the end of June ranged from 57 percent to 94 percent of normal.

While the Southeast was suffering with drought, above-normal flows and flooding were widespread in parts of the northern and southern Plains and from the Colorado Plateaus into the Great Basin. The most significant flooding occurred during June in Iowa and Utah. Severe thunderstorms in Iowa on the 30th of June caused record floods, with recurrence intervals in excess of 100 years, on several streams in the Des Moines River basin (table 1, event 62). A combination of snowmelt and small upland dam failures generated record floods on the Duchesne, the Weber, and the Provo Rivers in northern Utah (table 1, event 56).

Another significant event in Utah during the spring was the recording of the highest level of the Great Salt Lake since lake-level observations began in 1847. As stated in the summary of the winter season conditions, the elevation of Great Salt Lake on March 31 was 4,210.50 feet above sea level, 1.10 feet below the 1873 record high level of 4,211.60. By mid-May, the old record was surpassed and by the end of May the level stood at 4,211.80. A slow rise continued until June 8 when a dike was breached during a windstorm. At that time the lake stood at a record 4,211.85 feet above sea level. It fell to 4,211.45 feet by June 10, rose to 4,211.55 feet on June 20, then began a slow seasonal decline, falling to 4,211.40 feet by



7*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) spring conditions.

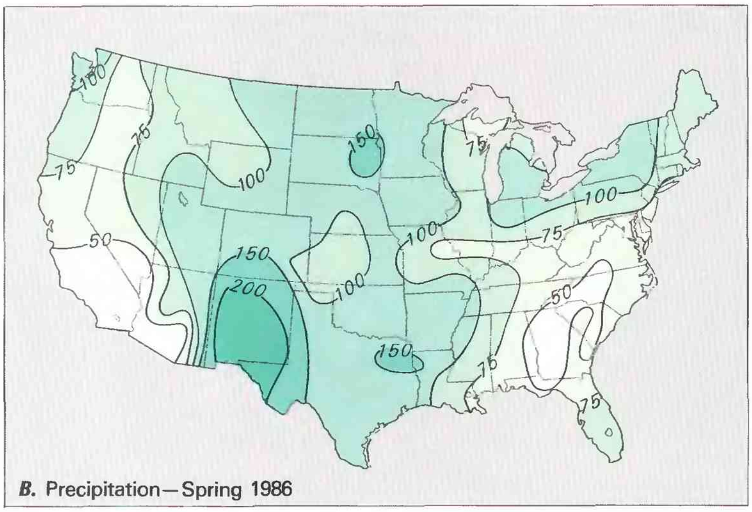
Figure 7. Hydrologic conditions during the spring (April–June 1986) of water year 1986. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

June 30. Had the breach not occurred, the maximum elevation of the lake would have been about 4,211.95 feet (table 1, event 56).

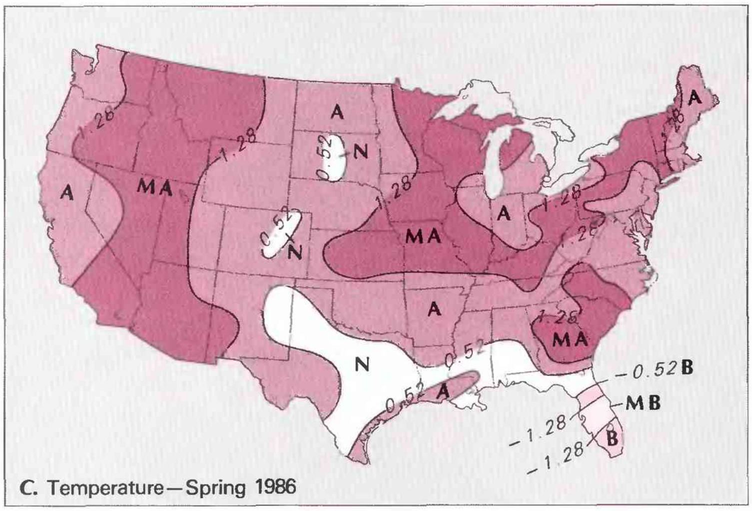
The spring precipitation anomaly pattern (fig. 7*B*) closely matched the streamflow. In the Southeast a very dry April and June along with a near-normal May combined to produce the driest spring season of the 20th century from central Virginia to southwest Georgia. The tenacity of the extreme dryness was unprecedented in the modern climate record. Other dry spells had persisted for longer periods, but the magnitude of the December through June dryness was unequaled in many parts of the Southeast. Meanwhile, other parts of the country, such as parts of the northern Great Plains and eastern New Mexico, had their wettest springs on record, which contributed to the excessively high streamflows and lake levels observed in these areas. The heavy rains during this time of the year are particularly significant considering that, especially in the northern Plains, spring normally is the wettest time of the year and nearly half the annual rainfall occurs during this season.

The accompanying temperature pattern during this spring season was one of anomalous warmth (fig. 7*C*), which undoubtably aided in the increased domestic water use and evaporation rates from reservoirs in the Southeast. Nearly the entire country had either above-normal or much-above-normal temperatures. The only major exception was the Florida peninsula where substantially cooler than normal temperatures prevailed.

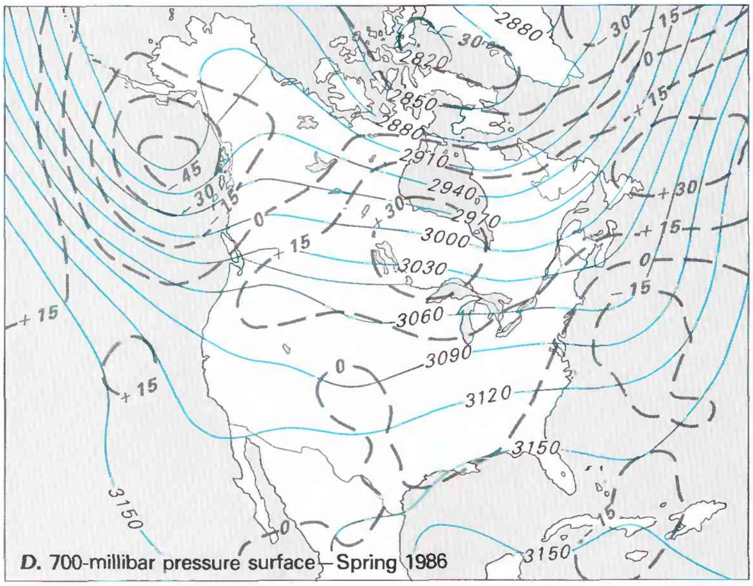
The mean circulation pattern that contributed to the anomalous warmth and wetness in the middle of the country and the extreme dryness and warmth in the Southeast is depicted in figure 7*D*. A strong Gulf of Alaska upper-level low and anomalously higher-than-normal 700-millibar heights over Canada helped produce the pattern of warmth over the United States. The anomaly pattern was much weaker over the conterminous United States due to the large number of "cut-off" low pressure systems and strong ridges that progressed from west to east across the country. These "cut-off" lows provided the mechanism for heavy rains and excessively high streamflows in the central States. The fact that these cyclonic systems were cut-off from the general circulation contributed to their relatively slow movement and long rainy periods. By the time the "cut-off" lows reached the East, however, they often either dissipated and became absorbed in an upper atmospheric long-wave anticyclonic flow or they intensified far enough east so that a dry northwesterly flow prevailed in the Southeast. This situation helped produce the record low streamflows observed in that area.



B. Precipitation—Spring 1986



C. Temperature—Spring 1986



D. 700-millibar pressure surface—Spring 1986

7B. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) spring total conditions.

7C. Temperature in the conterminous United States expressed as a departure from average (1951–80) spring conditions. (MA=much above, at least 1.28 standard deviations above the mean; A=above, between 0.52 and 1.28 standard deviations above the mean; N=near normal, between −0.52 and 0.52 standard deviations from the mean; B=below, between 0.52 and 1.28 standard deviations below the mean; MB=much below, at least 1.28 standard deviations below the mean.)

7D. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) spring conditions (black dashed line). Data in meters.

Figure 7. Continued.

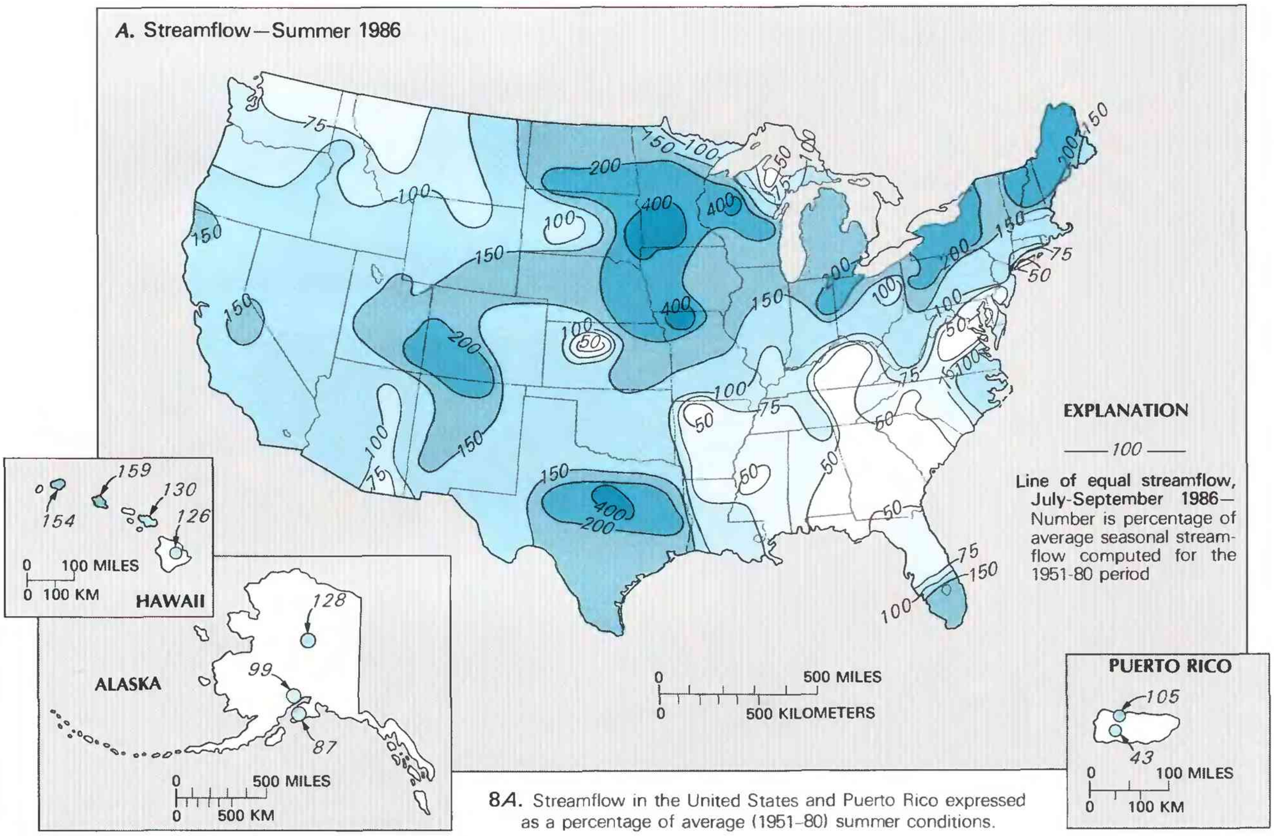
SUMMER 1986

The summer season (July–September 1986) was characterized by a continuation of the anomalous streamflow patterns. In general, flows remained high in the northern and southern Great Plains and low in the Southeast (fig. 8A). Moreover, this geographical pattern was very consistent from month to month. The magnitude of the most extreme departures, however, especially the area of very low flows in the Southeast, tended to decrease through the season. Nationwide streamflow conditions, as indicated by the combined flows of the "Big Three," experienced their normal seasonal decline. Even so, the flow of the "Big Three" remained above the summer season median.

The season began with an initial intensification of drought conditions in the Southeast where record low flows for July occurred at 11 index stations. Much of the Southeast had below-normal precipitation; many parts of Georgia, Mississippi, Arkansas, South Carolina, Louisiana, and Texas received less than 50 percent of their normal July precipitation. July was the seventh consecutive month of dry weather in the Southeast. The intensity of the dryness for the 7-month period December 1985 through July 1986 was greatest in the Carolinas and Georgia. In these areas the dryness during this period was the most severe on record, and many records date back to the turn of the 20th century or earlier. The extreme drought during July was maintained by a westward extension of the Bermuda High, which covered all of the Southeast. This, in combination with already parched soils, led to record-breaking heat, excessive insolation, and anomalously high evaporation and water-use rates from existing water supplies.

At the 16 index stations located in North and South Carolina, Georgia, and Alabama, July streamflow averaged only 36 percent of median. At the same time, the contents of reservoirs in the Southeastern States also were generally below their seasonal normal. Reservoir contents were quite variable, ranging from 38 to 96 percent of normal.

Despite the intense dryness in the Southeast, flows elsewhere across the Nation during July were abundant. Indeed, more than 75 percent of the index stations in the United States and southern Canada had flows in the normal to above-normal range as much of the area continued to have near- or above-normal rainfall. Heavy rains along coastal portions of the Southeast modified drought conditions in many areas during August. In response to the rain, streamflow at the 16 index stations in the Carolinas, Georgia, and Alabama increased to an average of about 69 percent of the median for the month. Even so, record monthly low flows occurred at five index stations in Georgia, Alabama, and Florida (table 1, event 82). Hurricane Charley helped alleviate the drought conditions along the coastal sections of North Carolina and the mid-Atlantic area, but by far the most beneficial rains resulted from an upper atmospheric low pressure trough that often was well south of its normal late summer position. Frontal activity associated with this trough aided the development of widespread convective activity over the Southeast.



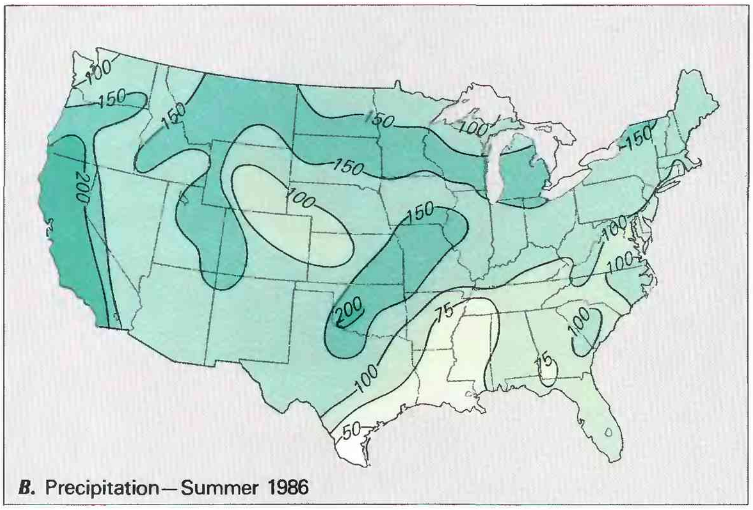
8A. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) summer conditions.

Figure 8. Hydrologic conditions during the summer (July-September 1986) of water year 1986. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climatic Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

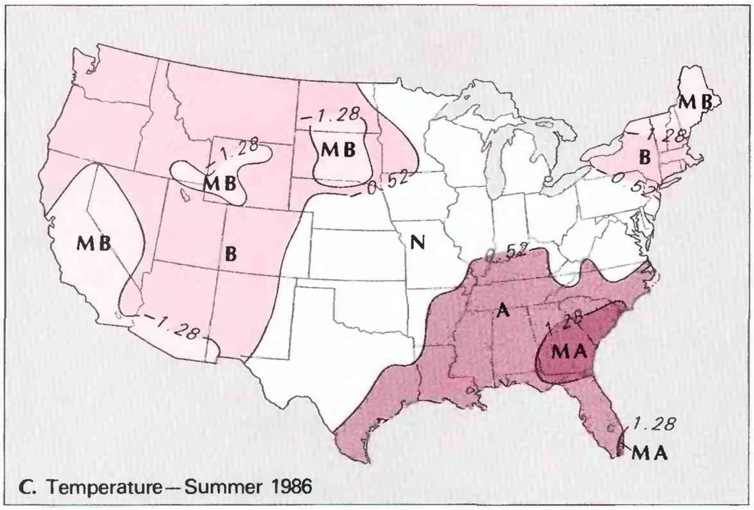
A significant hydrological and meteorological event occurred along the Kinnickinnic River at Milwaukee, Wis., in early August. A low-pressure system and a cold front produced nearly 7 inches of rain (5.24 inches in 2 hours) on the evening of August 6 causing both rural and urban flooding. The peak discharge of the Kinnickinnic River was nearly twice that of the 100-year flood (table 1, event 74; see article in this volume "Flood of August 6, 1986, in the Milwaukee Metropolitan Area, Wisconsin").

By season's end the dryness in the Southeast, although still widespread, had moderated significantly. In fact, a very wet September helped produce a rather wet summer across much of the Nation (fig. 8*B*). The very wet weather, however, was not welcome everywhere. Near the middle of the month severe flooding began in the central part of Michigan's Lower Peninsula. Peak discharges on many rivers and streams exceeded both the record peak and 100-year flood. Several dams failed as did the Flint River dikes in southern Saginaw County. Flood damages were estimated at $400 million with 28 counties declared Federal disaster areas (table 1, event 85; see article in this volume "Flood of September 10 to 15, 1986, Across the Central Lower Peninsula of Michigan").

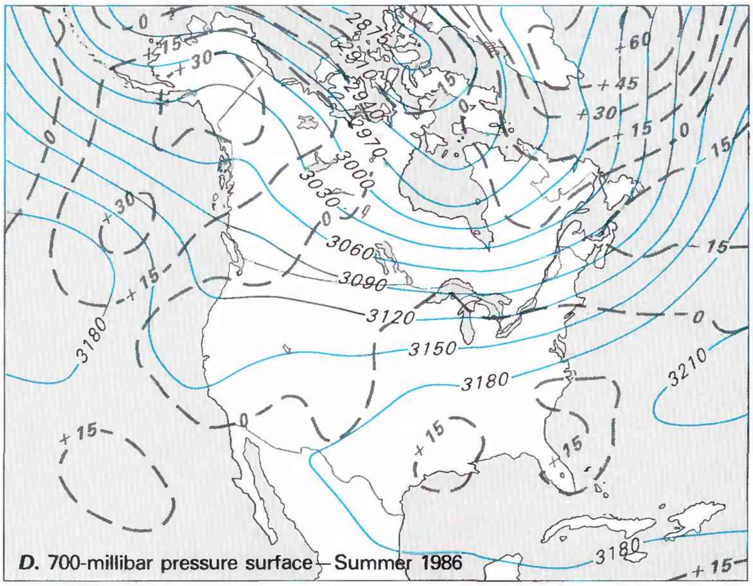
The extremely wet weather during September resulted from a series of weather disturbances in the upper atmosphere, which often became nearly stationary in the west. This led to some anomalously cold weather in this part of the country and, in fact, set the character of the entire season (fig. 8*C*). These cold unstable pools of air are reflected in the seasonal anomaly pattern of 700-millibar heights over the Western United States (fig. 8*D*). The contrast between the persistent warm air in the Southeast, which returned in September, and the cold air in the West provided the instability for the record breaking rains and floods in the western two-thirds of the country.



B. Precipitation—Summer 1986



C. Temperature—Summer 1986



D. 700-millibar pressure surface—Summer 1986

8*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) summer total precipitation.

8*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) summer conditions. (MA = much above, at least 1.28 standard deviations above the mean, A = above, between 0.52 and 1.28 standard deviations above the mean, N = near normal, between −0.52 and 0.52 standard deviations from the mean; B = below, between 0.52 and 1.28 standard deviations below the mean; MB = much below, at least 1.28 standard deviations below the mean.)

8*D*. Average height of 700-millibar pressure surface (blue line) over North America and departure from average (1951–80) summer conditions (black dashed line). Data in meters.

Figure 8. Continued.

SELECTED HYDROLOGIC EVENTS, WATER YEAR 1986

Many floods, droughts, and other water-related events occurred during water year 1986, as documented in the previous section of this report ("Review of Water Year 1986, Hydrologic Conditions and Water-Related Events"). In the "Selected Hydrologic Events Water Year 1986" section, several of those events, which were selected to illustrate a range of events that affected large numbers of people, required a variety of management actions to mitigate their effects, or were scientifically exciting, are described in more detail.

Weather-related events caused more than $10.5 billion in economic losses in water year 1986. Of this amount, flood damages were more than $6 billion—the highest amount of damages incurred since such records began and three times the 10-year (1976–85) average of $2 billion (U.S. Army Corps of Engineers, 1987). Flood-related fatalities totaled 208, just above the annual national average of 200 lives. Flash floods accounted for more than 80 percent of the death toll, and at least 60 percent of those deaths occurred in moving vehicles. Eight major floods occurred in water year 1986; these events are summarized in the previous section in table 1 (events 1, 8, 10, 31, 49, 52, 74, 85, 87, 90). Three of these events, which received nationwide attention, are expanded on in this section: "The Ruinous West Virginia Flood of November 1985", "Flood of August 6, 1986, in the Milwaukee Metropolitan Area, Wisconsin," and "Flood of September 10 to 15, 1986, Across the Central Lower Peninsula of Michigan." Unusually high amounts of precipitation occurred for the fifth straight year in Minnesota, and the resulting effects are described in the article "Unusual Hydrologic Events in Minnesota—*When it Rains . . . .*"

The effects of drought are more difficult to estimate, but they can be documented through reports of crop losses, forest fires, and mandatory restrictions on water use. An article in this section, "Drought in the Southeastern United States, 1985–86," describes the hydrologic effects of and management responses to the drought. Streams were below normal and most reservoirs were drained to record lows or near-record lows. More than 100,000 acres of land were burned, areas throughout the region imposed water-use restrictions, and agricultural communities were devastated. These conditions all contributed to more than $3 billion in damages (U.S. Army Corps of Engineers, 1987).

What is not reflected in the events listed in table 1 is some good news. The U.S. Army Corps of Engineers' dams, levees, and flood-protection projects prevented an estimated $27.3 billion in economic damages, about three times the 10-year average (U.S. Army Corps of Engineers, 1987). The 1986 water year also was a significant year for the U.S. Bureau of Reclamation, as described in this section in the article "Hoover Dam and the Central Arizona Project—A Milestone Year."

Water year 1986 also was the year that the public became aware of the health hazards of radon in the home. Because of the increased concern about radioactivity in the environment, the article, "Natural Radioactivity in Ground-Water—A Review," presents a review of naturally occurring radioactivity in ground water, the general areas of occurrence, and methods for treating the water. Finally, a scientifically exciting event related to glacier movement in Alaska is described in "Hubbard Glacier Near Yakutat, Alaska—The Ice Damming and Breakout of Russell Fiord/Lake, 1986." This event, perhaps without parallel in human experience, may have produced the greatest short-lived discharge of water in North America in recorded history.

REFERENCE CITED

U.S. Army Corps of Engineers. 1987, Annual flood damage report, fiscal year 1986: U.S. Army Corps of Engineers Report DAEN-CWH-W, 14 p.

DROUGHT IN THE SOUTHEASTERN UNITED STATES, 1985–86

By Harold G. Golden and Harry F. Lins

INTRODUCTION

A severe meteorological, hydrologic, and agricultural drought occurred in parts of the Southeastern United States during 1986. Rainfall was below normal throughout much of the Southeast during 1985, and, except for Arkansas, Florida, and Louisiana, remained much-below normal during the winter, spring, and early summer of 1986. This persistent rainfall deficiency resulted in a major drought over a large geographical area (fig. 9) during the summer of 1986.

The word "drought" has different meanings to different people. To a farmer a drought is a deficiency of moisture that affects the crops under cultivation—even 2 weeks without rainfall can stress many crops during certain periods of the growing cycle. To a meteorologist a drought is a prolonged period of moisture deficiency—a drought lasting 1 to 3 months is considered short term, 4 to 6 months is intermediate, and more than 6 months is long term. To a water manager a drought is a deficiency in water supply because of its effects on water availability and water quality. To a hydrologist a drought is defined in terms of the effects of periods of deficient precipitation on water resources—these effects can include deficient streamflow, declining reservoir contents, reduced soil moisture, and falling ground-water levels.

In 1985, precipitation and streamflow varied greatly throughout the Southeast, and monthly streamflow averages were below normal for much of the year. In much of Alabama, Georgia, Tennessee, North Carolina, and South Carolina, precipitation ranged from 65 to 95 percent of normal and streamflow ranged from 50 to 80 percent of normal. These 1985 dry conditions were followed by very low rainfall in the winter and spring of 1986. Streamflow in many rivers was below average for the first 7 or 8 months of 1986, which resulted in extreme low flows in eastern Alabama, eastern Tennessee, Georgia, and the Carolinas during July and August 1986. As of mid-August 1986, streamflow had increased from the minimum for the year and did not recede again to that extreme low.

Ground-water levels, which usually are highest in April and May, were below normal during those months in 1986. As the rainfall deficiency persisted, ground-water levels began to recede at greater than normal rates from already lower-than-normal levels. Ground-water levels remained much-below normal during the summer growing season as the rainfall deficiency continued. However, above-normal rainfall occurred in late summer and fall and provided recharge over most of the area; as a result, the water levels in most observation wells began to rise during September, October, or early November, depending on geographic location and depth of the wells.

CLIMATOLOGICAL CONDITIONS ASSOCIATED WITH THE DROUGHT

The progressive development of drought conditions across the Southeast during the winter and spring of 1986 resulted from anomalous seasonal patterns in the general atmospheric circulation. The most notable departures from normal were a relatively weak and variable flow in the subtropical jet stream over the Southeastern United States and the absence of low-pressure troughs over the lower and middle Mississippi River valley at the 700-millibar level (about 10,000 feet). Typically, during winter and spring months a strong subtropical jet flow coupled with occasional upper-level troughs over the Mississippi valley promotes the development of large-scale cyclonic storms over and along the margins of the Gulf of Mexico. Usually several such storms will form and move north-eastward, spreading abundant precipitation across the Southeast. In 1986, however, fewer than normal storms formed in the Gulf area and those that did form generally were weak and produced insufficient rain to break the drought. To summarize, the upper-level circulation of the winter and spring period was characterized by an alternative pattern of troughs displaced either west of normal (accounting for above-normal precipitation in the Central Plains, northern Mississippi River valley, and western Great Lakes area) or east of normal (along or just offshore of the East Coast) bringing enhanced precipitation to parts of Florida and extending well offshore into the Atlantic.

Although the late spring and early summer circulation pattern was close to normal, the typical surface pattern of convective showers and thunderstorms characteristic of the region never materialized. Through June and early July an upper-level trough persisted off the east coast with an adjacent upper-level ridge over the Southeast. The dry subsiding air associated with the ridge effectively blocked the normal influx of moist air from the Gulf of Mexico, leading to record dryness across much of the area by the end of July.

During the first 2 weeks of August, low pressure aloft moved over the Southeast bringing an increase in convective activity. In fact, many parts of the region received unusually large quantities of precipitation in mid-August. Although the moisture deficits by this time were very large, this abundant moisture did alleviate the streamflow-drought severity. By late August and throughout September, the Southeast again was largely under the influence of high pressure aloft, which resulted in below-normal precipitation. However, streamflows did not recede to the extreme lows of late July and early August.

HYDROLOGIC CONDITIONS ASSOCIATED WITH THE DROUGHT

PRECIPITATION

Precipitation during 1985 ranged from 65 to 95 percent of normal in much of the Southeast excluding the States of Arkansas, Louisiana, and Florida. The below-normal rainfall in 1985 was followed by extremely low rainfall in the winter and spring of 1986. The percentage of normal precipitation at selected stations in each State for the period January to August

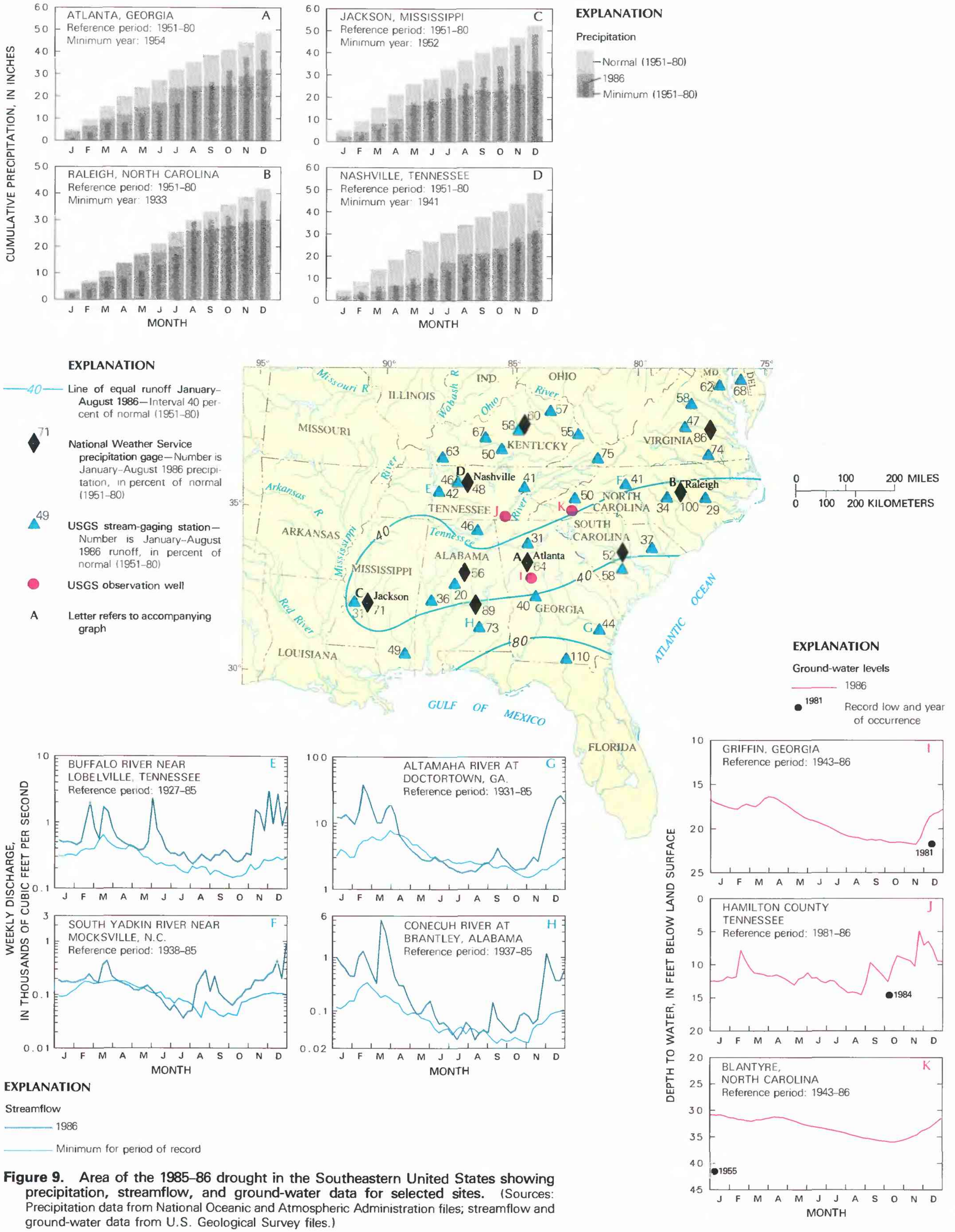


Figure 9. Area of the 1985–86 drought in the Southeastern United States showing precipitation, streamflow, and ground-water data for selected sites. (Sources: Precipitation data from National Oceanic and Atmospheric Administration files; streamflow and ground-water data from U.S. Geological Survey files.)

is shown in figure 9. Also shown are the cumulative monthly precipitation for 1986, normal precipitation for the 1951–80 reference period, and the previous minimum year of record for four locations—Atlanta, Ga., Raleigh, N.C., Nashville, Tenn., and Jackson, Miss. In Atlanta (fig. 9*A*) the cumulative precipitation in 1986 was lower than the minimum year of record (1954) for January–August and in Raleigh (fig. 9*B*) it was lower than the minimum year of record (1933) for January–June. In Nashville, Tenn. (fig. 9*C*), and Jackson, Miss. (fig. 9*D*), the cumulative precipitation was below the minimum year of record in the middle or early part of the year, respectively.

Rainfall in June and July produced runoff that alleviated the drought to some extent in Mississippi, Alabama, western Tennessee, and Kentucky. In late August, heavy rains following Hurricane Charley reduced the rainfall deficit for the year in parts of North and South Carolina and southern Georgia and locally produced flooding of small streams.

The chronology of the 1986 drought is documented by the drought-severity index maps shown in figure 10. Maps for mid-April to mid-September show the progression of the drought. In mid-April the extreme drought was limited to a small area in eastern Tennessee and the western Carolinas. By mid-July it had covered most of Georgia, the Carolinas, Virginia, Maryland, eastern Alabama, eastern Tennessee, and southeastern Kentucky. In mid-August the area of extreme drought remained about the same, but by September it had receded to eastern Alabama, eastern Tennessee, western North Carolina, and Georgia. This expansion and contraction of the drought area is consistent with the streamflow data discussed below.

STREAMFLOW

Streamflow in much of the Southeast was only 50 to 80 percent of normal for 1985. The low flows continued into the first 8 months of 1986, when many streams had the lowest seasonal flows of record for the season. The cumulative runoff for the year through August 1986 as a percentage of normal is shown in figure 9. From Mississippi to North Carolina the yearly runoff through August was less than 40 percent of normal. In other parts of the drought area streamflows were less than 80 percent of normal except for southern Georgia, which had heavy rains in late February. After these rains little precipitation occurred in southern Georgia until August, and streamflows were low from March through July.

Weekly flows for 1986 and the minimum weekly flows for the period of record at selected streamflow-gaging stations in Tennessee, Alabama, North Carolina, and Georgia are shown in figure 9*E–H*. Each of those stations had some daily flows below the previous minimums. New minimum flows of record also occurred in late July at several other long-term gaging stations (50 years or more of record) in Georgia.

A statistic widely used by water-quality and water-use managers to estimate the reliability of a surface-water source for water supply or for use in diluting waste discharge is the 7-day 10-year low flow (lowest average flow for 7 consecutive days with a 10-year recurrence interval). The 1986 flows were below this average flow for 54 days at the Georgia station, 34 days at the North Carolina station, and 28 days at the Alabama station; no days were below that average flow at the Tennessee station. Tennessee also uses the statistic 3-day 20-year low flow, and no days were below that flow at the Tennessee station. The hydrograph trends through August show that serious flow deficiences occurred and that new record minimum flows were set by many streams in the most severely affected parts of the Southeast. The time of occurrence of these record minimum flows in July and August is rare for the Southeast, where annual minimums usually occur in September and October. Also, the occurrence of the extreme low flow during months of high-evapotranspiration loss caused the recession in flow to be more rapid than had been previously experienced in this flow range in many streams.

When comparing monthly streamflow to normal (reference period 1951–80), July was the lowest month for this drought, and at many stations in the Southeast, July streamflow also was the lowest July flow of record. Streamflow for July 1986 expressed as a percentage of normal July flow is shown in figure 11.

In northern Georgia and the eastern Carolinas, streamflows during the 1986 drought were near the lowest in this century. The minimum daily flows of several streams in these areas were lower than those in 1931, 1941, 1954, and 1981 and were near the record low flow during the 1925 drought. In the most severely affected area, the recurrence intervals of the 1986 annual minimum daily flows for many streams were between 50 and 100 years. The 1986 annual streamflows in this area were much-below normal with recurrence intervals between 50 and 100 years.

RESERVOIR LEVELS

Many reservoirs in the Tennessee River basin were below normal summer levels in 1985, and several reservoirs in east Tennessee, north Georgia, and western North Carolina were still below normal in September 1986. However, mainstem reservoir levels were maintained at near-normal elevations because of less-than-normal releases for hydropower generation.

Lake Sidney Lanier in northern Georgia is the primary water supply for Metropolitan Atlanta and also is the most popular recreation lake of all the U.S. Corps of Engineers' reservoirs nationwide. In late October, Lake Lanier was at the lowest level recorded for that time of year—16 feet below normal summer lake level. Boaters were cautioned to watch for submerged objects because of the low lake level. (See figure 12.) In late August the Corps of Engineers significantly reduced flow releases from Lake Lanier. This, coupled with runoff-producing thunderstorms in the headwaters and below-normal air temperatures that reduced evaporation losses, reduced the rate of decline in the lake level during late August; by late October the lake level had begun to rise, and at year's end it was only 11 feet below normal summer level.

Elsewhere in Georgia, low reservoir levels caused boat ramps to be out of water, exposed objects normally submerged, and rendered the lakes esthetically unpleasant. Thus, recreation and visits decreased an estimated 25 percent at Allatoona Reservoir and 10 to 20 percent at Hartwell, Russell, and Clarks Hill Reservoirs.

The most severely affected reservoirs in Alabama were on the Coosa and the Tallapoosa Rivers. Deficient rainfall during the months of December 1985 through April 1986 resulted in below-normal reservoir levels. To conserve water, reservoir releases were reduced to minimum requirements. This practice was continued through the summer and reservoir levels in September remained below normal.

GROUND WATER

Ground-water levels in the areas affected by the drought generally were below average during mid-1986. In parts of the Piedmont (central Georgia and central Carolinas), water levels during the summer months were lower than during the same period of the 1981 drought. A record low water level was established at a Griffin, Ga., observation well during the fall (fig. 9*I*). In parts of southwest Georgia, larger-than-normal withdrawals for irrigation induced by the drought resulted in record low water levels. Elsewhere in southwest Georgia, below-normal precipitation reduced recharge and increased demand for irrigation to the extent that water levels in some areas reached record lows by the end of the summer.

In Tennessee, ground-water levels had been below normal since December 1985, and record low water levels were reached at two wells in middle Tennessee during April and May 1986. Water levels recovered slightly and were near normal throughout the State following rains in late May and early June; however, the rainfall was insufficient to maintain the rise in water levels and by August the water level had declined to a near record low in one well (fig. 9*J*) before levels began to rise again.

In early September, ground-water levels in unconfined aquifers in North Carolina remained well below normal in the western part of the State, were near normal in the central part, and were above normal in the eastern part. Ground-water levels began to rise in October in the western and central parts of the State (fig. 9*K*), and in January 1987 in the eastern part.

In east-central Alabama low ground-water levels were reflected in record low discharges of Coldwater Spring near Anniston in August.

EFFECTS OF THE DROUGHT

AGRICULTURE

The 1986 drought severely affected the agricultural economy of the area. The Georgia Department of Agriculture estimated losses at $319 million. Maryland reported losses of $117 million, South Carolina $165 million, North Carolina $325 million, and Virginia $303 million. In July and August, pastures in much of the drought area were in poor condition, supplemental feeding of livestock was required in many localities, and ranchers marketed more cattle than usual. As of mid-September, many counties in each State were declared eligible for Federal drought relief: Alabama, 67; Georgia, 159; Maryland, 22; Mississippi, 39; North Carolina, 81; South Carolina, 39; Tennessee, 75; and Virginia, 83.

Irrigation water use in southwest Georgia during 1986 exceeded the withdrawals made during the 1980–81 drought. In Georgia about 65 percent of the withdrawals were from ground-water sources and the remaining withdrawals were from surface-water sources. Irrigation use in other parts of the Southeast, although not as large, followed the same pattern. In North Carolina some water shortages resulted when irrigation ponds were depleted.

WATER SUPPLY

Shortages in surface-water supply were experienced throughout many areas of the Southeast in 1986. In Georgia, water-supply shortages first occurred in a few Atlanta metropolitan systems, primarily because of high demand and small reservoir storage. As the drought continued, several systems in the southern part of the metropolitan area also had water-supply problems. Several municipalities in north and central Georgia had surface-water-supply shortages.

North and South Carolina reported water-supply problems in a number of municipalities throughout the States, and in central Kentucky, several communities that rely on surface water experienced shortages and imposed use restrictions. Fortunately, precipitation in late August and early September helped abate most surface-water-supply problems.

Shortages of ground water from rural-domestic wells were noted primarily in the northern one-third of Georgia and in southern Tennessee where several hundred wells were reported dry. Most public-water supplies in these areas rely on surface water and also experienced water shortages.

Water shortages occurred in some Alabama communities that are supplied by ground water. Coldwater Spring, one of Alabama's largest springs and the source of water for about 70,000 people in the Anniston area, reached a record low flow in August. In the Mississippi Delta, record low ground-water levels were set in August because of the drought and heavy irrigation demands.

WATER QUALITY

Quality of the water in some major reservoirs, especially in the Tennessee River mainstem reservoirs, was seriously degraded by the drought. Water temperatures were uncharacteristically high at depths as great as 80 feet, dissolved-oxygen concentration and pH were lower than normal, and aquatic weed growth was excessive. In Kentucky Lake, fish reportedly were sluggish, about 65 percent of the catfish caught by commercial fishermen could not be sold because of their poor condition, and minor fishkills were reported. Some industries curtailed operations to reduce waste releases to the Tennessee mainstem reservoirs.

The Alabama Department of Environmental Management reported about 80 fishkills that were suspected to be related to wastewater discharges. Fishkills were reported in northwest and southwest Mississippi on the Yazoo River and Bogue Chitto, respectively. Fishkills reported in Georgia were primarily due to low streamflow and high temperatures. Significant water-quality effects reported by North Carolina include blue-green algae blooms and fishkills in the headwaters of Falls Lake near Raleigh, and fishkills in Middle Creek near Clayton.

Chloride and sodium concentrations were a problem for Chesapeake, Va., which has a water intake on the Northwest River. Abnormally high concentrations in August 1986 were caused by low freshwater flow in the river, which reduced the normal flushing and dilution in this tidal stream. Locally heavy rains and resultant runoff in late August reduced the problem. Fortunately, there were no reports of major algae blooms such as the one on the James River that caused taste and odor problems for Richmond, Va., during the 1980–81 drought.

MANAGEMENT ACTIONS IN RESPONSE TO THE DROUGHT

To conserve water and minimize the effects of reduced precipitation and streamflow in 1986, the affected States resorted to drought emergency plans or other management actions. Actions also were taken to minimize the effects of low flows on hydropower generation. These actions are described below.

The first major restrictions on water use in the Southeast region occurred in June 1986 in the Atlanta metropolitan area when several water authorities limited or banned outdoor water use. These restrictions were imposed because heavy demands caused by the drought exceeded the storage and distribution capacities of the systems or the maximum permitted withdrawals were being approached. During July, the Georgia Environmental Protection Division (EPD) notified more than 100 communities in north Georgia to adopt water-conservation measures, and most of the communities complied. Several of these communities imposed total bans on outdoor water use, and a few localities, because of insufficient supplies, also requested reductions in industrial use. In mid-August about 330 ground-water users, mostly in southern Georgia, were notified by EPD to adopt water-conservation practices by September 5. Most users implemented these practices, but before they became completely effective, rain in October reduced their impact.

The Kentucky Cabinet for Natural Resources issued a "water shortage watch" in mid-August to warn local officials of the potential for shortages if dry conditions persisted. The watch, which advised local officials to monitor water supplies and to begin conservation measures if shortages continued, was especially important for public water-supply systems that depend on small streams.

A Drought Task Force made up of representatives from State and Federal agencies was established by the Governor of Alabama in the summer of 1986 to consider all aspects of the drought. By October 1, 1986, the Task Force actions to reduce hydropower generation had resulted in a 25-percent reduction in releases from five reservoirs in the Coosa and the Tallapoosa River basins in Alabama.

As early as 1985, the State of Virginia in response to the drought conditions established a Drought Monitoring Task Force under the auspices

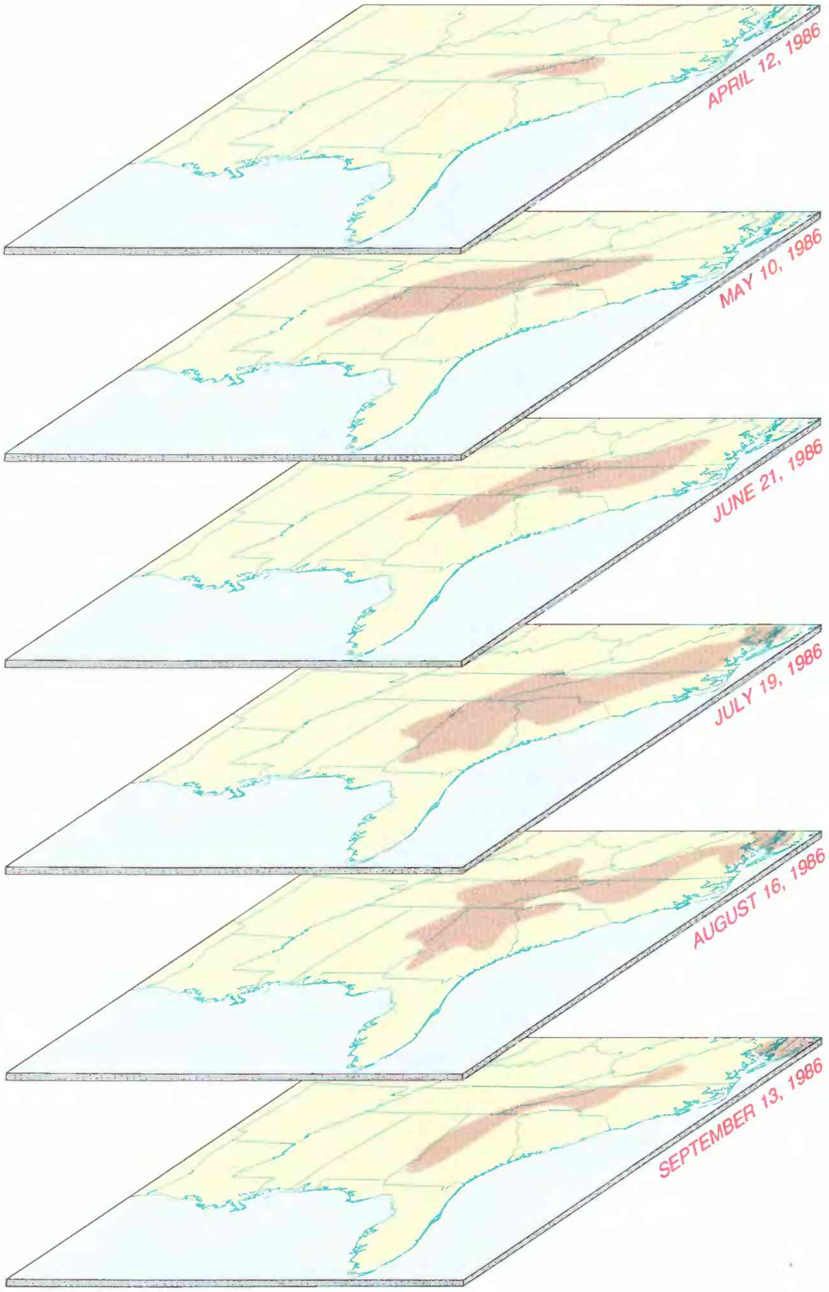


Figure 10. Area of extreme drought in the Southeastern United States, April 12, 1986, to September 13, 1986. The term "extreme drought" is derived from the long-term Palmer Drought Severity Index, which is based on precipitation, evapotranspiration, and soil moisture conditions—all of which are determinants of hydrologic drought. (Source: Data from National Oceanic and Atmospheric Administration and U.S. Department of Agriculture Joint Agricultural "Weekly Weather Crop Bulletin.")

of the Virginia Water Control Board. When drought conditions persisted into the spring of 1986, the Task Force was reactivated. It consisted of representatives from the Virginia Water Control Board, Department of Health (public water supplies), Department of Agriculture, Division of Forestry, Department of Emergency Services, State Climatologist, the National Weather Service, and the U.S. Geological Survey. The Task Force issued biweekly statements on current hydrologic and agricultural conditions as well as near- and long-term weather forecasts. In late August, the Virginia Governor's Office issued letters to all communities and large industrial water users requesting voluntary conservation of water in order to mobilize citizen participation in conservation efforts. Voluntary conservation of water was requested earlier in the summer in a few communities having shortages due to a lack of supply or to distribution problems.

The States of Georgia, Florida, and Alabama and the U.S. Army Corps of Engineers formed a drought-management committee to formulate water management action to combat the serious water shortage in the Apalachicola–Chattahoochee–Flint River basin. The committee coordinated many actions taken by the member organizations in response to the drought including reduction in reservoir releases, which reduced hydropower generation and releases for navigation, implementation of water-conservation measures, and water-use restrictions when necessary.

In South Carolina, voluntary restrictions on water use were requested in numerous municipalities and mandatory water-use restrictions were instituted in Camden and York. In North Carolina, mandatory water-use conservation measures were placed in effect by city officials in Durham, Charlotte, Bessemer City, Cherryville, Stoville, Landis, Hillsborough, Mount Pleasant, Concord, Atlantic Beach, and Orange-Alamane and also by the Orange Water and Sewer Authority. Voluntary conservation was requested in 26 additional systems including Winston-Salem and Greensboro.

Water-use restrictions were imposed by 17 water systems in east and central Tennessee. In August, Alabama requested a reduction in the use of water for some communities in DeKalb, Calhoun, Marion, and other central Alabama counties.

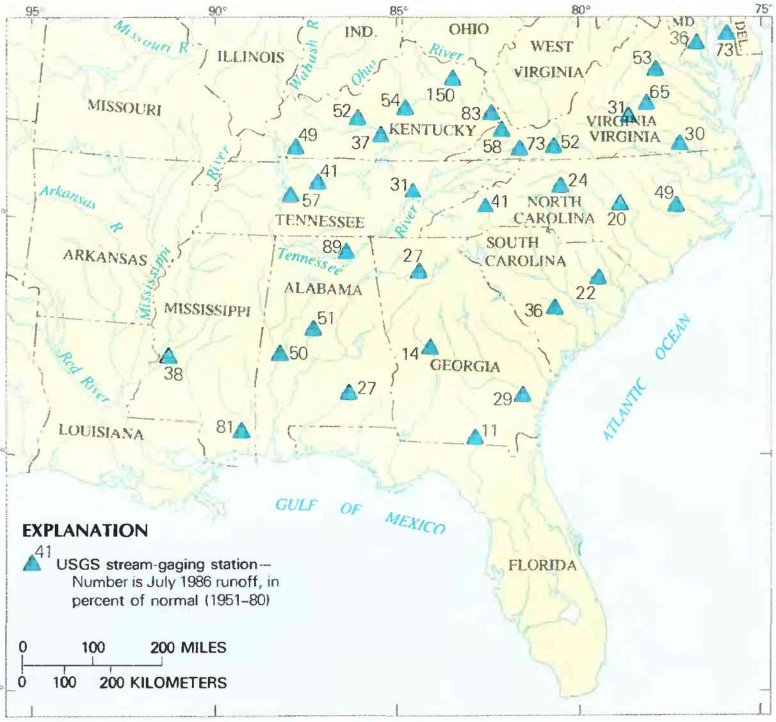


Figure 11. Streamflow for July 1986, the most severely affected month of the 1985–86 drought in the Southeastern United States. (Source: Data from U.S. Geological Survey files.)

By mid-September, many jurisdictions in the Southeast had lifted restrictions because of increased precipitation and the decrease in outside water use.

The 1986 drought also seriously affected hydropower generation in many areas of the Southeast. For example, power generation by the Corps of Engineers' reservoirs in northern Georgia and Alabama was reduced by 50 percent because of reduced streamflow. The Southeast Power Administration, which markets power generation by Corps facilities, was forced to purchase alternative power because of reduced hydropower generation resulting from the drought.

The Tennessee Valley Authority (TVA) reported that for the period January–May 1986, hydropower generation was only 50 percent of normal because of conservation measures at reservoirs in the Tennessee basin. However, increased precipitation, coupled with the conservation measures, produced near-normal elevations in many of the mainstem reservoirs during early September, permitting a return to near-normal hydropower generation.

The Alabama Power Company reported that hydropower generation was about 70 percent below average in May and about 60 percent below average in June. Hydropower generation in South Carolina was severely reduced because of low reservoir levels. On June 13th a South Carolina company ceased hydropower generation at Lake Murray where generation had been minimal for several months. When the drought eased later in the fall, hydropower generation was resumed.

Figure 12. Lake Sidney Lanier, Georgia, September 1986, at Young Deer Creek embayment on the north side of reservoir near Buford Dam. Water-level elevation was about 1,056 feet above sea level. Tree-line marks near-normal summer elevation of 1,071 feet. In October 1986, the reservoir level had receded to a minimum of 1,054.8 feet, which was only 2.1 feet above the record minimum level of 1,052.7 feet in December 1981. (Photograph courtesy of U.S. Army Corps of Engineers.)

CONCLUSIONS

An agriculturally, meteorologically, and hydrologically severe drought occurred in parts of the Southeastern United States during 1986. The drought began in 1985 in much of Alabama, Georgia, Tennessee, North Carolina, and South Carolina. During 1985 the annual precipitation ranged from 65 percent to 95 percent of normal and the annual streamflow ranged from 50 percent to 80 percent of normal. These dry conditions in 1985 were followed by very low rainfall in the winter and spring of 1986, which resulted in extreme low flows in eastern Alabama, eastern Tennessee, northern Georgia, and the eastern Carolinas during July and August 1986. These low streamflows were less than the previous minimum streamflows recorded at several gaging stations with 50 years or more of record. The timing of these extreme low flows in late July and early August was unusual because annual minimum flows in much of the Southeast usually occur in September and October.

In Atlanta, Ga., the precipitation for the first half of 1986 set a new record low for January-June, and in Raleigh, N.C., and Nashville, Tenn., it was the second lowest January-June on record. The cumulative streamflow through August 1986 was less than 40 percent of normal from Mississippi to North Carolina. In northern Georgia and the eastern Carolinas the streamflows during late July and August 1986 were near the lowest of this century.

Reservoir levels were below normal in north Georgia, east Tennessee, and the eastern Carolinas during the spring and summer of 1986. However, the mainstem reservoirs in the Tennessee River basin were maintained near normal throughout the dry period.

Ground-water levels in the drought-affected area generally were below average. During 1986, water levels in the most severely affected area were below average in the spring and declined to near-record lows in August in many observation wells.

The drought severely affected agriculture, and estimated losses in the Southeast exceeded $1 billion. Many counties in the affected Southeastern States were declared eligible for Federal drought relief. Water-supply shortages occurred in Georgia and the Carolinas as a result of low streamflows and declining ground-water levels.

Water-quality problems occurred in many streams in the Southeast and in the major reservoirs in the Tennessee River mainstem. Fishkills, odor problems, and excessive aquatic weed growth were reported in several States in the Southeast because of the low streamflow and high water temperatures. Most Southeastern States took management actions during this drought emergency and established a variety of drought contingency plans. In some places, particularly in north Georgia and the eastern Carolinas, water use was restricted.

Acknowledgments

The authors acknowledge the contributions of the following U.S. Geological Survey personnel who furnished the information on precipitation, streamflow, ground-water levels, and drought effects for their respective States: J. Brian Atkins, Alabama; A. Carroll Barker, South Carolina; Ronald D. Evaldi, Kentucky; Charles R. Gamble, Tennessee; Timothy W. Hale, Georgia; Catherine L. Hill, North Carolina; Robert W. James, Jr., Maryland; Byron J. Prugh, Jr., Virginia; and E. J. Tharpe, Mississippi.

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HUBBARD GLACIER NEAR YAKUTAT, ALASKA—THE ICE DAMMING AND BREAKOUT OF RUSSELL FIORD/LAKE, 1986

By Lawrence R. Mayo

INTRODUCTION

One of the most dramatic hydrologic events in the United States during this century occurred in May 1986, when the Hubbard Glacier, which originates in an ice field in the Canadian part of the St. Elias mountains and flows in a southerly direction through the Wrangell–St. Elias National Park and into Disenchantment Bay, sealed the entrance to Russell Fiord in the Tongass National Forest near Yakutat, Alaska, and transformed the fiord into Russell Lake. (See figures 13 and 14.) During the past century, the glacier had been encroaching gradually on the fiord, and it had been predicted (Post and Mayo, 1971) that by about 1990 the fiord would be blocked (dammed) by the advance of the Hubbard Glacier against the northern part of Gilbert Point. When this blockage did occur on May 29, 1986, Russell Fiord (now transformed into Russell Lake) filled rapidly, giving rise to the possibility that by 1987 the elevation of the lake would be so high that it would discharge into the Situk River basin. If that were to happen the new outlet at the southwestern shore of Russell Lake would seriously disrupt a world-renowned fish-spawning habitat, drown forests, inundate two roads, and flood a "bush" airstrip and numerous subsistence fishing camps. Rising lake levels potentially also could alter the local climate and possibly inject residual seawater from the fiord into local aquifers.

On October 8, 1986, before this could occur, the Hubbard Glacier ice dam failed, rapidly discharging an estimated 1.3 mi^3 (cubic miles) of lake water into Disenchantment Bay. The outburst flood maintained an hourly average discharge of 3,700,000 ft^3/s (cubic feet per second). This outburst may have produced the greatest short-lived discharge of water in North America since glacial-lake outburst floods occurred at the end of the Pleistocene Epoch (about 10,000 years ago).

The closure of the fiord and the subsequent outburst flood from the ice-dammed lake set the stage for potentially more dramatic hydrologic events in the years ahead, events that could have profound and long-term effects on the inhabitants of Yakutat and environs, the resources of the national park and the national forest, and the ecology of the area. In response to the importance of the Hubbard Glacier advance and the complexity of the natural processes of change in the geology, hydrology, and ecology of the region, the U.S. Secretary of Agriculture dedicated the Russell Fiord Wilderness Area as a GEOLOGIC INTEREST AREA, the 15th such in the national forest system. The observations of the Hubbard Glacier reported herein are the result of a cooperative project by two bureaus of the U.S. Department of the Interior—the U.S. Geological Survey and the National Park Service—and an agency of the U.S. Department of Agriculture—the U.S. Forest Service.

HISTORIC ADVANCE AND RETREAT OF HUBBARD GLACIER

Legends and stories told to early explorers, and which are still in the oral history and memory of the Tlingit native people of Yakutat, testify that major glacial advances in the past had overridden villages, changed the local ecology, and altered the courses of rivers, whereas major glacial retreats had opened new bays and provided new transportation routes (de Laguna, 1972). Hubbard Glacier last advanced to the Gulf of Alaska in A.D. 1130 ±160 years (Plafker and Miller, 1958) and formed a terminal moraine on which the town of Yakutat is now located (fig. 13). After this "Middle Ages" advance, the glacier retreated 20 to 30 miles; in about A.D. 1700 it again advanced (Plafker and Miller, 1958). Both of these advances left prominent submarine moraines in Yakutat Bay. After the A.D. 1700 advance the glacier again retreated, exposing land (west of Gilbert Point) that was named Haenke Island by the explorer Malaspina who mapped Disenchantment Bay in 1791 while searching for the elusive Northwest Passage. In 1891, I.C. Russell, the first scientist to conduct studies in the area, found Russell Fiord to be open to Disenchantment Bay. In 1895, the International Boundary Commission (1952) mapped the Hubbard Glacier terminus about 1.5 miles from the point where the damming of Russell Fiord was to occur in 1986 (fig. 14).

Since 1895, the glacier has advanced by depositing a protective submarine moraine across the entrance of Russell Fiord (and across the upper part of Disenchantment Bay). Recent fathometer measurements in water near the terminus and ice radar measurements through Hubbard Glacier behind the terminus reveal that a protective moraine extends across the mouth of the fiord almost to the sea surface at the ice cliff terminus of the glacier.

The advance of Hubbard Glacier is made possible because 95 percent of the glacier's 1,300-mi^2 (square mile) area lies in its accumulation area. Hubbard Glacier lost most of its ablation (ice melting) area after it had retreated about 35 miles from the mouth of Yakutat Bay since A.D. 1130. From a glaciological point of view a glacier can be divided into an accumulation area (accumulation > ablation) and an ablation area (ablation > accumulation). The line of demarcation between the two is called the

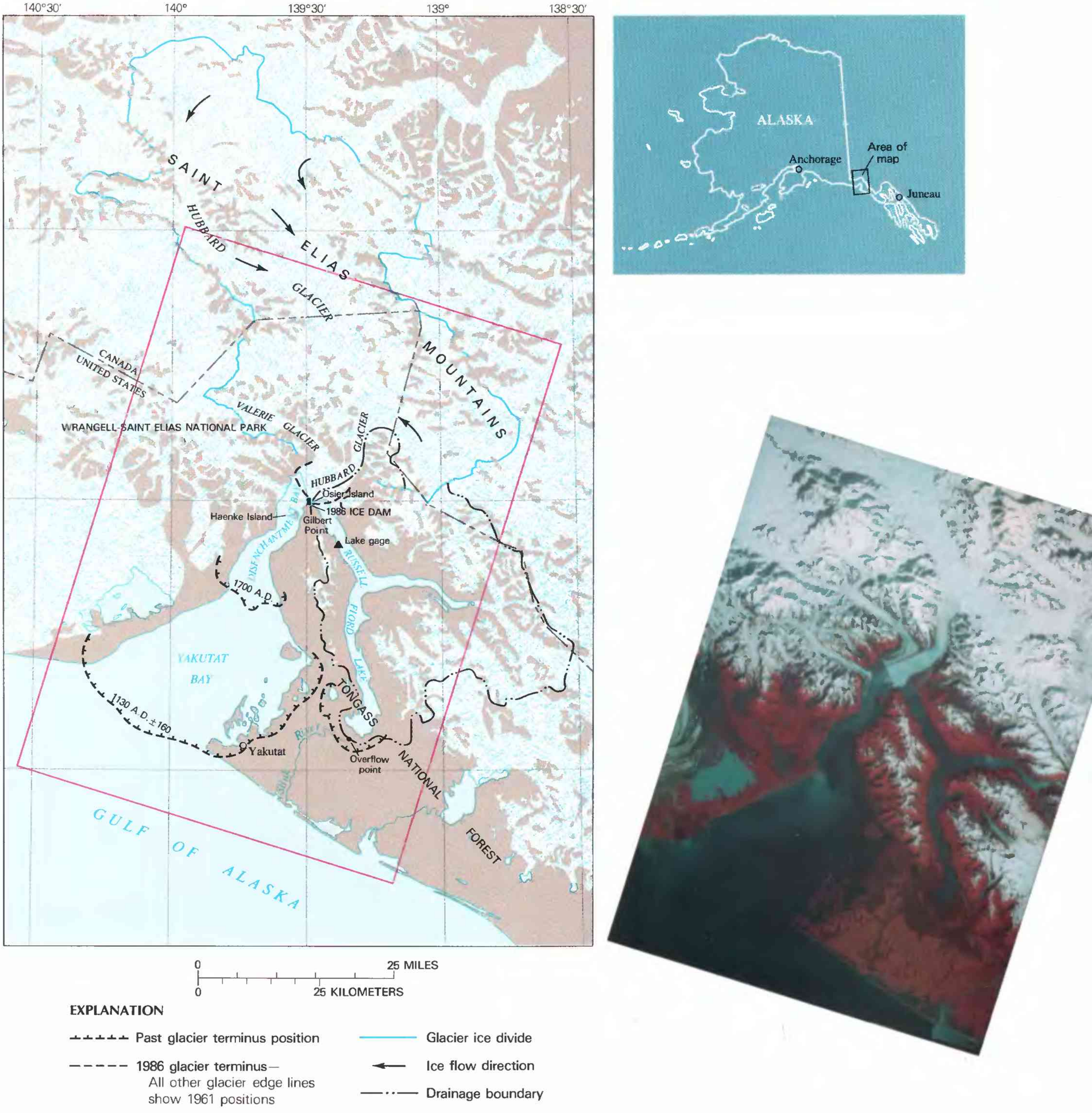

Figure 13. Hubbard Glacier, Russell Fiord/Lake, and Situk River, Alaska. (Sources: Ages of recent glacier advances by radiocarbon dating from Plafker and Miller, 1958; other data derived from U.S. Geological Survey topographic maps. Photograph is Landsat image of Hubbard Glacier area, September 11, 1986; PAO no. E-12582-35CT, EROS Data Center.)

equilibrium line. At the present time, most of the ice flowing from the vast accumulation area of the Hubbard Glacier is lost by calving. Only a small fraction of the ice volume either melts or is stored as the glacier lengthens and thickens; this results in a slow advance of the glacier. During the past century the Hubbard Glacier advance rate has increased gradually. From 1895 to 1961, the glacier advanced only about 3,300 feet at an average rate of 50 feet per year. From 1961 to 1985 the glacier advanced 2,600 feet at an average rate of 108 feet per year.

Before 1985 the terminal submarine moraine of Hubbard Glacier had been advancing into deep water, but in 1985 the terminus reached shallow water near Gilbert Point (fig. 13). The increased rate in glacier advance that culminated in the fiord closure in 1986 was caused primarily by reduced calving losses near Gilbert Point as the glacier entered progressively shallower water. From August 7, 1985, to June 12, 1986, the glacier advanced only 160 to 650 feet along its terminus into the deep water of Disenchantment Bay but it advanced 1,000 to 1,600 feet into the shallower Russell Fiord. It also advanced about 2,600 feet along a 1,600-foot-wide segment of the terminus, into the rock ridge below Gilbert Point. This advance blocked Russell Fiord from the sea and created Russell Lake on May 29, 1986. The average rate of advance from August 1985 to June 1986 in very shallow water in the vicinity of the new ice dam was about 3,300 feet per year.

The localized, rapid advance that caused the closure of Russell Fiord was assisted by soft sediments at the glacier terminus and by a surge of a tributary glacier. Soft marine silt and gravel were plowed up by the advancing ice terminus and were pushed above sea level. This effectively halted any further calving losses from that part of the terminus during the spring of 1986.At the same time, the Valerie Glacier, which is a 25-mile-long southeastward-flowing tributary to Hubbard Glacier, underwent a weak surge that increased its normal rate of ice flow from 3 to 6 feet per day to 100 feet per day. This ice flow from Valerie Glacier, which entered Hubbard Glacier north of its terminus, contributed to the accelerated movement of Hubbard Glacier into and across the mouth of Russell Fiord.

RUSSELL FIORD/LAKE

Tlingit Indians of Yakutat gathered berries and hunted beside a lake in the Russell Fiord basin in the years before about 1860 and witnessed the drainage of the lake (de Laguna, 1972). I.C. Russell (1893) observed shoreline features and a lack of vegetation on the fiord walls that indicated clearly the presence of the former glacier-dammed lake. River-delta sediments with two layers of lake sediments above sea level, dated at 6,000 and 4,000 years ago, were observed in October 1986 by George Plafker (U.S. Geological Survey), John Clague (Canadian Geological Survey), and the author, indicating that major glacier-dammed lakes formed several times in the recent past in Russell Fiord.

During the summer of 1985, tidal inflow apparently had been reduced by debris deposited by the glacier advance at the fiord's entrance, and fishermen noticed that about 20 feet of freshwater had accumulated on top of the saline water in the fiord. The channel closed completely on May 29, 1986, according to Mike Brahnum of Yakutat, and turned Russell Fiord into a lake once again. The freshwater flowing into Russell Lake in May 1986 floated on the residual seawater, isolating the seawater as had been predicted (Reeburgh and others, 1976). With inflow of oxygen by seawater advection eliminated by the closure, the trapped seawater was predicted to become anoxic within 2 years (W.S. Reeburgh, 1986, University of Alaska, oral communication).

Inflow to Russell Lake is from an 800-mi^2 drainage basin that is 50 percent glacier covered (fig. 13). The surface area of the lake ranges from 75 mi^2 when its surface is at sea level, to 100 mi^2 when the lake surface is elevated by 150 feet. Traces have been found of a lake shoreline at 150 foot elevation. The present outlet to the Situk River is at 130 feet.

Immediately after the lake formed in 1986 it was important to assess the possible outcome of a rising lake level: either the water would overflow the rising moraine dam at the glacier terminus or it would overflow into the Situk River basin. To calculate which of these two possibilities might occur, a prediction of the filling rate of the lake was needed. Inasmuch as no river gages were in operation in this region of Alaska and only one gage had been operated on a small stream 120 miles west for 11 years, the prediction had to be based on information extrapolated from research conducted on distant basins, as explained below.

Previous research at three glacierized drainage basins in Alaska produced a simple method for determining the average runoff rates expected from the glaciers (Mayo, 1986). An inverse relation exists between average glacier runoff rate and the equilibrium-line altitude (ELA) of glaciers—the altitude at which snow accumulation from precipitation is balanced by melting losses.

The average ELA of glaciers in the Russell Lake drainage basin is 2,600 feet, and the average runoff rate for glacier-covered areas was estimated to be 170 in/yr (inches per year). At Yakutat, the average precipitation rate is 135 in/yr, but inland from the Gulf of Alaska the precipitation decreases. If a precipitation rate of 120 in/yr is taken to be representative for the nonglacier areas of the basin and if evaporation is assumed to be 15 in/yr, then the runoff rate for nonglacier parts of the basin is estimated to be about 105 in/yr. This simple ELA/runoff model applied to the Russell Lake drainage basin indicated that the average annual water yield for the entire basin is about 138 in/yr, which is equivalent to an average annual flow of 7,700 ft^3/s.

To complete the prediction of lake-level rise, the average monthly discharge measurements from the Kenai River were used to estimate the seasonal variation of flow into the lake. The Kenai River was selected because it is at approximately the same latitude in Alaska as the Russell Lake basin, is near the Gulf of Alaska, and also contains glaciers and a major lake. The estimated monthly inflow to Russell Lake was used to develop the lake-height predictions shown in figure 15*A*.

During the summer of 1986, Russell Lake filled rapidly with freshwater, of which about 80 percent was from melted snow and glacier ice, and reached an elevation of 82.5 feet on October 7, 1986 (Seitz and others, 1986). The actual lake-height measurements (fig. 15*A*) were found to be consistent with the predicted runoff rates estimated for Russell Lake, and the measured filling of Russell Lake provided the first reliable runoff data for a glacierized basin in this region of Alaska, a region that may produce 5 percent of the Nation's runoff (Mayo, 1986).

STABILITY OF THE ICE DAM

The stability of the newly formed ice dam was uncertain during the summer of 1986 because it was only 1,600 to 2,000 feet wide, and the lake overflow point on the terminal moraine of the Hubbard Glacier was being pushed higher by the glacier only slightly faster than the lake was being filled (fig. 15*A*).

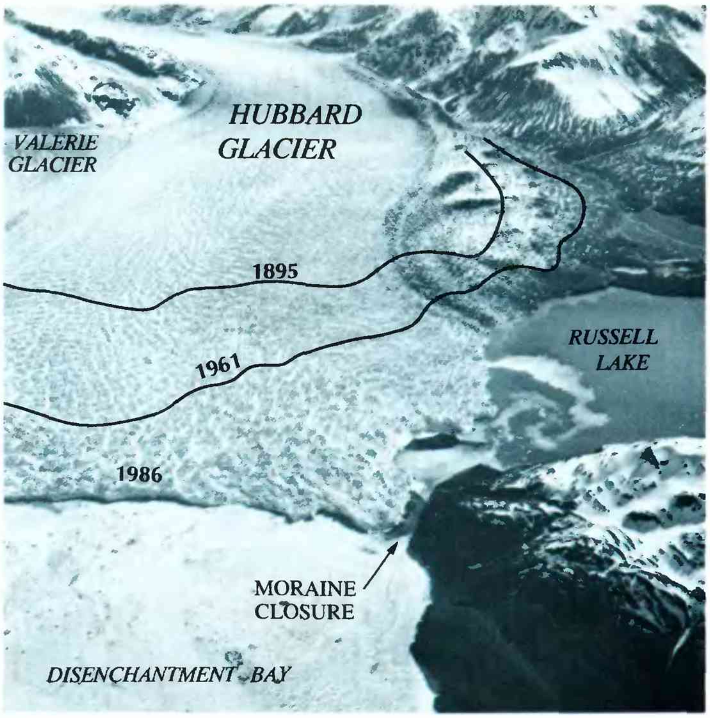

Figure 14. Oblique aerial photograph of the terminus of Hubbard Glacier, Alaska, June 13, 1986. View is northeast and shows the ice dam formed in May 1986 and the terminus position as mapped in 1895 by the International Boundary Commission (1952) and in 1961 by the U.S. Geological Survey (Mount St. Elias A-6, Alaska, map). (Source: U.S. Geological Survey photograph 86M1-51, by L.R. Mayo.)

The height of the ice dam itself could not be measured accurately because it was a complex array of spires and crevasses; it was estimated, however, to be about 3 times higher than the lake surface.

During the initial months after the lake formed, the most likely mode of dam failure appeared to be overtopping of the moraine at the glacier terminus. However, the advancing ice pushed the moraine up the steep mountainside at a rate that exceeded the rate of rise in lake level (fig. 15*A*); therefore, by September overtopping of the moraine was judged to be unlikely. Ice-dam failure by overflow did not occur. However, in August, the glacier terminus in Disenchantment Bay retreated 1,000 feet near the ice dam, which reduced the amount of ice flowing into the dam area. This sudden retreat may have been caused by a submarine landslide from the terminal moraine.

Stress on the ice dam from the flow of Hubbard Glacier caused ice compression between the glacier and the mountain and laterally directed ice extension parallel to the terminal moraine. From this motion, crevasses formed in the dam, separating a series of individual, narrow ice dams that pressed edge-on against the mountain front. Local runoff from rain and ice melt became trapped in the crevasses between these narrow dams, forming small lakes against the moraine that were higher than Russell Lake. Pressure from this trapped water increased the rate of lateral spreading of the ice. Movement of ice in the direction of the lake was effectively halted by the lake water pressure.

Calving of icebergs into Disenchantment Bay during the late summer exceeded the ice-replacement rate; consequently, the width of the ice dam decreased from 1,600 feet on August 7 to only 500 feet on October 7, 1986. During this period, muddy fresh water flowing from the dam after calving of each iceberg gave the appearance that lake water was leaking through the dam. However, muddy water also was flowing from the dam into Russell Lake. Apparently, water pressure in the dam was greater than the water pressure in the lake, a condition that blocked the outflow of any lake water. A greater water-pressure gradient in the ice dam relative to sea level was responsible for more calving on the ocean side than on the lake side of the ice dam.

Failure of the ice dam was thought to be imminent on September 26, 1986, when the ice dam was observed to be settling and breaking apart.

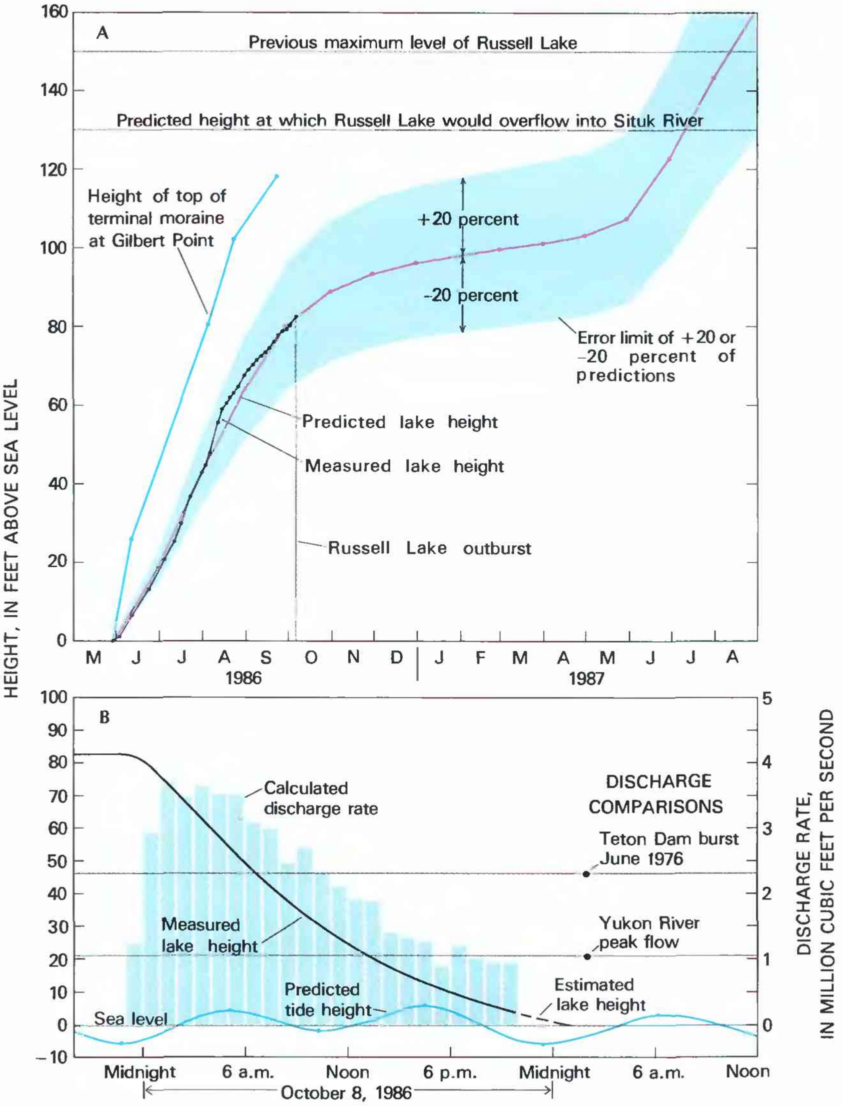

Figure 15. Measured and predicted rise of and discharge from Russell Lake, Alaska. *A*, Monthly lake-level rise and elevation of the moraine at Gilbert Point, May 1986 to October 1987. *B*, Discharge data for the outburst flood of October 8, 1986. (Sources: *A*, Measured lake heights from Seitz and others, 1986; predicted lake heights by L.R. Mayo; elevation of top of terminal moraine of the Hubbard Glacier at Gilbert Point measured by L.R. Mayo using aneroid altimeter. *B*, Lake-height data from Seitz and others, 1986; discharge data calculated by L.R. Mayo from lake-height data; Teton Dam burst discharge from Costa, 1985; Yukon River peak flow from Jones, 1983; tide predictions from NOAA tide tables for Alaska.)

On September 27, 1986, the U.S. Forest Service closed Russell Lake to float-equipped aircraft and boats because of the potential threat of strong currents in the lake if the dam failed. Similarly, the U.S Coast Guard issued a warning that no vessel should operate within 5 miles of Hubbard Glacier in Disenchantment Bay.

OUTBURST FLOOD OF OCTOBER 8, 1986

The outburst flood of Russell Lake began during the afternoon of October 7, 1986, when lake water began flowing through the ice dam carrying with it small bits of ice from the dam itself. At the same time, the lake was still rising and it continued to do so until 10:30 p.m. (Alaska Standard Time) on the evening of October 7, as a result of about 20,000 ft^3/s of water flowing into the lake; this was an indication that the flow of water out of the dam until 10:30 was less than this amount. Unfortunately, sunset occurred before the ice dam failed, and it was not possible to observe directly the breakout of Russell Lake. Blowing rain, wet snow, and fog also obscured the glacier during the night, further impeding visual observations. A rare display of St. Elmos's fire, a static discharge phenomenon produced by the blowing fog, made the breakout of the lake even more memorable and dramatic.

Just before midnight, a water-level monitoring station on Russell Lake began to register a drop in lake level. By 1:00 a.m. on October 8 a loud roar of water with frequent sounds of calving ice was heard by the author from the ridge 2,000 feet above the failing ice dam. The rate of lake decline and the noise level increased until about 2 a.m. Between 1:00 a.m. and 2:00 a.m., the fall of the lake level reached a rate of 5.5 feet per hour (Seitz and others, 1986), indicating a 1-hour average rate of discharge from the lake of about 3,700,000 ft^3/s (fig. 15*B*). From 2:00 to 3:00 a.m., the outburst discharge decreased temporarily, possibly because a very large iceberg could have partially blocked the outburst channel at 2 a.m. and remained there for part of the hour.

During the outburst flood, lake-height measurements telemetered at 15-minute intervals through the Geostationary Operational Environmental Satellite (GOES) communication system indicated that the peak discharge may have been as high as 4,100,000 ft^3/s at about 1:15 a.m. By comparison, the measured peak flow of the Yukon River, Alaska's largest river, is only 1,030,000 ft^3/s (Jones, 1983).

The peak discharge from the Russell Lake outburst flood was larger than would have been expected on the basis of a generalized analysis of both glacier and nonglacier dam failures worldwide (Costa, 1985). In fact, the peak outburst discharge from Russell Lake may have been the largest historical discharge on the North America Continent.

The ice-dam failure was gradual, not abrupt. Crumbling and flushing of ice from within the dam were observed during the evening of October 7. The increase of outburst discharge also was gradual. Once an initial breach in the ice dam was made, the steadily increasing rate of lake decline and the observed continuous din of individual calvings of ice indicate that the ice dam failed progressively by frequent calving of ice into a rapidly widening open river rather than through a tunnel in the ice. The ice dam calved progressively and was not removed "en masse."

At 5 a.m. the outburst was first seen and by then the ice dam was largely gone. A powerful river about 1,600 feet wide flowed from the lake near Osier Island to Disenchanment Bay where the ice dam had been (fig. 16). Moderate turbulence of the water moving in the lake towards the dam brought lake-bottom sediments to the surface for 2 miles before the water plunged through the outburst channel. Highly turbulent flow began at Osier Island. Even the largest icebergs floating into the channel were lost from sight in the foaming standing waves, which were about 30 feet high. The water with individual eddies as large as 300 feet in diameter was carried across Disenchantment Bay as a "river in the sea," a distance of about 4 miles. Most of the ice from the dam was trapped and floated in a large gyre on Disenchantment Bay between the outburst current and the calving terminus of Hubbard Glacier.

During the outburst flood, the channel widened not only by glacier calving but also by erosion of bedrock, moraine, and gravel along the shore of Russell Fiord. All but a remnant of the terminal moraine, which had been pushed 108 feet high onto the fiord wall, was washed away. Individual boulders as large as 50 feet in diameter were removed from the moraine by the outburst flood.

Landsliding from the fiord wall into the outflow from Russell Lake occurred continuously throughout the outburst flood. The mountain front was undercut by the swift current, and seismic tremors from the outburst possibly caused the continual release of individual rocks from the newly exposed face. Rock sliding was more continuous than episodic, at least after dawn. Erosion resulted in 500 to 1,000 feet of shoreline recession.

The retreating ice dam limited the outflow until only about 2 a.m., at which time the channel between the fiord wall and Osier Island (fig. 16) controlled the remaining lake drainage. Had the outburst channel width not been controlled by Osier Island, the peak discharge would have been several times greater, the lake would have emptied in only a few hours, and even more dangerous currents would have occurred throughout Disenchantment Bay.

Water discharge of the magnitude of the outflow of Russell Lake is rare in human experience and outbursts of this magnitude have not been measured previously. Fortunately, during the Russell Lake breakout direct measurements of the flood were possible. The water-surface speed through the outburst channel at 6 a.m., measured by timing the foaming turbulence between range lines surveyed by theodolite, was 36 ft/s (feet per second). At 9:00 a.m. the water-surface speed through the channel was measured by a hovering helicopter, equipped with microwave distance-measuring equipment, that tracked identifiable objects such as giant eddies or icebergs. At that time, average speed through the channel was 32 ft/s.

Forecasts made before the outburst flood that water currents in Russell Lake and Disenchantment Bay near Hubbard Glacier would be hazardous to any vessels were verified by observations of currents during the outburst. The swift and turbulent water submerged and tore apart large icebergs, which emerged again far out in Disenchantment Bay. Landsliding on one side and frequent calving on the other side of the channel made both shorelines hazardous as well.

By 2 p.m. October 8, outburst water covered 95 percent of the surface of Yakutat Bay and large icebergs had been carried into the Gulf of Alaska, creating a temporary hazard to vessels in areas that usually were free of ice. The outburst ended at about 3 a.m. on October 9, 1986, when the falling lake level met a rising tide in Disenchantment Bay.

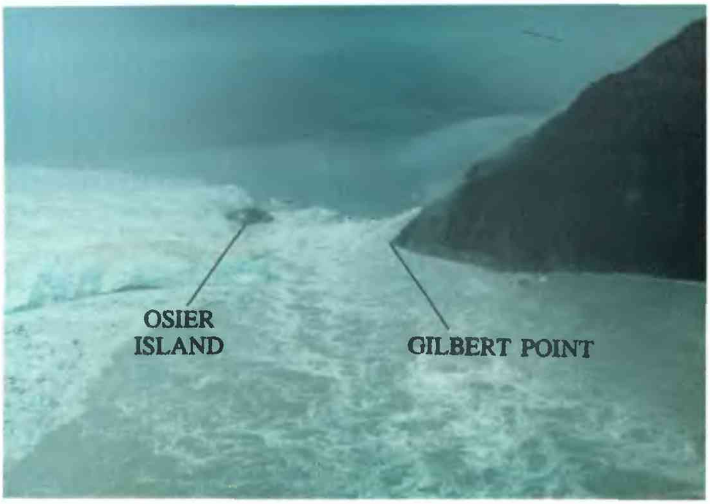

Figure 16. Oblique aerial photograph of "Russell River," Alaska, October 8, 1986, at 9:01 a.m. (Alaska Standard Time). View is east; in background is discharging Russell Lake and in foreground is Disenchantment Bay. Discharge rate from Russell Lake at this time was about 2,500,000 cubic feet per second. (Photograph by L.R. Mayo.)

THEORY OF TIDEWATER GLACIER VARIATIONS AND THE FUTURE MOVEMENT OF HUBBARD GLACIER

Hubbard Glacier is one of about 50 tidewater glaciers in Alaska that advance and retreat over several tens of miles in a cycle dominated by the water depth at the glacier terminus. Glacier advances and retreats resulting from this cycle are asynchronous because all the glaciers do not advance and retreat together under the influence of common climate change; the cycle period (usually many centuries) is unique for each glacier.

Austin Post (1975) proposed the theory that "Instability results when a tidal glacier retreats even a short distance into a deep basin from a stable position on a terminal shoal." Instability occurs because a glacier's calving rate of icebergs is directly proportional to the water depth at the terminus (Brown and others, 1982), and if for some reason the glacier retreats from the terminal moraine the calving rate in

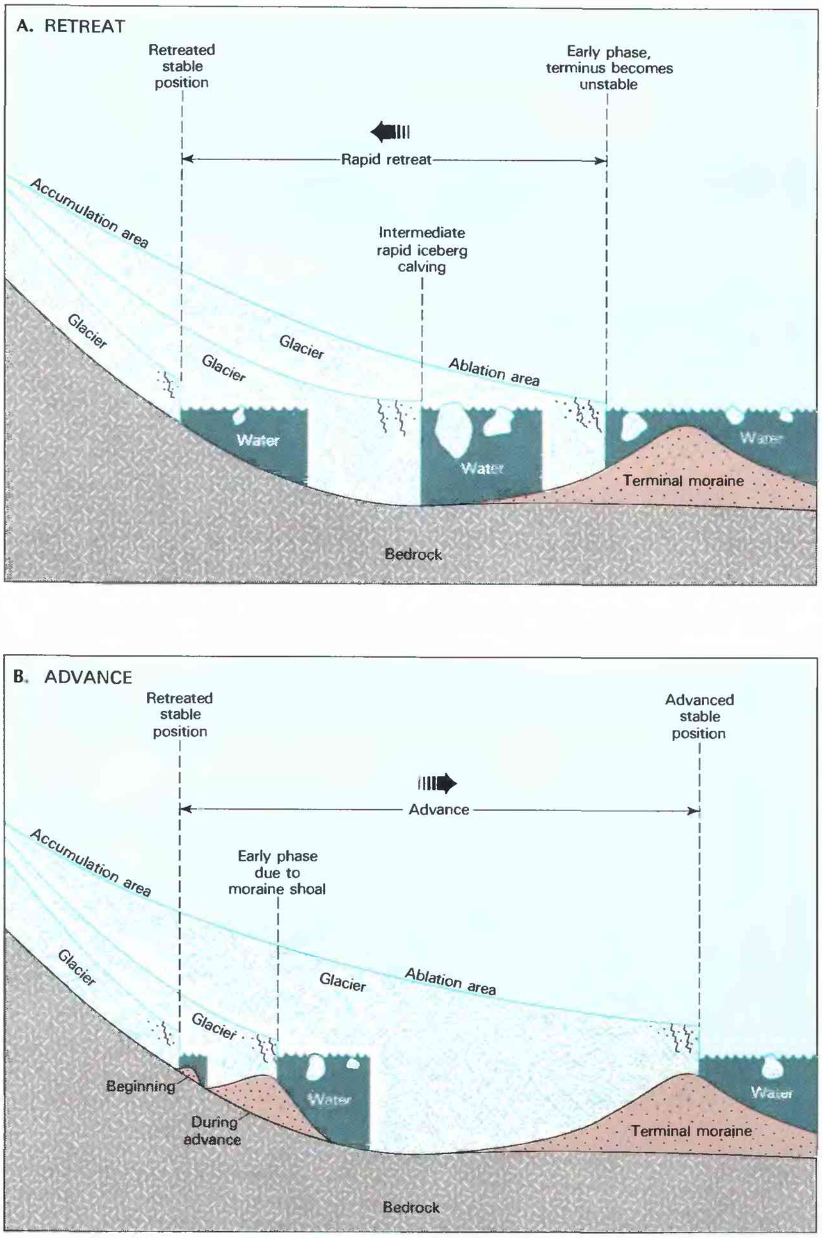

Figure 17. Schematic cross sections of a grounded tidewater glacier illustrating processes of (*A*) retreat and (*B*) advance in the calving glacier fluctuation cycle.

the deeper water behind the moraine becomes greater then can be supported by ice flow (fig. 17*A*). This theory has been used to explain why Columbia Glacier, 270 miles west of Hubbard Glacier, recently began a retreat that is expected to continue for decades, ultimately resulting in a retreat of the terminus of the glacier by 25 miles (Meier and others, 1985; Meier, 1986).

A glacier entering water, or remaining in water following retreat, such as Hubbard Glacier, can remain stable and again advance a great distance if the glacier deposits a protective submarine moraine shoal at the calving terminus (fig. 17*B*). The buildup of the moraine reduces the iceberg calving rate. If a tidal glacier has a large excess of snow and ice in its accumulation area and a small ablation area, and it carries sufficient rock debris to fill the fiord or lake with a moraine at the glacier terminus, the glacier can thicken behind the moraine, erode the glacier side of the moraine, and begin to advance again as it redeposits the moraine debris into the water at the glacier's terminus. Thus protected, a glacier can move the terminal moraine forward and advance into a body of deep water, a process that may take centuries to complete.

Eventually, however, glacier growth ceases because the accumulation of snow and ice in the accumulation area is balanced by the melting of ice in the newly enlarged ablation area. Such a tidal glacier can remain at an advanced, stable position for an indeterminate length of time. However, it will survive only so long as the snow accumulation rate in the accumulation areas exceeds both the snow and ice melting and the iceberg calving rate in the ablation area. If the glacier recedes only a short distance from its terminal moraine, an unstable retreat ensues (fig. 17*A*) as Post described, and the "calving glacier cycle" is complete. This process is responsible for major glacial advances and retreats of not only tidewater glaciers but also of glaciers that calve into lakes, such as Portage Glacier near Anchorage (Mayo and others, 1977).

The recession of a tidewater glacier can be stopped in either of two ways: when a glacier retreats onto land, or when moraine debris accumulates at the terminus to form a sand and gravel deposit between the water body and the glacier terminus.

During the last century, Hubbard Glacier has deposited and moved a protective terminal moraine shoal into Disenchantment Bay. The accumulation area of the glacier represents 95 percent of the total glacier area; therefore, the terminus undoubtedly will continue to advance in the near future. A warming of climate is not expected to reverse this process because moderate climatic warming in Alaska is associated with substantially increased snowfall in winter, which results in observed glacier growth (Mayo and Trabant, 1984). Hubbard Glacier is robust and, by January 1987, it had advanced over most of Osier Island; it is expected that within the next few years the glacier will have advanced across the outburst channel to form a new ice dam.

The next ice dam at Hubbard Glacier probably will be wider and stronger than the 1986 dam because of the continued advance of the glacier and because thickening has occurred along the entire terminus of the glacier. However, the ice dam may lack a substantial terminal moraine because the underlying unconsolidated marine sediments undoubtedly were eroded during the previous outburst.

Russell Fiord also could be dammed by a landslide from the fiord wall into its entrance. A major landslide could occur because the mountain was undercut by the outburst flood, the bedrock is highly fractured from previous large earthquakes, the area receives great amounts of precipitation, and earthquakes within the region are frequent and large.

The major uncertainty is whether the re-formed lake will rise higher than it rose in 1986 and thus threaten the stability of the entire terminal lobe of Hubbard Glacier. Should this happen, it could take several years for the glacier to redeposit a stabilizing terminal moraine.

Russell Lake after if forms again could potentially trigger an instability at the glacier front resulting in rapid calving and major retreat, Russell Lake would break out through the main part of the glacier, rather than being restrained between the fiord wall and Osier Island. An outburst flood through the glacier could carry away a large part of the terminus of Hubbard Glacier, therefore, exposing the terminus to deep water behind the terminal moraine. As a consequence, an immediate retreat of Hubbard Glacier could occur.

CONCLUSIONS

Russell Lake has formed several times in the geologic past. The processes involved and the time required to complete the previous closures are unknown. If the current advance of Hubbard Glacier continues as expected, Russell Fiord could eventually become sealed so completely that outburst floods from Russell Lake will no longer occur. Furthermore, the advance probably will continue for several centuries and will affect numerous local rivers, lakes, other glaciers, ground water, local climate, and geology.

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NATURAL RADIOACTIVITY IN GROUND WATER—A REVIEW

By Otto S. Zapecza and Zoltan Szabo

INTRODUCTION

Natural radioactivity and its effects on human health recently have become a major environmental concern because of the discovery of widespread occurrence of levels of radon in the air of homes at concentrations that exceed the U.S Environmental Protection Agency's (EPA) recommended maximum levels, particularly in the Eastern United States. Radon-222 in air, even in small concentrations, contributes to the high incidence of lung cancer among uranium miners in the Western United States (Archer and others, 1962). Recent estimates indicate that radon in indoor air may cause 5,000 to 20,000 lung-cancer fatalities annually in the United States (U.S. Environmental Protection Agency, 1986a).

A less publicized but also important health hazard is the presence in ground water of naturally occurring radioactive substances, which along with radon are known as radionuclides. In addition to radon, large concentrations of dissolved radium and uranium radionuclides have been detected in many ground-water supplies across the United States. All radionuclides dissolved in water are colorless, odorless, and tasteless and, thus, cannot be detected by our senses, unlike many water pollutants that may impart undesirable colors, odors, and tastes to water.

Although much is known about the theoretical geochemistry of radionuclides in ground water, it still is very difficult to forecast the amount of radionuclide activity in a particular ground-water supply because of the strong influence of local geologic, geochemical, and hydrogeologic conditions. Much of what is known about the distribution of radionuclides in water has been derived from analysis of water from public water-supply systems, which supply slightly more than 80 percent of the population in the United States (Solley and others, 1983). However, it is difficult to develop site-specific information about the occurrence and activities of radionuclides in specific aquifers because public water supplies commonly are a blend of water from numerous ground- and surface-water sources. Relatively little is known of the concentrations of radionuclides in private water supplies, which rely heavily on ground water and supply more than 20 percent of the total ground water used for human consumption.

In recent years, estimates have appeared in the scientific literature about the effects of radionuclides in ground water on human health. These estimates, and the growing body of scientific knowledge of the distribution and levels of radionuclides in ground water, have stimulated a review of the adequacy of standards and regulations for radionuclides in drinking water. Fortunately, conventional methods for treating raw water for some other contaminants also are effective in removing radionuclides found in ground water. (See table 2.)

GEOCHEMISTRY OF RADIONUCLIDES

Radionuclides are found as trace elements in most rocks and soils and are formed principally by the radioactive decay of uranium-238 and thorium-232, which are the long-lived parent elements of the decay series that bear their names (fig. 18). The parent elements produce intermediate radioactive daughter elements with shorter half-lives (half-life is the time required for half of the initial amount of the radionuclide to decay). Decay occurs by the emission of an alpha particle (a nucleus of the helium atom) or a beta particle (an electron) and gamma rays from the nucleus of the radioactive element. The geochemical behavior of a daughter element in ground water may be quite different from that of the parent element. However, the parent may govern the occurrence and distribution of the daughter element.

The most common radionuclides in ground water are radon-222, radium-226, uranium-238, and uranium-234 of the uranium-238 decay series, and radium-228 of the thorium-232 decay series. Other radionuclides of these two decay series, and all isotopes of the uranium-235 decay series, generally are not present in significant amounts in ground water, because most are highly immobile and many have very short half-lives that preclude the buildup of large concentrations.

The occurrence and distribution of radionuclides in ground water is controlled primarily by the local geology and geochemistry. For daughter radionuclides to be present in large concentrations, the parent radionuclide must be present in the rock material composing the aquifer. Each radioactive decay product has its own unique chemical characteristics, solubility, mobility, and half-life, which can be very different from those of the parent. For this reason, parent and daughter radionuclides in ground water are not usually found together in similar amounts (Gilkeson and others, 1983, p. 22); nor do they decay at similar rates or produce the same level of radioactivity. Therefore, a high concentration of one radionuclide in ground water at a specific site does not necessarily imply that similar concentrations of other radionuclides in the same decay series are present. For example, the parent/daughter radionuclide pairs uranium-238 or uranium-234/radium-226 or radium-226/radon-222 usually are not present in high concentrations in the same ground water.

The movement of many radionuclides is very dependent upon the radionuclide's solubility in water. Uranium, which is most soluble in bicarbonate-rich oxidizing (oxygen-rich) ground water with low total dissolved-solids content, is easily dissolved and transported by oxidizing ground water; thus, it can be transported to areas far from its original emplacement. Solubility of uranium tends to be enhanced by association with carbonate, phosphate, and fluoride

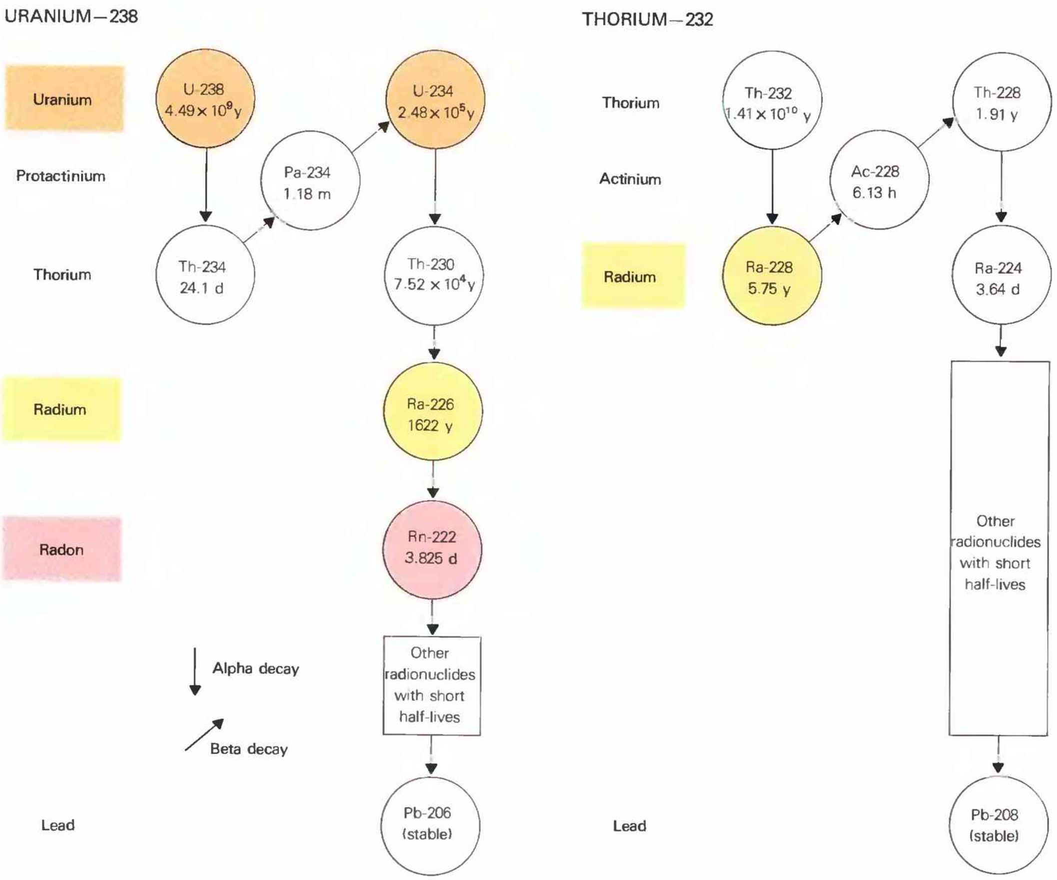

Figure 18. **Uranium-238 and thorium-232 radioactive decay series.** Colors indicate those radionuclides found most frequently in ground water. Times shown are half-lives—y = years, d = days, h = hours, m = minutes.

ions, or with organic compounds, especially humic substances (Langmuir, 1978, p. 556; Turner-Peterson, 1980, p. 163). Uranium is less mobile in reducing ground water, and it tends to be adsorbed very strongly onto humic substances in the aquifer. Conversely, radium is most mobile in chloride-rich reducing ground water with high total dissolved-solids content (Tanner, 1964, p. 261).

Field measurements of dissolved-oxygen concentration and oxidation-reduction potential (Eh) in parts of New Jersey have shown that these are important controls on radium-226 and uranium concentrations in ground water (Szabo and Zapecza, 1987). Where the ground water is reducing, elevated levels of radium-226 are associated with elevated gross alpha activities. Where the ground water is oxidizing, only small concentrations of radium-226 are associated with high levels of gross alpha activity. The high levels of gross alpha activity in oxidizing water are caused by dissolved uranium.

DRINKING-WATER STANDARDS AND MONITORING REQUIREMENTS

Because of the health hazards of radium-226 and -228 in drinking water the EPA has established maximum contaminant levels (MCL) to regulate total radium concentration in public water supplies. According to the EPA's National Interim Primary Drinking-Water Regulations (U.S. Environmental Protection Agency, 1986b) the maximum contaminant levels for radionuclides are:

Radium-226 and radium-228 combined	5 pCi/L
Gross alpha-particle activity (including radium-226 but excluding uranium and radon)	15 pCi/L
Gross beta-particle activity	4 millirems per year

Radioactivity in ground water commonly is measured in picocuries per liter (pCi/L)—1 pCi/L is equal to 0.037 disintegrations of the radionuclide per second per liter of fluid. In the fall of 1986, the EPA announced its intentions to expand its regulations to control radionuclides—radium-226 and -228, natural uranium, radon, and gross alpha, gross beta, and gamma emitters—in public water supplies (U.S. Environmental Protection Agency, 1986c).

The EPA requires that all public-water suppliers analyze composite water samples from their distribution systems for gross alpha-particle, gross beta-particle, and radium-226 activity every 4 years. Samples also are analyzed for radium-228 when the radium-226 activity exceeds 3 pCi/L. Gross alpha- and beta-particle activity are used to determine if further radiochemical analyses are necessary. Alpha emitters, such as radium-226, radon-222, and uranium add to the total gross alpha-particle activity. Radium-228 is a beta-particle emitter.

Although standards have not yet been established by the EPA for radon-222 or total uranium in drinking water, health physicists propose a 10,000 pCi/L limit for radon-222 in water (Cross and others, 1985, p. 649). On the basis of several assumptions about the volume of air in a dwelling, the amount of water consumed daily in various domestic uses, the efficiency of removal of radon from water by aeration and heating, and the proportions of water used for showering, laundering, and cleaning, Gesell and Prichard (1975) estimated that water containing 10,000 pCi/L of radon per liter would contribute about 1 pCi/L per liter of air in a dwelling. The EPA has recommended a 4 pCi/L limit for radon in air. A 10 pCi/L MCL for uranium in water has been suggested by Cothern and others (1983, p. 377).

Under present regulations, uranium and radon activity is subtracted from the total gross alpha concentration of the sample. Therefore, drinking water with high concentrations of radon or uranium can be supplied legally if the water does not exceed standards for other radionuclides.

Another deficiency in the current screening technique arises from the analysis required for monitoring radium-226, an alpha emitter, and radium-228, a beta emitter. Historically, it has been assumed that these radionuclides were present in water in a 1:1 ratio. However, in recent years investigators have shown that very little correlation exists between levels of radium-226 and radium-228 and that separate guidelines for each isotope are needed (Michel and Moore, 1980, p. 663; King and others, 1982, p. 1173; Menetrez and Watson, 1983, p. 13; Kriege and Hahne, 1982, p. 558; Cecil and others, 1987, p. 444). Hess and others (1985, p. 563) report that present screening procedures (measuring for radium-228 only if radium-226 is greater than 3 pCi/L) can miss from 10 to 50 percent of violations for total radium.

DISTRIBUTION OF RADIONUCLIDES IN GROUND WATER

Figure 19 shows generalized areas of the conterminous United States where various radionuclides exceed the following concentrations:

Radon (equivalent to about 1 pCi/L in air)	10,000 pCi/L
Radium	5 pCi/L
Uranium	10 pCi/L

The generalized areas shown in figure 19 reflect the dominant radionuclide detected in ground water; when other radionuclides are known to be present in the same area, they are indicated by a number. Information in figure 19 is based on a study of published reports; no field investigations were performed by the authors. Most of the data are from work by Cothern and Lappenbusch (1984) and Hess and others (1985), who examined the results of compliance data from a nationwide monitoring of more than 50,000 public water supplies for radioactivity in drinking water, and from data provided in published reports on individual States as indicated in the following discussions.

RADON

Radon in ground water is most prevalent in the Northeastern United States, especially in the New England area. High concentrations of radon have been detected in ground water associated with granitic and metamorphic rocks of Maine and New Hampshire (Brutsaert and others, 1981; Hall and others 1985). Radon concentrations commonly exceed 10,000 pCi/L, and a number of water samples were reported to have concentrations that ranged from 100,000 to 300,000 pCi/L. These high concentrations are attributed to uranium minerals in granites and uranium minerals in pegmatites associated with metamorphic rocks (Brutsaert and others, 1981, p. 413). Hess and others (1985, table 7) show that higher concentrations of radon occur most often in water from wells that yield small quantities of water. Many public supply systems in Maine draw their water from large-yielding, less radioactive glacial sand-and-gravel aquifers; whereas most self-supply wells draw their water from small-yielding, uranium-rich granites, pegmatites, and metamorphic rocks. This difference is significant because 40 to 50 percent of the population of Maine and New Hampshire depends on water from private self-supply wells (Hall and others, 1985). High concentrations of radon also have been detected in ground water associated with granitic and metamorphic rocks in Rhode Island (Hess and others, 1985, p. 571), Connecticut (Thomas, 1987, p. 352), Massachusetts (James H. Persky, U.S. Geological Survey, oral commun., 1987), New Jersey (Nicholls and Cahill, 1987, p. 424), Pennsylvania (Wanty and Gundersen, 1987, p. 135), North Carolina (Sasser and Watson, 1978, p. 667), South Carolina (King and others, 1982, p. 1175), and Georgia (Michel and Jordana, 1987, p.236).

RADIUM

Radium, in concentrations greater than 5 pCi/L, is present in ground water in the Southeastern and the North-Central States. In the Southeastern States concentrations of radium that exceed EPA drinking-water standards were reported locally in public supply systems in Georgia (Cline and others, 1983), North Carolina (Menetrez and Watson, 1983), South Carolina (Michel and Moore, 1980; King and others, 1982), and Virginia (U.S. Geological Survey, 1984, p. 430).

From Georgia to Virginia, most of the higher radium concentrations in ground water straddle the Fall

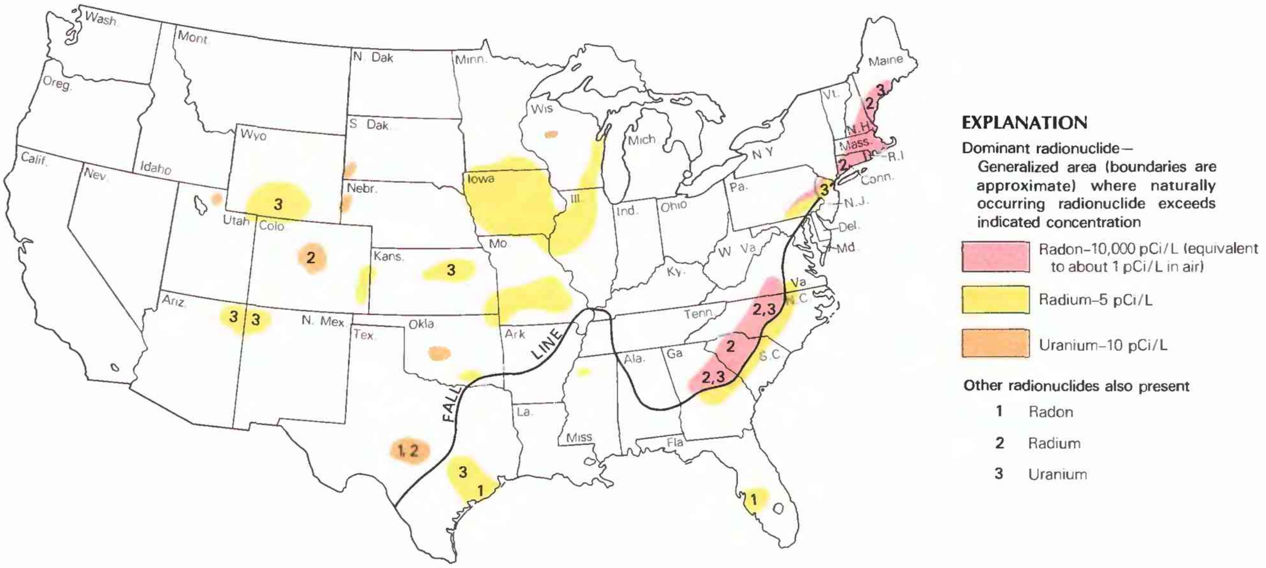

Figure 19. **Generalized areas of the conterminous United States known to have high concentrations of naturally occurring radionuclides in fresh ground water.** (Data are in picocuries per liter (pCi/L). (Source: Compiled from data in Cothern and Lappenbusch, 1984; Hess and others, 1985; Scott and Barker, 1962; Hall and others, 1985; Brutsaert and others, 1981; U.S. Geological Survey files, and other sources indicated in the text.)

Line, which separates fractured rock aquifers of the Piedmont province from the unconsolidated sand aquifers of the Coastal Plain province. The source of the radium-226 and radium-228 radionuclides are uranium- and thorium-bearing minerals respectively, contained in granites of the Blue Ridge and Piedmont provinces, and sands of the Coastal Plain that were derived from these granites (Michel and Moore, 1980, p. 665). Higher concentrations of radium-228 generally are found in Coastal Plain aquifers near the Fall Line. This is because the parent radionuclide thorium-232 is abundant in the sands, and because thorium is virtually immobile in ground water and has not migrated elsewhere. Therefore, radium-228 levels in ground water in the southeastern Coastal Plain decrease with distance from the Piedmont source (Hess and others, 1985, p. 561). Radium-226 is more widespread in ground water of the southeastern Coastal Plain because of the mobility of its parent uranium in ground water and the presence of uranium-rich phosphate deposits.

Radium concentrations that exceed EPA drinking-water standards occur less frequently in the fractured rock aquifers of the Piedmont province because nonsedimentary rocks adsorb radium onto mineral-grain surfaces much more effectively than do the unconsolidated sand aquifers of the Coastal Plain. This adsorbed radium, however, is a possible source for radon levels present in ground water of the Piedmont in this area (King and others, 1982, p. 1180).

Radium-226 and radium-228 in concentrations that exceed EPA drinking-water standards also are found widely throughout the North-Central States, particularly southern Minnesota and southern and eastern Wisconsin (Hahn, 1984), northern Illinois (Gilkeson and others, 1983, 1984), Iowa (Kriege and Hahne, 1982), and Missouri (Hess and others, 1985). Much of the radioactive water comes from wells that tap deep aquifers of Cambrian and Ordovician sandstones and dolomites and Cretaceous sandstones. Significant sources of dissolved radium-226 in ground water are the parent uranium-238, uranium-234, and thorium-230 radionuclides that have been chemically precipitated or adsorbed on the surfaces of silica in sandstone aquifers. Dissolved radium-228 in ground water is due primarily to the occurrence of thorium-232 enriched accessory minerals in the sandstones (Gilkeson and Cowart, 1987).

Other areas where radium concentrations in ground water exceed EPA drinking-water standards are more widely scattered, which could in part be because of insufficient sampling. These areas are near uranium-rich zones in Colorado, Wyoming, the Four Corners Region of Arizona and New Mexico, southeastern Texas, Kansas, Oklahoma, and northern Mississippi (Hess and others, 1985, p. 559; Cowart, 1981; Scott and Barker, 1961). High concentrations of radium-226 in reducing ground water have been detected in association with uranium-rich black mudstones in the Newark Basin of New Jersey (Zapecza and Szabo, 1987, p.47; Szabo and Zapecza, 1987, p. 283) and near uranium-rich phosphate beds in central Florida (Miller and Sutcliffe, 1985, p. 1). High concentrations of radium-226 and radium-228 occur in acidic, iron-rich ground water in a quartzite aquifer in eastern Pennsylvania (Cecil and others, 1987, p.437).

URANIUM

Uranium is widely dispersed in ground water because of the great mobility, the long half-life, and the relative abundance of this element. The highest concentrations in ground water are found in uranium-ore provinces, granites, and sediments derived from these granites in Colorado, Wyoming,

Table 2. Summary of conventional water-treatment methods that remove the most abundant naturally occurring radionuclides from ground water

[Source: Compiled from information in Reid and others, 1985; Brinck and others, 1978; Hahn, 1984; Lowry and Lowry, 1987; and Menetrez and Watson, 1983. > = greater than]

Water-treatment method				Effects of treatment		
Type	Suitable user		Efficiency in removal of radionuclide, in percent	Additional benefits	Potential problems	
	Public supply	Self supply			Radioactive-waste byproduct requiring proper disposal	Other
				RADON		
Granular activated carbon.	Yes	Yes	>90	No potential for radon to be released to indoor air. Little operational expertise required. Inexpensive. Long life: adsorbed radon decays away before radon adsorption capacity is exhausted.	Sludge—Can become radioactive and require licensed disposal at licensed radioactive-waste depository.	Cannister may have high gamma emissions; should be kept away from children. Radon removal capacity can be strongly diminished by organic compounds or iron in the water.
Aeration.	Yes	Yes	>90	No solid/liquid waste disposal problems. Little operational expertise required.	Radon in air.	Cannot be housed indoors, as can produce high levels of radon in indoor air; Moving parts need frequent repair.
				RADIUM		
Ion-exchange water softener.	Yes	Yes	81–97	Removes hardness. Little operational expertise required. Reliable. Removes radium until hardness-removal capacity is exhausted. Inexpensive and widely available.	Brine.	Adds sodium. Softened water is corrosive.
Radium selective complexor.	Yes	Yes	>90	Does not soften water. Little operational expertise required.	Sludge—Can become radioactive and require licensed disposal at licensed radioactive-waste depository.	Radium removal capacity can be diminished by high concentrations of other ions in waters, especially iron. Expensive.
Iron and manganese removal.	Yes	No	15–55	Removes iron and manganese. Does not soften water.	Liquid.	Low-removal efficiency; cannot be used on water containing more than 10 pCi/L radium. Unreliable. Operational expertise required. Suitable only for treating large volumes of water.
Barium co-precipitation.	Yes	No	High in laboratory studies.	Does not soften water.	Sludge.	Barium is a regulated pollutant and levels in water must be monitored. Operational expertise required. Suitable only for treating large volumes of water. Not tested extensively.
Manganese coated filters.	Yes	No	90	Does not soften water. Little operational expertise required.	Sludge.	May work only for a short period. Removal capacity can be affected by high amounts of iron in the water. Expensive. New technique and not readily available.
				RADIUM and URANIUM		
Reverse osmosis or electrodialysis.	Yes	Yes	>90	Decreases total dissolved solids.	Liquid.	Operational expertise required. Expensive to operate. Water can become corrosive.
Lime softening.	Yes	No	80–90	Removes hardness. Can operate continuously.	Liquid and sludge.	Adds sodium. Softened water is corrosive. Operational expertise required. Suitable only for treating large volumes of water. Unreliable in some circumstances.
				URANIUM		
Coagulation.	Yes	No	80	Removes other ions.	Liquid and sludge.	Operational expertise required. Sensitive to water pH. Suitable only for treating large volumes of water.
Anion exchange.	Yes	Yes	>90	-----	Brine.	Operational expertise required; difficult to recharge exchange resin. New, not widely available. Expensive.
Activated alumina columns.	Yes	No	>90	-----	Liquid.	Operational expertise required. New, not widely available.

New Mexico, Arizona, Utah, Oklahoma, South Dakota, Nebraska, and Kansas (Scott and Barker, 1962; Hess and others, 1985). In the Eastern United States, concentrations of uranium that exceed 10 pCi/L have been found in southeastern Maine (Wathen, 1987, p. 34), in the Piedmont of New Jersey (Szabo and Zapecza, 1987, p. 283), and in the Piedmont of Georgia and North Carolina (Cline and others. 1983; Menetrez and Watson, 1983).

HEALTH EFFECTS OF RADIONUCLIDES

In the past several years, there has been a renewed concern about the health effects of exposure to radon. Radon in water is a twofold health problem—it can enter the body by direct water consumption, or through inhalation when radon is liberated from water used for cleaning, showering, and various other purposes. The health risk from radon arises when it decays and its charged alpha-emitting progeny attach to dust, cigarette smoke, and other aerosol particles. These particles can be inhaled and attached to the lung interior, bringing alpha-emitting particles in constant and intimate contact with the cell lining of the respiratory system (Hess and others, 1985, p. 567). A recent estimate suggests that from 2,000 to 40,000 lung cancer fatalities per 70 years can be attributed to radon in public drinking water supplies in the United States (Cothern, 1987).

Consumption of water containing radium and, to a lesser degree, uranium can cause a significant accumulation of these radionuclides in human bone tissue. A significant dose may accumulate, producing bone and head-sinus cancers (Mays and others, 1985, p. 635; Wrenn and others 1985, p. 601). Hess and others (1985, p. 579) estimate almost 1,000 fatal cancers may occur per lifetime (70.7 years) in the United States, on the basis of the average level of radium (1.6 pCi/L) in public ground-water supplies in the United States. Mays and others (1985, p. 635) estimate the cumulative lifetime risk to 1 million people, each consuming 5 pCi/L of radium per day, to be 9 bone and 12 head cancers for radium-226. Radium-228, which is considered to be twice as hazardous as radium-226, was estimated to produce 22 bone cancers per million people. According to their estimates, lifetime ingestion of 5 pCi/L per day of uranium could induce 1.5 additional bone cancers per million people. Hess and others (1985, p. 580) estimate 105 fatal cancers may occur per lifetime in the United States on the basis of average concentration of uranium (0.8 pCi/L) in public water supplies of the United States. Uranium in ground water poses additional health risks because it also is chemically toxic. Uranium has been detected in significant concentrations in soft body tissues, particularly the kidneys (Wrenn and others, 1985, p. 601).

REMOVAL OF RADIONUCLIDES FROM GROUND WATER

Conventional water-treatment methods can remove as much as 95 percent of the radionuclides present in ground water (table 2). Each radionuclide has its own specific treatment method(s) that will remove it with the greatest efficiency. If several different radionuclides are present in the water, no single treatment method will remove all of them, and multiple treatment techniques may have to be applied. Therefore, it is essential to identify the radionuclide(s) present before selecting the specific water-treatment method(s). Water purveyors will need to consider how the radionuclide removal methods can be best integrated into their existing water-treatment processes.

Each radionuclide treatment method, besides providing benefits, does pose potential problems. One of the most serious is that material removed from the water constitutes a radioactive-waste product that requires proper disposal. Disposal of the material must be carefully coordinated with appropriate environmental regulatory agencies. The self-supply well owner is limited further by operating expenses and the lack of operational expertise. All the potential problems and benefits of a radionuclide water-treatment method must be carefully weighed before making a decision about which method to use.

Conventional water-treatment methods that remove the most abundant naturally occurring radionuclides (uranium, radium, and radon) from ground water are listed in table 2. Benefits and problems of each method also are given. Additional information including detailed methods of operation, comparison of operational expenses, and details about potential problems are reported by Brinck and others (1978), Hahn (1984), Reid and others (1985), Menetrez and Watson (1983), and Lowry and Lowry (1987), and in reports referenced therein. A summary of radioactive waste-disposal alternatives that can be managed by municipalities is given by Reid and others (1985, p. 685–686).

CONCLUSIONS

Health effects attributed to the consumption of drinking water containing radionuclides are based primarily on the analysis of water from public-supply distribution systems and not individual wells, and the risk factors generally are averaged nationwide. Water from private self-supply wells is not subject to EPA regulations and, therefore, relatively little data on the quality of the water are available. Of the more than 14 billion gallons per day of ground water withdrawn for human consumption by public-supply and self-supply wells, more than 20 percent is withdrawn by private self-supply wells (U.S. Geological Survey, 1985). In areas where radionuclides are present in ground water, self-supplied well water is suspected to contain higher levels than public supplies for the following reasons. In public-supply systems the residence time of ground water usually is relatively long because the water may be held in storage facilities and in the system itself for a period of time before being delivered to the consumer. This allows radionuclides with very short half-lives, such as radon-222 with a half life of 3.82 days, to decay to lower levels. In addition, public-water suppliers commonly mix water from several wells and/or surface-water sources. Generally, surface water has very low radionuclide activities (Hess and others, 1985, p. 563, 578). The mixing of waters with low levels of radionuclides dilutes the water and produces a finished water supply with lower levels of radionuclides when it is delivered to the consumer through the distribution system. In contrast, water supplies from domestic self-supply wells commonly are stored in small holding tanks for short periods and are not mixed with water from other sources.

Inasmuch as most of the data collected to determine radioactivity in ground water has come from the distribution lines of public water-supply systems, much additional work is needed to define levels of radioactivity in specific aquifers. Data collection and analysis are needed in rural areas where self-supply ground-water withdrawals are the primary source of water for human consumption. Areas near ore bodies, zones of uranium or thorium enrichment, and areas with high concentrations of radon in indoor air can be expected to have high concentrations of radionuclides in ground water. More detailed studies are needed to improve definition of the geochemistry of naturally occurring radionuclides, to identify constituents that might serve as indicators of their presence, to define mechanisms of their transport in ground water, and to determine their effects on human health.

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HOOVER DAM AND THE CENTRAL ARIZONA PROJECT —A MILESTONE YEAR

By Roy H. Rush[1]

During water year 1986, two events occurred that are major milestones in the history of western water development. First, the 50th anniversary of Hoover Dam was observed, and second, the Central Arizona Project began to deliver water to Phoenix, Ariz. (fig. 20). These two events are described below.

HOOVER DAM—THE PAST

Hoover Dam, the Nation's highest and third largest concrete dam, began its second 50 years of operation in water year 1986. The structure, which dams the Colorado River between Nevada and Arizona just east of Las Vegas, Nev., was designed to control river flow by forming Lake Mead, a 110-mile-long storage reservoir with a capacity of 32,471,000 acre-feet or nearly 2 years of normal Colorado River flow. (See figure 21.) It has successfully achieved this goal.

Before the dam was constructed, the flow of the 1,400-mile-long Colorado River was extremely variable, as it wound its way from the Colorado Rocky Mountains to the Gulf of California. In 1909, for example, an estimated maximum annual discharge of 25.2 million acre-feet occurred near Yuma, Ariz. At other times, river flow often was too low to be diverted for use by settlers along the lower river. Not only was the flow unpredictable, but the vast quantity of sediment carried downstream by the river clogged diversion structures and irrigation canals used by farmers and made the water unsuitable for use as a municipal water supply.

To overcome these problems, a plan was proposed to impound flood waters behind a 700-foot high dam and release the water as needed. The reservoir behind the dam was to be large enough to trap millions of tons of sediment that the Colorado carried every year without impairing the reservoir's storage capacity or interfering with the dam's energy-generating capability. On December 21, 1928, passage of the Boulder Canyon Project Act authorized the construction of Hoover Dam and related facilities for purposes of storage and delivery of water, hydroelectric power, flood control, and navigation.

In June 1931, initial dam construction started with excavation of a tunnel that would divert the river. By November 1932, the Colorado River had been diverted enabling the building of the dam to begin. During the following 2 years, specially designed equipment was used to build a structure that the American Society of Civil Engineers would later identify as one of the Nation's seven modern civil engineering wonders. One of the innovative ideas used during construction was the use of pierlike blocks of concrete (fig. 22) that were cooled by running ice-cold water through pipes embedded in the concrete blocks. Without artificial cooling, it would have taken more than a century for the dam to lose the heat created by the setting cement, and the cement would have shrunk and cracked as it cooled. On September 30, 1935, a full 2 years ahead of schedule, President Franklin D. Roosevelt dedicated the dam.

The Boulder Canyon Project meets a variety of water demands. It assures a dependable water supply for irrigation of about 650,000 acres in southern California and southwestern Arizona, and more than 400,000 acres in Mexico. Once Hoover Dam controlled the flow of the Colorado River and created a reliable water source, cities and water authorities in southern California looked to the Colorado River as a dependable supply to meet growing municipal demands. The Colorado River Aqueduct was completed in 1941 to deliver water to the Metropolitan Water District of Southern California service area. The District annually distributes more than 900,000 acre-feet of Colorado River water to more than 12 million people.

Power production and flood-control functions have similar stories of success. Between 1970 and 1980, the Hoover powerplant generated an average of nearly 3.5 billion kilowatt-hours of energy each year. It would take about 6 million barrels of oil to generate a similar amount of electric energy. With regard to flood control, Lake Mead, operated in

Figure 20. The lower Colorado River basin showing the location of Hoover Dam and the Granite Reef, Salt-Gila, and Tucson Aqueducts of the Central Arizona Project.

Base from U.S. Geological Survey National Atlas, 1970

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[1] U.S. Bureau of Reclamation.

Figure 21. Hoover Dam with Lake Mead in the background. (Photograph by Steve Van Denburgh, U.S. Geological Survey.)

Figure 22. Hoover Dam under construction, December 1933. (Photograph by U.S. Bureau of Reclamation.)

Figure 23. Hoover Dam was designated a National Historic Landmark on September 28, 1985. (Left to right: U.S. Senator Paul Laxalt (Nevada); Secretary of the Interior Don Hodel; Nevada Governor Richard Bryan; U.S. Senator Chic Hecht (Nevada); Assistant Secretary of the Interior for Water and Science Robert Broadbent. Photograph by U.S. Bureau of Reclamation.)

conjunction with upstream reservoirs, controls both flash floods and the high runoff that normally occurs each spring and summer. Nature can still muster astounding volumes of water, as seen in 1983 and 1984 when mountain snowpacks yielded to unseasonably warm weather (U.S. Geological Survey, 1985, p. 42–43), but such occurrences no longer cause widespread destruction.

Hoover Dam is an important part of the Nation's past and is now a National Historic Landmark (fig. 23). It also is very much a part of the water future of the Southwest.

CENTRAL ARIZONA PROJECT—THE FUTURE

The first section of the Central Arizona Project (CAP), a major water-resource development and management project under construction by the U.S. Bureau of Reclamation, was commemorated by the Secretary of the Interior on November 15, 1985, with the first delivery of project water to the Phoenix area. CAP consists of three sections (fig. 20): the 190-mile-long Granite Reef Aqueduct, which delivered water to Phoenix during water year 1986; the Salt–Gila Aqueduct, which is partially completed; and the Tucson Aqueduct, which is projected to be completed in 1991.

When the entire CAP aqueduct system is completed, it will be 337 miles long and will provide 60 percent of the State's surface-water supply. Each year, the system will bring an average of 1.5 million acre-feet of Colorado River water to central and southern Arizona. Other parts of the State and a part of western New Mexico also will benefit from CAP through water exchanges. Regulatory storage will provide the capability to divert as much as 2.2 million acre-feet per year from the Colorado River in years of surplus flow. It is predicted that the water supplied by CAP will offset about two-thirds of the ground water withdrawn within Arizona (U.S. Bureau of Reclamation, 1972).

The water conveyance and storage system of concrete-lined canals, inverted siphons, tunnels, dams creating regulating reservoirs, and pumping plants will enable water to be transported from Lake Havasu near Parker, Ariz., east to Phoenix, and then south to the San Xavier Indian Reservation southwest of Tucson, Ariz. Between the Colorado River and its final destination, the water will be lifted vertically nearly 2,900 feet.

Allocation of Colorado River water to specific uses is flexible and will change as users' demands change. Of the projected average annual diversion of 1.5 million acre-feet, 640,000 acre-feet will be allocated for municipal and industrial use, and about 310,000 acre-feet will be allocated for Indian reservation use. Agricultural uses will benefit from the remainder of the water.

These two major milestones in water-resources development—one old and one new—have had and will continue to have a profound effect on the water resources and economy of the Southwest.

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THE RUINOUS WEST VIRGINIA FLOOD OF NOVEMBER 1985

By Thomas H. Noonan[1]

In early November 1985, the remnants of Hurricane Juan dropped a moderate to heavy rainfall over the mid-Atlantic States. This remnant storm mingled with a significant low-pressure system moving in from the west and then the combined systems stalled over the Appalachian Mountains northeast of Elkins, W. Va. This unusual combination of weather systems, already containing an enormous amount of moisture, drew in additional moisture-laden air from the Atlantic Ocean. This system produced 4 to 8 inches of rain within 24 hours on November 3 and 4. From November 1 through 6, rainfall exceeded 18 inches over the western areas of Virginia, and was as much as 12 inches in West Virginia. (See figure 24.) The result was flooding from Washington, D.C., to Pittsburgh, Pa.

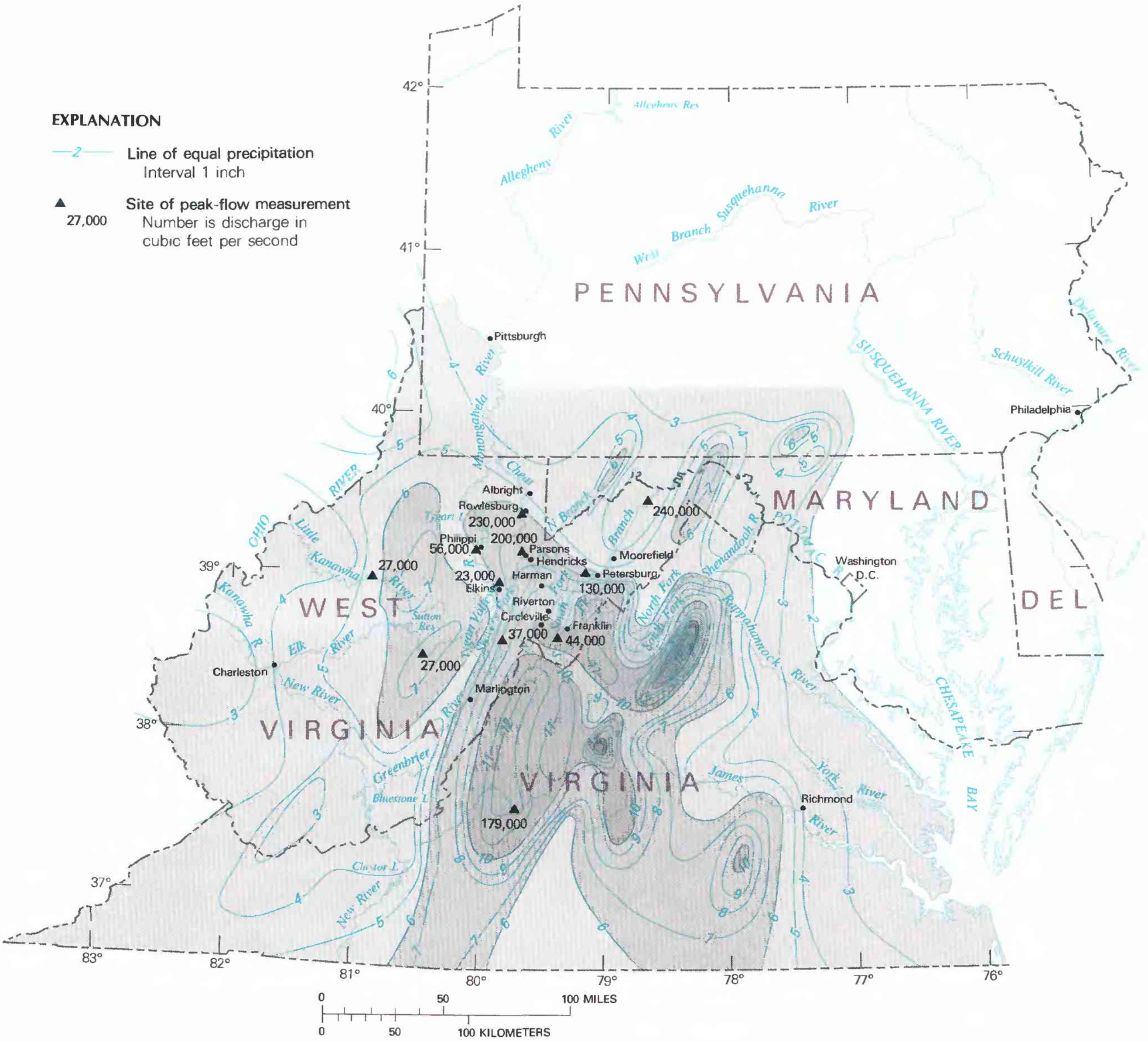

Figure 24. Precipitation and selected peak flows resulting from storm of November 1 to 6, 1985, West Virginia. (Sources: Precipitation data compiled by National Weather Service; peak-flow data from U.S. Geological Survey files.)

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[1] U.S. Soil Conservation Service.

The worst flooding occurred in West Virginia, with record-breaking floods along many of its rivers. In spite of antecedent dry conditions, the mountainous topography and the location and intensity of the storm created conditions that sent floodwaters raging northeastward into the Potomac River basin, east into the James River, southwest to the Greenbrier River, west along the Elk and the Little Kanawha Rivers, and northeastward into the Cheat and the Tygart Valley Rivers, which feed the Monongahela River. Although the flood frequency varied among locations, the 100-year flood frequency was greatly exceeded in many areas (G.S. Runner, U.S. Geological Survey, written commun., 1985).

The Federal Emergency Management Agency (FEMA) estimated damage in West Virginia to be nearly $700 million, and 29 counties of West Virginia were declared Federal disaster areas. Many of the small rural communities were devastated, and many cities and towns in West Virginia looked as though they had become war zones. More than 8,968 homes were damaged and about 4,000 were completely destroyed; 711 businesses were demolished or battered. Miles of roadways were either damaged or eliminated and 2,027 bridges washed away. FEMA estimates the total cost of Federal assistance exceeded $235 million. About 50 people lost their lives in the flood, and thousands were traumatized by the loss of loved ones, friends, homes, and a lifetime's possessions.

In the Potomac River basin the South Branch River reached 25.4 feet at the U.S. Geological Survey gaging station near Petersburg [drainage area 642 mi^2 (square miles)] and peaked at a record high of 130,000 ft^3/s (cubic feet per second) for an estimated recurrence interval of greater than 100 years. Badly damaged cities in the basin included Petersburg, Franklin, and Moorefield. Small communities such as Riverton and Circleville on the North Fork were nearly destroyed.

The 74 dams built by the U.S. Department of Agriculture, Soil Conservation Service (SCS), in the Potomac basin stored large volumes of water. These dams provided significant relief to beleaguered downstream communities. The storm was so severe that 21 of the 74 dams stored water to their full capacity (100-year storage), and experienced flow through their emergency spillways. Most of these dams were on the South Fork (of the South Branch) River.

Many other West Virginia communities also suffered hardships. The city of Marlington on the Greenbrier River was flooded and many buildings were lost. The towns of Parsons, Hendricks, and Harman in the headwaters of the Cheat River also were devastated. On the mainstem of the Cheat itself, raging floodwater, reaching phenomenal heights and velocities, flooded Albright leaving empty foundations where homes once stood. Discharges of 230,000 ft^3/s and flood stages of more than 27 feet were recorded near Rowlesburg on the Cheat River (drainage area 972 mi^2, with a recurrence interval greater than 100 years). That river rose into the city causing severe damage. The river simply stripped away a mobile-home park in the lower part of town. Although the velocities in the broader Tygart Valley River were somewhat less, the flood stage at Philippi was almost 32 feet and most of the city was under water as discharges reached 56,000 ft^3/s (drainage area 916 mi^2, with a recurrence interval between 50 and 100 years).

Rural communities also were hit hard. Farm buildings were damaged or knocked down. Silos were toppled and an undetermined number of livestock lost or drowned. Hundreds of thousands of chickens and turkeys were killed, drowned in poultry houses or scattered over miles of flood plain. The land itself was damaged as farm fields were eroded and river rocks were dropped everywhere. Valuable topsoil was washed from the land, and productive farm fields were littered with trash of all descriptions and tons of infertile sediment.

Debris was left along hundreds of miles of flood plain. This material included thousands of fallen trees and splintered parts of homes and other buildings. Flood plains and fields were littered with battered cars, pieces of mobile homes, appliances, and personal articles.

The depths and velocities of the mountain streams were sufficient to move the heavy rocks in the streambeds. As stream channels became choked with rocks, new channels formed continuously. Downed trees created battering rams, which flattened trailers like aluminum cans, and destroyed thousands of recreational sites.

During the aftermath, efforts to dig out from under this historic and ruinous flood were undertaken by the spirited people of West Virginia. Helping under FEMA coordination were Federal and State agencies including the U.S. Army Corps of Engineers and the West Virginia Highway Department: both undertook the massive job, among others, of removing condemned buildings. The SCS took leadership in burial of thousands of dead livestock and fowl, removed hundreds of stream blockages to prevent further flooding, cleared tons of debris from over 400 miles of rivers and streams, and assisted farmers in restoration work to return damaged farmland to production once again.

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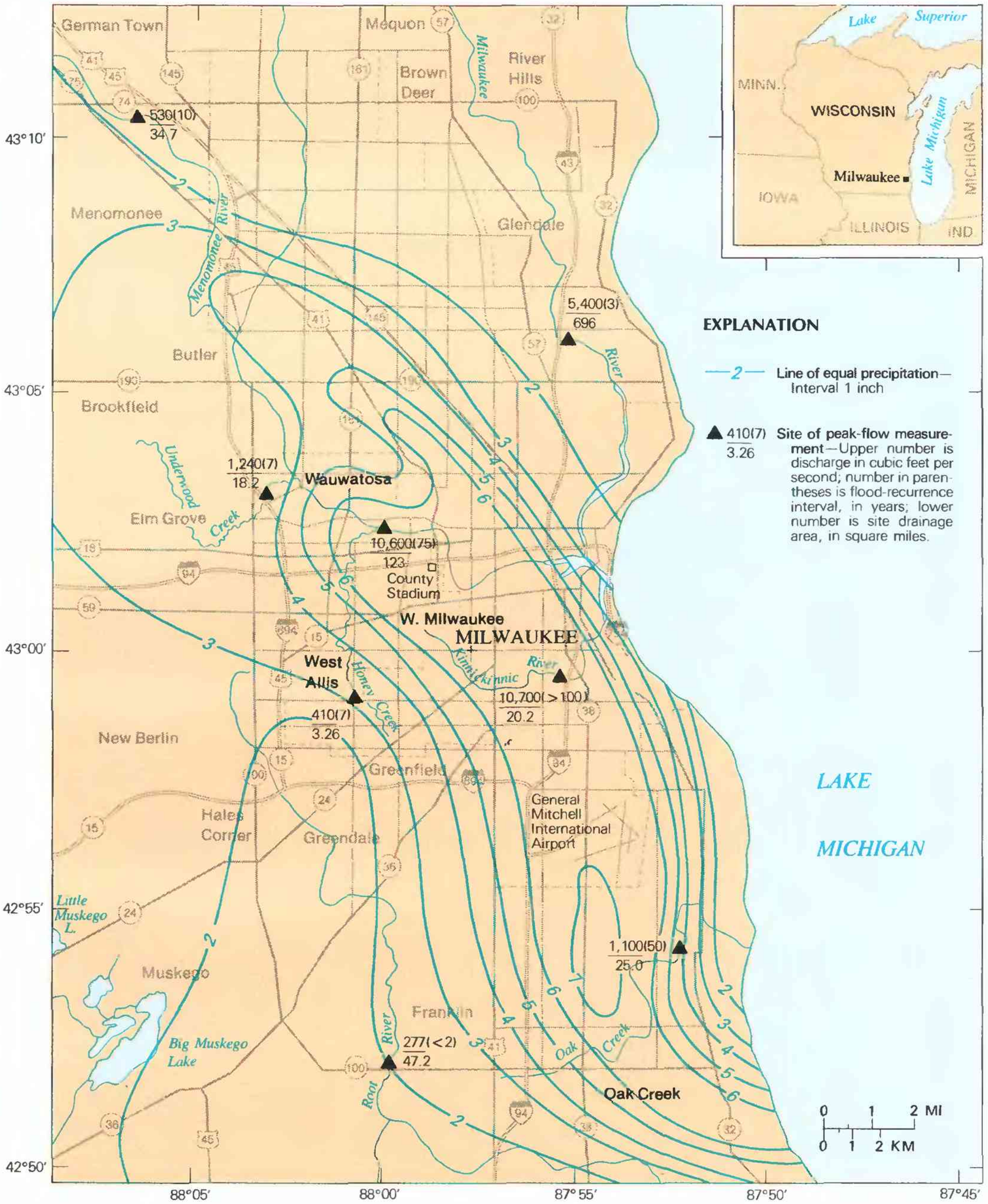
FLOOD OF AUGUST 6, 1986, IN THE MILWAUKEE METROPOLITAN AREA, WISCONSIN

By Warren A. Gebert

Shortly after midnight on August 6, 1986, a severe thunderstorm, which continued for 24 hours, occurred in the Milwaukee metropolitan area of southeastern Wisconsin. The storm caused record flooding in urban areas that resulted in two deaths and a range of property damages from $21 million to $30 million (Wisconsin Department of National Resources, 1986; U.S. Army Corps of Engineers, 1987).

The storm, which was produced by a low-pressure system that moved eastward through Iowa and across northern Illinois, was centered in a narrow band 1 to 4 miles wide and about 12 miles long. It extended from the city of Oak Creek to the northern part of the city of Wauwatosa (fig. 25). The total rainfall for the 24-hour period recorded at the National Weather Service rain gage at General Mitchell

Figure 25. Precipitation and selected peak flows resulting from the storm of August 6, 1986, Milwaukee, Wisconsin. (Source: Precipitation data compiled by Southeastern Wisconsin Regional Planning Commission; peak-flow data compiled by W.A. Gebert from U.S. Geological Survey files.)



International Airport in southeastern Milwaukee County was 6.84 inches. The maximum rainfall intensity occurred when 1.10 inches of rain fell during a 5-minute period. The maximum amount of rainfall varied from 6.00 to 6.84 inches and occurred in large areas of the cities of Oak Creek, Milwaukee, West Allis, and Wauwatosa and the village of West Milwaukee.

The Southeastern Wisconsin Regional Planning Commission (1986) estimated that the storm had an average recurrence interval of about 300 years for the 24-hour period. The greatest amount of rainfall during 2- and 3-hour periods was 5.24 to 5.73 inches, respectively. The recurrence interval for these intensities exceeds 500 years.

Extensive flooding occurred along two major rivers—the Menomonee and the Kinnickinnic—that flow through Milwaukee and its suburbs into Lake Michigan. Major floods also occurred along Oak Creek and other tributary streams. The floods caused the death of two people—an 11-year-old boy was swept away in the swift waters of the Kinnickinnic River and an elderly woman died of a heart attack in her flooded basement apartment.

The Wisconsin Department of Natural Resources (1986) estimated that the flooding caused $21 million of damages—$5 million to private property and $16 million to public facilities. Most of the damage to private property was caused by floodwater seepage into buildings. Flooding and sanitary-sewer backup damaged 10,000 basements. The damage varied from collapsed building foundations to damage of property stored in flooded basements. Milwaukee County Stadium, the home of the Milwaukee Brewers baseball team, was flooded to the fourth row of box seats (fig. 26).

General Mitchell International Airport was damaged severely by several feet of water that entered the lower level of the main terminal. The airport's electricity was shut off to avoid possible damage from a transformer explosion. Lightning struck one of the primary commercial runways, blowing a 4-foot hole in it. Estimated damage to the airport was nearly $2 million.

Streamflow information used to evaluate the extent and severity of the flood was provided by a network of 18 continuous-record gaging stations operated by the U.S. Geological Survey in cooperation with the Southeastern Wisconsin Regional Planning Commission, Milwaukee Metropolitan Sewerage District, and the Wisconsin Department of Natural Resources. Data obtained showed that the Kinnickinnic River had by far the largest flood, 10,700 ft^3/s (cubic feet per second) with a recurrence interval greater than 100 years, because almost the entire basin was in the area of heaviest rain. The Kinnickinnic River also is entirely an urban stream, whereas substantial parts of the watersheds of the other major rivers are in rural areas. Flood waters collected very rapidly in the urban areas due to the channelized waterways and storm sewers. Much of the Kinnickinnic River is concrete lined, and water moves rapidly through its smooth channel. Estimated water velocities of 20 feet per second occurred during the storm.

The peak flow of 10,600 ft^3/s on the Menomonee River at Wauwatosa was also a significant flood. The recurrence interval for the flood was about 75 years, which is high considering that the upper part of the 123-square-mile drainage area is not urbanized. It appears that the northwest-southeast orientation of the storm was about the same as that of the Menomonee River and the entire drainage area appeared to have received significant rain. The Milwaukee River, which has a much larger drainage area and did not receive much of the larger amounts of rain, had a flood with a recurrence interval of only about 3 years.

Figure 26. Flooding of Milwaukee County Stadium, Wisconsin, from August 6, 1986, storm. (Photograph courtesy of Richard Brodzelle, Milwaukee (Wisconsin) Sentinel.)

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FLOOD OF SEPTEMBER 10 TO 15, 1986, ACROSS THE CENTRAL LOWER PENINSULA OF MICHIGAN

By John B. Miller and Stephen P. Blumer

Torrential thunderstorms that began on September 10, 1986, resulted in unprecedented flooding in an east-west band across the entire Lower Peninsula of Michigan (fig. 27). The flooding claimed 6 lives, injured 89, contributed to the failure of 11 dams, threatened 19 additional dams, and caused basement flooding or structural damage to about 30,000 homes (Federal Emergency Management Agency, 1986a,b). Maximum recorded precipitation for the 48-hour period ending 8 a.m. September 12 was more than 13 inches at Big Rapids (National Oceanic and Atmospheric Administration, 1986), and the Big Rapids area sustained considerable damage (fig. 28). The areal extent of significant precipitation was widespread; records indicate that more than 10 inches of rain fell over a 3,500 mi² (square miles) area. Four primary road bridges and hundreds of secondary road bridges and culverts failed making 3,600 miles of road-

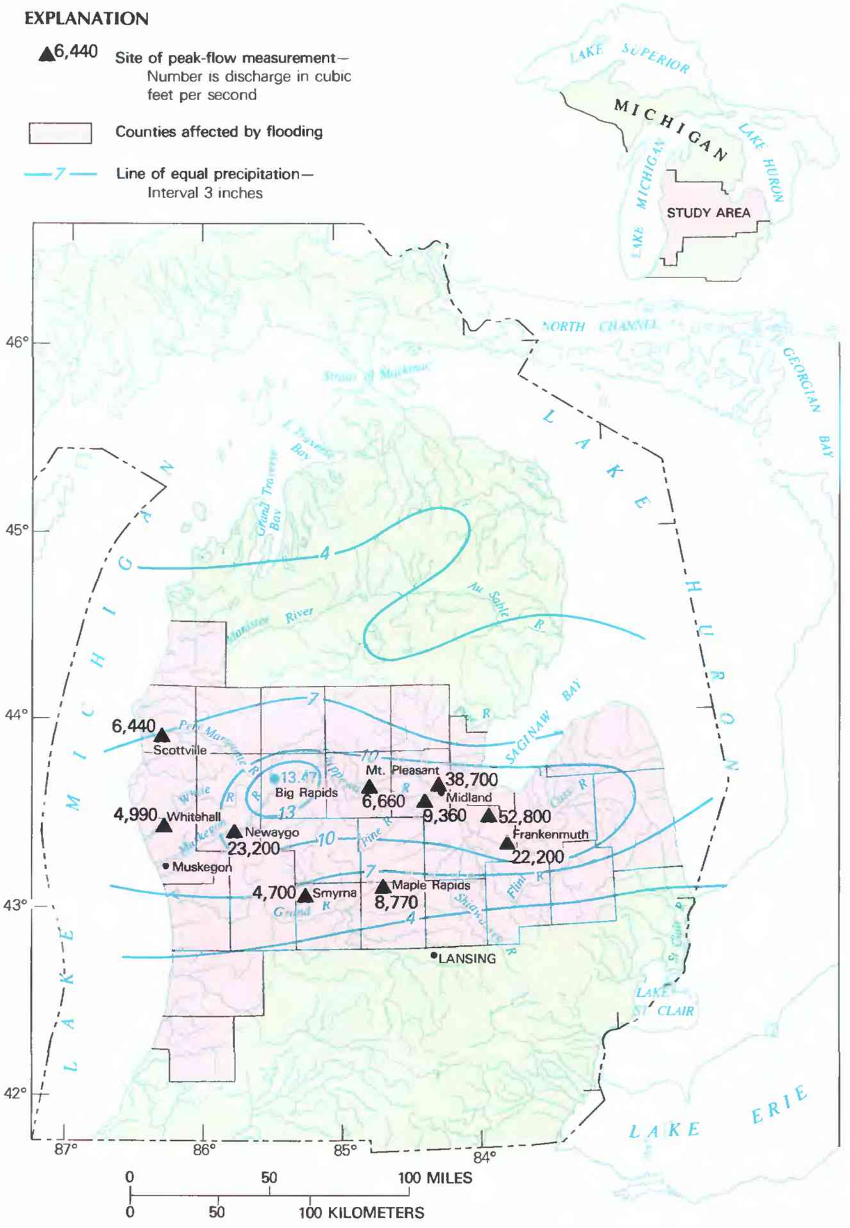

Figure 27. Precipitation and peak discharge of several rivers resulting from storms of September 10 to 12, 1986, in the central part of the Lower Peninsula of Michigan. The maximum recorded precipitation for this period was 13.47 inches at Big Rapids (blue circle). (Sources: Precipitation data from National Weather Service compiled by Michigan Department of Agriculture, Dr. Fred V. Nurnberger, State Climatologist; peak-discharge data from U.S. Geological Survey files.)

way impassable. The total extent of damage was in excess of $400 million to homes, businesses, utilities, governmental structures, and harvest-ready agricultural crops. A 28-county area of the State was declared a Federal disaster area by the President.

The extraordinarily severe rainfall was caused by a low-pressure system that developed over the central Great Plains on September 9, 1986. Northeastward movement of the system produced a warm front extending across the central part of the Lower Peninsula of Michigan the following day. Heavy precipitation was triggered by warm, moist air south of the front that collided with cold air from the north. The absence of upper atmospheric wind activity caused the storm pattern to remain relatively stationary over the State for several days. Hardest hit was an area measuring 60 miles north to south and 180 miles east to west, the area that coincided with the stagnated front. Rainfall amounts recorded in a 48-hour period ranged from 8 to more than 13 inches (Federal Emergency Management Agency, 1986b; National Oceanic and Atmospheric Administration, 1986). The rarity of this precipitation can be put in perspective by comparing these numbers with published frequencies of similar storms that are known to have occurred. A 2-day total of about 5.5 inches could be expected to occur once in 100 years (Miller, 1964). On the basis of this comparison, the present storm greatly exceeded the 2-day 100-year precipitation.

Crop damages were severe, especially in the Saginaw River basin where dikes were breached and thousands of acres of sugar beets, beans, potatoes, corn, and other vegetables were ruined. Of Michigan's 12 million acres of cultivated land about 1.5 million acres (Federal Emergency Management Agency, 1986b) were affected. In addition to the extensive crop losses, over 1,200 farm-related structures were flooded (fig. 29). The abnormally high precipitation for the remainder of September prolonged inundation of some agricultural acreage and prevented the salvage of many crops. Some farmers lost their entire crop. A major concern is that farmers will be unable to repay their outstanding loans. Flood losses suffered in 1985 forced farmers to borrow against the 1986 crop for working capital, and as a result of the September 1986 flood many farmers may be forced into bankruptcy.

Four major river basins discharging to the west into Lake Michigan were affected by the flooding. Two dam failures occurred in the upper part of the White River basin, contributing to the peak discharge of 4,990 ft^3/s (cubic feet per second) at Whitehall (drainage area, 406 mi^2), slightly less than the 5,400 ft^3/s peak of record discharge. The ratio of the peak discharge of September 13, 1986, to the 100-year flood is 0.78. The Pere Marquette River at Scottville (681 mi^2) and the Muskegon River at Newaygo (2,350 mi^2) attained new maximum peak discharges of 6,440 ft^3/s and 23,200 ft^3/s, respectively; the ratios of these discharges to the 100-year flood discharge are 1.37 and 1.23, respectively. One dam failure occurred on a tributary to the Pere Marquette River; two dam failures occurred on tributaries to the Muskegon River. Major flooding in the Grand River basin occurred along tributaries that drain from the north. Three dam failures on tributaries contributed to flooding in upstream areas; the Grand River itself was not as severely affected. Peak of record discharges for two of these tributaries—Maple River at Maple Rapids (434 mi^2) and Flat River at Smyrna (528 mi^2)—were 8,770 ft^3/s and 4,700 ft^3/s, respectively; the ratios of these discharges to the 100-year flood are 0.86 and 1.14, respectively.

On the eastern side of the State, the Cass, the Shiawassee, the Flint, and the Tittabawassee Rivers converge to form the Saginaw River, which drains north into Saginaw Bay and Lake Huron. The Cass River, which crested about 11 feet above flood stage, inundated the major business district of the city of Vassar and water levels reached second-floor apartments. Discharge of the Cass River at the downstream gaging station at Frankenmuth (841 mi^2) was 22,200 ft^3/s with a ratio to the 100-year flood of 0.96. The new peak stage at Frankenmuth exceeded the previous peak stage by more than 4 feet. Although flooding occurred in the Shiawassee and Flint River basins no new peaks of record were recorded. In fact, annual peak discharges for both rivers occurred as the result of a separate storm later in September. In the Tittabawassee River basin, the Chippewa River near Mt. Pleasant (416 mi^2) and Pine River near Midland (390 mi^2) attained new maximum peak discharges of 6,660 and 9,360 ft^3/s, respectively, with ratios to the 100-year flood of 1.08 and 1.19. One dam failure occurred in the headwaters of the Chippewa River. The Tittabawassee River at Midland peaked on September 13, at 38,700 ft^3/s, exceeding the previous maximum of 34,800 ft^3/s on March 28, 1916. The river crested at 33.89 feet, exceeding the record of 1916 by more than 4 feet. The ratio to the 100-year flood is 0.83. The Saginaw River peak discharge of 52,800 ft^3/s on September 15 did not exceed the previous peak of 68,000 ft^3/s recorded in 1904.

Subsequent rainfall in the last half of September magnified the effects of the original flooding and hindered recovery. The September 1986 rainfall exceeded the previous monthly high for any month by about 20 percent, adding additional historic perspective to the worst recorded flooding in this region of Michigan.

Figure 28. Floodwaters caused the collapse of Brookside Dairy Freeze into Mitchell Creek in Big Rapids, Michigan. (Photograph courtesy of Scott Harmsen, Bay City Times.)

Figure 29. Farmers bore the brunt of the damage done by floodwaters in the Saginaw River basin, Michigan. (Photograph courtesy of Midland Daily News.)

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UNUSUAL HYDROLOGIC EVENTS IN MINNESOTA—*WHEN IT RAINS...*

By Kurt T. Gunard

Hydrologic events in Minnesota during the past 5 years have been so unusual that they could occur only once or twice in an individual's lifetime—as frequently as the return of Halley's Comet.

As a result of above-normal precipitation over a consecutive 4- to 5-year period, ground-water levels, lake levels, and streamflow have been above average or excessive in many parts of Minnesota. Lake Superior on Minnesota's northeastern border has been at record-high levels for almost a year, resulting in increasing shoreline erosion and damage to shoreline structures. Many "inland" lakes, especially those with no apparent surface-water outlet, are at record-high levels, and shoreline flooding is causing extensive damage to lakeside property and homes. More than 40 lakes across central Minnesota are higher than anyone can remember. The long-duration flooding has destroyed hundreds of homes and cottages, and rendered onsite sewage-disposal systems inoperative, resulting in millions of dollars in property losses in addition to human misery from exposure, privation, and inconvenience. Severe flooding of cropland was localized; some fields were too wet to plant in the spring and others too wet to harvest in the fall. Such areas were only a small percentage of the total cropland, and the high rainfall produced record crop yields on farmland not affected by flooding.

Total precipitation in 1983 (39.04 inches) was the fourth wettest single-year total in 149 years in the Minneapolis–St. Paul area, which is representative of precipitation trends in much of the State. Additional precipitation in 1984 produced the wettest 2-year period on record with 75.99 inches. Continued high precipitation during 1985 brought the 3-year total to 107.65 inches, which is the wettest 3-year period on record. The period ending with 1985 also was the wettest 4-year period on record (137.88 inches), and the second wettest 5-year period on record at 159.65 inches (Kuehnast and Zandlo, 1986, p. 2–3). The metropolitan area around Minneapolis and St. Paul has never received greater precipitation since record keeping began in 1837. In parts of Ramsey, Anoka, and Hennepin Counties north and west of Minneapolis–St. Paul, annual precipitation has averaged more than 9 inches above normal for the 4 years ending in 1985.

During 1986, precipitation set another record—again in excess of 9 inches above normal in the metropolitan area. Most of this excess occurred after April 1. Adding the 36.61 inches of precipitation that occurred during 1986, the 5-year record (174.49 inches) for total precipitation was established. The period ending with 1986 also narrowly misses being the wettest 10-year period, exceeded only by the 10-year period ending in 1874 (J.A. Zandlo, Minnesota Department of Natural Resources, oral commun., 1987). It appears that Minnesota may be beginning a wet cycle similar to the 40-year wet period that began in the 1870's and extended over the turn of the century (Kuehnast and Zandlo, 1986, p. 4).

The flow of many rivers and streams in Minnesota has been excessive for many months in each of several consecutive years. Monthly flows from 2 to 20 times the long-term average have been common. These flows rank from 10th highest to the highest for the period of record; many of these flows occurred at locations where records are for 50 years or more. For example, the average monthly flow of the Crow River at Rockford in east-central Minnesota was 3,809 ft^3/s (cubic feet per second) during October 1985. This flow is 23 times greater than the normal October flow, which is based on 63 years of record, and is 2.5 times the previous high of record, 1,503 ft^3/s, which occurred in October 1968 (fig. 30).

A considerable number of monthly flow records for streams and rivers throughout Minnesota were broken in 1986, the greatest number of which were broken in May. Record-high May flows were recorded at each of the following index stations (part of a national network of streamflow stations used to assess runoff and availability of surface water on a current basis):

Buffalo River near Dilworth, in northwestern Minnesota—average flow was 923 ft^3/s, which is 4.4 times the long-term average May flow and the highest in 56 years of record; the previous high of 906 ft^3/s occurred in 1962.

Crow River at Rockford, in central Minnesota—average flow was 6,020 ft^3/s, which is 4.9 times the average May flow and the highest in 67 years of record; the previous high was 4,564 ft^3/s in 1975.

Mississippi River near Anoka, which drains most of north-central and central Minnesota—average flow was 39,960 ft^3/s, which is 2.7 times the average May flow and the highest in 55 years of record; the previous high was 38,490 ft^3/s in 1950.

Minnesota River near Jordan, which drains most of west-central and south-central Minnesota—average flow was 22,250 ft^3/s, which is 4.0 times the average May flow and the highest in 52 years of record; the previous high was 20,630 ft^3/s in 1944. A daily-flow record also was broken at the Jordan station by a flow of 35,800 ft^3/s on May 5; the previous mean daily high was 35,100 ft^3/s on May 26, 1960.

Mississippi River at St. Paul, which is downstream from the mouth of the Minnesota River and drains 45 percent of the area of Minnesota—average flow was 64,230 ft^3/s, which is almost 3 times the May average and the highest in 95 years of record; the previous high was only 48,460 ft^3/s in 1975. A new daily-flow record of 83,900 ft^3/s also was set at St. Paul on May 5; the previous daily high was 78,100 ft^3/s on May 4, 1975. September also was a month of record flow— 35,390 ft^3/s; the highest September flow in 95 years of record.

In addition to the above index stations, record flows also occurred at several other stream-gaging stations in Minnesota during May 1986. Two of these

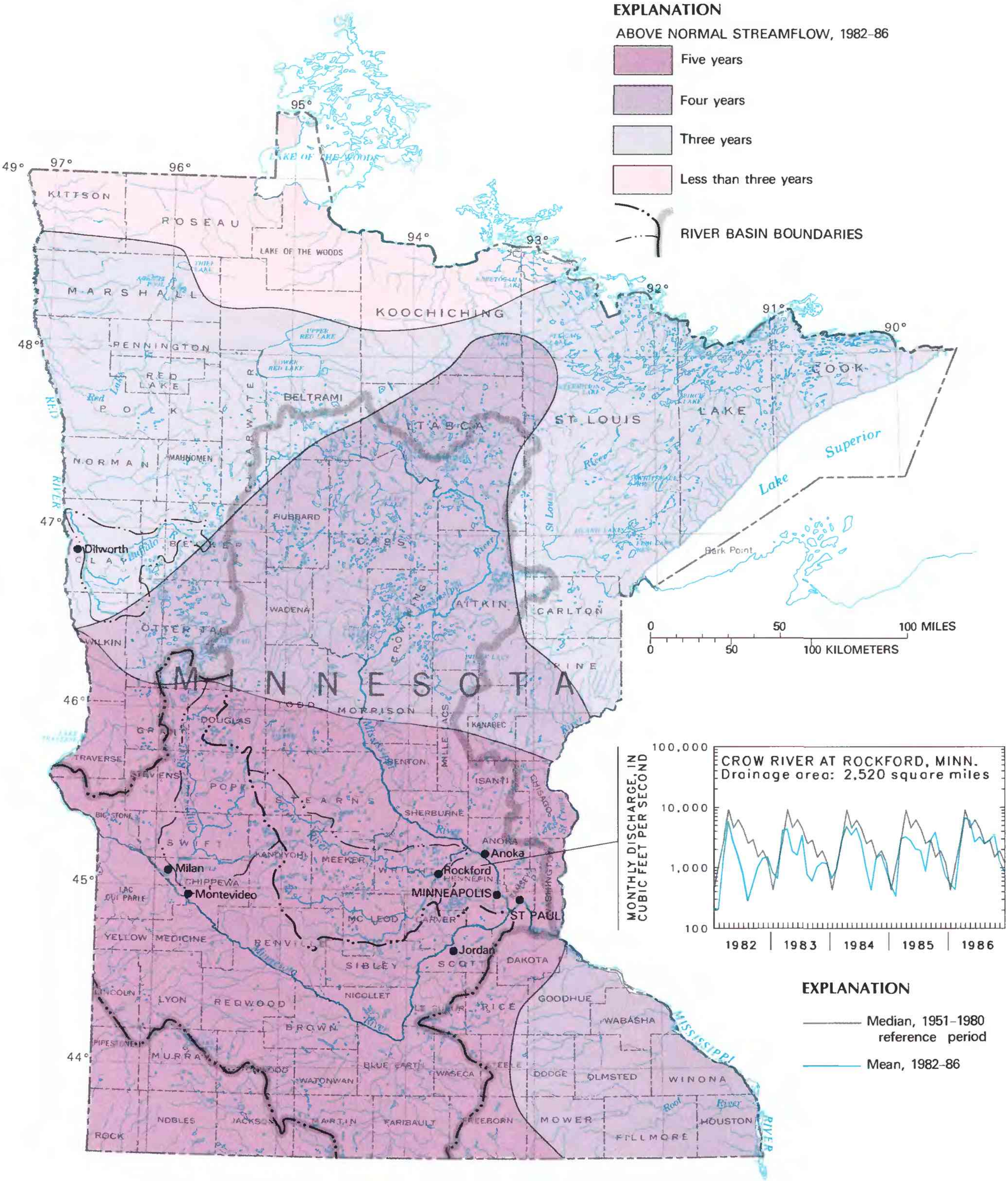

Figure 30. Composite streamflow of river basins in Minnesota where record streamflow occurred as a result of much-above-normal precipitation, 1982–86. Monthly discharge data are for streamgaging station at Crow River at Rockford, Minn., 1982–86. (Source: Compiled by K.T. Gunard from U.S. Geological Survey data.)

stations are in west-central Minnesota—one on the Chippewa River near Milan and the other on the Minnesota River at Montevideo. Average flow in the Chippewa River was 2,490 ft³/s, the highest flow in May in 49 years of record and 5.4 times the May average; the previous high average monthly flow of the Chippewa River was 1,715 ft³/s in 1972. In the Minnesota River at Montevideo, the May flow was 7,120 ft³/s, which is 5.4 times the May average and the highest average monthly flow in 76 years of record; the previous high was only 4,939 ft³/s in May 1969.

Near-record flows occurred at many other streamflow stations in Minnesota, both during 1986 and in the previous 4 years, indicating a high sustained-flow condition as a result of continued above-average precipitation. The Crow River at Rockford was the extreme example of sustained flow of Minnesota streams. Flow in the Crow River was in the excessive range (the highest 25 percent of flow in the reference period 1951-80) for 43 of the past 51 months; the last 27 of them consecutive (fig. 30). Although high flows were sustained for long periods in many streams in a large part of the State, contrary to what might be expected, no peaks-of-record occurred during the past 5 years. Streams generally remained within banks and only minor flooding occurred at isolated locations. Two lives were lost as a direct result of high-water levels at two of these locations.

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HYDROLOGIC PERSPECTIVES ON WATER ISSUES

INTRODUCTION

The "Hydrologic Perspectives on Water Issues" part of the 1986 *National Water Summary,* which is divided into two sections—Water-Quality Issues and Institutional and Management Issues— provides an introduction to some of the technical and institutional issues that must be considered in developing ground-water-management programs. Collectively, the articles in the "Hydrologic Perspectives on Water Issues" provide background information for the "State Summaries of Ground-Water Quality." This method of presentation was selected so that the individual State summaries, with their restricted page length, could concentrate on specifics pertinent to that State.

WATER-QUALITY ISSUES

"Factors Affecting Ground-Water Quality," discusses the technically complex subject of ground-water movement and the geologic environment through which ground water circulates. A knowledge of the principles involved can lead to a better understanding and appreciation of how ground-water quality varies in three dimensions and over time within an aquifer system, and how aquifers become contaminated by various human activities. In particular, these principles demonstrate the importance of understanding the flow systems of aquifers in order to protect ground water from contamination. Large withdrawals of ground water have profoundly affected flow patterns of some of the major aquifers in the United States and have directly contributed to water-quality degradation.

This introduction to principles and concepts is followed by six studies selected from the U.S. Geological Survey's Toxic Waste—Ground-Water Contamination Program to illustrate the diversity and complexity of ground-water contamination from point and nonpoint sources.

Point-Source Contamination. The first article, "Sewage Plume in a Sand-and-Gravel Aquifer, Cape Cod, Massachusetts," provides an example of the contamination that can occur in a shallow, permeable unconfined aquifer. About 2.6 billion cubic feet of the Cape Cod sole-source aquifer has been affected by the disposed sewage. The large amount of information collected at this site has documented in extraordinary detail the geometry and composition of a narrow, thin sewage plume that extends nearly 2 miles from the disposal beds.

The second and third articles deal with the behavior of wood-preservative wastes in two different hydrologic environments. More than 400 commercial wood-preserving plants are in operation in the United States. Most of the wastes from these plants include creosote, a complex distillate of coal tar containing a mix of aromatic and phenolic organic compounds. The health effects of creosote vary from chemical skin burns to long-term carcinogenic effects. Therefore, the mechanisms by which these contaminants are transported with and interact with the subsurface environment are of great interest and concern to ground-water managers. "Distribution and Movement of Wood-Preserving Compounds in a Surficial Aquifer, Pensacola, Florida" describes the movement of waste in a recharge area of an unconfined, highly permeable, shallow sand aquifer; the presence of a shallow confining layer of clay has inhibited contaminants from moving vertically. "Coal-Tar Derivatives in the Prairie du Chien-Jordan Aquifer, St. Louis Park, Minnesota" describes the contamination of an unconfined glacial-drift aquifer and the underlying water-supply aquifer.

Nonpoint-source contamination. The articles herein describe nonpoint sources of contamination related to various land uses—farm land in the Midwest and diversified land use in Eastern urbanized areas. Contamination of ground water by agricultural chemicals is of increasing concern to farmers and ground-water managers, especially in areas where irrigation water can carry fertilizers and pesticides from the surface into the ground-water system. "Agricultural Chemical Contamination of Ground Water in Six Areas of the High Plains Aquifer, Nebraska" points out that well depth, irrigation-well density, and nitrogen fertilizer use can explain 51 percent of the variation in nitrogen concentration in ground water. The distribution of nitrate correlated with the distribution of trazine herbicides, a weed killer frequently used on corn and soybeans, which suggests that nitrate concentration may be an inexpensive test to use in identifying potential areas contaminated by herbicides if herbicides are known to be used in the area under study.

The connection between land use and water quality in multiple land-use areas is described in two articles. "Relation of Land Use to Ground-Water Quality in the Outcrop Area of the Potomac-Raritan-Magothy Aquifer System, New Jersey" discusses the most extensively used aquifer for water supply in the New Jersey Coastal Plain. The area is heavily industrialized and has numerous landfills, surface impoundments, petrochemical storage tanks, and industrial facilities—all existing or potential sources of ground-water contamination. The study demonstrated the existence of an association of volatile organic compounds with industrial and urban-residential lands, pesticides with agricultural land, and phenols, believed to be derived from decaying vegetative matter, with undeveloped land. Benzene, a component of gasoline, was found in the petroleum-refining areas south of Camden, N.J.

"Relation of Land Use to Ground-Water Quality in the Upper Glacial Aquifer, Long Island, New York" describes the effects of extensive suburban development on ground-water quality. It appears possible that the detailed analyses of land-use and water-quality relations on Long Island, as well as in other areas of the country, will help ground-water-management agencies to better identify potential areas of ground-water contamination, thereby providing a basis for improvements in ground-water monitoring and protection programs.

INSTITUTIONAL-MANAGEMENT ISSUES

"Policy Challenges in Protecting Ground-Water Quality" by the U.S. Environmental Protection Agency describes the situation facing Federal, State, and local governments in protecting ground-water quality. "State and Local Strategies for Protection of Ground-Water Quality—A Synopsis" presents some of the conclusions from the National Research Council study on ground-water-protection programs.

WATER-QUALITY ISSUES

FACTORS AFFECTING GROUND-WATER QUALITY

By Richard H. Johnston

The Nation's ground-water reserves consist of waters of various chemical quality contained in numerous, complex aquifers. The water in these aquifers can be affected by both natural and human activities, and the extent to which the quality is affected by either natural processes or human activities varies with the hydrogeologic and climatic setting. In aquifers unaffected by human activity, the quality of ground water results from geochemical reactions between the water and rock matrix as the water moves along flow paths from areas of recharge to areas of discharge. Thus, "natural" water is variable in quality, and in very large, regional aquifer systems the quality of ground water also can change as the result of the mixing of waters from different aquifers within the system. In aquifers affected by human activity, the quality of water can be directly affected by the infiltration of human-induced compounds or indirectly affected by alteration of flow paths or geochemical conditions.

This article describes the basic hydrogeologic principles that can affect the movement of chemical constituents in ground water and the quality of the water. It also serves as an introduction to several subsequent discussions of point and nonpoint sources of ground-water contamination, and provides pertinent background information for understanding the individual State summaries of ground-water quality in the later part of this volume.

NATURAL GROUND-WATER SYSTEMS

HYDROLOGIC FACTORS AFFECTING GROUND-WATER QUALITY

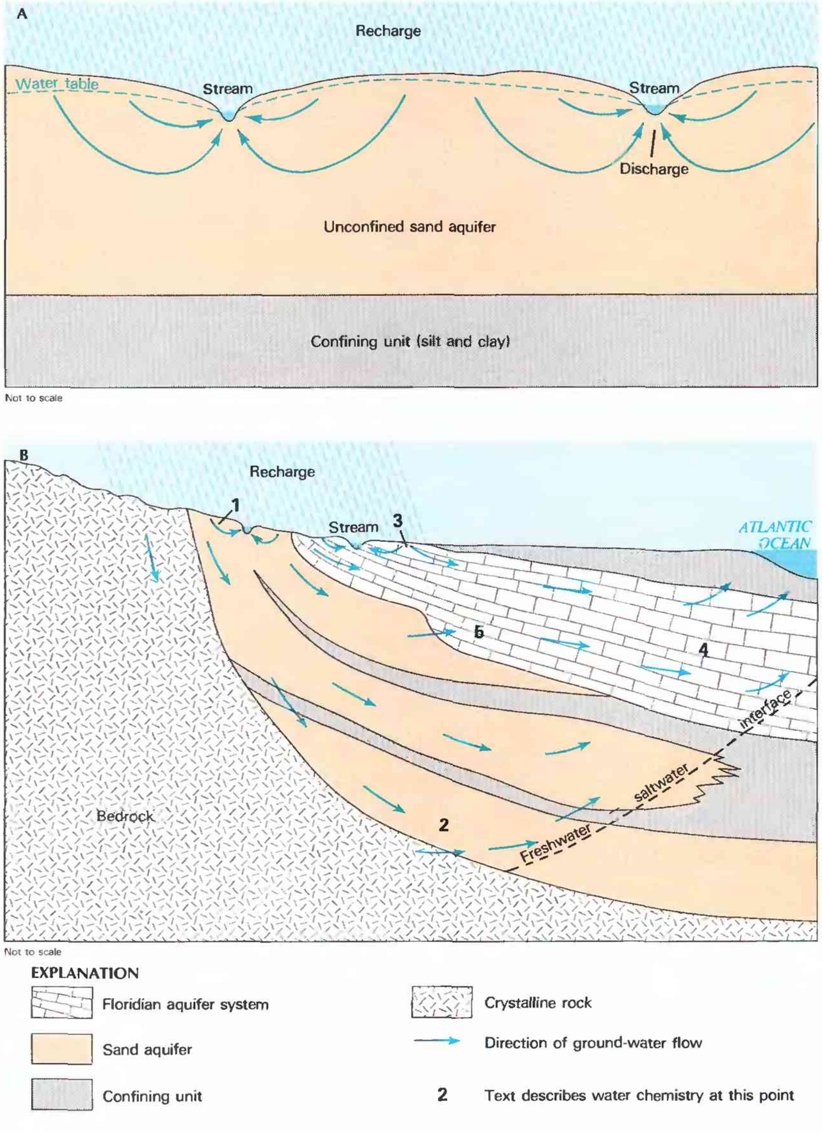
Ground-Water Flow Systems

A ground-water flow system includes aquifers (water-yielding units) and confining beds (units that restrict flow of water). Water enters the flow system in recharge areas and moves through the aquifers and confining units, according to their hydraulic properties and the hydraulic gradients, to discharge areas (Heath, 1983, p. 14). Climate, topography, and geology determine the nature and location of natural areas of recharge and discharge. Movement of ground water normally is by flow through small openings, such as the pore space between sand grains or hairline fractures in a granite. In some highly productive aquifers, movement occurs through larger openings, such as solution channels in limestone and tubular openings in basalt.

The geometric arrangement of aquifers and confining units in an area (hydrogeologic framework) is determined by the stratigraphy and geologic structure. *Stratigraphy is the branch of geology that is concerned with the composition, sequence, and correlation of stratified (layered) rocks. Geologic structure is concerned with folding and fracturing of rocks due to movements of the Earth's crust.* Folding of the rocks can cause jointing or cleavage that increases permeability, or it can close up primary openings and decrease permeability. Faults can disrupt the continuity of aquifers or confining units and thereby restrict ground-water flow. Alternatively, fault zones can be permeable and enhance ground-water flow.

A ground-water flow system can be simple—one aquifer with short flow paths to a nearby stream or spring (fig. 31*A*). Conversely, a flow system might be complex—several aquifers and confining units and flow paths that range in length from hundreds of feet to a hundred miles or more (fig. 31*B*). Water following the longer (regional) flow paths may cross river-basin boundaries and State boundaries in addition

Figure 31. Hydrogeologic framework and associated ground-water flow systems in the Atlantic Coastal Plain. *A*, Simple flow system in Delaware; *B*, complex flow system in Georgia. (Sources: Modified from *A*, Johnston, 1977; *B*, Barker, 1985).



to several geologic formations and ultimately (after many years or centuries) discharge at a river or the ocean.

Recharge to aquifers tends to be spread over very large areas. In the Eastern United States, natural recharge rates can be very high as on Long Island, N.Y., where the recharge rate is about 1 Mgal/d/mi^2 (million gallons per day per square mile) (Cohen and others, 1970, p. 12). This rate is equivalent to about one-half of Long Island's total precipitation of 44 inches annually. Conversely, in the arid Western United States, recharge rates generally are very low (perhaps in the range of 500 gal/d/mi^2 (gallons per day per square mile)), except in or near some less arid mountainous areas. Discharge from aquifers might occur over large areas as leakage into rivers or the ocean, or it might occur as point discharge, such as the large springs of Florida and Idaho. Before pumping of ground water by humans, an equilibrium condition exists in ground-water systems—that is, the long-term natural recharge rates and discharge rates are equal.

Rates of Ground-Water Flow

Ground water moves very slowly, and most ground water always is moving along a flow path from where it is recharged to where it is discharged. Shallow ground water generally moves at rates that range from much less than a foot per day to as much as several feet per day. An exception to this is in aquifers that have conduit-like openings, such as basalt and karstic limestone, where water may move much faster. Deeply circulating ground water moves extremely slowly—sometimes as little as a few feet or less per century.

The velocity at which ground water moves depends upon the permeability and porosity of the rocks along its route and the hydraulic gradient. Assuming the same permeability, ground water moves faster as the hydraulic gradient increases. Highly permeable rocks, such as sand and gravel and some limestone, provide less resistance to flow; consequently, given the same hydraulic gradient, ground water will generally move faster in those rocks than in less permeable rocks such as clayey sand, granite, or shale.

The average time required for ground water to move along different flow paths from recharge to discharge areas is shown in figure 32. Water in the shallow sand aquifer shown in figure 31*A* would reach a stream in a few days to a few years after recharge. However, water moving through the deeper parts of the Floridan and sand aquifer systems shown in figure 31*B* would require thousands of years to reach discharge points. Under most natural conditions, the type of rock through which water flows from a recharge area to a point of discharge is more important in determining natural ground-water quality than is the rock-water contact time. However, water moving along deep, long flow paths may, in succession, come in contact with rocks of different composition, thus increasing the opportunity for changes in the water chemistry.

Flow rates shown in figure 32 are average rates. On a small scale within an aquifer, flow velocities vary greatly and generally are greater than the average rates shown. The paths actually taken by the water are tortuous and involve movement in pore spaces between and around grains in a sand aquifer or through a maze of joints or fractures in a fractured rock aquifer. (See figure 33.) Thus, the velocity of flow through individual pores would exceed the average velocity through an aquifer. Also, the average velocity within the most permeable horizons of an aquifer tends to exceed the average velocity through the aquifer as a whole. The rates shown in figure 32 can be termed the average linear velocity (Freeze and Cherry, 1979, p. 71), which is the flow (or volumetric flux) divided by the cross-sectional area and porosity of the aquifer through which flow occurs.

Fluid velocity and molecular diffusion are two processes that move the dissolved constituents (called "solutes") in ground water. Within an aquifer, local variations in fluid velocity cause the solutes to spread out in a process called "dispersion," which results in a decrease in the solute concentrations as the solutes move through the aquifer (fig. 33*A*). Molecular diffusion, which is unrelated to the hydraulic gradient, causes the solutes to spread in a direction that tends to equalize their concentration. Molecular diffusion generally is not important in shallow, faster moving ground water but may be significant in deep, slower moving systems.

HYDROCHEMICAL FACTORS AFFECTING GROUND-WATER QUALITY

Chemical Processes

By Roger W. Lee

Water chemistry can be explained by one or more combinations of three of the most significant natural chemical reactions and one physical process that affect ground-water quality, as follows:

- Dissolution-precipitation (exsolution) reactions
- Oxidation-reduction (redox) reactions
- Ion-exchange processes
- Mixing of ground waters

The dissolution-precipitation (exsolution) process involves water-rock-gas relations. An important dissolution reaction is uptake of carbon dioxide (CO_2) in the soil zone to form carbonic acid (H_2CO_3); the reaction causes dissolution of aquifer materials. As a result, the chemistry of ground water often reflects the primary suite of minerals in an aquifer. For example, dissolution of calcite ($CaCO_3$) in a limestone would produce mostly calcium and bicarbonate ions in solution. Aluminosilicate minerals such as feldspars (for example, albite) might be partially dissolved or "weathered" as cations and silica are removed, leaving products such as clay minerals. Precipitation or exsolution can occur when the water becomes saturated with ions or molecules that are contained in the aquifer material; examples include the precipitation of calcite or quartz or the loss of CO_2 gas (exsolution). Evaporation of water from a shallow unconfined aquifer also can occur, increasing concentrations of dissolved constituents in the water remaining in the aquifer and perhaps causing precipitation of a mineral. This process is particularly

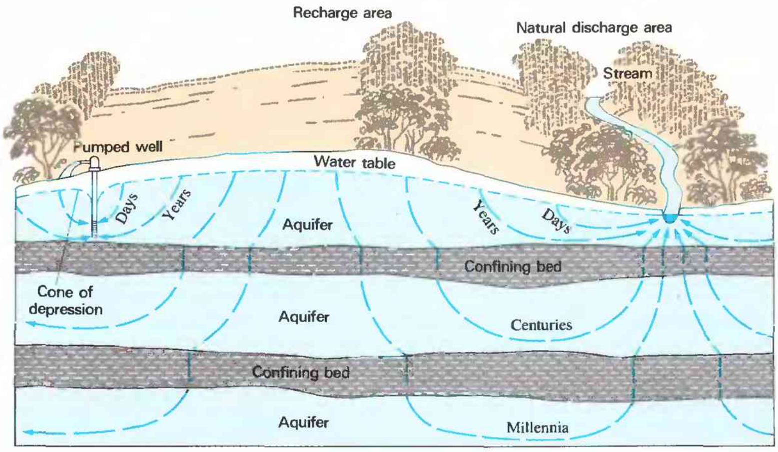


Figure 32. Rates of ground-water flow. (Source: Adapted from Heath, 1983, p. 14.)

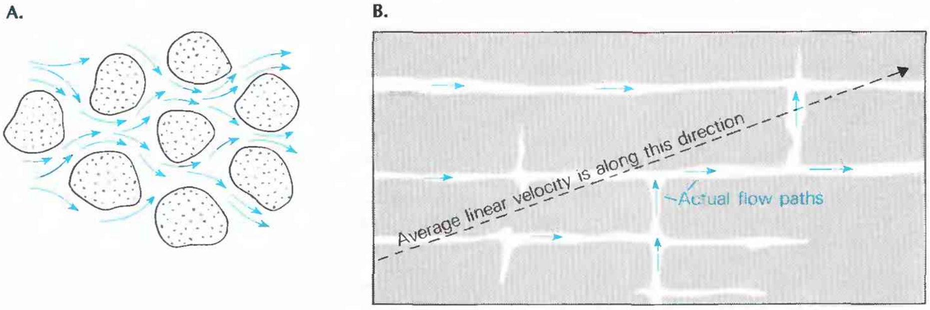


Figure 33. Concepts of velocity and dispersion in ground-water flow. *A*, Dispersion in a granular deposit; *B*, average linear velocity of ground water in a fractured rock aquifer. (Source: *A*, Heath, 1983, p. 19).

important in arid areas of the Western United States.

Oxidation-reduction reactions occur throughout ground-water systems, although in many instances their effects are manifest in chemical constituents that may be present in low concentrations in ground water and, therefore, may be overlooked. Oxidation-reduction takes place when electrons are exchanged between electron-poor (oxidized) constituents and electron-rich (reduced) constituents. This type of process must, therefore, involve both oxidizable species, such as sulfide in pyrite (FeS_2) or carbon in peat or lignite, and reducible species, such as sulfur (+6) in gypsum ($CaSO_4 \cdot 2H_2O$). Ground water near areas of recharge might contain some dissolved oxygen and therefore be in an oxidizing geochemical environment. Dissolved oxygen in ground water is common in unconfined aquifers, and it has been observed in some confined aquifers. In parts of aquifers where oxygen has been depleted and the ground-water system is closed to atmospheric oxygen, reduction of certain chemical species is accompanied by the oxidation of other chemical species. For example, the bacterial reduction of sulfate (SO_4^{-2}) to sulfide (S^{-2}) can occur as organic matter is oxidized to CO_2. Many redox processes involve bacteria that "catalyze" a specific reaction, using available organic matter.

The dominant form of ion exchange is the exchange of cations in the aquifer material for cations in the water, although anion exchange has been documented. Cation exchange occurs whenever cations in solution are not in equilibrium with cations adsorbed on the rock materials through which the water flows. The exchange of cations occurs most commonly when clay minerals are abundant in the aquifer framework. The most common cation exchange process in aquifers involves the exchange of aqueous calcium ions for adsorbed sodium ions, or natural "softening" of the water.

Mixing of ground waters is largely a process of physical alteration where waters from different sources mix as a result of hydrogeologic controls on ground-water movement. When the chemical makeup of waters differs, the process of mixing can produce dramatic changes in the water chemistry. Mixing of waters that are at equilibrium with their respective aquifer minerals can alter equilibrium and cause extensive rock-water interactions. Mixing of ground waters, especially fresher ground water with saline water, is most common in downgradient parts of aquifers (for example, in coastal areas or deep sedimentary basins where salty water usually is present downgradient) or where ground water flows from one aquifer into another (fig. 31*B*).

Geologic Environment

As described in the section on chemical processes, the nature of the geologic units in an area directly affects the chemical constituents in ground water. The mineral composition of rocks is a very important influence on the water quality. Equally important is the hydrogeologic framework; that is, the sequence, thickness, and arrangement of the aquifers and confining units. This framework and the topography determine the paths that ground water follows, affect the rates of ground-water flow, and determine the sequence in which ground water moves through different rock types.

Most rocks are complex mixtures of minerals that differ widely in their stability toward or solubility in water (Hem, 1985, p. 190). This fact, plus the complicating factors resulting from variations in the sequence and arrangement of rock units, makes it difficult to generalize about the influence of lithology on ground-water quality. The chemical character and evolution of ground water in various rock terrains are described by Hem (1985) and Freeze and Cherry (1979) and are summarized briefly here.

Rocks are classified broadly as sedimentary, igneous, or metamorphic on the basis of their origin. Sedimentary rocks (which were deposited by water or wind) constitute most of the world's great aquifers and are classified as either indurated (limestone, shale, and sandstone) or nonindurated (granular deposits such as sand, gravel, and glacial outwash). Igneous rocks are formed by solidification from lava (such as basalt) or from molten rock in the subsurface (such as granite). Metamorphic rocks are derived from sedimentary or igneous rocks that have been changed by heat and pressure and include such rocks as gneiss and slate.

Water in limestone terrain—that is, rocks composed of calcium carbonate ($CaCO_3$)—is perhaps easiest to characterize. Calcium carbonate is relatively soluble in water containing carbon dioxide (CO_2); consequently when water comes into contact with the rock, some of the limestone will be dissolved, and, therefore, the chemical quality of this water generally is dominated by calcium and bicarbonate. However, if the limestone is associated with dolomite ($CaMg(CO_3)_2$, a calcium-magnesium-bicarbonate water may result. If gypsum ($CaSO_4{\cdot}2H_2O$) beds occur with the limestone and dolomite, the result may be a calcium-magnesium-sulfate type water.

Water in granular deposits (such as sand, gravel, and glacial outwash) and weathered rocks of all types tends to vary widely in chemical composition depending on the mineralogy of the deposits. Many of the extensive quartz sand (SiO_2) aquifers of the Atlantic Coastal Plain are of marine origin and contain shell fragments; dissolution of the shell material results in a calcium-bicarbonate type water. However, in deeper parts of these sand aquifers where dissolved-solids concentrations are much higher, the water is either a sodium-bicarbonate type or a sodium-chloride-bicarbonate type (Cushing and others, 1973, p. 39–47). The sodium water is caused either by ion exchange or by mixing of the circulating fresh ground water with saline sodium-chloride water that occurs in the deeper parts of all Coastal Plain aquifers.

Water in metamorphosed sedimentary rocks, such as gneiss and slate, generally is low in dissolved solids (Hem, 1985, p. 201). The primary reason is that these rocks contain silicate minerals that are less soluble than, for example, a limestone.

Igneous rocks vary greatly in their permeability and mineral composition. Extrusive igneous rocks (lava flows, volcanic ash, and cinder beds) usually contain zones of high permeability—the prolific basalt aquifers of the Pacific Northwest and Hawaii are examples. In contrast, intrusive igneous rocks (formed below land surface), such as the granites of the Piedmont and New England provinces, usually have low permeability because water movement is restricted to fractures in the rock. Igneous rocks generally are classified according to their mineral content. Granite is rich in quartz and sodium-potassium feldspar and, thus, the ground water is relatively high in silica, sodium, and potassium, although the water characteristically is low in total dissolved solids. Basalts are composed mostly of calcium-sodium feldspars and ferromagnesian minerals, and a typical basalt water contains dissolved calcium, magnesium, sodium, and bicarbonate (Hem, 1985, fig. 44), but the water might be very low in total dissolved solids.

Most of the great aquifers in the United States are in sedimentary rocks. To illustrate the influence of stratigraphy and geologic structure on ground-water flow and chemistry, two areas of sedimentary rocks in the Atlantic Coastal Plain (fig. 31*A*, *B*) and an area in central Texas (fig. 34) are described below.

Much of the Delmarva Peninsula in the Atlantic Coastal Plain is mantled with sandy sediments that form an extensive unconfined aquifer (Cushing and others, 1973, p. 46). The recharge rate to this sand aquifer is high—about two-thirds of a million gallons per day per square mile (Johnston, 1977, p. 7). The sand aquifer is separated hydraulically from underlying artesian (confined) aquifers in many parts of Delaware by a confining unit of silt and clay. In many areas, leakage to and from the underlying artesian aquifers is negligible. As late as the mid-1970's, pumpage rates from the unconfined aquifer were very small compared to natural rates of recharge and discharge. Discharge from the unconfined aquifer occurs mostly as seepage to nearby streams (fig. 31*A*) or, along the coast, to the ocean. Most ground water discharging to streams moves along short flow paths (less than a mile) from points of recharge to discharge. Because the sands are not very soluble and flow paths are short, the dissolved-solids content of the ground water is low, generally less than 100 mg/L (milligrams per liter) (Cushing and others, 1973, p. 47). Silica, calcium, sodium, and bicarbonate are the principal natural constituents—all in very low concentrations.

In coastal Georgia, the hydrogeologic framework is more complex because the aquifers and confining units consist of beds of sand, clay, silt, limestone, dolomite, and gypsum. The clastic beds (sand, silt, and clay) form a regional sand aquifer system, and the carbonate rocks (limestone and dolomite) form the highly productive Floridan aquifer system (fig. 31*B*). The limestone units of the Floridan generally grade into or interfinger with the sandy units, and thus a hydraulic connection exists between the Floridan system and the sand aquifer system. Ground water enters the two aquifer systems in their outcrop areas in central Georgia, and much of the water moves along relatively short flow paths to discharge at nearby streams (Barker, 1985, p. 331). The deeper flow tends to move along nearly horizontal paths in a generally east and southeast direction towards the Atlantic Ocean. Some water leaks upward from the sand aquifers into the Floridan where the sand and limestone are in contact and favorable hydraulic gradients exist. Near the coast, flow is upward in the Floridan but discharge is impeded by several hundred feet of clay confining beds (Bush and Johnston, 1987). In the deep sand aquifers, flow is northeasterly towards discharge areas in South Carolina (Barker, 1985, fig. 6).

The ground-water chemistry in the two aquifer systems mirrors the geologic framework and the ground-water flow systems. Where the sand aquifers crop out (fig. 31*B*, area 1), the shallow ground water is very low in dissolved solids (less than 50 mg/L) and is dominated by calcium and bicarbonate (Lee, 1985, p. 1547). In the middle and deeper parts of the sand aquifer system (fig. 31*B*, area 2), the dissolved-solids content is higher (100 to 1,000 mg/L) and the water is dominated by sodium bicarbonate and sodium chloride ions. In the limestone outcrop areas of the Floridan (fig. 31*B*, area 3), dissolution of calcite produces low to moderate increases in dissolved solids and the water is predominantly a calcium bicarbonate type (Sprinkle, 1982). Dissolved-solids concentration is maintained at less than 250 mg/L from the recharge areas downdip (and downgradient) in the Floridan nearly to the Georgia coast. In the deeper parts of the upper Floridan aquifer near the coast (fig. 31*B*, area 4), dissolution of gypsum adds calcium sulfate to the ground water, which results in a calcium-magnesium-bicarbonate-sulfate type water that has dissolved solids in the range of 250 to 500 mg/L (Sprinkle, 1982). Water in the upper Floridan is naturally fresh along the Georgia coast, and sodium-chloride water does not occur in the aquifer until far offshore. Upward leakage from the sand aquifers into the Floridan (fig. 31*B*, area 5) has lowered dissolved calcium concentrations and increased sodium content; however, the water is still a typical Floridan calcium-bicarbonate type (Sprinkle, 1982).

As shown in figure 34, geologic structure exerts a strong influence on the circulation of ground water and the water quality in the Edwards aquifer of central Texas. The Edwards is a highly productive aquifer composed of extensively faulted, fractured, and cavernous limestone and dolomite (Maclay and Small, 1984, p. 1). Wells tapping the aquifer have some of the highest yields in the world—reportedly in excess of 16,000 gal/min (gallons per minute).

In the San Antonio area, some high-angle faults vertically displace the entire thickness of the Edwards aquifer (fig. 34). The faults act as barriers to downdip ground-water flow and divert flow to either the northeast or the southwest along the trends of the faults. Some of these faults coincide with a major change in ground-water quality, referred to as the "bad-water" line (Maclay and Small, 1984, p. 28). Updip of the "bad-water" line, total dissolved solids is less than 1,000 mg/L; downdip of the line, total dissolved solids increases rapidly from 1,000 to about 9,000 mg/L (Maclay and others, 1980, p. 13). Permeability also decreases markedly downdip of the line, partly because of the sedimentary history of the rocks and partly because the restricted circulation of freshwater has not developed an integrated network of cavernous zones in the limestone (Maclay and Small, 1984, p. 28). The faults that obstruct the flow of ground water in the Edwards aquifer have prevented flushing of saline water from the parts of the aquifer downdip of the faults, causing a marked change in water quality that coincides with the location of certain faults.

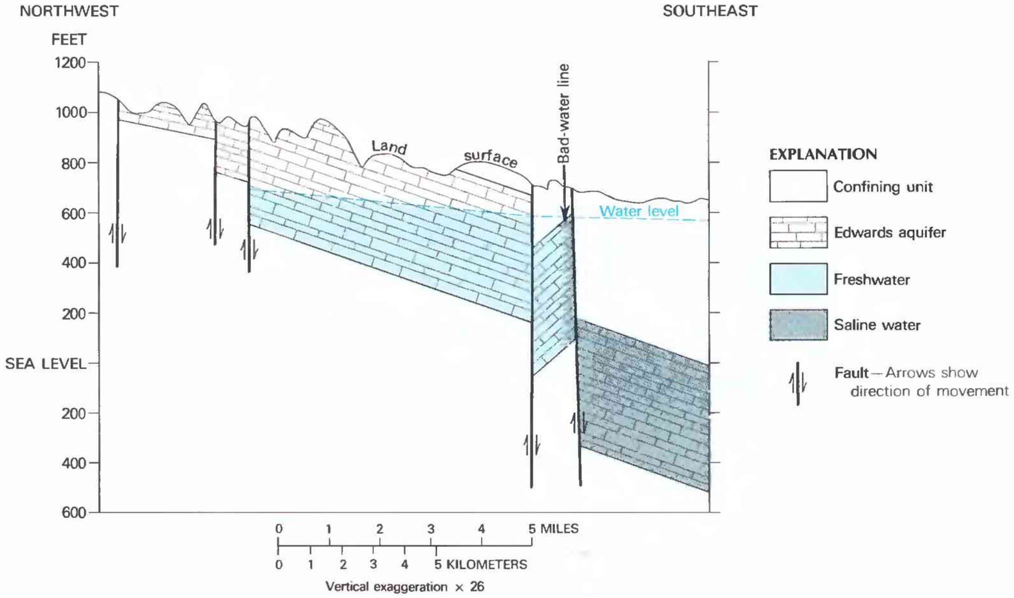


Figure 34. Effects of geologic structure on ground-water quality in the Edwards aquifer, Hays County, Texas. (Source: Modified from Small, 1986, fig. 3.)

EFFECTS OF HUMAN ACTIVITIES ON GROUND-WATER SYSTEMS

GROUND-WATER PUMPAGE

Large withdrawals of ground water have profoundly altered the flow systems and geochemical conditions of some of the major aquifers in the United States. The decline of ground-water levels due to pumping from wells has caused changes in the location and size of some recharge areas, large reductions in natural discharge, and in some parts of the arid West, major losses in aquifer storage. The hydrologic response of aquifers to pumping from wells was explained concisely for the first time by Theis (1940) and is summarized briefly here. Theis noted that aquifer response is determined by the distance from the pumped wells to the localities of recharge and natural discharge and by the character of the cone of depression in the aquifer (an area of reduced hydraulic head surrounding a pumped well), which depends upon the values of transmissivity and storage coefficient. He further noted that "all water discharged by wells is balanced by a loss of water somewhere." Initially, some water always is withdrawn from storage in the aquifer. As pumping rates and the number of wells increase, cones of depression tend to coalesce and form broad areas of lowered water levels. If there are nearby recharge or discharge areas, water will be diverted from these areas instead of withdrawing additional water from storage. The lowered water levels create hydraulic gradients that tend to induce more recharge into the aquifer, often by an expansion in the size of the recharge area, and to decrease the rate of aquifer discharge. Reduced streamflow or lowered lake levels may be the result. Thus, for an extensively developed aquifer, the location of the recharge and discharge areas may be different from those that existed before development.

The location of recharge areas can be very important in the protection of aquifers from water-quality degradation. Consequently, it should never be assumed that recharge and discharge areas are the same under all hydrologic conditions because those areas move dynamically in response to pumping and other hydrological changes in the aquifer system. The ground-water divides that separate ground-water basins also move in response to recharge or pumping patterns. The natural ground-water divides may correspond to a topographic or river-basin divide, but after the aquifer is developed the new divides may not.

To illustrate these changes, the following discussion examines two of the most extensively developed ground-water systems in the United States—the Central Valley aquifer system in California and the Floridan aquifer system. The response of these two aquifer systems to development is illustrated in figure 35.

Central Valley Aquifer System

The most intensive and longest term development of ground water in the United States has occurred in the Central Valley of California, primarily in the San Joaquin Valley. Pumpage from wells, mostly for irrigation, averaged about 10 bgd (billion gallons per day) between 1961 and 1977 (fig. 35*A*). This amount is more than five times the estimated predevelopment recharge rate of 1.8 bgd (Williamson and others, 1987, fig. 24).

The Central Valley's aquifer system is composed of alluvial deposits of sand, gravel, silt, and clay with minor amounts of volcanic deposits. Before development began, most recharge was supplied by infiltration of streamflow at the heads of alluvial fans at the edges of the foothills that surround the Valley. Then ground water moved towards the center of the valley and discharged as evapotranspiration and seepage to streams (fig. 36*A*). Pumpage increased steadily throughout the 1940's, 1950's, and 1960's, primarily in the San Joaquin Valley. This caused ground-water levels to decline hundreds of feet and changed the pattern of ground-water circulation over a large area. An example of the changes in ground-water flow after development in the western part of the San Joaquin Valley is shown in figure 36*B*.

The estimated present-day recharge is more than five times the predevelopment recharge (fig. 35*A*), and it is provided mainly by infiltration from irrigated lands that are largely supplied by imported surface waters and pumpage (Williamson and others, 1987). However, the amount of present-day recharge is less than the amount of water discharged from the aquifer system, which is primarily by pumpage. Thus, valley-wide some water continues to be removed from storage resulting in continued lowering of water levels even though some parts of the aquifer system are experiencing water-level rises owing to localized decreases in pumpage and to increased application of imported surface water for irrigation.

The large decline in water levels in the Central Valley, particularly in the San Joaquin Valley, has caused permanent compaction of subsurface clays, which has resulted in a loss of ground-water storage and a lowering of the land surface (Ireland and others, 1984). Although the vertical permeability of the clays has probably been decreased by compaction, the vertical hydraulic connection across the aquifer system has actually increased owing to the construction of about 100,000 wells with long sections of screen or perforated casing (Williamson and others, 1987). These multiscreen wells also provide the potential for mixing of waters from different sand and gravel layers because the wells enable ground water to flow between the sand and gravel layers that are separated by layers of less permeable silt and clay.

This example illustrates several ways in which human activities can affect the ground water of a region. Recharge and discharge areas can be changed by ground-water development. As a result of extensive ground-water development, the former discharge area of the shallow aquifer in the San Joaquin Valley now is largely a recharge area. Most post-development recharge is supplied by irrigation return flow rather than infiltration of streamflow in upland areas; most ground-water discharge is pumpage (Williamson and others, 1987). These changes in the ground-water-flow system may redirect poor-quality water in some areas towards pumping centers. This includes the movement of saline water

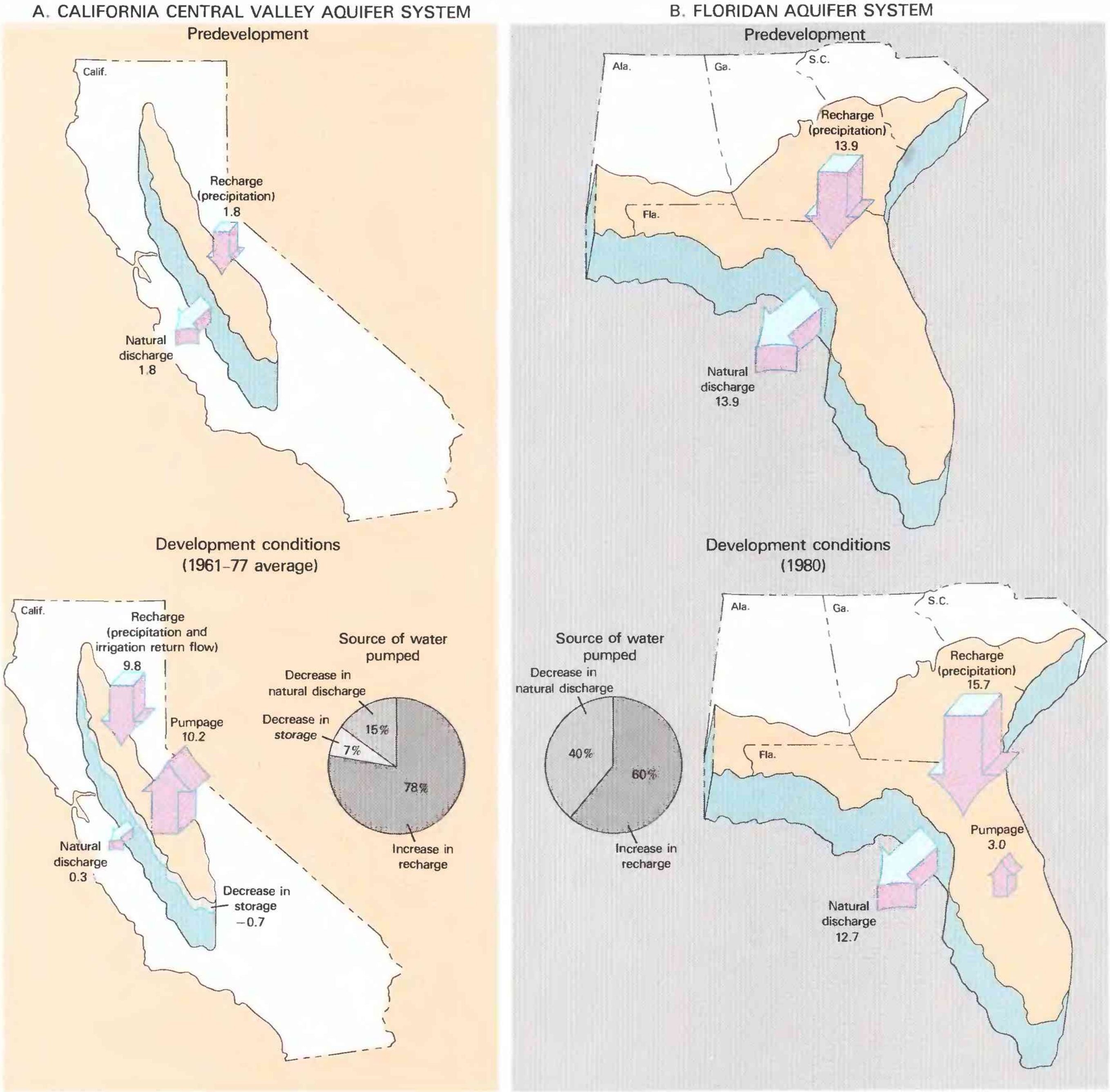


Figure 35. Comparison of aquifer response before and after development in the arid West (*A*, California Central Valley aquifer system) and the humid East (*B*, Floridan aquifer system). Values are in billion gallons per day. (Sources: Modified from *A*, Williamson and others, 1987; *B*, Bush and Johnston, 1987.)

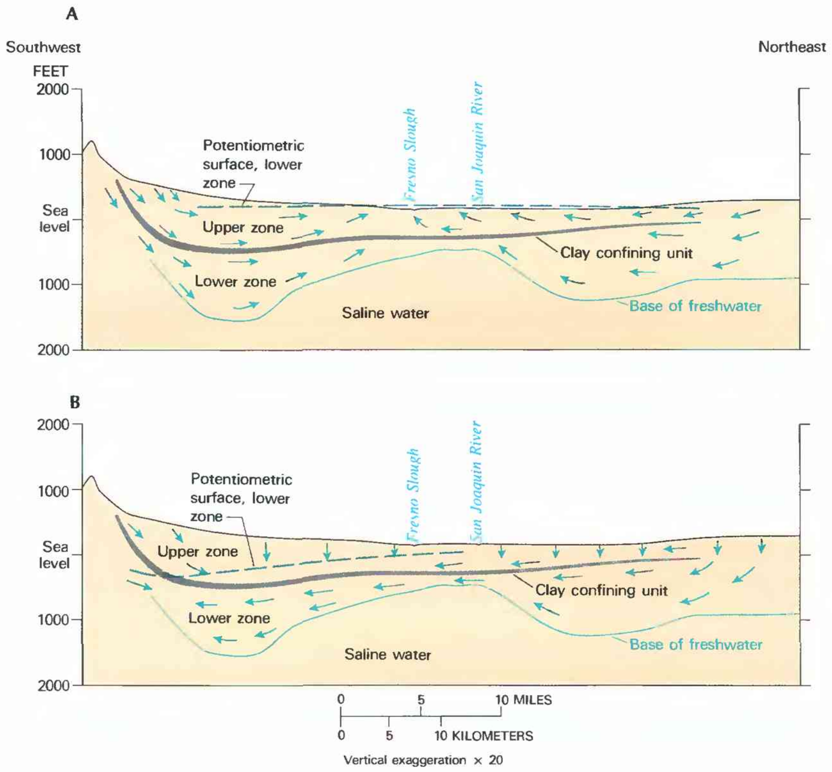


Figure 36. Comparison of ground-water-flow conditions before and after development in the San Joaquin Valley, California. *A*, Before development, about 1900; *B*, after development, 1966. Note change in potentiometric surface of lower zone. Arrows show general direction of ground-water flow. (Source: Modified from Bull and Miller, 1975, fig. 20.)

found beneath the freshwater in the Central Valley (fig. 36) and poor-quality water found above, or within, the fresh ground water. For example, shallow water along the west side of the San Joaquin Valley, which has dissolved solids ranging from 1,000 to 5,000 mg/L, has a potential to move towards pumping centers because of changes in the ground-water flow system. In addition, water quality in the shallow aquifer is being changed by irrigation return flow. Fertilizers and pesticides have been leached by irrigation water and are present in small amounts in the shallow aquifer in the Central Valley. A widely used nematodicide has been found in ground water in every county in the San Joaquin Valley (Bertoldi and Sun, 1986, p. 11). In parts of the San Joaquin Valley, selenium, which is believed to be essential to human and animal nutrition in minute amounts but which can be toxic at relatively low concentrations, is being leached from seleniferous soil by applied irrigation waters, and eventually this might cause an increase in selenium concentration in the shallow ground water in the western side of the San Joaquin Valley. The downward hydraulic gradient due to pumping and the increased hydraulic connection among individual aquifer layers (provided by multilayer-screened wells) creates an opportunity for poor-quality water to move from shallow aquifers into deep aquifers. Because of the increase in the recharge area in the Central Valley, accidental spills of toxic chemicals or applied fertilizers and pesticides have a greater potential to contaminate ground water.

Floridan Aquifer System

The Floridan aquifer system, which underlies all of Florida, the southern part of Georgia, and small parts of adjoining Alabama and South Carolina, is the most extensively pumped ground-water system east of the Mississippi River. About 3 bgd is withdrawn from the Floridan. It is the principal source of public, industrial, and agricultural water supply in the southeastern United States, except in south Florida where it contains saline water (Bush and Johnston, 1987). High average rainfall (about 53 inches per year), with little surface runoff, provides abundant recharge to the Floridan. The Floridan contains thick beds of highly permeable limestone, and transmissivity generally is very high. Individual wells yielding several thousand gallons per minute are common.

Development has not greatly altered the flow system of the Floridan. Overall, pumpage from wells is balanced by increased recharge and decreased discharge from the aquifer system (fig. 35*B*) and the change in storage has been negligible. The dominant feature of the Floridan's flow system, both before and after development, is discharge from springs. Currently, pumpage is less than 20 percent of the recharge rate; however, the pumpage is distributed unevenly throughout the Floridan aquifer system (Bush and Johnston, 1987). Large withdrawals have caused long-term water-level declines in three broad areas: the western panhandle of Florida; west-central Florida, southeast of Tampa; and a coastal strip extending from Hilton Head, S.C., to Jacksonville, Fla., and 50 to 80 miles inland. All three areas are located where the Floridan is confined by thick clay beds and are distant from the outcrop (recharge) areas. About 500 Mgal/d is pumped from the Floridan in the Hilton Head–Jacksonville coastal area (Krause and Randolph, 1987). Figure 37 shows a generalized hydrogeologic section that extends from the outcrop area of central Georgia southeast to the coast and passes through

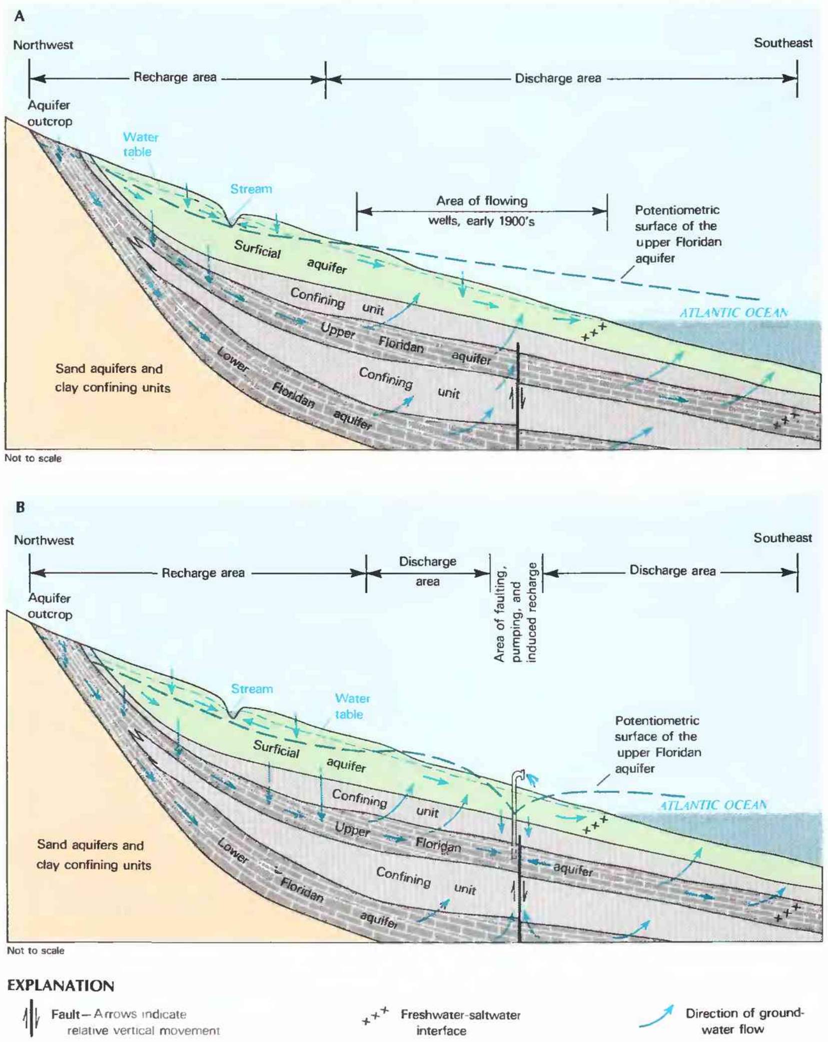


Figure 37. Comparison of ground-water-flow conditions before and after development in the Floridan aquifer system, southeastern Georgia. *A*, Before development, pre-1900; *B*, after development, early 1980's. (Source: *A, B,* Krause and Randoph, 1987, fig. 14)

Brunswick, Ga., which is a center of heavy pumpage. Before development, the flow system was comparatively simple with recharge occurring directly in the outcrop areas, or by downward leakage further downgradient, and discharge occurring as upward leakage near the coast (fig. 37*A*).

Postdevelopment changes to the flow system include formation of a shallow cone of depression at Brunswick owing to pumping of 80 to 100 Mgal/d in recent years. The water level in the upper Floridan is now below sea level at the center of the cone, and the vertical hydraulic gradient is downward, making the area of the cone a potential recharge area (Krause and Randolph, 1987). However, recharge by vertical leakage is impeded by several hundred feet of clay overlying the Floridan. The thick clay beds, combined with the great distance to the outcrop recharge area, provide natural protection against the infiltration of contaminants introduced at the land surface. In addition, freshwater is present in the Floridan for many miles offshore, providing a buffer against lateral intrusion of seawater (fig. 37*B*). However, ground-water quality has been degraded by upward migration of saline water into the upper Floridan aquifer (Wait and Gregg, 1973). The mechanism by which the saline water invaded the upper Floridan is upward movement from the lower Floridan (which contains salty water at higher head) along conduits that are probably nearly vertical faults (Krause and Randolph, 1987).

In general, degradation of water quality in the Floridan has been caused mainly by human activities other than pumping from wells and subsequent changes to the flow system. Although the potential for saline-water intrusion has been created by water-level declines in some coastal areas, intrusion of saline water into wells actually has occurred only at Brunswick, Ga., and a few localities on Florida's east coast. On the other hand, contaminants from surface or near-surface sources have infiltrated into the upper Floridan throughout the area where the aquifer is very close to land surface. As discussed in the Florida State summary of ground-water quality later in this volume, more than 1,000 wells in the aquifer have been found to contain ethylene dibromide (EDB)—a nematodicide—in concentrations exceeding drinking-water standards. These wells are located in agricultural areas and represent one-third of Florida's counties. Some contamination of public supply wells due to leaking gasoline storage tanks also has occurred in outcrop areas of the upper Floridan aquifer.

CONTAMINANTS IN GROUND WATER

Ground-water contamination refers to any degradation of ground-water quality resulting from human activities. To provide guidance for water use, the U.S. Environmental Protection Agency (1986a,b) established water-quality criteria (*see* National Drinking-Water Regulations, *in* Supplementary Information section of this volume) that include—

Recommended concentration limits for certain, not particularly harmful constituents, such as chloride, iron, and dissolved solids.

Maximum permissible concentrations for highly toxic substances, such as some pesticides, certain metals, and radionuclides.

The most serious problems of ground-water contamination generally have resulted from the introduction into the ground water of organic chemicals (especially pesticide residues or byproducts, oils, phenols, and solvents) and metals (especially chromium, lead, and mercury) from a variety of human activities. Fortunately, serious ground-water contamination has occurred in only a small part of the Nation's ground-water supply. However, such contamination often is in areas of heaviest ground-water use. Cleaning up an extensively contaminated aquifer is expensive and time consuming; the best cleanup strategy may be difficult to determine because of the complexities of the hydrogeologic framework and ground-water flow system. Clearly, the high costs and uncertain results of aquifer cleanup make the prevention of ground-water contamination whenever possible a very desirable national goal (Conservation Foundation, 1987, p. 13).

Sources of Contaminants

Contaminants may enter freshwater aquifers from at least 33 generic sources (Office of Technology Assessment, 1984, p. 43). These sources may be classified broadly as either point or nonpoint sources. Point sources are derived from localized areas (a few acres or less in size) and include—

Landfills (industrial and municipal)
Surface impoundments (lagoons, pits, and ponds)
Underground storage tanks (petroleum, toxic chemicals, and wastes)
Spills of chemicals, oil, or brine during transport or transfer operations
Injection wells (hazardous waste and brine disposal) or abandoned oil wells

The first four point sources are considered to be major contamination problems by the EPA (U.S. Environmental Protection Agency, 1984, p. 13) on the basis of information supplied by State agencies. However, EPA stated (p. 16) that "information on the current extent of contamination is far from adequate to quantify the severity of the problem."

Nonpoint sources actually consist of activities or processes that introduce contaminants over a broad area, rather than in a specific area. Nonpoint sources can range in size from several acres to hundreds of square miles and can consist of multiple point sources, such as septic tank drainfields. Significant nonpoint sources include—

Agricultural pesticides and fertilizers
Septic tank drainfields and cesspools
Encroachment of saline water
Road salt applications
Animal feed lots
Mining operations

The above nonpoint sources also were indicated as being intermediate significant contamination problems (U.S. Environmental Protection Agency, 1984, p. 13).

Contaminants can enter aquifers by five basic mechanisms as illustrated in figures 38 and 39 and described below.

Downward percolation to the water table from a surface source.—Liquids from surface impoundments or spills infiltrate the ground and percolate downward to the water table. Infiltration of precipitation or runoff into landfills dissolves chemicals and metals and collects bacteria that results in a liquid called "leachate," which percolates downward to the water table. In a similar manner, precipitation dissolves pesticides and de-icing road salts from agricultural lands and highway rights-of-way and transports these nonpoint-source contaminants downward to the water table.

Downward percolation to the water table from sources in the shallow subsurface.—This mechanism operates in a manner similar to the one described above except that the source is located below the land surface. Sources include leaking petroleum and chemical storage tanks and buried wastes.

Leakage from a source below the water table.—The most common examples of this mechanism are brine leakage from abandoned oil wells and poorly constructed injection wells. In the latter situation, fluid wastes that are intended to be emplaced in a deep saline aquifer leak into a shallow freshwater aquifer due to defects, such as casing breaks or poor grouting, in an injection well.

Intrusion of naturally occurring saline water into freshwater aquifers as a result of pumping from wells.—Intrusion may occur by lateral movement of salty water towards wells or by "upconing" of saline water located beneath pumping wells. In either situation, the cause is a reduction of hydraulic heads due to withdrawals and creation of a hydraulic gradient from the saline-water source towards wells tapping a freshwater aquifer.

Movement of contaminants between aquifers by short-circuiting natural flow paths.—As illustrated in figure 39, a short-circuiting mechanism might occur in a well or along a natural geologic feature such as a fault. In either situation, the well or fault zone acts as a conduit for transmitting poor-quality water from one aquifer to another. Movement via wells might occur either outside the well casing in an unsealed annulus or inside the casing of a well open to more than one aquifer through screens or perforations. Examples of this type of contamination are given in the previous discussion of the Central Valley in California and in the article "Coal-Tar Derivatives in the Prairie du Chien-Jordan Aquifer, St. Louis Park, Minnesota." Short-circuiting along faults occurs because the fault zone is more permeable than the confining unit separating two aquifers. Pumping from a freshwater aquifer might induce poor-quality water to move from a contaminated or saline aquifer into the freshwater aquifer. An example of contamination by this mechanism is given in the previous discussion of the Floridan aquifer system (fig. 37*B*).

Movement of Contaminants Through Aquifers

After entering the aquifer, contaminants dissolved in ground water (solutes) will move in the direction of the prevailing hydraulic gradient. This process of contaminant transport by flowing ground water is termed "advection." Variations in permeability, as in a sequence of sand and silt layers, will cause the moving front of contaminants to be irregular—the higher permeability sands generally will contain contaminants farthest from the source because water containing the solutes moves faster in the sands than in the less permeable silts. Local variations in flow velocity on the scale of individual sand grains or rock particles cause dispersion of the solutes as described earlier and illustrated in figure 33*A*. The dispersion process causes dilution of solute concentrations in the direction of ground-water flow and, to a lesser extent, perpendicular to the flow direction. Dilution of solutes due to dispersion is controlled by the flow velocity, which, in turn, is a function of local variations in aquifer characteristics. Solutes also can be diluted by molecular diffusion and by some of the chemical processes previously discussed. Solutes in ground water that move slowly along deep flow paths have greater opportunity for diffusion and attachment to earth materials (sorption) than the solutes in shallow ground water that moves faster along short flow paths. On the other hand, contaminated water following deep flow paths has the potential to invade a much greater volume of aquifer.

Liquids that do not mix with water are termed "immiscible." Contaminants that are immiscible in water, such as petroleum, will be separated from the flowing ground water by a distinct boundary (or interface), and their movement is governed by pressures along the interface. Frequently, immiscible contaminants occur in discrete pockets within ground water. These pockets move in response to gravity and in response to pressures exerted on them through the surrounding water. Liquids that are less dense than water, such as gasoline, will tend to accumulate as a layer just above the water table. More dense liquids, including many organic liquids such as chloroform and bromoform, will tend to move downward through the ground water and accumulate as a layer just above a confining bed.

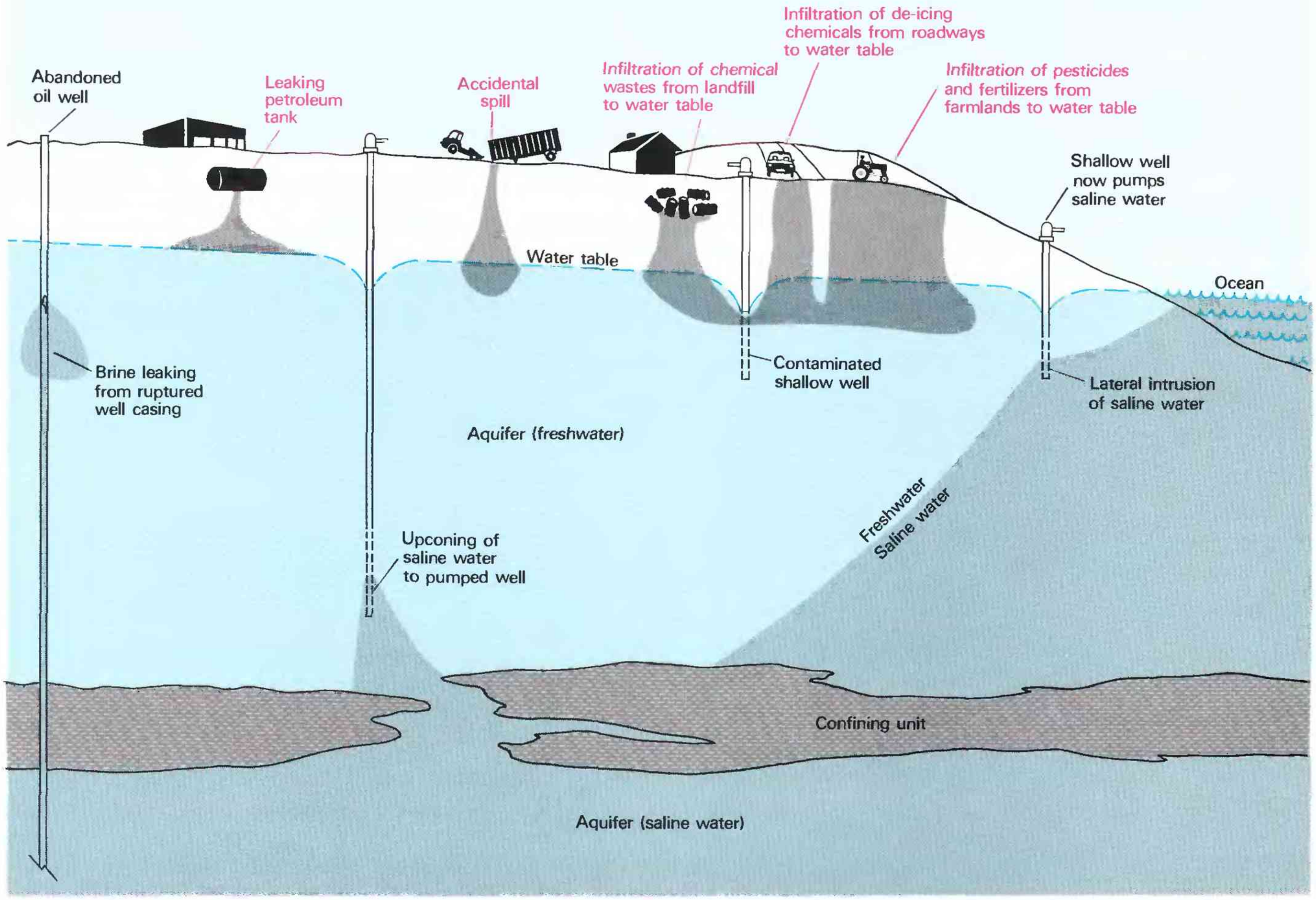


Figure 38. Mechanisms of ground-water contamination.

Chemical processes can reduce substantially the concentrations of contaminants in ground water. The attenuation of inorganic substances is primarily the result of adsorption, precipitation, oxidation, or reduction, whereas the attenuation of organic substances is primarily the result of adsorption (on particulate organic matter) and bacterial action (Cherry and others, 1984, p. 46, 55). Bacterial action breaks down many toxic organic substances into harmless species, such as carbon dioxide, water, nitrate, and sulfate in anaerobic environments. Toxic metals in contaminated ground water may be adsorbed by clay, iron oxide, or organic matter. A study of contamination caused by metal-plating wastes on Long Island, N.Y., showed that chromium and cadmium were adsorbed most effectively on hydrous iron-oxide coatings of aquifer sand grains (Ku, 1980).

Some contaminants are practically nondegradeable in ground water. Crude oil and its derivatives especially are persistent because they generally are not affected by the chemical processes in ground-water systems (Jackson, 1980, p. 198).

Contaminants ultimately leave aquifers either by natural discharge as spring flow or seepage to lakes, streams, or the sea or as a result of pumping from wells. Contaminants can circulate through shallow or local flow systems in a relatively short time; however, contaminants that move with the regional ground-water flow into the deeply confined parts of aquifers might persist in the subsurface for thousands of years. Therefore, contaminants from waste-storage facilities or leaking wells that infiltrate deep aquifers can persist for long periods of time.

VULNERABILITY OF AQUIFERS TO CONTAMINATION

The vulnerability of an aquifer to contamination from pollutant sources at or near the land surface is controlled by the flow system, the hydrogeologic framework, and the climate. Specific factors that affect the degree of contamination of ground water include:

- Length of and residence time in the flow path from the contaminating source to the aquifer. Short flow paths decrease the opportunity for adsorption, chemical reactions with soil minerals, and biodegradation and, thus, increase the potential for contamination. Conversely, longer flow paths from land surface to the water table lessen the potential for contamination.
- Mineral composition of the soil and rocks in the unsaturated zone between land surface and the water table. High clay content and presence of organic materials increase adsorption and thus lessen the potential for contamination.
- Potential for biodegradation (transformation of contaminants by reactions caused by microbes). This process depends upon the microbe species present.
- Precipitation. Low amounts of precipitation result in small amounts of recharge to aquifers and thus, lessen the potential for contamination from pollutants whose mobility is dependent on entrainment in or flushing by recharge water.
- Evapotranspiration. High evapotranspiration rates reduce recharge and thus, lessen the potential for contamination from pollutants whose mobility is dependent on entrainment or flushing by recharge water.

The vulnerability of aquifers to contaminants from landfills, surface impoundments, spills, and underground storage tanks is of special concern. Consequently, investigations of the suitability of sites for waste disposal or for evaluating the vulnerability of aquifers to contamination are concerned primarily with surface and near-surface sources. However, problems caused by short-circuiting mechanisms (those that bypass natural geologic barriers), although difficult to identify, should not be overlooked in assessing aquifer vulnerability. A multiaquifer well that is abandoned and covered over or an unmapped geologic fault can easily escape detection.

In general, shallow, permeable, unconfined aquifers with high recharge rates are most vulnerable to surface contamination because the short flow paths from the land surface to the water table decrease the potential for adsorption, chemical reactions between contaminants and minerals in the soil, and biodegradation. Deep, confined aquifers tend to be much less vulnerable to contamination from surface sources because they are protected by confining beds. However, in some regionally extensive aquifers, hydrologic conditions can be such that some parts of the aquifer are very vulnerable to contamination, whereas other parts are much less vulnerable. For example, the unconfined, limestone outcrop areas of the Floridan aquifer system with high recharge rates are highly susceptible to contamination from surface sources (fig. 31*B*), whereas toward the coast, the Floridan is confined by increasingly thick sections of clay and silt and is much less susceptible to surface-introduced contaminants.

The vulnerability of aquifers to contaminants introduced directly in the subsurface is more difficult to characterize. Contamination of aquifers resulting from multiaquifer wells (fig. 39) and abandoned, leaking oil wells (fig. 38) will occur despite natural geologic barriers to surface contamination. However, the volume of aquifer that is ultimately contaminated is dependent upon the aquifer properties and on the location from which the contamination is introduced into the flow system. Contaminants introduced in recharge areas or within the influence of pumped wells will migrate and spread more rapidly than contaminants introduced into deep, unpumped parts of an aquifer where ground-water flow is more sluggish. The principal features of hydrogeologic frameworks and ground-water flow systems that affect an aquifer's vulnerability to contamination are summarized in table 3.

Aquifers highly vulnerable to contamination from surface sources are especially common in many parts of the humid Eastern United States. These aquifers are glacial outwash aquifers, composed primarily of sand and gravel; outcrop areas of major sand and carbonate aquifers in the Atlantic and Gulf Coastal Plains; and outcrop areas of carbonate aquifers in the Appalachian Valleys and Interior Low Plateaus.

Several detailed examples of contamination in these types of highly vulnerable aquifers are given later in this volume. One example is a sand-and-gravel aquifer (glacial outwash) on Cape Cod, Mass., which is very susceptible to surface contamination because of its shallow occurrence, high permeability, and low adsorption characteristics. Sewage effluent has percolated downward into the aquifer producing a plume of sewage-contaminated ground water that is about 2 miles long at present. (See article "Sewage Plume in a Sand-and-Gravel Aquifer, Cape Cod, Massachusetts.") Another example of a contaminated sand-and-gravel aquifer is in Pensacola, Fla., where degradation of organic compounds from a wood-preserving facility has been caused by microbial activity and sorption on aquifer sediments. (See article "Distribution and Movement of Wood-Preserving Compounds in a Surficial Aquifer, Pensacola, Florida.") In New Jersey and on Long Island, N.Y., coastal-plain aquifers have been studied to determine if the chemical quality of shallow ground water is related to the type of land use. In New Jersey, the occurrence of chlorinated organic compounds in the outcrop area of a major sand aquifer system can be related directly to urban, industrial, and agricultural land use. (See article "Relation of Land Use to Ground-Water Quality in the Outcrop Area of the Potomac-Raritan-Magothy Aquifer System, New Jersey.") Similarly, on Long Island, changes in ground-water quality in a glacial outwash aquifer, specifically the high concentrations of nitrates and volatile organic compounds, can be related to agricultural and industrial land uses. (See article "Relation of Land Use to Ground-Water Quality in the Upper Glacial Aquifer, Long Island, New York.")

In many parts of the arid West, low rainfall, high topographic relief, low recharge rates, and the presence of a deep aquifer with a topographically low discharge area result in deep-lying water tables. Such conditions favor the protection of aquifers against contamination. An example of these conditions is found in south-central Nevada where there is an extensive carbonate aquifer. This permeable aquifer occurs beneath most of the intermontane valleys where it is overlain by thick layers of alluvium and volcanic tuff. In some highland areas, the carbonate aquifer crops out, but in general, it is overlain by a unit of tuff of very low permeability (Winograd and Thordarson, 1975, p. C45). The tuff may contain perched water (zones temporarily filled with water above the water table); however, the carbonate aquifer generally has a very thick unsaturated zone. (See figure 40.) On the basis of geologic, hydraulic, hydrochemical, and isotopic data, Winograd and Thordarson (1975, p. C119) concluded that the carbonate aquifer provides hydraulic connection between at least 10 intermontane basins. In effect, the aquifer acts as a huge tile drain with a topographically low outlet, which is a group of springs located near the California-Nevada State line.

The average annual precipitation in south-central Nevada is low, ranging from about 4 inches in the valleys to almost 16 inches in the highlands, and the potential evapotranspiration rates greatly exceed the annual precipitation. Thus, recharge rates are very low. Downward movement of recharge through the tuff unit is very slow—perhaps requiring several tens of thousands of years to reach the carbonate aquifer (Winograd and Thordarson, 1975, p. C114). The combination of a very deep-lying water table and thick confining beds above the aquifer in most areas provides great natural protection against surface contaminants reaching the carbonate aquifer.

Table 3. Principal geologic and hydrologic features that influence an aquifer's vulnerability to contamination

Feature determining aquifer vulnerability to contamination	Low vulnerability	High vulnerability
	A. HYDROGEOLOGIC FRAMEWORK	
Unsaturated zone.	Thick unsaturated zone containing clay and organic materials.	Thin unsaturated zone in sand, gravel, limestone, and basalt.
Confining unit.	Thick confining unit of clay or shale above aquifer.	No confining unit.
Aquifer properties.	Silty sandstone or shaly limestone of low permeability.	Cavernous limestone, sand and gravel, gravel, or basalt of high permeability.
	B. GROUND-WATER-FLOW SYSTEM	
Recharge rate.	Negligible recharge rate, as in arid regions.	Large recharge rate, as in humid regions.
Location within a flow system (proximity to recharge or discharge area or point).	Located in the deep, sluggish part of a regional flow system.	Located within a recharge area or within the cone of depression of a pumped well.

SITE EVALUATION FOR POTENTIAL GROUND-WATER CONTAMINATION

Site evaluation for potential ground-water contamination is an approach that estimates the possibilities for ground-water contamination at a site for given contaminants. Application of site evaluation is desirable to assist in locating sites (for example, waste-disposal sites) that might prevent or minimize the effects of contaminants on ground-water systems. Site evaluation is best conducted with detailed, accurate, local hydrologic information; however, obtaining that information for large areal evaluation is expensive. A number of screening reconnaissance methods have been proposed for evaluating the contamination potential of aquifers using information on the geology, hydraulic properties, and ground-water flow. These methods generally use a relative numerical rating system for evaluating the local hydrogeologic conditions. One of the earliest methods proposed is "based on weighted values for five factors whose relative significance can be evaluated from measurements or estimates made at the sites" (LeGrand, 1964, p. 962). The five factors are—

Depth to the water table
Sorption capacity of shallow deposits
Permeability of shallow deposits
Water-table gradient
Distance to point of use

Low point values are assigned where the factor at a site will provide little or no protection to an aquifer; high values are assigned where the factor provides high protection. For example, a shallow depth to the water table (less than 10 feet) receives zero points, whereas an extremely deep lying water table (1,000 feet) receives 10 points. Total point counts (sum

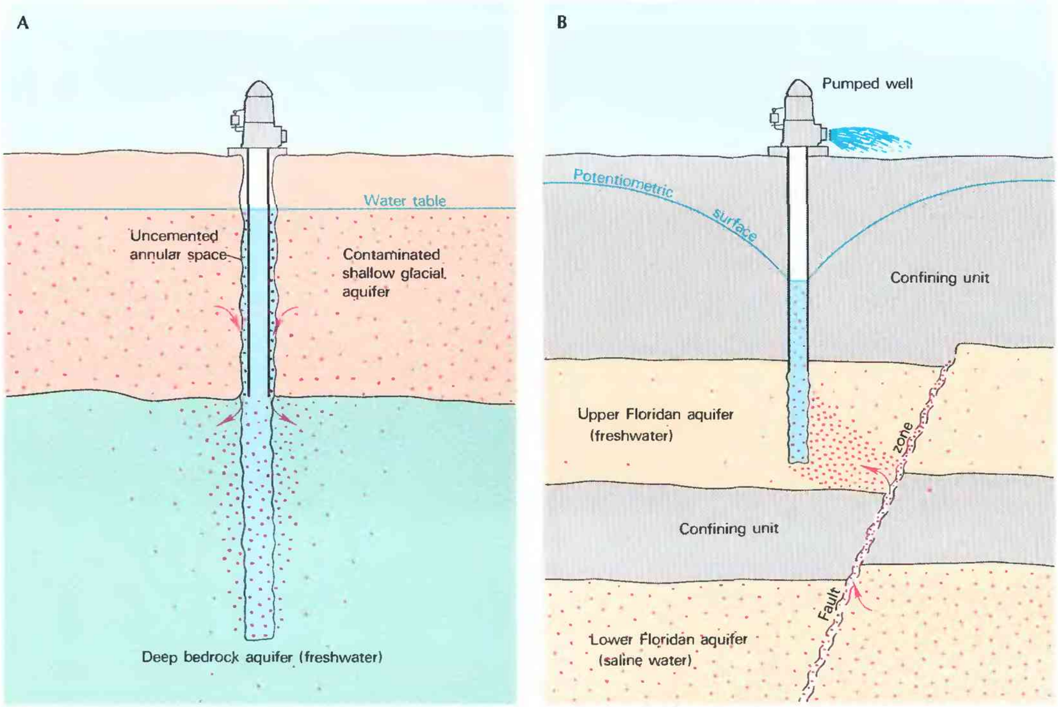


Figure 39. Movement of contaminants between deep and shallow aquifers by short-circuiting natural flow paths. *A*, Downward movement of contaminated water from shallow glacial aquifer into deeper bedrock aquifer via well annulus, St. Louis Park, Minn; *B*, upward movement of saline water from lower Floridan aquifer into freshwater upper Floridan aquifer via fault, Brunswick, Ga.

of the 5 factors) are interpreted as follows: 0–4, contamination imminent; 4–8, contamination probable; and so forth with counts about 25 indicating that contamination is very unlikely.

More recently, a system for evaluating the vulnerability of aquifers to contamination was prepared by Aller and others (1985). This method is called the DRASTIC index and it is intended to evaluate the "pollution potential" for any hydrogeologic setting in the United States. The DRASTIC method consists of two parts:

1. The hydrogeologic setting of a site is identified on the basis of a classification of the major ground-water regions of the United States by Heath (1984).
2. The DRASTIC index for a site is evaluated by assigning point values to mappable physical characteristics that form the acronym DRASTIC as follows:

Depth of water
Recharge (net)
Aquifer media
Soil media
Topography (slope)
Impact on the vadose zone
Conductivity (hydraulic) of the aquifer

Each of these characteristics is assigned a point value; a higher point value indicates greater vulnerability and a lower value indicates less vulnerability to contamination. Weighting factors also are used to give greater or lesser importance to each characteristic (Aller and others, 1985, p. 31–126). The typical values given for materials or conditions may be accepted as is, or changed, if more accurate local information is available. A summary rating for a site is simply the sum of the point values for the seven characteristics. Applying the DRASTIC method to aquifers in the Southeastern U.S. Coastal Plain, for example, shows that the limestone outcrop areas of the Floridan aquifer system (fig. 31*B*, area 3) would be assigned a DRASTIC index of 218, indicating a very high vulnerability to contamination, whereas the deep confined sand aquifers (fig. 31*B*, area 2) would be assigned an index of 53, indicating very low vulnerability.

When applying numerical rating methods, such as the LeGrand or DRASTIC method, that rely upon estimating geologic and hydrologic characteristics, several factors should be kept in mind:

- Numerical rating methods are useful primarily for evaluating potential contamination from surface or near-surface sources such as landfills and shallow underground storage tanks.
- Ground-water development can change the hydrologic characteristics such as depth to the water table, directions of ground-water flow, recharge rates, and locations of recharge areas. Thus, hydrologic information based on current ground-water withdrawals must be used.
- Numerical rating methods applied over regional areas might not account sufficiently for local variation in hydraulic properties and geohydrologic conditions, or might not take into account all factors affecting the potential for contamination, therefore possibly underestimating the potential for contamination.
- Numerical rating methods are not strictly applicable for evaluating contamination from sources in the deep subsurface, especially where natural geologic barriers have been short circuited (fig. 39).

Although numerical rating methods are useful for preliminary screening of potential waste-disposal sites, or to estimate the potential contamination over large areas, the final selection of a major waste-disposal site or evaluation of an existing one requires field hydrogeologic data collection and an analysis of the ground-water flow system. Once data are in hand, analysis of ground-water flow systems is best accomplished by computer modeling that simulates predevelopment conditions, present-day ground-water pumping, and future projected development. In recent years, a variety of computer models have been developed for simulating the transport of contaminants by ground water (Pinder, 1984).

SUMMARY

The most important factors concerning ground-water quality can be summarized as follows:

- The natural chemical quality of ground water in any area is controlled by the geology and the related ground-water flow system. Consequently, the natural chemical quality of ground water is determined largely by the types of rock through which the water moves from recharge to discharge points.
- The water chemistry observed in aquifers can be attributed to one or more of these natural processes: (1) dissolution and precipitation, such as the dissolution of calcite ($CaCO_3$) in a limestone aquifer; (2) oxidation-reduction reactions such as the reduction of sulfate (SO_4^{-2}) to sulfide (S^{-2}) when organic matter is oxidized to carbon dioxide (CO_2) by bacterial action; (3) ion exchange, for example, the exchange of calcium ions in ground water for adsorbed sodium ions in the aquifer material; (4) mixing of ground waters of different compositions such as the mixing of fresh and saline water in coastal areas or deep parts of aquifers.
- Changes in water quality may be caused by ground-water development. Pumping from wells always causes a decline in ground-water levels. This decline, in turn, influences the speed at which ground water flows and the direction of the flow. These changes from natural conditions may result in degradation of water quality in coastal areas by causing salty water to merge with freshwater and in other areas by causing poor-quality water from saline or contaminated aquifers to flow into freshwater aquifers.
- Recharge areas of aquifers are extremely important because contaminants from sources at or just below the land surface (such as dumps and leaking storage tanks) can move directly into the aquifer in these areas. Thus, knowledge of the location and extent of recharge areas is vital in the protection of ground water. However, the location and size of recharge areas may not be static. Under natural conditions, many ground-water flow systems simply consist of recharge in highland areas and discharge to lowland stream valleys and coastal areas. Natural discharge areas can be converted into "new" recharge areas as a result of large withdrawals from wells that alter hydraulic gradients and flow directions. Thus, it should never be assumed that the predevelopment and present-day recharge areas have the same boundaries or even occupy the same areas.
- Most contaminants dissolved in water (solutes) move with the ground-water flow. Therefore, the ground-water flow system must be defined in order to determine the path of the solutes.
- The vulnerability of aquifers to contamination from land surface or near-surface sources (such as leaking landfills and leaking buried storage tanks) is dependent primarily upon the depth to the water table, the mineral composition of the soil and rocks in the unsaturated zone, the recharge rate, and the potential for biodegradation. Shallow, highly permeable aquifers, such as sand and gravel and limestone, are highly vulnerable to contamination from sources at the land surface or shallow subsurface. Deep confined aquifers generally are much less vulnerable because they are protected by confining beds. However, confined aquifers can be contaminated by sources that originate in the deep subsurface, such as leaking oil wells, or by contaminants bypassing natural geologic barriers along permeable fault zones or through multiaquifer wells.

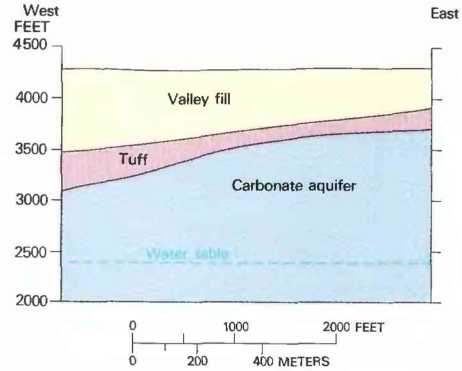


Figure 40. Carbonate aquifer with very deep water table, south-central Nevada. (Source: Modified from Winograd, 1981, fig. 3.)

- Reconnaissance methods can provide rapid evaluation of the potential for ground-water contamination from surface and near-surface sources if information on the local geology and ground-water flow is available at a site. However, it is difficult to assess the potential for contamination of deep, confined aquifers where the contaminants bypass natural geologic barriers.
- Ground water is easily contaminated and is very difficult to clean up. The selection of the best clean-up method can be assisted by computer-based models that predict the movement of contaminants in ground water. Unfortunately, the lack of needed hydrologic, geologic, and chemical data at many sites severely limits the ability of scientists to use predictive models.

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POINT-SOURCE GROUND-WATER CONTAMINATION

SEWAGE PLUME IN A SAND-AND-GRAVEL AQUIFER, CAPE COD, MASSACHUSETTS

By Kathryn M. Hess

Fifty years of disposal at one site of treated sewage onto the sandy soils of Cape Cod, Mass., has created a plume of contaminated ground water more than 2 miles long. Concentrations of the contaminants are high enough to render much of the affected ground water nonpotable (fig. 41). The sewage plume was first identified and defined during an investigation by the U.S. Geological Survey in cooperation with the Massachusetts Department of Environmental Quality Engineering, Division of Water Pollution Control (LeBlanc, 1984a). Contaminant distributions within the plume reflect the variable history of the source of contamination and the physical, chemical, and microbiological processes controlling the transport and fate of the contaminants within the aquifer. The plume is an example of the extensive contamination that can occur in shallow, unconfined, highly permeable aquifers such as the sand-and-gravel aquifer underlying Cape Cod. It also is an example of point-source contamination from surface impoundments, one of five point sources as explained in this volume in the article "Factors Affecting Ground-Water Quality."

SOURCE AND EXTENT OF SEWAGE CONTAMINATION

The sewage plume is in a shallow, unconfined aquifer located in Falmouth, Mass., 70 miles southeast of Boston (fig. 42). This aquifer, which is a Pleistocene glacial-outwash-plain deposit (Oldale, 1976, p. 4), is composed of 90 to 140 feet of stratified sand-and-gravel deposits and is underlain by less-permeable deposits of silty sand and sandy till (fig. 43). The capacity of the aquifer sediments to adsorb contaminants is low, partly because the sediments contain less than 1 percent clay-size particles. Average horizontal hydraulic conductivity of the aquifer is 190 to 380 ft/d (feet per day) and the porosity is about 35 percent. Annual recharge to the unconfined aquifer from precipitation averages 21 inches. Movement of the ground water is southward (fig. 42*A*) toward Nantucket Sound at an average velocity of 0.9 to 1.5 ft/d, as determined from measurements of hydraulic conductivity, porosity, and hydraulic gradient (LeBlanc, 1984b, p. B22; Garabedian and others, 1987, p. B14).

The source of contamination is a rapid-infiltration sewage-treatment plant at Otis Air Base. Effluent discharged from the plant is typical domestic sewage containing organic and inorganic contaminants (Thurman and others, 1984). After secondary treatment, sewage from the plant discharges onto sand beds, rapidly percolates 20 feet to the water table, and is transported away from the disposal site by flow within the aquifer. In 1986, the treatment plant discharged about 300,000 gallons per day onto the disposal beds. Since the plant began operation in 1936, more than 2.5 billion gallons of treated sewage has been discharged onto the beds.

Rapid infiltration—a common method of sewage disposal—can affect ground-water quality downgradient from any disposal site. The extent of water-quality degradation depends on the type and quantity of contaminants coming into the treatment plant, the effectiveness of the plant in removing contaminants, the properties of the ambient ground water, and the physical and chemical properties of the aquifer that control the transport, dispersion, and attenuation of contaminants. The sewage plume downgradient from the Otis Air Base rapid-infiltration beds is an example of the interaction of these factors.

The plume of contaminated ground water is defined by the distribution of inorganic and organic species such as boron, chloride, nitrate, ammonia, volatile organic compounds, and detergents (figs. 42,43). Concentrations of three of these chemical indicators of contamination—chloride, boron, and total nitrogen—in the sewage effluent, the contaminated ground water within the sewage plume, and the uncontaminated ground water are given in the table below (LeBlanc, 1984a, table 2).

Figure 41. Foaming caused by detergents in ground water from a well located 10,000 feet downgradient from Otis Air Base sewage-treatment plant, Cape Cod, Massachusetts 1983. (Photograph by D.R. LeBlanc.)

Source of water sample	*Constituent, as of 1979*		
	Chloride (*mg/L*)	*Boron* (*μg/L*)	*Total nitrogen* (mg/L)
Treated sewage, Otis Air Base sewage-treatment plant	33	510	19
Contaminated ground water 3,000 feet from disposal beds.	28	280	16
Uncontaminated ground water in area.	8	7	.4

Boron, a component of detergents and other household cleansers, is a useful indicator of sewage contamination because of the large contrast in boron concentrations of contaminated and uncontaminated water. In domestic sewage, boron commonly is found at concentrations greater than 500 μg/L (micrograms per liter) (see table). In contrast, ground water on Cape Cod that is unaffected by sewage contamination has a boron concentration that generally is less than 10 μg/L. In addition, boron is transported readily through sand and gravel without significant retardation by chemical reactions or sorption and is considered a possible indicator of the movement of conservative contaminants in ground water at the site. The areal extent of boron contamination downgradient from the sewage-treatment plant is shown in figure 42*B*.

In 1982 the Cape Cod aquifer was declared a sole-source aquifer for public water supply (U.S. Environmental Protection Agency, 1982); about

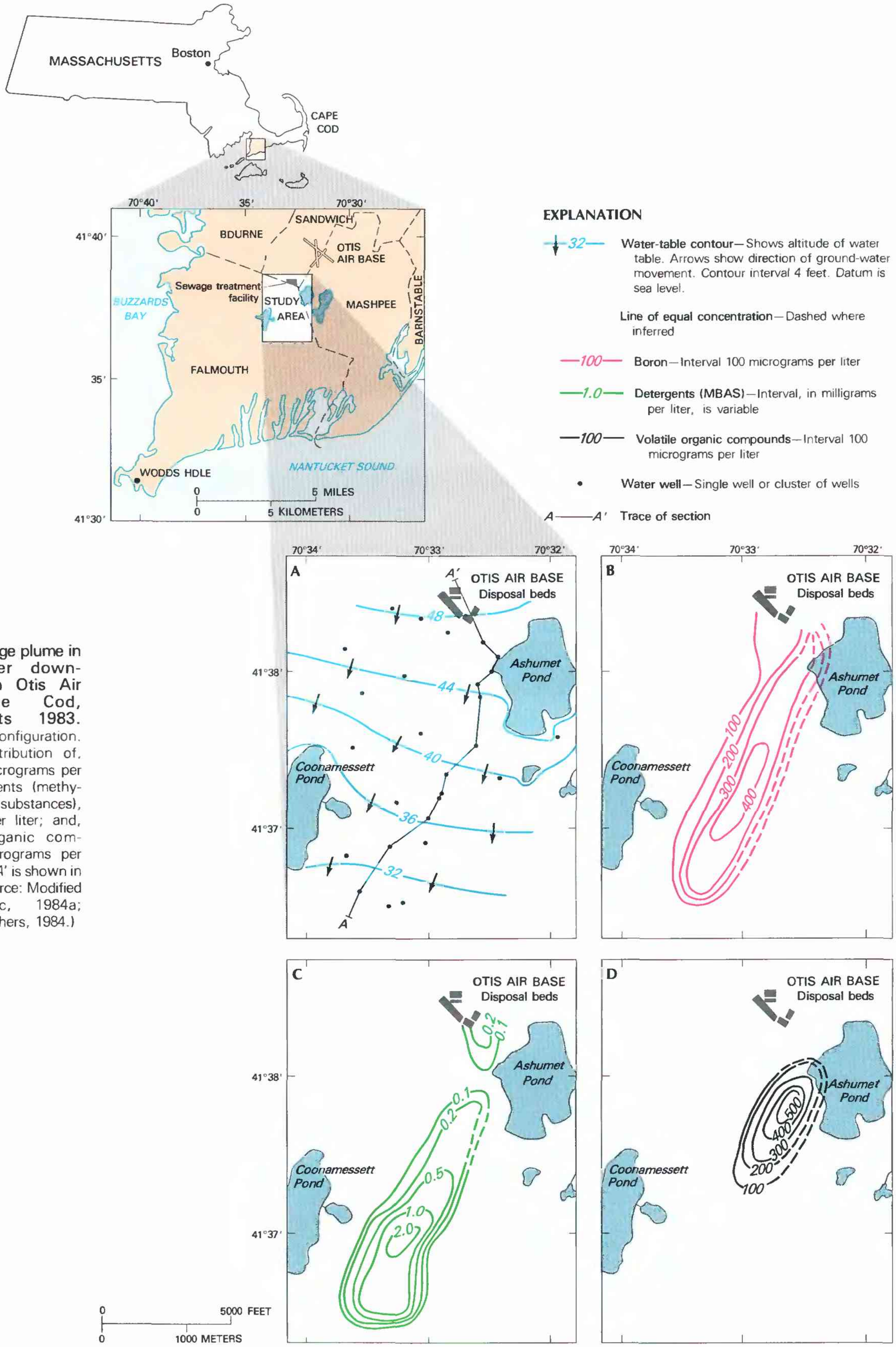

Figure 42. Sewage plume in ground water downgradient from Otis Air Base, Cape Cod, Massachusetts 1983. *A*, Water-table configuration. *B–D*, Areal distribution of, *B*, boron, in micrograms per liter; *C*, detergents (methylene-blue-active substances), in milligrams per liter; and, *D*, volatile organic compounds, in micrograms per liter. Section *A–A′* is shown in figure 43. (Source: Modified from LeBlanc, 1984a; Thurman and others, 1984.)

2.6 billion cubic feet of this aquifer is affected by the disposed sewage. The plume of contaminated ground water defined by boron extends more than 11,500 feet south of the treatment plant and is 2,500 to 3,500 feet wide (fig. 42*B*). However, the plume is only 75 feet thick and is overlain by as much as 40 feet of uncontaminated ground water (fig. 43*A*). The source of the uncontaminated water above the plume is areal recharge from precipitation. Although the plume seems to be traveling only in the sand-and-gravel aquifer, recent evidence indicates that some of the contaminants may be entering the underlying, less permeable sediments.

MOVEMENT OF CONTAMINANTS

The physical processes that transport, disperse, and dilute the contaminants in the plume are being investigated by studying the distribution of nondegradable constituents in the sewage. Elongation of the plume in the direction of ground-water flow (fig. 42*B*) is the result of advection, the transport of dissolved contaminants by flowing ground water. The high rate of ground-water flow (0.9 to 1.5 ft/d) has caused contaminants to migrate more than 2 miles downgradient from the disposal site. The mixing of contaminated and uncontaminated waters causes the plume to spread and the contaminant concentrations to decrease as the contaminants are transported downgradient. Limited dilution of contaminants in the core of the plume indicates that dispersion—that is, spreading and dilution—is small in the aquifer. Boron concentrations remain greater than 300 μg/L, or more than 60 percent of the source concentration, as far as 7,000 feet downgradient from the disposal beds (fig. 43*A*). Additional evidence of the low dispersion transverse to the direction of flow is the limited thickness and narrow width of the plume as far as

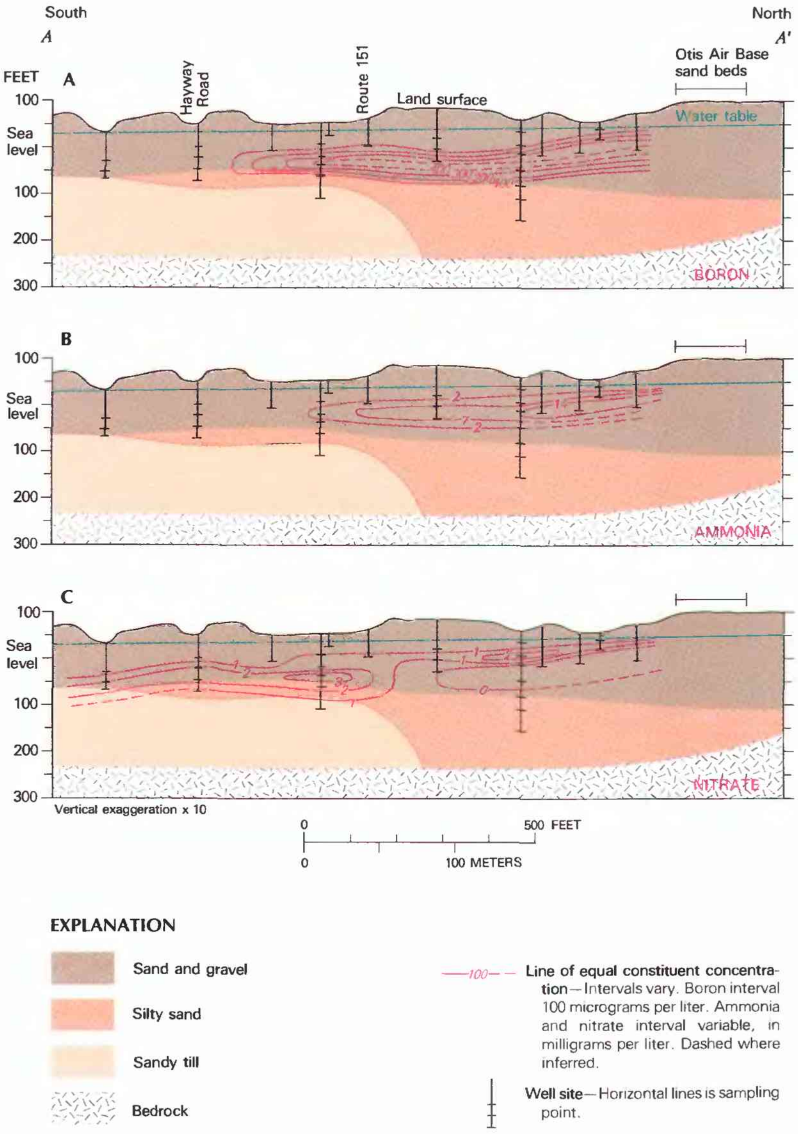

Figure 43. Vertical distribution of selected water-quality characteristics in ground water near Otis Air Base, Cape Cod, Massachusetts 1978–79. *A*, Boron, in micrograms per liter; *B*, ammonia, as nitrogen, in milligrams per liter; and *C*, nitrate as nitrogen, in milligrams per liter. See figure 42 for location of section *A–A'*. (Source: Modified from LeBlanc, 1984a.)

10,000 feet from the disposal site and the presence of a zone of uncontaminated ground water overlying the plume. Because the leading edge of the plume is not yet defined in sufficient detail, only limited information can be obtained from the sewage plume to define the longitudinal dispersion of contaminants. Field-tracer experiments conducted at the site (Garabedian and others, 1987, p. B14–B15), however, indicate that the longitudinal dispersion is much greater than transverse dispersion in this aquifer.

The transition zone between the overlying uncontaminated water and the contaminated water of the plume is thin as indicated by vertical profiles of water-quality characteristics 1,000 feet downgradient from the disposal beds (fig. 44). The transition from a specific conductance of 40 μS/cm (microsiemens per centimeter at 25°Celsius) in the uncontaminated water to 350 μS/cm within the plume occurs over less than 10 feet (fig. 44*A*). Over this same interval, dissolved oxygen decreases from 5 mg/L (milligrams per liter) to almost 0 mg/L (fig. 44*B*). This thin transition zone is further evidence of the small vertical dispersion occurring during transport of the contaminants.

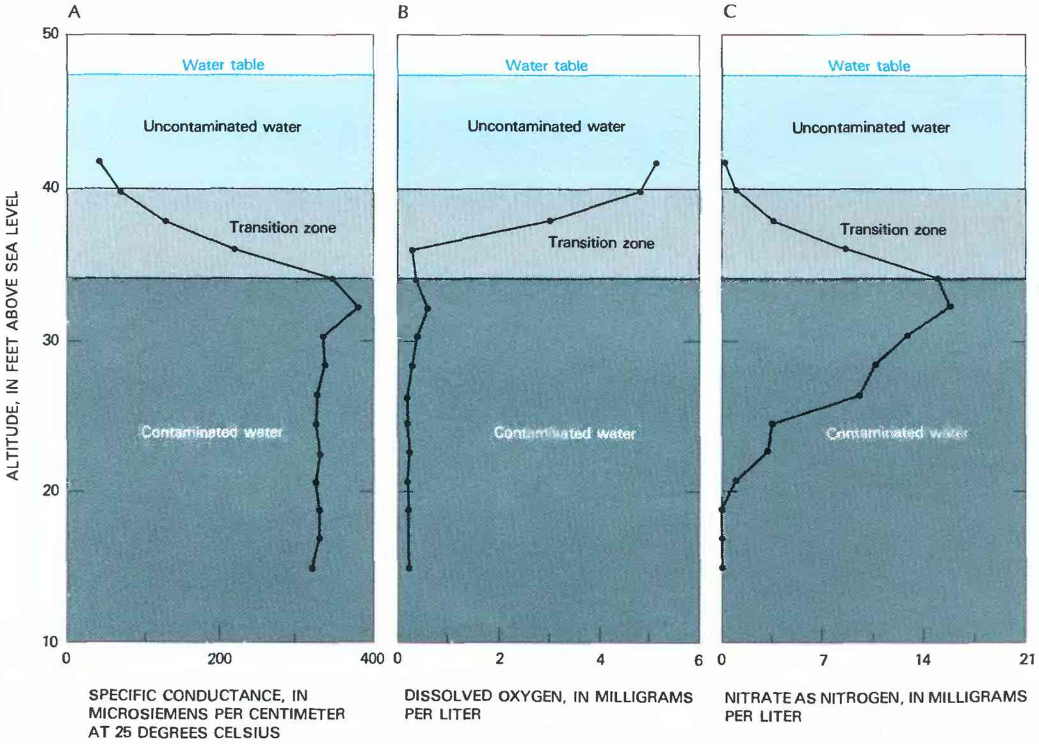

Figure 44. Vertical profiles of water-quality constituents 1,000 feet downgradient from sewage-treatment disposal beds, Otis Air Base, Cape Cod, Massachusetts (Source: Compiled from unpublished data from R.L. Smith, U.S. Geological Survey.)

Immediately below this transition zone is a zone of elevated nitrate concentrations. This zone was not observable from the nest of original monitoring wells because their screens were set 25 feet apart vertically and they straddled the 20-foot-thick zone. The detailed vertical profiles shown in figure 44 were obtained from analyses of water samples withdrawn from closely spaced sampling ports on a multilevel sampler designed to span the 25 feet between the original two monitoring wells. Precise location of the plume boundaries requires sampling at small vertical intervals because of the limited vertical spreading of the contaminants. Microbiological processes within the aquifer commonly are associated with the steep concentration gradients and thin zones of elevated concentrations located at the plume boundaries. Therefore, accurate vertical delineation of transition zones in the plume is necessary in the investigation of biochemical processes affecting contaminant transport.

VARIATIONS IN EFFLUENT COMPOSITION

The variability of contaminant concentrations within the plume resulting from changes in the composition of the effluent discharged onto the disposal beds must be identified before the effects of chemical and microbiological processes on contaminant distributions can be understood. Concentrations of constituents in the effluent at the treatment plant were not measured before 1974. As a result, the exact composition of the treated sewage over the 50-year history of disposal is not known. Detergents, however, are one contaminant for which the history of effluent composition can be deduced (LeBlanc, 1984a, p. 20–22; Thurman and others, 1986).

Synthetic detergents (surfactants) were first used in large quantities in the United States about 1946. Those detergents were predominantly not readily biologically degradable forms. To reduce the environmental effects of detergent use, biodegradable detergents replaced the nonbiodegradable type in 1964. As a result, nonbiodegradable detergents were introduced to the aquifer over an 18-year period (1946–64) and are being transported as a zone, or slug, of elevated detergent concentrations that extends 3,000 to 11,000 feet downgradient of the disposal beds (fig. 42*C*). Detergent concentrations in this zone exceed 0.5 mg/L MBAS (methylene-blue-active substances)—a measure of surfactants—and cause the water to foam when agitated (fig. 41). Between the treatment plant and the zone of elevated detergent concentrations (0 to 3,000 feet downgradient), the ground water contains low levels of detergents (fig. 42*C*), thus showing a direct result of the decision to stop using nonbiodegradable detergents after 1964.

Volatile organic compounds (VOC) also are distributed in a slug-shaped zone within the sewage plume (fig. 42*D*), suggesting that their distribution also may be a function of temporal changes in the composition of the sewage plant effluent. Total VOC concentrations exceed 10 μg/L in a zone that extends 2,500 feet to 8,000 feet downgradient from the disposal site (Thurman and others, 1984; Barber and others, 1984). The maximum concentration detected is greater than 600 μg/L. Compounds detected include trichloroethene, tetrachloroethene, and dichloroethene. The transport and attenuation of these organic compounds also can be affected by sorption onto aquifer material and biochemical degradation. Therefore, the observed VOC distribution probably is a function both of variations in effluent composition over time and in chemical and microbiological processes in the aquifer.

EFFECTS OF CHEMICAL AND MICROBIOLOGICAL PROCESSES ON SEWAGE PLUME

The effects of chemical and microbiological processes are superimposed on the distribution of contaminants caused by effluent variations and physical transport. These processes decrease the concentrations of some chemical species and increase the concentrations of others. The effects of these processes acting on contaminants in the plume are illustrated by the distributions of dissolved organic carbon (DOC) and nitrogen species.

Microbial activity consumes DOC in the contaminant plume. Near the contamination source, biological reactions convert DOC to inorganic carbon (carbon dioxide and bicarbonate). Elevated alkalinity and decreased DOC levels within 2,000 feet of the disposal beds indicate that, relative to the rates of DOC consumption elsewhere in the plume, this conversion occurs rapidly in this zone near the source. An observed reduction in bacterial population with distance downgradient from the treatment plant (Harvey and others, 1984, p. 1199) may be directly related to the decrease in nutrients (DOC) needed by the organisms.

The relative concentrations of the two primary nitrogen species—ammonia and nitrate—differ significantly along the longitudinal axis of the plume (fig. 43*B*,*C*). These observed distributions of ammonia and nitrate probably can be explained by adsorption and biologically mediated chemical reactions (Ceazan and others, 1987; LeBlanc, 1984a, p. 18). The total nitrogen concentration in the effluent discharged onto the disposal beds averages about 20 mg/L. Nitrate and ammonia are both found in the effluent, although the ratio of the two species varies seasonally. Close to the disposal site, from 1,000 to 5,000 feet downgradient, nitrate is not present in the core of the plume, but ammonia concentrations exceed 10 mg/L, and dissolved oxygen is low or absent. The lack of nitrate in the core may be a result of microbial activity near the disposal beds—possibly reduction of nitrate to ammonia or loss of nitrate to nitrogen gas through denitrification (Smith and Duff, 1987). In this zone, nitrate is found only in the thin mixing and reaction zone between overlying uncontaminated, oxygenated water and contaminated, anoxic ground water (fig. 44*C*). Beyond 5,000 feet, ammonia concentrations decrease in the core of the plume, nitrate is present at concentrations as high as 3 mg/L, and dissolved oxygen is present (fig. 43*B*,*C*). This transition from ammonia to nitrate in the core of the plume may result from oxidation of ammonia to nitrate through nitrification by bacteria and from the adsorption of ammonia on the aquifer sediments. Laboratory and field experiments are underway to identify the chemical and microbiological processes controlling the distribution of nitrogen species observed in the contaminant plume.

SUMMARY

A plume of contaminated ground water more than 2 miles long has been created by 50 years of disposal of effluent from a sewage-treatment plant on Otis Air Base, Cape Cod, Mass. Approximately 2.6 billion cubic feet of the Cape Cod sole-source aquifer has been affected by the disposed sewage. Low tranverse dispersion in the aquifer has restricted the contaminants to a narrow, thin plume. This limited mixing has resulted in high contaminant concentrations in the core of the plume as far as 1 mile downgradient of the disposal site and in steep vertical chemical gradients between the contaminant plume and surrounding uncontaminated water.

This plume is an example of the contamination that can occur in a shallow, permeable, unconfined aquifer—the type of aquifer contaminated at many U.S. Environmental Protection Agency Superfund sites in the Northeastern United States. Detailed field study of contaminated sites such as the Cape Cod study improves our understanding of the physical, chemical, and biological processes controlling transport and fate of contaminants in ground water. Only through understanding these processes, which determine the concentration and distribution of ground-water contaminants, can the behavior of these contaminants be accurately predicted and used to prevent, monitor, and clean up ground-water contamination.

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POINT-SOURCE GROUND-WATER CONTAMINATION

DISTRIBUTION AND MOVEMENT OF WOOD-PRESERVING COMPOUNDS IN A SURFICIAL AQUIFER, PENSACOLA, FLORIDA

By Bernard J. Franks

More than 400 commercial wood-preserving plants are in operation in the United States (von Rumker and others, 1975, p. 271); many of them discharge their wastes to onsite impoundments which, in turn, leak into underlying aquifers. Most of these wastes include creosote, a complex distillate of coal tar, which is the wood preservative most extensively used by industry. Because of its complex chemical composition, consisting of some 200 "major" constituents and several thousand "minor" components (U.S. Department of Agriculture, 1981), creosote is difficult to characterize. It is heavier than water, and it is composed of a mixture of complex organic molecules, primarily aromatic and phenolic compounds, with a small percentage of nitrogen-, oxygen-, and sulfur-substituted aromatic compounds.

A substantial data base on health effects of selected compounds found in wood-preservative mixtures already exists because of the large volume of these chemicals used by industry. Health effects vary from immediate chemical skin burns, as a result of direct contact with creosote, to long-term carcinogenic effects from specific compounds in the mixtures (U.S. Department of Health and Human Services, 1983).

How these contaminants are transported through and interact with subsurface environments is of great concern to ground-water managers. In response to this concern, a former wood-preserving plant in Pensacola, Fla., was selected as a study area. The plant was chosen because of its long, uninterrupted history (1902–81) of discharging wastewaters to unlined surface impoundments, the availability of a preliminary data base (Troutman and others, 1984), and the high probability of transferring the findings of an investigation of organic compounds associated with wood-preserving wastewaters to other sites where similar problems exist. This article describes the site and the processes that affect the distribution and movement of these compounds in the subsurface; it also is an example of one of the five point sources of ground-water contamination as explained in this volume in the article "Factors Affecting Ground-Water Quality."

SITE DESCRIPTION AND HYDROGEOLOGY

The wood-preserving plant site is in Pensacola, Escambia County, Fla., about 1,500 feet north of Pensacola Bay, an important commercial fishery, and near the entrance to Bayou Chico (fig. 45*A*). The site is underlain by a surficial sand-and-gravel aquifer, which consists primarily of quartz sand and gravel, interbedded locally with discontinuous silt and clay lenses; this aquifer is the source of water supply for the city of Pensacola. The site has all the characteristics that contribute to high vulnerability of aquifer contamination (see article in this volume, "Factors Affecting Ground-Water Quality"). The site is on a thin unsaturated zone, which overlies an unconfined, highly permeable, surficial sand aquifer in the humid Southeastern United States. In addition, the site lies within a recharge area. One factor that limits the extent of contamination at the Pensacola site is the presence of a shallow confining layer along the coast, which inhibits contaminant movement downgradient from the impoundments. This confining layer inhibits contaminants from moving vertically downward in two ways—the physical presence of the layer acts as a barrier to vertical movement, and the water pressures below the confining layer are higher than those above the layer, thus limiting downward movement of water in the aquifer.

During the years of plant operation, the wood-treatment wastes were discharged into unlined ponds hydraulically connected to the surficial aquifer. Over the years, large but unknown quantities of the waste have infiltrated the soil down to the water table. The wastes have separated into two distinct phases—a denser-than-water hydrocarbon phase that moved vertically downward until intercepted by a confining layer, and an aqueous phase that includes the water-soluble components of creosote.

Movement of the water-soluble contaminants in the subsurface is controlled by ground-water flow, which is directed generally southward toward Pensacola Bay. Flow velocities range from 0.1 to 3.0 ft/d (feet per day). However, these flow paths and velocities are influenced locally by the distribution of the confining silts and clays. A small drainage ditch south of the two unlined ponds intercepts shallow ground-water flow and has a marked effect on the configuration of the water-table surface and also on contaminant transport.

Because of phenolic-compound concentrations in excess of 10 mg/L (milligrams per liter), the U.S. Environmental Protection Agency in 1982 included the site on the Federal "Superfund" list of hazardous waste sites. In 1983, an Emergency Response Team dewatered the ponds, treated the liquid, and placed a clay cap over the former impoundments. This was done to alleviate a potential public health hazard caused by abnormally high water levels that spilled over the embankments and flowed southward along natural drainage paths and directly into Pensacola Bay. The primary source of subsurface contamination, the dense hydrocarbon phase that had already entered the aquifer, was not affected by this cleanup operation.

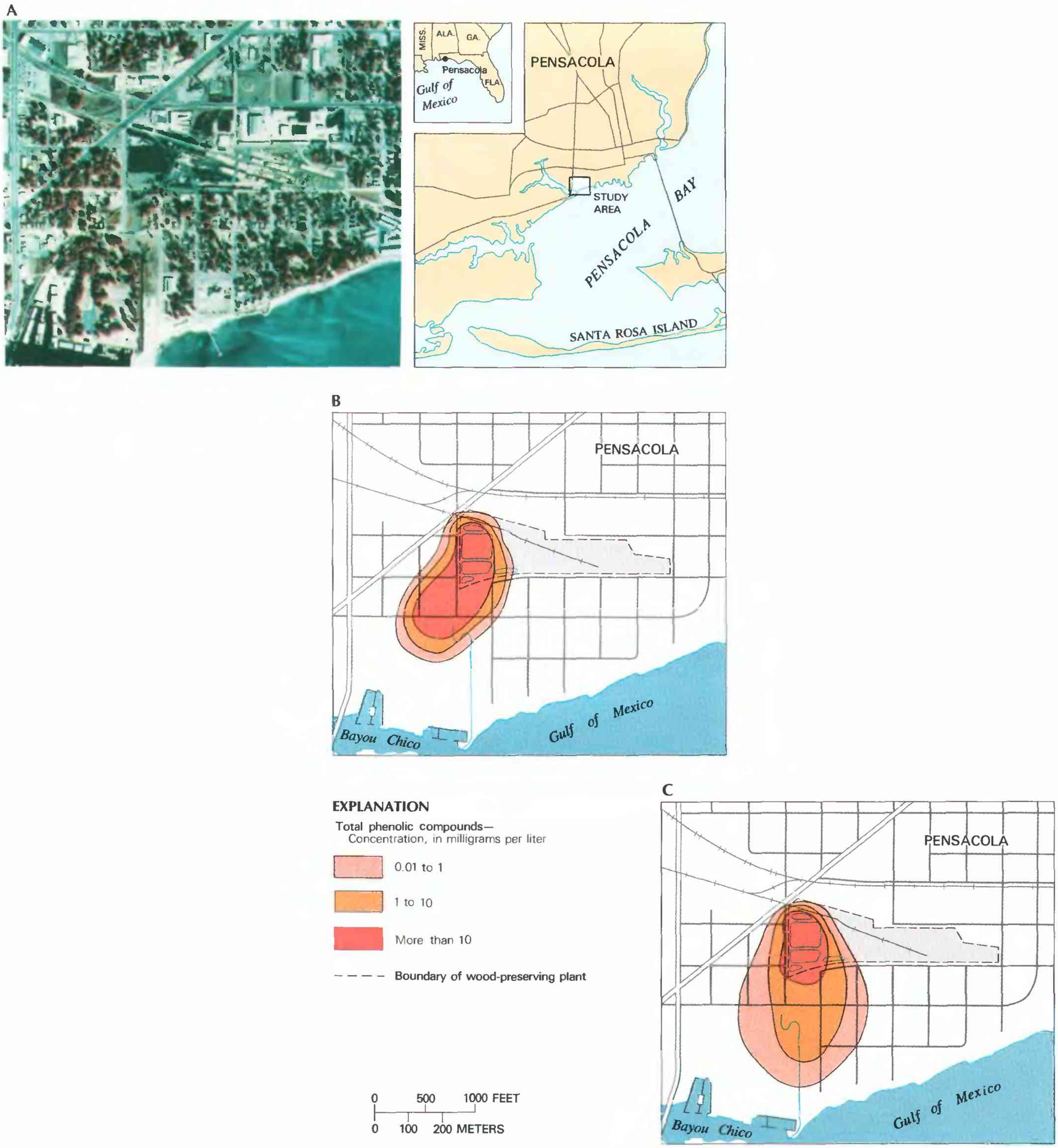

Figure 45. Areal distribution of total phenolic-compound contamination in a surficial aquifer at a wood-preserving plant, Pensacola, Florida, March 1985. *A*, Location of plant site. *B–C*, Extent of contamination in, *B*, the water-table zone and, *C*, the shallow semiconfined zone. (Source: Modified from Franks and others, 1986).

EXTENT AND CHARACTER OF CONTAMINATION

Contamination from the wood-preserving plant has resulted in the generation of anaerobic leachate, which has significantly affected the water chemistry of the aquifer. In the contaminated water, the pH is about 5.4, the dissolved-solids concentration is about 350 mg/L, the dissolved-oxygen concentration is zero, and many of the water-soluble components of creosote are found in concentrations near their limits of water solubility. In addition, hydrogen sulfide, methane, ammonia, iron, nitrogen, and dissolved organic carbon all increase markedly in concentration in the aqueous phase downgradient from the impoundments. In contrast, the uncontaminated ground water has a pH of about 6.0; the dissolved-solids concentration generally is less than 150 mg/L; the dissolved-oxygen concentration is greater than zero; it is free of organic contaminants, hydrogen sulfide, methane, and ammonia; and it contains low concentrations of iron, nitrogen, and dissolved organic carbon.

Contamination is separable into two zones: a plume in the water-table zone, which is 15 to 30 feet below land surface and above a shallow clay lens; and a deeper lying plume, which is 50 to 110 feet below land surface and below the clay lens. Areally, the contamination extends about 1,200 feet downgradient from the impoundments and includes the water-soluble components of creosote, as well as inorganic compounds and gases resulting from degradation of the organic compounds within the aquifer. Distribution of total phenolic compounds in each of the two zones (fig. 45*B*,*C*) is representative of the extent of most contamination. The waste plumes are much less extensive, both areally and vertically, than expected from calculations based on measured ground-water gradients. For the plume in the water-table zone, in particular, this attenuation is partly a result of ground water discharging into a drainage ditch that in turn discharges directly into Pensacola Bay.

PHYSICAL, CHEMICAL, AND MICROBIAL PROCESSES OF CONTAMINATION

Ongoing interdisciplinary research at the site includes investigations of the hydrogeology and ground-water flow system, the extent of organic compounds found in the aquifer, microbial and inorganic processes active in the subsurface, and the effects of contaminants on the ecology of Pensacola Bay. Results of these investigations are being used by concurrent Superfund-related activities at the site to document the extent of contamination (NUS Corporation, 1984) and to support discussion of feasible restoration activities at the site (NUS Corporation, 1985). Preliminary results, which have been documented by Mattraw and Franks (1986) and Ragone (1988), include:

- A three-dimensional ground-water flow model was developed to simulate ground-water flow in the aquifer. Three horizontal layers in the model correspond to lithologic heterogeneities in the system (fig. 46)—a water-table zone, a shallow semiconfined zone, and a deeper confined zone. Contamination is limited to the upper two layers, because of a combination of the distribution of the clay layers and the upward hydraulic gradient that prevails near the coast south of the impoundments. The contaminated shallow sands are characterized by relatively rapid movement of ground water (as much as 3 ft/d) and ease of contaminant transport from the source.
- The aquifer is highly contaminated by organic compounds, including organic nitrogen compounds, such as quinoline (as much as 90 mg/L); double-ring aromatic compounds, such as naphthalene (as much as 15 mg/L); and phenolic compounds, such as 3,5-dimethylphenol (as much as 13 mg/L). The organic nitrogen compounds undergo extremely rapid attenuation to virtually nondetectable levels (less than 0.01 mg/L) within 400 feet of the source. Most of the other compounds persist to about 1,200 feet downgradient before being eliminated from the aqueous phase. These distances, which are shorter than those predicted on the basis of hydraulic considerations, suggest that other processes are selectively attenuating the compounds.
- Microbial degradation processes (both anaerobic and aerobic) probably are the most significant mechanisms in contaminant attenuation. Sequential degradation of phenolic compounds has been documented, and continuing research is describing anaerobic degradation of the substituted aromatic compounds. Many of these compounds appear to be degradable, through intermediate simpler organic compounds, into methane and carbon dioxide.
- Dissolved gases (methane and carbon dioxide) and inorganic constituents (hydrogen sulfide, ammonia, and iron) are indicative of some of the byproducts resulting from breakdown of selected organic contaminants. In contaminated parts of the water table, water is anaerobic throughout the zone. Unusually high values of stable isotope ratios of carbon and sulfur are byproducts of microbial degradation. For instance, the lighter carbon-12 isotope preferentially forms methane (gas), whereas the heavier carbon-13 enriches the inorganic carbon (aqueous) phase. The carbon-13 to carbon-12 ratio is greatest beneath the impoundments, and decreases with distance away from the source of contamination. The presence of an iron-rich clay in the contaminated aquifer possibly is a result of interactions between the clay and organic contaminants.
- Sorption does not appear to be a significant process in most of the aquifer composed of clean quartz sands. Interactions (including sorption) between minerals in the clay lenses and organic contaminants may be quite important in the attenuation of selected compounds.

In addition to the ground-water flow system, possible ecological effects on the nearshore estuarine environments of Pensacola Bay also have been studied. Benthic organisms from Pensacola Bay have been collected and analyzed for bioaccumulation of organic compounds indicative of creosote contamination. Some evidence of bioaccumulation has been found, although at very low concentrations.

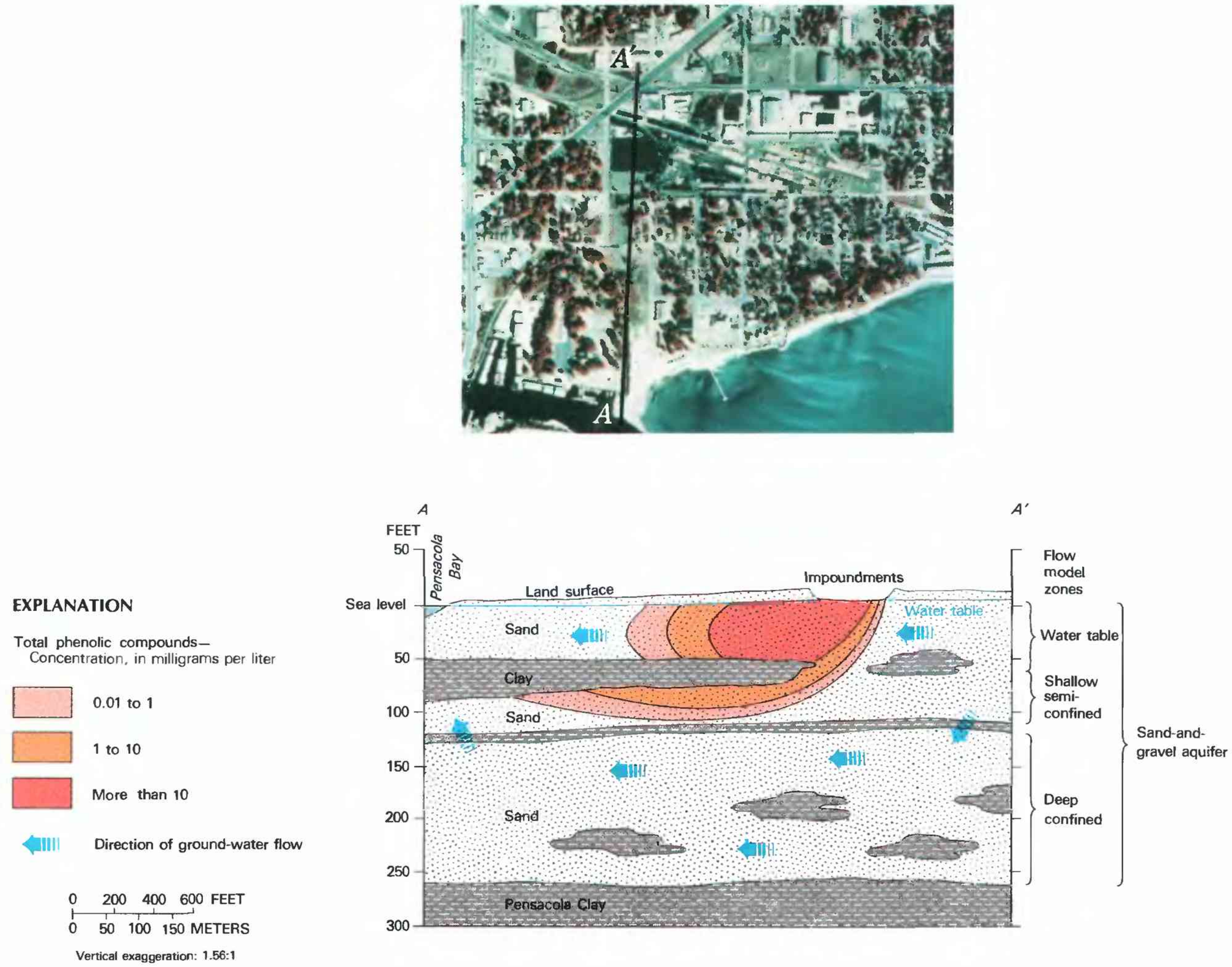

Figure 46. Vertical distribution of phenolic-compound contamination in a surficial aquifer, Pensacola, Florida, March 1985.

Much of the attenuation of organic contaminants at this and other contaminated sites that cannot be accounted for by conventional advective calculations (including dilution) is probably a result of microbial degradation. It has been generally recognized that certain phenolic compounds in the subsurface are anaerobically biodegraded to methane and carbon dioxide (Godsy and others, 1983). In samples from the Pensacola site, a sequential disappearance of organic nitrogen compounds (quinoline), volatile fatty acids, phenol, methylphenol, and quinolinone has been documented (Godsy and others, 1987, p. A18). Volatile fatty acids, which are not present in wood-preserving wastes, are a byproduct of biologic activity; they have been observed throughout the contaminated ground water along with the occurrence of methane, which suggests that methanogenesis may be an important process in contaminant attenuation.

It is evident from this summary of results of the ongoing research being conducted at the Pensacola site that physical, chemical, and microbial processes must all be evaluated when attempting to understand and predict the effects of contamination on the subsurface environment. Because some combination of these processes will operate in all aquifers, results from this interdisciplinary investigation can be useful at other sites of ground-water contamination. Data on wastewater migration from surface impoundments into the subsurface clearly indicate that surficial aquifers are highly susceptible to contamination from a variety of sources. The wide variety of potential contaminants combined with local heterogeneities in the subsurface environment, however, result in unique contaminated systems that are difficult to document. After contaminants leak into a surficial aquifer (a relatively rapid process), the generally slow rates of attenuation, chemical reactions, and physical mixing, combined with large volumes of contaminants in the subsurface, suggest that natural restoration of the aquifer would require hundreds of years after the source of contamination is removed.

SUMMARY

Creosote wastes from an abandoned wood-preserving plant in Pensacola, Fla., that contain numerous organic compounds have infiltrated into the subsurface from surface impoundments at the plant. An evaluation of the hydrogeologic characteristics of the site and extensive data collected to define the extent of contamination show that wood-preserving compounds are abundant in the subsurface and that they are being selectively degraded by microbial activity, possibly sorbed onto aquifer sediments, and removed from the aqueous phase. Contamination extends to a depth of 110 feet below land surface, and about 1,200 feet downgradient from the impoundments. The waste plumes are much less extensive, both areally and vertically, than expected on the basis of measured ground-water gradients. Byproducts of microbial degradation of the contaminants that have been identified include volatile fatty acids, methane, and carbon dioxide. The complexities of investigating and delineating the extent of organic contaminants in ground-water systems make aquifer cleanup and restoration an interdisciplinary and long-term task. Results of these investigations are being used by concurrent Superfund-related activities at the site to document the extent of contamination and support discussion of feasible restoration activities at the site.

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POINT-SOURCE GROUND-WATER CONTAMINATION

COAL-TAR DERIVATIVES IN THE PRAIRIE DU CHIEN–JORDAN AQUIFER, ST. LOUIS PARK, MINNESOTA

By Marc F. Hult and James R. Stark

Between 1918 and 1972, a coal-tar distillation and wood-preserving plant operated on an 80-acre site in St. Louis Park, Minn., a suburb of Minneapolis (fig. 47). Release of the coal-tar derivatives to the environment resulted in a long history of ground-water contamination, more recent remedial actions, and litigation. In 1932, when the first public water-supply well was drilled, the region's principal aquifer, the Prairie du Chien–Jordan, which is 250 to 350 feet below land surface, was discovered to be contaminated (Minnesota Department of Health, 1938). The need for additional public supply was satisfied in 1936 by the construction of new wells in the St. Peter aquifer upgradient from the area of contamination; however, the source of contamination was not removed, and the mechanisms by which ground water in the area was contaminated were not understood.

By 1978, creosote-like fluids had accumulated in the glacial-drift aquifer at depths as much as 50 feet below the water table (Hult and Schoenberg, 1984), and trace amounts of coal-tar compounds, including suspected carcinogens, were detected in public-supply wells completed in the Prairie du Chien–Jordan aquifer (Minnesota Department of Health, 1978). (See figure 48.) Coal-tar derivatives migrated northward in the Prairie du Chien–Jordan aquifer because of local reversals in the regional gradient caused by ground-water withdrawals and the flow of water into the aquifer from other aquifers through wells that tap several aquifers (multiaquifer wells) (Hult, 1984). Aided by computer simulations of ground-water flow (Stark and Hult, 1985a,b), Federal, State, and local agency personnel and representatives of the former plant have designed a system to control hydraulic gradients and, thereby, the direction of contaminant transport in the Prairie du Chien–Jordan aquifer and to treat and use contaminated water from the wells. A long-term strategy is being developed to monitor contamination in overlying aquifers. This article describes the site, the extent and character of the contamination, and the remedial actions taken; it also portrays one of the five point sources of ground-water contamination as explained in this volume in the article "Factors Affecting Ground-Water Quality."

HYDROGEOLOGY

The St. Louis Park area is underlain by glacial drift that forms the shallowest aquifer in the region. The highest concentrations of contaminants, including undissolved coal tar, occur in the drift aquifers. (See figure 48.) Shallow wells in the drift and in the uppermost bedrock aquifer, the Platteville, have been contaminated since at least 1938, but these aquifers are not used for public supply and few wells are completed in them. The Prairie du Chien–Jordan aquifer is the major ground-water resource, and about 80 percent of ground-water withdrawal in the St. Louis Park and Minneapolis–St. Paul metropolitan area is from this aquifer. The aquifer is 200 to 550 feet below land surface and generally is protected from nearsurface sources of contamination by overlying glacial drift, two bedrock confining beds (Glenwood and basal St. Peter) and two bedrock aquifers (Platteville and St. Peter). The Prairie du Chien–Jordan aquifer consists of the Jordan Sandstone—a fine- to coarse-grained quartzose sandstone—and the dolomite of the overlying Prairie du Chien Group. The permeability of the upper part of the aquifer is due mostly to jointing and to enlargement of joints by dissolution of carbonate minerals. The solution channels permit contaminants to move large distances rapidly, sometimes in unexpected directions, once they have entered the aquifer. Distribution of pumpage from the Prairie du Chien–Jordan aquifer constantly is changing areally and temporally, in part because the demand for water changes seasonally. The potentiometric surface fluctuates about 30 feet between summer and winter and has declined about 40 feet since 1885. These changes, coupled with the hydraulic and chemical stresses created by flows into the aquifer through the bores of multiaquifer wells, have created a complex distribution of contaminants in the aquifer.

The entire area is underlain by the Mount Simon–Hinckley aquifer at depths of 800 to 1,000 feet below land surface. This aquifer, which provides about 15 percent of the ground-water withdrawals, is protected from surface sources of contamination by the overlying St. Lawrence–Franconia and Eau Claire confining unit (not shown in figure 48).

EXTENT AND CHARACTER OF CONTAMINATION

At the plant site, coal tar was distilled into creosote, which then was used as a preservative in the treatment of lumber. Coal tar is a complex mixture of several hundred individual compounds produced by heating coal in the absence of air. In general, the solubility in water and the volatility of coal-tar constituents decrease with increasing molecular weight; in contrast, the density, boiling point, tendency to be sorbed on aquifer materials, and resistance to biodegradation of individual compounds increase with increasing molecular weight. Of particular concern with respect to health risk to humans is a class of compounds called polynuclear aromatic hydrocarbons (PAH), which are a major constituent in coal tar. Some of the PAH are considered to be carcinogenic (Minnesota Department of Health, 1978), and it has been recommended (Hickok and others, 1981) that 28 ng/L (nanograms per liter) be the upper limit of PAH concentration in drinking water. The health risk of individual PAH compounds generally increases with increasing molecular weight. Coal tar from the site also contains nitrogen-bearing compounds (Pereira and others, 1983) and phenolic compounds (Ehrlich and others, 1982; Hult and Schoenberg, 1984).

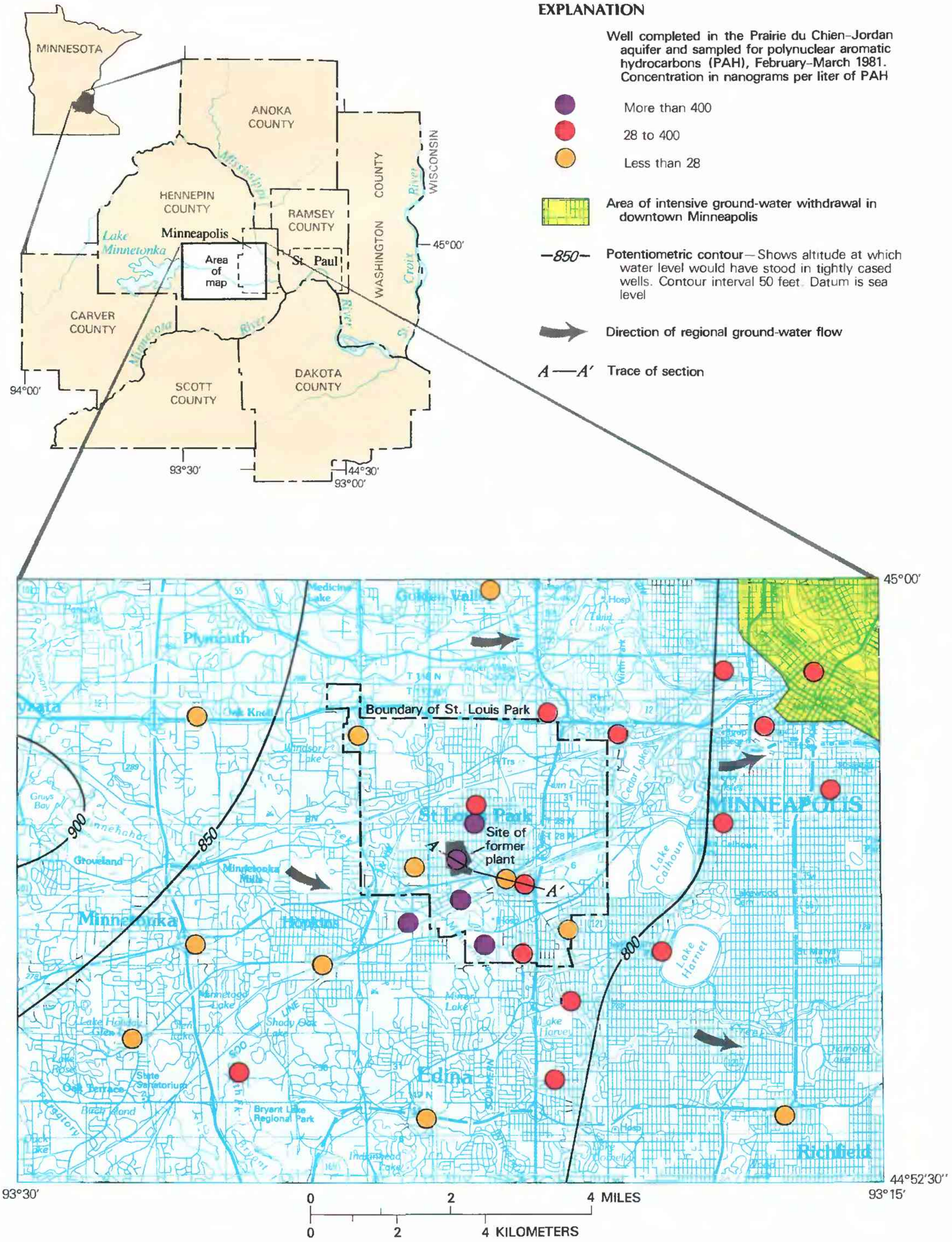

Figure 47. Regional potentiometric surface and extent of contaminated wells in the Prairie du Chien-Jordan aquifer, St. Louis Park, Minnesota, January-February 1981. Polynuclear aromatic hydrocarbons (PAH), some of which are considered to be carcinogenic, were detected in samples from several wells; the Minnesota Department of Health has set a standard of 28 ng/L (nanograms per liter) as the upper limit of PAH concentrations in drinking water. Section *A–A′* is shown in figure 48. (Source: Modified from Hult, 1984, and Hult and Schoenberg, 1984.)

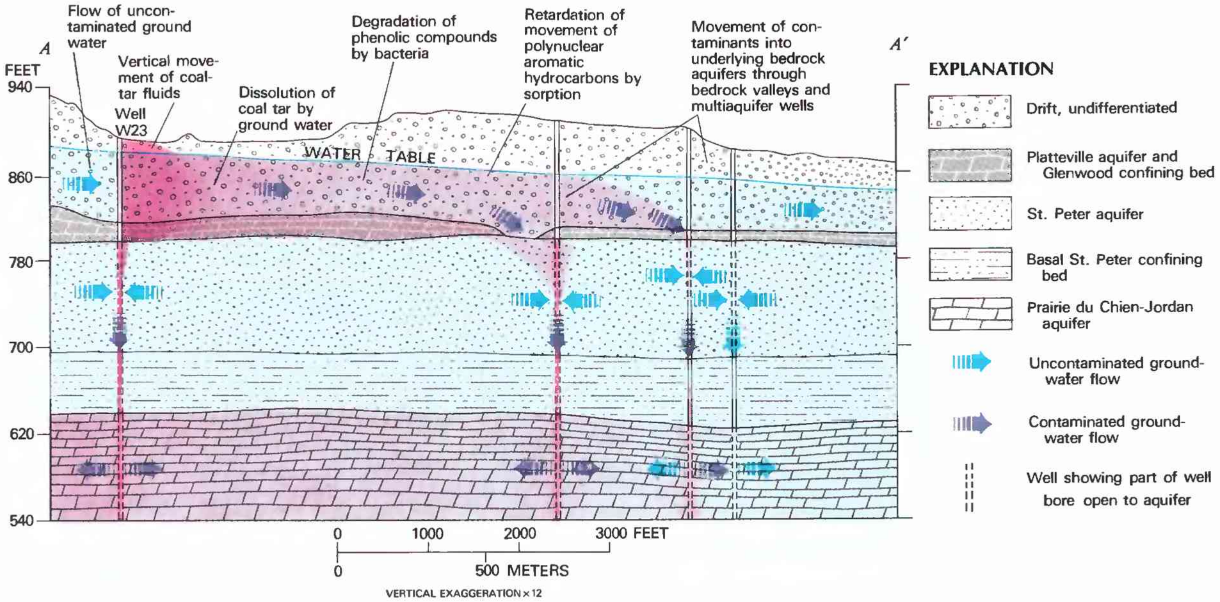

Figure 48. Hydrogeologic section showing direction of contamination migration in ground water, St. Louis Park, Minnesota, 1978. See figure 47 for location of section *A–A′*. (Source: Modified from Hult, 1984.)

In 1932, the first St. Louis Park public water-supply well was drilled 3,500 feet east of and downgradient from the plant site. The well was completed in the Prairie du Chien–Jordan aquifer at a depth of 540 feet, and it yielded water with a coal-tar taste (Minnesota Department of Health, 1938). Efforts to avoid zones of contaminated water by reconstructing the well to block the contaminated water were unsuccessful, and the well was abandoned for public water-supply purposes. Four years later the city of St. Louis Park drilled two additional wells within 2,000 feet upgradient from the plant site in the overlying St. Peter aquifer. These wells yielded water of satisfactory quality. No other public wells were taken out of service owing to contamination until 1978 when four wells completed in the Prairie du Chien–Jordan aquifer, within 2,000 feet upgradient from the plant site, yielded water with trace amounts of PAH. During 1978–81, six wells, completed in the Prairie du Chien–Jordan aquifer and within 4,000 feet of the plant site, yielded water containing trace amounts of coal-tar compounds and their use as drinking-water wells was discontinued.

Coal-tar derivatives entered the ground-water system through two major paths: spills and drippings at the plant site and surface runoff and plant process-water discharges to ponds and wetlands at the plant site, which percolated through the unsaturated zone to the water table. Direct discharges of coal-tar wastes to the surface resulted in contamination of the glacial drift. The fluid, which closely resembles creosote in chemical composition, moved downward through the glacial drift because it is denser than water, but it also moved more slowly than the water because it is more viscous. As the fluid moved, some was left behind in the pores of the outwash sand through which it migrated. Ground water flowing past the fluids in the drift preferentially leaches the more highly soluble constituents. PAH concentrations in ground water in the drift and Platteville aquifers are controlled primarily by selective dissolution of the organic compounds. Once in the ground water, contaminants have moved downward with the water because of vertical hydraulic gradients, and, most significantly, through wells that connect more than one aquifer.

The major processes that affect movement of PAH in the drift and in the Platteville and St. Peter aquifers, as well as the general extent of contamination in these aquifers, are shown in figure 48. Dissolved contaminants move eastward and downward with the flowing ground water because of hydraulic gradients. Sorption of high-molecular-weight compounds by the aquifer increases the relative differences in concentrations of organic substances in the water. Some individual phenolic compounds are degraded by bacteria under anaerobic conditions (Ehrlich and others, 1982), whereas some other low-molecular-weight compounds are degraded by aerobic bacteria in oxygenated (oxygen-bearing) parts of the aquifer. Ground-water flow through well bores and through a drift-filled bedrock valley, where no confining bed separates the drift and bedrock aquifer systems, provides a mechanism to transport contaminants to aquifers below. The major source of contamination in the Prairie du Chien–Jordan aquifer was through a deep well at the plant site (fig. 47, W23). When first evaluated in 1978 by the U.S. Geological Survey, the well was found to contain coal tar at a depth of 595 feet. Approximately 150 gal/min (gallons per minute) of contaminated water was measured entering the well through a leak in the casing from upper aquifers and flowing down the bore of the well into the Prairie du Chien–Jordan. At least four other wells also permitted water to flow into the aquifers, although at lower flow rates and with much lower contaminant concentrations. By 1981, coal-tar derivatives in the aquifer had moved about 2 miles northeast and south of the former plant and into the Prairie du Chien–Jordan despite the fact that regional ground-water flow is to the southeast (fig. 47).

REMEDIATION

Remediation of ground-water contamination began in 1975 when the surface area of the plant site was graded and visibly contaminated soils were removed. Storm-water-retention ponds were constructed and connected to the storm-sewer system in an attempt to reduce the flow of contaminated water to the aquifers. The extent of subsurface contamination was revealed by examination of numerous soil borings and analysis of water from monitoring wells installed at that time. In 1978, a program was begun to reduce the downward movement of contaminants through wells. Federal, State, and local agencies began identifying and evaluating the possible effects of individual multiaquifer wells in the area around the plant site. Testing by the U.S. Geological Survey included borehole flow-velocity measurements, geophysical logging, visual inspection of wells with downhole television cameras, and chemical analyses.

Approximately 30 other uncased or ungrouted bedrock wells were identified as potential pathways for the flow of contaminated water from upper, more highly contaminated aquifers into the Prairie du Chien–Jordan aquifer. These interaquifer connections were found to be the result of open-hole construction, leaks in casings, and flow in the annular space between the casing and the borehole. Improperly constructed wells were permanently sealed or new casings installed by the Minnesota Department of Health to reduce the potential for interaquifer contamination.

A column of coal tar about 100 feet long was removed from the deep well (well W23) on the plant site; the well was then reconstructed to prevent flow from the overlying St. Peter to the Prairie du Chien–Jordan aquifer. These steps eliminated the major sources of contamination to the Prairie du Chien–Jordan aquifer, but the 60 years of leakage left the aquifer extensively contaminated. An approach to contain and manage the contaminated water in the aquifer still needed to be developed.

In 1984, a computer-based mathematical ground-water-flow model was developed to simulate and evaluate the movement of coal-tar derivatives within the Prairie du Chien–Jordan aquifer (Stark and Hult, 1985a,b). The model was calibrated for steady-state conditions using data from before (1885–1930) and during (winter conditions, 1970's) significant pumping stress; changing conditions were simulated for a period (1977–80) in which pumping stress and seasonal changes in the potentiometric head were significant. Model simulations indicated that the potentiometric surface of the Prairie du Chien–Jordan aquifer was raised by as much as 3 feet in the area of the plant site by water introduced into the aquifer through wells open to more than one aquifer. The mound of ground water in the Prairie du Chien–Jordan created at these wells has significantly affected the transport of contaminants in the aquifer. Based on the simulation model results, a plan was developed to control the withdrawal from five wells in order to alter the flow direction of ground water in the vicinity of the plant site. The simulations also showed, however, that potentiometric surfaces are sensitive to changes in withdrawal rates at wells outside the area that was under the control of the plan. Management of discharges from these wells will be important to overall effectiveness of the remedial-action plan. The model was constructed assuming that pumping at wells outside the area would be at similar rates and seasonal trends as in the past.

The city of St. Louis Park is implementing a gradient-control plan, similar to that tested by the simulation model. The effect of pumping wells will control ground-water gradients and the expansion of the contaminated water volume in the Prairie du Chien–Jordan aquifer. Water pumped from two of the gradient-control wells is being treated with activated granular carbon to remove organic compounds and then is used in the public water-supply system for St. Louis Park. Water pumped from the other wells is discharged to sewers or used for industrial processes and cooling.

Additional studies and monitoring of coal-tar contamination in the drift and upper bedrock units, where contaminant concentrations are much higher than in the Prairie du Chien–Jordan aquifer, are underway. However, these aquifers are not important sources of drinking water. A plan to remediate contamination in these units has yet to be developed.

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NONPOINT-SOURCE GROUND-WATER CONTAMINATION

AGRICULTURAL CHEMICAL CONTAMINATION OF GROUND WATER IN SIX AREAS OF THE HIGH PLAINS AQUIFER, NEBRASKA

By Hsiu-Hsiung Chen and A. Douglas Druliner

The economy of Nebraska is linked closely to irrigated agriculture, which in turn is linked closely to the High Plains aquifer. This aquifer is the primary water supply for about 96 percent of the more than 71,000 registered irrigation wells in the State, most of which have been installed in the past 35 years. Nebraska also is typical of many High Plains States in that agricultural productivity depends heavily on the use of fertilizers and pesticides. In 1984, for example, an estimated 200 million pounds of fertilizer and 30 million pounds of pesticide active ingredients were applied to farmlands (Powers, 1984). This usage of fertilizers and pesticides has affected the quality of water in the High Plains aquifer system (Exner and Spalding, 1976; Junk and others, 1980; Spalding and others, 1980).

Elevated concentrations of nitrate in ground water have been shown to be related to fertilizer application. In Nebraska, nitrate concentrations have been mapped in several parts of the State (Exner and Spalding, 1976); thus, nitrate can be used to illustrate the extent of the contamination of ground water by fertilizers. However, less is known about the spatial and temporal distribution of pesticides in ground water. Little also is known about the processes and variables that control the movement of fertilizers and pesticides in ground water.

This article describes the results of a study to assess the relation of concentrations of nitrate-nitrogen (hereafter referred to as nitrate) and triazine herbicides in ground water to selected variables such as precipitation, soil permeability, depth to water, aquifer characteristics, land use, and fertilizer use. Six areas that represent diverse hydrogeologic, climatic, soil conditions, and agricultural land uses were selected for the study (fig. 49)—(1) Buffalo and Hall Counties, (2) Gosper, Phelps, and Kearney Counties, (3) Chase and Hayes Counties, (4) York County, (5) Box Butte County, and (6) Garfield and Wheeler Counties and most of Holt County. The article also is an example of nonpoint-source contamination of ground water as explained in this volume in the article "Factors Affecting Ground-Water Quality."

HIGH PLAINS AQUIFER

The High Plains aquifer extends from South Dakota to Texas and underlies parts of eight States, with 37 percent of the aquifer underlying Nebraska. In Nebraska, the aquifer underlies about 65,000 square miles, or about 85 percent of the State. The aquifer is unconfined to partially confined and consists predominantly of the Tertiary Ogallala Formation and hydraulically connected overlying and underlying deposits. In areas 1, 2, and 4, the aquifer is underlain by Cretaceous shale and chalk deposits; in area 5 and parts of areas 3 and 6, it is underlain by Tertiary silt and clay deposits. The saturated thickness of the High Plains aquifer in Nebraska ranges from less than 1 foot to more than 1,000 feet; however, in the six study areas, the saturated thickness ranges from less than 100 feet to 800 feet (Pettijohn and Chen, 1983).

Characteristics of the six study areas are presented in table 4. These six areas are representative of much of the High Plains aquifer in Nebraska. The average hydraulic conductivity values range from less than 10 to 200 ft/d (feet per day) in the aquifer, but most of the study areas have hydraulic conductivity values between 5 and 149 ft/d (table 4). Specific discharge, the product of hydraulic conductivity and hydraulic gradient, is a measure of the rate of discharge (that is, flow) of ground water per unit area measured at right angles to the direction of flow. The average specific discharge values range from 0.01 to 0.3 ft/d. Specific yield, the ratio of the volume of water that will drain under the influence of gravity to the volume of the saturated aquifer, ranges from less than 0.10 in parts of area 1, 2, and 6 to more than 0.25 in areas 2 and 3. Depths to water for wells sampled in all areas range from 3 to 239 feet. Depths to water are greatest in areas 3 and 2, with median depths of 95 and 92 feet, respectively. Estimates for the migration velocity in the six study areas range from 0.06 to 1.50 ft/d and average about 0.38 ft/d. The migration velocity is defined as the specific discharge divided by the volumetric porosity. In areas affected by pumpage from large-production wells, the hydraulic gradient is increased, thereby increasing the rate of flow near the wells.

Recharge primarily is from deep percolation of precipitation. Mean annual precipitation increases eastwardly in Nebraska and ranges from 17 inches in area 5 to 27 inches in area 4. Ground-water discharge in most areas occurs principally as irrigation-well pumpage, but it also may occur as evapotranspiration and seepage to streams, lakes, and wet meadows.

In 1984, the number of registered irrigation wells in the six study areas ranged from 886 in area 5 to 6,407 in area 1. The effects of intensive irrigation development on water levels in the High Plains aquifer system are indicated by declines from predevelopment levels of more than 30 feet in areas 3 and 5, less than 25 feet in area 6, and less than 20 feet in areas 1 and 4 (Ellis and Pederson, 1985, p. 36, 48). In contrast, water levels have risen by more than 50 feet in much of area 2 as a result of recharge from surface-water diversions for irrigation (Ellis and Pederson, 1985, p. 22).

FERTILIZER AND PESTICIDE USAGE

About 94 percent of the land in the six areas is used for agriculture. Corn is the dominant crop in all but area 5. Corn-production techniques presently

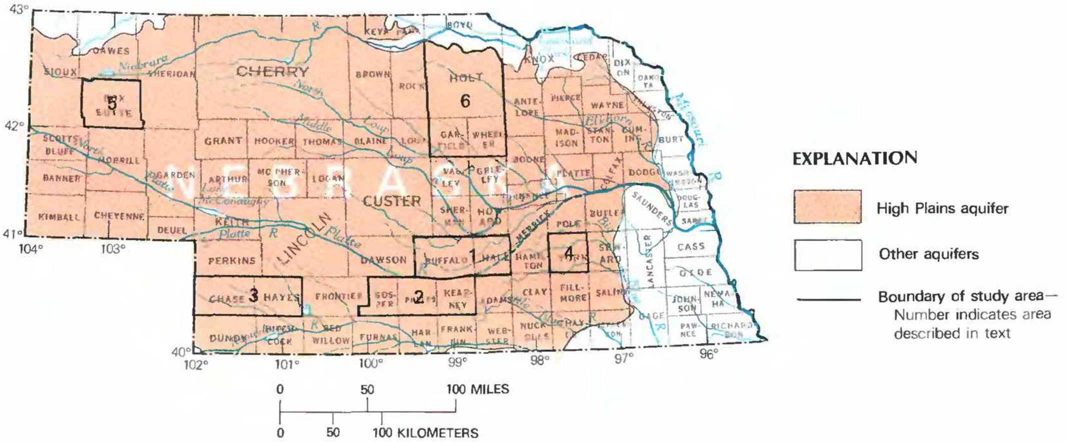

Figure 49. High Plains aquifer in Nebraska and location of six study areas described in this article. (1) Buffalo and Hall Counties, (2) Gosper, Phelps, and Kearney Counties, (3) Chase and Hayes Counties, (4) York County, (5) Box Butte County, and (6) Garfield and Wheeler Counties and most of Holt County. (Source: U.S. Geological Survey files.)

involve the use of large quantities of nitrogen fertilizers and pesticides. Farmers commonly apply from 80 to 260 pounds of total nitrogen per acre, mostly as anhydrous ammonia to supplement residual nitrogen in the soil. Lesser amounts of nitrogen are applied to other crops, such as sorghum, sugar beets, and wheat. Most of the nitrogen not used by crops is oxidized to nitrate in the soil. Nitrate, which is water soluble and extremely mobile, can be leached readily from the root zone to the aquifer (Madison and Brunett, 1985, p. 93).

Between 1978 and 1982, herbicides applied in Nebraska increased by 30 percent, from 18.7 million pounds to 24.3 million pounds. Insecticide applications dropped by 7 percent during the same period, from 5.6 to 5.3 million pounds (Johnson and Byers, 1979, p. 9, 10; Johnson and Kamble, 1984, p. 1). Of the herbicides, 29 percent of the applications were of atrazine. Other heavily applied herbicides were butylate, alachlor, propacholor, cyanazine, and 2,4-D. Of the insecticides, 29 percent of the use was of fonofos, followed by terbofos and carbofuran. Inasmuch as the use of insecticides varies depending on the degree of insect infestation, changes in total insecticide applications do not necessarily represent a regional trend.

EXISTING GROUND-WATER ANALYSES

Nitrate analyses were available for 2,388 ground-water samples collected in the six study areas between 1936 and 1983. Most of the data were collected as part of large areal studies designed to characterize the regional ground-water quality of various parts of the High Plains aquifer in Nebraska. For ease of comparison, nitrate concentrations in all forms have been converted to nitrate-nitrogen concentrations. Sufficient historical data were available in area 1 to test for the existence of trends in nitrate

Table 4. Summary of data from 82 well sites in the six study areas of the High Plains aquifer, Nebraska, 1984

[Units: ft/d, feet per day; in/h, inches per hour; wells/mi², wells per square mile; lb/acre, pounds per acre; mg/L, milligrams per liter]

Independent variable	Unit	Descriptive statistics					Relative importance of independent variable (based on correlation coefficient) to ground-water contamination by—	
		Maximum	Minimum	Mean	Median	Standard deviation	Nitrate	Triazine herbicide
Hydraulic gradient	......	0.0053	0.0006	0.0023	0.0020	0.0011	5	8
Hydraulic conductivity	ft/d	149	5	52	40	36	3	5
Specific discharge	ft/d	0.2998	0.0128	0.0759	0.0565	0.0576	7	2
Depth to water	feet	239	3	73	47	60	4	7
Well depth	feet	550	40	199	180	109	1	3
Annual precipitation	inches	39.3	12.0	25.2	26.2	6.5	6	6
Soil permeability	in/h	9.0	0.76	2.46	1.30	2.12	9	9
Irrigation-well density	wells/mi²	8	0	3.1	2.6	2.2	2	4
Nitrogen-fertilizer use	lb/acre	260	0	124.8	147.3	81.6	8	.....
Nitrate concentration	mg/L	45	0.10	7.6	3.05	10.31	.....	1

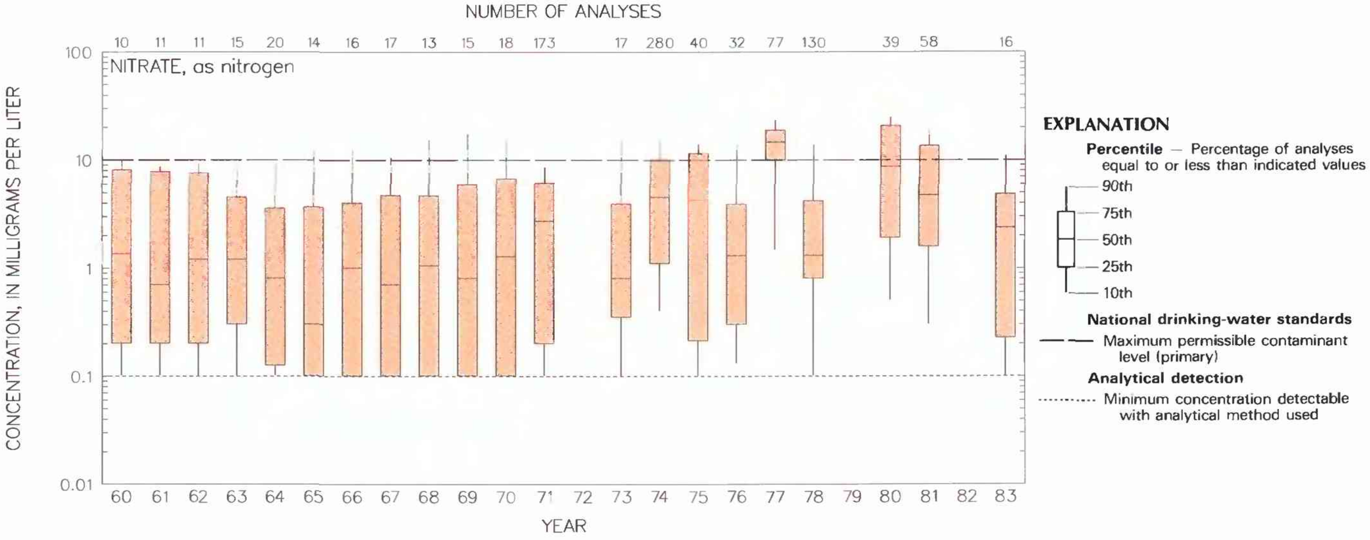

Figure 50. **Summary of nitrate concentrations in ground water in Buffalo and Hall Counties, Nebraska, 1960–83.** Data based on years in which 10 or more analyses of well water were available. (Source: Compiled from U.S. Geological Survey and University of Nebraska Conservation and Survey Division data.)

concentrations at the 95-percent confidence level. The seasonal Kendall test (Crawford and others, 1983) showed that nitrate concentrations increased an average of 0.12 mg/L (milligrams per liter) per year between 1960 and 1983 (fig. 50).

The areal distribution of available nitrate data, mainly from the middle to late 1970's, indicated a number of sites in areas 1, 2, 4, 5, and 6 where nitrate concentrations in ground water equaled or exceeded 10 mg/L, the U.S. Environmental Protection Agency (EPA) recommended maximum limit of concentration in drinking water. The estimated percentages of surface area of each study area in which nitrate concentration in ground water equaled or exceeded the 10 mg/L limit were 10.5 percent (area 1), 5.5 percent (areas 2 and 5), and 6.4 percent (area 6).

Historical pesticide data are more difficult to obtain. No pesticide data were collected in Nebraska before 1977. From 1977 to 1982 several studies were conducted by the University of Nebraska Conservation and Survey Division in parts of areas 1 and 6. Water from 14 wells in area 1 was analyzed for 12 pesticides by Spalding and others (1980), and atrazine was detected in all 14 samples; alachlor was detected in water from two wells. In a separate study in area 1 in which 17 wells were sampled, Junk and others (1980) detected atrazine in all samples, alachlor in 2 samples, and dieldrin (an insecticide) in 1 sample. It is not surprising that atrazine appeared so widespread in ground water. The potential for ground-water contamination with atrazine is relatively high because it is applied frequently on row crops, it is moderately soluble, and it has a relatively long half-life in soil (4-57 weeks) and in ground water (10–106 weeks). (The half-life of a pesticide is a measure of time required for the pesticide to degrade to half of its original activity.) Although concentrations of organic pesticides in ground water often are several orders of magnitude less than nitrate concentrations, their presence is of concern because of their potentially adverse effect on plant and animal life. At present there are no maximum limits recommended by the EPA for concentrations of the herbicides, atrazine or alachlor, in drinking water.

Ground-water sampling for this project during 1984 focused on atrazine and other triazine herbicides (ametryne, cyanazine, prometone, prometryne, propazine, simetryne, and simazine) as indicators of ground-water pesticide contamination. During the 1984 irrigation season, 82 wells distributed among the six study areas were sampled and analyzed by the U.S. Geological Survey for nitrate, and 57 of these wells were analyzed for triazine herbicides. The sampled wells were free from any obvious point-source contamination and were chosen to represent a diversity of hydrologic conditions.

Nitrate concentrations for these 82 samples ranged from less than 0.1 to 45 mg/L, with a mean of 7.6 mg/L and a median of 3.05 mg/L (table 4). The recommended maximum concentration limit of 10 mg/L of nitrate as nitrogen was exceeded in samples from 18 wells (22 percent). Area 1 (5 out 15 samples) and area 6 (8 out of 22 samples) had the greatest number of samples with concentrations exceeding 10 mg/L; area 3 had no samples with concentrations exceeding this limit.

Another statistical procedure, the median test (Conover, 1980), indicated that median nitrate concentrations differed significantly among the six study areas at the 95-percent confidence level. This suggests that hydrogeologic, climatic, soil, and land-use variables, or combinations of these variables, affect the movement of nitrate into ground water.

Water from 57 of the 82 wells was analyzed for triazine herbicides. Eighteen (32 percent) of these samples contained detectable amounts of triazine herbicide, with concentrations ranging from less than 0.1 to 2.3 μg/L (micrograms per liter). All 18 samples contained atrazine—concentrations in 6 of the samples were at the reporting limit of 0.1 μg/L. Two of the 18 samples also contained propazine, and 1 of the 18 samples contained simazine at the reporting limit of 0.1 μg/L. As shown in table 5, areas 1 and 2 had the highest percentages of detected triazine herbicides in water—triazine herbicides were present in 50 percent of the wells sampled in area 1 and 44 percent of the wells sampled in area 2. Triazine herbicides were not detected in the nine wells sampled in area 3.

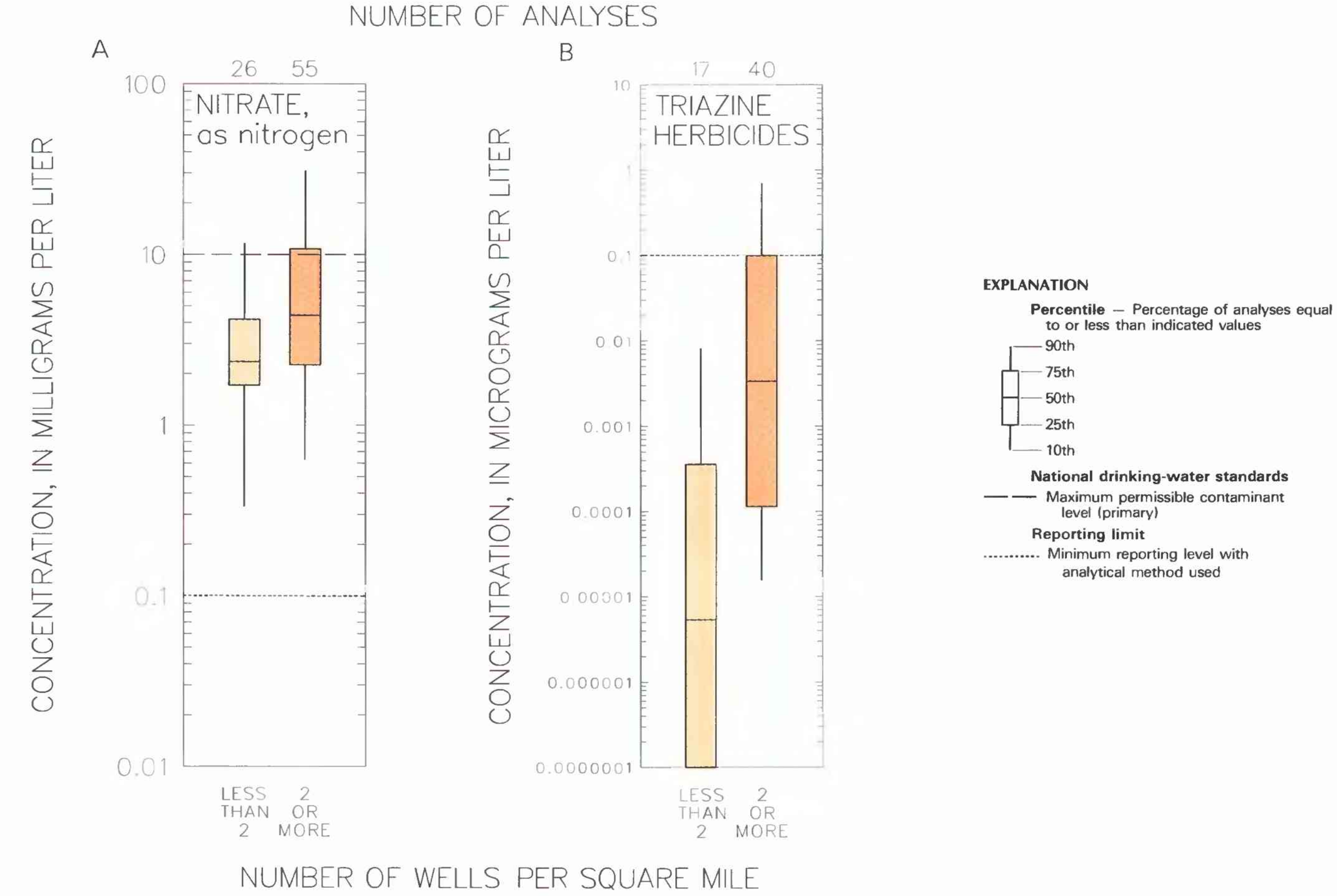

Figure 51. Relation of contaminants in ground water to intensively irrigated land (more than 2 wells per square mile) and less intensively irrigated land (less than 2 wells per square mile) in six areas of Nebraska. *A*, Nitrate concentrations; *B*, estimated triazine-herbicide concentrations. (Sources: *A*, U.S. Geological Survey files; *B*, values below the reporting limit were estimated using the methods proposed by Helsel and Gilliom, 1986.)

RELATION OF GROUND-WATER CONTAMINANTS TO LAND USE AND HYDROGEOLOGIC VARIABLES

The relation of agricultural land use to contaminants in ground water was evaluated statistically. Sampled wells were grouped according to the irrigation-well density in the vicinity of the sampled well. They were classified as being (1) in an intensively irrigated area if two or more irrigation wells were present within the same 1-square-mile area containing the sampled well, or (2) in a less intensively irrigated area if less than two irrigation wells were present within the same section.

Nitrate concentration levels were significantly greater beneath intensively irrigated areas (fig. 51*A*) at the 95-percent confidence level (ranked T-test in Conover, 1980). Similarly, triazine-herbicide concentrations were significantly larger in the intensively irrigated group at the 95-percent confidence level (fig. 51*B*).

Linear correlation and regression analyses were used to determine a preliminary relation between the amount of nitrate or triazine herbicide in the aquifer and a group of land use, hydrogeologic, climatic, and soils variables measurable at well locations and suspected of having some influence on nitrate or pesticide concentrations. Ten variables were evaluated—hydraulic gradient, hydraulic conductivity, specific discharge, depth to water, well depth, annual precipitation, soil permeability, irrigation-well density, nitrogen-fertilizer use, and nitrate concentration. (See table 4.)

Data from the 82 well sites sampled in 1984 were used in a linear regression equation to determine which of the 10 variables were related to water quality. Correlation between nitrate concentrations or triazine-herbicide concentrations and each of the selected independent variables were performed. Rankings based on these correlation coefficients indicate the relative importance of the relation (table 4).

Three of the nine independent variables (hydraulic conductivity, well depth, and irrigation-well density) had correlation coefficients with nitrate concentrations greater than 0.40. Six of the nine independent variables (hydraulic conductivity, specific discharge, well depth, annual precipitation, irrigation-well density, and nitrate concentration) had correlation coefficients with triazine-herbicide concentration equal to or greater than 0.40. The confidence level for these correlations was 95 percent. This indicates that concentrations of nitrate and triazine herbicides in ground water are sensitive to local hydrogeologic, climatic, and land-use characteristics.

To evaluate the effects of more than one variable at a time, multiple linear regressions were computed for nitrate and triazine-herbicide concentrations. A combination of three variables (well depth, irrigation-well density, and nitrogen-fertilizer use) explained 51 percent of the total variation of nitrate concentration in these samples of ground water. The remaining six variables explained less than 2 percent of the total nitrate variation when added to the regression model, and so could be ignored. Similarly, two variables (specific discharge and well depth) explained 60 percent of the variations in triazine-herbicide concentrations.

The physical interpretation of these equations implies that nitrate and triazine-herbicide concentrations are greater in ground water that is near the surface and beneath fields that are heavily irrigated and fertilized with nitrogen. The equations also suggest that ground-water contamination with these chemicals is greater in areas with high hydraulic conductivities and (or) steep hydraulic gradients.

When nitrate concentration is combined with specific discharge in a two-variable equation, 84 percent of the variation in triazine-herbicide concentration is explained. The remaining variables each explained less than 1 percent of the total variation when added to the regression model. Nitrate concentrations alone, however, explained 61 percent of the variation in triazine-herbicide concentrations. This indicates that nitrate concentrations may be an inexpensive test to identify areas of the High Plains aquifer where the presence of detectable amounts of triazine-herbicides in ground water might be expected.

SUMMARY

The quality of shallow ground water in the High Plains aquifer in Nebraska is affected by the application of nitrogen fertilizers and triazine herbicides at the surface. These effects are greatest in intensely irrigated areas where agricultural chemicals can more easily be infiltrated to the subsurface.

A trend of increasing nitrate concentrations in water from the High Plains aquifer in study area 1 (Buffalo and Hall Counties) is statistically significant for 1960 to 1983. Nitrate concentrations may be increasing in the other five study areas, but insufficient data prevent the detection of such trends.

Based on both pre-1984 and 1984 data, concentrations of triazine herbicides greater than the reporting limit probably are common in ground water of many areas of Nebraska. Detectable concentrations were found in 32 percent of the samples collected during 1984 from parts of 10 Nebraska counties. Pesticide-use data collected during the study and from published reports indicate that the potential exists for ground-water contamination with other widely used pesticides; however, data presently are not available to evaluate the extent of contamination. The data do suggest that many of the hydrogeologic, soil, climate, and land-use variables that are associated with nitrate contamination of ground water are also associated with pesticide contamination of ground water.

Multiple-regression analyses were used to test the adequacy of nine variables in predicting nitrate and triazine-herbicide concentrations in ground water. Three variables (well depth, irrigation-well density, and nitrogen-fertilizer use) explained 51 percent of the variation in nitrate concentrations. Two variables (specific discharge and well depth) explained 60 percent of the variation in triazine-herbicide concentrations. Similarly, with the addition of nitrate concentration as a variable, two variables (nitrate concentration and specific discharge) explained 84 percent of the variation in triazine-herbicide concentrations. Nitrate concentration alone explained 61 percent of the total variation. This suggests that nitrate concentration may be an inexpensive test to identify areas of the High Plains aquifer where the presence of detectable amounts of triazine-herbicide concentrations in ground water might be expected.

Table 5. Occurrence of nitrate and triazine herbicides in the six study areas of the High Plains aquifer, Nebraska, 1984

[ND = Not detected; < = less than]

	Study area (see figure 49 for location)					
	1	2	3	4	5	6
	NITRATE (reporting limit, 0.1 milligrams per liter)					
Number of samples:						
Analyzed	15	9	15	10	11	22
Nitrate detected	15	9	15	10	11	22
Concentration, in milligrams per liter:						
Median	2.2	7.1	2.3	5.8	3.3	3.6
Mean	13.1	6.4	2.4	8.2	4.6	9.1
Range	0.1–45.0	0.2–14.0	1.0–4.0	2.5–28.5	2.4–13.0	0.2–39.0
	TRIAZINE HERBICIDE (reporting limit, 0.1 micrograms per liter)					
Number of samples:						
Analyzed	10	9	9	6	10	13
Triazine detected	5	4	0	2	2	5
Concentration, in micrograms per liter:						
Median[1]	0.08	0.01	ND	<0.01	<0.01	<0.02
Mean[1]	0.31	0.05	ND	0.39	0.07	0.10
Range[1]	<0.1–1.43	<0.1–0.30	ND	<0.1–2.30	<0.1–0.71	<0.1–0.90

[1] Values below the reporting limit were estimated using the methods proposed by Helsel and Gilliom (1986).

Hydrogeologic, climatic, soil, and land-use variables can be related to nonpoint-source ground-water contamination in agricultural areas of Nebraska. Further testing will determine the reliability and transferability of these relations to other agricultural areas. The seriousness of the ground-water quality problem in Nebraska is recognized by State Legislative Bill 894, which authorizes the establishment of special ground-water-quality protection areas by local Natural Resources Districts or by the Nebraska Department of Environmental Control. Area designations are restricted to nonpoint sources of ground-water contamination and may result in the regulation of agricultural-management practices within the area. The water-quality data obtained by this study and the relations revealed between contaminant concentrations and readily measured land-use and hydrogeologic variables will help in the identification of existing problem areas, the identification of potential problem areas, and the relative importance of management practices that contribute to the problem.

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NONPOINT-SOURCE GROUND-WATER CONTAMINATION

RELATION OF LAND USE TO GROUND-WATER QUALITY IN THE OUTCROP AREA OF THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM, NEW JERSEY

By George R. Kish, Eric F. Vowinkel, Thomas V. Fusillo, and William A. Battaglin

In the New Jersey Coastal Plain, the most extensively used aquifer for water supply is the Potomac-Raritan-Magothy aquifer system (Vowinkel, 1984, p. 22). This aquifer system crops out in a northeastward band from Pennsville to Perth Amboy (fig. 52*A*). The area is heavily industrialized with numerous landfills, surface impoundments, petrochemical storage tanks, and industrial facilities. It also includes more than 175 waste-disposal sites (see "New Jersey Ground-Water Quality" summary in this volume), of which 19 sites are on the U.S. Environmental Protection Agency's National Priorities List (U.S. Environmental Protection Agency, 1986, p. 21078-21098). These land uses, the potential sources of contaminants, and the regional geohydrology make the aquifer system vulnerable to contamination.

This article evaluates the effects of land-use activities on the quality of water in the Potomac-Raritan-Magothy aquifer system of New Jersey. It also is an example of nonpoint-source contamination of ground water as explained in this volume in the article "Factors Affecting Ground-Water Quality." The outcrop of the aquifer system was divided into a "southern" area and a "northern" area (fig. 52*A*) because these areas were investigated separately. The northern-area study was initiated as a result of the findings from the southern-area study. Data for the southern area are mostly from Fusillo and others (1984) and for the northern area from Barton and others (1987).

LAND USE AND POPULATION

Land use in the study area is classified according to categories developed by Anderson and others (1976) and is based on data obtained from high-altitude aerial photography (Fegeas and others, 1983) and New Jersey atlas overlays (New Jersey Department of Environmental Protection, 1975-76). Three broad land-use categories—undeveloped, which includes forested land, wetland, water, and otherwise barren land; agricultural; and urban, which consists of residential, commercial, industrial, transportation, and other built-up land—were used to classify the predominant (greatest percentage) land use within one-quarter mile radius of a well. In addition, for this article the urban land-use category in the southern study area was subdivided into industrial and urban-residential to enable a more detailed analysis to be made of the difference between those two land uses; this subdivision is not shown in figure 52*A*, but is discussed in the text and is shown in figure 53*B*. The percentage of land area in each category was then calculated from data in Fegeas and others (1983).

Much of the study area lies in the heavily urbanized corridor between Philadelphia and New York. By 1930, Camden, Trenton, and Perth Amboy had become major urban centers for manufacturing, whereas the other areas along the aquifer outcrop remained largely undeveloped or agricultural. Between 1950 and 1960, major land-use changes took place as population and manufacturing increased dramatically in this corridor, especially in previously undeveloped areas, and as suburban communities expanded around the urban centers. Metals production, electrical-machinery manufacturing, and chemical, plastics, and rubber production flourished (Brush, 1958, p. 94-97). By 1954, New Jersey led the Nation in the production of chemicals, and the petroleum industry had become firmly established in the Camden area (Cunningham, 1954, p. 193-199).

From 1950 to 1980, the population in the six counties that the study area includes increased by 87 percent to just over 2 million people, as agricultural and undeveloped areas became urbanized (Ellsworth, 1953, p. 5; U.S. Bureau of the Census, 1983, p. 368). During that 30-year period, Burlington and Middlesex Counties, which were primarily agricultural during the first half of the century, experienced population increases of 167 percent and 125 percent, respectively. In contrast, cultivated farmland decreased by 37 percent and 47 percent in the same two counties, for a loss of about 107,000 acres (New Jersey Crop Reporting Service, 1957, p. 9; U.S. Bureau of the Census, 1983, p. 381). According to the 1974 National Cartographic Information Center (NCIC) land-use data, the northern study area had 34 percent undeveloped land, 26 percent agricultural land, and 40 percent urban land; the southern area had 30 percent undeveloped land, 20 percent agricultural land, and 50 percent urban land.

POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM

The New Jersey Coastal Plain is a wedge of unconsolidated sediments that thicken and dip southeastward toward the Atlantic Ocean. The oldest sediments of the Potomac-Raritan-Magothy aquifer system are the Potomac Group and the Raritan and Magothy Formations of Cretaceous age, which overlie crystalline bedrock. This aquifer system consists of three aquifers, identified as the upper, middle, and lower aquifers (Zapecza, 1984, p. 14). A typical hydrogeologic section through the southern study area is illustrated in figure 52*C*. The lower aquifer is not present in the northern study area.

The Potomac-Raritan-Magothy aquifer system crops out in a narrow band, 3 to 6 miles wide, adjacent

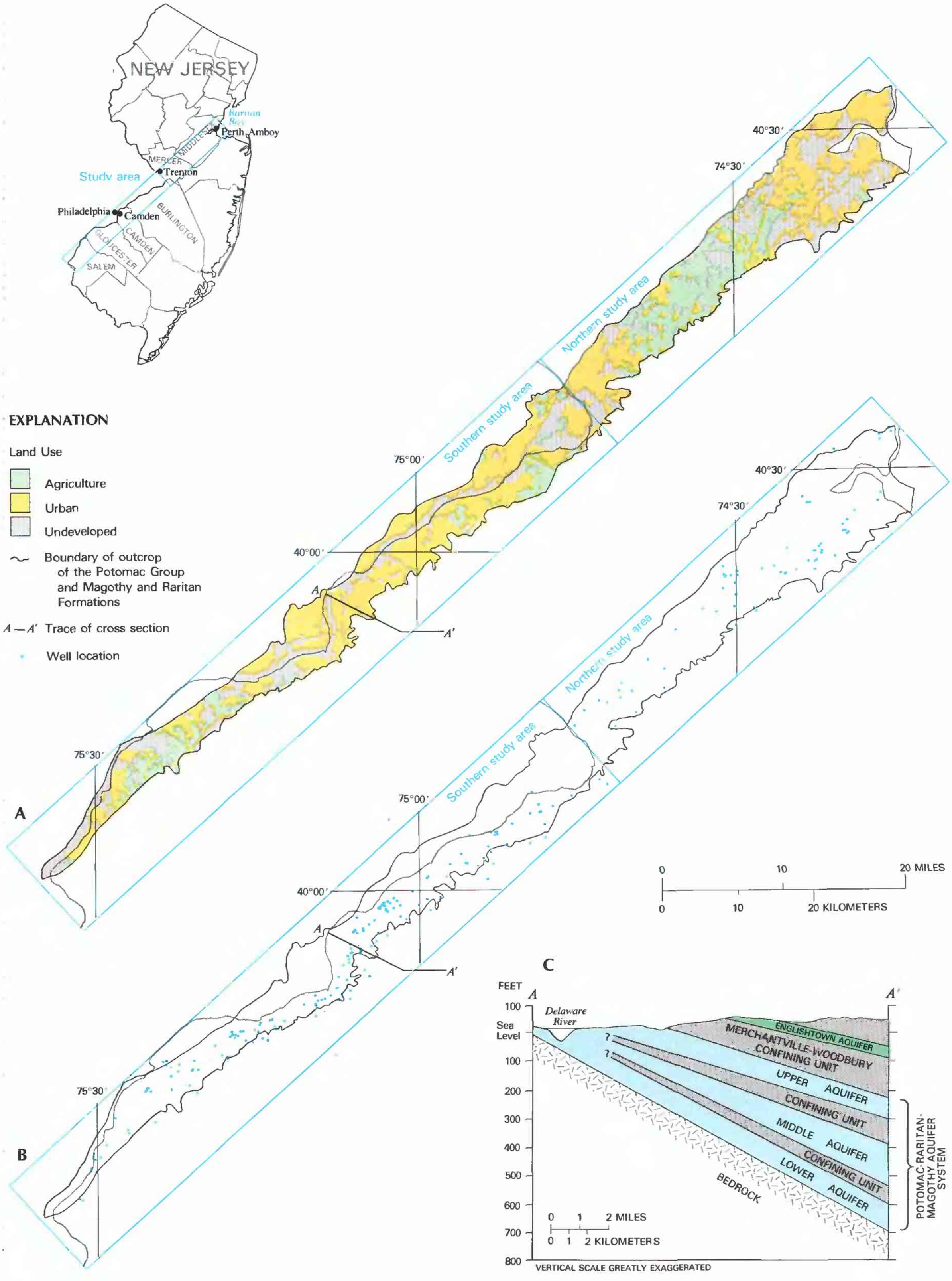

Figure 52. Land use and well locations along the most extensively used aquifer system in New Jersey. *A*, Land use and the Potomac-Raritan-Magothy aquifer system. *B*, Wells used in this study. *C*, Generalized hydrogeologic section through the southern study area. (Sources: *A*, Compiled by W.A. Battaglin from National Cartographic Information Center land-use data; *B*, from U.S. Geological Survey files; *C*, modified from Fusillo and others, 1984, fig. 2.)

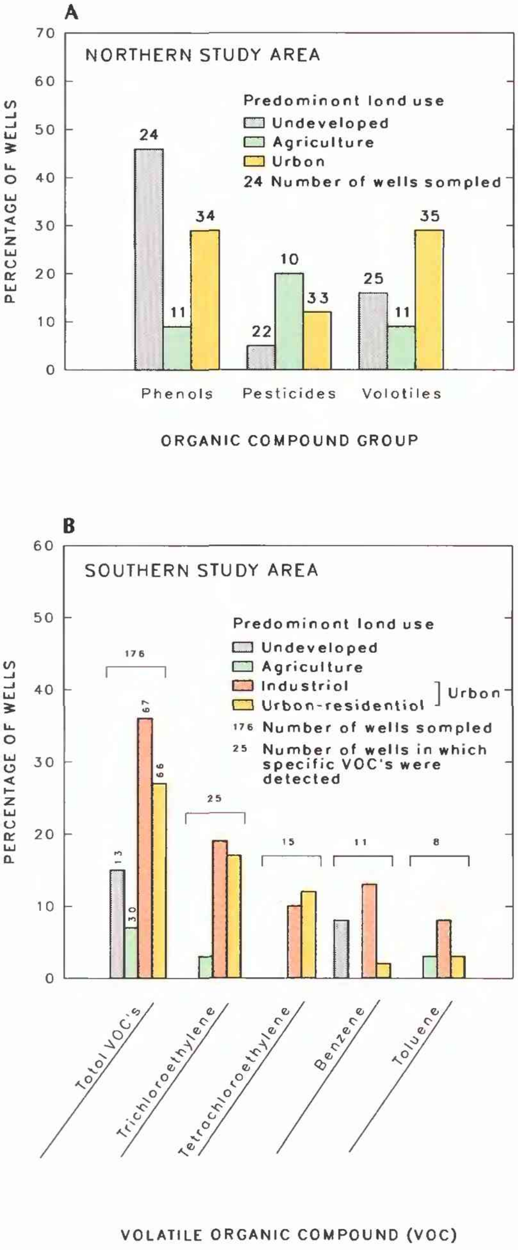

Figure 53. Frequency of detection of selected organic compounds by land use in the Potomac-Raritan-Magothy aquifer system, New Jersey. *A*, Northern study area; analysis of three types of organic compounds, 1984–85. B, Southern study area; analysis of selected volatile organic compounds, 1980–82. (Sources: *A*, Modified from Barton and others, 1987, fig. 16.; *B*, modified from Fusillo and others, 1985.)

to and under the Delaware River in southern New Jersey, and extends northeastward into Raritan Bay (fig. 52*A*). In general, the upper and middle aquifers are under water-table conditions in the outcrop area. Further downdip, the aquifer system is confined from above by the thick clay of the Merchantville-Woodbury confining unit. Increases in ground-water withdrawals in response to development in the study area have caused declining water levels in the aquifer system. In the northern part of the aquifer system, saline water from Raritan Bay has infiltrated (Leahy, 1985, p. 18); in the southern part of the aquifer system, flow from the Delaware River has been induced into the aquifer system (Luzier, 1980, p. 2).

LAND USE AND ORGANIC COMPOUNDS IN GROUND WATER

To represent the different land-use categories, water samples were collected from wells of various depths, yields, and uses. (Well locations are shown in figure 52*B*.) In the northern study area, these samples were analyzed between 1984 and 1985 for three types of organic compounds—phenols (69 wells), pesticides (65 wells), and aromatic and chlorinated volatile compounds (71 wells). In the southern area, the samples were analyzed between 1980 and 1982 for selected aromatic and chlorinated volatile organic compounds only (176 wells). The results are shown in figure 53.

NORTHERN STUDY AREA

Total recoverable phenols were found in 22 of the 69 wells (32 percent), and concentrations ranged from 1 to 11 μg/L (micrograms per liter). They were present in 46 percent of the wells in undeveloped land and in 29 percent of the wells in urban areas (fig. 53*A*). Phenolic compounds, which occur naturally in water (Thurman, 1985, p. 143), are degradation products of humic and fulvic acids (Stevenson, 1982, p. 426); consequently, greater abundance of these compounds in the undeveloped areas could be the result of degradation of vegetative matter.

Pesticides were detected at low concentrations (at or less than 0.5 μg/L) in 7 of the 65 wells (11 percent). No organophosphorus insecticides were detected, but three organochlorine insecticides (DDD, lindane, and dieldrin) were detected. The absence of organophosphorus insecticides reflects their declining use and their low persistence in the environment (Gilliom, 1985, p. 90); the presence of the organochlorine insecticides reflects their long-term persistence in the environment, even though the use of these insecticides has declined significantly since the mid-1960's (Gilliom, 1985, p. 87). Two triazine herbicides (atrazine and simazine) were detected. Atrazine is used primarily in corn-growing areas, and its use has increased rapidly in the last 20 years (Gilliom, 1985, p. 90). As might be expected, pesticides were found more frequently in agricultural areas (20 percent) than in other land-use areas (fig. 53*A*).

Volatile organic compounds were detected in 15 of the 71 wells sampled (21 percent). The most

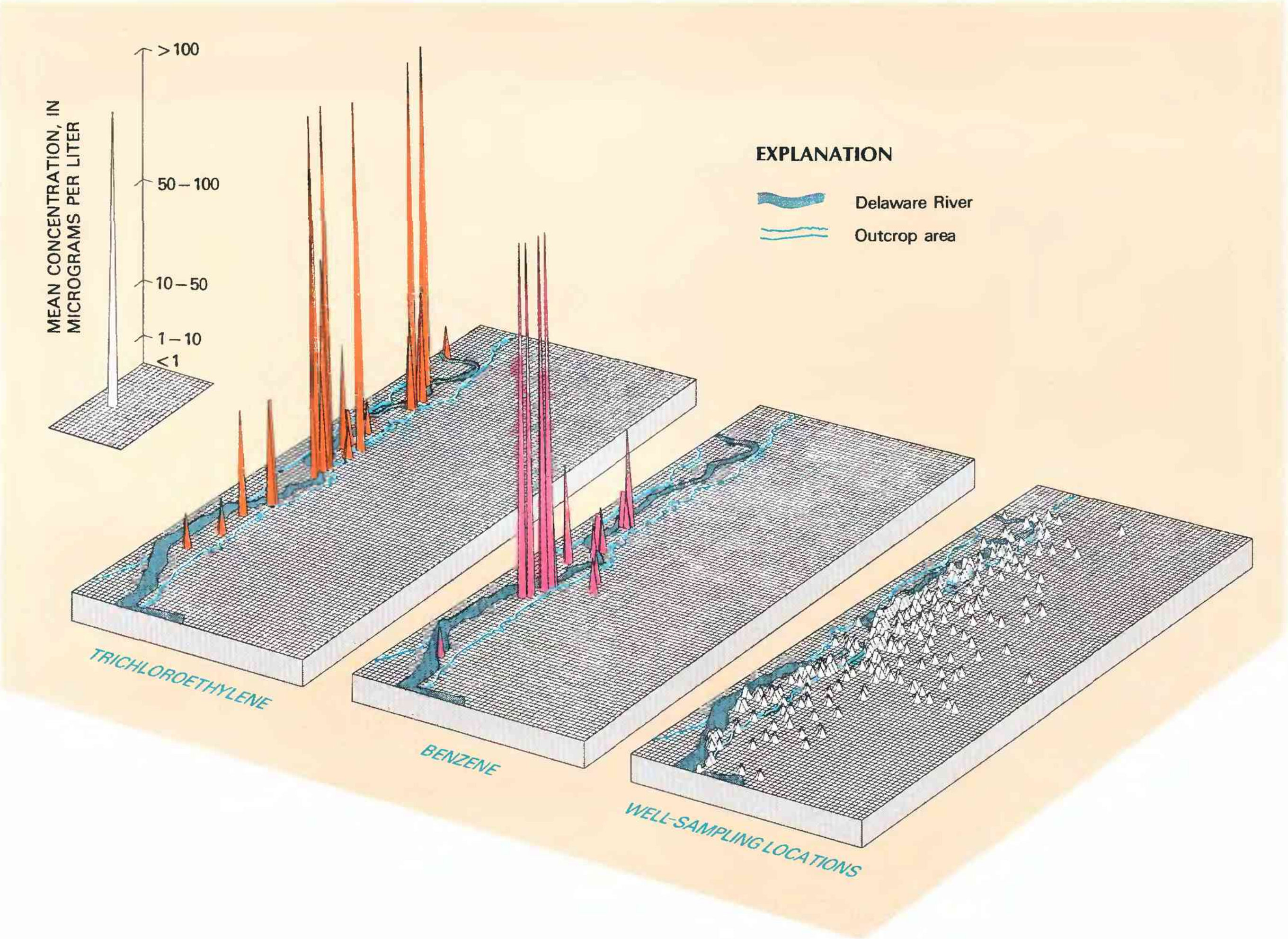

Figure 54. Mean concentrations of trichloroethylene and benzene in the southern Potomac-Raritan-Magothy aquifer system in New Jersey 1980–82. (Source: Fusillo and others, 1985, fig. 5.)

commonly identified compounds were tetrachloroethylene, benzene, 1,1,1-trichloroethane, toluene, and trichloroethylene, which commonly are used as industrial solvents, degreasers, or fuels. They were detected more frequently in water samples from urban areas (29 percent) than in agricultural areas (9 percent) or undeveloped areas (16 percent) (fig. 53*A*).

SOUTHERN STUDY AREA

The variation in the occurrence of four volatile organic compounds with land use in the southern study area is shown in figure 53*B*. At least one volatile organic compound was detected in 46 of the 176 wells sampled (26 percent). The most commonly detected compounds were trichloroethylene (detected in 25 of 176 wells), tetrachloroethylene (15 wells), benzene (11 wells), 1,1-dichloroethane (11 wells), toluene (8 wells), and 1,2-dichloroethane (7 wells). Trichloroethylene and tetrachloroethylene were found in about the same percentage of wells in industrial and urban-residential areas, possibly as a result of their widespread use in both areas. Benzene and toluene, on the other hand, were found much more frequently in industrial areas than in urban-residential areas. The apparently high percentage of wells contaminated with benzene in undeveloped areas might be biased by the small number of wells sampled (13) in undeveloped areas and the fact that two wells in undeveloped areas found to be contaminated were both affected by chemical or petrochemical operations located more than a quarter of a mile from the well.

Of the 46 wells found to contain volatile organic compounds, chlorinated volatile compounds were detected in 38 wells; two or more chlorinated volatile compounds were found in 19 of the 38 wells. Trichloroethylene and tetrachloroethylene, the two most frequently detected chlorinated compounds, were widely distributed and exhibited similar areal distribution patterns. Aromatic volatile hydrocarbons, such as benzene and toluene, exhibited distribution patterns somewhat different from those of the chlorinated volatile compounds. The difference between the distributions of trichloroethylene (the most commonly detected chlorinated volatile compound) and benzene (the most commonly detected aromatic volatile compound) in the southern study area is illustrated in figure 54. The areas of high concentrations of trichloroethylene and benzene occur in different parts of the outcrop area, most likely due to the different source of the compounds (Fusillo and others, 1985, p. 357). Benzene, widely used in the chemical industry, is a component of gasoline and was found most frequently in the petroleum-refining areas south of Camden. Trichloroethylene has been used as a degreaser, an industrial solvent, a dry-cleaning solvent, and a septic-tank cleaner, and was found more evenly distributed within industrial land.

Significant differences in the concentrations of volatile organic compounds were found between the outcrop area and the downdip area of the aquifer system (Fusillo and others, 1985, p. 357). The concentrations of trichloroethylene and benzene were significantly higher in the outcrop area than in the downdip area (fig. 54). Fusillo and others (1985) attribute these higher concentrations to downward head gradients, shallow depths to water, the high density of urban land uses and potential contamination sources, and the sandy surficial deposits and leaky confining units in the outcrop area.

SUMMARY

Specific groups of contaminants appear to be associated with certain land uses in the outcrop area of the Potomac-Raritan-Magothy aquifer system in New Jersey. In the northern study area, volatile organic compounds appear to be associated most closely with urban land, pesticides with agricultural land, and phenols with undeveloped land.

In the southern study area, chlorinated volatile organic compounds, such as trichloroethylene and tetrachloroethylene, were associated with industrial and urban-residential land, and aromatic volatile organic compounds, such as toluene and benzene, with industrial areas. Trichloroethylene was distributed fairly evenly in the urban areas, and appears to reflect its diverse use as a degreaser, dry-cleaning solvent, septic-tank cleaner, and industrial solvent. Benzene, a component of gasoline, was found principally in the petroleum-refining areas south of Camden. Contamination in the southern study area seems to be confined to the outcrop area, which has the greatest density of industrial and urban land uses. Little contamination has migrated downdip into the confined part of the aquifer system. The aquifer system downdip of the outcrop area is relatively uncontaminated because industrial land uses are absent, the head gradients are small, causing ground water to move slowly, and confining units thicken downdip, retarding leakage of contaminants from the land surface.

Heavy pumpage in the Camden area has significantly lowered ground-water levels in the Potomac-Raritan-Magothy aquifer system, creating a large cone of depression (Leahy, 1985, p. 12). These ground-water declines have led to a search for additional ground-water supplies for the Camden area. The results of these water-quality studies in the southern study area have assisted the New Jersey Department of Environmental Protection in developing new water supplies from uncontaminated areas.

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NONPOINT-SOURCE GROUND-WATER CONTAMINATION

RELATION OF LAND USE TO GROUND-WATER QUALITY IN THE UPPER GLACIAL AQUIFER, LONG ISLAND, NEW YORK

By David A. V. Eckhardt and Edward T. Oaksford

About 2.6 million people in Nassau and Suffolk Counties on Long Island, N.Y., depend on ground water for public supply. The sole source of potable water for those counties is the Long Island aquifer system, which provides sufficient freshwater to meet present (1986) demands. However, contamination from a variety of human activities has begun to restrict its use in a number of localized areas. This article presents an evaluation of the effects of those human activities on the ground-water quality in the upper glacial (water-table) aquifer on Long Island. It also is an example of nonpoint-source contamination of ground water as explained in this volume in the article "Factors Affecting Ground-Water Quality."

The approach used in this study is based on the premise that the types and amounts of chemicals that reach shallow ground water are related to land use (Helsel and Ragone, 1984; Ragone, 1984). Testing the relation between land use and ground-water quality required accurate characterization of land use, hydrogeologic conditions, ground-water quality (through representative sampling), and valid statistical analysis.

Nassau and Suffolk Counties, the two easternmost counties on Long Island (fig. 55) were selected for this evaluation because extensive data on land use and ground-water quality were available. These counties have a broad range and assemblage of land uses—highly developed suburban land, agricultural land, and relatively undeveloped, pristine land. The water-quality discussion is limited to selected major inorganic chemical constituents and selected volatile organic compounds because of their association with human activities and because considerable data on their occurrence in the Long Island aquifer system are available.

LAND USE AND POPULATION

Land use on Long Island has been described extensively by the Nassau County Planning Commission (1959), the Suffolk County Department of Planning (1962), the Nassau-Suffolk Planning Board (1968), the Long Island Regional Planning Board (1977, 1982a,b), and Koppelman (1978a,b). As part of the 1981 land-use survey by the Long Island Regional Planning Board (1982a), a color land-use map of the Nassau-Suffolk County region was divided into a grid of 762 square cells, each representing 1,440 acres. Land-use categories defined by the Long Island Regional Planning Board include vacant (undeveloped), recreational, open space, institutional, residential (subdivided into low, medium, intermediate, and high density based on dwelling-unit density), agricultural, transportation (including communications and utilities), commercial, marine commercial, and industrial lands. For the purposes of this article, the Planning Board's land-use categories are recombined into 10 land-use categories to provide the basis for grouping ground-water quality data (tables 6, 7). Recreational and open space are combined as recreational lands; intermediate- and high-density residential land use are combined as high-density use; and commercial and marine commercial are combined as commercial use.

To simplify the portrayal of land-use patterns on a map, these 10 land-use categories were further combined into six categories: undeveloped; recreational and institutional; low-density residential (includes low- and medium-density categories); high-density residential (includes intermediate- and high-density categories); agricultural; and industrial, commercial, and transportation. The dominant land use, in terms of land area, in each grid cell was plotted to represent the generalized 1981 land-use patterns in Nassau and Suffolk Counties (fig. 55*A*).

According to the 1981 land-use survey (Long Island Regional Planning Board, 1982a), residential land use accounted for 32 percent of the two-county area. The remaining land was vacant (27 percent), recreational (16 percent), agricultural (8 percent), transportation (7 percent), institutional (5 percent), commercial (3 percent), and industrial (2 percent).

Population density (fig. 55*B*) was derived from a population survey compiled from U.S. Bureau of the Census data for 1980 by the Long Island Regional Planning Board (Carole Swick, Long Island Regional Planning Board, written commun., 1985). The greatest concentration of population is in the southwestern part of Nassau County (more than 5 people per acre), whereas the lowest concentration is in the eastern half of Suffolk County (1 to 2 people per acre).

LONG ISLAND AQUIFER SYSTEM

Long Island is underlain by unconsolidated deposits that unconformably overlie gently southward-sloping, relatively impermeable crystalline bedrock (fig. 56). The deposits are less than 200 feet thick in northeastern Nassau County but increase in thickness southward to about 2,000 feet in south-central Suffolk County. The aquifer system consists of three major aquifers—the upper glacial, the Magothy, and the Lloyd. The upper glacial aquifer is composed of Pleistocene moraine and outwash deposits typical of glacial deposits in Northeastern United States. The water table is primarily in the glacial aquifer, which underlies about 92 percent of the two-county area (the glacial deposits are unsaturated in 8 percent of the region, primarily in northeastern Nassau and northwestern Suffolk Counties). In general, the aquifer is thickest near the north shore of the island and in

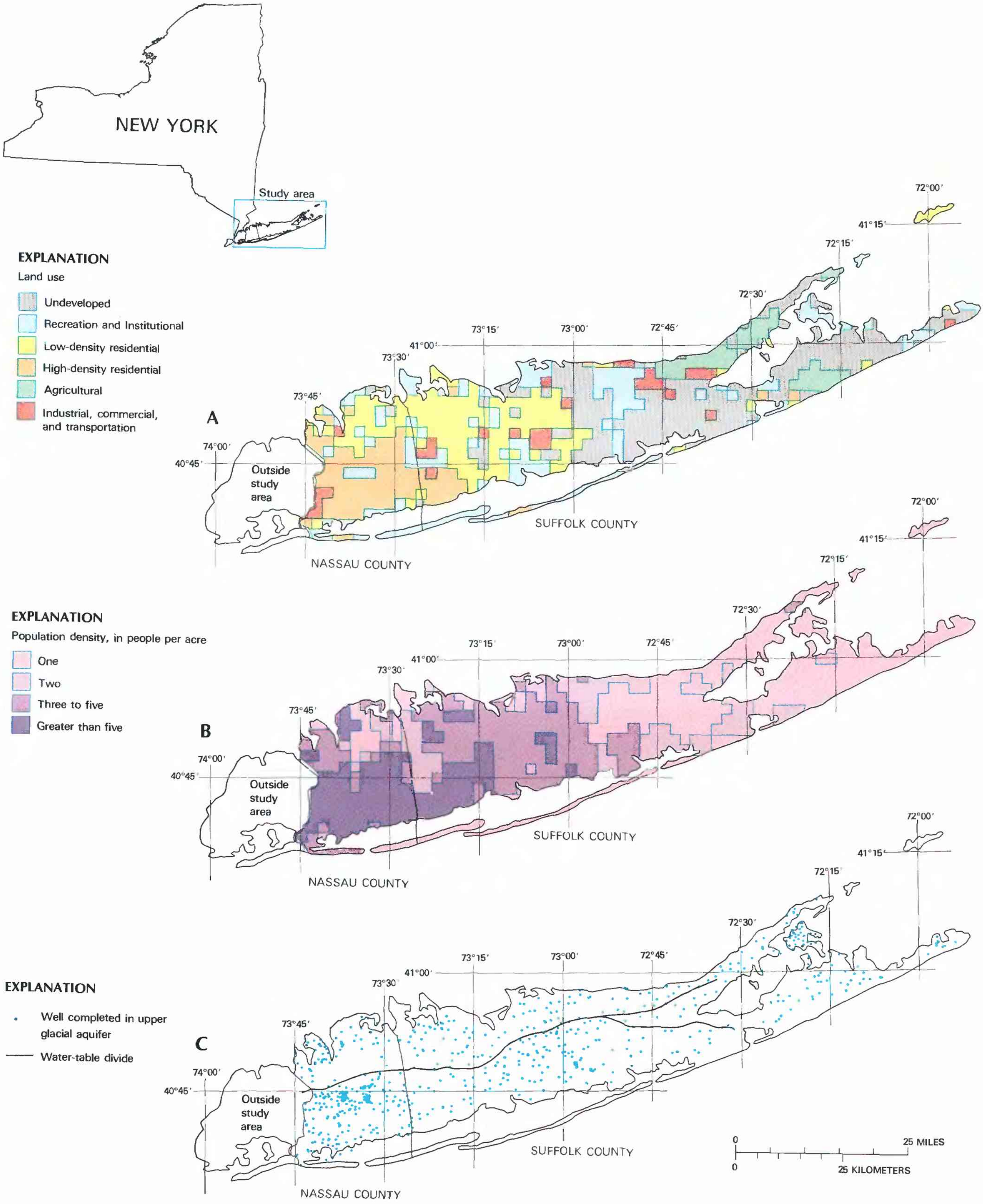

Figure 55. Land use, population density, and well locations, Nassau and Suffolk Counties, Long Island, New York. *A*, Major land uses, 1981. *B*, Population density, 1980. *C*, Wells used in this study. Note: Low-density residential is four or fewer housing units per acre (combined low- and medium-density residential categories from Long Island Regional Planning Board, 1982a); high-density residential is five or more housing units per acre (combined intermediate- and high-density residential categories from Long Island Regional Planning Board, 1982a); transportation category also contains communication and utilities facilities. (Source: Eckhardt and others, 1988.)

Table 6. Summary of selected inorganic chemical constituents in ground water in relation to land use, Nassau and Suffolk Counties, Long Island, N.Y., 1978–84

[Analytical data are from the most recent sampling date at each well. Median concentrations, expressed in milligrams per liter, were computed using methods of Gilliom and Helsel (1986). Sources: Modified from Eckhardt and others, 1988]

Land-use category	Inorganic chemical constituent								
	Nitrate, as nitrogen			Chloride			Total dissolved solids		
	Wells sampled	Median concentration	Tukey test[1]	Wells sampled	Median concentration	Tukey test[1]	Wells sampled	Median concentration	Tukey test[1]
Undeveloped	79	0.7	C	80	15	BCD	42	82	D
Recreational[2]	77	1.9	BC	96	13	CD	55	105	BCD
Institutional	64	2.4	AB	71	20	ABC	52	170	AB
Low-density residential[3]	29	2.8	AB	34	12	D	30	112	ABCD
Medium-density residential[4]	133	2.9	AB	134	16	BCD	81	78	CD
High-density residential[5]	71	4.6	AB	78	31	A	49	202	A
Agricultural	58	6.0	A	60	20	ABC	14	128	ABC
Transportation[6]	46	2.0	BC	57	23	AB	32	152	AB
Commercial	27	3.3	AB	33	25	AB	17	142	ABC
Industrial	26	2.3	AB	32	22	AB	19	110	BCD
All land uses	610	2.4	....	675	18	.....	391	111	.....

[1] Median concentrations with same letter for Tukey's test are not significantly different; for example, median nitrate concentrations in undeveloped areas (C) are not significantly different from those in recreational (BC) and transportation (BC) areas at the 95 percent level of confidence.

[2] Includes parkways.

[3] Less than two housing units per acre.

[4] From two to four housing units per acre.

[5] More than four housing units per acre.

[6] Includes utility and communication facilities.

Table 7. Summary of wells that had samples containing detectable amounts of selected volatile organic compounds in relation to land use, upper glacial aquifer, Nassau and Suffolk Counties, Long Island, N.Y., 1978-84

[Analytical data are from the most recent sampling date at each well. Reporting limit for each compound has varied from 5 to 1 micrograms per liter depending on the year and variable analytical interferences. Source: Modified from Eckhardt and others, 1988]

Land-use category	Percentage of wells sampled that contained detectable concentrations of indicated volatile organic compound (number of wells sampled given in parentheses)					
	1, 1, 1-Trichloroethane	Tetrachloroethylene	Trichloroethylene	Chloroform	1, 2-Dichloroethylene	Benzene
Undeveloped	0 (76)	0 (76)	0 (76)	7 (76)	0 (68)	0 (74)
Recreational[1]	19 (64)	12 (64)	11 (64)	8 (64)	0 (59)	0 (57)
Institutional	38 (47)	21 (47)	17 (47)	2 (44)	2 (46)	0 (42)
Low-density residential[2]	12 (26)	8 (26)	8 (26)	8 (25)	0 (24)	0 (21)
Medium-density residential[3]	29 (129)	21 (129)	13 (129)	4 (129)	4 (115)	2 (123)
High density residential[4]	42 (92)	33 (92)	37 (93)	22 (77)	12 (83)	2 (70)
Agricultural	0 (55)	2 (55)	4 (55)	4 (55)	0 (40)	0 (54)
Transportation[5]	17 (59)	15 (59)	14 (59)	14 (59)	2 (50)	9 (58)
Commercial	29 (49)	42 (48)	41 (49)	14 (49)	11 (45)	2 (49)
Industrial	47 (45)	51 (45)	44 (45)	9 (44)	12 (43)	2 (44)
All land uses	24 (642)	20 (641)	18 (643)	9 (622)	5 (573)	2 (592)

[1] Includes parkways.

[2] Less than two housing units per acre.

[3] From two to four housing uits per acre.

[4] More than four housing units per acre.

[5] Includes utitities and communication facilities.

eastern Suffolk County. Hydraulic conductivity is greatest (270 ft/d [feet per day] and higher) in the southern part of the island, where outwash deposits are coarse sand and gravel (McClymonds and Franke, 1972); it is about 130 ft/d and lower in the north-central area, where till deposits contain more silt and clay than elsewhere. The upper glacial aquifer is connected hydraulically to the underlying Magothy aquifer of Cretaceous age except along the southwestern part of the island (not shown in fig. 56) where the Gardiners Clay separates the two aquifers.

Fresh ground water originates as precipitation, which, on Long Island, averages about 44 inches annually. About half the precipitation percolates through sandy soils at land surface as recharge to the aquifer system; the remainder runs off, transpires, or evaporates. In general, water north of the regional ground-water divide, which trends east-west along the island, moves northward through the aquifer system toward Long Island Sound, and water south of the divide moves southward toward the Atlantic Ocean (fig. 55*C*). Horizontal-velocity components in the upper glacial aquifer generally range from 1 to 2 ft/d; vertical flow is much slower, especially where clay units are present. Residence time of water in the shallow upper glacial aquifer generally is less than 30 years (Franke and Cohen, 1972).

LAND USE AND GROUND-WATER QUALITY

Water-quality data used in this study are based on analyses of water samples from wells in the upper glacial aquifer. These data primarily are from the U.S. Geological Survey's National Water-Data Storage and Retrieval System (WATSTORE); additional data were provided by several Long Island agencies.

A total of 13,894 analyses were compiled from ground-water samples collected from 903 wells (fig. 55*C*) during the water years 1978 to 1984. Only the most recent analysis for each constituent of interest was used for each well in the statistical analyses; this method provided the basis for the determination of current water quality amid changing land-use conditions by equally weighting the data from each well. The study used wells screened in the uppermost part of the water-table aquifer (mostly upper glacial aquifer) to define the relation of land use to ground-water quality. These wells had a median screen depth below the water table of 31 feet and a 25th- to 75th-percentile range of 17 to 86 feet.

The water-quality data were grouped by the 10 land-use categories. The basis for grouping was the land use occupying the greatest percentage of land area in the one-half-mile radius around each well, which was identified from the 1981

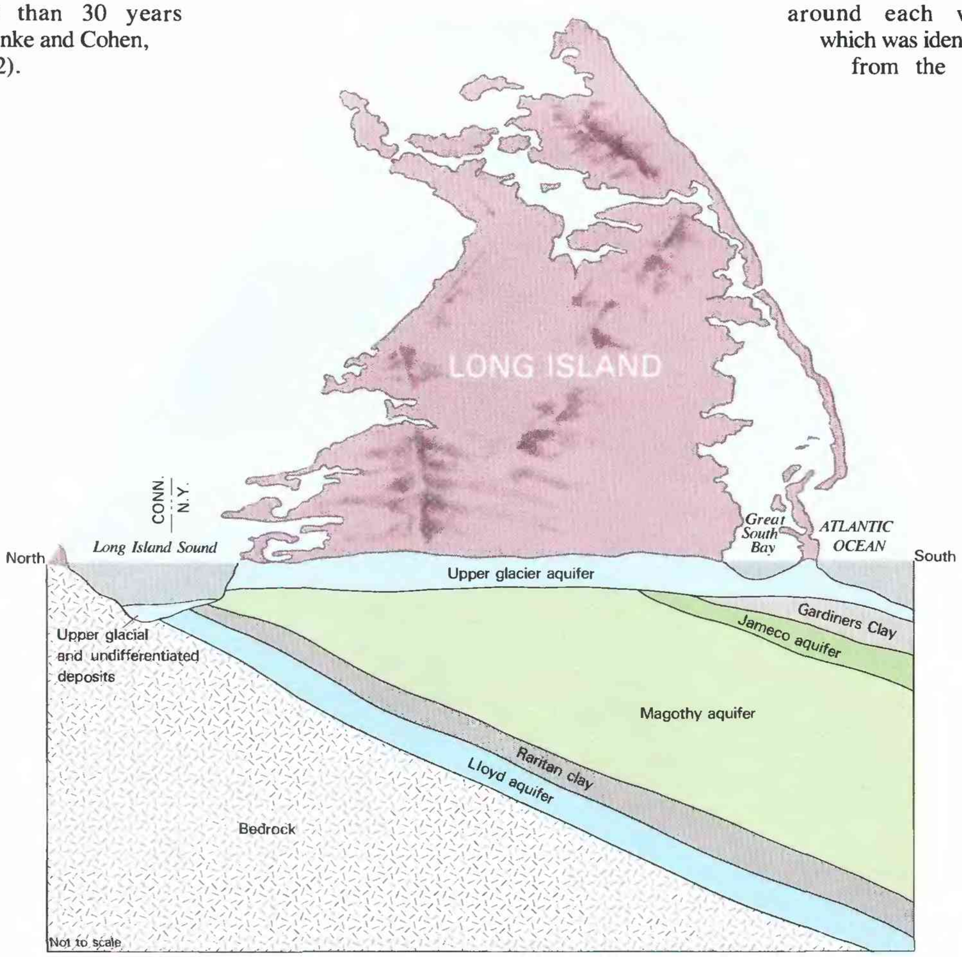

Figure 56. Generalized geologic section of the Long Island aquifer system in Nassau County, New York. (Source: Modified from Franke and McClymonds, 1972, p. F10.)

land-use map compiled by the Long Island Regional Planning Board (1982a). This one-half-mile radius of influence around each well was used because ground water in the upper glacial aquifer moves about one-half mile in 7 years at an average flow rate of 1 ft/d. Thus, the ground-water quality observed between 1978 and 1984 should reflect land-use conditions portrayed in 1981.

The strength of nonparametric statistical procedures in analyzing skewed data populations (Helsel and Ragone, 1984) was the basis for their choice in this study to test the hypothesis that ground-water quality is related to land-use practices. Each grouping of chemical constituents was tested for significant differences among land-use categories using the 95-percent confidence level, which implies that there is less than a 5-percent chance that the observed differences in ground-water quality among land-use categories occurred from a random arrangement of data.

INORGANIC CHEMICAL CONSTITUENTS

Statistical procedures (Kruskal-Wallis tests, *see* Conover, 1980) indicated that the 10 land uses differed significantly in concentrations of inorganic chemical constituents present in the underlying ground water. The pattern of those differences was identified by using Tukey's honest-significance tests (Stoline, 1981). Results for nitrate, chloride, and total dissolved solids are shown in table 6; results for other constituents are given in Eckhardt and others (1988). Tukey's results indicate that the highest concentrations of nitrate, chloride, and total dissolved solids occur in the agricultural, commercial, institutional, and high-density residential categories; the lowest concentrations occur in the undeveloped and recreational categories. More specifically, ground water from wells in undeveloped areas had the lowest median concentrations of nitrate, sulfate, potassium, calcium, and alkalinity and the lowest median specific conductance. Ground water from wells in agricultural areas had the highest median concentrations of nitrate, sulfate, and calcium, whereas ground water from wells in high-density residential areas had the highest median concentrations of chloride, potassium, and total dissolved solids and the highest median specific conductance.

Tukey's honest-significance tests indicate which median concentrations in table 6 are not significantly different from the median concentrations associated with other land uses at the 95-percent confidence level. Test results are shown by placing one or more letters in the "Tukey test" column for each constituent and land use. Median concentrations that have the same letter are not significantly different. For example, the median concentration of total dissolved solids associated with low-density residential land use (112 mg/L) has ABCD listed in the "Tukey test" column. This indicates that this median concentration is not significantly different from the total dissolved solids concentration of any of the other land uses because each of the other land uses has one (or more) of the letters ABCD listed. In contrast, the median concentrations for medium-density residential land use (CD) appears to be significantly different from

institutional (AB), high-density residential (A), and transportation (AB) land uses.

Concentrations of nitrate in ground water from each of the land-use categories are shown in figure 57. The range in concentrations is proportional to the level of contamination—the largest range and median concentrations of nitrate are in agricultural and high-density residential areas, whereas the smallest range and median concentrations are in undeveloped, transportation, and recreational areas.

VOLATILE ORGANIC COMPOUNDS

Ground water in the upper glacial aquifer has been contaminated by volatile organic compounds from a variety of sources, including industrial discharges, landfills, municipal-wastewater discharges, underground storage tank leaks, industrial spills, and domestic cesspools (Nassau County Department of Health, 1981; Suffolk County Department of Health Services, 1984). The most common volatile organic compounds detected in water from the upper glacial aquifer (table 7) were 1,1,1-trichloroethane (TCA), tetrachloroethylene, trichloroethylene (TCE), and 1,2-dichloroethylene, possibly derived from industrial solvents and cesspool cleaners; chloroform, possibly derived from the oxidation of humic substances by chlorine; and benzene, possibly derived from gasoline, other fuels, or solvents.

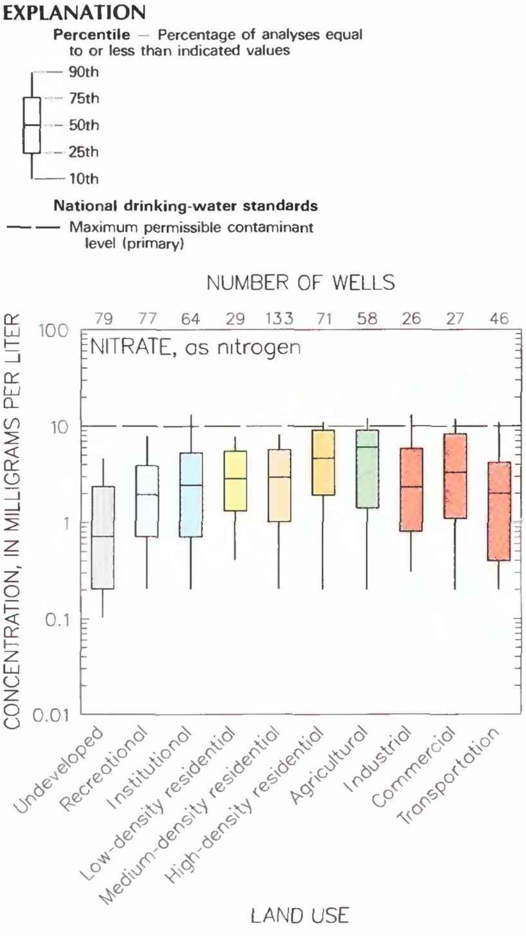

Figure 57. Nitrate concentrations in ground water in relation to land use, Nassau and Suffolk Counties, Long Island, New York, 1978–84. The reporting limit for nitrate has varied from 0.4. to 0.0 milligrams per liter depending on the year and variable analytical interferences. (Source: Eckhardt and others 1988.)

1,1,1-Trichloroethane, tetrachloroethylene, and trichloroethylene were detected most frequently in water from wells in industrial, commercial, high-density residential, and institutional land-use areas. These compounds were detected less frequently in water from recreational areas (which include vehicular parkways that traverse Long Island), transportation areas, and medium-density residential areas. These compounds were not detected in water from undeveloped areas and were detected infrequently in water from agricultural and low-density residential areas. Chloroform was the only volatile organic compound detected in water from all 10 land-use categories; it was found most frequently in water from wells in high-density residential areas (22 percent of wells). Benzene was detected most frequently (9 percent of wells) in water from wells in transportational areas.

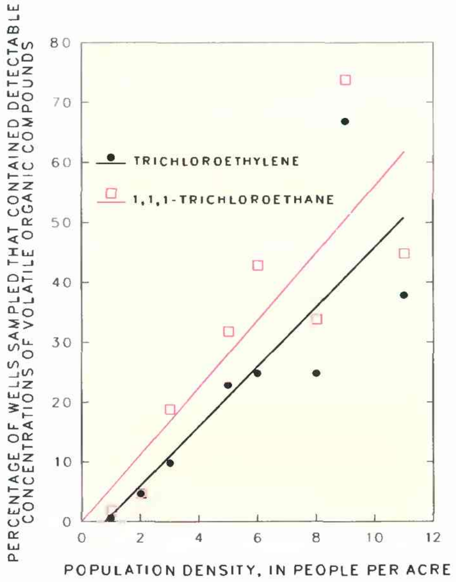

Figure 58. **Percentage of wells in which trichloroethylene and 1,1,1- trichloroethane were detected in relation to population density, Nassau and Suffolk Counties, Long Island, N.Y., 1978–84.** Reporting limits ranged from 5 to 1 micrograms per liter over time. (Source: Eckhardt and others, 1988.)

In many areas where population density commonly exceeds 5 people per acre, land use is a complex mixture of the more intense land-use categories. Population density, in this case, showed significant correlation to selected organic compounds. Correlations between population density and the detection frequencies of trichloroethylene and 1,1,1-trichloroethane were made by plotting the frequency of detection for each compound for wells falling within a given population-density category. The coefficient of determination (R^2) of a linear regression between detection percentages and population density (fig. 58) is 0.69 for trichloroethylene and 0.72 for 1,1,1-trichloroethane. The relation was developed only for areas having fewer than 11 people per acre because insufficient data existed for areas of higher population density. Both organic compounds are detected more frequently as population density increases, most notably in south-central Nassau County and southwestern Suffolk County where population density commonly exceeds 5 people per acre.

SUMMARY

Results of this study indicate that contamination from human activities has affected water quality in the upper glacial (water-table) aquifer in Nassau and Suffolk Counties of Long Island. Statistical comparisons of water-quality data in 10 land-use categories indicate a correlation between land use and water quality in the aquifer. Specific results include:

- *Ground water from undeveloped areas* had the lowest median concentrations of nitrate, sulfate, potassium, calcium, and alkalinity and the lowest median specific conductance. Volatile organic compounds were detected least frequently in water from wells in this category.
- *Ground water from agricultural areas* had the highest median concentrations of nitrate, sulfate, and calcium.
- Ground water from high-density residential areas had the highest median specific conductance and the highest median concentration of chloride, potassium, and total dissolved solids. Water from wells in this category also had the second-highest median concentration of nitrate, the second-highest detection frequency of 1,1,1-trichloroethane, and the third-highest detection

frequency of trichloroethylene and tetrachloroethylene. Chloroform was detected in water from wells in all land-use areas, but most frequently in high-density residential areas. Volatile organic compounds were detected relatively infrequently in ground water from wells in low-density residential areas.

- 1,1,1-Trichloroethane, tetrachloroethylene, and trichloroethylene, which were the most commonly found volatile organic compounds, were detected most frequently in ground water from industrial, commercial, institutional, and high-density residential areas.
- Spatial distribution of trichloroethylene and 1,1,1-trichloroethane was related directly to population density. The compounds were detected most frequently in central and south-central Nassau County and west-central Suffolk County, where population density commonly exceeds 5 people per acre. Land use in these areas is a heterogeneous mixture of medium- to high-density residential, commercial, industrial, institutional, and transportation areas, which together affect ground-water quality in a way that can be quantitatively represented best by population density.

Refinement of land-use and water-quality relations on Long Island will help ground-water management agencies to identify areas of potential ground-water contamination, thereby providing a basis for improvements in ground-water monitoring and ground-water protection strategies.

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INSTITUTIONAL AND MANAGEMENT ISSUES
POLICY CHALLENGES IN PROTECTING GROUND-WATER QUALITY

By Marian Mlay[1]

Ground-water contamination is a growing problem that has greatly challenged the ingenuity and institutional capacity of government at all levels in the United States. Although national attention has been drawn to major incidents, such as the 'Valley of the Drums,'' newspapers daily report on more local concerns. There may be reports of the closure of public drinking-water wells because of industrial pollution, the discovery of an abandoned landfill, or proposals to spread sludge from municipal waste-treatment plants on local fields. Such reports have raised widespread concern about the current and future suitability of ground water as a source of drinking water and have led to a search for the best means to protect the resource. The issuance of a U.S. Environmental Protection Agency (EPA) ''Ground-Water Protection Strategy'' and the recent passage of two new laws by Congress to help States protect their ground-water resources are among a number of steps being taken to address the ground-water contamination problem.

COMPLEXITIES OF GROUND-WATER PROTECTION

For many reasons, protecting ground water is substantially more difficult than protecting air and surface-water resources. The concentrations of contaminants found in aquifers may be considerably higher than those found in surface waters. The rates of movement and mixing of ground water are dramatically slower than those for air and surface water. As a result, the dilution of contaminants is much less in ground water than in surface water. Ground water generally moves inches per day whereas rivers flow at the rate of feet per second. Ground water is not as easily accessible for monitoring as air and surface-water resources are. Taking a sample of ground water may require drilling a well and the information obtained may be significantly different from that collected a short distance away from the sampling point.

While there is over a quarter century of Federal management experience in controlling surface-water pollution, the history of human-induced contaminants in ground water is just beginning to be documented. Data are sorely lacking, as are the highly skilled personnel needed to collect and interpret data. The range of pollutants to be addressed is considerably broader and more complex than before as early environmental regulators were solely concerned with physical and inorganic chemical pollutants, such as particulates in the air and suspended solids in surface water. Modern regulators are faced with a host of esoteric synthetic chemicals that may be potentially carcinogenic or mutigenic to humans in concentrations as low as parts per trillion.

The magnitude of the regulatory problem also is different. To protect air quality, the country must regulate a relatively small number of automobile manufacturers, a few thousand large industries, and a somewhat greater number of smaller industries. Protecting ground water involves controlling discharges from tens of thousands of hazardous waste dumps, 23 million septic-tank drain fields, hundreds of thousands of surface impoundments, and millions of underground storage tanks, and the use of millions of pounds of pesticides and fertilizers each year. The potentially regulated community contains not just a relatively few big industries, but countless small businesses, farmers, and even individuals. Further, few technologies exist that completely prevent contamination from most sources and those that are available may be too expensive or societally unacceptable. If contamination cannot be contained, the uses of the contaminants must be altered, sometimes dramatically.

Although prevention is complex, cleanup of contaminated ground-water is even more difficult. For surface water and air resources, stopping the source of contamination usually enables the remaining contaminants to be diluted and transported from the area. In ground water, containing the source of ground-water contamination is only the start. Contaminants may adhere to soils and aquifer materials, or they may be chemically transformed into more dangerous compounds. Consequently, steps must be taken to prevent the movement of the contaminants into drinking-water supplies. Wells may have to be drilled to pump out the contaminated ground water before it reaches drinking-water supply wells. Otherwise, the drinking-water well may have to be abandoned for another source, if an alternative source exists, or the water may have to be treated before use. These options can be enormously expensive, and they are not always effective.

Finally, the public concern over ground water appears to be even greater than in other environmental media. For example, people have long abandoned the use of water directly from rivers and streams for human consumption without some form of treatment, but they still expect ground water to be free of any contamination and always readily available for drinking water.

EPA's GROUND-WATER PROTECTION STRATEGY AND PROGRAMS

In the late 1970's, the EPA recognized that ground-water contamination was a growing problem and that the Federal role in this area was fragmented, largely undefined, and clearly controversial. The agency drafted and later issued its ''Ground-Water Protection Strategy'' (U.S. Environmental Protection Agency, 1984), to document what is known about the problem and, given the historical and legal context of

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[1] Director, Office of Ground-Water Protection, U.S. Environmental Protection Agency.

ground water, an appropriate EPA approach. This context was a key to the deliberation. In particular, the approach recognizes that the States have the principal role in protecting ground water, mainly because of their historical and legal roles in land use, water allocation, and public health protection. The lack of overriding Federal legislation also suggested that the States would have to assume a major role in ground-water protection.

The Federal Government, in contrast, is responsible for controlling certain contaminants and activities affecting ground water, such as the use of pesticides and control of hazardous-waste sites. It also conducts research, sets drinking-water standards, characterizes the resource, gathers information, and provides technical and financial assistance to the States. Several Federal agencies are involved to varying degrees with protecting ground-water quality. EPA has the lead ground-water-quality protection role while the U.S. Geological Survey provides substantial information characterizing the Nation's ground-water resources and their hydrogeologic and geochemical framework. Other agencies of the Departments of the Interior and Agriculture are responsible for protecting the resource in the extensive lands under their management, and the Department of Defense is responsible for controlling potentially polluting sources of contamination associated with defense installations.

EPA's strategy was designed to rationalize and better use the many statutes EPA has for protecting ground water and for responding to the call from the public and State and local governments for assistance. These statutes include the Resource Conservation and Recovery Act (RCRA); the Toxic Substances Control Act (TSCA); the Safe Drinking Water Act (SDWA); the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); and the Clean Water Act (CWA). The strategy has four broad objectives:

- To enhance the ability of States to respond to specific ground-water contamination problems and to prevent future contamination by assembling needed institutional relations and authorities.
- To deal more effectively with ground-water contamination problems of major national concern, such as pesticides, underground storage tanks, and other diffuse sources of contamination.
- To create a consistent and rational policy for the protection and cleanup of ground water, and to answer the question "how clean is clean?".
- To strengthen EPA's internal ground-water organization, recognizing that ground water is an integral and often predominant part of most EPA programs.

Implicit throughout the strategy is the hard question of "who pays?". Certainly CERCLA provided some answers for the cleanup of abandoned hazardous waste dumps. But for the many thousands of smaller sites and for the arduous process of preventing future contamination, this question remains, as yet, unanswered.

The issues defined in the strategy have not changed since it was written; however, the sophistication and intensity of the debate have heightened, and the debate has moved to a broader arena.

POLICY ISSUES FACING FEDERAL, STATE, AND LOCAL GOVERNMENT

FEDERAL AND STATE ROLES

Clean-air and surface-water statutes established Federal responsibility for setting and enforcing resource protection standards with provisions for program delegation to eligible States. Comparable Federal authority does not exist for ground water; rather, Federal statutes focus on sources of contamination or contaminants.

More and more contaminant sources and chemicals are being widely recognized as affecting ground water. As the number grows, questions increase about how to prevent contamination of ground water by the 33 categories of highly localized sources (Office of Technology Assessment, 1984, p. 45). One approach might be to require Federal permits for all dischargers to ground water. Another might be to establish an ambient standard for ground-water protection and require all dischargers to meet that standard. Both approaches are major components of past legislation that focused on reducing contaminant loadings in air and surface water. Unfortunately, these approaches were not totally effective for air and surface water, and they are far less effective for ground water where attenuation mechanisms are less well understood and the contaminant loadings cannot be similarly measured and managed. Further, Federal regulation of the many sources of contamination affecting ground water would directly involve EPA in local land-use determinations, such as the approval of septic systems or industrial sites, the approval of pesticide and fertilizer usage on particular sites, and the water allocation decisions to prevent saltwater intrusion in coastal areas.

Another approach, used in the EPA "Ground-Water Protection Strategy" and in the Safe Drinking Water Act Amendments of 1986 (SDWAA), is to help and encourage States to initiate protection programs that are designed to meet particular State needs and hydrogeologic settings. The EPA Strategy fostered the creation of State ground-water protection strategies, which EPA now supports through Clean Water Act, section 106 grants. Nearly all States now have or are in the process of defining State ground-water protection strategies and some have made significant progress in implementing their strategies.

The SDWAA Wellhead Protection Program provides Federal support for States to focus protection efforts on high-risk areas around public water wells. It too affords substantial management flexibility for States to accommodate local situations. This approach avoids Federal intrusion into land-use and water-allocation decisions, allows flexible protection approaches to evolve, and permits the States to focus attention on categories of sources that actually affect their ground waters in any given location. This approach also maintains a State and Federal partnership, which recognizes that each party has a concern for and understanding of the problem. It creates a national effort through leadership and the advancement of knowledge, rather than unilateral requirements.

EPA'S DIFFERENTIAL PROTECTION POLICY

"How clean" ground water should be—either as a result of cleanup or preventative actions—also has been a hotly debated issue. Establishing a goal for ground-water protection is the core of EPA's strategy. EPA recognized that despite the flexibility of the goals written into most of its statutes, there is an expectation by some that ground water should never receive contaminants and should be restored to predevelopment conditions. For synthetic chemicals, ambient concentrations would be essentially zero. In the majority of cases, a nondegradation policy for ground water is a technically and socially impossible goal, although it is appealing to a public that greatly fears synthetic chemicals in their ground-water supply.

The difference between expectation and reality is recognized by EPA. In its strategy, the Agency adopts a differential protection policy, which recognizes that not all ground water is the same and that there is a need for greater prevention and cleanup of high-risk, high-use areas. Clearly some ground water is used for drinking water and some has potential for such use. But some is not potable either because of natural salinity or because of extensive and widespread human-induced contamination. The policy also recognizes that different hydrogeologic settings of ground water are more or less vulnerable to contamination and that protection actions can be varied depending on these conditions.

EPA developed a ground-water classification system that establishes a framework and process for applying a differential protection policy to EPA programs. A similar approach has already been adopted in about half the States and is often "back-doored" by others whose stated nondegradation policy is unworkable in site-specific situations. States often apply aquifer classification prospectively through mapping of aquifers and critical ground-water areas. In contrast, EPA applies classification on a case-by-case basis to individual Federal permits and cleanup activities associated with the various statutory authorities that EPA administers.

Another aspect of this "how clean is clean" issue is whether the same standard should be used for prevention and for cleanup. The reference point that EPA and the States have used for ground water is the drinking-water standard or maximum contaminant levels (MCL) or equivalents, with deviations from that reference point based on use, value, and vulnerability of the resource. The EPA establishes prevention programs that will attain the MCL or a higher standard, if feasible. However, cleanup of the ground water beyond elimination of the source of contamination is extremely expensive and rarely completely successful. It is obvious that public water-supply systems are unlikely to install new wells at or near a former Superfund site. Yet, there is some public demand to restore these sites to levels that are cleaner than drinking-water standards. Responding to this demand in most cases would stress public and private funds that would preserve water supplies far more effectively if the funds were used to prevent future contamination by utilizing technology, best management practices, and siting restrictions. There are, furthermore, serious technical reservations about our ability to achieve long-term remediation to such extremely low concentrations. Distinguishing between standards for cleanup and prevention, and designing ground-water programs that provide for greater balance between these two activities, will provide greater water-supply protection.

PROGRAM MANAGEMENT

Effective management of ground-water protection activities within EPA and the rest of the Federal Government also is a perplexing problem. EPA recognized the futility of creating a single organizational unit to encompass all ground-water activities because ground water is an integral part of most EPA programs. Consequently, EPA established a ground-water office to provide leadership to the development of its ground-water policy, to coordinate ground-water activities at the regional level, and to manage programs that focus on the ground water as a resource including State strategies and wellhead-protection programs. Although such a cross-cutting role without direct program-management authority is difficult, building a consensus by using the strategy as a focal point appears to be a realistic approach to knitting together many individual programs. Many State governments have used the creation of State Ground-Water Coordinating Committees and State Ground-Water Protection Strategies to build a unified approach among many State agencies.

WHO PAYS?

And finally, who pays for the cleanup of contaminated ground water and for the damages caused by contamination? What costs should be borne by local, State, or Federal Government or the private sector? Should a farmer be financially responsible for the contamination caused by his use of a pesticide, or should the manufacturer of that pesticide be responsible? Should a public water-supply system bear the costs of associated treatment or should a private well owner bear the cost of moving the well or drilling it deeper to avoid that pesticide contamination? Should the Federal Government pay to test all community public water-supply wells for a wide array of contaminants given that one round of tests would cost about $30 million? Should fees be charged to all potential dischargers to pay for prevention and cleanup programs? What administrative arrangement would be feasible to charge fees to the 23 million septic tank owners in the Nation or every business that might spill a chemical on the ground?

These questions are very hard to answer because of the difficulty in tracking contaminants, the extensive area of contamination that may result from some human activities, and the high costs and long-term uncertainty of current technologies for pollutant remediation.

FUTURE TRENDS

Perhaps the most obvious trend in public policy related to ground water is the rising number of forums, committees, institutes, and legislators who view ground-water contamination as a major issue and who are engaging in the debate at the local, State, and national level. Many challenges face us as we try to forge a public policy for ground-water protection among these disparate groups. Progress must be made despite the compromises inherent in our limited though growing knowledge of ground-water resources and the threats to those resources. It also must be recognized that any human activity, no matter how carefully it is controlled, poses some risk to ground water. To be effective, public policy must take advantage of and build on existing institutions and laws. Public policy must be flexible to allow for changes in technology and public perception. Finally, the policy must be understood and supported by the public.

Ground-water protection presents a major challenge to the Nation. The costs of detection, prevention, and cleanup are considerably higher than we have experienced with other forms of pollution. The task facing all levels of government to manage the resource for its intended uses is difficult and controversial. New understanding and new ideas are needed to achieve a workable and publicly acceptable approach. EPA believes its Ground-Water Protection Strategy and the thought and discussion that it has engendered will help to bring the country closer to agreement on how to protect the quality of the Nation's ground-water resources and the health of the public who depend upon that resource for much of their drinking water.

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STATE AND LOCAL STRATEGIES FOR PROTECTION OF GROUND-WATER QUALITY—A SYNOPSIS

By Sheila D. David[1]

Ground-water protection is a complex issue because virtually every human activity has the potential to affect ground-water quality to some degree, and conditions across the country vary greatly. Recent ground-water programs, especially those at the Federal level, have focused on cleaning up ground-water contamination that has resulted from past waste-disposal practices; however, such remedial actions are very expensive. For example, the U.S. Environmental Protection Agency (EPA) estimates that the average cleanup cost of sites under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Superfund Amendments and Reauthorization Act of 1986 (SARA) ranges between $30 and $40 million (R.F. Weston, Inc., 1986, p. 2). Clearly, in the long run it is more cost effective to prevent contamination from occurring. Continued economic development of the United States, population growth, and the potential health effects of new synthetic organic chemicals make it imperative that ground-water management programs focus on the prevention of contamination as well as on the cleanup or mitigation of existing contamination.

In late 1984, the National Research Council (NRC) was requested by the EPA to establish a Committee on Ground-Water-Quality Protection to identify and review several State and local ground-water-protection programs to determine their effectiveness in protecting ground water from contamination. The resulting report, *Ground-Water Quality Protection— State and Local Strategies* (National Research Council, 1986), describes a wide range of approaches to the protection of ground water and identifies those technical and institutional features that show progress and promise in protecting ground-water quality. The committee concluded that no single approach will accommodate the wide range of physical, economic, and social settings in which ground water must be managed and protected.

Although the report is not a complete inventory of all ground-water-protection approaches presently being applied in the United States, the committee believed that the programs used in the States of Arizona, California, Colorado, Connecticut, Florida, Kansas, Massachusetts, New Jersey, New York, and Wisconsin and locally by Dade County, Fla., Cape Cod, Mass., and Long Island, N.Y., collectively cover most of the major approaches to ground-water protection that have been attempted. As a result of the review, the committee classified the approaches to ground-water protection into five program areas:

- Information collection and management systems
- Ground-water-classification systems
- Ground-water-quality standards
- Control of contamination sources
- Implementation of ground-water-protection programs

INFORMATION COLLECTION AND MANAGEMENT SYSTEMS

A ground-water-protection program to be successful needs to define existing ground-water problems and to evaluate proposed strategies for coping with the problems. These activities require an information system that describes the location of the water resources, the vulnerability of these resources to contamination, and the present and future land-use activities and water uses that may affect ground water. Major components of a ground-water-management information system are listed in table 8.

Perhaps the most basic need of a ground-water-protection program is an understanding of the aquifer's characteristics and the properties of the overlying soils. This information defines the suitability of an aquifer as a water supply, its vulnerability to contamination at different locations, the utility of the water for different uses, and the direction of movement of

Table 8. Major components of an information system needed for ground-water-management decisions

[Source: Modified from National Research Council, 1986, p. 76]

- Hydrogeology
  - Soil and unsaturated zone characteristics
  - Aquifer characteristics
    - Depths involved
    - Flow patterns
    - Recharge characteristics
    - Transmissive and storage properties
    - Ambient water quality
    - Interaction with surface water
    - Boundary conditions
    - Mineralogy, including organic content
- Water extraction [withdrawals] and use patterns
  - Locations
  - Amounts
  - Purpose (domestic, industrial, agricultural)
  - Trends
- Potential contamination sources and characteristics
  - Point sources
    - Industrial and mining waste discharges
    - Commercial waste discharges
    - Hazardous material and waste storage
    - Domestic waste discharges
  - Nonpoint sources
    - Agricultural
    - Septic tanks
    - Land applications of waste
    - Urban runoff
    - Transportation spills (can also be considered a point source)
    - Pipelines (energy and waste) (can also be considered a point source)
- Population patterns
  - Demographic
  - Economic trends
  - Land-use patterns

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[1] National Research Council, Committee on Ground-Water-Quality Protection.

contaminants, if they get into the aquifer. [See the article, "Factors Affecting Ground-Water Quality" in the 1986 *National Water Summary*.]

At the State level, hydrogeologic information commonly is used to locate and permit individual facilities, such as industrial sites or landfills. Examples of the use of such information are Connecticut, which has based its ground-water-classification system on the mapping of ground-water basins, and Vermont and New York, which have mapped valley-fill aquifers to define the location of potential water supplies (National Research Council, 1986, p. 77).

On a local level, hydrogeologic information has been integrated fully with ground-water-management plans in several areas. Nassau and Suffolk Counties, Long Island, N.Y., have based a hydrogeologic zoning plan on knowledge of regional flow patterns and interaquifer connections. The hydrogeologic information, which helped define aquifer recharge areas where potential sources of pollution must be controlled, resulted in a coordinated zoning plan for local land-use controls, county ordinances, State laws, and regulatory programs (National Research Council, 1986, p. 77).

An extensive data base can require years of study to develop; however, in many areas, existing data are adequate to develop preliminary maps of aquifer boundaries suitable for the enactment of zoning and other protective ordinances. The Massachusetts Department of Environmental Quality Engineering, for example, has developed a water-supply-protection atlas for use by State and local governments. The atlas contains four types of information: (1) sources of public water supply, (2) contamination sources, such as surface impoundments, hazardous waste sites, landfills, and road-salt storage areas, (3) aquifer information, and (4) surface-water drainage basins. The U.S. Geological Survey presently is assisting the State to computerize the atlas data (National Research Council, 1986, p. 78).

Ambient water-quality information provides the basis for classifying ground-water resources, helps indicate areas vulnerable to contamination, and may lead to the development of regulations or guidelines for underground storage tanks, sewering, and density of land use. Significant amounts of information are available on inorganic compounds in ground water; however, for organic compounds, such as pesticides, organic solvents, and petroleum products, more information is needed to help identify the full range of water-quality problems. Analyses of organic and toxic substances are still scarce, but a number of States are implementing or planning to implement monitoring networks. Florida, California, Long Island, N.Y., and Cape Cod, Mass., for example, have programs underway to collect information on organic and toxic substances (National Research Council, 1986, p. 80–82).

Another key component in making ground-water-quality decisions is knowledge of the magnitude of ground-water withdrawals, use of the water, and effects of the withdrawals. In Arizona, the registration of withdrawal wells and the metering of withdrawals within designated management areas is central to implementation of its 1980 Ground Water Management Act. In areas near the ocean, patterns of withdrawal influence the intrusion of saline waters into coastal aquifers. As the public realizes the necessity of dealing with supplies that are being contaminated or that are being depleted, water reuse and artificial recharge of aquifers are becoming more attractive management options. The Phoenix and Tucson, Ariz., Active Management Areas, for example, plan to reuse all of their wastewater by year 2025. Any States considering the use of wastewater and artificial recharge must consider their effects on existing ground-water quality (National Research Council, 1986, p. 82–83).

Another information element needed to support ground-water protection decisions is the pattern of production or use of potentially contaminating substances. The contents of such a data base might include (National Research Council, 1986, p. 83–84):

- Quantities of and the chemical composition of potentially contaminating material
- Location and type of use
- Industry or reason for use
- Time of use

When combined with information about aquifer vulnerability and the location of water-supply systems, the patterns of chemical production or use can help target efforts to reduce sources of contamination, protect aquifers, detect improper waste disposal, and monitor water quality.

Because of the very large number of potential contaminants that could be included in a monitoring program and the high cost of organic chemical analyses, which precludes routine determinations for all constituents, the use of existing information in ground-water-protection programs is particularly important. An example of this approach to monitoring is California's system of pesticide information. Pesticide-use data have allowed the State to focus monitoring efforts on those pesticides that are known to have been applied in a specific area and, thus, develop a cost-effective monitoring program (National Research Council, 1986, p. 84, 87–88).

Finally, information on population distribution and land use provides the basis for projecting possible effects of future development on the demands for water and on the quality of the resource. [See the following articles in the 1986 *National Water Summary*: "Agricultural Chemical Contamination of Ground Water in Six Areas of the High Plains Aquifer, Nebraska," "Relation of Land Use to Ground-Water Quality in the Outcrop Area of the Potomac-Raritan-Magothy Aquifer System, New Jersey," and "Relation of Land Use to Ground-Water Quality in the Upper Glacial Aquifer, Long Island, New York".] The committee encouraged State and local agencies involved in ground-water-protection plans to use long-term programs to accumulate the necessary hydrogeologic and related information and to collect and format the information in ways that assist ground-water-management decisions and evaluation of the protection programs' effectiveness. They also noted the importance of adequate laboratory facilities and information-management systems to program success.

GROUND-WATER-CLASSIFICATION SYSTEMS

A number of States have used the properties of aquifers and their vulnerability to contamination, ambient water quality, and present and potential water use and land use to classify geographic areas, aquifers, or parts of aquifers so that differential levels of protection can be applied to ground water in various locations. Classification systems focus limited resources on the protection and restoration of valuable but vulnerable aquifers, provide a basis for coordinating ground-water-management activities at different levels of government, and guide the development of ground-water standards, land-use management, source controls, and remedial actions (National Research Council, 1986, p. 93–94).

Connecticut developed and implemented a classification system on the basis of present and future beneficial water uses that, in turn, are defined by the ambient water quality. The system contains four classes, each of which is associated with specific water uses and is compatible with specific discharges to ground water. The State has a policy to restore ground-water quality when possible to a quality suitable for private [self-supplied] drinking-water supplies without treatment (class GA), if the ground water is classified as unsuitable for potable use unless treated because of existing or past land uses (class GB) or the aquifer is more suitable for receiving permitted discharges than for development as a public or private water supply (class GC). Specific areas are designated as suitable for public or private drinking-water supplies without treatment (class GAA). In those areas, discharges are restricted to human or animal wastes and minor cooling and clean-water discharges. This classification system, which has become a powerful tool for industrial and local planning, can be used by local planners to control nonpoint sources of pollution through zoning or other enforcement mechanisms and to influence the type of remedial action taken to cleanup or control existing uncontrolled hazardous waste sites or landfills. The system also facilitates recognition of the relation between drilling new water supplies and the placement of waste-disposal sites (National Research Council, 1986, p. 100). [See figure 59 for example of Connecticut's water-quality classification system.]

Other States, such as Colorado, use total dissolved solids to broadly classify ground water on the basis of its quality into three categories of beneficial uses: (1) suitable for all uses (total dissolved solids less than 3,000 mg/L (milligrams per liter)), (2) suitable, but not ideal, for most uses (total dissolved solids between 3,000 and 10,000 mg/L), and (3) generally unsuitable for most beneficial uses (total dissolved solids greater than 10,000 mg/L). In Colorado, primary and secondary drinking-water standards have been developed for category 1, and absolute limits have been set for selected contaminants that might impair use; primary standards only apply to category 2, and no standards apply to category 3 (National Research Council, 1986, p. 102).

The committee recommended that the States consider classifying ground water in conjunction with a mapping program that identifies critical areas and resources for protection. Insufficient data should not preclude the development of information if a phased approach is adapted to the classification and mapping effort.

GROUND-WATER-QUALITY STANDARDS

Statewide standards for ambient ground-water quality establish upper limits for specific constituents that are consistent with the beneficial uses of the water. A significant issue for the States is the adoption of ambient standards for individual organic contaminants to protect the ground water for existing and future uses such as drinking water, irrigation, and habitat protection. Because of the complexity of the task involved in setting scientifically based standards, most States look to EPA to perform this function or to provide them with technical information on which to base standards. Such standards then become one basis for regulatory and enforcement action to limit point and nonpoint discharges of pollutants to ground water (National Research Council, 1986, p. 110).

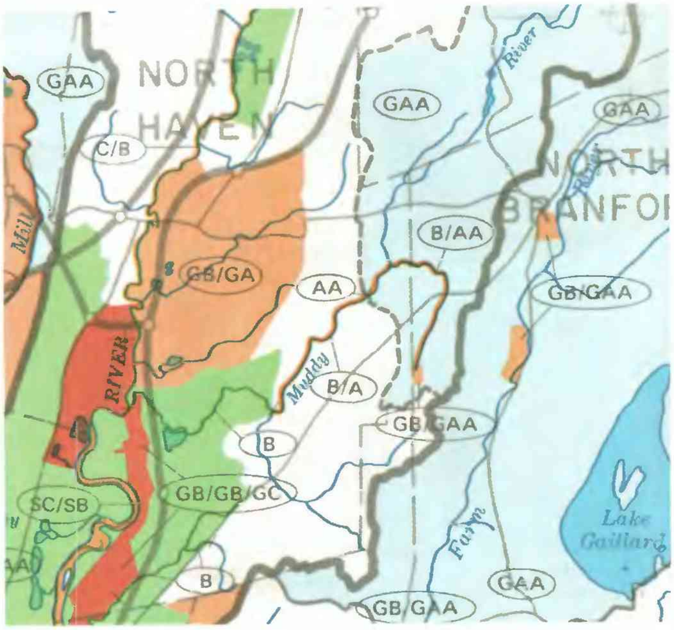

Figure 59. Example of water-quality classification system used by Connecticut. (Source: From Murphy, 1987.)

A related issue that States believe is important, but have not yet addressed, is soil-quality standards. Water that percolates through contaminated soil may leach contaminants into the underlying ground water. Therefore, establishment of acceptable levels of contaminants in soil becomes important, although uniform standards for all hydrogeologic situations might be inappropriate.

A tiered approach to standards for ground-water quality has been adopted by a number of States. Wisconsin, for example, requires that all State regulatory agencies identify all substances already detected in ground water or which have a reasonable probability of reaching ground water. Two standards will be developed for each substance: a "preventive action limit," which functions as a warning signal and as standards for facility design, and "enforcement standards," which define when violations of ground-water-quality standards have occurred. The more stringent preventive action limits are intended to give regulatory agencies time to take preventive measures to ensure that the enforcement standards are not reached or exceeded (National Research Council, 1986, p. 112).

Kansas has used ground-water-quality standards for chloride and specific conductance to protect ground water for drinking water and livestock use. With respect to organic compounds, Kansas uses a two-tiered approach, similar to that used in Wisconsin, that sets "notice levels" and "action levels" (National Research Council, p. 113).

Florida has adopted Federal drinking-water standards. For additional organic compounds, the EPA's health advisories and "suggested no adverse response levels (SNARLS)" are used. New Jersey uses health-based standards for drinking-water supplies in most of the State. However, environmentally based ground-water standards are used to protect surface-water quality in the ecologically fragile Central Pine Barrens area (National Research Council, 1986, p. 113–114).

Water-quality standards are established by different levels of government for various purposes. Federal drinking-water standards apply to all public water-supply systems. These numerical standards can be applied directly to ground water to protect beneficial uses or they can be used to define when degradation of high-quality water takes place. The committee concluded that the application of numerical standards to ground water is a matter of State policy and should be applied on the basis of the goals and objectives of the State's ground-water-protection program. No uniform approach appears to be appropriate on a national basis (National Research Council, 1986, p. 116).

CONTROL OF CONTAMINATION SOURCES

The ability to control or manage the sources of contamination is requisite for the prevention of ground-water contamination. The committee determined that the major options for controlling or managing sources of contamination are the management of hazardous materials and waste; the management of municipal solid waste; the control of underground storage tanks, nonpoint-source contaminants, and land uses; and the reduction of sources of contamination.

MANAGEMENT OF HAZARDOUS MATERIALS AND WASTE

Effective management of hazardous materials and waste is vital to a ground-water-protection program. To protect significant sources of ground water, management actions must include the ability to eliminate or reduce the production of waste; to assure safe handling of wastes during production, use, handling, storage, treatment, and disposal; to control and restrict the location of hazardous material and waste activities; and to provide strategies that encourage all segments of society, including individuals, to properly manage hazardous materials and wastes (National Research Council, 1986, p. 116–117). Three States that have implemented effective management programs are Florida, New Jersey, and California.

Florida law prohibits land disposal of hazardous waste, and the State is conducting a comprehensive hazardous-waste assessment that will be used to develop a long-term waste-disposal strategy. The State has conducted a series of "amnesty days" during which individuals or firms can bring solvents, pesticides, and other hazardous substances to central collection areas. Locally, Dade County has developed a strong hazardous-waste-management program that has defined and listed more than 900 chemicals as hazardous; it also has identified the location of 8,000 waste generators. The county requires a permit for any firm that handles, generates, or disposes of hazardous waste (National Research Council, 1986, p. 117–118).

New Jersey requires certain industrial establishments to acquire State certification that hazardous wastes have not been released on the property or that releases have been cleaned up before the property can be sold; otherwise the New Jersey Department of Environmental Protection can void the transaction and fine establishments for failure to comply with the law. The Environmental Cleanup Responsibility Act of 1983 has been controversial and costly to industry, but it does provide incentives to all parties involved in property transactions to make sure that environmental responsibilities are met.

California must cope with some 3.5 million tons of hazardous waste that is shipped offsite each year for treatment, storage, and disposal in 7 landfill sites. Registering, permitting, and inspecting 1,300 hazardous-waste facilities, 1,100 waste haulers, and 22,000 waste generators is a herculean task. Managers of California's program believe that it is critical to convert from its present landfill-based disposal system to a treatment- and neutralization-based system and also to require a reduction in the volume of wastes generated (National Research Council, 1986, p. 120–122).

The committee recommended that a plan for treating, storing, or disposing of hazardous waste within its own boundaries should be an essential part of each State's ground-water-protection program. Such a plan should include a siting process for transportation, storage, and disposal facilities, including regional and onsite industrial incinerators (National Research Council, 1986, p. 122).

MANAGEMENT OF MUNICIPAL SOLID WASTE

Another essential component of a ground-water-protection program is a comprehensive solid-waste-management program to control sanitary landfills and the disposal of incineration ash. By virtue of their size and number, solid-waste landfills are a major source of ground-water contamination. Because of a shortage of space for landfills, many States are seeking alternative ways of managing solid wastes. New Jersey requires each county to develop its own solid-waste-management program and has a goal for each county of recycling about 25 percent of its waste. New York provides communities with as much as 50 percent of the cost of construction of incineration/resource-recovery facilities and has prohibited the siting of new or expanded solid-waste municipal landfills within deep-flow recharge areas in Nassau and Suffolk Counties on Long Island (National Research Council, 1986, p. 123–125).

Kansas also requires counties to develop and implement solid-waste-disposal programs but without State aid. The Connecticut Department of Environmental Protection has used their ground-water-classification system to close landfills in some areas. A recent solid-waste-management law requires individual towns to develop short- and long-term solid-waste-management plans and fosters the use of regional resource-recovery plants (National Research Council, 1986, p. 125–126).

The committee recommended that State and local agencies give serious consideration to reducing waste quantities by means of recycling, incinerating, and establishing resource-recovery facilities. These activities should be looked at in the context of an integrated environmental-management program with monitoring requirements, discharge or emission limits, and ambient environmental quality standards for both ground-water and air resources that use comparable concepts of risk assessment (National Research Council, 1986, p. 128).

CONTROL OF UNDERGROUND STORAGE TANKS

Underground storage tanks are present in and near every population center. The committee recommended that all States consider developing a plan for monitoring and inspecting storage tanks. The plan should incorporate design standards for new tanks, monitoring and testing requirements, and a process for upgrading existing tanks located in important ground-water recharge areas (National Research Council, 1986, p. 131).

CONTROL OF NONPOINT-SOURCE CONTAMINANTS

Nonpoint sources of ground-water contamination are very difficult to control. Fertilizers and other chemicals from agricultural lands, parks and golf courses, lawns, and septic systems; road salts; and runoff from urban areas and feedlots contribute to the degradation of ground-water quality in many areas.

As mentioned earlier in this article, information on pesticide usage, persistence, mobility, and toxicity can aid States and localities in predicting where contamination is likely to occur and in designing appropriate monitoring programs. California was the only State reviewed by the committee that collects and maintains detailed information about pesticide usage. States without pesticide-usage information might attempt to estimate usage from sales data and cropping patterns. This type of spatial information is essential to establishing where to monitor for specific pesticides.

Variability in soil and water conditions also can result in significant regional differences in ground-water contamination by pesticides. This variability must be considered in designing pesticide-monitoring programs and reducing usage. One approach to reducing pesticide usage is the adoption of an integrated pest-management program that promotes the use of nonchemical means of pest control and enhances the effectiveness of pesticides by improving the timing and placements of the chemicals.

Other nonpoint sources of concern include the disposal of hazardous materials by home owners and small businesses. A number of States have ''amnesty day'' programs to periodically collect such materials and properly dispose of them.

The committee recommended that the States give considerable attention to the control of pesticides by developing a data base on the spatial and temporal distribution of pesticides applied, by registering pesticides for State use based on the pesticides' chemical characteristics, by monitoring pesticides to ensure that presently registered, potentially leachable pesticides do not reach the ground water, and by encouraging a reduction in usage (National Research Council, 1986, p. 146).

LAND-USE CONTROLS

Virtually every human activity has the potential to affect ground-water quality to some extent. The risk of contamination is controlled by the vulnerability of the aquifer to contamination and the type, amount, and location of contaminant discharges to the aquifer that might result from the land-use activity. Of particular concern are discharges from land-use activities in major aquifer-recharge areas or near water-supply wells. Thus, another approach to the control of contamination sources is to prohibit or restrict certain land-use activities within designated critical areas. Such controls typically are applied at the local level to provide different levels of protection to aquifers based upon their classification. Local land-use controls to protect ground water have been implemented by numerous communities in Connecticut, Florida, Massachusetts, and New Jersey.

The committee examined a number of components of these programs (National Research Council, 1986, p. 153–169):

- Delineation of critical areas to protect aquifers based upon the hydrogeologic setting (Long Island Regional Planning Board's application of hydrogeologic zoning to aquifer recharge areas) and well hydraulics (Cape Cod Planning and Economic Development Commission's delineation of zones of contribution around well fields and Dade County's well-field protection ordinance).
- Restrictions of ground-water development near areas of known contamination.
- Land-use-zoning requirements to restrict housing density and prohibitions on a range of future activities.
- Health regulations to control land-use activities. For example, the use of septic-system permits to control housing density and to prohibit certain industrial development (Suffolk County, N.Y.), and the use of general bylaws and health regulations to control the storage and handling of hazardous and toxic materials (Cape Cod, Mass.).

- County and municipal ordinances to control the storage and handling of toxic and hazardous materials without actually prohibiting their use.
- State-level aquifer mapping and classification programs to protect aquifers on the basis of their use by major municipal water-supply systems by restricting the siting of industrial operations that use, generate, transport, or dispose of hazardous and toxic materials.
- Property transfer and lien laws used to certify that a piece of property is free from major contamination before the property can be sold and to allow the use of property assets, in cases of bankruptcy and related foreclosures, to compensate the State for the cost of remedial action.

Table 9. Criteria for effective ground-water-protection programs

[Source: Modified from National Research Council, 1986, p. 5–7]

Criterion	Scope
Goals and objectives.	Protection programs should clearly define goals and objectives, reflect understanding of ground-water problems, have adequate legal authority, and have criteria for evaluating program success and the need for modifications.
Information.	Programs should be based on information that permits resources and issues to be defined and preventive strategies to be evaluated.
Technical basis.	Effective programs require a sound technical basis with which to link actions to results.
Source elimination and control.	Long-term program goal should be to eliminate or reduce the sources of ground-water contamination.
Intergovernmental and interagency linkages.	Comprehensive protection program must link actions at every level of government into coherent, coordinated action.
Effective implementation and adequate funding.	Programs must have adequate legal authority, resources, and stable institutional structures to be effective.
Economic, social, political, and environmental impacts.	A preventive program assumes that ground-water protection is the least costly strategy in the long run. Protective actions should be evaluated in terms of their economic, social, political, and environmental effects.
Public support and responsiveness.	Programs must be responsive and credible to the public.

The committee concluded that land-use controls are a good complement to source-control programs and can significantly increase ground-water protection. Although these programs generally are implemented at the local level, the State government can encourage their use. Such controls are most effective when implemented before the development of critical areas.

SOURCE REDUCTION

A very attractive technique for protecting ground water is simply the reduction or elimination of contamination sources. Source-reduction strategies summarized by the committee included (National Research Council, 1986, p. 147–149):

- Prohibiting polluting activities by eliminating discharges, banning usage of certain products, or prohibiting certain activities in important recharge areas.
- Altering industrial operations to eliminate or reduce waste quantities.
- Substituting industrial and consumer products that are less polluting than existing products.
- Recycling and reuse of chemicals, petroleum products, and wastes.
- Using alternative waste-disposal strategies such as neutralization or treatment prior to discharge to the ground.

The committee recommended that the States consider regulatory and economic incentives for industry, government, commercial entities, and the public to reduce the generation of wastes and sources (National Research Council, 1986, p. 150).

IMPLEMENTATION OF GROUND-WATER-PROTECTION PROGRAMS

A final area of concern to the committee was the factors that affect the successful implementation of ground-water-protection programs. Certainly, effective programs must be based on adequate legal authority, which, in turn, provides the basis for development of regulations for the implementation of programs. Compliance with statutory and regulatory goals depends upon surveillance and monitoring programs that assess the ambient quality and trends, identify contamination sources, assess compliance, and evaluate program effectiveness in meeting goals. Similarly, implementation of programs requires trained professional staff and proper equipment. Major criteria for effective ground-water-protection programs are given in table 9.

Adoption of a State ground-water-management program requires a supportive climate that is determined, in part, by the public's perception of ground-water problems and issues and the need for action. Education can play a key role in raising public awareness of ground-water resources and their importance. Agencies have many opportunities to use extension services, county agricultural agents, and other mechanisms to keep ground-water issues in the mind of the public and to provide technical assistance. Citizen interest groups are very often critical in mobilizing support for ground-water-protection programs.

The committee considered the role of economic analysis in the evaluation of ground-water-protection programs and strategies. The committee concluded that effective ground-water-protection programs have significant costs associated with them that can, in some instances, exceed the value of the resource or costs of remedial actions. Therefore, economic analyses should be conducted of existing and proposed ground-water-protection measures so that experience can be gained with techniques and data requirements, and decision makers can become familiar with the results of such analyses.

SUMMARY

The review of State ground-water-protection plans and elements by the National Research Council Committee on Ground-Water-Quality Protection identified many promising program elements. However, no program was found that addressed all aspects of ground-water protection in a comprehensive fashion. Although no single State program can be offered as a model for other States, collectively the program elements described by the committee offer a wide array of approaches to ground-water-quality management in use today. Furthermore, the differences in the States' physical, social, and political conditions suggest that no single strategy for dealing with ground-water problems can be recommended for all States or localities.

The committee recommended eight criteria for a comprehensive ground-water-protection program:

- Clearly stated goals and objectives
- A good information base about the resource and the problems
- A sound technical basis
- Actions to eliminate or reduce sources of contamination
- Mechanisms to coordinate actions at different governmental levels
- Adequate legal authority and funding
- A process for evaluating economic, social, political and environmental effects
- Credibility with the public

Many programs examined by the committee were relatively new and lacked criteria and information with which to measure their effectiveness. Because ground-water protection is a long-term process, it is imperative that information-gathering programs be put in place to measure program success. Despite these limitations, the committee concluded that many of the program elements implemented by the States as part of their ground-water-protection programs clearly have been beneficial.

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STATE SUMMARIES OF GROUND-WATER QUALITY

SYNOPSIS OF STATE SUMMARIES OF GROUND-WATER QUALITY

INTRODUCTION

The "State Summaries of Ground-Water Quality" part of the 1986 *National Water Summary* describes the ground-water quality of each State, the District of Columbia (combined with Maryland), Puerto Rico, the U.S. Virgin Islands, and the Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. (Hereafter, the term "State" is used for all of these geographic areas). For each State, the summary provides the following information:

- Overview of ground-water quality and related water-quality issues;
- Discussion of water quality in principal aquifers, including background quality, the effects of land use on water quality, and the potential for future water-quality changes;
- Description of ground-water-quality management in the State; and
- Selected references on ground-water resources, quality, and management.

Each State summary also includes three multicolor illustrations that show:

- Selected geographic features and 1985 population distribution (fig. 1),
- Location of principal aquifers and presentations of data that depict water quality in the principal aquifers (fig. 2), and
- Location of selected waste sites, areas of naturally impaired ground-water quality, and areas reflecting human-induced contamination (fig. 3).

Basic ground-water principles and common ground-water terms are used in the State summaries without definition. Some of these principles are described in this volume in the article "Factors Affecting Ground-Water Quality," and selected terms are defined in the Glossary. Additional discussions of basic ground-water terms and principles and of the general features of ground-water occurrence in the United States are given by Heath (1983, 1984); general information and principles governing ground-water quality are given by Hem (1985). The aquifer descriptions and maps in each State summary are derived, for the most part, from the State presentations in the 1984 *National Water Summary* (U.S. Geological Survey, 1985). Only the aquifers used most intensively in that State as water-supply sources are described in the text and shown in accompanying figures. Aquifer names sometimes differ from State to State; thus, an aquifer that crosses a State boundary might be identified by one name in one State and by another in the adjacent State. Supplemental information on the described aquifers can be obtained from the reports listed in each State's "Selected References."

Ground-water contamination often is associated with population centers; therefore, population distribution (1985) is shown in figure 1*B* of each State summary. Information on background water quality of a State's principal aquifers is presented in figure 2*C* using a box and whisker diagram (Velleman and Hoaglin, 1981). For each aquifer, the diagrams show the percentage of water analyses that is equal to or less than the indicated constituent concentration. For example, 90 percent of the analyses of water samples from an aquifer are equal to or less than the constituent concentration indicated by the position of the upper end of the vertical line extending upwards from the box in each diagram. Therefore, 10 percent of the water samples have concentrations greater than that indicated by the upper end of the top whisker. For purposes of simplification, the observed maximum and minimum values are not indicated in these diagrams. The percentile distribution of each constituent represents the range of water quality in the principal aquifers, although the degree of representation differs from aquifer to aquifer depending on the spatial distribution, depth, and number of samples included in the analyses. For the most part, no attempt was made to characterize vertical or horizontal water-quality changes within an aquifer even though such differences commonly are observed.

Background water-quality data generally were obtained from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) data base, which contains data that have been collected and analyzed by the U.S. Geological Survey in cooperation with State water agencies (U.S. Geological Survey, 1975). As of 1986, WATSTORE contained water-quality data for more than 164,000 wells. Additional ground-water-quality data were retrieved from available State computerized water-quality data bases.

The location of selected waste sites and the generalized areas of water-quality concerns (fig. 3 of each State summary) were compiled from State, U.S. Environmental Protection Agency (EPA), and U.S. Geological Survey data sources. The areas of naturally impaired water quality and areas reflecting human-induced contamination of ground water are generalized and do not imply that a particular condition is present uniformly at every point within the areas delineated. The following types of sites are identified in each figure 3, although not all types are shown in all States:

- CERCLA (Comprehensive Environmental Response, Compensation, and Liability Act of 1980) sites on the National Priorities List ("Superfund" sites) of the U.S. Environmental Protection Agency (1986). Most of these sites are landfills and surface impoundments identified by EPA for long-term remedial action because they are known to discharge chemicals into the ground water. As of June 1986, there were 703 CERCLA sites on the National Priorities List. (See figure 60.)
- RCRA (Resources Conservation and Recovery Act of 1976) sites. These sites are, for the most part, hazardous-waste disposal facilities for municipal and industrial solid wastes.
- IRP (U.S. Department of Defense Installation Restoration Program) waste-disposal facilities or areas of contamination undergoing detailed investigation or remedial action ("phase II, III, IV sites") as of September 1985 (U.S. Department of Defense, 1986).
- Waste-disposal wells. These are EPA class I underground injection wells that place wastes below aquifers that are sources of drinking water.
- Other sites. Unless otherwise shown in separate categories, the "other sites" include waste-disposal wells, IRP sites undergoing preliminary assessment ("phase I sites"), sites that are part of State cleanup programs, and selected sites of special concern to ground-water managers.

The degree of knowledge about ground-water quality reflected in the individual State summaries differs greatly among the States and generally reflects past efforts devoted to data collection, interpretation, and research on ground-water resources. The State summaries indicate that, although potential contamination sources and problem areas have been identified in many States, insufficient data have been collected to determine quantitatively how much contamination of ground water has occurred.

NATIONAL PERSPECTIVE ON GROUND-WATER QUALITY

Overall, the quality of the Nation's ground water is good. Virtually all the States note that most of their ground water meets State and Federal drinking-water standards and that the quality of the ground water is suitable for most uses. In general, the bulk of the Nation's fresh ground water is fit to drink.

This assessment of the Nation's ground-water quality must be tempered by the fact that the water-quality descriptions in the State summaries largely are based on analyses of inorganic chemicals. Although ground-water analyses of toxic constituents and synthetic organic chemicals are relatively scarce, available data have led to the growing realization that these chemicals locally have contaminated shallow aquifers in many parts of the country. Existing data, however, generally have been collected to monitor the quality of drinking-water supplies or to evaluate waste sites and not to provide an assessment of quality of the ground-water resource. Reports of contamination are likely to increase as the search for contamination intensifies and as more sophisticated analytical techniques are used to detect trace amounts of these chemicals in water.

At present, standards for many toxic and organic chemicals have not been set because the effects of small concentrations of these chemicals on human health and wildlife are unknown. The presence of organic or toxic chemicals in very small concentrations in ground water does not necessarily imply a health or environmental threat, but their presence does raise questions about the source of the chemicals and the possibility that concentrations might increase over time to toxic levels.

Given the very large number of sources of contamination, the relatively high susceptibility of shallow aquifers to the effects of human activities related to waste disposal and land uses, and the great technical difficulties involved in attempting to remove a contaminant once it enters an aquifer, the potential for more ground-water contamination is a very real and serious problem. Fortunately, much can be done to prevent future contamination of the ground-water resource as well as to mitigate existing contamination. Actions being taken are described in each State summary in the "Ground-Water-Quality Management" section.

BACKGROUND WATER QUALITY

The State summaries describe ground water of diverse quality moving through many different types of aquifer systems. Ultimately, the quality of water in these aquifers is affected by both natural processes and human activities. Natural chemical quality of ground water is determined largely by the types of rocks through which

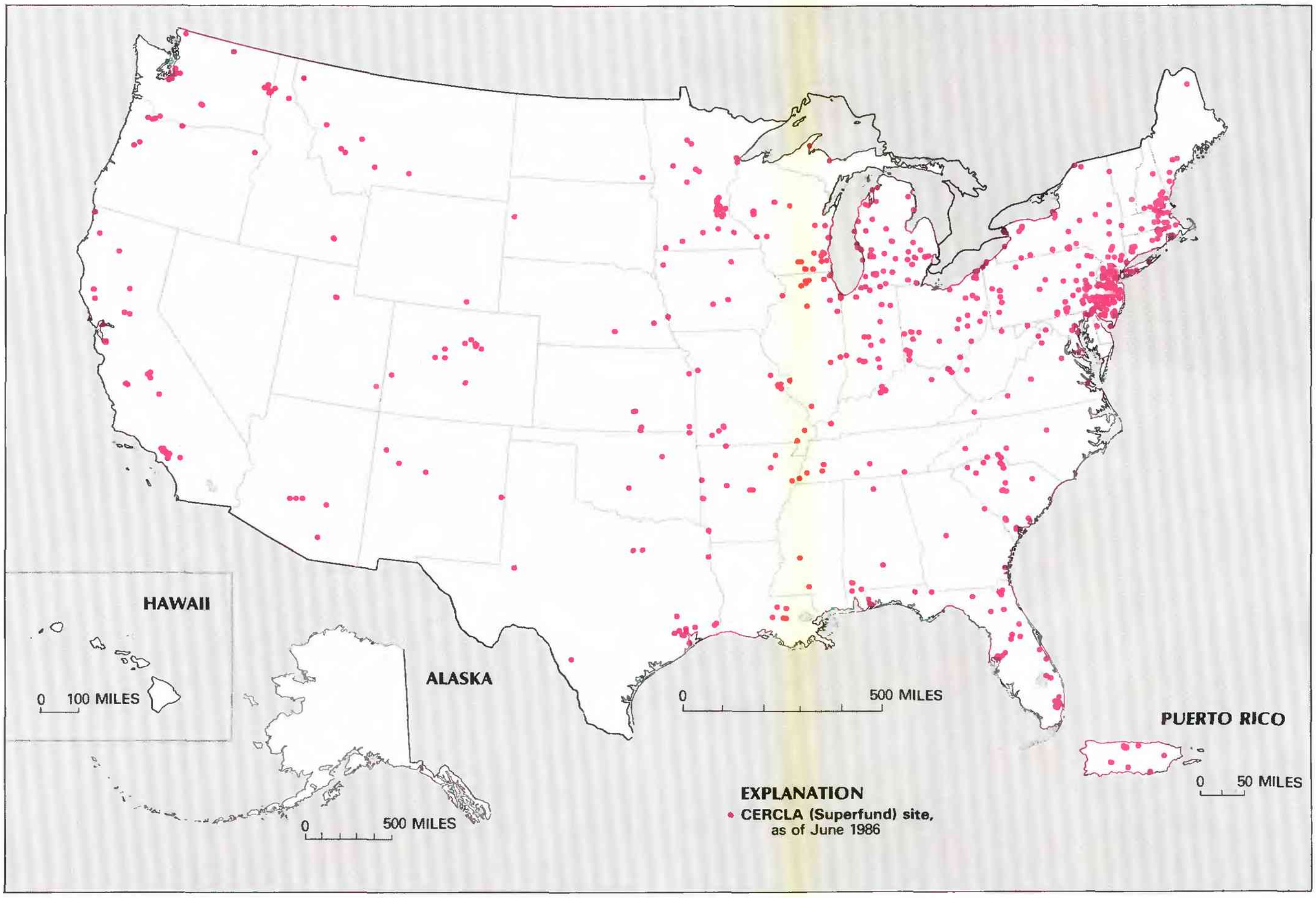

Figure 60. Sites on National Priorities List under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), June 1986.

the water moves, and various chemical processes, such as dissolution and precipitation, oxidation and reduction, ion exchange, and biological activity within aquifers. These dynamic processes and the mixing of waters of different composition account for water-quality changes within the aquifers. (For a more detailed discussion, see the article in this volume, "Factors Affecting Ground-Water Quality.")

Even though the quality of most of the Nation's ground water is good, in some locations ground water contains one or more naturally occurring chemical constituent or property, leached from the soil or rock by percolating water, that exceeds Federal or State drinking-water standards or otherwise impairs use. All the "State Summaries of Ground-Water Quality" report some areas of naturally impaired ground water owing to one or more of the causes listed below (numbers in parentheses indicate the number of State summaries that mention impaired use):

- Organisms, such as bacteria (4).
- Metals and other substances, such as arsenic (12), boron (3), nitrate (12), radium (7), radon (8), selenium (8), and uranium (3), that are toxic to humans, livestock, or crops in relatively small concentrations.
- Constituents or properties, such as chloride (32), dissolved solids (41), fluoride (16), hardness (32), hydrogen sulfide (5), iron (36), manganese (22), and sulfate (24), that are not necessarily toxic but which can impair the usefulness of the water for certain purposes.

Nationally, one of the most common water-quality concerns is the presence of dissolved solids (all the dissolved salts) in concentrations exceeding 500 mg/L (milligrams per liter) or chloride in excess of 250 mg/L, the recommended maximum limit in the secondary drinking-water standards. (See table of Federal drinking-water standards in "Supplemental Information" part of this volume.) Ground water with dissolved-solids concentrations in excess of 500 mg/L is found toward the seaward ends of coastal aquifers, and is common in aquifers at depths greater than a few hundred feet below the land surface in many parts of the United States. Although such water is not recommended for drinking under Federal guidelines, some western States, such as Nevada and Texas, do allow a maximum of 1,000 mg/L dissolved solids in drinking water. Despite the higher salt content, water exceeding these drinking-water standards often is suitable for other uses such as the irrigation of salt-tolerant crops, industrial cooling, and livestock watering.

Although not toxic, iron and manganese in concentrations greater than 300 μg/L (micrograms per liter) and 50 μg/L, respectively (the limits recommended for secondary drinking-water standards), can impair the taste of water; stain plumbing fixtures, glassware, and laundry; and form encrustations on well screens, thereby reducing well-pumping efficiency. These constituents commonly occur in sand and gravel aquifers as oxide coatings on sediment grains. In the absence of dissolved oxygen, iron and manganese are easily dissolved in acidic water. In Massachusetts, for example, an aquifer below a 5-foot-thick layer of peat, which removes dissolved oxygen and adds humic acids to ground water, yielded water with 19,000 μg/L iron. In Connecticut, concentrations of iron (as large as 40,000 μg/L) and manganese (as large as 14,000 μg/L) are a common water-quality problem.

Most ground water that is not affected by human activity contains less than 10 mg/L nitrate as nitrogen—the maximum concentration allowed in primary drinking-water standards (Feth, 1966, p. 49). In a few isolated areas, naturally occurring nitrate-rich deposits cause large concentrations of nitrate in the ground water. Such an area is in Nevada where the north-central part of the Las Vegas Valley basin-fill aquifer contains water with naturally occurring nitrate concentrations in excess of 300 mg/L.

HUMAN-INDUCED SOURCES OF GROUND-WATER CONTAMINATION

For this discussion, sources of ground-water contamination are grouped according to the following classification: waste disposal, storage and handling of materials, mining activities, oil and gas activities, agricultural activities, urban activities, and other sources. (See table 10.) Under this classification, the sources of contamination most frequently mentioned in the State summaries include, in order of frequency, landfills, agricultural applications of fertilizers and pesticides, septic systems, underground storage tanks, surface impoundments, saline intrusion, and accidental spills (table 10). In addition to common inorganic constituents and heavy metals, the State summaries mention about 100 organic chemicals (including 49 pesticides) that frequently are detected in well water. These chemicals are listed in the "Supplemental Information" part of this volume. The most frequently reported chemicals, in decreasing order of occurrence, were trichloroethylene (TCE), benzene, tetrachloroethylene (PCE), phenolic compounds (general), toluene, chloroform, pentachlorophenol, creosote, 1,1,1-trichloroethane, and xylene.

Waste disposal of liquid or solids in or on the earth is perhaps the best-known source of ground-water contamination. This form of waste disposal received an impetus in the 1970's when Federal and State air quality and surface-water quality legislation caused many surface-water waste discharges to be replaced by waste disposal in lagoons, as spray irrigation, and in landfills. Waste disposal can take a number of forms: septic systems; landfills; surface impoundments; waste-injection wells; and the direct application of stabilized wastes to the land (landfarming). In addition, a considerable amount of unregulated disposal, such as illegal dumping, contributes to ground-water contamination.

Septic system onsite sewage disposal is the largest source, by volume (820 to 1,460 billion gallons per year), of waste discharged to the land (Office of Technology Assessment, 1984, p. 267). Nearly any household chemical poured down the drain of a home served by a septic system can find its way into the local ground-water system. Organic solvents, such as trichloroethylene, that are sold commercially to clean septic systems, frequently are contaminants.

Landfills are a traditional method of disposing of solid waste. Although facilities can be engineered to be relatively impermeable, precipitation and storm runoff still can percolate through most landfills and leach contaminants from the wastes.

Surface impoundments are another common form of waste storage or disposal. Some impoundments are lined to prevent seepage, and the liquid fraction of the waste evaporates. In most impoundments, however, the liquid fraction discharges to streams and seeps through the bottom of the impoundment. An example of contamination from a waste-disposal surface impoundment is given in the article in this volume "Sewage Plume in a Sand-and-Gravel Aquifer, Cape Cod, Massachusetts."

Storage and handling of waste materials results in ground-water contamination owing to leaks from both above-ground and underground storage tanks, accidental spills during handling of chemicals and wastes, or from poor housekeeping practices on industrial and commercial sites. Underground storage tanks appear to be a leading source of ground-water contamination from benzene, toluene, and xylene, all of which are organic compounds contained in diesel and gasoline fuels. Although leaking underground storage tanks are reported in many States, contamination generally is localized.

Mining of coal, uranium, and other substances and the related mine spoil can lead to ground-water contamination in a number of ways. The removal of underground coal leaves shafts and tunnels that can intersect aquifers and collect water. Exposing the pyrite- (iron sulfide) bearing coal to oxygen in the atmosphere can lead to the formation of sulfuric acid. In addition to the mining, piles of tailings left after mineral extraction are exposed for many years to leaching by precipitation. Contaminants, such as arsenic, copper, iron, lead, manganese, molybdenum, radium, selenium, sulfate, and thorium, leach from the waste piles and infiltrate local aquifers.

Oil and gas production can contaminate fresh ground water by a variety of mechanisms. During production, oil wells produce brines that are separated from the oil and stored in surface impoundments. EPA estimates that there are 125,100 brine-disposal impoundments that might affect the local ground water by seepage and 161,400 EPA class II brine injection wells. Each well poses a potential source of contamination. If, when a well is abandoned, it is not properly plugged, contaminated water can move vertically from one aquifer to another.

Agriculture is the most widespread of human activities that directly affect ground water. Fertilizer applications (nitrate contamination) and pesticide applications are among the most common sources of contamination described in the State summaries (44 State summaries). The most frequently mentioned pesticides detected in ground water were the fumigants ethylene dibromide (EDB) and 1,2-dichloropropane; the insecticides aldicarb, carbofuran, and chlordane; and the herbicides alachlor and atrazine.

The percolation of irrigation water into the soil dissolves soil salts and transports them downward through the soil profile. Evapotranspiration of applied water concentrates salts in the soil and increases the salt load to the ground water.

Raising livestock in feedlots and poultry in confinement concentrates volumes of animal wastes, a potential source of nitrate contamination. Animal wastes often are collected in impoundments from which they infiltrate to the ground water.

Urban activities that contribute to ground-water contamination include the use of septic systems, underground storage tanks, and surface impoundments; the application of fertilizers and pesticides to lawns, parks, and golf courses; accidental chemical and other hazardous waste spills; and sewer systems. The State summaries frequently provide examples of ground-water contamination related to high population density and urban and industrial land uses.

Runoff from storms in urban areas is introduced into the shallow ground-water system through infiltration basins, drainage wells, or, where present, sinkholes. Urban runoff commonly contains hydrocarbons, bacteria, dissolved solids, road deicing salt, lead, cadmium, and other trace metals that can find their way quickly into the shallow ground-water system. Where major highways and urban streets are heavily salted, concentrations of chloride in the local ground water can increase above secondary drinking-water standards of 250 mg/L.

Population growth increases the demand for water, and, where aquifers are the principal water source for a community, increased withdrawals can lead to the formation of large cones of depression. Such declines in ground-water levels can increase recharge and, thereby, increase the potential for contamination of ground water from activities on the land's surface.

Other sources of ground-water contamination mentioned in the State summaries include atmospheric deposition, surface-water/ground-water interactions, and saline intrusion, which is the most frequently mentioned (29 State summaries). The encroachment of saline water into the freshwater parts of aquifers is an ever-present threat when water supplies are developed from the highly productive coastal plain aquifers of the United States, or from aquifers underlain by saline water in the interior of the country.

MANAGEMENT OF GROUND-WATER QUALITY

Management of the Nation's ground-water quality is primarily the responsibility of State and local governments. As noted in the State summaries, State legislation and programs for managing ground water, including its quality, are increasing rapidly. Effective management of ground water requires a comprehensive understanding of how ground-water systems function, a properly designed sampling network to evaluate the aquifer system, and effective programs to implement procedures for ground-water protection.

The degree to which ground-water quality is managed, and the amount of data collected to guide such management, differs widely from State to State. Assignment of management responsibilities for ground-water protection also differs among the State agencies. Within a State, the number of State agencies involved in the protection and collection of ground-water information ranges from two to eight, and averages about five. Presently, most States have designated a lead agency (usually an environmental or health agency) or committee to coordinate ground-water-quality planning within the State.

In many States, legislation and assignment of water-quality-management responsibilities have existed for many years. Recently, emphasis has increased on planning and enactment of new legislation to address ground-water protection and agency responsibilities. Most States now have some form of ground-water-quality management programs or planning activities. Several States have created new agencies to address water-quality concerns. In addition, most States have enacted new legislation since 1977 to expand or redefine the responsibility of the State for ground-water protection. Many States operate water-quality observation networks to monitor ground-water quality in the State and to conduct special studies in areas with water-quality problems; however, the size and areal coverage of these networks vary greatly. All States monitor the quality of public water supplies, and many have adopted water-quality standards and monitor hazardous- and nonhazardous-waste sites. About half the States have conducted some pesticide sampling. All of these activities are needed to accomplish the difficult task of supplying growing numbers of public, industrial, agricultural, and recreational water users with adequate quantity and quality of water while continuing to protect the present resource.

Table 10. Activities contributing to ground-water contamination

[Source: Data compiled from "State Summaries of Ground-Water Quality" part of the 1986 *National Water Summary* unless otherwise indicated]

Activity	States citing	Estimated sites[1]	Contaminants frequently cited as result of activity	Remarks
Waste disposal:				
Septic systems	41	22 million.	Bacteria, viruses, nitrate, phosphate, chloride, and organic compounds such as trichloroethylene.	Between 820 and 1,460 billion gallons per year discharged to shallowest aquifers (Office of Technology Assessment, 1984, p. 267).
Landfills (active)	51	16,400	Dissolved solids, iron, manganese, trace metals, acids, organic compounds, and pesticides.	Traditional disposal method for municipal and industrial solid waste. Unknown number of abandoned landfills.
Surface impoundments	32	191,800	Brines, acidic mine wastes, feedlot wastes, trace metals, and organic compounds.	Used to store oil/gas brines (125,100 sites), mine wastes (19,800), agricultural wastes (17,200), industrial liquid wastes (16,200), municipal sewage sludges (2,400), other wastes (11,100) (U.S. Environmental Protection Agency, 1987, p. 89).
Injection wells	10	280,800	Dissolved solids, bacteria, sodium, chloride, nitrate, phosphate, organic compounds, pesticides, and acids.	Wells used for injecting waste below drinking-water sources (550), oil/gas brine disposal (161,400), solution mining (22,700), injecting waste into or above drinking-water sources (14), and storm-water disposal, agricultural drainage, heat pumps (96,100) (U.S. Environmental Protection Agency, 1987, p. 78).
Land application of wastes	12	19,000 land application units.	Bacteria, nitrate, phosphate, trace metals, and organic compounds.	Waste disposal from municipal waste-treatment plants (11,900), industry (5,600), oil/gas production (730), petroleum and wood-preserving wastes (250), others (620) (U.S. Environmental Protection Agency, 1987, p. 81.
Storage and handling of materials:				
Underground storage tanks	39	2.4–4.8 million	Benzene, toluene, xylene, and petroleum products.	Useful life of steel tanks, 15–20 years. About 25–30 percent of petroleum tanks may leak (Conservation Foundation, 1987, p. 131).
Above-ground storage tanks	16	Unknown.	Organic compounds, acids, metals, and petroleum products.	Spills/oveflows may contaminate ground water.
Material handling and transfers.	29	10,000–16,000 spills per year.	Petroleum products, aluminum, iron, sulfate, and trace metals.	Includes coal storage piles, bulk chemical storage, containers, and accidental spills.
Mining activities:				
Mining and spoil disposal—coal mines.	23	15,000 active; 67,000 inactive.	Acids, iron, manganese, sulfate, uranium, thorium, radium, molybdenum, selenium, and trace metals.	Leachates from spoil piles of coal, metal, and nonmetallic mineral mining contain a variety of contaminants. Coal mines are sources of acid drainage.
Oil and gas activities:				
Wells	20	550,000 production; 1.2 million abandoned.	Brines.	Contamination from improperly plugged wells and oil brine stored in ponds or injected underground.
Agricultural activities:				
Fertilizer and pesticide applications.	44	363 million acres.[2]	Nitrate, phosphate, and pesticides.	Fertilizer applied 1982–83, 42.3 million tons per year (U.S. Bureau of the Census, 1984, p. 654); active ingredients of pesticides applied 1982, 660 million pounds (Gianessi, 1987, p. 3).
Irrigation practices	22	376,000 wells; 49 million acres irrigated[3]	Dissolved solids, nitrate, phosphate, and pesticides.	Salts, fertilizers, pesticides can concentrate in ground water. Improperly plugged abandoned wells contamination source.
Animal feedlots	17	1,900	Nitrate, phosphate, and bacteria.	Primarily in the Corn Belt and High Plains States (Office of Technology Assessment, 1984, p. 284).
Urban activities:				
Runoff	15	47.3 million acres urban land.[4]	Bacteria, hydrocarbons, dissolved solids, lead, cadmium, and trace metals.	Infiltration from detention basins, drainage wells, pits, shafts can reach ground water. Karst areas particularly vulnerable.
Deicing chemical storage and use.	14	Not reported.	Sodium chloride, ferric ferrocyanide, sodium ferrocyanide, phosphate, and chromate.	Winter 1983, 9.35 million tons dry salts/abbrasives, 7.78 million gallons of liquid salts applied (Office of Technology Assessment, 1984, p. 285).
Other:				
Saline intrusion or upconing	29	Not reported.	Dissolved solids and brines.	Present in coastal areas and in many inland areas.

[1] Estimated number of sites from U.S. Environmental Protection Agency (1987) unless otherwise indicated.

[2] U.S. Bureau of the Census, 1984, p. 658, 1982 data.

[3] U.S. Bureau of the Census, 1984, p. 639, 1982 data.

[4] U.S. Bureau of the Census, 1984, p. 195, 1980 data.

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STATE SUMMARIES OF GROUND-WATER QUALITY

ALABAMA
Ground-Water Quality

In Alabama, ground water is the major source for public supply—about 52 percent of the population depends on ground water (see population distribution, fig. 1). The principal area for ground-water withdrawal is the Coastal Plain of Alabama. All principal aquifers (fig. 2) generally produce water that does not exceed the U.S. Environmental Protection Agency (EPA) national primary drinking-water standards for dissolved nitrate (as nitrogen) and fluoride, and secondary drinking-water standards for dissolved solids, sulfate, and fluoride. The principal aquifers contain water that is soft to moderately hard. Dissolved solids, nitrate, fluoride, sulfate, and hardness are important indicators for the acceptability of water for public supply.

Forty-three hazardous-waste sites require monitoring of ground-water quality under the Alabama Hazardous Waste Management Act and the Federal Resource Conservation and Recovery Act (RCRA) of 1976. In addition to these RCRA sites, six sites have been placed on the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c), and two other sites have been proposed for the list. These six Superfund sites require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. At 28 of the RCRA sites and 4 of the CERCLA sites, contamination has been detected in the shallow ground-water system (fig. 3*A*). An additional 475 sites are on the EPA Emergency and Remedial Response Information System (ERRIS) list. In addition, the U.S. Department of Defense has identified 89 sites at 3 facilities where contamination has warranted remedial action.

In 1981, the U.S. Geological Survey in cooperation with the Geological Survey of Alabama began a ground-water-quality monitoring program to determine background water quality in the aquifers. Initially, 50 wells were chosen; by 1985, the number had increased to 96. The analyses primarily are for the major inorganic constituents and the more common trace elements. Determinations of organic contamination in Alabama's aquifers have been limited to specific sites under projects directed by State and county agencies and private industry.

WATER QUALITY IN PRINCIPAL AQUIFERS

Principal aquifers in Alabama (fig. 2*A*1) are grouped into two types—those within the Coastal Plain and those north of the Coastal Plain (fig. 2*A*2). The aquifers within the Coastal Plain consist primarily of a sequence of unconsolidated sediments, whereas those outside the Coastal Plain consist of consolidated sediments, carbonate rocks, and igneous and metamorphic rocks (U.S. Geological Survey, 1985, p. 123). More than 62 percent of the State's ground-water withdrawals are from the Coastal Plain aquifers (Baker, 1983).

The freshest ground water in Alabama, commonly containing less than 100 mg/L (milligrams per liter) of dissolved solids, occurs in the recharge areas of all the principal aquifers. Downdip in Coastal Plain aquifers, the dissolved-solids concentrations become as large as 30,000 mg/L. Within the area of the non-Coastal Plain aquifers, the primary sources for public supply are surface water, spring flow, and a few deep wells. Iron concentrations larger than 300 μg/L (micrograms per liter) and corrosive waters (pH less than 5) are the common water-quality problems in the non-Coastal Plain aquifers. Iron also is a local problem in the Coastal Plain aquifers.

Naturally impaired water quality in southwestern Alabama (fig. 3*B*) resulted from connate, highly mineralized water migrating upward along faults. Information is not available to determine if the water quality is continuing to change. All major aquifers in the area are affected, and the only sources of fresh ground water are discontinuous terrace deposits and alluvium along the rivers.

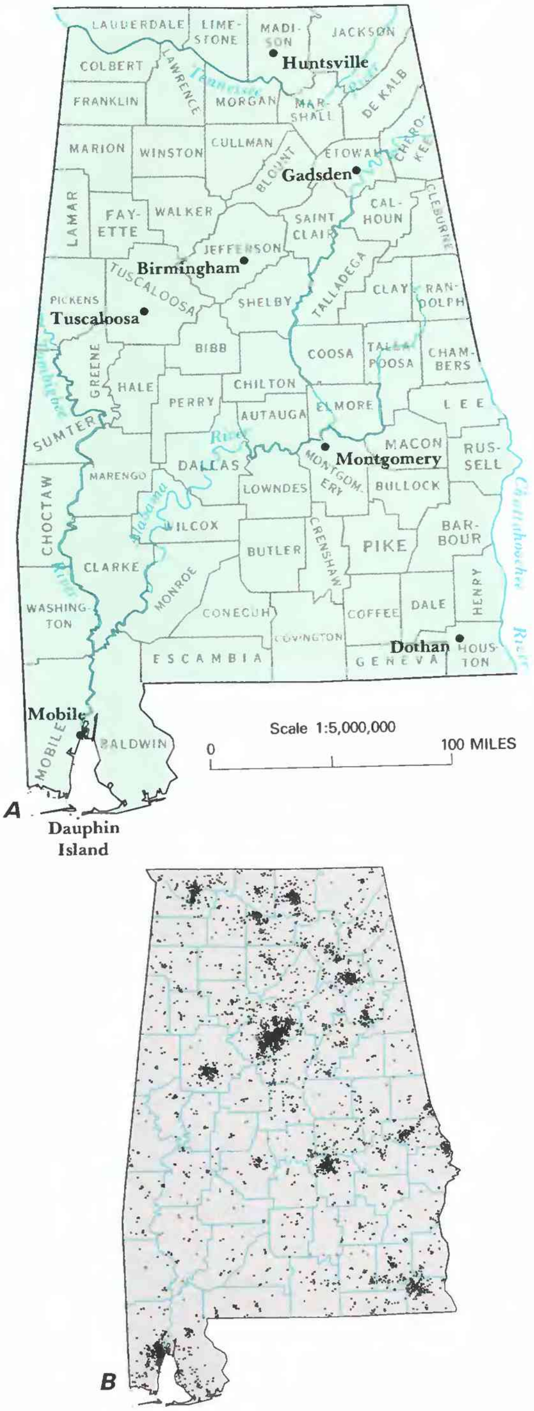

Figure 1. Selected geographic features and 1985 population distribution in Alabama. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

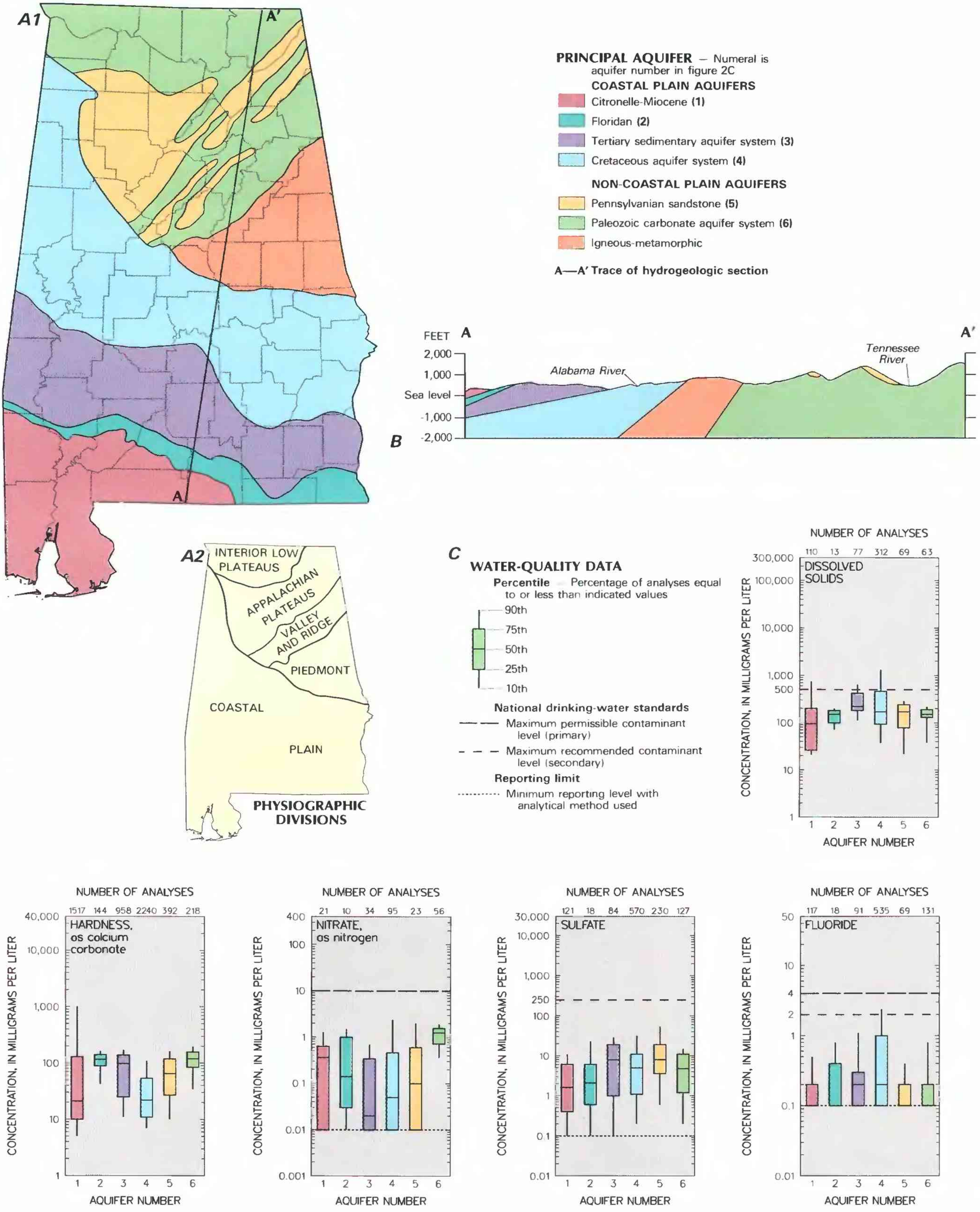

Figure 2. Principal aquifers and related water-quality data in Alabama. *A1*, Principal aquifers; *A2*, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1940-86. (Sources: *A1*, Johnston, 1933; Carlston, 1942. *A2*, Fenneman, 1938; Raisz, 1954. *B*, Copeland, 1968; Barksdale and Moore, 1976. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

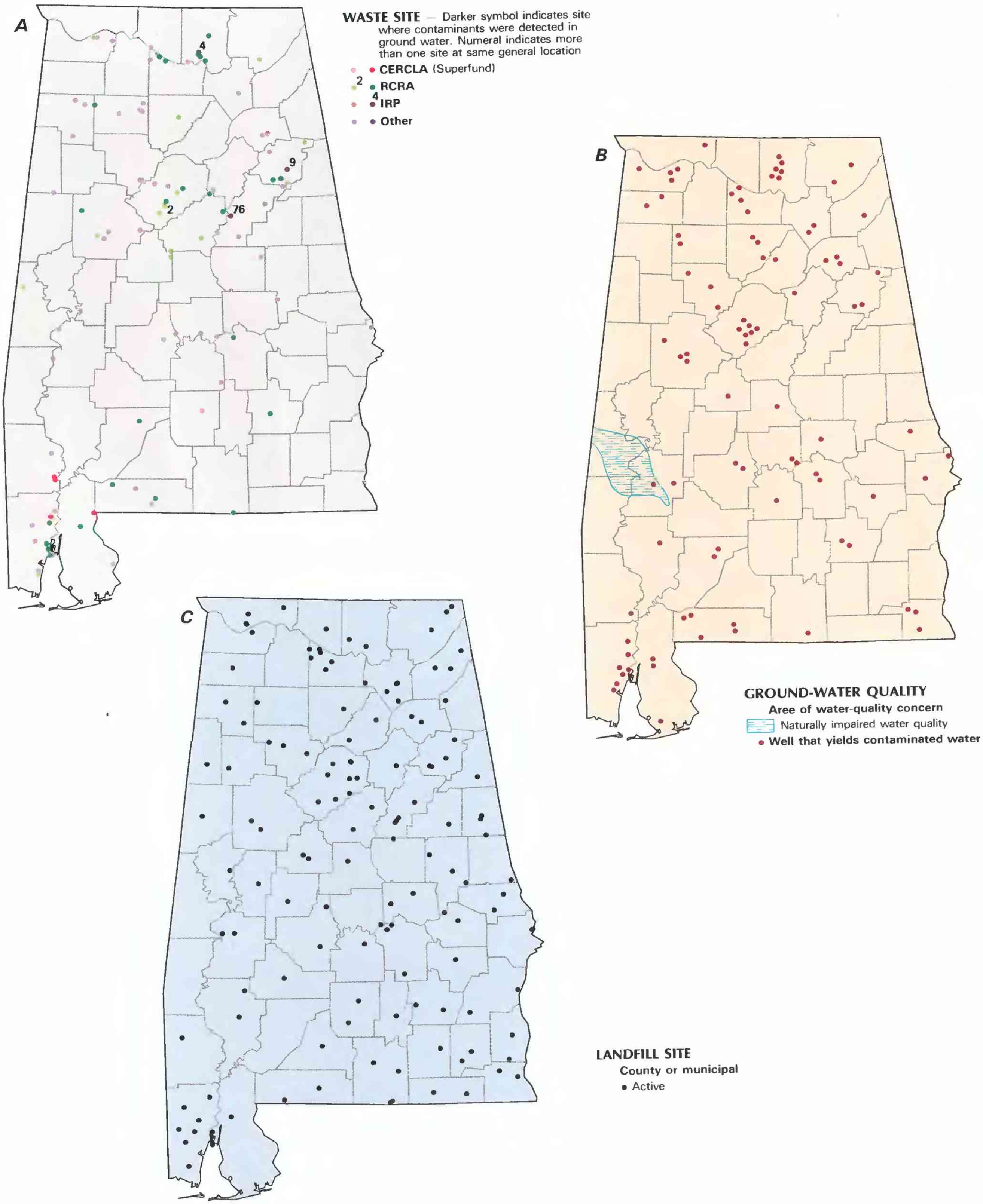

Figure 3. **Selected waste sites and ground-water-quality information in Alabama.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, Fred Mason, Alabama Department of Environmental Management, written commun., 1986; U.S. Department of Defense, 1986. *B*, *C*, Fred Mason, Alabama Department of Environmental Management, written commun., 1986.)

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is shown in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), sulfate, and fluoride analyses of water samples collected from 1940 to 1986 from the principal aquifers in Alabama. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include maximum concentrations of 10 mg/L nitrate (as nitrogen) and 4.0 mg/L fluoride, and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L sulfate, and 2.0 mg/L fluoride.

Coastal Plain Aquifers

The Coastal Plain aquifers consist of, from youngest to oldest, the Citronelle-Miocene aquifer, the Floridan aquifer, the Tertiary sedimentary aquifer system, and the Cretaceous aquifer system (fig. 2*A*1, 2*B*). Overall, the quality of water produced from these aquifers is very good for most uses, because most water is produced from the shallowest available aquifer. In the downdip sections of the aquifers, the water becomes progressively more mineralized. A shallow aquifer producing relatively unmineralized water usually is available for development, except in the southwestern section of the Coastal Plain in parts of Choctaw, Clarke, Marengo, Monroe, and Sumter Counties. This area contains faults, many caused by the upward migration of salt; the domes of salt have pierced the overlying sediments, providing an avenue for movement of very mineralized water from below.

The Citronelle-Miocene aquifer has the widest range for values of dissolved solids and hardness (fig. 2*C*) in the principal aquifers. Because it is the uppermost available of the Coastal Plain aquifers, the Citronelle-Miocene aquifer is used even when the water approaches objectionable quality. Although the range of dissolved-solids concentrations for the Citronelle-Miocene aquifer and the Cretaceous aquifer system is similar, the maximum concentration in a potential water well in the Citronelle-Miocene aquifer is about 20,000 mg/L, almost four times the maximum for water in the Cretaceous aquifer system. The values for dissolved-solids concentrations in the Cretaceous aquifer system are large, however, because the aquifer is tapped farther downdip and at a deeper interval than most of the other Coastal Plain aquifers.

Figure 2*C* shows that the 90th-percentile value for dissolved-solids concentration in three Coastal Plain aquifers—the Citronelle-Miocene, the Tertiary, and the Cretaceous—exceeded the national drinking-water standard of 500 mg/L. The only Coastal Plain aquifer with 90th-percentile dissolved-solids concentrations that did not exceed the standard is the Floridan aquifer system, which is tapped at relatively shallow depths near its recharge area where the mineral concentration in the water is small.

Hardness of water used for most domestic purposes is not objectionable at concentrations smaller than 100 mg/L (Hem, 1985, p. 159). Except for the Floridan aquifer, median values of hardness for Coastal Plain aquifers were smaller than 100 mg/L and all but the Citronelle-Miocene aquifer had concentrations smaller than 200 mg/L for 90 percent of the wells sampled (fig. 2*C*).

Large nitrate concentrations are indicators of aquifer contamination from barnyards, septic tanks, and fertilizers. Concentrations of nitrate (as nitrogen) larger than 10 mg/L are considered to be a hazard to infants less than about 1 year old. The largest median nitrate concentration for Coastal Plain aquifers (fig. 2*C*) was for the Citronelle-Miocene aquifer (0.36 mg/L), possibly as a result of intense farm-related fertilization and irrigation that are common on the outcrop of this aquifer. However, the maximum nitrate concentration for a Coastal Plain aquifer in Alabama was 7.2 mg/L for a water sample from the Cretaceous aquifer system; water from the other three Coastal Plain aquifers had maximum concentrations of 2.0 mg/L or less.

Sulfate is one of the major anions occurring in natural waters. Sulfate is important in public and industrial water supplies because of its taste and laxative effects, particularly among transient and infrequent users. It is also important because waters containing appreciable amounts of sulfate form hard scales in boilers and heat exchangers. At sulfate concentrations smaller than the drinking-water standard, taste and laxative effects are rare. Because sulfate removal processes are relatively expensive, if sulfate concentrations are excessive, use of an alternate source or blending is desirable.

Sulfate concentrations exceeded drinking-water standards in 2 of 570 samples from wells completed in the Cretaceous aquifer system. The source of the large concentrations in the two samples is uncertain; however, the samples were from areas in which the Cretaceous aquifer system contains large amounts of pyrite.

Median sulfate concentrations were smaller than 10 mg/L for each of the principal aquifers. The 90th-percentile sulfate concentrations for each of the principal aquifers also were very small, ranging from 11 to 54 mg/L. Consequently, even though the secondary standards for sulfate occasionally are exceeded, most of the ground-water samples contain acceptable concentrations of sulfate.

Fluoride is a normal constituent of all diets and is an essential nutrient. At optimum levels in drinking water, fluoride has been shown to have beneficial effects in decreasing the occurrence of tooth decay and to produce no ill effects.

The primary standard for fluoride was exceeded at places in three of the Coastal Plain aquifers. The maximum fluoride concentrations ranged from 1.0 mg/L for samples from wells in the Floridan aquifer to 6.5 mg/L for samples from the Cretaceous aquifer system. However, median concentrations were 0.1 to 0.2 mg/L for each of the principal aquifers. The 90th-percentile fluoride concentrations did not exceed the primary standard for any of the principal aquifers and exceeded the secondary standard only for samples from the Cretaceous aquifer system. A few small communities and trailer parks in Alabama have abandoned their own wells because they were producing water with fluoride concentrations larger than 4.0 mg/L and have connected to larger public water systems (J.A. Power, Alabama Department of Environmental Management, oral commun., 1987).

Although several theories have been advanced as to the sources of the fluoride in ground water in Alabama, the exact sources and processes are largely unknown. LaMoreaux (1948, p. 36) noted that in the Alabama Coastal Plain deposits "there is a close relation between fluoride in ground water and sands which contain pyrite, lignite, phosphate, volcanic materials, and glauconite." Carlston (1942) theorized that the large fluoride concentrations in ground water in Cretaceous areas of Alabama (primarily Eutaw Formation) are derived from phosphate and volcanic ash deposits.

Non-Coastal Plain Aquifers

The principal non-Coastal Plain aquifers are the Pennsylvanian sandstone aquifer and the Paleozoic carbonate aquifer system, located in the central and northern parts of the State (fig. 2*A*1). One other non-Coastal Plain aquifer—the igneous-metamorphic aquifer—was identified as being significant (U.S. Geological Survey, 1985, p. 124) because it is the only source of ground water in the Piedmont area of Alabama. This aquifer is not discussed in this report because too few chemical analyses are available for meaningful analysis.

The Pennsylvanian sandstone aquifer consists of sandstones containing water primarily in joints, fractures, and bedding planes. The Paleozoic carbonate aquifer system is the predominant source of ground water north and east of the Coastal Plain, and consists of cavernous limestone and dolomite that range in geologic age from Mississippian to Cambrian (Johnston, 1933; Barksdale and Moore, 1976).

The maximum dissolved-solids concentration for the non-Coastal Plain aquifers was 780 mg/L for the Pennsylvanian sandstone aquifer. However, the median concentrations for these aquifers, 170 mg/L for the Pennsylvanian and 150 mg/L for the Paleozoic, are similar to those for the Coastal Plain aquifers. The relatively small values for maximum dissolved-solids concentrations are smaller than might otherwise be expected, because wells in the non-Coastal Plain aquifers are shallow and are located in recharge areas that annually receive only slightly mineralized water from rainfall.

Hardness values are relatively small for the non-Coastal Plain aquifers (fig. 2*C*). The median values were 65 mg/L for the Pennsylvanian sandstone aquifer and 120 mg/L for the Paleozoic carbonate aquifer system. Hardness values for 90 percent of the sampled wells in these aquifers were smaller than 200 mg/L.

Nitrate concentrations in the non-Coastal Plain aquifers were less than the national drinking-water standard of 10 mg/L (fig. 2*C*). The Pennsylvanian sandstone aquifer had a maximum value of 7.0 mg/L, and the Paleozoic carbonate aquifer system had a maximum value of 3.2 mg/L. However, there is a marked difference in the 10th-percentile, 25th-percentile, and median values of nitrate between the Paleozoic carbonate aquifer system and the other aquifers in Alabama. Whereas the 10th-percentile value for the other five aquifers is less than detection limits, the Paleozoic carbonate aquifer system had a 10th-percentile concentration of 0.36 mg/L, a value that is equal to or larger than the median concentration for other aquifers. The median concentration for the Paleozoic carbonate aquifer system was 1.3 mg/L. These large increased concentrations possibly resulted from fertilization of crops within the Interior Low Plateaus area (fig. 2*A2*) of Alabama. Cotton and other row crops have been grown in the area since the early 1800's.

Sulfate concentrations in the non-Coastal Plain aquifers exceeded secondary standards in 13 of 230 samples from wells in the Pennsylvanian sandstone aquifer. All 13 samples of water from Pennsylvanian aquifers with large concentrations of sulfate are from wells 200 feet deep or less located in the Warrior coal field (Fayette, Tuscaloosa, and Walker Counties), which has been extensively mined for coal. Less than 10 percent of the samples from the Paleozoic carbonate aquifer system exceeded the secondary standard for fluoride.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has deteriorated in some areas owing to migration of more mineralized water to areas of intensive pumping, leaching of minerals from spoils produced by the surface mining of coal, leaking underground storage tanks, or downward migration of leachates from surface impoundments and landfills. Long-term data are not available to document most changes in water quality in Alabama. A monitoring network of wells was established in Alabama in 1981 under a joint program between the U.S. Geological Survey and the Geological Survey of Alabama. The deterioration of ground-water quality generally is documented by the large concentrations of constituents in affected wells (fig. 3*B*) compared with the background water quality of unaffected wells.

Intensive Pumping

Coastal areas are the most susceptible to migration of extremely mineralized water caused by intensive pumping. Water from a well tapping the Citronelle-Miocene aquifer, located on an offshore island in southern Mobile County, has had chloride concentrations increase from about 100 mg/L during 1955 to about 800 mg/L during 1976 (Chandler and Moore, 1983). Water from another well located farther inland had chloride concentrations increase from about 250 mg/L during 1967 to about 400 mg/L during 1976. Chandler and others (1985) reported that intensive pumping has caused saltwater encroachment in the Citronelle-Miocene aquifer in a small area of southern Baldwin County.

Leaching of Mine Spoils

Several coal seams are present in the Pottsville Formation, which contains the Pennsylvanian sandstone aquifer. The Pottsville Formation contains many soluble minerals that become exposed to oxidation and precipitation and produce leachates during widespread excavation associated with surface coal mining. Leachates commonly contain increased concentrations of dissolved solids, sulfate, iron, and manganese. Contamination of the ground water generally is localized and depends upon the presence of the soluble minerals (Puente and others, 1982, p. 9).

Leaking Underground Storage Tanks

The Alabama Department of Environmental Management has information on more than 13,000 sites, with an average of 3 underground storage tanks per site (John Poole, Alabama Department of Environmental Management, oral commun., 1986). However, the Department believes that their information is incomplete and estimates that more than 40,000 underground storage tanks are present in the State. The State has not developed a regulatory program requiring leak detection but has received 20 reports of ground-water contamination in 1986 caused by leaking tanks.

Waste Sites

Hazardous waste is treated, stored, or disposed at 75 RCRA facilities that are at various stages of permitting or closure in Alabama. Forty-three of these facilities have ground-water monitoring systems (fig. 3*A*), and some level of ground-water contamination has been detected at 28 of the facilities (Fred Mason, Alabama Department of Environmental Management, oral commun., 1986). Six priority sites are related to CERCLA and four of those sites have reported ground-water contamination (fig. 3*A*). Also, two proposed CERCLA sites have reported ground-water contamination. An additional 475 sites are on CERCLA's ERRIS list (Fred Mason, oral commun., 1986) and, of these sites, preliminary assessments have been completed at 442. Monitoring programs are designed to detect ground-water contamination, which includes increased concentrations of trace metals, acidity, volatile organic constituents, and priority pollutants. Operations that may contribute to ground-water contamination include: metal plating operations, plating wastes (metals), wood treating, solvent disposal (degreasing operations), pesticide production, battery processing and disposal (metals and acids), and industrial chemical production.

As of September 1985, 175 hazardous-waste sites at 5 facilities in Alabama had been identified by the U.S. Department of Defense (1986) as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the EPA Superfund program. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 175 sites evaluated under the program, 72 sites contained contaminants but did not present a hazard to people or the environment. Eighty-nine sites at 3 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at 63 of these sites has been completed under the program.

Waste-disposal sites not categorized as RCRA, CERCLA, or IRP sites are identified as "other" in figure 3*A*. These other sites include 56 disposal sites associated with manufacturing, coal mining, oil and gas production, electric power generation, and miscellaneous other industrial activities. (Some of these sites are too close to be plotted with separate symbols in fig. 3*A*.)

In addition to the sites described above, Alabama has 137 county and municipal landfill sites (fig. 3*C*). Each landfill is monitored with a minimum of three wells. One well is positioned upgradient in the natural ground-water flow pattern to establish background ground-water quality. At least two wells are positioned downgradient to evaluate potential effects from the landfill on ground-water quality. Leachate sampled from the landfills may contain increased concentrations of contaminants including iron, manganese, chromium, lead, and organic chemicals.

POTENTIAL FOR WATER-QUALITY CHANGES

The aquifers most susceptible to contamination are the non-Coastal Plain aquifers. In these aquifers the normal avenues for water movement are fractures, bedding planes, and solution features that collect flow and could permit relatively rapid transport of contaminants. These aquifers are recharged over their entire extent, allowing the whole aquifer to be susceptible to direct contamination from the surface. Susceptibility is also increased by the aquifers either being exposed at the land surface or being recharged through a relatively thin (usually less than 100 feet) mantle of residuum, which provides an easy avenue for downward contaminant migration.

An example of contamination to one of these aquifers is Coldwater Spring in Calhoun County, which receives water from the Paleozoic carbonate aquifer system. Concentrations of organic chemicals, which did not exceed the national drinking-water standards, were detected in 1982. The source of contamination has not been identified. Several point sources located in the area could be sources of contamination. As of 1986, no increase in the organic chemicals has been detected at the spring.

The Coastal Plain aquifers also are susceptible to contamination from the surface in their recharge areas. Wells that tap Coastal Plain aquifers in their recharge areas could become directly contaminated. However, most large-yield wells in these aquifers are farther downdip in the confined zones and, therefore, are less susceptible to direct contamination from the surface. Even in the outcrop areas of the Coastal Plain aquifers, flow through the porous unconsolidated sediments aids in faster dispersion of contaminants than would occur in the non-Coastal Plain aquifers.

GROUND-WATER-QUALITY MANAGEMENT

Alabama has existing and pending legislation pertaining to ground-water-quality management. All programs not under RCRA are managed under standards prescribed by the Clean Water Act (formerly referred to as the Federal Water Pollution Control Act or Federal Water Pollution Control Act Amendments of 1972) Pub. L. 92–500, as amended by Pub. L. 95–217, Pub. L. 95–576, Pub. L. 96–483 and Pub. L. 97–117, 33 U.S.C. 1251 et seq.

The Alabama Department of Environmental Management has developed a comprehensive ground-water protection law for consideration by the 1988 State legislature. The law addresses the requirements of the EPA's ground-water protection strategy and underground storage-tank program. The legislation also will provide the Alabama Department of Environmental Management with the authority to protect all aquifers and recharge areas in Alabama that are extremely vulnerable to contamination and are irreplaceable because of no reasonable alternative source of drinking water. The Alabama Surface Mining Commission has regulatory powers to minimize ground-water contamination due to surface mining. The Geological Survey of Alabama has regulatory responsibility for the protection of ground-water quality related to the disposal of brines generated by the exploration and production of oil and gas. The Alabama Farm Bureau has recently proposed legislation that would regulate agricultural ground-water use.

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ALASKA
Ground-Water Quality

In Alaska (fig. 1), about 70 percent of the population obtains water from ground-water sources. About 104,000 of the 276,000 people using ground water (38 percent) obtain their supply from privately owned systems (U.S. Geological Survey, 1985, p. 129). Most of the ground water in the major withdrawal areas is suitable for drinking and most other purposes. The median concentration of dissolved solids in most areas does not exceed the State's drinking-water standard of 500 mg/L (milligrams per liter) (Alaska Department of Environmental Conservation, 1979). Except for water from bedrock in the Fairbanks area, nitrate (as nitrogen) concentrations are considerably smaller than the drinking-water standard of 10 mg/L (fig. 2). Objectionable iron and hardness concentrations can occur in most areas; however, these conditions can be improved by using relatively inexpensive treatment systems.

Water quality has been degraded in several areas as the result of septic-system effluents or landfill leachates, but the number of persons affected is small. Contamination of the shallow unconsolidated aquifers (fig. 2*A*) by organic contaminants from probable fuel-tank leakage also has been identified at 16 locations. The quality of ground water is naturally impaired in the Fairbanks area, where the concentration of arsenic in water from many wells in bedrock exceeds the State's drinking-water standard of 50 μg/L (micrograms per liter) (fig. 2*B*). Concentrations of arsenic as large as 10,000 μg/L have been reported (Johnson and others, 1978).

Alaska has no hazardous-waste sites on the U.S. Environmental Protection Agency's (1986c,d) National Priorities List. However, at 47 military installations in Alaska a total of 193 waste sites had been identified, as of September 1985, by the U.S. Department of Defense (1986) as potential hazardous-waste sites under provisions of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Ninety-two of these sites at 45 military installations (fig. 3) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at one of these sites has been completed under the program.

The four major sources of potential contamination of aquifers are onsite septic systems, land disposal of wastes, leakage from abandoned fuel tanks, and saltwater intrusion.

WATER QUALITY IN PRINCIPAL AQUIFERS

Aquifers have been mapped in some detail only in parts of the widely separated major population centers—Fairbanks, Juneau, Anchorage, and Kenai-Soldotna (fig. 1*B*). All water-yielding formations in Alaska have been grouped into two principal aquifers (fig. 2*A*)—unconsolidated alluvium and glacial outwash deposits, and bedrock (U.S. Geological Survey, 1985, p. 129–130). The most extensive development and withdrawal of ground water to date (1986) has been at Anchorage, where more than half of the State's population resides. Two other areas of large-scale ground-water use are the Tanana River valley in interior Alaska, which includes the city of Fairbanks, and a petrochemical industrial complex on the Kenai Peninsula. Nearly all ground-water development in Alaska has been in unconsolidated aquifers. About 1 percent of the State's total ground-water withdrawal is from bedrock.

A data base adequate to describe areal variations in the chemical quality of ground water is available for only a few places, such as Juneau, Kenai, Anchorage, and Fairbanks. Few data have been collected for large areas of the State, and outside of these major population centers, most water-quality data are for the unconsolidated aquifers. Most of the sampled water from the unconsolidated aquifers contains less than 400 mg/L dissolved solids (fig. 2*B*) and is considered to be suitable for most uses. Known concentrations of dissolved solids in ground water range from about 25 mg/L in stream-channel alluvium to 6,400 mg/L in shallow wells in some coastal areas. Except in the Fairbanks and Anchorage areas, the bedrock aquifers are virtually undeveloped, and little is known about the quality of the contained water.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*B*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), iron, and arsenic analyses of water samples collected from 1949 to 1976 from the principal aquifers in Alaska. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a, b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen) and 50 μg/L arsenic, and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 300 μg/L iron. For these variables, the State drinking-water standards are the same as the national standards.

Unconsolidated Aquifers

Most of the sampled water from the unconsolidated aquifers does not exceed the drinking-water standard. Calcium and magnesium, which contribute to the hardness of water, and bicarbonate are the major dissolved ions. In most of the wells, hardness accounts for 60 to 80 percent of the dissolved-solids concentration. In many communities, wells drilled near the coast yield water of sodium bicarbonate or sodium chloride type.

Iron is present in concentrations that exceed drinking-water standards in a large number of shallow wells in most areas of the State. Concentrations larger than 1,000 μg/L are common (fig. 2*B*). Iron concentrations larger than about 300 μg/L can cause staining of laundry and plumbing fixtures and can impart a taste to the water.

One of the few areas of Alaska where natural ground-water quality could be considered to be unsuitable for some uses is the Copper River basin (Emery and others, 1985). As a general rule, the ground water becomes more mineralized with increasing depth in the upper Copper River basin. Saline springs in the area are the surface manifestation of saline ground water present in the marine sedimentary rocks that underlie much of the glacial-lake deposits (Grantz and others, 1962). Upward movement of water from these older sedimentary rocks has affected the quality of water in the overlying unconsolidated aquifers. Water in the unconsolidated aquifers is characterized by large concentrations of dissolved solids (as much as 10,000 mg/L), sodium, chloride, iron, and manganese.

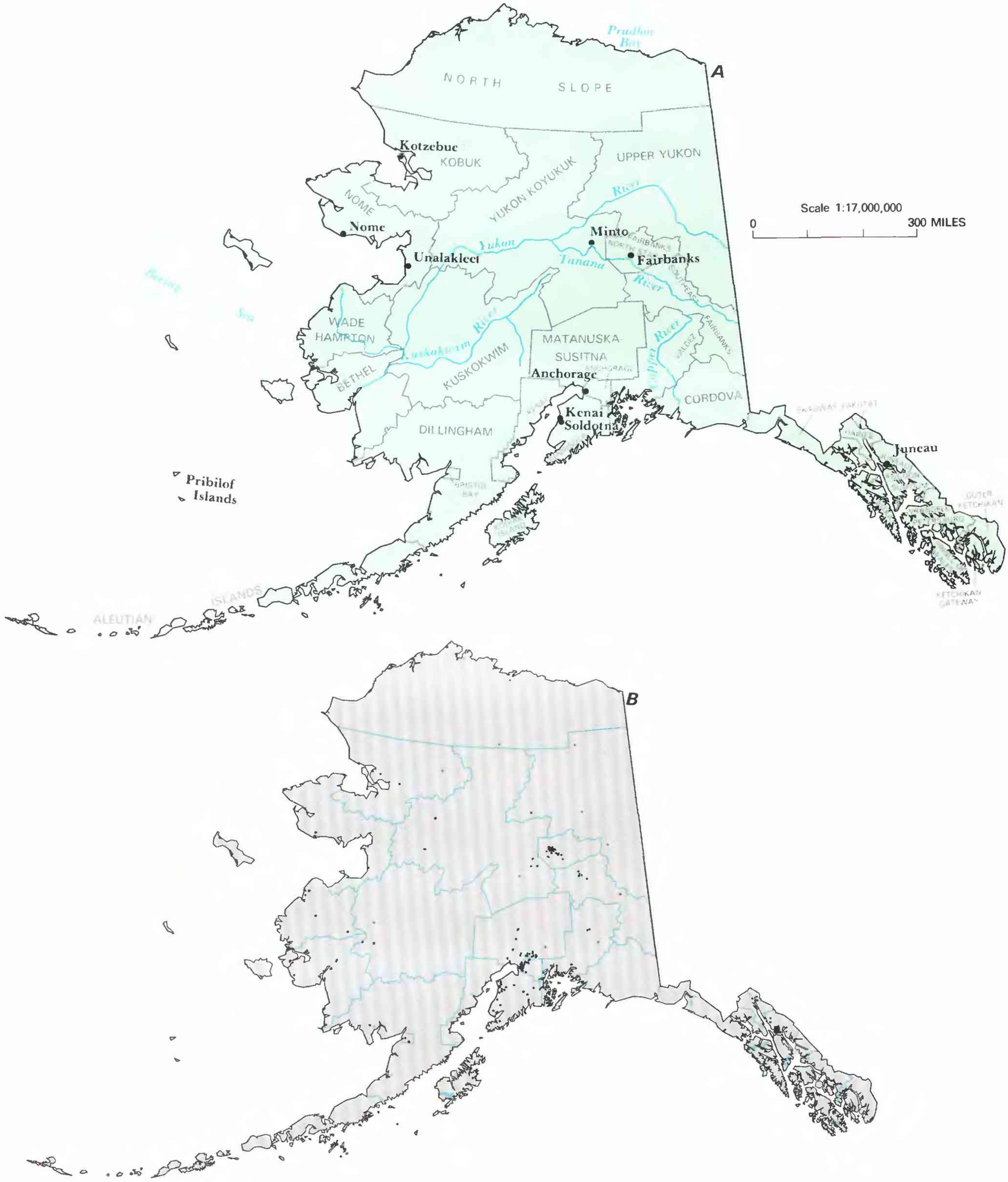

Figure 1. Selected geographic features and 1985 population distribution in Alaska. *A*, Geographic areas, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

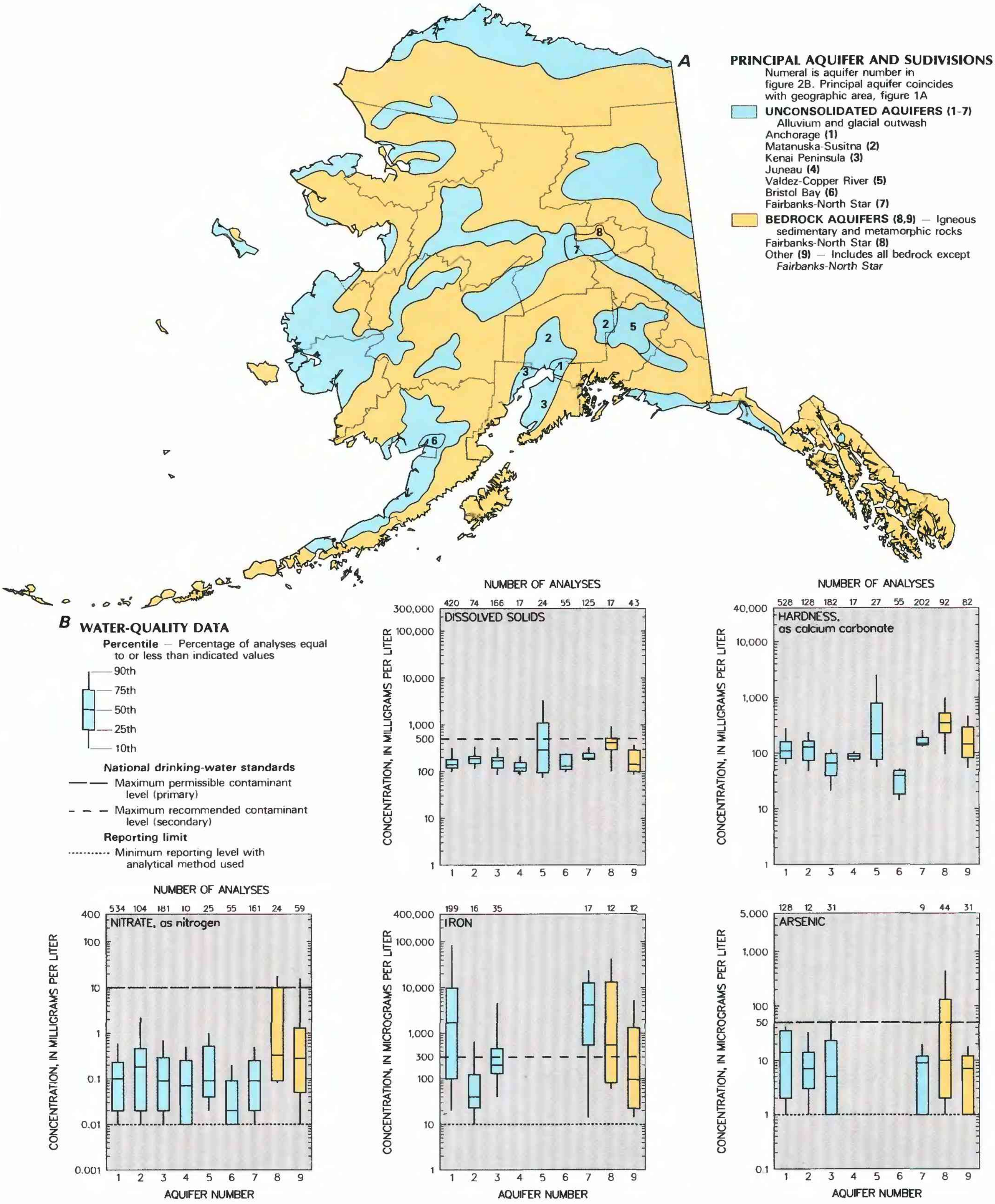

Figure 2. Principal aquifers and related water-quality data in Alaska. *A*, Principal aquifers. *B*, Selected water-quality constituents and properties, as of 1949-86. (Sources: *A*, U.S. Geological Survey, 1985. *B*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

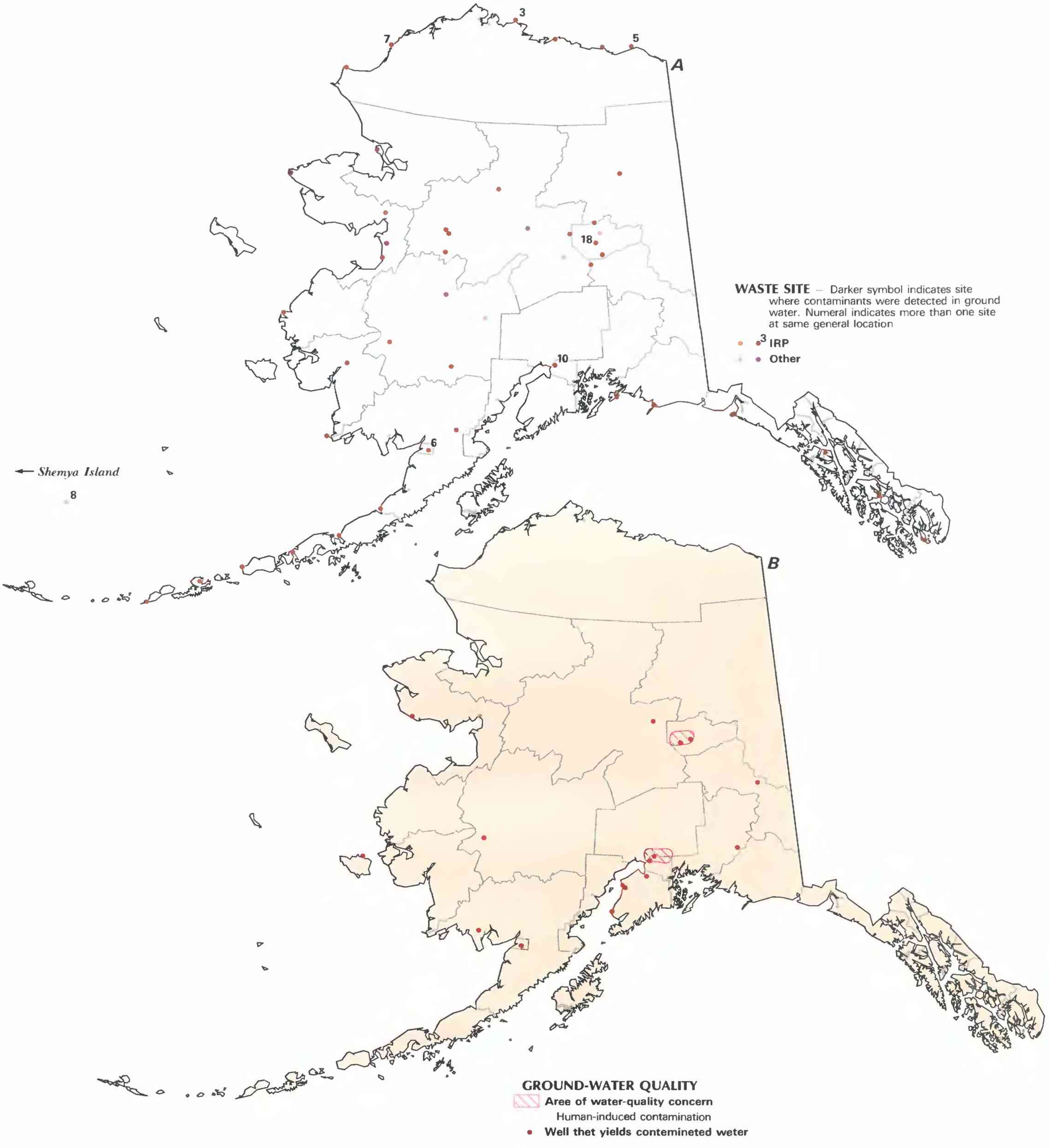

Figure 3. Selected waste sites and ground-water-quality information in Alaska. *A*, Department of Defense Installation Restoration Program (IRP) sites, as of 1985. *B*, Areas of human-induced contamination and distribution of wells that yield contaminated water, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A*, U.S. Department of Defense, 1986. *B*, Alaska Department of Environmental Conservation files, 1986. *C*, Henry Friedman, Alaska Department of Environmental Conservation, oral commun., July 1986.)

Figure 3. Selected waste sites and ground-water-quality information in Alaska—Continued.

The summary (fig. 2*B*) shows the variability in chemical quality of the water from unconsolidated aquifers for the major areas of water withdrawal. For many areas of the State, the number of wells having water-quality information is too small to be adequate for statistical inference. For these areas, a general indication of the range in dissolved-solids concentrations in shallow unconsolidated aquifers can be gained from an analysis of stream water-quality data for low-flow (or base-flow) periods. During winter in interior Alaska, the ground is frozen, no surface runoff occurs, and any streamflow is sustained by ground-water discharge.

Dissolved-solids concentration is considered to be a useful index of overall water quality, but available data do not provide representative coverage for winter streamflow in Alaska. However, specific conductance, which is affected by dissolved-solids content, is a characteristic commonly measured in field water-quality determinations. For most natural waters in Alaska, the dissolved-solids concentration ranges from 55 to 65 percent of the specific-conductance value. The following table (Zenone and Anderson, 1978) indicates ranges of specific-conductance values measured during base-flow periods for streams in Alaska, except for the southeastern part of the State, where base flow has not been defined.

Summary of specific-conductance values for base flow of streams in Alaska

[Base-flow period is November 1 to April 30, when surface runoff is small or nonexistent; μS/cm, microsiemens per centimeter at 25 degrees Celsius]

Geographic area (fig. 1*A*)	Range of specific conductance (μS/cm), 1949-76
North Slope	225-350
Kobuk, Nome	150-250
Kuskokwim, Wade Hampton	250-300
Southeast Fairbanks, Upper Yukon, Yukon-Koyukuk	250-400
Bethel	100-240
Dillingham	50-100*
Kenai Peninsula	100-300
Valdez-Copper River	300-500

*Affected by significant volume of lake storage.

In coastal areas of Alaska, the natural ground-water quality can be affected by saltwater intrusion. Coastal aquifers that contain freshwater may be hydraulically connected to the ocean or other saline-water bodies. Under natural conditions, the direction of ground-water flow generally is toward the coast. If pumping lowers the water table or potentiometric surface so that the natural gradient is reversed, saline water will move into the freshwater aquifer. Increases in salinity of the water resulting from pumping stress on the aquifer have occurred at Indian Cove, a small community near Juneau. Six of 18 wells currently in use there produce brackish water having dissolved-solids concentrations larger than 1,000 mg/L (Dearborn, 1985).

In island settings and on offshore bars and spits, fresh ground water generally occurs as an unconfined, lens-shaped body floating on saline ground water. Theoretically, in this situation, there is a 40-foot-thick zone of fresh ground water below sea level for each foot of water-table altitude above sea level (Todd, 1980, p. 496). This situation exists at St. George Island, in the Pribilof Islands in the Bering Sea (Anderson, 1976), and at Fire Island near Anchorage (A.J. Feulner, U.S. Geological Survey, written commun., 1964). Other areas where fresh ground water probably occurs only as thin lenses above salty water are at Unalakleet, Kotzebue, and the coastal fringes of the Yukon and Kuskokwim River deltas in western Alaska.

The role of permafrost in directly imparting a particular type of mineralization to ground water is probably minor. A decrease in the rate of ground-water movement by permafrost provides a longer time for reactions between the water and the enclosing rocks than in regions without permafrost (Williams and van Everdingen, 1973). Chemical reaction rates and saturation concentrations of some constituents also are affected by low water temperatures. Ground water beneath permafrost usually is of nearly constant quality at a particular site, although it may differ in composition from one area to another.

Bedrock Aquifers

Because the bedrock aquifers in most areas of Alaska are undeveloped, very little is known about their water quality. In general, the concentration of dissolved solids in water from bedrock aquifers is larger than that present in the unconsolidated aquifers and the chemical quality is more variable.

One of the areas of more intensive development of bedrock aquifers is in fractured schist of the uplands near Fairbanks. The chemical composition of the water in the schist is extremely variable, and in many instances the presence of large concentrations of several constituents renders the water unsuitable or marginal for domestic use (fig. 2*B*). The hardness of ground water from sampled wells in the Fairbanks area ranges from 17 to 1,000 mg/L, and more than 50 percent of sampled wells have a hardness larger than 300 mg/L (Johnson and others, 1978). Only 7 percent of the sampled wells have a hardness concentration less than 100 mg/L, a level not considered to be objectionable for most uses. Concentrations of iron also are generally large in the Fairbanks area (fig. 2*B*).

Arsenic and nitrate concentrations that exceed the drinking-water standards are common in water from wells completed in the bedrock aquifers near Fairbanks. The primary source of these constituents and the mechanism by which they enter the ground water have not been conclusively demonstrated, but they are considered to be most likely natural (Johnson and others, 1978). For most wells sampled, arsenic concentrations range from 0 to 10,000 μg/L. In most bedrock wells, nitrate concentrations are smaller than 10 mg/L as nitrogen, but water from 21 percent of wells sampled exceeds this value.

EFFECTS OF LAND USE ON WATER QUALITY

In most of Alaska, ground water is an untapped resource that has been virtually unaffected by humans. However, in the major urban areas and in some outlying villages, ground-water quality has been locally degraded, primarily due to seepage from septic systems, landfills, and abandonded fuel-storage tanks. Sites where ground-water contamination has been documented are shown in figure 3.

The rapid growth of population in the Anchorage area has resulted in the construction of many large residential developments outside the city's water- and wastewater-system boundaries. These developments use onsite water sources and wastewater-disposal systems. In many areas, subdivision lots of one-half acre or less are served by individual wells and septic systems. The number of operating septic disposal systems in the greater Anchorage area is about 9,000, or about one for every eight residences. Local contamination of ground water has been caused by septic-system effluent in several areas of Anchorage and Fairbanks. Also, some private water supplies have been contaminated by drainage of surface water into wells that either were improperly constructed or had damaged casing at the ground surface.

Ground water has been contaminated locally in the Anchorage area by the disposal of solid waste directly into lakes that are connected hydraulically to the ground-water system, or by surface disposal in landfills where the water table is shallow (Zenone and others, 1975). Shallow ground water beneath the Merrill Field landfill in Anchorage and the old Greater Anchorage Area Borough landfill (closed since 1977), where near-surface materials are saturated, is severely contaminated by leachate produced within the refuse. Leachate at these two sites is characterized by large concentrations of organic carbon, iron, and manganese, combined with concentrations of dissolved solids ranging from 2 to 20 times greater than adjacent, unaffected ground water.

In addition to bacterial and other contamination from septic systems, and the naturally occurring large concentrations of arsenic and nitrate in the Fairbanks area, a significant ground-water-contamination problem in Alaska is leakage from underground fuel-storage tanks. The rapid population growth in Alaska subsequent to the discovery of petroleum at Prudhoe Bay resulted in the development and conversion of large tracts of land surrounding the major urban centers, from rural homestead areas to suburban communities. Before this development, many rural residents relied on individual buried storage tanks for their home and auto fuel supplies. As other fuel sources became available or when rural residents migrated to newly constructed subdivisions, many of these storage tanks were abandoned. In addition, the expansion and widening of the State's highway system have caused the displacement or relocation of commercial service centers and subsequent abandonment of their fuel-storage facilities. Because suburban development is taking place in the same locations, the potential for degradation of aquifers from leaking fuel tanks is a major concern. Leakage from underground fuel tanks has contaminated aquifers locally in the Nome, Minto, Fairbanks, Anchorage, and Soldotna areas (fig. 3*B*).

The largest area of aquifer contamination from possible fuel-tank leakage identified to date (1986) is near Peters Creek, a small suburban community northwest of Anchorage. In April 1986, concentrations of benzene that exceeded the State's drinking-water standards were found in 15 privately owned wells in a Peters Creek subdivision. Significant concentrations of toluene and xylene also were detected in these wells. The delineated zone of aquifer contamination encompasses an area of about 40 individual residence lots. Organic compounds indicative of diesel or gasoline fuels were detected in ground water at several other locations (fig. 3*B*) throughout the State (Henry Friedman, Alaska Department of Environmental Conservation, written commun., 1986).

To date (1986), neither the State nor the Federal government has had a systematic statewide monitoring program to detect organic contaminants in ground water. The number of wells or aquifers that may be contaminated as the result of fuel-tank leakage presently is unknown. However, because of the many tanks in the ground, especially in rural Alaska, the number of wells affected could be significant.

POTENTIAL FOR WATER-QUALITY CHANGES

For large areas of Alaska, minimal information is available on the quality of ground water. The instances of ground-water contamination reported here probably represent the major types of contamination that are most likely to occur, but the extent of aquifers affected presently is unknown.

The potential for increase in ground-water contamination from improperly constructed or failing septic disposal systems is relatively large. Of the approximately 9,000 septic systems in the Anchorage area, many have been installed in the last 10 years. As the efficiency of these systems decreases with age, the possibility exists for an increase in the volume of inadequately treated effluent reaching the shallow ground water.

A large but currently unknown number of old landfills and dump sites exists throughout the State. Many of these sites are the result of construction activities or military operations during World War II, and, in most instances, the type of materials they contain is unknown. These sites are a potential source of contamination.

Under Phase I of its Installation Restoration Program, the U.S. Department of Defense (1986, p. 28–30) has evaluated 193 waste-disposal sites at 47 military installations in Alaska to determine their potential for contamination (fig. 3*A*). In Phase-II studies, which are similar to the remedial investigations of the CERCLA process, 92 sites at 45 military installations were considered to present a hazard significant enough to warrant response action. Investigations at these sites are now being completed and either no contamination has been detected or assessment data are being evaluated (U.S. Department of Defense, 1986, p. 28–30); remedial action has been completed at one site.

Ground-water quality beneath or adjacent to municipal landfills (fig. 3*C*) outside the Anchorage and Fairbanks urban areas is unknown. Solid-waste disposal in areas of permafrost is, in effect, a storage of material from which a contaminating leachate could be produced if the frozen mass of waste and adjacent permafrost were to be naturally or artificially thawed (Straughn, 1972).

The practice of using lagoons for wastewater disposal and treatment at remote construction camps and villages throughout Alaska is a potential source of contamination for ground-water supplies. Some of these lagoons are near shallow water-supply wells and infiltration galleries. The lagoons function as sources of local ground-water recharge, and successful operation of the wells and galleries may depend on the permeability and porosity of the same small body of unfrozen material that is recharged by the lagoons.

Accidental oil or fuel spills that occur during major construction projects, and disposal of petrochemical wastes, oil-field brines, and drilling muds are other potential sources of contamination of ground water. Also, leaks from underground fuel storage tanks may increase contamination, because many such tanks exist and may soon reach their design lifetime.

All major population centers except Fairbanks lie partly in coastal areas. Imminent development of Alaska's offshore petroleum and other resources will ensure that future growth and water demand will be concentrated in coastal areas. Additional development of ground-water supplies in those areas will require consideration of the potential for saltwater intrusion.

In the Copper River basin, saline water is pumped from wells and issues from several springs. The connate origin of the saline water has been confirmed by exploratory drill holes (Williams, 1970). Dissolved-solids concentrations of these waters range from 760 to 53,000 mg/L. The potential exists for degradation of the shallow fresh (or at least brackish) water, should excessive pumping cause saline water to migrate or leak upward through the confining beds (Emery and others, 1985).

GROUND-WATER-QUALITY MANAGEMENT

Alaska Statutes Title 46, Chapter 3 (1971), adopts a policy to "conserve, improve, and protect public health and safety, terrestrial and aquatic life, natural resources, and the environment." To implement the policy, authority to adopt water-quality and pollution-control standards was given to the Alaska Department of Environmental Conservation (DEC). Alaska's water-quality standards, established in Title 18, Chapter 70 of Alaska Administrative Code (1984), apply to all water including ground water, and are used primarily as a basis for establishing conditions in wastewater-discharge permits issued by the DEC; developing best management practices to control nonpoint sources of pollution; determining the effect of human activities on identified uses of the water; and enforcing actions against operations that adversely affect water quality.

In applying the water-quality standards, the Alaska DEC samples and analyzes State waters, associated plant and animal life, and wastewater discharges. The DEC also requires dischargers to analyze wastewater effluent and receiving waters to assist in protecting water quality. Under the State Drinking-Water Act (Alaska Department of Environmental Conservation, 1979), operators of community water systems are required to monitor water supplies periodically for conformance to State standards.

The DEC is authorized under Title 46, Chapter 3 (1971), to manage hazardous-waste and solid-waste programs. The State has a federally approved solid-waste-management program and has been delegated full authority for solid-waste management under subtitle D of the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Authority for hazardous-waste management has not yet (October 1986) been delegated and currently is administered by the U.S. Environmental Protection Agency. Current State statutes authorize the development of regulations that are in conformance with RCRA, and routine ground-water monitoring is required at all land disposal facilities that serve more than 2,000 people or receive 5 tons or more of waste per day. Monitoring requirements generally are limited to those contaminants in the standards that are appropriate and practical for a particular discharger. Ground water is of primary concern to the State in granting land-disposal permits, and a significant part of RCRA grant funds will be directed toward ground water.

Several short-term (3–5 years) networks for monitoring ground-water quality currently are operated by the U.S. Geological Survey in cooperation with the Municipality of Anchorage, the Fairbanks–North Star Borough, and the Matanuska–Susitna Borough. The primary objective of these networks is to monitor potential contamination from landfills (25 wells) and areas of septic disposal systems (35 wells). The State does not currently (1986) have a program of ground-water classification or statewide ground-water-quality monitoring. The Alaska DEC samples water-supply wells as a part of special studies or in response to reported or suspected instances of water contamination.

As of 1986 only a small fraction of Alaska's ground water has actually been assessed. The fact that so little is known about ground-water quality, or about the extent of actual or potential contamination, is a function of the large size of the State and the limited staff assigned to ground-water-quality protection. Also, State agencies have been in existence for a relatively short time and, therefore, have had limited opportunity to establish a comprehensive data base. The present level of geologic and hydrologic information for the major aquifer systems in most of Alaska is inadequate to provide for sound management decisions or ground-water protection. To provide for future management of Alaska's ground-water resources, additional information is needed on the existing quality of water and on the location, types, and potential severity of ground-water contamination.

The Alaska DEC presently (1986) is in the initial stages of developing a coordinated statewide ground-water-quality protection program in conformance with guidelines of the U.S. Environmental Protection Agency. As a part of this program, DEC has contracted with the Alaska Department of Natural Resources to inventory the availability of ground-water-quality data in Alaska, and to inventory sites of known ground-water contamination (William

Ashton, Alaska Department of Environmental Conservation, written commun., 1986). The results of the assessment (scheduled to be completed in early 1989) will provide an improved data base for developing a comprehensive ground-water-quality management program for Alaska.

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ARIZONA
Ground-Water Quality

In Arizona, ground-water-quality problems are a major concern because ground water is the principal source for public supply. In 1983, about two-thirds of the water used in the State was derived from ground-water sources (U.S. Geological Survey, 1985a), and ground water supplied 65 percent of the population (fig. 1). In 1983, about 73 percent of the ground water withdrawn was used for agriculture; the remainder was used for public, industrial, domestic, and stock purposes. According to Kister (1973), about 95 percent of all ground-water withdrawals in the State were from alluvial aquifers in the Basin and Range lowlands water province (fig. 2*A*2).

Ground-water-quality problems exist locally at several locations throughout the State. With some exceptions, ground water generally meets drinking-water standards established by the Arizona Department of Health Services (ADHS) and the U.S. Environmental Protection Agency (1986a,b). In the nine major areas of ground-water withdrawal within the State (fig. 2*A*2), the median concentration of dissolved solids is less than the State's recommended maximum contaminant level of 500 mg/L (milligrams per liter). In all areas, the median concentration of nitrate plus nitrite (as nitrogen) is less than the maximum contaminant level of 10 mg/L for drinking water. Degradation of water quality in many areas throughout the State is associated with urbanization, irrigation, and leachates from mine tailings and surface impoundments.

Five hazardous-waste sites in the State (fig. 3*A*) require monitoring of ground-water quality under the Resource Conservation and Recovery Act (RCRA) of 1976. In addition to the RCRA sites, five sites are included in the U.S.Environmental Protection Agency's (EPA) National Priorities List (NPL) of hazardous-waste sites (U.S. Environmental Protection Agency, 1986c). These five sites require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Four additional sites have been proposed for inclusion on the NPL by the EPA. Contamination of ground water has been detected near all RCRA and CERCLA sites in Arizona. Arizona has six military facilities where hazardous-waste sites have been identified under the Installation Restoration Program (IRP).

The ADHS and the Arizona Department of Water Resources (ADWR) operate ground-water-quality monitoring networks primarily as part of special studies or near known or suspected contaminated areas. Water-quality data have been collected by the U.S. Geological Survey as part of various projects through the years. These data are stored and maintained in the National Water Data Storage and Retrieval System (WATSTORE) data base, which is maintained by the Geological Survey. With enactment of the Arizona Environmental Quality Act of 1986, new efforts will be made by the State to develop and implement ground-water-quality monitoring networks.

WATER QUALITY IN PRINCIPAL AQUIFERS

The principal aquifers in Arizona (fig. 2*A*1) consist of unconsolidated alluvium (alluvial aquifers), consolidated sedimentary rocks (sandstone aquifers), and crystalline igneous and metamorphic rocks (bedrock aquifers). The occurrence and quality of water in the principal aquifers are controlled by the geology and physiography in three distinct water provinces (fig. 2*A*2)—Basin and Range lowlands, Central highlands, and Plateau uplands (Kister, 1973). Background water quality in the principal aquifers is described for each water province.

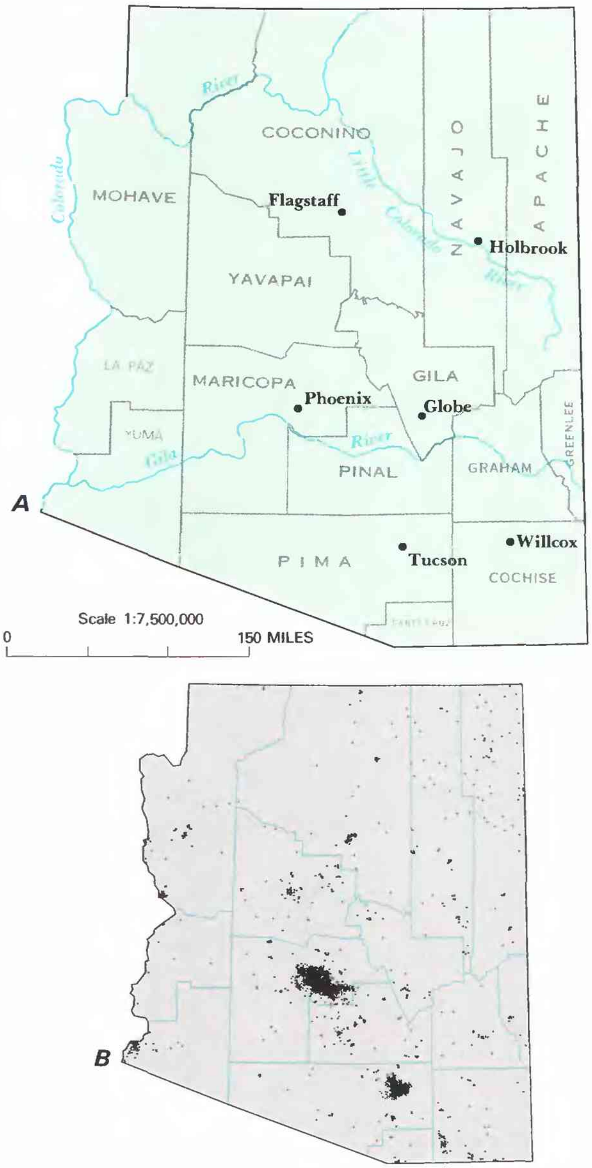

Figure 1. Selected geographic features and 1985 population distribution in Arizona. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's WATSTORE data base is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate plus nitrite (as nitrogen), fluoride, and sulfate analyses of water samples collected from 1965 to 1985 from the principal aquifers in 13 selected ground-water basins (fig. 2*A*2). Percentiles of these variables are compared to national standards

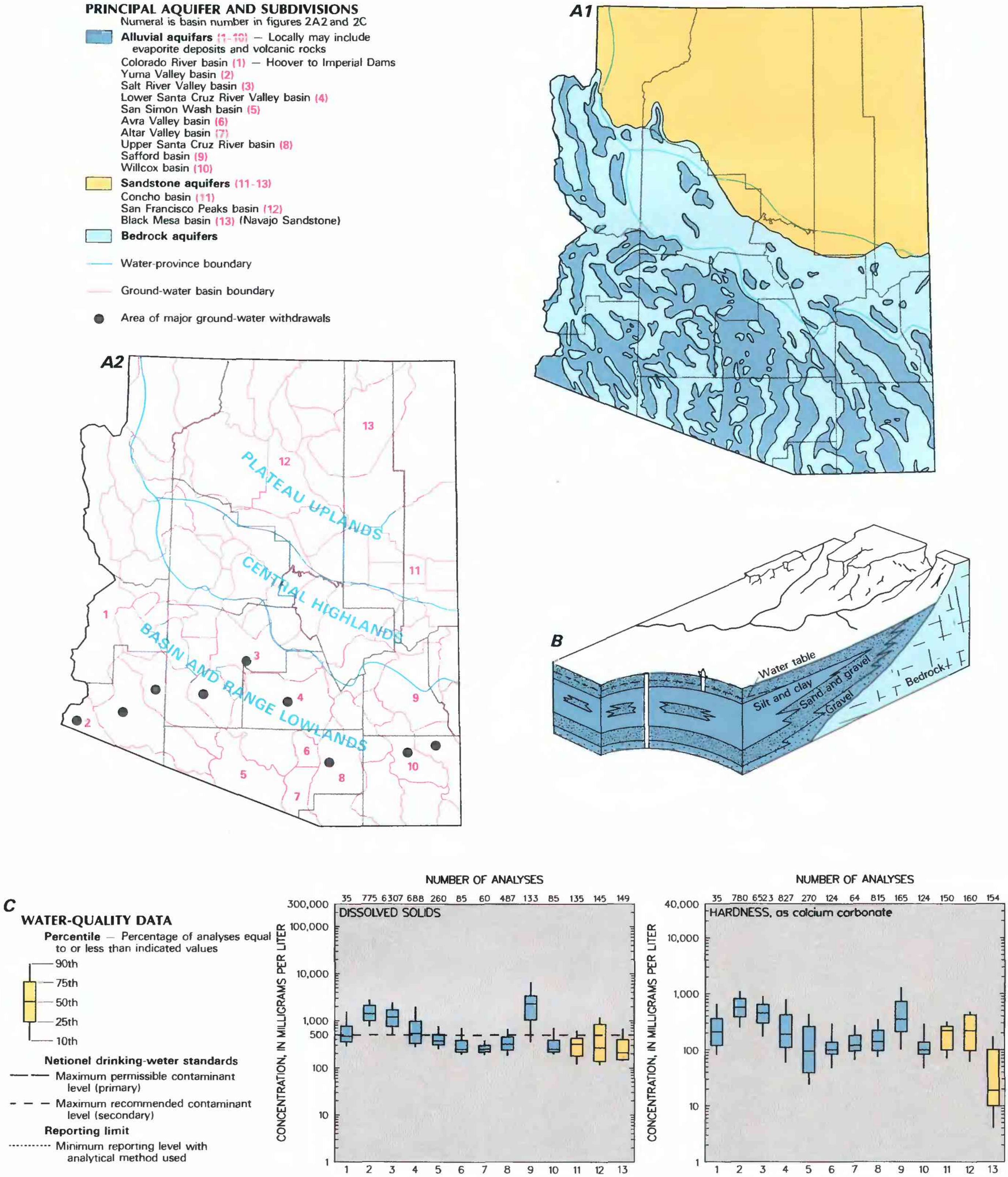

Figure 2. **Principal aquifers and related water-quality data in Arizona.** *A*1, Principal aquifers. *A*2, Water provinces, ground-water basins, and areas of major ground-water withdrawals. *B*, Generalized block diagram. *C*, Selected water-quality constituents and properties, as of 1965-85. (Sources: *A*1, Anderson, 1980; Cooley, 1963. *A*2, U.S. Geological Survey, 1985a,b. *B*, Compiled by N.D. White and T.W. Anderson from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen) and 4 mg/L fluoride; the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 2 mg/L fluoride, and 250 mg/L sulfate. The statistics do not consider changes in water quality with depth or areal distribution.

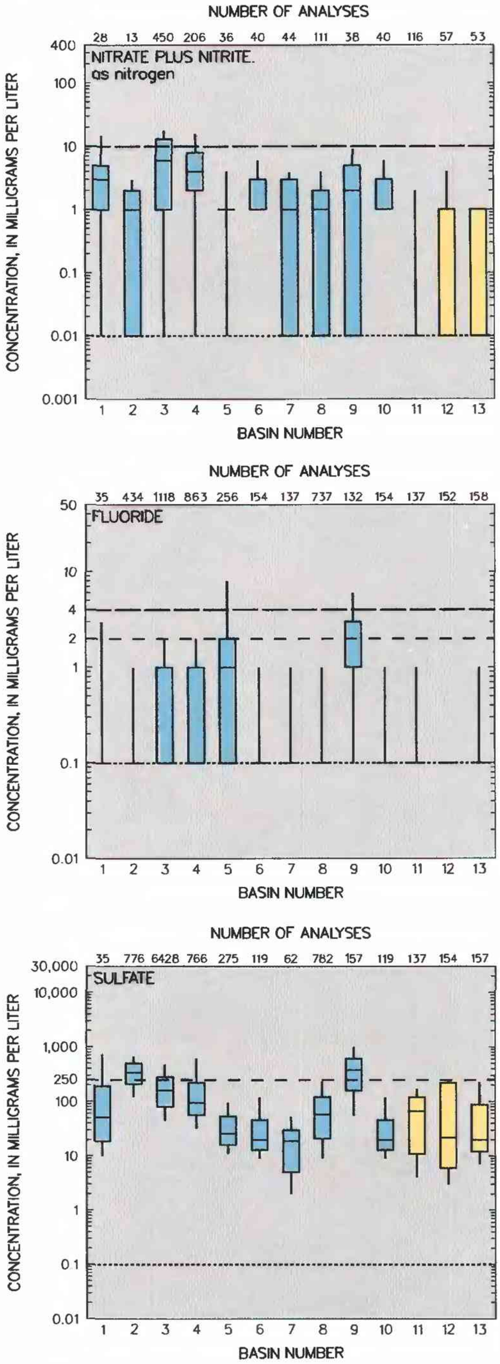

Figure 2. Principal aquifers and related water-quality data in Arizona—Continued

Basin and Range Lowlands

The Basin and Range lowlands water province is characterized by isolated north- to northwest-trending mountain ranges separated by broad alluvial basins. The alluvial aquifers in this province are composed of deposits derived from surrounding mountains. Older sedimentary and crystalline rocks (bedrock aquifers) generally are denser and more cemented than the younger overlying deposits and yield usable water only where extensively fractured or faulted (U.S. Geological Survey, 1985b, p. 136).

Alluvial aquifers in this province are the most productive aquifers in the State. About 95 percent of the ground water withdrawn in Arizona is from these alluvial aquifers (Kister, 1973). Quality of water in the alluvial aquifers varies with location and depth within the province. The local lithology and mineralogy of the alluvial sediments affect the chemical composition of the water. In some places, dissolved-solids concentrations decrease with increasing depth, which results in a change in water type. In Pinal County, the Willcox and Tucson areas, and the western part of Salt River Valley basin (figs. 1*A*, 2*A*2), the water type changes from a calcium bicarbonate to a sodium bicarbonate at greater depths. According to Robertson (1986, p. 69), concentrations of naturally occurring fluoride, barium, arsenic, and chromium in the Basin and Range lowlands alluvial aquifers range from trace amounts to 5 to 10 times the State and Federal maximum contaminant levels of 4 mg/L, 1 mg/L, 0.05 mg/L, and 0.010 mg/L, respectively.

Dissolved-solids concentrations in water from the alluvial aquifers (fig. 2*C*, basins 1–10) range from less than 100 to more than 40,000 mg/L, but generally are less than 1,000 mg/L. However, median dissolved-solids concentrations in basins 2, 3, 4, and 9 and median sulfate concentrations in basins 2 and 9 exceed the recommended EPA secondary drinking-water standards of 500 mg/L and 250 mg/L, respectively (fig. 2*C*). The median concentrations of nitrate plus nitrite (as nitrogen) and fluoride in water from the alluvial aquifers in the Basin and Range lowlands do not exceed EPA primary drinking-water standards (fig. 2, basins 1–10). Water in alluvial aquifers in basins 2, 3, and 9 is generally hard or very hard (greater than 120 mg/L as calcium carbonate).

Central Highlands

The Central highlands water province is a mountainous area that separates the Basin and Range lowlands from the Plateau uplands. The province consists principally of rugged, sharply pinnacled ranges and volcanic mountains. Igneous, metamorphic, and consolidated sedimentary rocks (bedrock aquifers) form the core of the province and only where rocks are fractured or faulted are there usable amounts of water. A few valleys are filled with alluvium that provides minor amounts of water (U.S. Geological Survey, 1985b, p. 136). Data indicate that ground water in the province generally contains less than 1,000 mg/L of dissolved solids although some springs yield saline water to streams (Kister, 1973).

Plateau Uplands

In the Plateau uplands water province, most of the water is derived from consolidated sedimentary rocks (Sandstone aquifers)—mainly the Coconino, Navajo, and Dakota Sandstones. Because of relatively sparse population, only about 3 percent of the total ground water withdrawn in Arizona is from the aquifers in this province. Ground water is used mostly by scattered farms and rural homesites, industrial sites, and a few population centers such as Flagstaff, Holbrook in central Navajo County, and the White Mountains recreational areas in southern Apache County (fig. 1*A*).

Median concentrations of dissolved solids, nitrate plus nitrite (as nitrogen), fluoride, and sulfate in water from the sandstone aquifers in the Plateau uplands do not exceed EPA primary or secondary drinking-water standards for these constituents (fig. 2*C*, basins

11–13). However, dissolved-solids concentrations in water from the sandstone aquifers range from 90 to more than 12,000 mg/L. In the Coconino Sandstone, concentrations of dissolved solids range from less than 500 mg/L in the northeastern part of the province to more than 25,000 mg/L north of the Little Colorado River in the south-central part. The Navajo Sandstone yields water that generally contains less than 1,000 mg/L dissolved solids throughout the province. Water from the Dakota Sandstone contains from 1,000 to 3,000 mg/L of dissolved solids.

In addition to the sandstone aquifers, water is obtained from alluvial aquifers and the voids within the crystalline igneous and metamorphic rocks. However, the amount is very small.

Principal constituents in ground water in the Plateau uplands province are calcium, sodium, bicarbonate, sulfate, and chloride. These constituents form five general water types—calcium bicarbonate, sodium bicarbonate, sodium sulfate, calcium sulfate, and sodium chloride. Water that contains dissolved-solids concentrations of less than 500 mg/L generally is calcium bicarbonate or

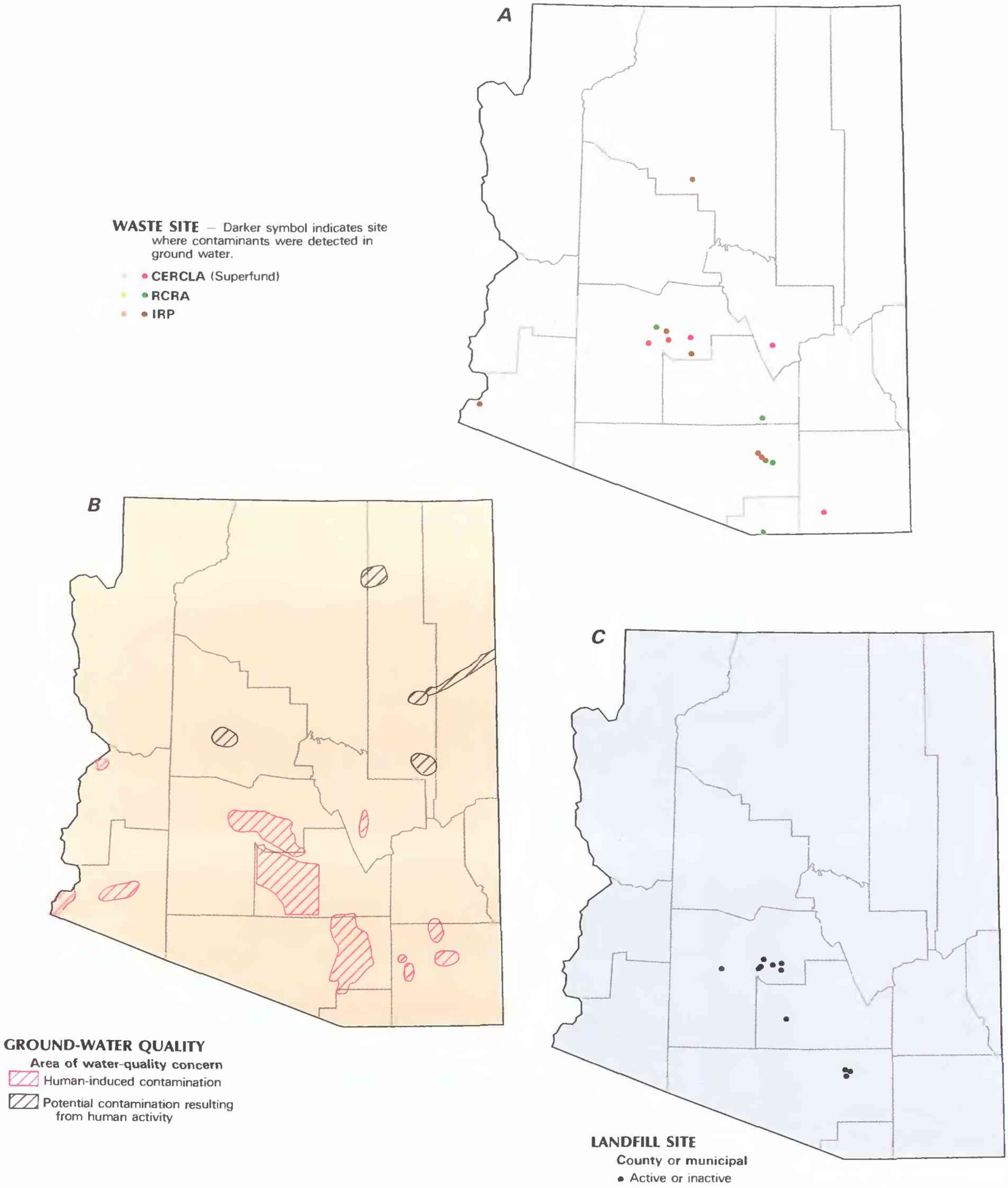

Figure 3. Selected waste sites and ground-water-quality information in Arizona. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of January 1, 1987; Resource Conservation and Recovery Act (RCRA) sites, as of January 1, 1987; Department of Defense Installation Restoration Program (IRP) sites, as of January 1, 1987. *B*, Areas of human-induced and potential contamination as of January 1, 1987. *C*, County and municipal landfills, as of January 1, 1987. (Sources: *A*, *B*, *C*, Arizona Department of Health Services, 1986.)

sodium bicarbonate type water. Water that contains more than 500 mg/L generally is sodium sulfate, calcium sulfate, or sodium chloride type water. Gradations occur between chemical types. Very mineralized water that contains dissolved-solids concentrations greater than 3,000 mg/L generally is a sodium sulfate, calcium sulfate, or sodium chloride type water. Minor constituents in ground water in the Plateau uplands, such as fluoride, nitrate, magnesium, silica, and iron, vary considerably and, except for fluoride and nitrate, the concentrations meet water-quality criteria for most uses (Kister, 1973).

EFFECTS OF LAND USE ON WATER QUALITY

In some areas, changes in ground-water quality are caused by (1) recirculation of salts in irrigation water, (2) leachates from mining operations, (3) runoff from urban areas, (4) disposal of toxic wastes, and (5) leachates from landfills (fig. 3). According to the Arizona Department of Health Services (1986), contamination of water in 347 wells has been documented. Of these wells, 115 contained pesticides, 173 contained volatile organic compounds, and 59 exceeded maximum contaminant levels of such compounds as ethylene dibromide (EDB), 1,2-dibromo-3-chloropropane (DBCP), tetrachloroethylene (PCE), and trichloroethylene (TCE).

Irrigation

In 1983 the Pima Association of Governments (PAG) completed a study of part of the upper Santa Cruz River basin alluvial aquifer, Pima County (basin 8, fig. 2*A*2), which determined the effects of different types of land uses on the quality of ground water. Results showed that agricultural irrigation caused an increase in the amount of nitrate in the aquifer (Pima Association of Governments, 1983a).

Significant changes in concentrations of dissolved solids (as much as 500 mg/L) in ground water have occurred since 1910 in an irrigated agricultural area in the Willcox basin, Cochise County basin 10, (fig. 2*A*2). These changes may have been caused by removal of saline water from the shallow alluvial aquifer by irrigation pumping and by movement of the saline water in the shallow aquifer toward extensively pumped areas where large water-level declines have been recorded. In the Willcox basin alluvial aquifer, a significant increase in dissolved solids has occurred as a result of recharge of irrigation water containing salts in areas where depth to water is less than 100 feet (Kister and others, 1966). In another part of the Willcox basin aquifer, water contains elevated levels of dissolved solids which presently range from 501 to 1,000 mg/L where water levels have risen about 13 feet since 1910 (Mann and others, 1978). In both instances, the increase in dissolved-solids concentrations may have resulted from recirculation of salts from irrigation water to the water table. In many other places overlying the Willcox basin aquifer, salt from irrigation water is also being deposited in the soil, but it may be many years before salt reaches the saturated zone because the depth to water table is more than 200 feet below land surface.

In 1979 and 1980, the ADHS sampled 170 wells for DBCP, a soil fumigant, in Maricopa and Yuma Counties and found 59 wells that contained water with detectable concentrations (Arizona Department of Health Services, written commun., 1984). Four public and 55 privately owned water-supply wells were affected. The four public wells were removed from service and all private well owners were notified of the results. DBCP, a pesticide used in Arizona since 1955 for control of nematodes on citrus, cotton, and other crops, was banned for some uses in 1977 because it was linked to human male sterility and was carcinogenic in laboratory animals. Use of DBCP reached a peak in 1979 when 495,800 pounds were applied for pest control. In 1984, the ADHS sampled 92 wells across the State for DBCP and 43 wells for EDB. Preliminary results indicate a significant incidence of contamination (Arizona Department of Health Services, written commun., 1984). EDB is used as a soil fumigant for controlling nematodes and as an anti-knock additive in leaded gasoline. EDB was banned for most uses in 1983 after it was found to be carcinogenic in laboratory animals. Since the mid-1950's, from 150,000 to 200,000 pounds per year of EDB have been used in Arizona agriculture (Arizona Department of Health Servies, written commun., 1984).

Mining

According to a study by the PAG of ground water and tailings ponds in the upper Santa Cruz River basin (basin 8, fig. 2*A*2), the quality of water in the alluvial aquifer has been degraded locally by recharge from tailings ponds. Analyses of well water downgradient from tailings ponds showed increases in hardness, sulfate, dissolved solids, and other constituents (Pima Association of Governments, 1983b, p. 13). The results indicate a possibility of future contamination of public water-supply wells in the area.

For at least the past 40 years, ground-water quality in the Pinal Creek basin near Globe has been degraded also as the result of seepage of acidic mining and milling process solutions (Envirologic Systems, Inc., 1983). According to Eychaner and Stollenwerk (1985, p. 141), very acidic water is moving through the shallow alluvial aquifer and discharging to streams in the area. The resulting plume of contaminated ground water, which is about 11 miles long and about 2,000 feet wide (fig. 3*B*), contains more than 16,000 mg/L of dissolved solids. A sample of water from a well near Globe had a pH of 3.6 and concentrations of 10,800 mg/L sulfate, 3,000 mg/L iron, 150 mg/L copper, and 73 mg/L manganese.

Contamination of ground water by sulfates associated with copper mining in Cochise County is being studied by the U.S. Geological Survey. Ground water downgradient from a mine-tailings pond is contaminated with sulfate, ranging from 650 to 850 mg/L (G.R. Littin, U.S. Geological Survey, written commun., 1986). The presence of sulfate does not represent a health hazard but instead affects the esthetic quality of the water. The sulfate ion exerts a laxative effect following short-term exposure, and affects the taste and odor of drinking water. A maximum sulfate concentration of 250 mg/L is recommended on the basis of taste and odor consideration (U.S. Environmental Protection Agency, 1986d). Because the alluvial aquifer is the principal source of drinking water for the residents in Cochise County and is susceptible to contamination, the presence of sulfate could present a potential health concern.

Urbanization

In 1979, a study was begun of the chemical quality of water from urban runoff in Phoenix for the Maricopa Association of Governments (MAG). Sampling of runoff from storm drains showed that lead and other trace elements did not pose a threat to ground water (Schmidt, 1981, p. 21). Cadmium concentrations in the runoff water, however, were found to be greater than the EPA maximum contaminant levels of 0.010 mg/L for drinking water. Sampling of ground water in the area most likely to be affected by the urban storm runoff showed no contamination from this source during the study. Determinations of hydrocarbons were not made as part of this investigation, but other studies in the Western United States have shown that hydrocarbons in urban runoff may be a source of ground-water pollution.

A similar study in 1983 and 1984 in the Phoenix area addressed the effect of the use of dry wells for disposal of runoff from urban areas. Runoff entering dry wells at a commercial site contained large concentrations of total lead (60–230 μg/L, micrograms per liter), iron (480–1,000 μg/L), and manganese (80–150 μg/L), and small concentrations of diazinon (0.7–29 μg/L), dacthal (trace), and other hydrocarbons associated with plasticizers and paving materials. Analyses of ground water from monitor wells at the site, however, showed no evidence of contamination for the same constituents (Schmidt, 1985, p. 47).

Waste Disposal

Hazardous waste is treated, stored, or disposed of at five RCRA sites (fig. 3*A*). These wastes are a known or potential hazard to the quality of ground water, and the ADHS and the EPA have determined that ground water has been contaminated at several of these sites. Arizona currently has five EPA CERCLA (Superfund) sites (fig. 3*A*), and an additional four sites are proposed for inclusion in the Superfund program. Several hazardous-waste sites at six facilities also have been identified by the U.S.Department of Defense as part of their IRP as having potential for contamination. The purpose of the IRP is to identify and evaluate hazardous-waste disposal at military facilities and closely parallels the EPA's Superfund program under CERCLA. Phase-I studies—Installation Assessment and Records Search—have been completed at all eight IRP sites. Phase-II studies—Confirmation—have been completed or are being conducted at sites that require further study.

For purposes of this report, wastes are categorized into five major groups—light industry, mining, agricultural, municipal and county, and military. Most waste sites are in densely populated areas near Phoenix and Tucson (figs. 3*A* and 3*C*). Waste sites commonly associated with light industry in Arizona are above and below ground storage tanks, lined and unlined ponds, and landfills. Wastes from these sites are mainly volatile organic compounds and trace metals, such as chromium, that are unique to the particular industry. Gasoline and solvents from leaking underground storage tanks have been documented in ground water at 11 locations in Arizona. Wastes from mine-tailings ponds are generally acidic and contain trace metals, such as copper, iron, manganese, and chromium. Acid, trace metals, sulfate, and cyanide from mining and metal-finishing activities contaminate ground water in many locations. Agricultural wastes consist mainly of nitrogen compounds and pesticides.

Municipal and county landfills sites are numerous, variable, and widespread throughout Arizona. Except for the sites in Phoenix and Tucson (fig. 3*C*), however, only a small amount of data has been collected to evaluate their effects on the quality of ground water. Military installations also have a wide variety of waste-disposal areas, including surface impoundments, evaporation ponds, active and buried landfills, and unlined sets for drying sludge from wastewater treatment. Even though the types of wastes are many, municipal, county, and military waste sites are contaminated mainly by volatile organic compounds, such as TCE and PCE.

POTENTIAL FOR WATER-QUALITY CHANGES

Ground-water studies throughout the State by agencies of the State and Federal governments have shown that the alluvial aquifers are subject to recharge from stream runoff as well as from evaporation ponds and other methods of waste disposal. Therefore, the potential for changes in the quality of water in these aquifers is significant. Monitoring and other efforts required by Arizona's recently enacted Environmental Quality Act, however, may help to prevent future contamination.

In 1983 the PAG developed a computer model to predict trends in ground-water quality in an area south of Tuscon and to project the effects that agriculture, mining, and wastewater treatment and disposal might have on water quality. Using future conditions considered most likely, the model indicated that contributions of nitrate (as nitrogen) from agriculture to ground water would decrease and that percolation of treated effluent to the water table would have a localized effect. The model also indicated that, in the absence of mitigation, contaminant plumes from copper-mine tailing ponds in the area would eventually contaminate local drinking-water supplies (Pima Association of Governments, written commun., 1983).

GROUND-WATER-QUALITY MANAGEMENT

The Arizona Environmental Quality Act of 1986 established a Department of Environmental Quality (ADEQ) to administer State programs on water quality, air quality, solid waste, and hazardous waste beginning July 1, 1987. ADHS will develop and implement programs during the 1986 fiscal year (May 1986 through June 1987); thereafter, these programs will be transferred to the new department.

The general provisions of the Environmental Quality Act are as follows:

1. Establish an aquifer classification and aquifer protection permit program. Under this program, the Director of ADEQ is required to identify and define boundaries of all aquifers in the State, adopt new water-quality standards, develop programs to control point-source and nonpoint-source discharges to surface water, develop permit programs for aquifer protection and underground-injection control, require monitoring, and adopt other rules as necessary to enforce the law.
2. Establish aquifer reclassification processes.
3. Authorize filing of citizen suits for violation of environmental-quality standards.
4. Establish maximum civil penalty of $25,000 per day per violation and criminal classifications for certain violations.
5. Establish the Water Quality Assurance Revolving Fund for environmental cleanup.
6. Abolish the Board of Pesticide Control and transfer the responsibilities to three agencies—the Commission of Agriculture and Horticulture, the Industrial Commission, and the Department of Environmental Quality.
7. Establish the following advisory bodies, boards, and committees:
   (a) Water Quality Advisory Council,
   (b) Agricultural Best Management Practices Advisory Committee on Nitrogen Fertilizer and a Committee on Concentrated Animal-Feeding Operations,
   (c) Water Quality Appeals Board,
   (d) Joint Legislative Committee on Water Quality Assurance Revolving Fund Revenues, and
   (e) Joint Legislative Pesticide Oversight Committee.
8. Require annual reports to the Governor and Legislature on
   (a) pesticide-control activities,
   (b) well-sampling activities, and
   (c) violations and enforcement of water-quality and hazardous-waste-disposal standards. Require a report every 5 years on contaminant levels in aquifers and the effects of regulation and best-management practices.
9. Require the Auditor General to contract for an independent performance review to be conducted in fiscal year 1989 on the regulatory program established by this Act.

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Sampling acidic, metal-laden ground water from monitoring wells near Globe, Arizona. For at least the past 40 years, acidic water originating from mining and milling process solutions has caused extensive ground-water contamination in this copper-mining area of Arizona. In 1986, water from several wells in the area contained concentrations of aluminum, copper, and iron exceeding 100 milligrams per liter. (Photograph by James H. Eychaner, U.S. Geological Survey.)

Prepared by Lester R. Kister, Dean B. Radtke, U.S. Geological Survey, and Chuck Graf, Arizona Department of Health Services

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ARKANSAS
Ground-Water Quality

In Arkansas, ground water is the major source for public-supply and rural self-supplied systems; about 55 percent of the population (fig. 1) depends on ground water (Harold Seifert, Arkansas Department of Health, written commun., 1986). Water quality in the principal aquifers (fig. 2) is acceptable for most uses; however, in many areas of the State the water contains undesirably large concentrations of iron and hardness.

Degradation of water quality in several areas, commonly reflected in increased dissolved-solids or nitrate concentrations, is associated with urbanization, irrigation, and waste disposal (fig. 3). Organic contamination also has been detected in the shallow zones of some aquifers. Possible sources of contamination include underground storage tanks, surface impoundments, saline aquifers, irrigation returns, landfills, and septic tanks.

Twenty-six hazardous-waste sites require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 or are included in the National Priorities List (NPL) of Superfund hazardous-waste sites identified by the U.S. Environmental Protection Agency (1986c) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. As of September 1985, 13 sites at 2 Federal facilities were planned for confirmation studies to determine if remedial action is required.

Monitoring of ground-water quality is increasing. In 1937 the Arkansas Department of Health began a ground-water-quality monitoring program for public water supplies. This program currently (1986) includes 793 wells. Several inorganic constituents are monitored, as mandated by the Safe Drinking Water Act; an increasing number of organic constituents also are monitored. In 1969, the U.S. Geological Survey, in cooperation with the Arkansas Geological Commission, established a water-quality network to monitor constituents in the principal aquifers of the State. Samples taken from this 25-well network are analyzed for inorganic, organic, radiochemical, and bacteriological constituents. These wells are sampled on a 5-year rotational basis. The Arkansas Department of Pollution Control and Ecology (ADPCE) is now (1986) establishing a ground-water-quality network as part of its responsibilities in administering its Ground Water Protection Strategy.

WATER QUALITY IN PRINCIPAL AQUIFERS

Most of the ground-water supplies in the State are obtained from six aquifers or aquifer systems—the alluvial, the Cockfield, the Sparta, the Wilcox, and the Nacatoch aquifers, and the Ozark aquifer system (fig. 2*A*1, 2*B*). These aquifers are regionally significant and, except for rural-domestic supplies, constitute the source of nearly all ground-water withdrawals in the State.

Because wells are drilled primarily where these aquifers are known to contain freshwater, most water-quality data are from these areas. Therefore, the following water-quality summary is based on information principally from areas having water quality that is suitable for most uses.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate plus nitrite (as nitrogen), chloride, and iron analyses of water samples collected from 1945 to 1986 from the principal aquifers in Arkansas. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L (micrograms per liter) iron.

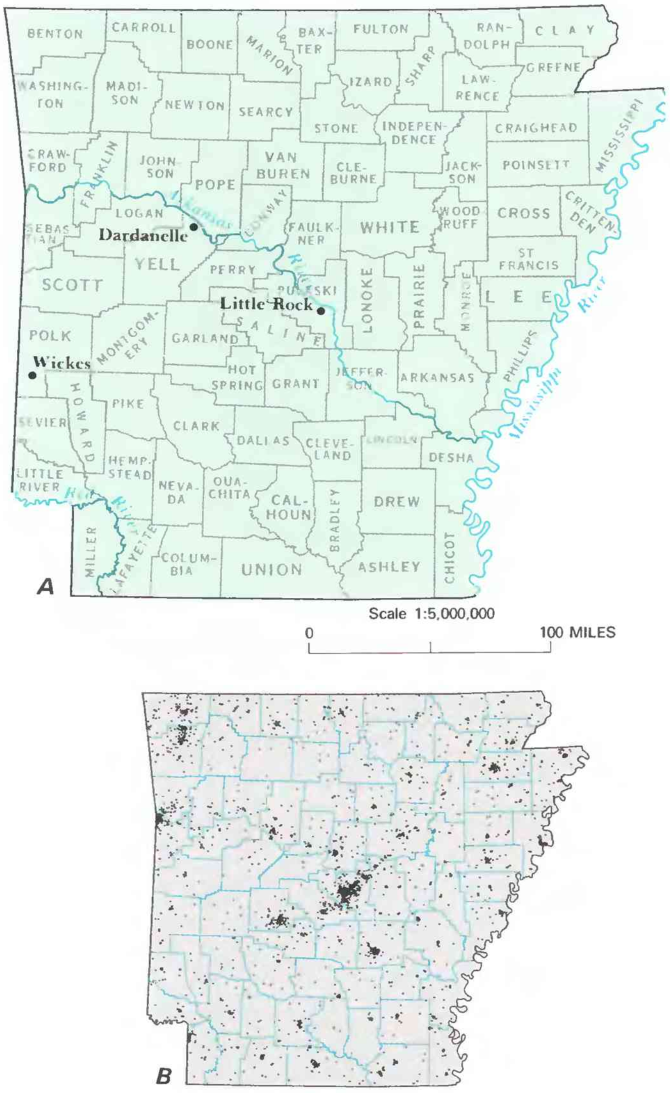

Figure 1. Selected geographic features and 1985 population distribution in Arkansas. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

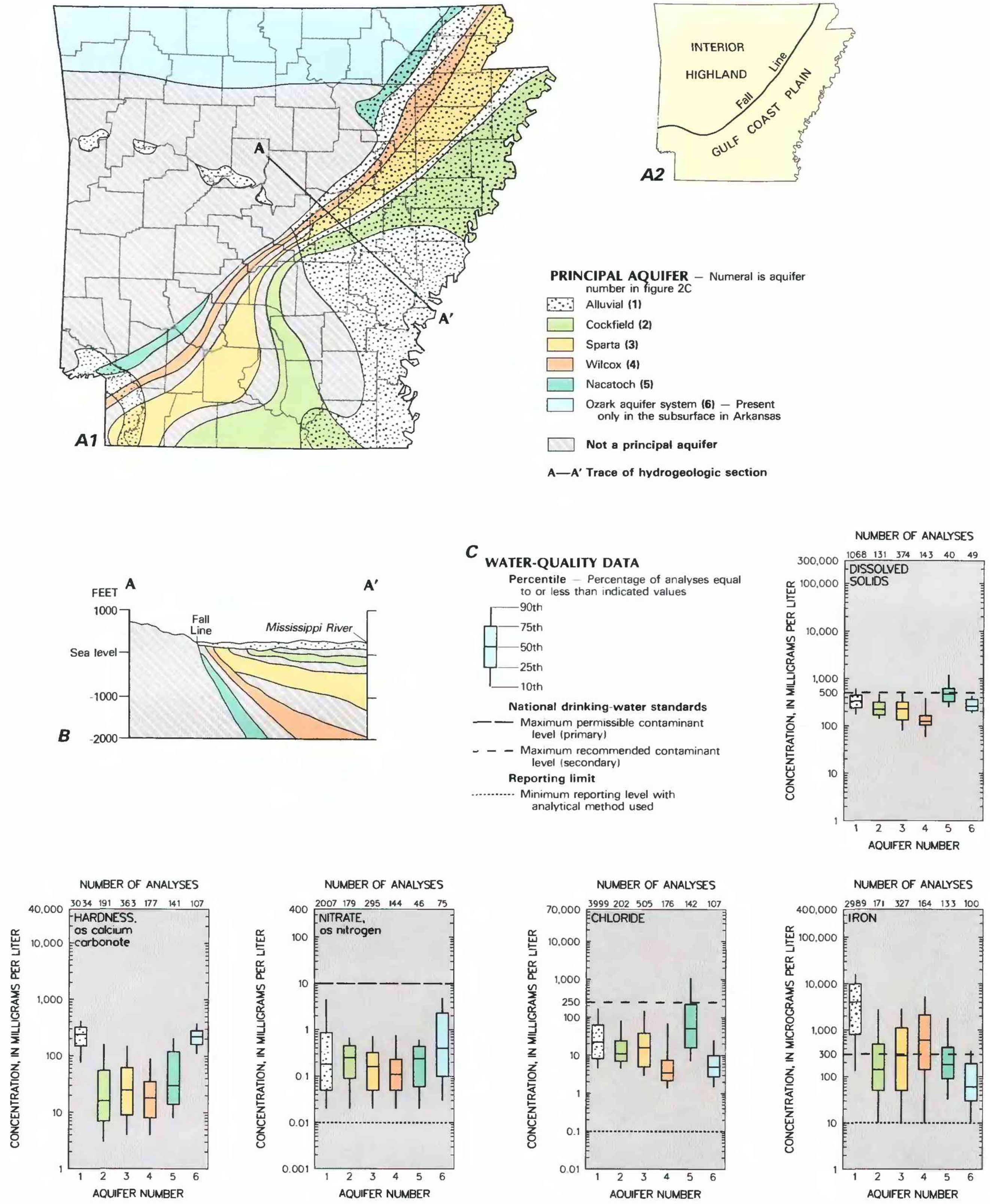

Figure 2. Principal aquifers and related water-quality data in Arkansas. *A*1, Principal aquifers; *A*2, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1945-86. (Sources: *A*1, U.S Geological Survey, 1985; *A*2, Fenneman, 1938; *B*, U.S. Geological Survey; 1985, *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

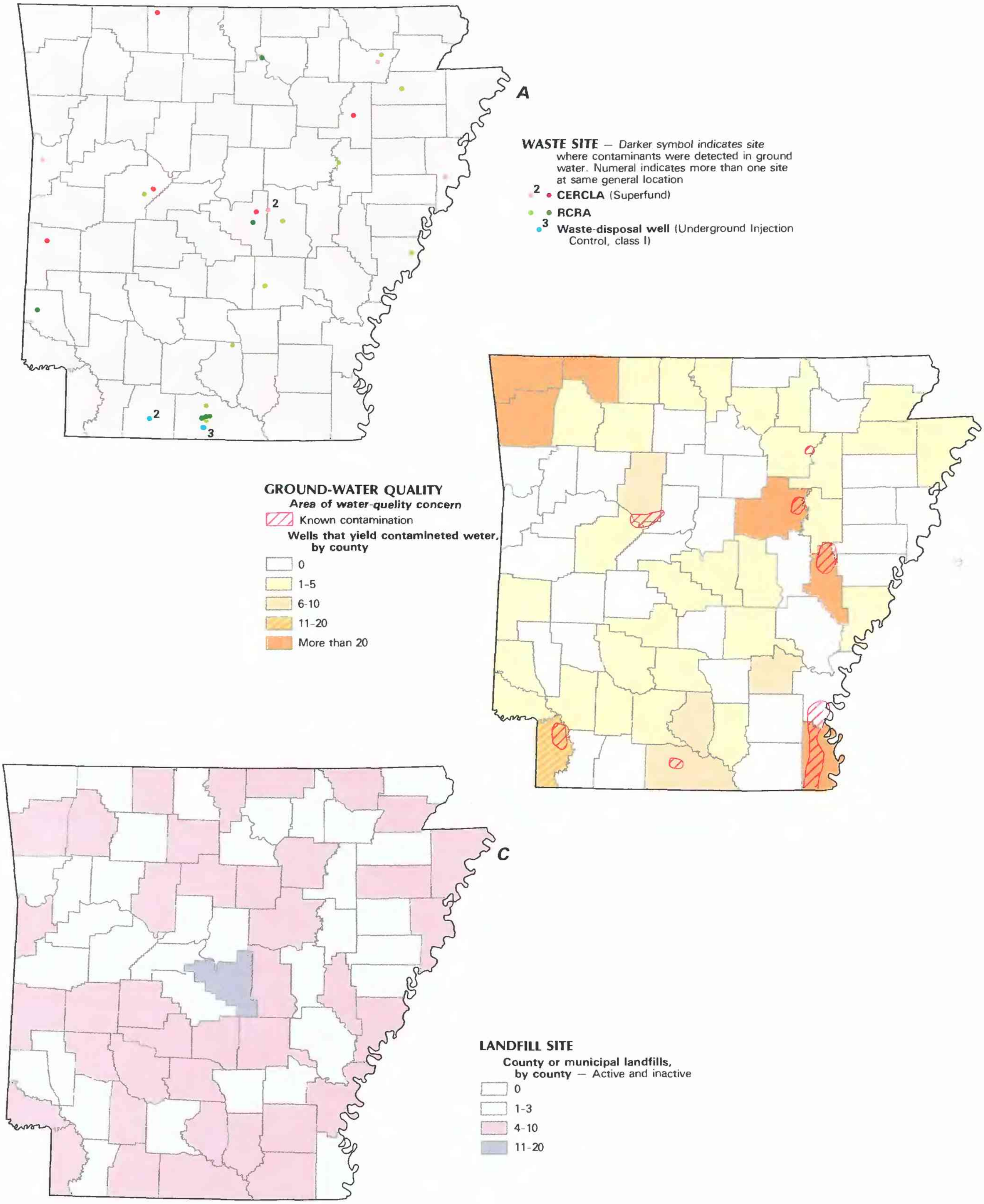

Figure 3. Selected waste sites and ground-water-quality information in Arkansas. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of 1986. *B*, Areas of known contamination and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Arkansas Department of Pollution Control and Ecology files. *B*, U.S. Geological Survey files; Arkansas Department of Health files; Cox and others, 1980; MacDonald and others, 1976. *C*, Arkansas Department of Pollution Control and Ecology files; U.S. Geological Survey files.)

Alluvial Aquifer

Alluvium is the principal source of water for irrigation in Arkansas, making it the most intensively used aquifer in the State. Alluvial deposits blanket much of eastern Arkansas, the Red River Valley in southwestern Arkansas, and isolated areas along the Arkansas River in the Interior Highlands (fig. 2*A*1). Generally, water from the alluvial aquifer is of acceptable quality for irrigation and, with treatment, for public supply (fig. 2*C*).

The median dissolved-solids concentration is 330 mg/L, which is much smaller than the limit of 1,000 mg/L commonly used to judge the suitability of water for irrigation—however, concentrations are about 4,000 mg/L in parts of Chicot, Desha, Miller, Monroe, Independence, and White Counties, making water in these areas unsuitable for most purposes.

Hardness and iron concentrations can be undesirably large. With a median hardness concentration of 240 mg/L, much of the water within the alluvium is very hard. This hardness, coupled with median iron concentration of 4,000 μg/L, makes this water undesirable for public supply and rural-domestic use without significant treatment.

The median concentration of nitrate in water from the alluvium is 0.18 mg/L, but the maximum value measured was 67 mg/L, which far exceeds the drinking-water standard. Increased nitrate concentrations in the shallow alluvium usually result from a leaking septic tank or a surface source such as a feedlot which affects the well.

Chloride concentrations generally do not exceed drinking-water standards, except in parts of Chicot, Desha, Miller, Monroe, Independence, and White Counties. Increased chloride concentrations usually are associated with increased sodium.

Cockfield Aquifer

The Cockfield aquifer ranks fifth in total ground-water withdrawals in the State. It is present in much of eastern Arkansas and is a sole source for ground water in some areas. Its principal use is for public and rural-domestic supply, and generally the water is of good quality for these purposes (fig. 2*C*).

The median concentrations of water from the Cockfield aquifer are 220 mg/L dissolved solids, 16 mg/L hardness, 0.25 mg/L nitrate, 11 mg/L chloride, and 140 μg/L iron. Based on these values, the water generally is soft and does not exceed the drinking-water standards. Although most iron concentrations were considerably smaller than the 300-μg/L standard, more than 25 percent of the samples exceed the standard.

Sparta Aquifer

The Sparta aquifer ranks second in total ground-water withdrawals in the State. Located in much of the eastern half of the State, the aquifer is used extensively for industry and public supply and increasingly for irrigation. Generally, water of the Sparta aquifer is of good quality for drinking (fig. 2*C*).

The median concentrations for water from the Sparta aquifer are 226 mg/L dissolved solids, 25 mg/L hardness, 0.16 mg/L nitrate, 16 mg/L chloride, and 280 μg/L iron. Thus, the water is soft and generally does not exceed drinking-water standards. However, exceptions occur in Union County for dissolved solids and chloride. About half of the iron concentrations exceed the drinking-water standards, indicating that some treatment for iron removal might be necessary.

Wilcox Aquifer

The Wilcox aquifer occurs in most of the Gulf Coastal Plain of Arkansas, but is a major source of water only in northeastern Arkansas where it is known as the "1,400-foot sand." The aquifer is used primarily for public and industrial supplies and ranks fourth in total ground-water withdrawals in the State. The Wilcox aquifer has the best water quality of the six principal aquifers in the State (fig. 2*C*).

The median concentrations for dissolved solids, nitrate, and chloride are all considerably smaller than the drinking-water standards. More than 75 percent of the samples contained water that is soft. Only iron concentrations detract from an otherwise excellent water quality. About half of the measured iron concentrations are larger than 600 μg/L.

Nacatoch Aquifer

The Nacatoch aquifer underlies the Gulf Coastal Plain of the State but contains freshwater only in parts of northeastern and southwestern Arkansas (Petersen and others, 1985). It is used primarily for public and industrial supplies and ranks sixth in total ground-water withdrawals in the State. The Nacatoch aquifer has water quality that is marginally acceptable for rural-domestic and public supply (fig. 2*C*).

About half of the measured dissolved-solids concentrations of the Nacatoch aquifer exceed the drinking-water standard. The water ranges from soft to hard. The median concentration of nitrate (0.24 mg/L) indicates no general problem with surface contamination. About 25 percent of the chloride concentrations exceed the standard. Even though most iron concentrations are smaller than 300 μg/L, iron concentrations have exceeded the standard in a significant number of wells.

Ozark Aquifer System

The Ozark aquifer system, located in the Interior Highlands in the northern quarter of the State (fig. 2*A*1), ranks third in total ground-water withdrawals in the State (Holland and Ludwig, 1981). It consists of as many as 24 individual aquifers that may contribute significant amounts of water to a well. The water, which is used for public, industrial, and agricultural supplies, generally is of good quality for drinking (fig. 2*C*).

Less than 10 percent of the dissolved-solids values exceed the drinking-water standard. Hardness values indicate a hard to very hard water requiring treatment to decrease the calcium and (or) magnesium to acceptable levels. Nitrate concentrations, although generally smaller than 10 mg/L, indicate the possibility of surface contamination of some of the aquifers in the Ozark aquifer system. Bacteria concentrations in some areas also indicate contamination (MacDonald and others, 1976; Cox and others, 1980). Chloride and iron concentrations generally do not exceed the drinking-water standards.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has deteriorated in some areas because of the effects of urban and rural development, ground-water withdrawal, and waste-disposal practices. Investigations by the U.S. Geological Survey in cooperation with the Arkansas Geological Commission and the ADPCE have documented these changes (Morris and Bush, 1986; Fitzpatrick, 1985; Broom and others, 1984).

Urban and Rural Development

The area most affected by urban and rural development (fig. 1*B*) is northern and northwestern Arkansas in the Interior Highlands. The geology of this area is primarily limestone, dolomite, and sandstone with extensive fracture systems and solution channels. These openings allow surface water to rapidly infiltrate to the ground water. Therefore, without protective measures, facilities such as septic tanks, underground storage tanks, sewage lagoons, and chicken houses built in these areas have a significant potential of contaminating nearby ground water. The contamination may be detected as increased nitrate concentrations and unacceptable coliform bacteria concentrations. This type of contamination has been reported in Washington County (MacDonald and others, 1976), in Benton County (Cox and others, 1980), and in Carroll County (Harold Seifert, Arkansas Department of Health, oral commun., 1986) (fig. 3*B*).

In other areas of the State, contamination of public-supply wells by hydrocarbons has been reported. The source of this contamination is suspected to be underground storage tanks (Harold Seifert, Arkansas Department of Health, oral commun., 1986). The towns affected and dates of occurrence were Wickes in Polk County (1977) and Dardanelle in Yell County (1984) (fig. 1*A*).

Ground-Water Withdrawals

Ground-water withdrawals for irrigation, industrial, and public supply use have contributed to the deterioration of ground-water quality in Arkansas (fig. 3*B*), particularly in Chicot, Desha, Lincoln, Monroe, and Union Counties (Morris and Bush, 1986; Fitzpatrick, 1985; Broom and others, 1984). In some areas, withdrawals for irrigation have lowered the water table, allowing saline water from underlying aquifers to replace the freshwater. Consequently, chloride concentrations have increased by 3,700 percent in some areas. Chloride concentrations in water from a well located within the contaminated area of Monroe County (fig. 3*B*) increased from 22 mg/L in 1949 to 830 mg/L in 1975 (fig. 4). Significant, but less dramatic, changes have occurred in the other affected areas.

Waste-Disposal Practices

The RCRA list currently (1986) includes nearly 1,000 sites in the State where hazardous wastes are generated, stored, treated, or disposed. Of these sites, 16 are operated or have been operated as a hazardous-waste landfill, land treatment, or surface-impoundment unit that require ground-water monitoring programs for each hazardous-waste management facility (fig. 3*A*). The ADPCE has determined that shallow ground water has been contaminated at six of these sites. Ground-water-quality monitoring at the six sites has detected concentrations of arsenic, barium, cadmium, chromium, lead, mercury, nitrate, selenium, silver, polychlorinated biphenyls (PCB), pentachlorophenol (PCP), cresote products including chlorinated dibenzo-furan (CDF), ethylene dibromide (EDB), chloride, gasoline, oil, and tribromophenol; extreme values of pH also have been detected. At the other 10 sites either no contamination has been detected or monitoring data have not yet been evaluated (Gary Martin, Arkansas Department of Pollution Control and Ecology, oral commun., 1987). An additional 10 sites have been included in the NPL (U.S. Environmental Protection Agency, 1986c). Ground-water contamination has been detected at five of these CERCLA (Superfund) sites. Contaminants at one or more of these five sites include trichloroethene (TCE), tetrachloroethene (TTCE), benzene, chlorinated dibenzo-dioxin (CDD), (CDF), (PCP), arsenic, chromium, 2,3,7,8-TCDD (dioxin), chlorinated benzene, chlorinated phenol, and the herbicides 2,4-D and 2,4,5-T (Mark Satterwhite, U.S. Environmental Protection Agency, written commun., 1987).

Six Class I injection wells (fig. 3*A*) currently are regulated by the Underground Injection Control (UIC) Program (U.S. Environmental Protection Agency, 1984; David Thomas, Arkansas Department of Pollution Control and Ecology, oral commun., 1986), which is administered jointly by the ADPCE and the Arkansas Oil and Gas Commission. These wells are used for underground disposal of hazardous and nonhazardous waste.

POTENTIAL FOR WATER-QUALITY CHANGES

Ground-water problems could occur almost anywhere in the State. The potential for ground-water contamination by hazardous materials disposed on the land surface generally coincides with the rates of recharge to aquifers. Permeable materials that allow water to recharge aquifers will also allow contaminants to enter the ground-water system. A more detailed discussion of aquifer contamination potential, with locations, is given by Bryant and others (1985).

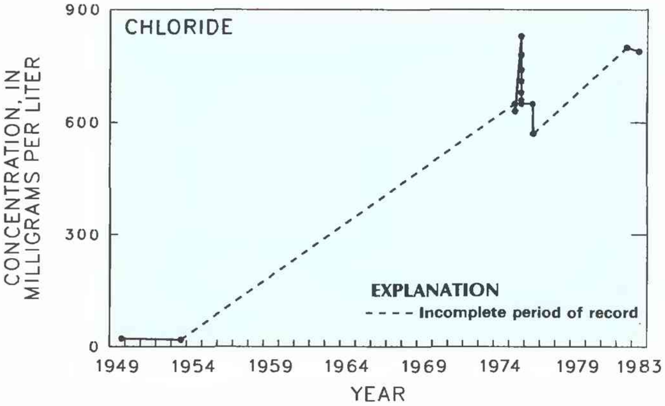

Figure 4. Change in chloride concentration in the alluvial aquifer, Monroe County, Arkansas 1949-83. (Source: U.S. Geological Survey files.)

Areas of large potential recharge are characterized by surficial material that readily allows infiltration of water. These include the surface of alluvial deposits, outcrop areas of confined aquifers, upland terrace deposits lacking a clay cap, and areas of extensive fracture systems or solution channels in the Interior Highlands. Areas of moderate recharge have surficial materials that retard the percolation of water or have a ground-water system that is capable of storing only limited amounts of water. Areas of small recharge potential have thick, relatively impermeable clays that lie directly beneath the land surface.

Several categories of waste have the potential to effect future changes in ground-water quality. Whether these wastes actually affect ground-water quality will be determined by the type of waste, the operation of disposal sites, and the location of sites with respect to ground-water recharge areas.

Waste-disposal sites in Arkansas generally can be categorized as petroleum industry, manufacturing and storage, municipal, military installation, and agricultural wastes. Waste at some of these sites has a greater chance of infiltrating a ground-water supply than others. A facility that temporarily stores wastes in containers for subsequent disposal offsite is less likely to affect ground water than one that stores long term in surface impoundments. As of 1979, more than 7,600 such impoundments were located in the State (Chesney, 1979).

Petroleum Industry

Waste sites commonly associated with petroleum industries are landfills, lined and unlined surface impoundments (6,000 according to Chesney, 1979), and land farms where wastes are treated, stored, or disposed. These wastes usually are acidic and contain trace metals, such as chromium and lead, and toxic organic chemicals such as toluene, benzene, and ethyl benzene. Several of these impoundments hold saline wastewater resulting from oil extraction operations. An estimated 20,000 acres of land has been damaged in southern Arkansas by saltwater and petrochemical residues (Arkansas Department of Pollution Control and Ecology, 1984). This water has a large potential for entering the shallow ground-water system. A second possibility for ground-water contamination lies in the abandonment of oil and gas test wells. Improperly plugged wells can leak saline water to the surface and to the overlying freshwater-bearing aquifers through which they were drilled.

Manufacturing and Storage

Products manufactured in Arkansas include fertilizers, herbicides and insecticides, clothing, paper, treated wood, metal-plating products, and many others. The waste associated with the production of these products includes chlorinated solvents, toluene, benzene, methanol, pesticides, arsenic, chromium, lead, pentachlorophenol, ethylene dibromide (EDB), and other metals and toxic organic chemicals.

Municipal

Municipalities are responsible for the treatment of domestic and, in many instances, industrial wastes. Generally, these wastes can reach a ground-water supply in two ways—buried distribution lines may leak directly to an aquifer, or improperly lined treatment lagoons may leak to a ground-water supply. In addition, Arkansas has 303 active and inactive (abandoned) municipal and county landfill sites (fig. 3*C*). Little data have been collected to evaluate their effects on the quality of ground water.

Military

Military installations have a wide variety of waste-disposal areas including surface impoundments, evaporation ponds, chemical-disposal pits, active and inactive landfills, and unlined beds for drying sludge from wastewater treatment. The types of wastes are many and include oils, solvents, paint, photographic chemicals, miscellaneous degreasing agents such as trichloroethylene, warfare agents such as mustard gas, plating wastes, sulfuric acid, and methyl ethyl ketone.

As of September 1985, 13 hazardous-waste sites at 2 facilities in Arkansas had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the Environmental Protection Agency (EPA) Superfund program. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. These 13 sites were scheduled for confirmation studies to determine if remedial action is required.

Agricultural Practices

The widespread use of insecticides and herbicides essential to crop production has the potential to affect the ground water. Pesticides applied to row crops may percolate to ground water. Irrigation practices may increase the chance of infiltration. Improper storage or disposal of pesticide containers, especially near wells, may result in direct infiltration along the outside of an improperly sealed well casing.

GROUND-WATER-QUALITY MANAGEMENT

The ADPCE has the primary responsibility for ground-water quality protection in the State. This authority was given in the Arkansas Water and Air Pollution Control Act, Act 472 of 1949, as amended. Various acts and (or) agencies have control over various aspects of State ground-water quality.

- The Arkansas Surface Coal Mining and Reclamation Act of 1979, Act 134 of 1979 as amended, administered by the ADPCE.
- The Arkansas Open Cut Land Reclamation Act, Act 336 of 1977 as amended.
- The Arkansas Solid Waste Management Act, Act 237 of 1971; Arkansas Solid Waste Management Code, Act 238 of 1978, administered by the ADPCE.
- The Arkansas Hazardous Waste Management Act, Act 406 of 1979 as amended, administered by the ADPCE.
- The Arkansas Underground Injection Control Program, jointly overseen by ADPCE and the Arkansas Oil and Gas Commission.
- The Rural Abandoned Mine Program administered by the U.S. Soil Conservation Service.
- Act 96 of 1913 established the Arkansas Department of Health, giving that agency the power to develop regulations to control pollution and general sanitation regulations that prohibit the contamination of ground water.
- Act 402 of 1977 gave the Arkansas Department of Health specific authority to develop regulations for septic tanks and their use by both individuals and subdivisions.
- The Hazardous Materials Transportation Act of 1977, Act 421 of 1977, administered by the Arkansas Transportation Commission.
- Railroad Transportation Procedures of Hazardous Materials, Act 651 of 1979.
- ADPCE Regulation No. 1 for the Prevention of Pollution by Saltwater and Other Field Wastes Produced by Wells in New Fields or Pools.
- ADPCE Regulation No. 2, as amended, Arkansas Water Quality Standards Interim Revision.
- Pest Control Law, Act 488 of 1975.
- Pest Control Act and Regulations, Act 410 of 1975.
- Pesticide Use and Application Act and Regulations Act 389 of 1975.

To fulfill its responsibility, the ADPCE currently (1986) is developing and implementing a Ground Water Protection Strategy. A State interagency technical advisory committee, the Ground Water Quality Protection Steering Committee, provides guidance as this strategy is implemented. The Steering Committee has made several recommendations directed toward improving the State's ground-water information base. A series of ground-water monitoring prototypes covering typical geologic and population areas of the State has been completed and plans for implementation have been proposed. Cooperation between the major data-collecting agencies in the State is being encouraged through the Ground Water Quality Protection Steering Committee. This monitoring information, when added to the existing data base, will support the expanded ground-water protection activities of the future.

In addition, the Arkansas Soil and Water Conservation Commission oversees the Arkansas State Water Plan. This plan evaluates water-resource problems and management strategies necessary to protect water for its most beneficial uses.

With regulations in place to protect ground-water quality there is a need to know the existing quality of ground water and to continually monitor this quality to detect any changes. For example, the quantity of trace metals and organic compounds in most of the State's ground water is not well known.

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Measurement of water flowing from an irrigation well in a rice field. The U.S. Geological Survey in cooperation with the Arkansas Geologic Commission collected well yield and water-quality information from the alluvial aquifer near Brinkley, Arkansas. The results of chloride analyses were used to map the extent and magnitude of saltwater intrusion into the alluvial aquifer. (Photo courtesy of the U.S. Department of Agriculture, Soil Conservation Service.)

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CALIFORNIA
Ground-Water Quality

Nearly 18 million people, about 69 percent of the population of California (fig. 1) rely on ground-water supplies. Ground water in principal aquifers (fig. 2) may not be suitable for all public-supply, domestic, agricultural, and industrial uses because of dissolved minerals or temperature but may support selected uses consistent with the quality of the water.

The California State Water Resources Control Board (SWRCB) made a ground-water-quality assessment from 1984 to 1985 based on designated water use in 139 of 461 ground-water basins in the State identified by the California Department of Water Resources (DWR). The 139 basins comprise 79 percent of the surface area of all basins and include the top-priority basins based on population, use, and water-quality problems. Ground-water quality in the 139 basins is generally good, based on criteria established by SWRCB. Seventy-six percent of the ground-water basins assessed support designated water uses; whereas, 14 percent partially support uses. Water quality is unknown in about 8 percent of the basins assessed. Ground water of poor quality was found in parts or all of 21 basins (California State Water Resources Control Board, 1986).

At 71 hazardous-waste sites (fig. 3), monitoring and evaluation of ground-water quality is required by the Federal Resource Conservation and Recovery Act (RCRA) of 1976. In addition to the RCRA sites, 34 other sites are included by the U.S. Environmental Protection Agency (EPA) in the National Priorities List (NPL) of hazardous-waste sites (U.S. Environmental Protection Agency, 1986c) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Ground-water contamination from organic solvents, pesticides, acids, and trace metals has been detected at 26 of the 34 CERCLA sites. The California Department of Health Services (DOHS) has about 120 additional sites on a State toxic substances priority list where monitoring and evaluation are in progress.

Twenty-three sites on 12 military installations were recommended for cleanup in phase IV of the U.S. Department of Defense (DOD) Installation Restoration Program (IRP), and remedial action has been completed at 11 sites as of September 1985.

Numerous ground-water-quality monitoring programs are conducted by other

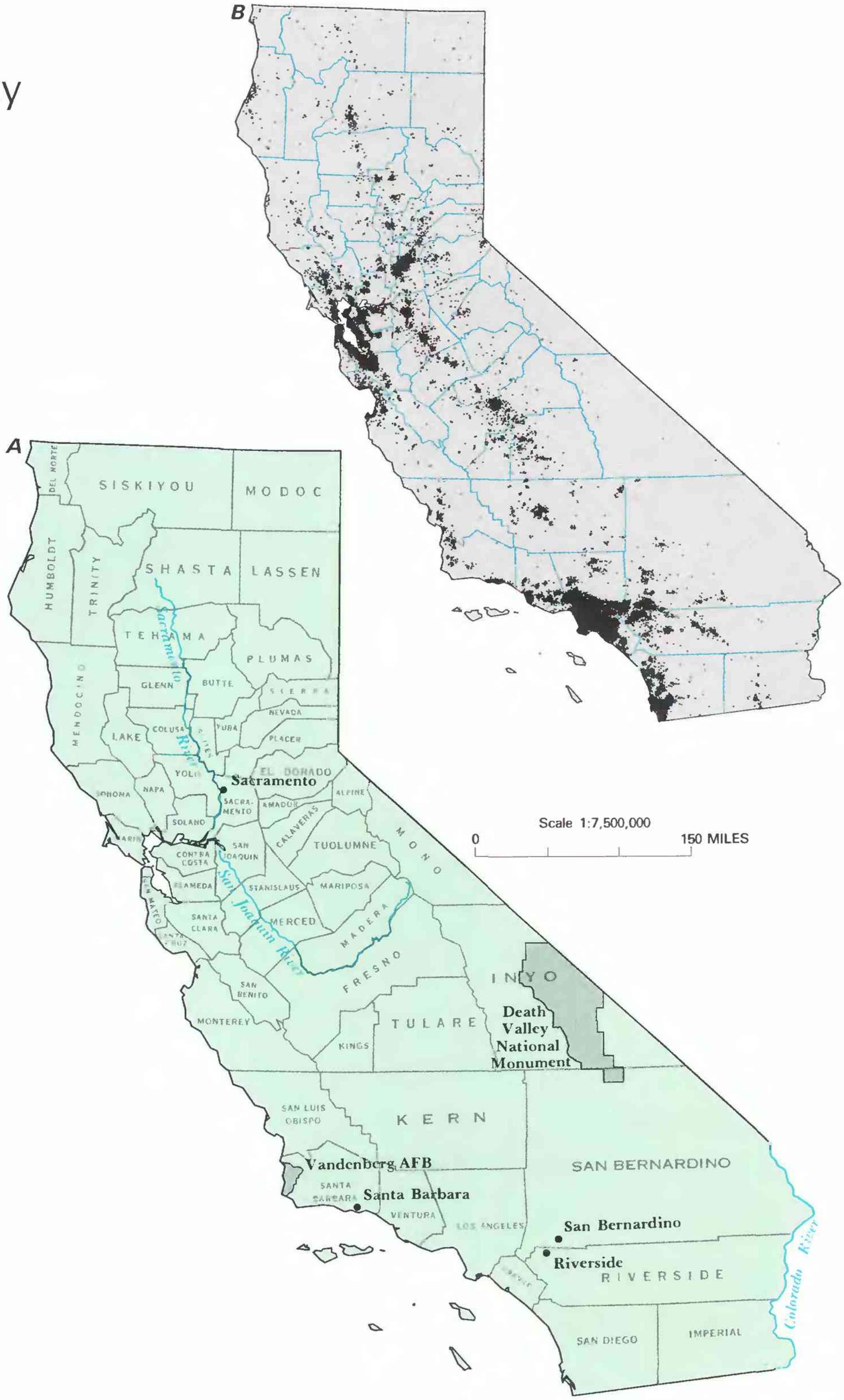

Figure 1. Selected geographic features and 1985 population distribution in California. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

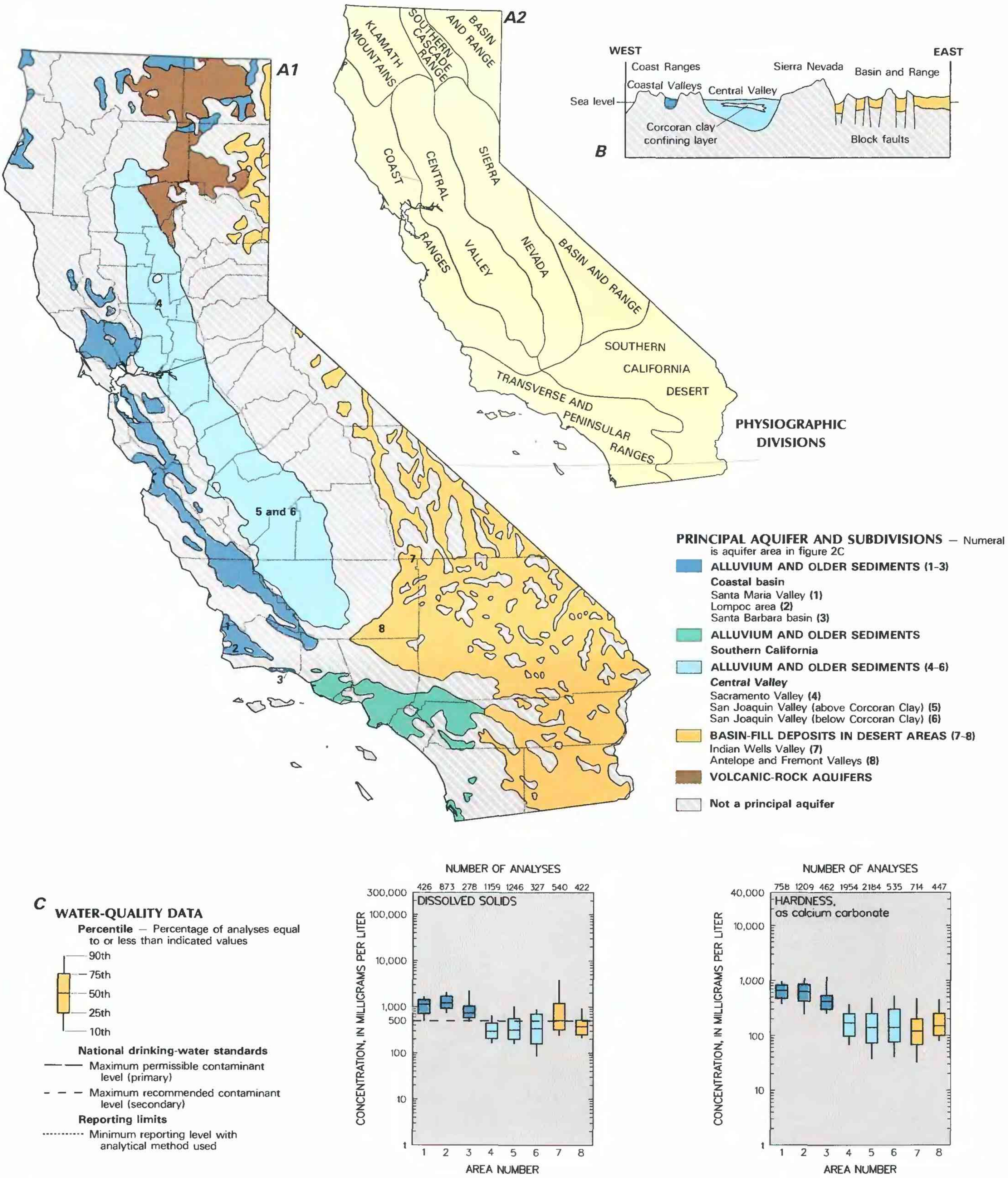

Figure 2. **Principal aquifers and related water-quality data in California.** *A1*, Principal aquifers; *A2*, Physiographic provinces. *B*, Generalized geologic section. *C*, Selected water-quality constituents and properties, as of 1986. (Sources: *A1*, California Department of Water Resources, 1975c, 1980a. *A2*, Fenneman, 1946. *B*, Compiled by A.M. Spieker from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

Federal, State, and local agencies. The DWR and cooperating agencies, including the U.S. Geological Survey, collect and analyze water-quality data from over 1,200 wells. Analyses from an additional 400 wells are furnished to DWR by other local water agencies. The SWRCB has compiled information, including well characteristics and analyses types, for all ground-water-quality networks statewide.

WATER QUALITY IN PRINCIPAL AQUIFERS

The two principal types of aquifers in California (fig. 2*A*1) are alluvium and older sediments, and volcanic rocks. The alluvial and sedimentary aquifers are geographically divided into four areas: coastal basins, southern California, Central Valley, and desert areas (U.S. Geological Survey, 1985, p. 147). Within these areas, DWR has identified 461 ground-water basins, of which 248 are considered significant sources of ground water (California Department of Water Resources, 1975a). The hydrologic characteristics of individual ground-water basins are governed by complex geologic relations, and multiple aquifers are common.

The volcanic rock aquifers are mainly in northern California. Most water is found in fractures, rubble zones, and sand and gravel layers interbedded between lava flows. The volcanic rock aquifers are not used extensively (U.S. Geological Survey, 1985, p. 150).

Ground water supplies about 40 percent of California's annual applied water needs. Ground-water withdrawals are largest in the Central Valley (fig. 2*A*2), which consists of the Sacramento and San Joaquin Valleys. Significant pumpage also occurs in southern California alluvial basins and in the Santa Clara and Salinas Valley coastal basins (U.S. Geological Survey, 1985, p. 151).

BACKGROUND WATER QUALITY

Diagrams summarizing dissolved-solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), chloride, and boron data for aquifers in selected alluvial and sedimentary basins in California are shown in figure 2*C*. All data as of 1986 were compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Insufficient data were available to describe ground-water quality in the volcanic rock aquifers. Sample depth was considered only in the San Joaquin Valley, where diagrams are shown for samples above and below the Corcoran Clay (fig. 2*C*). Extreme constituent values discussed in the text are not shown. National standards that specify the maximum concentration or level of a contaminant in drinking-water supply have been established by the EPA (U.S. Environmental Protection Agency, 1986a,b). The primary maximum contaminant level standards are health related and legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 250 mg/L chloride.

Alluvium and Older Sediments—Coastal Basins

The Santa Maria Valley (fig. 2*A*1, area 1) is an extensively developed agricultural basin overlying coastal alluvium and older sediments. Excessive ground-water withdrawals and recycling of water for agricultural, municipal, and industrial uses have caused accumulation of solutes and increased concentrations of nitrate as nitrogen in ground water (Hughes, 1977). The most severe degradation of ground-water quality has occurred in the western part of the valley, where dissolved-solids concentrations may exceed 2,000 mg/L in shallow wells. The median concentration of dissolved solids is more than 1,000 mg/L (fig. 2*C*). Nitrate-plus-nitrite (as nitrogen) concentrations are as large as 50 mg/L in some areas, and concentrations in excess of 10 mg/L occur in more than 25 percent of the samples (fig. 2*C*).

Agriculture is a major land use in the Lompoc area (fig. 2*A*1, area 2). Ground water is the primary source of supply for agriculture in this area. The presence of Vandenberg Air Force Base and a Federal prison here have increased concerns about ground-water quality. Dissolved-solids concentrations are generally about 1,000 to 1,500 mg/L in the eastern part of the Lompoc area and 1,500 to 3,000 mg/L in the western part (Miller, 1976). Extremely large concentrations of dissolved solids (as much as 24,000 mg/L) in some wells near the coast are the result of saltwater intrusion. The median hardness of water samples is 630 mg/L (as calcium carbonate). Water with 180 mg/L or more hardness is classified as very hard (Hem, 1985). Drinking-water supplies delivered by local purveyors, including the Air Force, are treated to reduce the hardness to about 150 mg/L.

In the Santa Barbara basin (fig. 2*A*1, area 3), ground water provides part of the city water supply, which has been stressed by demands from increasing population. Evidence of saltwater intrusion has been found in wells near the coast for many years (Martin, 1984). Many wells, especially in the coastal area, yield water with dissolved-solids concentrations greater than 1,000 mg/L. The median concentration of dissolved solids in the basin is 738 mg/L. Inland, at production wells owned by the city of Santa Barbara, dissolved-solids concentrations are generally less than 500 mg/L. Chloride concentrations in ground water in the Santa Barbara basin range from 15 to 18,000 mg/L.

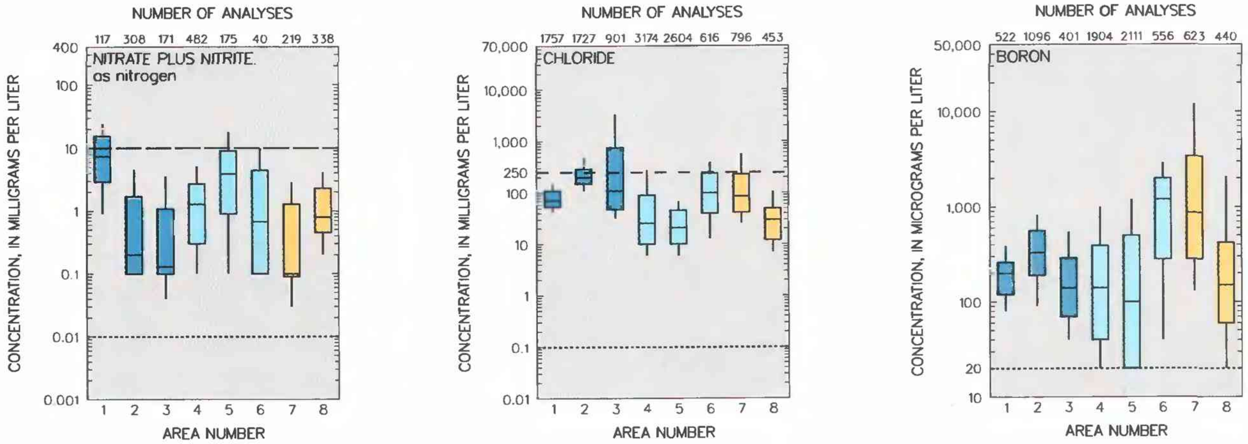

Figure 2. Principal aquifers and related water-quality data in California—Continued.

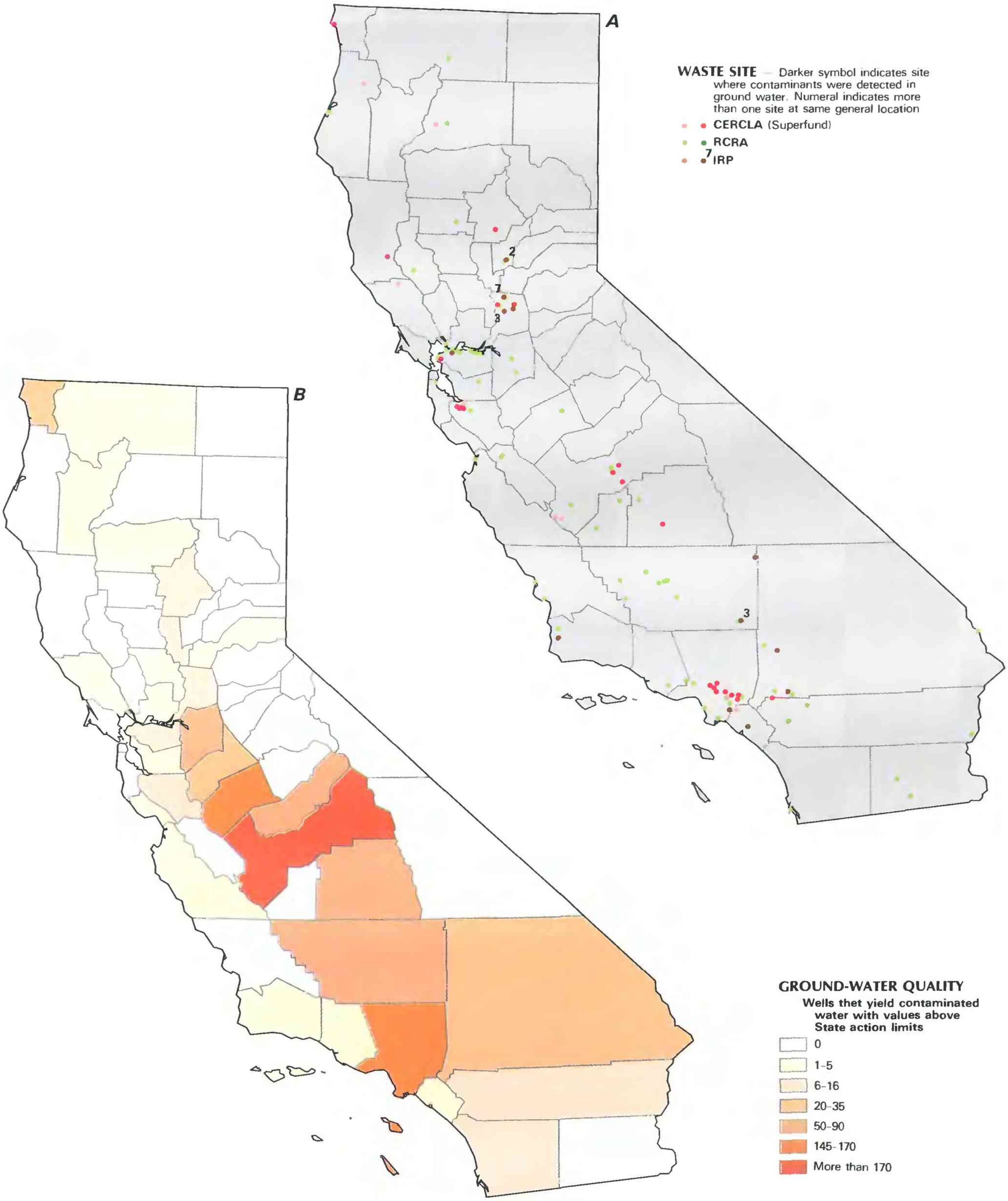

Figure 3. Selected waste sites and ground-water-quality information in California. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; and Department of Defense Installation Restoration Program (IRP) sites, as of 1985. *B*, Distribution of wells that yield contaminated water, as of 1986. *C*, County or municipal landfills, as of 1986. (Sources: *A*, U.S. Department of Defense, 1986; information from Environmental Protection Agency and California State Water Resources Control Board. *B*, Cohen and Bowes, 1984; California Department of Health Services, 1986; and information from California Regional Water Quality Control Boards. *C*, information from California Waste Management Board.)

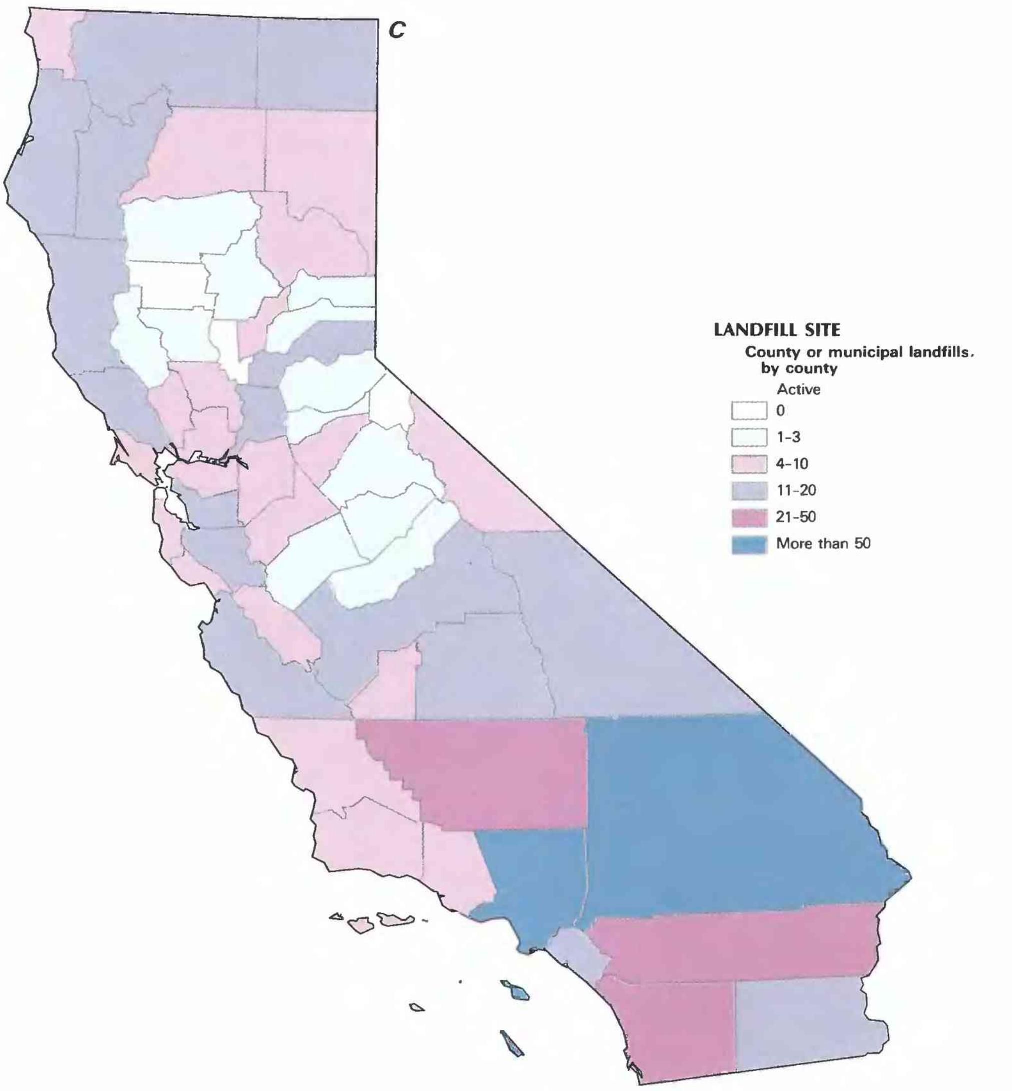

Figure 3. Selected waste sites and ground-water-quality information in California—Continued.

Alluvium and Older Sediments—Central Valley

In the Sacramento Valley (fig. 2*A*1, area 4), concentrations of dissolved solids are typically less than 500 mg/L. The median dissolved-solids concentration is 296 mg/L. Two large areas in the southern part of the Sacramento Valley have dissolved-solids concentrations ranging from 500 to 1,500 mg/L. Localized sites may contain concentrations greater than 1,500 mg/L (Fogelman, 1982). Hull (1984) postulated that upwelling of saline water from marine sedimentary deposits contributes to larger dissolved-solids concentrations in some areas. In the southwestern part of the Sacramento Valley, boron concentrations commonly exceed 750 μg/L (micrograms per liter) (Fogelman, 1983), the limit recommended by the EPA for long-term irrigation on boron-sensitive plants. Recharge from greatly mineralized thermal springs in the Coast Ranges (fig. 2*A*2) contributes to the large boron concentrations.

Ground-water quality differs areally and with depth in the primarily agricultural San Joaquin Valley (fig. 2*A*1, areas 5 and 6). Dilute surface-water runoff from crystalline rocks of the Sierra Nevada recharges the eastern side of the valley, whereas ground-water recharge from the west side originates in sedimentary rocks of the Coast Ranges. Above the Corcoran Clay (area 5), dissolved-solids concentrations increase from east to west. Concentrations range from less than 200 mg/L to more than 2,000 mg/L, with isolated concentrations larger than 8,000 mg/L. Below the confining clay layer (area 6), the distribution pattern is similar, but dissolved-solids concentrations rarely exceed 1,000 mg/L. Median values for nitrate plus nitrite (as nitrogen) are 3.9 mg/L in water samples from wells above the Corcoran Clay and 0.68 mg/L below the Corcoran Clay.

Basin-Fill Deposits in Desert Areas

Physiographically, many desert basins in California are characterized by broad alluvial fans and plains sloping to playas, creating closed drainage basins that are usually dry. Hydrologic characteristics can differ considerably from basin to basin and within basins. Indian Wells Valley and Antelope and Fremont Valleys (fig. 2*A*1, areas 7 and 8) are selected for discussion as having typical water-quality characteristics of many basin-fill deposits in desert areas.

Ground water is the only source of water in Indian Wells Valley (fig. 2*A*1, area 7). Water levels are declining as a result of increased public, industrial, and agricultural usage (Berenbrock, 1987). Poor-quality ground water has been documented in many areas of the valley, especially in the shallow playa deposits. There is a major concern that poor-quality water may move toward areas of significant pumping where water is still of relatively good quality. Dissolved-solids concentrations range from 190 to 67,000 mg/L, with the largest concentrations found in shallow wells in the playa. The median dissolved-solids concentration is 510 mg/L, only slightly exceeding the 500-mg/L drinking-water standard. Chloride concentrations range from 17 to 39,000 mg/L, with a median concentration of 86 mg/L.

Antelope and Fremont Valleys (fig. 2*A*1, area 8) are intersected by numerous faults and are separated hydrologically into many subbasins and areas. Generally, surface drainage terminates at the Rosamond and Rogers Lake playas in Antelope Valley, and Koehn Lake playa in Fremont Valley. Imported water from northern California into several areas of Antelope Valley has altered the natural hydrologic regime. Dissolved-solids concentrations are generally less than 500 mg/L in Antelope and Fremont Valleys, and the median concentration is 375 mg/L. Some wells, especially near the playas where drainage terminates, yield water with dissolved-solids concentrations as large as 4,200 mg/L; however, the 90-percentile concentration is less than 1,000 mg/L.

EFFECTS OF LAND USE ON WATER QUALITY

Water-quality degradation has occurred in many areas as a result of irrigation return flow, application of agricultural pesticides and fertilizers, improper waste disposal and industrial practices, and saltwater intrusion.

Agriculture

In 1980, nearly 200 commercial crops were grown on 9.5 million acres of irrigated land in California (California Department of Water Resources, 1983). Agriculture is extensive in most counties in the Central Valley, parts of Imperial, Riverside, and San Bernardino Counties, and many coastal and southern California basins. Widespread use of pesticides in these agricultural areas has contaminated hundreds of wells, and several State agencies have implemented pesticide-monitoring programs to document the extent of the problem.

Dibromochloropropane (DBCP) is the most widespread pesticide contaminant found in ground water. Of 8,190 private and public-supply wells sampled from 1979 through 1984, 2,522 wells had DBCP contamination. More than one-third of the wells sampled in Fresno County were contaminated with DBCP. In Merced, Tulare, and Madera Counties, nearly one-quarter of the sampled wells had DBCP contamination. The State action level of 1 part per billion DBCP was exceeded in 1,455 wells (Cohen and Bowes, 1984). State action levels are informal guidelines for drinking water based on health considerations. The action levels are not legally enforceable but are regarded by most water suppliers the same as maximum contaminant levels established by government regulations. More than 50 other pesticides, including 1,2-dichloropropane and ethylene dibromide (EDB), had been detected in samples from 255 wells through 1984.

In the central part of the western San Joaquin Valley, selenium concentrations in shallow ground water and subsurface agricultural drainage water commonly exceed 100 μg/L, and in places exceed 1,000 μg/L. In 1984, State and Federal agencies, including the U.S. Geological Survey, began intensive investigations of the occurrence, distribution, and movement of selenium in the San Joaquin Valley.

Industry

In 1980, organic chemicals were found in several domestic water-supply wells in Los Angeles County, and more than 50 wells were eventually closed. In response to the discovery of contamination of these wells and wells in the San Joaquin Valley and San Bernardino-Riverside area, the State legislature passed Assembly Bill 1803 in 1983. This bill requires monitoring of organic chemicals in public drinking-water systems in heavy- and light-industrial and agricultural areas. During phase I of the implementation of the Bill, large water systems with 200 or more hookups were monitored. Smaller water systems are currently being monitored in phase II.

In initial data from phase I, 33 organic chemicals were detected in ground-water samples. Five of the most frequently detected chemicals in descending order of occurrence were tetrachloroethylene, also called perchloroethylene (PCE), trichloroethylene (TCE), DBCP, chloroform, and 1,1-dichloroethylene (1,1-DCE). Four of the 5, and 29 of the 33 organic chemicals are used in industrial and manufacturing processes. Of 2,947 wells sampled during phase I, PCE was detected in 199 wells with a maximum concentration of 166 μg/L. TCE was detected in 188 wells with a maximum concentration of 538 μg/L. Concentrations of chloroform as large as 54 μg/L were found in 116 of the wells sampled, but some samples with large concentrations may be associated with chlorination of the well supply. Wells with the largest 1,1-DCE concentrations—as large as 78 μg/L—were generally from samples in greatly urbanized areas (California Department of Health Services, 1986).

Waste Disposal

Hazardous waste is disposed of at 71 RCRA sites (fig. 3*A*), creating a potential hazard to ground-water quality. The status of ground-water contamination near these sites is listed as "unknown" by EPA until additional monitoring programs are started and current data evaluated. However, ground-water contamination has been detected at 26 of the 34 CERCLA sites on the NPL (fig. 3*A*). The list of contaminants is extensive and includes industrial cleaning solvents, pesticides, acids, and trace metals. TCE and PCE have been found in the ground water at several of the 26 sites. At one site, leaking organic solvents disposed of in a lined evaporation pond contaminated more than 50 private wells. At another site, several private wells were contaminated with DBCP after wastes from pesticide and fertilizer production were disposed of in unlined ponds and in a company-owned landfill.

As of September 1985, 405 hazardous-waste sites at 34 facilities in California have been identified by the DOD as part of their IRP as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA, and has four phases: assessment (I), confirmation (II), technology development (III), and remedial action (IV). EPA presently ranks these sites under a hazardous ranking system and may include them in the NPL. Of the 405 sites evaluated under the program, one site contained contaminants but did not present a hazard to people or the environment. Twenty-three sites at 12 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at 11 of these sites has been completed under the program.

The distribution by county of wells that yield contaminated water above State action levels, as of 1986, are shown in figure 3*B* (based on information obtained from the SWRCB). Except for Fresno County, which had 1,052 wells that yield contaminated water exceeding State action levels, and Merced and Los Angeles Counties, the 12 other counties reporting wells that yield contaminated water had 90 or less.

California has 651 active county or municipal landfill sites (fig. 3*C*). Los Angeles County has 117 sites, followed by San Bernardino County (89), and Kern County (26). Sufficient data are not available for an evaluation of the effects of these sites on the quality of ground water. Total numbers of inactive or closed landfill sites are not available but probably number several hundred.

Saltwater Intrusion

Saltwater intrusion generally occurs in coastal areas when ground-water levels are lowered below sea level by pumping. Fourteen important coastal basins, including Santa Clara Valley (Santa Clara County), Morro basin (San Luis Obispo County), the Salinas Valley (Monterey County), Oxnard Plain basin (Ventura County), and coastal basins in Los Angeles and Orange Counties, have documented saltwater intrusion, and it is suspected in many other basins (California Department of Water Resources, 1975b). In many areas, such as Los Angeles and Orange Counties, inland migration of saltwater has been halted or reversed by reduced or controlled pumping, use of barrier injection wells, and (or) artificial recharge.

POTENTIAL FOR WATER-QUALITY CHANGES

Population in California is expected to increase by 10.6 million, from 23.8 million in 1980 to 34.4 million in 2010 (California Department of Water Resources, 1983). About 50 percent of the increase is expected in urbanized and water-deficient southern counties—Los Angeles, Orange, Riverside, San Bernardino, and San Diego. Irrigated acreage is projected to increase by about 700,000 acres, to 10.2 million acres in 2010, with increases primarily in the Central Valley. Overall, the State's average annual ground-water overdraft is projected to increase from 1.8 million acre-feet in 1980 to 2.9 million acre-feet in 2010.

On the basis of these projections, the potential for change in ground-water quality in many basins is considerable. In the past, overdraft of ground water has led to saltwater intrusion in some coastal basins. In other basins, overdraft has increased dissolved-solids concentrations in ground water. Increased pumpage may cause contaminated ground water to migrate toward pumping centers.

Agriculture and associated land uses—feed lots, septic tanks, and processing plants—have contaminated and changed the quality of ground water in many basins. Also, ground water in some urban basins has been contaminated and changed by leaky underground storage tanks, waste disposal, and the chemicals used in industry. Leakage of solvents and gasoline from underground storage tanks and piping is considered a major source of potential ground-water contamination. Numerous instances of contamination from leaks have occurred, from metropolitan areas to the isolated Stovepipe Wells Village in Death Valley National Monument.

Of additional concern are abandoned wells in areas that were primarily agricultural, but have been urbanized. If the abandoned wells are not properly sealed, they may act as conduits for contaminants from the land surface to ground water.

Changes in agricultural practices may be necessary to avoid increased salinity in shallow ground water. New and additional ways of transporting water to deficient areas also may be required. Enforcement of existing laws and protection-monitoring programs will be an essential part of safeguarding California's water supplies.

GROUND-WATER-QUALITY MANAGEMENT

The DWR and SWRCB are the principal water-management agencies of the State. DWR engages in statewide water-supply planning activities and conducts ground-water quantity and quality investigations in support of statewide planning efforts. Information, technical advice, and assistance are provided to other water agencies. The SWRCB and nine California Regional Water Quality Control Boards establish and enforce water-quality standards for State water supplies, including ground water. The DOHS investigates the quality of ground-water supplies used as sources of drinking water. The California Department of Food and Agriculture investigates ground-water supplies subject to pesticide contamination, and the California Department of Conservation, Division of Oil and Gas, controls oil- and gas-related underground-injection activities.

Federal water-quality legislation is implemented through several State agencies. The Public Water Supply provisions of the Safe Drinking Water Act are implemented by DOHS, as are CERCLA, RCRA, and the Toxic Substances Control Act. The Clean Water Act is administered by the SWRCB. Primary control for underground injection oil and gas wells (Class II) has been assigned to the Department of Conservation, Division of Oil and Gas, by EPA.

Users of ground water generally are not regulated. Exceptions are in adjudicated basins and in water districts that have powers to tax pumpage. Water rights in nine of the State's ground-water basins have been adjudicated as a result of conflicts among users. Pump taxes have been set by 5 of the 12 agencies authorized to do so. The SWRCB, in cooperation with DWR, is in the process of establishing water-well construction standards. Drillers are licensed by the Contractor's State License Board; well logs produced during drilling activities are maintained by DWR.

California is developing a ground-water protection strategy through the Interagency Coordinating Committee, an organization of State agencies having ground-water responsibilities. The committee is chaired by SWRCB, the lead agency for developing the strategy. Participating agencies include the Departments of Water Resources, Health Services, Conservation, Food and Agriculture, and the Waste Management Board. Development of the ground-water protection strategy is expected to be completed in 1987. A major feature of the strategy will be a policy of nondegradation of the ground-water resource.

Ground-water-level measurements by many agencies are compiled and monitored statewide by DWR (California Department of Water Resources, 1975c). Ground-water-quality monitoring programs are conducted by many agencies in California. The California State and Regional Water Quality Control Boards monitor ground-water quality under various programs related to waste-discharge regulation. The SWRCB funds DWR to do supplemental monitoring of mineral and suspected toxic-pollutant quality in four of the Priority I ground-water basins. This monitoring changes annually in the number and selection of wells and chemical constituents for each basin, expanding on the efforts of other government agencies. These data are being collected to meet the requirements of the EPA in accordance with Public Law 92–500 of the Federal Water Pollution Control Act Amendments of 1972 (California Department of Water Resources, 1980b, p. 3). Plans are underway for extension of this program to include more Priority I basins.

The DOHS is conducting a large-scale one-time program to monitor public ground-water supplies for toxic pollutants. This program is a result of passage of two State laws (Assembly Bill 1803 of 1984 and Assembly Bill 1803 of 1985). This work is well underway, and data from the program are available (California Department of Health Services, 1986). A third law (Assembly Bill 2058 of 1985) requires DOHS to initiate controls on underground injections. These controls are supposed to be consistent with, but more stringent than, those of the EPA.

Another State statute (Assembly Bill 2021 of 1985) requires the Department of Food and Agriculture to determine which pesticides have the capability to infiltrate the soil and contaminate ground water. Significant ground-water monitoring for pesticides will be done in support of this program, which has been implemented recently.

In addition to programs of State agencies, local agencies do significant ground-water-quality monitoring. The Santa Clara Valley Water District has done extensive monitoring for toxic organics in the Santa Clara Valley ground-water basin (Gloege, 1984). This basin is recharged by infiltration of surface water regulated by the Santa Clara Valley Water District. Water retailers pump from the basin, under control of the water district, which regulates and taxes withdrawals.

Cooperative programs between State and Federal agencies, including the U.S. Geological Survey, account for significant ground-water-level and -quality data collection at several hundred sites in the State.

The DWR has for many years maintained a limited statewide ground-water-quality monitoring network for mineral constituents. The DWR is budgeted for fiscal year 1986-87 to extend this program to the monitoring of toxic pollutants, in coordination with other agencies.

California is a large State, with vast and diverse ground-water resources. It can realistically be expected that several years of intensive work will be necessary to develop an effective ground-water-quality data base. The approach of State agencies will be to set priorities for the needed work and move ahead as rapidly as possible.

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COLORADO
Ground-Water Quality

Ground water in Colorado (fig. 1) generally is suitable for most uses and constitutes 18 percent of the total water used. Of the total quantity of ground water used, 96 percent is for irrigation, 2 percent for public supply, 1 percent for rural domestic supplies, and 1 percent for livestock and industrial uses (U.S. Geological Survey, 1985, p. 153). Public supplies provide ground water to 320,000 people—11 percent of the 1980 population of 2,889,964 (U.S. Bureau of the Census, 1981).

Water in the principal aquifers (fig. 2) generally does not exceed national drinking-water standards for nitrate, sulfate, and iron; dissolved-solids concentrations generally are smaller than 1,000 mg/L (milligrams per liter). In some locales, contamination of ground water with inorganic and organic chemicals has resulted from waste disposal, mineral extraction and processing, and urbanization (fig. 3). In agricultural areas, dissolved-mineral content is increased by evapotranspiration and water use and reuse; also, increased nitrate plus nitrite concentrations may result from leaching of animal waste or nitrogen fertilizer. Pesticides applied on agricultural and forested land eventually may enter the ground-water system.

The Colorado Department of Health is responsible for coordinating efforts to protect the quality of the State's ground-water resources. The present public-water-supply monitoring program maintained by the Department has identified 55 of 546 public ground-water-supply systems that contain dissolved substances in concentrations that exceed State drinking-water standards (Colorado Department of Health, 1977). Routine testing is required by the Department for inorganic chemicals, selected organic chemicals (including trihalomethanes), and bacteria in public ground-water supplies. Trihalomethanes are a family of organic compounds, including chloroform, that results from a mixing of chlorine (for disinfection) with water containing natural organics. Tests for organic chemicals such as insecticides, herbicides, and solvents (including trichloroethylene) are not required for ground-water supplies. Private wells are not tested routinely; however, bacteria tests are required before the sale of a residence wherein the occupants must rely on ground water for their water supply.

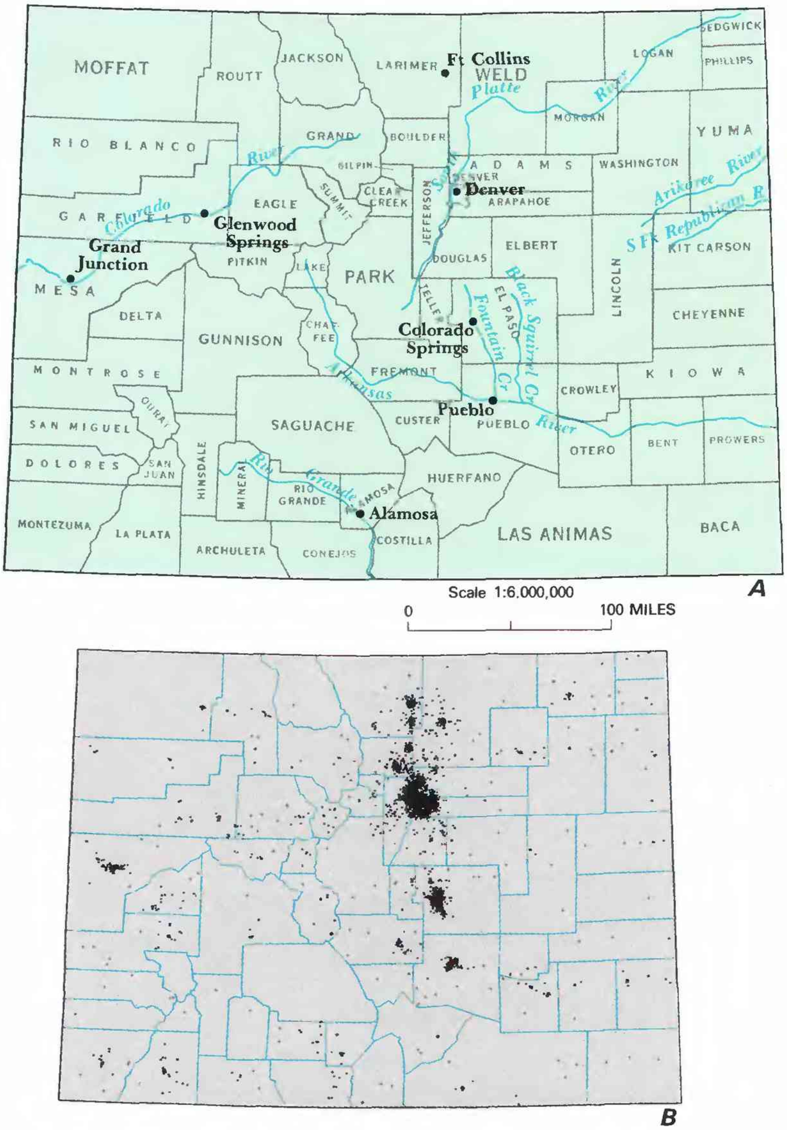

Figure 1. Selected geographic features and 1985 population distribution in Colorado. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Colorado has seven principal aquifers or aquifer systems (fig. 2*A*), all differing in water quality. The four aquifers consisting of unconsolidated deposits account for most of the withdrawals. These aquifers are the alluvial aquifer along the South Platte River and its tributaries, the alluvial aquifer along the Arkansas River and its tributaries, the High Plains aquifer in eastern Colorado, and the San Luis Valley aquifer system in the Rio Grande basin. The remaining three principal aquifers consist of consolidated rock: the Denver Basin aquifer system underlying parts of the South Platte and Arkansas River basins, the Piceance Basin aquifer system northeast of Grand Junction in the Colorado River basin, and the Leadville Limestone aquifer near Glenwood Springs in the Colorado River basin. Aquifers in the Dakota, Morrison, and Entrada Formations are not principal aquifers in Colorado but are shown in figure 2*A* because of their significance in adjacent States. In many areas of the State, wells yield water from other aquifers; however, these other aquifers provide only a small percentage of the total volume of water used.

BACKGROUND WATER QUALITY

The background water quality presented in this report does not represent pristine water quality. Before irrigation development,

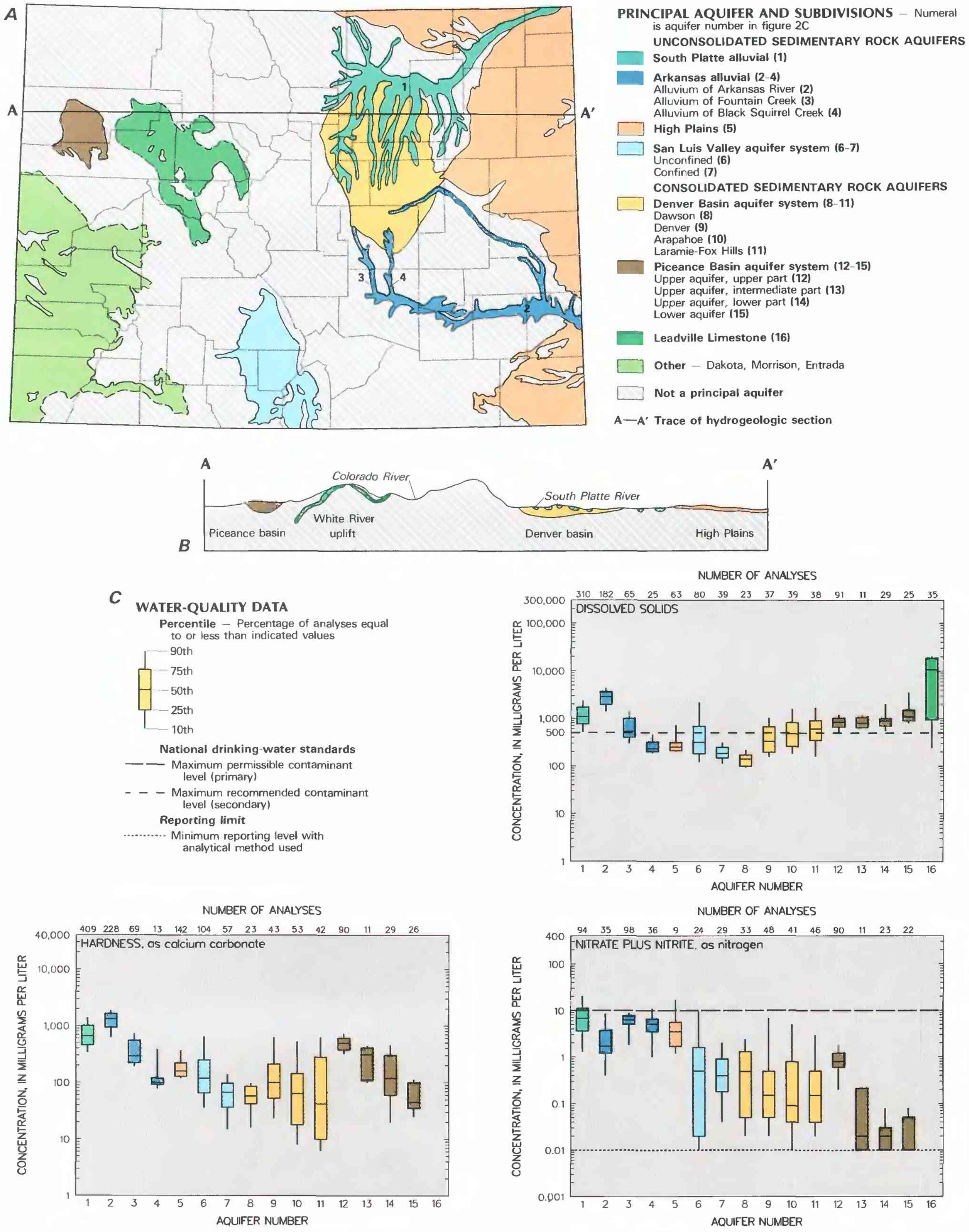

Figure 2. Principal aquifers and related water-quality data in Colorado. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1954-86. (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a, b.)

for example, the alluvial aquifers had a much thinner saturated thickness than at present and may not have been hydraulically connected with many reaches of the South Platte and Arkansas Rivers; the quality of water in these aquifers before irrigation development is not known. Since as early as the 1860's, irrigation-water applications and ditch leakage have recharged the alluvial aquifers, raising water levels to the extent that water now discharges from those aquifers by evapotranspiration or seeps to streams, augmenting and sustaining flow for downstream diversions. It is the quality of water in these aquifers that is reported in this section. Since irrigation development began, use and reuse of surface water for irrigation has resulted in increased mineralization of water through evapotranspiration and drainage from irrigated land. Some of this surface water that is unused by plants enters the ground-water system and increases the dissolved-solids concentrations in the ground water. As a result, dissolved-solids concentrations increase in a downgradient direction in alluvial aquifers along the South Platte River, the Arkansas River (fig. 4), and the Rio Grande.

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness as calcium carbonate, nitrate plus nitrite (as nitrogen), sulfate, and iron analyses of water samples collected from 1954 to 1986 from the principal aquifers in Colorado. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L sulfate, and 300 μg/L (micrograms per liter) iron.

The number associated with each of the aquifers in the discussion that follows refers to the location of the aquifer in figure 2*A* and the graphic summary of water-quality data in figure 2*C*. The national drinking-water standard (U.S. Environmental Protection Agency, 1986a) specifies a maximum permissible concentration for nitrate. However, most samples were analyzed for nitrate plus nitrite. Because nitrite is rapidly oxidized to nitrate, these values are comparable for oxygenated natural-water systems. Therefore, concentrations of nitrate plus nitrite are compared with the standard for nitrate; "nitrate concentrations" as used throughout this report refers to "nitrate plus nitrite concentrations (as nitrogen)."

South Platte Alluvial Aquifer

The South Platte alluvial aquifer (fig. 2*A*, aquifer 1) consists of about 4,000 mi² (square miles) of gravel, sand, silt, and clay along the South Platte River and tributaries in northeastern Colorado. About 1,100 Mgal/d (million gallons per day) of water is withdrawn from this aquifer for supplemental irrigation supply. Numerous public-supply systems and many individual rural-domestic and stock wells also derive water from this alluvial aquifer.

The median dissolved-solids concentration exceeded 1,000 mg/L. Recharge by percolation from surface-water applications, leakage from reservoirs and irrigation ditches, and leakage from the river results in a general increase in dissolved-solids concentrations in a downgradient direction. However, because of recharge from bordering deposits of dune sand, from the Denver Basin aquifer system, and from the High Plains aquifer, differences in quality are more apparent across the valley than downvalley. Water on the edges of the aquifer commonly had a smaller dissolved-solids concentration (Hurr and others, 1975) than water in the center of the valley. Water commonly was very hard; calcium and sulfate were the dominant constituents. Dissolved nitrate concentrations exceeded the national drinking-water standard in more than 25 percent of the samples.

Arkansas Alluvial Aquifer

The Arkansas alluvial aquifer consists of gravel, sand, silt, and clay in a 1- to 5-mile-wide band along the Arkansas River and tributaries in southeastern Colorado. The aquifer yields about 300 Mgal/d of water for supplemental irrigation supply and is the source of public supply for several cities. Water-quality data are adequate to divide the aquifer into three areas, each having different water-quality characteristics.

Water from the alluvial aquifer along the Arkansas River from Pueblo downstream to the State line (aquifer 2) had a median concentration of dissolved solids of 2,900 mg/L. The median concentration increased from 1,530 mg/L near Pueblo to 3,500 mg/L near the State line (fig. 4). The larger concentrations to the east limit the irrigated crops to those that are salt tolerant. Water from this aquifer was very hard. Water from more than 90 percent of the wells sampled contained concentrations of sulfate in excess of the national drinking-water standard.

Water from the alluvial aquifer along Fountain Creek (aquifer 3), a tributary to the Arkansas River that flows through Colorado

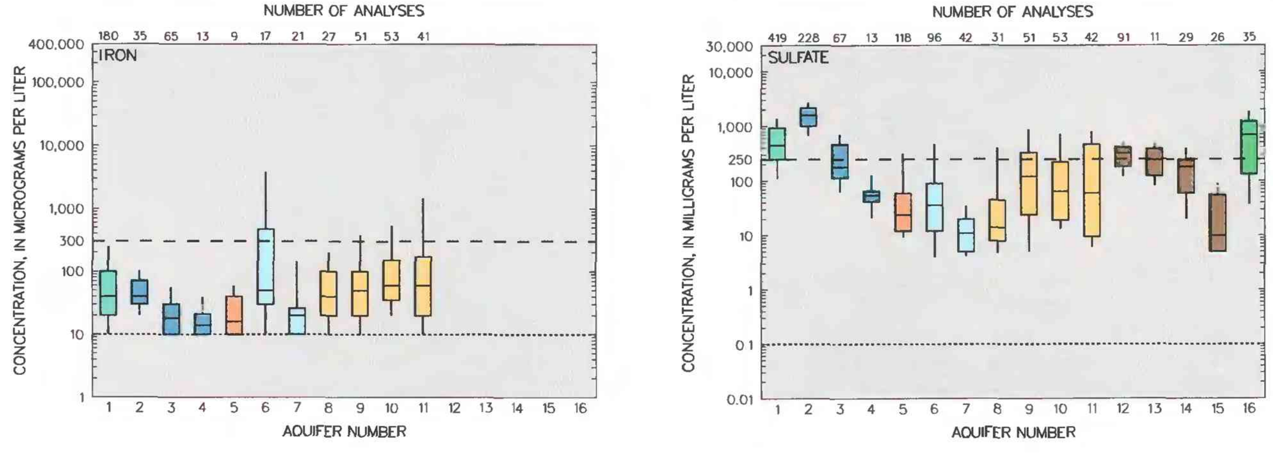

Figure 2. Principal aquifers and related water-quality data in Colorado—Continued.

Springs, had a median dissolved-solids concentration of 530 mg/L. Concentrations of dissolved solids, hardness, and sulfate increased toward the southern part of this aquifer (Cain and Edelmann, 1986). Water from this aquifer was moderately hard to very hard; sulfate concentrations exceeded the national drinking-water standard of 250 mg/L in water from fewer than one-half the wells sampled. Water from the northern part of the aquifer is used as a public water supply for Colorado Springs and several suburban communities.

Water from the alluvial aquifer along Black Squirrel Creek (aquifer 4), an ephemeral tributary to the Arkansas River east of Colorado Springs, had a median dissolved-solids concentration of 230 mg/L. Water from three-fourths of the wells sampled was moderately hard. None of the samples had concentrations of sulfate in excess of the national drinking-water standard.

High Plains Aquifer

The High Plains aquifer (aquifer 5) is composed mainly of unconsolidated to partly consolidated gravel and sand but also contains minor amounts of clay, silt, and caliche. About 900 Mgal/d of water is withdrawn from the aquifer for irrigation; a lesser quantity is withdrawn for rural-domestic and livestock use. In Colorado, the aquifer is divided by the Arkansas River into two sections—a northern section of about 11,000 mi^2 and a southern section of about 2,800 mi^2.

Data for the two sections are combined in figure 2*C* because the differences are small at the scale of that figure. In the northern section, the median dissolved-solids concentration was 230 mg/L; calcium and bicarbonate were the dominant constituents. The water was moderately hard to hard. In the southern section, the median dissolved-solids concentration was 470 mg/L; sodium and sulfate became more prevalent. Fluoride concentrations (not shown in fig. 2*C*) in water from some parts of the High Plains aquifer exceeded 2.0 mg/L. In part of Kiowa County, the reported dissolved-solids concentrations were as much as 2,140 mg/L (Gutentag and others, 1984); the very hard water commonly has naturally occurring sulfate, fluoride, and dissolved-solids concentrations exceeding national drinking-water standards.

San Luis Valley Aquifer System

The San Luis Valley aquifer system consists of unconsolidated gravel, sand, clay, and volcanic and volcaniclastic rocks in a 3,200-mi^2 basin near Alamosa. About 400 Mgal/d of water from the aquifer are used for supplemental irrigation supply, and lesser quantities are used for public and rural-domestic supply. The aquifer system comprises an unconfined aquifer less than about 130 feet thick and a confined aquifer as much as several thousand feet thick. The two aquifers are separated by discontinuous layers and lenses of fine-grained sand, clay, or volcanic rock.

Water from the unconfined aquifer in the San Luis Valley aquifer system (aquifer 6) had a median dissolved-solids concentration of 315 mg/L, and concentrations were larger than 2,200 mg/L in 10 percent of the samples. The water ranged from soft to very hard. Concentrations of sulfate had a median value of 36 mg/L, but sulfate was larger than 476 mg/L in 10 percent of the samples. More than 25 percent of the samples contained iron in excess of the 300 μg/L specified in the national drinking-water standard. The largest concentrations of dissolved constituents occurred downgradient in the central part of the valley northeast of Alamosa.

Water from the confined aquifer in the San Luis Valley aquifer system (aquifer 7) had a median dissolved-solids concentration of 184 mg/L. This water generally was softer and had smaller concentrations of dissolved solids and sulfate than water from the unconfined part of this aquifer system. Analyses of water from the confined aquifer indicate a downgradient increase in concentrations of dissolved solids (Emery and others, 1973).

Denver Basin Aquifer System

The Denver Basin aquifer system underlies a 6,700-mi^2 area of east-central Colorado near Denver. The system comprises four aquifers (Dawson, Denver, Arapahoe, and Laramie–Fox Hills), which have a maximum combined thickness of about 3,200 feet between Denver and Colorado Springs, and thin toward the margins of the bowl-shaped basin. The aquifers yield about 30 Mgal/d of water for public-supply, rural-domestic, and commercial use from beds of consolidated sandstone and conglomerate.

Water from the Dawson aquifer (aquifer 8), the uppermost aquifer in the system, had dissolved-solids concentrations smaller than 200 mg/L in most areas. The water was a calcium bicarbonate, sodium bicarbonate, or sodium sulfate type and ranged in hardness from soft to hard. Sulfate concentrations smaller than 25 mg/L, which prevailed in the central part of the aquifer, increased to more than 250 mg/L in a few areas on the margin of the aquifer. Iron concentrations generally ranged from 20 to 100 μg/L, but concentrations as large as 8,500 μg/L have been measured in water from this aquifer.

Water from the underlying Denver aquifer (aquifer 9) had dissolved-solids concentrations smaller than 700 mg/L in most areas. In the central part of the aquifer, the water is a calcium bicarbonate type; near the margins of the aquifer, the water is a sodium bicarbonate or sodium sulfate type. Sulfate concentrations ranged from 2 mg/L in the central part of the aquifer to more than 2,000 mg/L in a few areas at the aquifer margin. Iron concentrations generally ranged from 10 to 150 μg/L.

Water from the underlying Arapahoe aquifer (aquifer 10) generally had dissolved-solids concentrations smaller than 1,000 mg/L. Very hard water with sulfate concentrations larger than 1,000 mg/L may be present near the margins of the aquifer, but soft water containing less than 200 mg/L sulfate was common in most areas. Iron concentrations commonly ranged from 20 to 200 μg/L but exceeded 6,000 μg/L in water from a few widely scattered wells.

Water from the Laramie–Fox Hills aquifer (aquifer 11), the lowermost aquifer in the Denver Basin aquifer system, generally had dissolved-solids concentrations smaller than 1,200 mg/L. The sodium bicarbonate to sodium sulfate type water commonly is soft, but hard water may be present near the margins of the aquifer. Sulfate concentrations were smaller than 200 mg/L in most areas. Concentrations of iron commonly were less than 200 μg/L, but concentrations of as much as 79,000 μg/L have been measured. In areas of reducing conditions in the aquifer, sulfate minerals and natural organic matter may be reduced to hydrogen sulfide and methane gases. When these gases are present in sufficient concentrations, water pumped from this aquifer may have a putrid odor, may effervesce, and may be unacceptable for some uses.

Piceance Basin Aquifer System

The Piceance Basin aquifer system comprises two aquifers that underlie 1,600 mi^2 northeast of Grand Junction. The upper aquifer consists of stream-valley alluvium, the Uinta Formation, and the upper part of the Green River Formation. The lower aquifer consists of the middle part of the Parachute Creek Member of the Green River Formation. The two aquifers are separated by the oil-shale-rich Mahogany Zone. Near-surface ground water is the main source of supply for rural-domestic and agricultural use.

Water quality in the aquifer system changes with depth. Concentrations of nitrate, calcium, magnesium, and sulfate decrease with depth. Conversely, concentrations of dissolved solids, sodium, alkalinity, fluoride, boron, and lithium increase with depth. Water quality in the upper aquifer ranges from a very hard, mixed cation bicarbonate sulfate type near the top (aquifer 12) to a moderately hard, sodium bicarbonate type near the base (aquifer 14). At intermediate depths (aquifer 13), the water quality is intermediate.

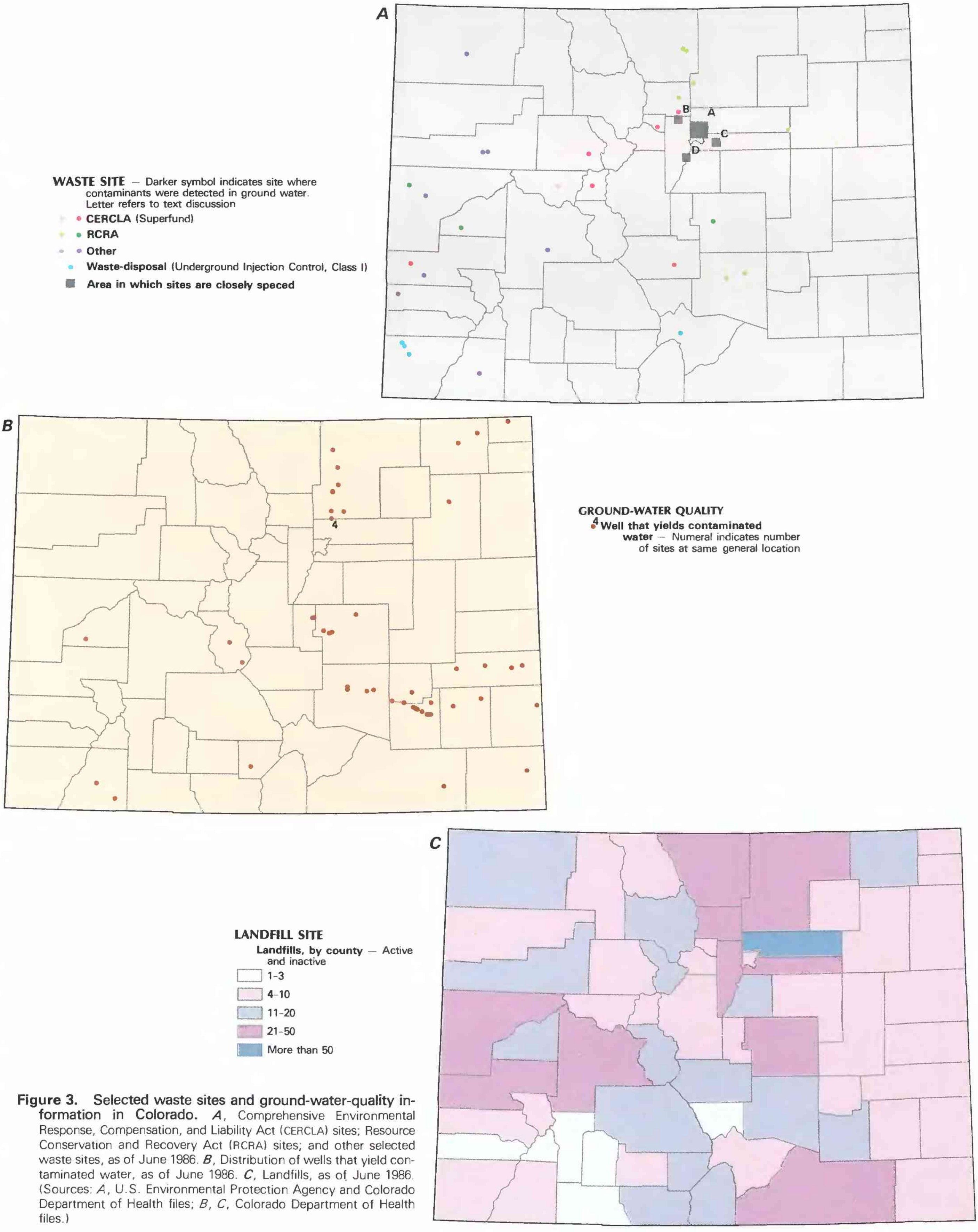

Figure 3. Selected waste sites and ground-water-quality information in Colorado. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of June 1986. *B*, Distribution of wells that yield contaminated water, as of June 1986. *C*, Landfills, as of June 1986. (Sources: *A*, U.S. Environmental Protection Agency and Colorado Department of Health files; *B*, *C*, Colorado Department of Health files.)

Water from the lower aquifer (aquifer 15) is a soft, sodium bicarbonate type. Dissolved-solids concentrations for samples from the lower aquifer generally ranged from 660 to 4,100 mg/L; however, concentrations as large as 30,000 mg/L have been measured and probably are the result of water that dissolves deposits of soluble salts along fractures, solution vugs, or in open boreholes. The usefulness of the water from the lower aquifer is limited by its sodium bicarbonate type as well as by large concentrations of fluoride and boron.

Leadville Limestone Aquifer

The Leadville Limestone aquifer (aquifer 16) underlies much of the northern part of western Colorado but has not been extensively developed as a water supply. Samples collected from springs and other discharge areas indicate that in zones less than 1,000 feet deep, dissolved-solids concentrations were smaller than 500 mg/L. Data from deep wells and springs issuing from deep fracture systems, however, indicate that dissolved-solids concentrations increase with depth; values are larger than 200,000 mg/L in some samples. Some water samples from this aquifer had sulfate concentrations among the largest in the State.

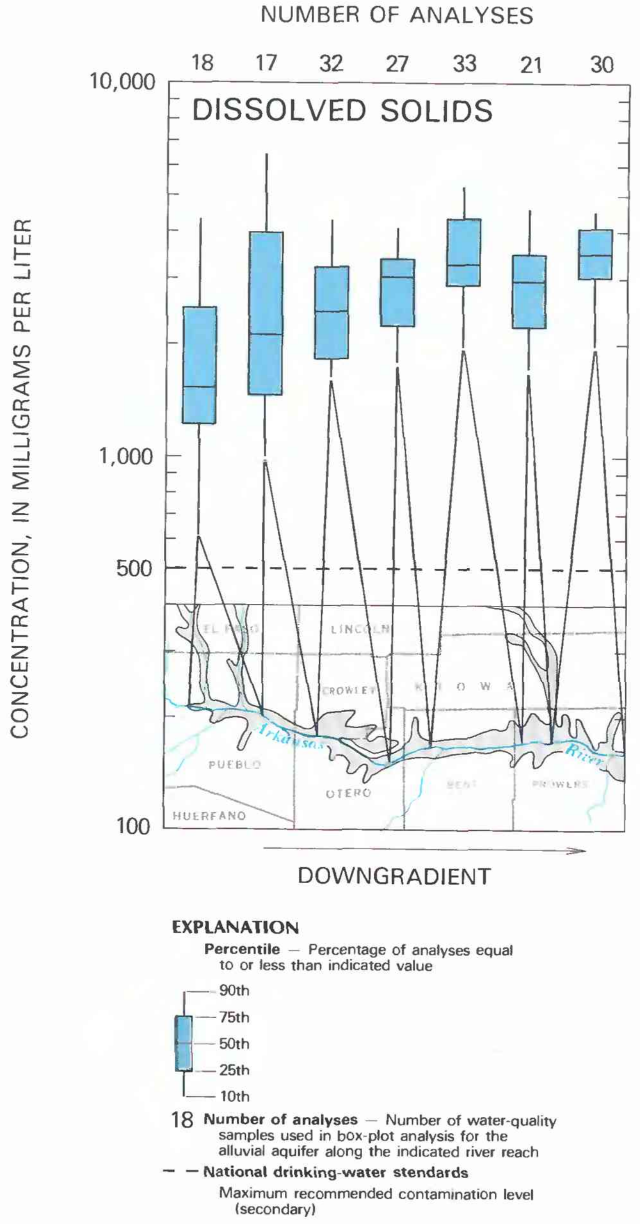

Figure 4. Increase in dissolved-solids concentration downgradient in the Arkansas alluvial aquifer, Colorado, 1964-82. (Source: U.S. Geological Survey files.)

Other Aquifers

In many areas of Colorado, water is available from other aquifers in quantities sufficient to be locally significant. The quality of water in these aquifers differs considerably. Water from some wells completed in the Dakota Sandstone in southeastern Colorado contains large concentrations of naturally occurring gross alpha radiation, uranium, radium, and radon (Felmlee and Cadigan, 1979; Crouch and others, 1984; Leonard, 1984). Also, water from a fractured crystalline rock aquifer west of Denver generally is acceptable for drinking but locally had gross alpha radiation in excess of 15 picocuries per liter (in 11 of 26 wells sampled) and significant differences in concentrations of 15 chemical constituents (Hall, 1979).

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has changed in some areas because of the effects of waste disposal, mineral extraction and processing, urbanization, and agriculture. Water-quality changes in some areas have been documented by areal investigations of the U.S. Geological Survey. More commonly, documentation of the changes is the result of an evaluation of a specific site. Water-quality changes have been investigated at 15 sites under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Of these 15 sites, 12 have been included in the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c); 1 is being considered for possible inclusion in the NPL, and 2 are at Federal facilities. Water-quality changes have been documented at 9 of the 12 sites on the NPL and at the other 3 sites. Water-quality changes also have been documented at 7 of 19 sites where ground-water quality is monitored under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 and at 8 Uranium Mill Tailings Remedial Action Project (UMTRAP) sites under the Radiation Control Act of 1978. Remedial action has been recommended at 2 Department of Defense facilities under the Installation Restoration Program (IRP) (U.S. Department of Defense, 1986).

Figure 3*A* shows the location of CERCLA, RCRA, and IRP sites; sites identified as "other" include UMTRAP, Federal facility, and proposed CERCLA sites. In some areas, the sites are too closely spaced to show individually in figure 3*A*. Types of sites in each of these areas are identified in the following table:

	Area letter			
Type of site	A	B	C	D
	Number of sites in area			
CERCLA (Superfund) site	4	—	1	—
RCRA site	5	2	1	1
IRP (U.S. Department of Defense) site	2	—	—	—
Other				
U.S. Department of Energy site	—	1	—	—
Proposed CERCLA site	—	—	—	1
Total number of sites	11	3	2	2

Away from these sites, there is no program for monitoring the quality of ground water, except for public-supply systems as required by the Colorado Department of Health. Constituent concentrations in ground water that exceed the State drinking-water standards (Colorado Department of Health, 1977) have been documented for wells that supply 55 public systems—gross alpha radiation in 19 systems, nitrate in 14 systems, fluoride in 10 systems, radium in 9 systems, selenium in 8 systems, arsenic in 2 systems, lead in 1 system, and gross beta radiation in 1 system (fig. 3*B*).

Waste Disposal

Contaminants have been detected in ground water at 7 of the 19 RCRA sites used for surface impoundment or disposal of hazardous waste. Contaminants from waste disposal have been detected in ground water at an additional 7 sites—4 sites listed in the NPL (U.S. Environmental Protection Agency, 1986c), 1 site being evaluated under CERCLA for possible inclusion in the NPL, and 2 sites at Federal facilities. Many of these sites are located near Denver.

Several investigations are in progress near the Rocky Mountain Arsenal where wastes from production of chemical-warfare agents and pesticides have been deposited by the U.S. Army and private companies. The Army is investigating contaminants in the arsenal area and contaminant migration in ground water north and northwest of the arsenal. The U.S. Environmental Protection Agency (EPA) is investigating the location, types, and possible sources of contaminants at several sites including Sand Creek industrial site southwest of the arsenal. This site includes a closed landfill, a former oil refinery, a chemical company, and closed acid-disposal pits. Contaminants include acidic wastes, pesticides, hydrocarbons, trichloroethylene, tetrachloroethylene, and other industrial solvents. The long history and multiple sources of contamination present a difficult problem in waste management. Trichloroethylene contamination of a public-water supply in southwestern Adams County (fig. 3*A*, area A) recently required a quick response to protect drinking water. To address the problem of protecting drinking water, an activated-carbon filtration system is used to remove trichloroethylene and other contaminants from the public water supply of the 30,000 residents served by the South Adams County Water and Sanitation District. Residences that formerly relied on shallow private wells in some areas have been connected to the now-treated public water supply.

Northwest of Denver in Jefferson County (fig. 3*A*, area B) are 2 RCRA sites and 1 Department of Energy (DOE) site. At the Rocky Flats Plant, chemical and nuclear wastes have been disposed or released at 91 sites, including a surface impoundment, a field on which liquid wastes were sprayed, and a landfill. Detailed assessments of possible ground-water contamination there are being developed by the Department of Energy.

Colorado has 783 known landfill sites (fig. 3*C*), 554 of which are closed. For many of these landfills, the composition of the deposited wastes is unknown, and ground-water contamination has not been investigated. However, evaluation of two landfills in the Denver area resulted in both being added to the NPL. At the Lowry landfill in Arapahoe County (fig. 3*A*, area C), trace concentrations of volatile organic compounds (benzene, toluene, and tetrachloroethylene) have been detected 0.3 mile from the landfill in water from the Denver Basin aquifer system (fig. 2*A*) despite the presence of thick shale beds that underlie the landfill and retard downward contaminant movement. At the Marshall landfill in Boulder County, contamination has been detected in water from alluvial aquifers both on and off the site. Contamination of the underlying bedrock aquifer has not been confirmed.

Mineral Extraction and Processing

Many of the waste-disposal sites where ground-water contamination has been documented (fig. 3*A*) are related to mineral extraction and processing. Two CERCLA sites include active uranium-processing facilities in Fremont and Montrose Counties, where molybdenum, selenium, and uranium have been introduced into ground water. Ground-water contamination also has occurred at the eight UMTRAP sites.

Drainage from hundreds of abandoned mines and tailing piles produces acidic water containing large concentrations of heavy metals (cadmium, copper, iron, lead, manganese, and zinc). Although many of these mines and tailing piles do not overlie a principal aquifer, the drainage from them affects hundreds of miles of streams and may contaminate locally important aquifers. Sites near Leadville (Lake County) in the Arkansas River drainage and Central City (Gilpin County) in the South Platte River drainage are CERCLA sites at which contamination has been documented (fig. 3*A*). A large sudden discharge from Argo Mine drainage tunnel (draining mines near Central City) in 1980 introduced large concentrations of heavy metals into the South Platte River drainage; wells supplying drinking water were contaminated by the discharge. Large, sudden discharges from the Yak Tunnel (draining mines near Leadville) in 1983 and 1985 introduced large concentrations of heavy metals into the Arkansas River drainage. The Colorado Department of Health has identified the process of using cyanide to leach gold and silver from abandoned tailing piles as 1 of 11 activities that affect ground-water quality but which are not currently (1986) controlled.

Four Underground Injection Control Program (UIC) Class I wells (U.S. Environmental Protection Agency, 1984) inject nonhazardous fluids associated with carbon-dioxide production beneath aquifers used as sources of drinking water (see fig. 3*A*.) Nearly 1,000 brine-disposal wells not shown in figure 3*A* also are associated with oil and gas production (UIC Class II wells). Improper construction of oil and gas wells or corrosion of the well casing that allowed poor-quality deep ground water to migrate into freshwater aquifers may have been the cause of taste, odor, and color characteristics noted in water from a few private wells in Boulder County in 1984. Abandoned exploratory oil and gas wells also may provide hydraulic conduits for interaquifer movement of water or for discharge of ground water at the land surface where it could contaminate surface water.

Urbanization

From 1950 to 1980, the rural population in Colorado increased from 493,771 to 560,095, and the urban population increased from 831,318 to 2,329,869; 90.2 percent of the State's urban population lives along the Front Range from Fort Collins on the north to Pueblo on the south (fig. 1*B*). Within the urbanized areas, sources of contamination may include septic-disposal systems, leaking lagoons used for sludge disposal, accidental spills, leaking underground tanks used for storage of petroleum products, and the approximately 10,000 tons of sand and salt used annually for deicing roads in the State.

The use of septic disposal systems has resulted in biological contamination of private well-water supplies. Thousands of wells in Colorado reportedly are known to be or are suspected of being contaminated by septic systems. Shallow, fractured, crystalline-rock aquifers (not shown in fig. 2*A*) are particularly susceptible. Analyses of about 800 water samples from wells and springs in the mountainous part of Jefferson County indicated that the national drinking-water standard for coliform bacteria (an indicator of biological contamination) was exceeded in 20 percent of the samples, and the standard for dissolved nitrate was exceeded in 5 percent of the samples (Hofstra and Hall, 1975). Public-supply pumpage has induced recharge of nitrogen-containing sewage effluent from Fountain Creek into an alluvial aquifer (fig. 2*A*, aquifer 3) (Edelmann and Cain, 1985). As a result, median concentrations of nitrate in water from the aquifer have increased from less than 3 to 6 mg/L during the last 20 to 30 years, and some wells have been removed from production because of concentrations larger than specified in the national drinking-water standard. Water from 11 of 20 wells along Fountain Creek that were sampled in 1984 contained volatile organic compounds, including chloroform, 1,1,1-trichloroethane, and trichloroethylene (Cain and Edelmann, 1987). These compounds, which commonly are present in sewage effluent, are used as industrial solvents, dry-cleaning fluids, and septic-tank cleaners. Along the South Platte alluvial aquifer (fig. 2*A*, aquifer 1), 11 public-supply systems exceeded the drinking-water standard for nitrate, the sources of which may be agricultural as well as urban.

Agriculture

Irrigation practices affect the dissolved-solids concentrations in water from the South Platte alluvial aquifer, the Arkansas alluvial aquifer, the San Luis Valley aquifer system, and the High Plains aquifer. Evapotranspiration consumes water but leaves the salts. Water use and reuse have resulted in dissolved-solids concentrations increasing downgradient. This trend is shown in figure 4 for the Arkansas alluvial aquifer. Siebenthal (1910) reported that irrigation in the San Luis Valley resulted in alkali accumulation in the soil and the abandonment of some cultivated land around Mosca and Hooper (Alamosa County). Part of the abandoned land subsequently was reclaimed by soil drainage (Powell, 1958). In the High Plains, ground water along the valleys of the Arikaree and South Fork Republican Rivers, where depth to water generally is less than 20 feet and irrigated agriculture has been practiced since before 1950, has a larger dissolved-solids concentration than ground water in adjacent areas where depths to water are greater and irrigation has been practiced for a shorter time.

Nitrates may reach the ground water as leachate from animal wastes or commercial fertilizers. Irrigated agriculture along Black Squirrel Creek may have contributed to increased concentrations of dissolved nitrate in the alluvial aquifer (fig. 2*A*, aquifer 4) by providing infiltrating water that can transport these constituents. Dissolved nitrate concentrations are larger than 5 mg/L in areas that have been farmed for many years. In the unconfined aquifer of the San Luis Valley aquifer system (fig. 2*A*, aquifer 6), concentrations of nitrate exceed the 10-mg/L national drinking-water standard in the irrigated area northwest of Alamosa (Edelmann and Buckles, 1984). In the High Plains aquifer (fig. 2*A*, aquifer 5), nitrate concentrations exceed the specified 10 mg/L in a few locations in Kiowa and Cheyenne Counties.

In addition to pesticides commonly used in irrigated agriculture, ethylene dibromide, which is used on forested areas to control the Mountain Pine Beetle, might be a potential source of ground-water contamination. However, analyses for pesticides in ground water have been insufficient to permit any conclusions about pesticide contaminations.

POTENTIAL FOR WATER-QUALITY CHANGES

The alluvial aquifers of the South Platte and the Arkansas River valleys, the unconfined aquifer in the San Luis Valley aquifer system, and, to a lesser extent, the High Plains aquifer are susceptible to contamination because of shallow water levels and locally permeable soils. Conditions such as these increase the likelihood that contaminants at the land surface may reach the ground-water systems. These aquifers also are susceptible to contamination because the aquifers are hydraulically connected with streams that may transport contaminants or that may be used for disposal of wastewater. Long-term increases in dissolved-solids concentrations may occur as a result of leaching of soils by irrigation return flow and evapotranspiration from the water table. Also, expected urbanization in these areas may result in increased quantities of wastewater discharged to streams and in changes in water use from irrigated agriculture to public-water supply.

The practice of applying fertilizers or insecticides directly with the irrigation water by linking a storage tank to the well (chemigation) could permit the introduction of a large quantity of undiluted insecticide or nitrogen fertilizer directly into the aquifer through a well not equipped with a backflow-prevention device. In 1987, the Colorado Chemigation Act (C.R.S. 35–11–101 to 116) gave the Colorado Department of Agriculture the responsibility to administer a permit program for chemigation practiced on or after January 1, 1990.

Future water-quality changes in the Denver Basin aquifer system can be expected near the margins of the bedrock aquifers. In the deeper parts of the system, water-quality degradation may occur as hydraulic heads decline, but the effects are expected to be less severe than near the margins of the aquifers. Hydraulic-head declines in the bedrock aquifers may expand the area in which ground water, and any contaminants it contains, flows downward from alluvial aquifers into the bedrock aquifers. However, migration to deeper parts of the aquifer system probably will be slow.

The oil-shale resource in the Piceance basin aquifer system is enormous. Development of this resource in the Piceance basin aquifer system may result in increased concentrations of dissolved solids, sodium, alkalinity, fluoride, boron, lithium, potassium, sulfate, and organic substances in the near-surface ground water and in streamflow (Tobin and others, 1985).

The Leadville Limestone aquifer is susceptible to contamination owing to its shallow recharge area and relatively rapid ground-water movement. The aquifer contributes substantial quantities of water to streams, providing a pathway for ground-water contaminants to enter surface water. Water from the Leadville Limestone currently (1986) is not being developed for energy-related industry and expanding recreational communities but has potential for such future use. Such use could have major adverse effects on the water quality.

GROUND-WATER-QUALITY MANAGEMENT

On July 15, 1985, Governor Richard Lamm issued Executive Order No. D0049 85, relative to ground-water protection. The order (1) declared a statewide goal to ". . . provide maximum beneficial use of ground-water resources . . . by preventing or controlling those activities which have the potential to impair existing or future beneficial uses . . . or to adversely affect the public health"; (2) directed all State agencies to strive to achieve that goal; (3) gave the Colorado Department of Health primary responsibility for coordinating efforts within the State for protection of ground-water quality; and (4) directed the 14 agencies that deal with ground-water issues to sign a "Memorandum of Agreement for the Protection of the Quality of Groundwater Resources of the State."

The Colorado Department of Health is establishing a prevention-oriented, ground-water-protection program under the Colorado Water Quality Control Act. The initial phase established standards for beneficial uses statewide. For each beneficial use, a list of contaminants and concentrations that could impair the use was adopted. The Colorado Water Quality Control Commission, a governor-appointed body to administer the Colorado Water Quality Act, has adopted the standards (Colorado Water Quality Control Commission, 1987). Supplemental standards may be adopted in the future. The Commission has received proposals to adopt standards for organic compounds and radioactive materials that would apply irrespective of use classification and to adopt standards specific to the area near the Rocky Mountain Arsenal. Standards will not be enforceable until control regulations are adopted. The second phase includes adopting control regulations for facilities or activities that are not regulated with respect to ground water.

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Aquifer testing in the Redstone 21-9 geothermal well at Glenwood Springs, Colo., November 1984. Tera Therma Inc. participated with the U.S. Geological Survey, Wright Water Engineers, and the U.S. Bureau of Reclamation in conducting the test. The test was conducted to analyze the hydraulic properties of the Leadville Limestone and the Dyer Dolomite, to determine the degree of interconnection between these aquifers and the overlying alluvium, and to determine the effects of discharge of water through the wells on the nearby springs. During the 4-day test, the discharge of the well decreased from 2,300 to 1,740 gallons per minute and the temperature of the water ranged from 45 to 49° C. (Photograph by Arthur Geldon, U.S. Geological Survey.)

Prepared by Glenn A. Hearne, Jaye Lindner-Lunsford, Doug Cain, Kenneth R. Watts, Stanley G. Robson, Robert L. Tobin, Ralph W. Teller, and Paul A. Schneider, Jr., U.S. Geological Survey, and Mary J. Gearhart, Colorado Department of Health, Water Quality Control Division, Groundwater Unit

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CONNECTICUT
Ground-Water Quality

Ground water is a major source of supply in Connecticut. Annual withdrawals total about 150 Mgal/d (million gallons per day) (U.S. Geological Survey, 1985, p. 161), and public-supply and private wells provide drinking water to one-third of the State's population (fig. 1). Almost all of the 1,250 public-supply wells currently meet water-quality standards established by the Connecticut Department of Health Services (1985), and ground water beneath more than 90 percent of the land in the State is considered to be suitable for drinking without treatment (Connecticut Department of Environmental Protection, 1986, p. 34).

U.S. Geological Survey data indicated that most ground water in Connecticut is of the calcium-bicarbonate type, with dissolved-solids concentrations being small (fig. 2)—median concentrations for all major aquifers are less than 250 mg/L (milligrams per liter). A few naturally occurring constituents may be present in sufficiently large concentrations to affect the potability of the water and its use for some industrial purposes. Concentrations of iron and (or) manganese larger than 300 and 50 μg/L (micrograms per liter), respectively, are common in all major aquifers, and water from both carbonate- and sedimentary-rock aquifers is commonly hard to very hard (more than 120 mg/L as $CaC0_3$). Large concentrations of sulfate (greater than 250 mg/L), chloride (greater than 250 mg/L), and sodium (greater than 20 mg/L), occur locally in the sedimentary-rock aquifer.

Connecticut's major aquifers, (fig. 2), described in the 1984 National Water Summary (U.S. Geological Survey, 1985, p. 161–166), are shallow and susceptible to contamination. Stratified-drift aquifers are more susceptable to contamination than are bedrock aquifers.

The urbanized and industrialized nature of much of Connecticut has resulted in numerous incidences of ground-water contamination. The most common causes are application of pesticides, improper handling and disposal of solvents, leachate from solid-waste disposal sites, leakage from petroleum storage tanks, and improper storage of road salt. These causes account for 882 of the 928 public- and private-well contamination incidences that have affected about 150,000 people since about 1979 (Connecticut Department of Environmental Protection, 1986, p. 35). The most widespread contamination resulted from the use of the pesticide ethylene dibromide (EDB) in the tobacco-growing areas of north-central Connecticut.

Connecticut contains 70 sites that require monitoring of ground-water quality under the Federal Resource and Conservation Recovery Act (RCRA) and 7 sites that are included on the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986a) under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). The State also monitors ground-water quality or supervises such monitoring at more than 80 additional sites where wastes are disposed of, or where discharges to ground water are permitted. Some impairment of ground-water quality has been detected at almost all monitored sites (E.B. Patton, Connecticut Department of Environmental Protection, oral commun., 1986).

Incidences of ground-water contamination detected by State and local agencies increased significantly over the last decade largely because of more comprehensive monitoring and analyses. Practices such as burial of fuel storage tanks and improper waste disposal, the prospect of continued urban growth, the potential for accidental spills of chemicals, the likely strengthening of State drinking-water standards, and the hydrogeologic characteristics of major aquifers suggest that ground-water contamination will continue to be a problem in Connecticut. Furthermore, ground water and surface water are so interrelated in Connecticut that their quality cannot be managed separately. Yields of large public-supply and industrial wells commonly depend on induced recharge from surface-water bodies. Conversely, ground water under natural conditions discharges mainly to streams, lakes, and estuaries. State water-quality management efforts are focused on conjunctive management of ground water and surface water within the framework of major river basins.

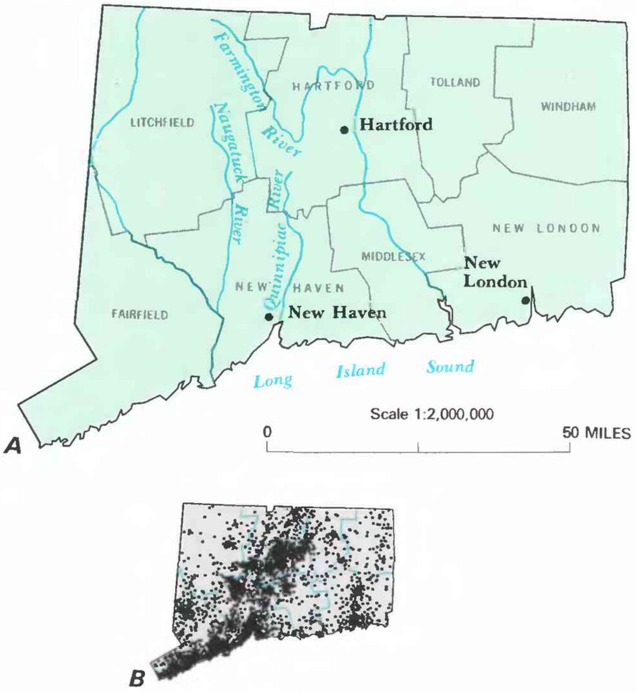

Figure 1. Selected geographic features and 1985 population distribution in Connecticut. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Connecticut has two types of aquifers (fig. 2*A*)—stratified-drift aquifers composed of unconsolidated sand and gravel of glacial origin, and consolidated bedrock aquifers that are differentiated into sedimentary-, crystalline- (noncarbonate), and carbonate-rock aquifers (U.S. Geological Survey, 1985, p. 161). Stratified-drift aquifers, although unevenly distributed within the State, are the most productive. They are the primary source of ground water for public supply and large industrial or commercial uses. Bedrock aquifers underlie the entire State and are the principal source of water for self-supplied domestic use. The typical relationship between stratified-drift and bedrock aquifers is show in figure 2*B*.

Most of the estimated 225,000 wells in Connecticut tap the upper part of the saturated zone (within 300 feet of land surface) and produce water that may have been in the aquifer only a few months to a few decades. The quality of this water in each major aquifer is generally good to excellent and suitable for most uses. Its chemical composition resembles precipitation that has been slightly altered by contact with aquifer materials. Limited data are available from deeper wells. Therefore, the quality of ground water at depths greater than 300 feet is largely unknown.

BACKGROUND WATER QUALITY

Selected water-quality variables in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) for 1953–85 have been statistically summarized in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen,), sulfate, and iron analyses of water samples and show the variability of the chemical quality of water from the four principal aquifers in Connecticut. Percentiles of these variables are compared to national standards that specify the maximum concentration or level in a drinking-water supply as established by the U. S. Environmental Protection Agency (1986 b,c). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking water standards include maximum concentra-

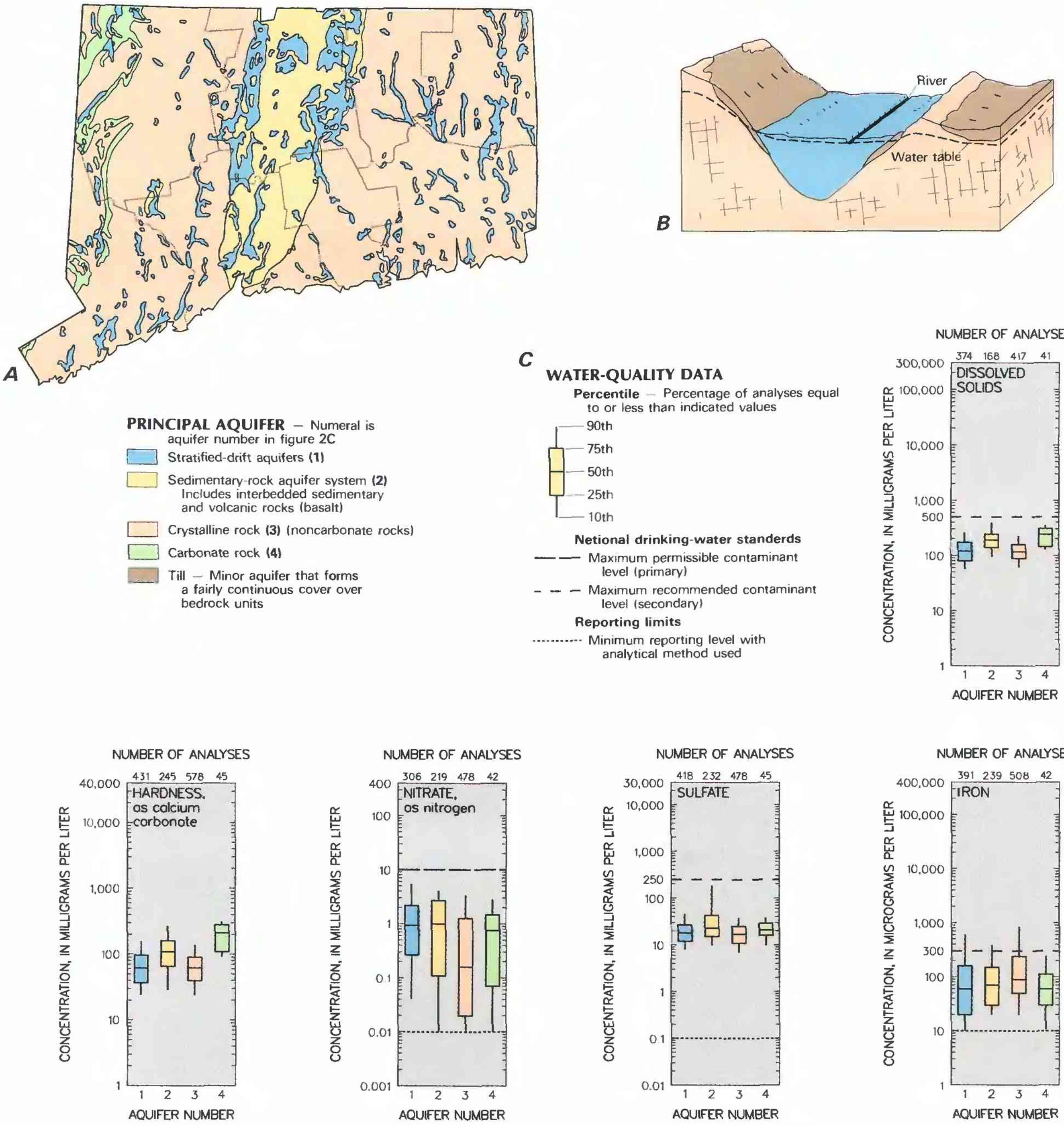

Figure 2. Principal aquifers and related water-quality data in Connecticut. *A*, Principal aquifers. *B*, Generalized block diagram. *C*, Selected water-quality constituents and properties, as of 1953-85. (Sources: *A*, Meade, 1978. *B*, Mazzaferro and others, 1979. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 b,c.).

tions of 500 mg/L disssolved solids, 250 mg/L sulfate, and 300 μg/L iron.

The water-quality data were interpreted without considering differences in hydrogeologic setting, well construction, or sampling methods. Data from wells known to be affected by point sources of contamination or saltwater intrusion were excluded. The remaining analyses are believed to represent natural ground-water quality, but a few may be affected by nonpoint sources of contamination. When more than one analysis of water from a well was available, the median concentration of a constituent was used to calculate the summary statistics for the aquifer.

Dissolved Solids

The median concentration of dissolved solids in water from all four aquifers (fig. 2*C*) is smaller than 250 mg/L, which is considerably less than the 500-mg/L standard for potable water supplies. The water from the carbonate-rock aquifer has the largest median dissolved-solids concentration (240 mg/L), but no samples from this aquifer exceeded 500 mg/L. Fewer than 1 percent of the wells in the stratified-drift and crystalline-rock aquifers produced water with more than 500 mg/L dissolved solids. The sedimentary-rock aquifer, however, yielded water with more than 500 mg/L dissolved solids in about 8 percent of the sampled wells, and con-

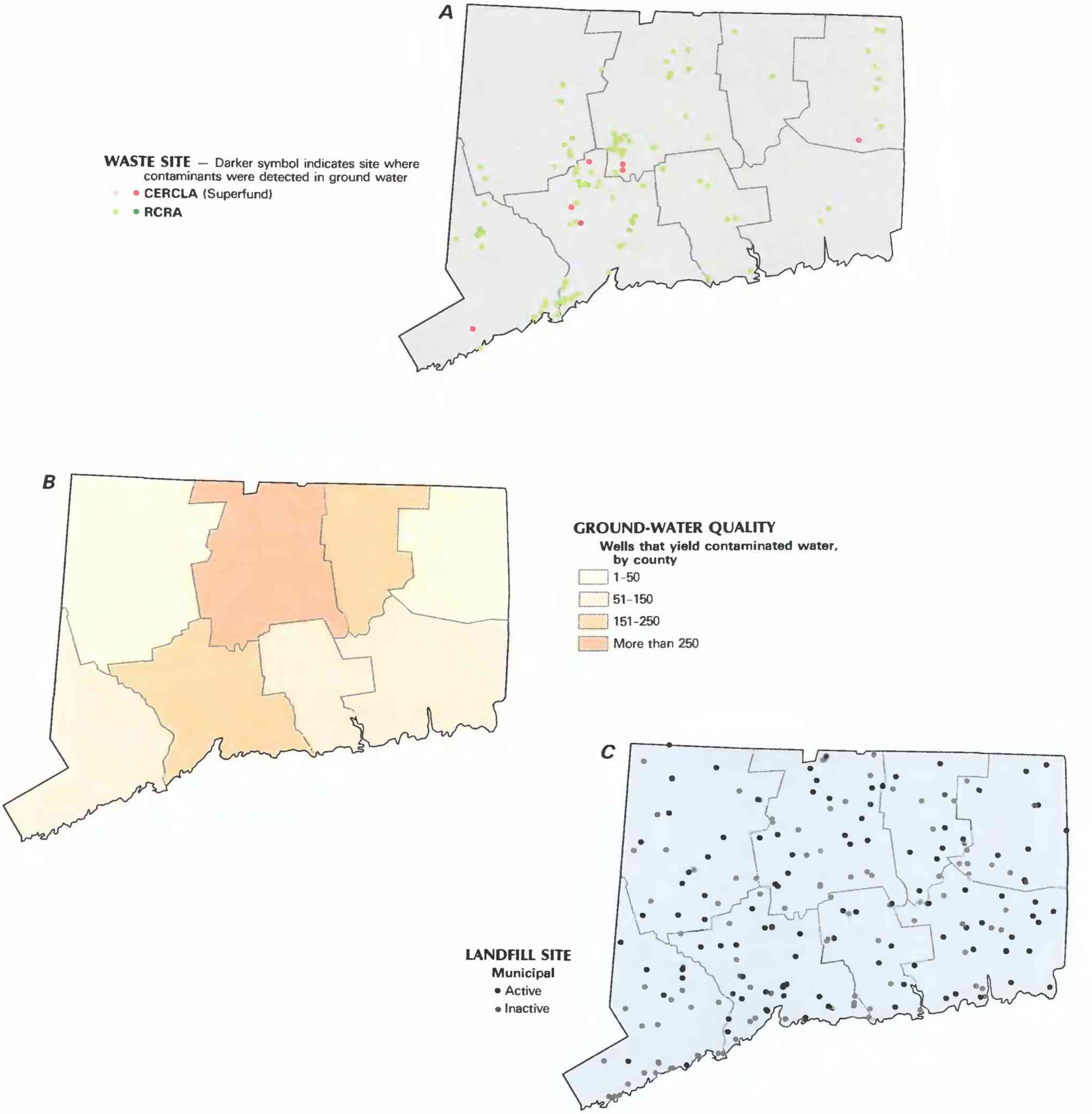

Figure 3. **Selected waste sites and ground-water-quality information in Connecticut.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of January 1987; and Resource Conservation and Recovery Act (RCRA) sites, as of January 1987. *B*, Distribution of wells that yield contaminated water, as of April 1986. *C*, Municipal landfills, as of August 1986. (Sources: *A*, *B*, *C*, Connecticut Department of Environmental Protection files.)

centrations as large as 3,100 mg/L have been reported (Randall, 1964, p. 97).

Large dissolved-solids concentrations also occur locally in some aquifers near the coast. Mazzaferro and others (1979, p. 69) report dissolved-solids concentrations as large as 16,000 mg/L resulting from saltwater intrusion into the sedimentary-rock aquifer near New Haven.

Sulfate

The large dissolved-solids concentrations in water from the sedimentary-rock aquifer primarily result from large sulfate concentrations. The median sulfate concentration of water from the sedimentary-rock aquifer (23 mg/L) is similar to that of the other aquifers. However, in 7 percent of the samples, concentrations ranged from 250 mg/L (the secondary drinking water standard) to as large as 1,600 mg/L. The source of sulfate is thought to be the solution of gypsum (Ryder and others, 1981, p. 62), which is locally abundant (Hubert and others, 1978, p. 25).

Hardness

Calcium and magnesium, which contribute to the hardness of water, are two principal elements that compose the carbonate-rock aquifer. Consequently, water from this aquifer has the largest median hardness (210 mg/L), and nearly 70 percent of the water samples are classified as hard to very hard. About 40 percent of the wells in the sedimentary-rock aquifer yield hard to very hard water, whereas only 15 percent of the wells in the stratified-drift and crystalline-bedrock aquifers produce water of similar hardness.

Nitrate, Chloride, and Sodium

Median nitrate (as nitrogen) concentrations in ground water are small, 1.0 mg/L or less in all aquifers, and only 1 percent of all wells produce water that contains more than 10 mg/L. In north-central Connecticut, Ryder and others (1981, p.63) found the largest nitrate concentrations in the upper 75 feet of stratified-drift aquifers. Median concentrations of chloride and sodium (not shown in fig. 2*C*) are also small, less than 12 mg/L and 10 mg/L, respectively, in all aquifers. However, concentrations as large as 3,000 mg/L of chloride and 410 mg/L of sodium have been measured in water samples from the sedimentary-rock aquifer. Sodium concentrations exceeded the State's drinking-water standard of 20 mg/L (Connecticut Department of Health Services, 1985) in about 12 percent of the water samples from all aquifers.

Iron and Manganese

Large concentrations of iron (as large as 40,000 μg/L) and manganese (as large as 14,000 μg/L) are a common natural ground-water-quality problem in Connecticut. Concentrations of iron and manganese greater than 300 μg/L and 50 μg/L, respectively, may impair the taste of water and stain plumbing fixtures, glassware, and laundry. Although median concentrations of iron (fig. 2*C*) and manganese (not shown in fig. 2*C*) are significantly smaller than these levels in all four aquifers (90 μg/L or less, iron; 24 μg/L or less, manganese), about 17 percent of all samples exceeded the recommended standard for one or both constituents. Large concentrations of iron most commonly occur in the crystalline-rock aquifer, whereas large manganese concentrations are more common in the stratified-drift aquifers.

Radionuclides

Large concentrations of two naturally occurring radionuclides, radon and radium, have been discovered recently in ground water in some parts of the State (Connecticut Department of Health Services, written commun., 1986). Radon concentrations from 100 to 89,400 pCi/L (picocuries per liter) have been measured during reconnaissance sampling of wells in parts of the crystalline-rock aquifer consisting of high-grade metamorphic rocks of granitic composition. Such rocks are likely sources of radon. Although the median radon concentration is smaller than 5,000 pCi/L, 25 percent of the 63 samples exceeded 10,000 pCi/L. Additional ground-water samples in other rock units presently are being analyzed for radon by the Connecticut Department of Health Services (DOHS). Radium concentrations in 5 of 115 samples collected from community-supply wells during 1979 exceeded the primary drinking-water standard of 5 pCi/L.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has been impaired in some parts of the State and has improved in other parts. The impairment in water quality is primarily because of waste disposal, pesticide application, leaks and spills of fuels and industrial solvents, and storage of road salt. Contaminants generally have been transported through the unsaturated zone to underlying aquifers, although some have been emplaced below the water table or have entered the aquifer by induced infiltration of surface water. Generally, contamination is restricted to an area within a few hundred to a few thousand feet of the source, as well as to shallow depths, because of the limited extent of most ground-water flow systems and the placement of many waste-disposal facilities near areas of ground-water discharge. Where ground-water quality has improved, it is primarily because of improvements in waste-disposal, agricultural, and industrial practices; dilution or natural degradation of contaminants; discharge of contaminated ground water; and decrease or elimination of pumping.

Presently (1986) ground water beneath about 8 percent of the State is known or suspected of being affected by pollution (Connecticut Department of Environmental Protection, 1986, p. 34). The contamination that has occurred can be attributed largely to waste disposal, agriculture, urbanization, and induced recharge.

Waste Disposal

There are 104 RCRA sites, 7 CERCLA sites and 216 known active and inactive municipal mixed-waste landfills in Connecticut (fig. 3). Twenty-six RCRA sites have been cleaned up but are still subject to post-closure permit requirements. The State also contains numerous other waste-disposal facilities not shown in figure 3, including 3 hazardous-waste sites at the U. S. Naval base in New London, an estimated 1,000 or more industrial waste-disposal sites, and more than 350,000 private, domestic sewage-disposal systems. The three hazardous-waste sites at the U. S. Naval base were identified by the U. S. Department of Defense as part of their Installation Restoration Program (IRP) as having potential for contamination (U. S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S Environmental Protection Agency (EPA) Superfund Program under CERCLA. Other known waste-disposal sites, excluding domestic sewage-disposal systems, have been inventoried by the Connecticut Department of Environmental Protection (DEP). Although all parts of the State contain such sites, they are most common in urbanized and densely populated areas (see figs. 1*B* and 3).

The total effect of waste disposal on ground-water quality is unknown. The DEP has detected contamination in the shallow part of the saturated zone at all CERCLA sites, as well as most RCRA sites and mixed-waste landfills that are monitored (E. B. Patton, Connecticut Department of Environmental Protection, oral commun., 1986). Data on specific RCRA sites and landfills where contamination of ground water has been detected could not be compiled in time for this report, and the information is not shown in figure 3. Leachate from landfills has contaminated 139 wells since about 1979 (Connecticut Department of Environmental Protection, 1986,

p. 35), and a single landfill in southern Connecticut has contaminated several hundred million gallons of ground water (Miller and others, 1974, p. 209).

Improper disposal of industrial solvents, mainly organohalides such as trichloroethylene, is another major cause of contamination. More than 44 public-supply wells have been contaminated by solvents to date (Connecticut Department of Environmental Protection, 1986, p. 35), including at least 20 in the Quinnipiac and Farmington River basins (Connecticut Department of Environmental Protection, 1985a, p. 7; 1985b, p. 10). Domestic and industrial wells in several towns also have been contaminated by solvents. Other industrial-waste contaminants include trace metals, phenol, cyanide, and organic compounds other than solvents (Handman and others, 1979, p. 44–45).

Agriculture

Before 1983 few incidences of ground-water contamination were attributable to agricultural practices. Ground water in some farming areas had nitrate concentrations larger than 10 mg/L as a result of application or storage of chemical fertilizers and manures (Cushman and others, 1964, p. H 66; Connecticut Department of Health Services, written commun., 1976; Handman and others, 1979, p. 48). Few instances of pesticide contamination of ground water had been reported.

During the fall of 1983, contamination of ground water by EDB—a soil fumigant used for tobacco—was detected and subsequently found to affect at least 50 square miles in north-central Connecticut. Through August 1986, water samples from 268 private and 54 public wells have had EDB concentrations that equaled or exceeded the drinking-water standard of 0.10 μg/L established for Connecticut (S. J. Klobukowski, Connecticut Department of Health Services, oral commun., 1986), making this the most significant ground-water-quality problem in the State.

An investigation recently sponsored by the State of the occurrence of pesticides in public-supply wells detected the soil fumigant 1,2-dichloropropane in a well field in south-central Connecticut. No other chlorinated or organophosphate pesticides were detected in samples from 25 utilities supplying an estimated 60 percent of the ground water withdrawn for public supply (Frink and Hankin, 1986, p. 4).

Urbanization

Many areas in Connecticut are extensively urbanized, particularly the coastal parts of Fairfield and New Haven Counties, the Connecticut Valley lowland that extends from New Haven to Hartford, the Naugatuck River valley, and the New London area (see fig. 1*A*). Ground-water contamination in urban areas may be attributed to a readily identifiable cause, such as leakage of fuel from buried tanks, or to less identifiable cumulative effects of human activities. Major causes of contamination in urban parts of Connecticut include leakage from storage tanks containing fuels and other chemicals, accidental spills of fuels and chemicals, uncovered storage of road salt, and use of pesticides.

There are tens of thousands of buried storage tanks, mainly containing fuel oil or gasoline, in the State. Many have leaked because of deterioration, accidental rupture, or improper installation, and a number of incidents of ground-water contamination have been cited (Connecticut Department of Environmental Protection, 1986, p. 35–36). Petroleum and chemical spills are investigated regularly by the DEP. From July 1977 to June 1982, DEP reported spills totaling about 2.7 million gallons (Connecticut Department of Environmental Protection, 1983, p. 73). An estimated 1.8 million gallons were spilled on land, and, where there was neither quick response nor effective clean up, it is likely that a substantial amount reached the saturated zone.

In addition to contamination from readily identifiable sources, recent studies of ground-water quality in two stratified-drift aquifers indicate more subtle changes related to land use. Preliminary findings by Grady and Weaver (1987) indicate that (1) ground water in agricultural areas has the largest median concentrations of sulfate and total ammonia plus organic nitrogen, (2) ground water beneath residential areas contains larger median concentrations of several inorganic constituents, including sodium, chloride, dissolved solids, ammonia, nitrate plus nitrite (as nitrogen), detergents, and nickel, than undeveloped and agricultural areas, and (3) ground water in industrial/commercial areas has the largest median specific conductance, pH, carbon dioxide, calcium, magnesium, chloride, bicarbonate, dissolved solids, boron, and strontium concentrations. These conclusions are tentative and will be evaluated further by the U.S. Geological Survey in ongoing studies relating ground-water quality in stratified-drift aquifers to land use.

Induced Recharge

Most of the stratified-drift aquifers in Connecticut are hydraulically connected to streams, lakes, and estuaries (including Long Island Sound). Where these surface-water bodies are contaminated or salty, intense pumping has resulted in deterioration of ground-water quality. Induced recharge of surface water has been cited as the cause of water contamination in stratified-drift aquifers adjacent to the Naugatuck River (Wilson and others, 1974, p. 63–64). Changes in ground-water quality in aquifers adjacent to the Quinnipiac River also have been attributed to induced recharge (Mazzaferro and others, 1979, p. 64 and 69).

Induced recharge of saline water is a problem in coastal areas. About 100 private wells and 10 public-supply wells have been affected in the Old Lyme area of southwestern New London County (Connecticut Department of Health Services, written commun., 1986), and historical incidences have been described in New Haven and other coastal areas (Brown, 1928; Thomas and others, 1968, p. 72; Ryder and others, 1970, p. 44; Mazzaferro and others, 1979, p. 69).

POTENTIAL FOR WATER-QUALITY CHANGES

Future changes in ground-water quality are uncertain as improvements resulting from more comprehensive water-quality management may, in the aggregate, be greater or lesser than the negative effects resulting from increased population and urbanization. Stratified-drift aquifers are most susceptible to contamination and are likely to be most affected in the future. Land-use decisions will be an important factor in determining future ground-water quality in these aquifers.

State and Federal legislation and regulations have improved management of many sources of pollution, such as solid-waste disposal, underground storage of fuel and chemicals, and industrial use and disposal of toxic and hazardous materials. For example, because of State policy and regulations, few additional landfills are expected, and more communities are turning to resource-recovery methods to solve solid-waste disposal problems. Replacement of old underground storage tanks with modern corrosion-resistant tanks, equipped with leak-detection systems, should alleviate one of the more pervasive sources of ground-water contamination. Management of most hazardous materials generated, stored, treated, or disposed of in the State will decrease the potential for these materials to enter the environment and migrate into aquifers. These factors, together with recent trends toward improved quality of surface water (Connecticut Department of Environmental Protection, 1986), less agricultural acreage, and more stringent controls on waste disposal and land use near public-supply wells have and will continue to improve ground-water quality in some parts of Connecticut.

Other factors, however, indicate that the potential for additional incidences of ground-water contamination is not likely to diminish soon. Connecticut's population increased by 23 percent between 1960 and 1980 (U.S. Bureau of the Census, 1981). Industrial growth, as measured by the number of operating manufacturing establishments, increased by 15 percent between 1967 and 1982 (U.S. Bureau of the Census, 1984). This growth has resulted in advancing urbanization around the principal cities and towns within Hartford, Fairfield, Middlesex, New Haven, and New London Counties. New residential, commercial, and industrial development in rural parts of the State has occurred at the expense of agricultural and undeveloped lands as the total area of farmland decreased by one-half between 1959 and 1982 (U.S. Bureau of the Census, 1985). While farmland is decreasing, the acreage on which commercial fertilizers and pesticides are applied is increasing (U.S. Bureau of the Census, 1985). Conversion of agricultural or undeveloped lands to golf courses, parks, and athletic fields commonly results in additional applications of agricultural chemicals. Increased residential development, with 89 percent of rural and 22 percent of urban households using onsite septic systems (Handman and others, 1979, p. 26), can affect ground-water quality through septic effluents, salting of high-density residential road and sidewalk networks, and application of lawn and garden chemicals.

Expanding industrial and commercial development entails the use and transport of greater volumes of hydrocarbons, industrial chemicals, and other hazardous substances, with proportionately greater opportunities for inadvertent spills, leaks, or discharges of these materials during their storage, handling, and disposal. Over the past 8 years, the number of spills and leaks reported to the DEP has increased from about 600 to over 2,000 (B. D. Coss, Connecticut Department of Environmental Protection, written commun., 1986). This large increase may partly reflect increased compliance with reporting requirements.

Stratified-drift aquifers are the most susceptible to contamination from nonpoint and point sources. The same hydrologic characteristics that cause these aquifers to be favorable sources for large supplies of water, facilitate the entry and migration of contaminants. The combination of relatively large transmissivity, shallow depth to the water table, absence of confining beds, moderate to large hydraulic gradients, thin and pervious soils, the hydraulic connection with surface-water bodies that receive waste discharges, and the generally extensive development of the recharge areas overlying stratified-drift aquifers significantly enhances the potential for their contamination.

Bedrock aquifers are less susceptible to contamination as they are mantled in most areas of the State by unconsolidated deposits of till or stratified drift. However, where bedrock is exposed at the surface or the overlying materials are thin (a common condition in upland areas) contaminants may readily enter along fractures and move rapidly away from their source with little attenuation. The resulting contamination can be difficult to predict or control because knowledge of bedrock flow systems is sparse and such systems commonly are complex.

GROUND-WATER QUALITY MANAGEMENT

Connecticut has a comprehensive program for managing its ground-water resources that originated with passage of the Clean Water Act of 1967 (Connecticut General Statutes, Chap. 446K, Sec. 22a) and the program has been strengthened by subsequent State statutes and Federal clean-water legislation. The program goals are to restore and maintain ground water to a quality consistent with its use for drinking without treatment. Excepted cases are where ground water in a zone of influence of a permitted discharge is suspected of being contaminated and there is no overiding need to improve quality, or the classification goal is GC (areas constituting less than 1 percent of the State that may be suitable for environmentally safe waste disposal).

The DEP, lead agency for ground-water-quality management, administers regulatory programs developed under authority of State and Federal Clean Water Acts (Connecticut General Statutes, Chap. 446K, Sec. 22a and Public Law 92-500 as amended), the Federal Resource Conservation and Recovery Act of 1976 (Public Law 94-580) and Part C (Underground Injection Control Program) of the Safe Drinking Water Act of 1974 (Public Law 93-523 as amended). In 1986, DEP also was designated lead agency for the Wellhead Protection Program authorized by amendment to the Safe Drinking Water Act.

The DOHS implements State and Federal Safe Drinking-Water Act programs for development and enforcement of quality standards for drinking water. DOHS also has responsibility to insure that utilities do adequate planning and facilities construction, and protect public-supply sources.

Connecticut's "Water Quality Standards and Criteria" revised in 1980 (Connecticut Department of Environmental Protection, 1980), establish site-specific water-quality criteria and goals that are the basis of the State's ground-water-quality management program. These criteria and goals, together with the classification system adopted for all ground water in the State, are the bases for the DEP permit-issuance and enforcement policies and determine ground-water-quality management priorities. This overall strategy to protect ground water significantly affected the development of the Federal Ground Water Protection Strategy Program and has been a model for several other states. Because of the broad range of ground-water protection issues and interrelations with surface water, DEP has begun using a basin-planning approach similar to that established by the Federal Clean Water Act to identify specific problems, management priorities, and abatement strategies in different geographic areas.

DEP is required by Connecticut's 1967 Clean Water Act to issue permits for surface-water and ground-water discharges and to take enforcement actions against known or suspected sources of pollution. The permit process for surface-water discharges is coordinated with the National Pollution Discharge Elimination System. The scope of Connecticut's permit program has been expanded since 1967 through subsequent regulatory authorities, while the adoption of quality standards and classifications for ground water provides a strong framework for issuance of permits. The discharge-permit program significantly has improved the State's capability to manage ground-water quality through control of waste placement and treatment, improved construction and maintenance of disposal facilities, and increased monitoring of waste discharges.

Investigations and monitoring of suspected contamination sites are the principal means for detecting contamination. Where responsible parties are identified, enforcement actions to abate or prevent contamination are issued by DEP. Polluters are required to provide alternate sources of drinking water to homes with wells that yield contaminated water. A State grant program provides potable water if the polluter cannot be identified.

State agencies and municipalities have taken other measures to manage ground-water quality. The DEP controls the handling, storage, and disposal of hazardous materials and solid wastes, operates a spill-prevention and response program to minimize contamination from spills and leaks of fuels and chemicals, sets standards for underground tanks, large waste-disposal systems, and road-salt storage and application, and together with DOHS, conducts investigations of known or suspected contamination.

The management of the protection of public-supply sources has high priority. The DOHS has an extensive regulatory program that requires utilities to control land use near public-supply wells, to monitor the quality of water, and to submit long-range plans that will identify aquifers to be protected. Planning has been strengthened by the recently instituted Connecticut Plan for Public Water Supply Coordination—a process to coordinate the planning of public water-supply systems that is overseen by DOHS.

Land use is an important factor in protecting water quality inasmuch as most large withdrawals are from stratified-drift aquifers. The DEP is working directly with municipalities to ensure that future land use is consistent with long-term protection of drinking-water resources and also plans to develop a Wellhead Protection Program under provisions of the Federal Safe Drinking Water Act that will afford further protection to public-supply wells. Several municipalities, under impetus of the State's "208 Program", already have placed controls on land-use activities in areas that recharge stratified-drift aquifers. Presently, the State is moving towards a stronger local/State aquifer-protection program, and DEP is to submit a report to the Legislative Environment Committee in early 1987 on the need for additional controls to improve protection of important stratified-drift aquifers.

The establishment in 1983 of a Diversion Permit Program under authority of the Connecticut Water Policy Diversion Act (Connecticut General Statutes Sec. 22a–365) provides for coordinated management of the State's water resources. The program requires permits for all surface-water diversions and for ground-water withdrawals greater than 50,000 gallons per day. It further requires that ground water and surface water be considered part of a single hydrologic system and that the impacts of diversions and withdrawals on the quantity and quality of water resources be assessed in the context of basin-wide water use and allocation.

Although Connecticut is fortunate in having obtained a large amount of hydrogeologic information for managing ground water during the past 50 years, there are still significant data needs. The least information is on existing water use and future water demands. Information is needed also to define changes in background-water quality, yields of major aquifers and stream-aquifer systems, the effects of induced recharge from waste-receiving streams, the transport of contaminants in aquifers (particularly fractured bedrock aquifers), and the effects of diversions and droughts on surface- and ground-water resources. The adequacy of water-resources information should improve soon through development of water-utility supply plans, the coordinated planning under the Connecticut Plan for Public Water Supply Coordination, the Connecticut Water Use Program conducted in cooperation with the U.S. Geological Survey, and studies of major stratified-drift aquifers by DEP and the U.S. Geological Survey.

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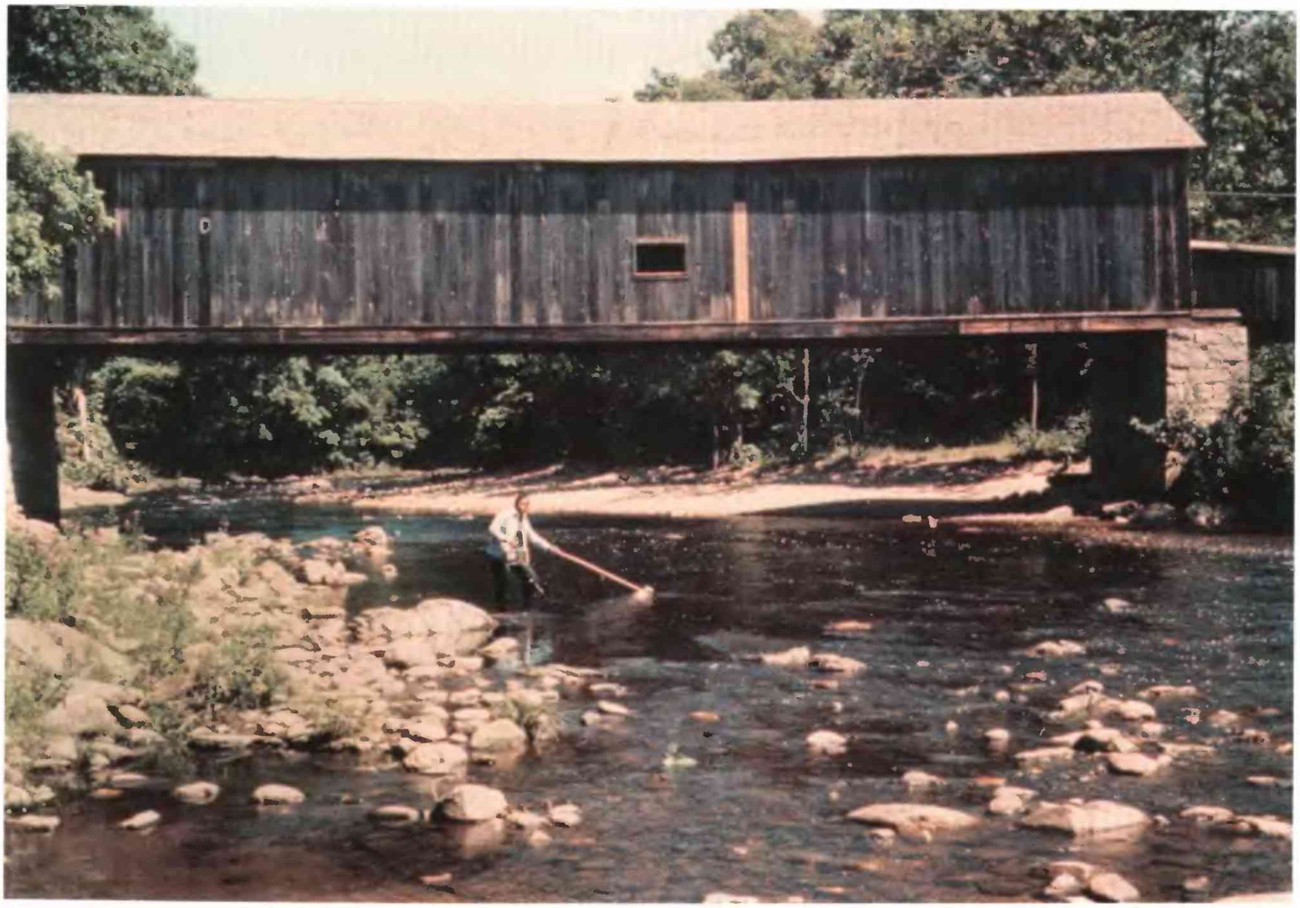

Water-quality measurement being taken on the Salmon River near East Hampton, Conn. during low flow. Natural low flow in streams is sustained by inflow of ground water. Therefore the quality of the water in most streams at low flow can be used as an indicator of the quality of the ground water in the area. (Photograph by U.S. Geological Survey.)

Prepared by Robert L. Melvin, Stephen J. Grady, and Denis F. Healy, U.S. Geological Survey; "Ground-Water Quality Management" section by Fred Banach, Connecticut Department of Environmental Protection, Water Compliance Unit

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DELAWARE
Ground-Water Quality

Sixty-seven percent of the population in Delaware (fig. 1*B*)—about 400,000 people—is served by ground water. The Delaware Department of Natural Resources and Environmental Control reported that ground-water use for public supply in 1982 was 10.2 billion gallons of a total ground-water withdrawal of 22.1 billion gallons. The largest development of ground water is for public and industrial supply in intensely populated areas of New Castle County (fig. 1*A*), where the Potomac aquifer is the primary source.

Ground water is generally of good quality suitable for most uses except in the downdip parts of confined aquifers that contain saline water. Treatment to remove dissolved iron is needed in some parts of the unconfined aquifer, aquifers of the Chesapeake Group, and the Potomac aquifer (fig. 2). Nitrate plus nitrite concentrations commonly are a problem in the unconfined aquifer, principally in Kent and Sussex Counties in areas associated with agriculture and the poultry industry. Septic systems also are a potential source of nitrate. Intrusion of brackish or saline water has occurred in the unconfined aquifer adjacent to Delaware Bay and the Atlantic Ocean. Contamination from waste-disposal practices causes localized problems in the unconfined aquifer and subcrop areas of the Potomac aquifer system. Most of the industrial waste-disposal sites are located in New Castle County along the Delaware River (fig. 3*A*). Contaminants from these sites include iron, manganese, dissolved solids, organic acids, and volatile organic compounds.

Strict controls on waste-disposal practices and implementation of a State ground-water management strategy are intended to minimize contamination problems from newly constructed waste-disposal sites. Remedial action at four hazardous-waste sites has started or is planned under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. One site at one Federal facility was identified, in September 1985, as requiring remedial action in accordance with CERCLA. The State anticipates an increasing problem from deteriorating underground fuel-storage tanks, and has adopted standards that require monitoring around old and new tanks to detect leakage and has initiated cleanups at several sites. Nitrate contamination associated with agriculture and poultry processing will continue to be a problem.

WATER QUALITY IN PRINCIPAL AQUIFERS

Delaware has two principal types of aquifers (fig. 2*A*): the unconsolidated sedimentary deposits of the Coastal Plain that underlie the southern 94 percent of the State; and the crystalline bedrock of the Piedmont, located north of the Fall line, that comprises the remaining 6 percent. About 97 percent of all ground-water withdrawals are from the Coastal Plain aquifers (Delaware Department of Natural Resources and Environmental Control, 1982).

Eight principal Coastal Plain aquifers are used for water supply in Delaware. The aquifers are composed of sand and gravel interbedded with silt and clay. Water quality is generally suitable for most uses. Saline water is present in downdip parts of most confined Coastal Plain aquifers (Cushing and others, 1973). The Potomac and unconfined aquifers are the major water-supply sources in the State and also are the most susceptible to contamination.

BACKGROUND WATER QUALITY

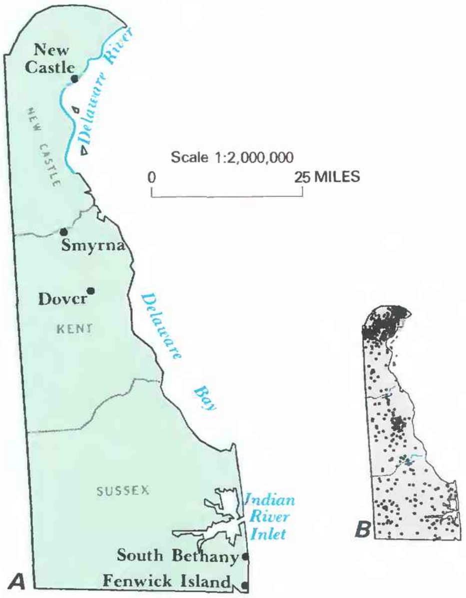

Figure 1. Selected geographic features and 1985 population distribution in Delaware. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) and data from the Delaware Department of Health and Social Services is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate plus nitrite (as nitrogen),chloride and iron analyses of water samples collected from 1956 to 1986 from the principal aquifers in Delaware. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include maximum concentrations of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L (micrograms per liter) iron.

Unconfined Aquifer

The unconfined aquifer (fig. 2*B*) is areally continuous, thickens from north to south beneath the Coastal Plain of Delaware, and serves as a recharge area for underlying aquifers (U.S. Geological Survey, 1985, p. 167). It is the principal source of domestic and some public water supplies in Kent and Sussex counties. The largest use of water from the unconfined aquifer is for crop irrigation from April through October. Withdrawals from the unconfined aquifer for irrigation in Sussex County averaged 9 Mgal/d (million gallons per day) in 1982 (Delaware Department of Natural Resources and Environmental Control, 1982).

Soil permeability and drainage can result in significant effects on water quality in the unconfined aquifer. Sodium and bicar-

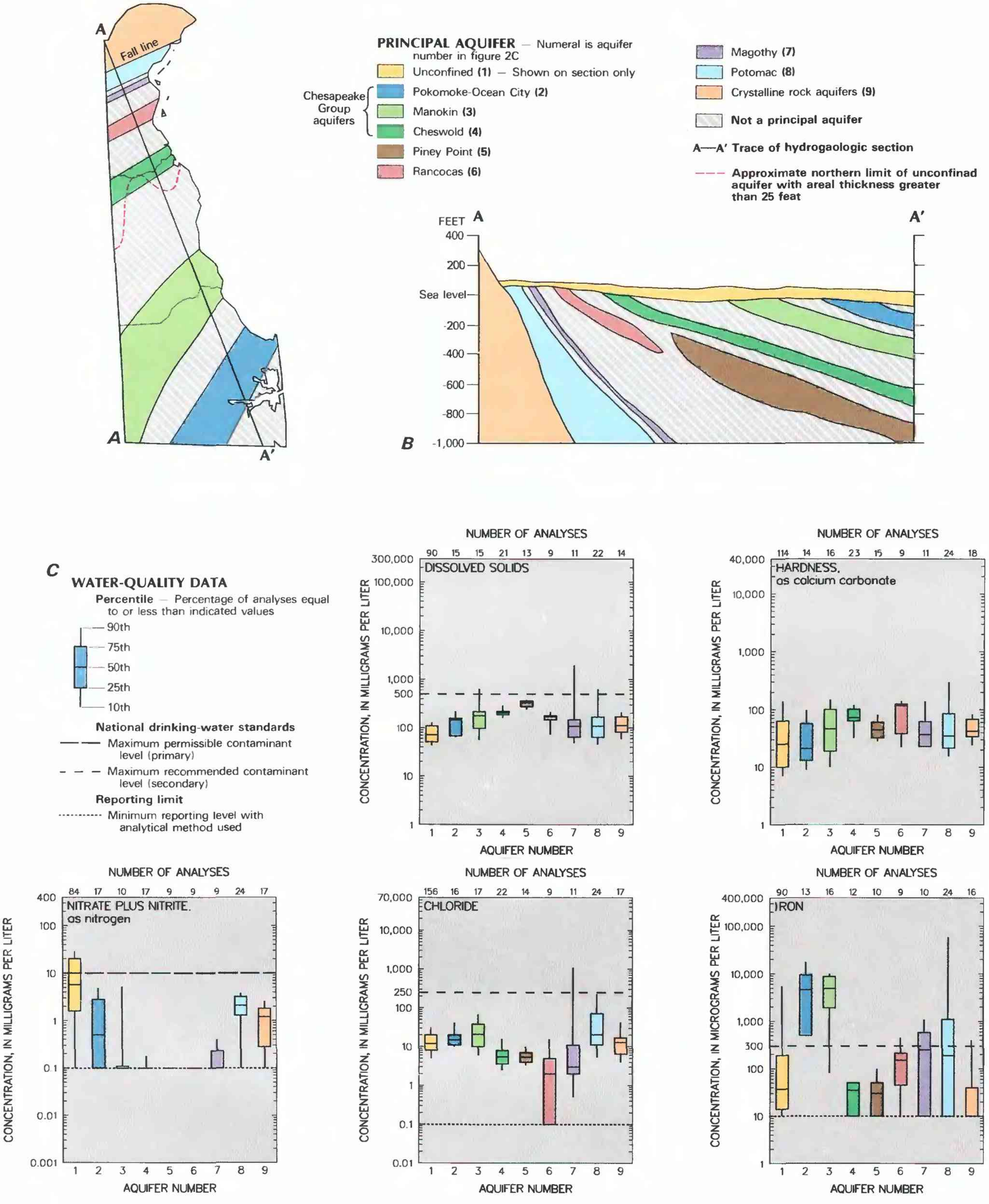

Figure 2. **Principal aquifers and related water-quality data in Delaware.** *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1956-86. (Sources: *A*, *B*, Cushing and others, 1973; Sundstrom and Pickett, 1971; Hodges, 1984. *C*, Analyses compiled from Delaware Department of Health and Social Services, 1986, and U.S. Geological Survey, 1976-86; national drinking-water standards from U.S. Environmental Protection Agency, 1986a, b.)

bonate are the major ions in water under oxidizing conditions that occur beneath well-drained soils (fig. 4*A*). Where soils are poorly drained, reducing conditions prevail, and dissolved iron can be a major ion in the water (fig. 4*B*). Areas where naturally occurring dissolved iron can be a problem are primarily in western Kent County and southeastern Sussex County (fig. 3*B*). Under natural background conditions, dissolved-solids concentrations are about 60 mg/L, nitrate plus nitrite concentrations are smaller than 4 mg/L, and chloride concentrations are about 6 mg/L (Denver, 1986, p. 34).

Chesapeake Group Aquifers

Aquifers of the Chesapeake Group subcrop the unconfined aquifer in Kent and Sussex Counties (U.S. Geological Survey, 1985, p. 168). The Cheswold aquifer is a major source of water supply in the Dover area. The Pocomoke-Ocean City and Manokin aquifers are important sources of withdrawals for industrial and municipal use in Sussex County and supply large seasonal pumpage in the coastal resort areas.

Water in the Cheswold aquifer is moderately hard as a result of dissolution of carbonate (shell) material in the sediments. Nitrate plus nitrite concentrations are virtually undetectable, and chloride concentrations are very small (fig. 2*C*). Iron concentrations in water from the Pocomoke-Ocean City and the Manokin aquifers commonly exceed the 300-μg/L standard for drinking water. Although concentrations of chloride are considerably smaller than 250 mg/L in both aquifers (fig. 2*C*), saltwater intrusion is potentially a problem near the Atlantic Ocean.

Piney Point Aquifer

The Piney Point aquifer is the only completely confined unit in Delaware. It supplies 80 percent of industrial and municipal water used in Kent County (Leahy, 1982, p. 13). A natural ion-exchange process in the sediments (glauconitic greensands) enriches sodium in the water (Spoljaric, 1986). Concentrations of sodium larger than 100 mg/L have been measured. Water of the Piney Point aquifer has the largest average concentration of dissolved solids in the freshwater part of any aquifer utilized in Delaware (fig. 2*C*).

Rancocas and Magothy Aquifers

Southern New Castle County is the principal area of use of the Rancocas and Magothy aquifers. Water of the Rancocas aquifer has the most hardness and least chloride concentration of the aquifers in Delaware (fig. 2*C*). No nitrate plus nitrite was detected in any of the water samples from the Rancocas aquifer. The largest dissolved-solids concentration noted on the 90th-percentile line of the Magothy aquifer (fig. 2*C*) is from a well near Dover, where the aquifer contains brackish water.

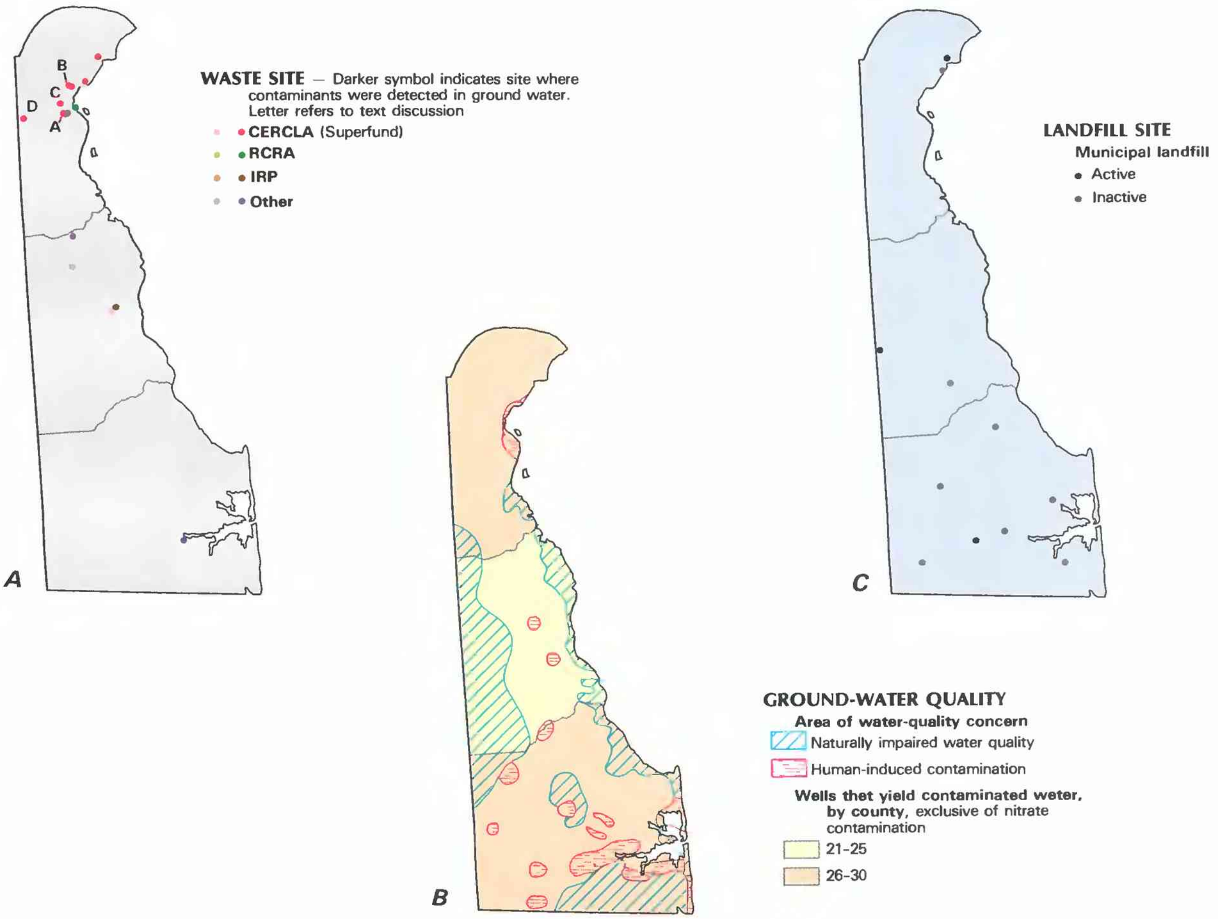

Figure 3. Selected waste sites and ground-water-quality information in Delaware. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of August 1986. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of August 1986. *C*, County landfills, as of August 1986. (Sources: *A*, Augustus Mergenthaler, Delaware Department of Natural Resources and Environmental Control, written commun., 1986. *B*, R.B. Howell, Delaware Department of Health and Social Services, oral commun., 1986; Ritter and Chirnside, 1982; Robertson, 1977. *C*, M.A. Apgar, Delaware Department of Natural Resources and Environmental Control, written commun., 1986.)

Potomac Aquifer

The Potomac aquifer consists of several sandy zones interbedded with clay. The Potomac sands are susceptible to contamination from the surface because the overlying unconfined aquifer is relatively thin. This condition is evidenced by larger nitrate plus nitrite concentrations in the Potomac than in the other confined aquifers (fig. 2*C*). Intrusion of brackish water from the Delaware Bay into the Potomac aquifer has also been documented (Scott Phillips, U.S. Geological Survey, oral commun., 1986). The intruded water is the source of the large chloride concentrations shown in figure 2*C*.

Crystalline Rock Aquifers

The crystalline rock aquifers in the Piedmont of Delaware are used for domestic, commercial, and industrial water supplies in northern New Castle County. The Piedmont bedrock is composed of granodiorite, gabbro, schist, gneiss, and a small area of marble. Little water-quality data are available for these aquifers, and water-quality characteristics shown in figure 2*C* do not include data from wells in marble.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has been affected by municipal and industrial waste-disposal practices, chemical spills, leaking underground storage tanks, agricultural practices, leachate from septic tanks, and saline-water intrusion. Many types of ground-water contamination originate from point sources, such as septic tanks or landfills, that affect the aquifer directly downgradient. Agricultural applications of manure and fertilizer, and saline-water intrusion, affect ground water in extensive areas.

Waste-Disposal Practices

Two sites in Delaware are regulated under the Resource Conservation and Recovery Act (RCRA) of 1976 and contamination has been detected at both; 9 sites are included on and 4 sites are proposed for the National Priorities List (NPL) of CERCLA (fig. 3*A*), including one U.S. Department of Defense (DOD) facility site. The four sites proposed for the NPL are shown as "other sites" in figure 3*A*. Contamination has been detected in ground water at 12 of these 15 sites and 4 of them are known or suspected to have contaminated nearby domestic or public wells.

As of September 1985, 12 hazardous-waste sites at one facility in Delaware have been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 12 sites in the program, 2 contained contaminants but did not present a hazard to the environment. One site at one facility (fig. 3*A*) was considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Most of the industrial disposal or spill sites that have contaminated ground water are located in New Castle County near the Delaware River (fig. 3*A*). Waste substances include volatile organic compounds such as trichloroethylene and benzene, brine sludge containing mercury, heavy metals, and vinyl chloride. In much of this area, the unconfined aquifer is thin and most of the contaminated ground water discharges to saline surface water, thus limiting the extent of the contaminant plumes within the aquifers. Little development of public and domestic water supplies has occurred in the industrialized area, although six shallow domestic wells west of the area have been contaminated by ethylene dichloride and vinyl chloride leached from disposal pits (fig. 3*A*, site A).

Disposal sites located in the sandy recharge area of the Potomac aquifer pose the greatest threat to ground-water quality in central New Castle County because of the large withdrawals from that aquifer system. Leachate from the Army Creek Landfill (fig. 3*A*, site B), used for disposal of municipal and industrial waste from 1960 to 1968, has caused the limitation of withdrawals of water from some nearby public and industrial wells in the Potomac aquifer. Recovery wells installed on the Army Creek site by New Castle County are currently being used to curtail movement of the contaminant plume and to remove contaminants from the aquifer. An alternative involving hydrologic isolation of the landfill is pending formal approval by the EPA. Leachate from the Tybouts Corner Landfill, (fig. 3*A*, site C), which previously accepted county, municipal, and industrial wastes, has contaminated two domestic wells in the Potomac aquifer. Residents in the area of the landfill that could potentially be affected have been connected to a public water system. The EPA has required extensive reconstruction, capping, and drains around the landfills. A contaminant recovery-well system also will be installed downgradient of the landfill based on EPA decision.

Two municipal water supplies have been contaminated with organic chemicals. In the town of New Castle (fig. 1*A*), a shallow infiltration system in the unconfined aquifer was contaminated with a variety of organic chemicals of an undetermined origin. These wells have been abandoned, and the town now withdraws water from the Potomac aquifer. Trichloroethylene was found in the wells used to supply the town of Smyrna (fig. 1*A*). The town installed aeration and carbon filtration to overcome the problem.

The landfills shown in figure 3*C* include only regulated countywide facilities. Previously, domestic solid waste was disposed on a less centralized, local basis, and several additional abandoned landfills are located throughout the State. No known contamination of water supply or domestic wells caused by abandoned landfills in Kent County has occurred, and only two instances of domestic well contamination in Sussex County are known. The landfills are generally located in rural areas. The two regulated landfills in New Castle County are located along the Delaware River and do not threaten water-supply wells.

The Delaware Solid Waste Authority now manages all domestic and industrial nonhazardous solid-waste disposal in the State. New municipal landfills are lined, and ground-water quality is closely monitored. Abandoned landfills that contaminate the ground water generally are unlined and located in abandoned sand and gravel pits. Trash commonly was disposed in pits that intersected the water table. Leachate from the abandoned municipal landfills contains detectable concentrations of organic carcinogens for which no health standards have been established. The most extensive water-quality problem caused by landfill leachate is related to organic decomposition of the trash that produces anaerobic conditions in the ground water and mobilizes iron and manganese.

Underground Fuel-Storage Tanks

State officials are aware of 10 domestic and 5 public-supply wells that have been contaminated by leaking underground fuel-storage tanks. More than 100 instances of leaking tanks have been documented by the presence of fumes in basements and other subsurface structures. The State believes that the potential problems with hydrocarbons are much greater than known because of the large number of aging gasoline tanks located in densely populated areas.

Products leaking from underground storage tanks generally float on top of the water table. Leaks are commonly detected by the presence of benzene, xylene, and toluene in the ground water.

Agricultural Practices

The most widespread land use in the Coastal Plain of Delaware is agriculture. Contamination of the unconfined aquifer by agricultural nutrients, particularly by nitrate, has been documented extensively in areas of crop production (Ritter and Chirnside, 1982; Denver, 1986). Poultry production is a major industry, and large quantities of poultry manure are being stored and spread on fields. Some of the largest nitrate plus nitrite concentrations reported in Delaware were in the unconfined aquifer downgradient from chicken houses (Ritter and Chirnside, 1982, p. 138). Chloride, calcium, magnesium, and potassium concentrations also are increased above background levels in areas affected by agriculture (fig. 4*C*). Insecticide and herbicide use has increased greatly in the last 10 years but no intensive study of their effects on ground water has been conducted.

Most of the known nitrate problems are in Sussex County in areas with well-drained soils where fertilizers leach readily into the aquifer. Several areas of nitrate problems in Kent and Sussex Counties are shown in figure 3*B*. There also is evidence that irrigation promotes nutrient leaching. Nutrients have moved more deeply into the unconfined aquifer in irrigated areas than in nonirrigated areas.

The number of wells and people affected by nitrates has not been documented, and no documented health problems have been associated with large nitrate concentrations in Delaware. In Kent and Sussex Counties, agricultural acreage is increasing, and irrigated acreage has almost doubled from 1974 to 1983 (Ritter and others, 1985). These trends indicate that nutrient contamination in the unconfined aquifer will continue to increase.

Septic Systems

Leachate from domestic septic systems also is a cause of nitrate contamination in the unconfined aquifer. Septic system leachate generally is not a problem on isolated lots in rural areas. It can, however, be a problem in developments with closely spaced, individual septic systems. Septic contamination of the unconfined aquifer was documented in private wells in an unsewered development south of Dover, and is suspected at several mobile home parks with individual septic systems (R. B. Howell, Delaware Department of Public Health and Social Services, oral commun., 1986).

Saline-Water Intrusion

As a result of ground-water pumping, saline water has intruded the unconfined aquifer along the Atlantic coast (fig. 3*B*). Chloride concentrations exceeding the drinking-water standard of 250 mg/L currently are a problem in shallow domestic wells in South Bethany and on Fenwick Island. Some problems also have been detected near the Indian River Inlet and at some locations along the Delaware Bay. Public-water suppliers in the coastal resort towns that previously withdrew water from the unconfined aquifer either have drilled deeper wells into the confined Chesapeake Group aquifers or have moved their well fields inland. The Chesapeake Group aquifers used for public supplies presently (1986) are not affected by saline-water intrusion in Delaware.

POTENTIAL FOR WATER-QUALITY CHANGES

The potential for new sources of contamination in the aquifers of Delaware is generally decreasing because of recent Federal and State regulations governing waste disposal and increased public awareness of ground water and its importance. Cleanup efforts are planned or underway for several sites. Areas of the aquifers that are contaminated or threatened by contamination may cause local availability problems as water use increases.

Nitrate contamination of the unconfined aquifer associated with crop production has the potential to increase as more acreage is put into production and irrigation increases. Increasing irrigation efficiency, better poultry manure storage, and use of proper spreading rates for fertilizers, encouraged by the State, will help decrease nutrient contamination of ground water. Some problems are unavoidable in the sandy soils common to Delaware (Ritter and Manger, 1985), where infiltration rates are rapid and percolation of contaminants is facilitated. The State also has new regulations for septic systems which eventually should decrease the extent of aquifer contamination from septic systems. The extent of ground-water contamination from herbicides and insecticides in the unconfined aquifer is undefined.

Legislation and regulations have recently been developed that regulate installation of new underground fuel-storage tanks and require existing tank systems to be upgraded by 1991.

GROUND-WATER-QUALITY MANAGEMENT

Two State agencies are responsible for different aspects of ground-water quality. The Department of Natural Resources and Environmental Control allocates water use, issues permits, and monitors waste-disposal sites. The Department of Health and Social Services monitors the quality of public water supplies. One Federal interstate agency, the Delaware River Basin Commission, is involved in basin-wide ground-water planning and management.

Delaware is using the National Interim Primary and Secondary Drinking Water Regulations (U.S. Environmental Protection Agency, 1986a,b) in the implementation of the Safe Drinking Water Act (SDWA) and RCRA under delegation of authority from the Federal government. The Underground Injection Control Program of the SDWA is used to regulate cooling-water returns from ground-water heat pumps. Delaware also has regulations for other types of waste injection, although, at the present time, there are no injection wells in the State. Hazardous material is tracked under RCRA by the waste manifest system.

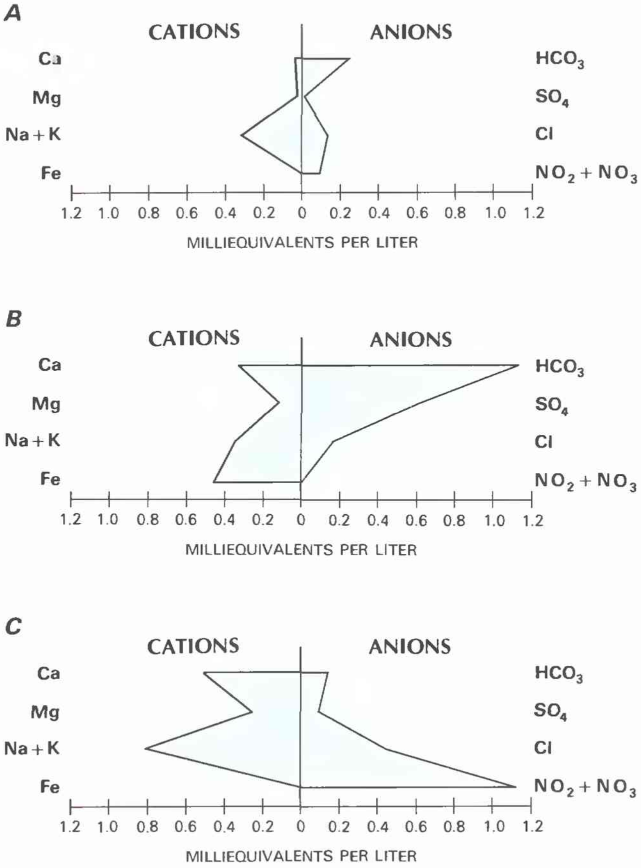

Figure 4. Water-quality characteristics in the unconfined aquifer, Delaware. *A*, Background water, oxidizing environment. *B*, Background water, reducing environment. *C*, Water affected by agriculture. (Source: *A*, *B*, *C*, Denver, 1986.)

Under CERCLA, also called Superfund, EPA has made decisions on remedial actions to be taken at Tybouts Corner Landfill (fig. 3*A*, site C) and at site D (fig. 3*A*) and is in the process of selecting alternatives for remedial action at Army Creek Landfill (fig. 3*A*, site B) and at site A (fig. 3*A*). Response time and actions taken to handle spills of hazardous chemicals under CERCLA authority in Delaware are considered to be good by State officials.

Delaware adopted a ground-water protection strategy in 1983 as a result of Section 208 of the Clean Water Act. The State is currently reviewing the strategy and plans to update it to meet current needs. The strategy allows for differential protection of ground water by permitting some limited degradation in areas where the public and environment are not adversely affected. The goal of the program is to manage ground water so that there will be enough for future needs. Permits are issued for well construction, water development, and waste disposal. All ground-water-management decisions attempt to integrate surface- and ground-water quality and quantity considerations. Data on water use and water quality are available to support State ground-water protection programs. Additional regulations in the State require that all well drillers and septic system designers and installers be licensed. Geologists in the private sector also must be registered.

The Information and Education Office of the Department of Natural Resources and Environmental Control provides public educational brochures that explain ground-water concerns and existing regulatory programs. A State Water Conference also is held yearly to inform the public about current water issues and regulations.

The presence of toxic substances and organics in ground water is receiving increasing attention through monitoring of waste sites and analyses of water from public wells.

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FLORIDA

Ground-Water Quality

Florida's population in 1980 was about 9.7 million and currently (1986) is increasing at a rate of about 6,000 persons per week. Most major population centers are in south and central Florida (fig. 1). As population increases, so do the demands for water supply and waste assimilation.

Florida has abundant ground-water resources. Large quantities of potable water are obtainable from each of the principal aquifers in most areas of the State (fig. 2). Because of its abundance and availability, ground water is the principal source of freshwater for public-supply, rural, and industrial uses and is the source for about half of the water used for irrigation. More than one-half of the 7,300 Mgal/d (million gallons per day) of freshwater used in Florida for all purposes comes from ground-water sources (Leach, 1983), and about 90 percent of Florida's population depends on ground water for drinking water.

Potential sources of ground-water contamination are numerous in Florida. Some of these sources include 6,000 surface impoundments for waste disposal; 9,600 drainage wells; 60,000 underground gasoline storage tanks; 800 municipal landfills; more than 400 potential hazardous-waste sites; and the 60,000-per-year increase in septic tanks. Perhaps as many as one-fourth of Florida's 300 active municipal landfills and almost half of the hazardous-waste sites are suspected of degrading the quality of ground water (fig. 3). Florida is ranked second in pesticide application in the Nation, but thirty-third in planted acreage. Currently, some 9,500 pesticide formulations are used in the State (Stoddard Pickrell, Florida Department of Environmental Regulation, oral commun., 1987). They comprise various combinations of more than 600 active ingredients, of which more than 45 are "restricted-use pesticides."

Regionally, the inorganic quality of water from the principal aquifers used for public supply does not exceed State primary drinking-water standards. In many parts of the State, however, ground-water supplies commonly exceed secondary drinking-water standards. For example, a recent sampling of 120 major public supplies serving about 30 percent of the State's population indicated no violations of primary drinking-water standards. However, the concentration of dissolved solids exceeded the secondary standard of 500 mg/L (milligrams per liter) in about 20 percent of the supplies (Irwin and others, 1985).

Data on the organic quality of water from the State's principal aquifers are limited; nevertheless, occasional incidences of organic contamination of ground water that may affect human health

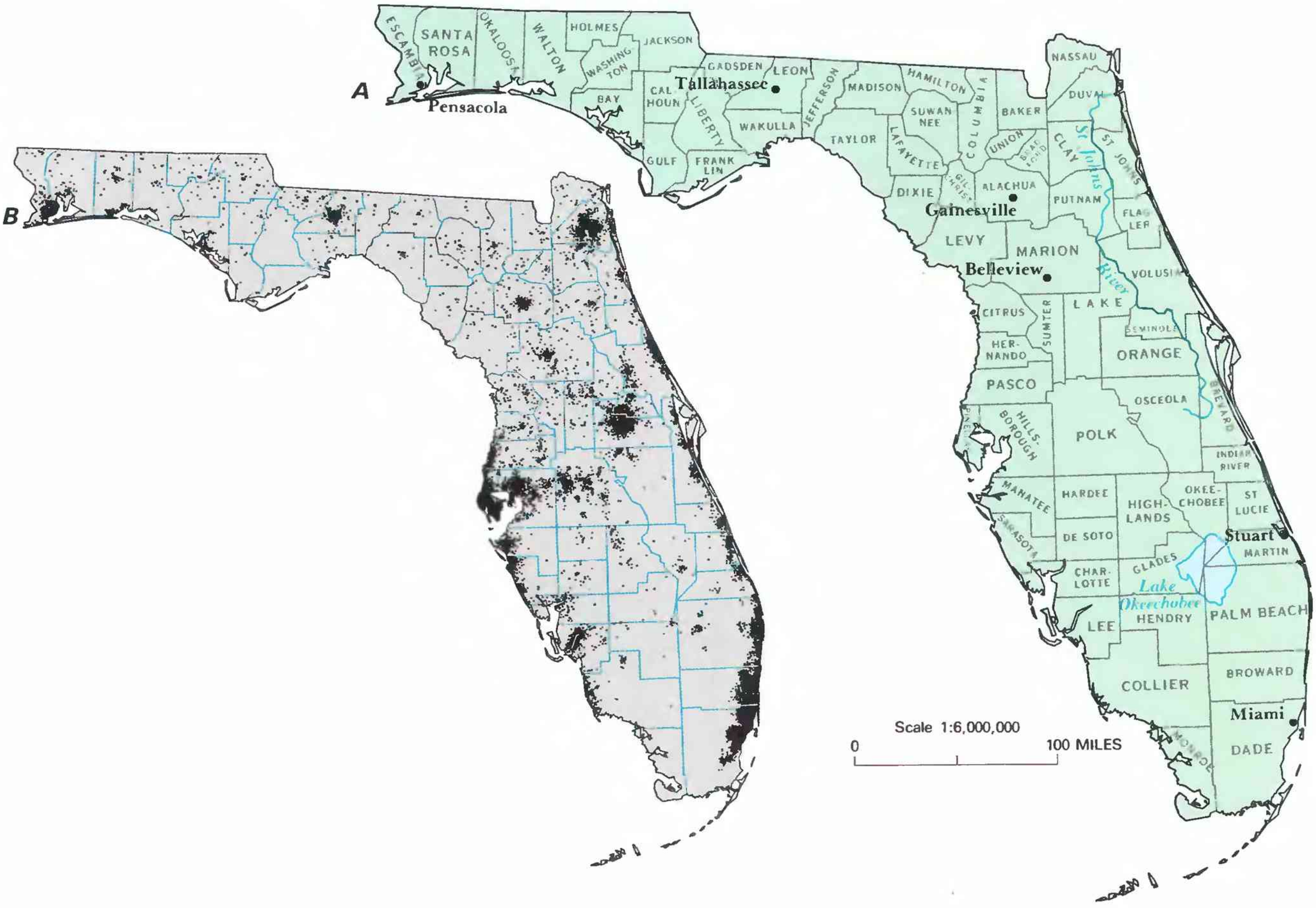

Figure 1. Selected geographic features and 1985 population distribution in Florida. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

and welfare are a reality in Florida. Irwin and others (1985) indicated that six public supplies contained some trace amounts of organic contamination, but none of the contamination exceeded drinking-water standards. During the last few years, the ground water used for public supplies in both Belleview and Stuart (fig. 1*A*) was contaminated by gasoline (Florida Department of Environmental Regulation, 1986a). The contamination at Belleview was extensive enough to result in abandonment of the city's well field. Contamination of ground water used for public supply from industrial organic compounds, primarily trichloroethylene and vinyl chloride, also has been discovered in Pensacola and several southeastern Florida coastal communities (G.M. Dykes, Florida

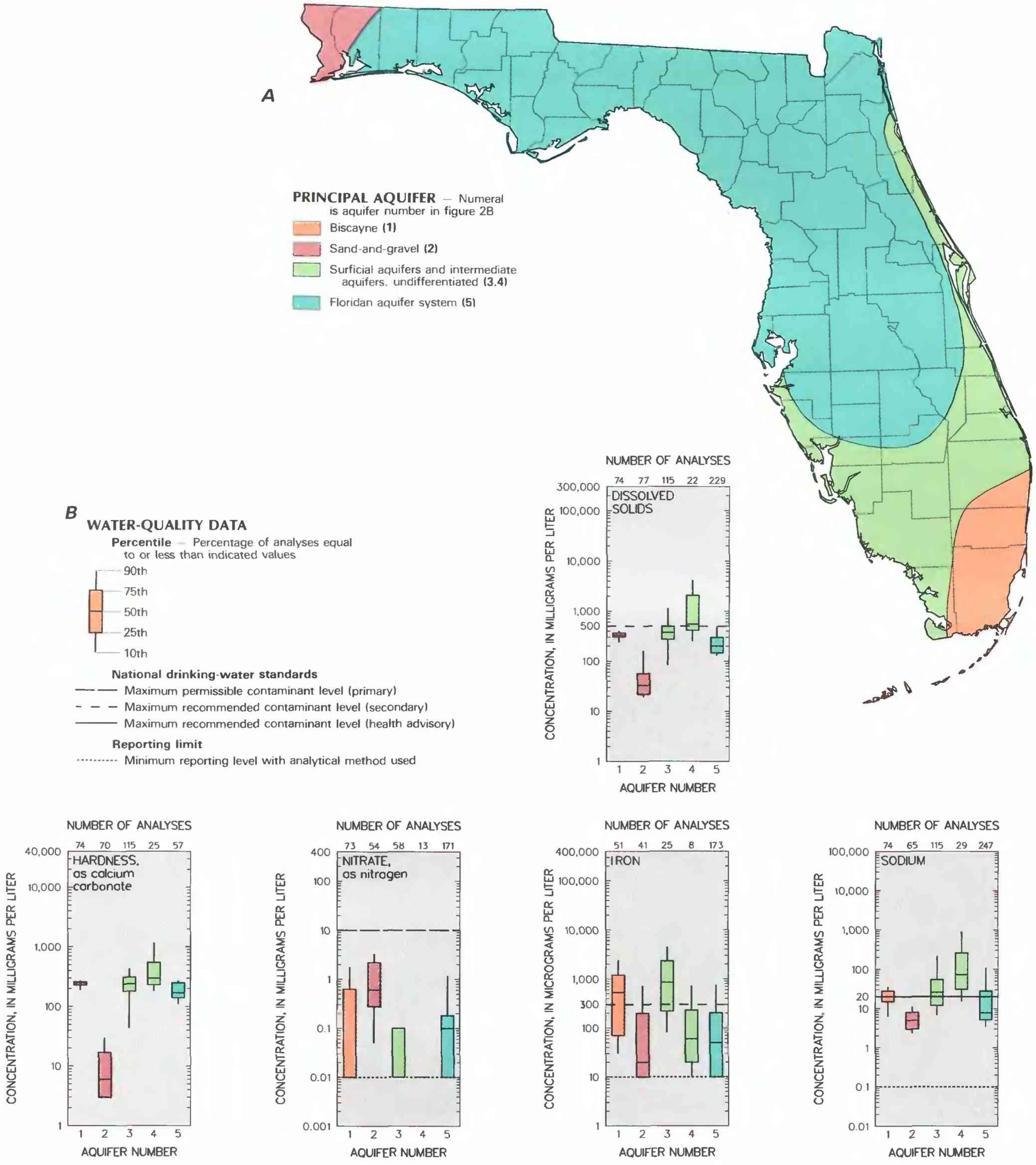

Figure 2. Principal aquifers and related water-quality data in Florida. *A*, Principal aquifers. *B*, Selected water-quality constituents and properties, as of 1970–86. (Sources: *A*, U.S. Geological Survey, 1985. *B*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a, b.)

Department of Environmental Regulation, oral commun., 1986). Organic chemicals also have contaminated public-supply wells near Gainesville in Alachua County. The organic pesticide ethylene dibromide (EDB) was identified in more than 1,000 public-supply wells throughout the State's agricultural regions (G.M. Dykes, Florida Department of Environmental Regulation written commun., 1986). Although water contaminated with EDB is usually treatable with granular activated carbon, the widespread contamination illustrates the vulnerability of ground-water resources in Florida.

State agencies have identified 413 potential hazardous-waste sites; of these, 86 are at various stages of permitting and monitoring pursuant to the Federal Resource Conservation and Recovery Act (RCRA) of 1976, the Florida Resources Recovery and Management Act of 1980, and the Florida Water Quality Assurance Act of 1983. Preliminary monitoring indicates that about 10 percent of the RCRA land-disposal sites have contaminated ground water. There are 39 class I (U.S. Environmental Protection Agency, 1984) Underground Injection Control (UIC) waste-disposal well sites in Florida—7 industrial and 32 municipal (Florida Department of Environmental Regulation, 1985b). Florida has 39 hazardous-waste sites that have been either proposed or included in the National Priorities List (NPL) (Superfund) of hazardous-waste sites compiled by the U.S. Environmental Protection Agency (1986c). Ground-water contamination has been confirmed at 32 of these "Superfund" sites, and site remedial action is being initiated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. At four of the CERCLA (Superfund) sites, the U.S. Environmental Protection Agency (EPA) has invoked "immediate removal" cleanup action under CERCLA. In addition there are 20 waste sites at 4 federal facilities in Florida under the U.S. Department of Defense Installation Restoration Program (IRP).

Statewide, 70 hazardous-waste sites, which include selected CERCLA, RCRA, and State Action (part of Florida Resources Recovery and Management Act of 1980) sites, are undergoing cleanup. The majority, or 48 sites, are being cleaned by the responsible party, and the remaining 22 sites are being cleaned with government funds—15 with State funds (Florida Department of Environmental Regulation, 1985c).

WATER QUALITY IN PRINCIPAL AQUIFERS

The principal aquifers in Florida are the Biscayne aquifer, the sand-and-gravel aquifer, the surficial and intermediate aquifers, and the Floridan aquifer system (fig. 2*A*). The hydrogeologic characteristics of these aquifers have been described previously (U.S. Geological Survey, 1985, p. 173–178).

Water in the sand-and-gravel aquifer is the least mineralized, with concentrations of dissolved solids exceeding 100 mg/L generally only in coastal areas where saltwater intrusion occurs. Except for water in the sand-and-gravel aquifer, ground water in Florida is classified as hard to very hard. Concentrations of nitrate and fluoride in Florida's ground water are considerably smaller than the maximum prescribed by State drinking-water standards. Iron, however, is common in undesirable concentrations throughout Florida, particularly in water from the Biscayne and surficial aquifers.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*B*. The summary is based on dissolved solids, hardness, nitrate (as nitrogen), sodium, and iron analyses of water samples collected from 1970 to 1986 from the principal aquifers in Florida. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 300 μg/L (micrograms per liter) iron. For these variables, State drinking-water standards are the same as the national standards.

Biscayne Aquifer

The Biscayne aquifer (fig. 2, aquifer 1) underlies all Dade and Broward Counties and parts of Palm Beach and Monroe Counties. The aquifer consists of a very permeable limestone in southern and western Dade County that becomes less permeable in the northern and eastern parts of the county (U.S. Geological Survey, 1985). The Biscayne aquifer has been designated by the EPA as a "sole source" drinking-water supply, with a public-supply withdrawal of about 461 Mgal/d (Leach, 1983). The aquifer is managed carefully to control saltwater intrusion. Water in the Biscayne aquifer is primarily a calcium bicarbonate type and does not exceed standards for most uses. Concentrations of dissolved solids are smaller than 400 mg/L in about 90 percent of the samples analyzed, although most water is classified as very hard. Concentrations of nitrate and fluoride are considerably smaller than drinking-water standards, with respective median values of 0.01 and 0.30 mg/L. Iron concentrations in untreated ground water are commonly larger than the secondary drinking-water standard of 300 μg/L. Iron is commonly associated with the large natural organic content of the region's ground-water resource. This large natural organic content has contributed to the formation of trihalomethanes during chlorination of public-water supplies.

Sand-and-Gravel Aquifer

The sand-and-gravel aquifer (fig. 2, aquifer 2) is the major source of water supply in the western part of the Florida Panhandle, with a public-supply withdrawal of about 34 Mgal/d (Leach, 1983). The aquifer thickness exceeds 700 feet in northwestern Escambia County. The aquifer thins to the south and east and pinches out in central Walton County (U.S. Geological Survey, 1985). The major inorganic chemical constituent in water from this aquifer is sodium chloride, with concentrations of dissolved solids smaller than 60 mg/L in about 75 percent of the aquifer. The water is considered to be soft and suitable for most uses, although safeguards against corrosion may be needed in some instances. Concentrations of sodium, nitrate, and fluoride generally do not exceed the drinking-water standards. Iron concentrations in the ground water, however, may exceed the secondary drinking-water standard of 300 μg/L in about 10 percent of the samples analyzed. Near the coast, saltwater intrusion can occur.

Surficial and Intermediate Aquifers

Surficial aquifers (fig. 2, aquifer 3) are present in much of the east coastal and south-central parts of Florida. These aquifers are little used where more plentiful supplies are available from deeper aquifers that contain potable water. Statewide, withdrawal for public supply is estimated at about 80 to 90 Mgal/d (Leach, 1983). The surficial aquifers consist of sand and shell with minor limestone beds. These aquifers are used most intensively for public supply in the area southwest of Lake Okeechobee and in scattered towns along the east coast (U.S. Geological Survey, 1985). In general, the major inorganic chemical composition of water from the surficial aquifers is calcium bicarbonate. Concentrations of dissolved solids generally are smaller than about 1,200 mg/L in

90 percent of the samples analyzed; however, concentrations of several thousand milligrams per liter are not uncommon in some areas. Saltwater intrusion and flowing artesian wells that tap deeper, saline aquifers can greatly affect salinity in the surficial aquifers. The water is considered to be hard to very hard. On the average, concentrations of nitrate, fluoride, chloride, and dissolved solids

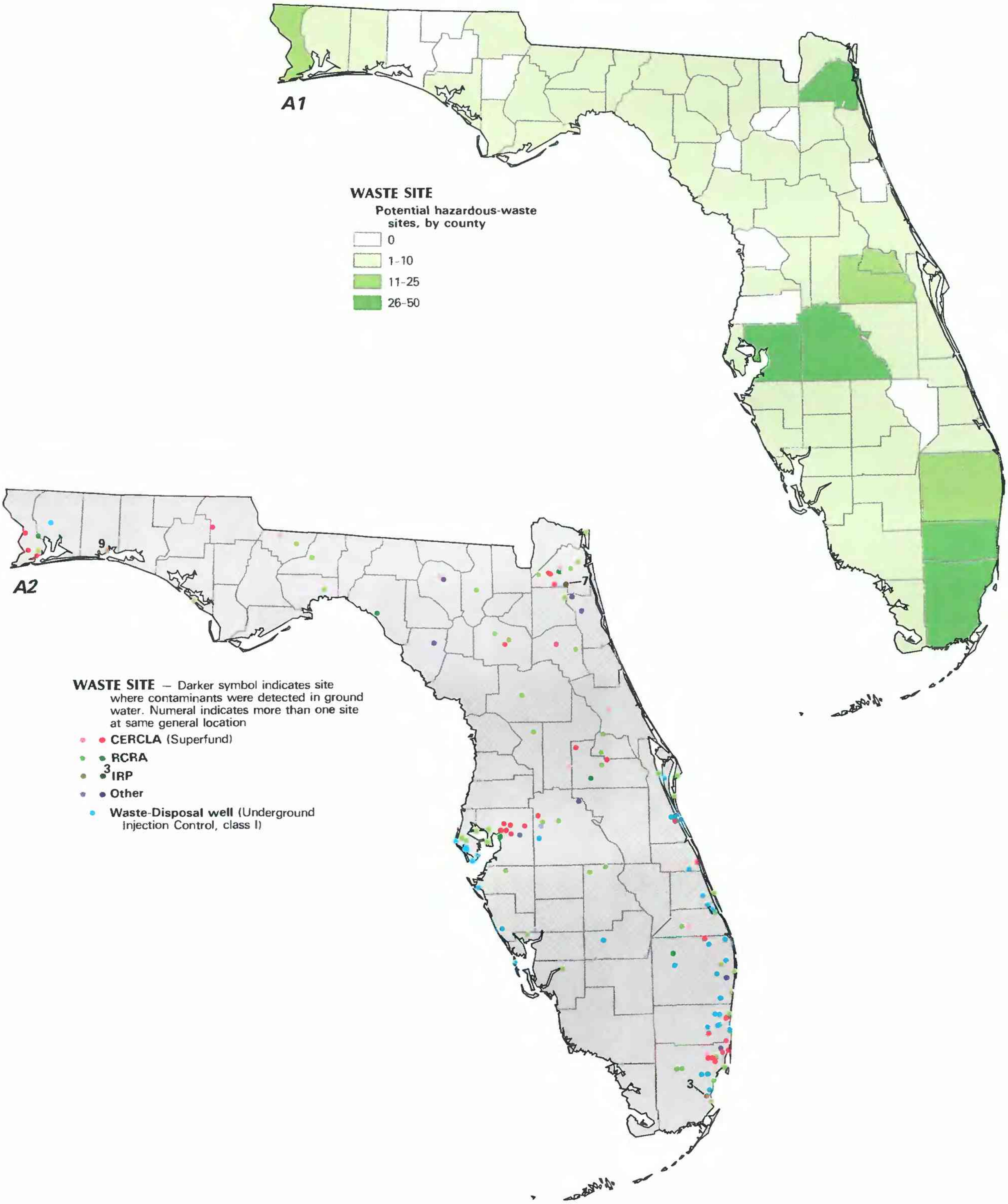

Figure 3. Selected waste sites and ground-water-quality information in Florida. *A1*, Potential hazardous-waste sites. *A2*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1986. *B*, Summary of reported incidences of human-induced contamination, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A1*, *A2*, Florida Department of Environmental Regulation, 1986b; U.S. Department of Defense, 1986. *B*, Florida Department of Environmental Regulation, 1985a, 1986a. *C*, Florida Department of Environmental Regulation, 1985a.)

do not exceed drinking-water standards. Iron concentrations exceed the standards in more than half of the samples analyzed.

In southern Florida and along the eastern part of peninsular Florida, one or more aquifers are present between the local surficial aquifer and the underlying Floridan aquifer system; these are informally referred to as intermediate aquifers (fig. 2, aquifer 4) (U.S. Geological Survey, 1985). The rocks that contain the intermediate aquifers are mainly limestone and shell beds interbedded with sand and clay. Intermediate aquifers are an important source of water for public supply and irrigation in coastal southwestern Florida from about Sarasota County to Lee County where the underlying Floridan aquifer system contains nonpotable water (U.S.

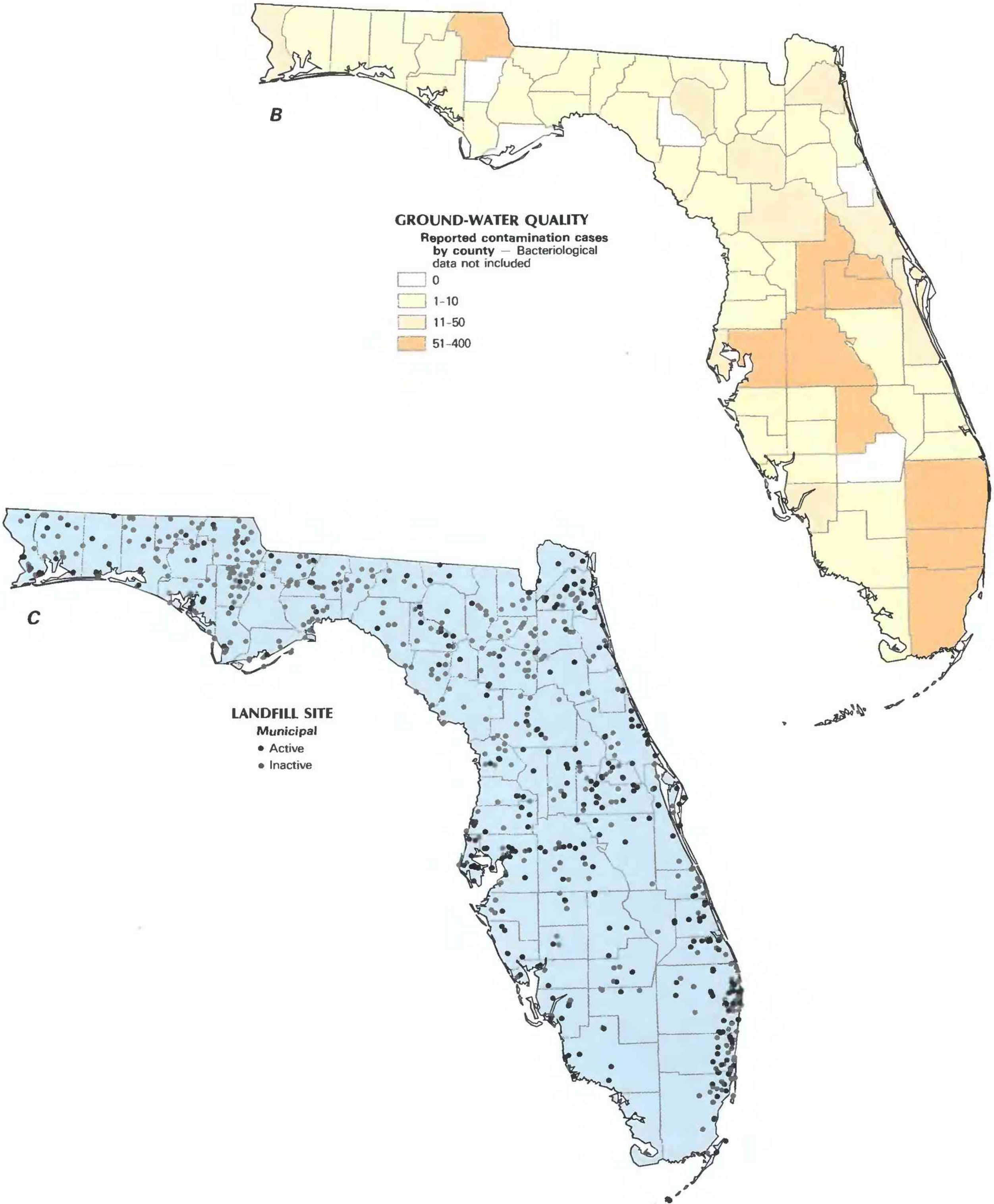

Figure 3. Selected waste sites and ground-water-quality information in Florida—Continued.

Geological Survey, 1985). The public-supply withdrawal is estimated at about 156 Mgal/d (Leach, 1983). The major inorganic chemical composition of water from the intermediate aquifers generally is a mixed calcium magnesium bicarbonate, with concentrations of dissolved solids of about 550 mg/L or larger in about 50 percent of the samples analyzed. The water from these aquifers is considered to be hard to very hard. Nitrate, fluoride, and iron concentrations generally do not exceed drinking-water standards, but sodium, chloride, and dissolved solids commonly do. saltwater intrusion and upward movement of saline water from the deeper aquifer commonly result in unsuitable water quality for most uses in many areas.

Floridan Aquifer System

The Floridan aquifer system (fig. 2, aquifer 5), one of the most productive sources of ground water in the United States, extends across all of Florida, southern Georgia, and adjoining parts of Alabama and South Carolina. The Floridan is the lowermost part of the ground-water reservoir in Florida. It consists of as much as 3,500 feet of limestone and dolomite beds that are interconnected hydraulically to differing degrees (U.S. Geological Survey, 1985).

Total pumpage from the aquifer system in Florida exceeds 2,000 Mgal/d (P.W. Bush, U.S. Geological Survey, written commun., 1984) and the public-supply withdrawal is about 460 Mgal/d (Leach, 1983). Many public-supply systems tap the Floridan aquifer system, including most major cities in the northern half of the State. The Floridan also is a major source of water for industrial, irrigation, and rural uses.

The major inorganic chemical constituent in the water is calcium bicarbonate, with a concentration of dissolved solids smaller than 500 mg/L in about 90 percent of the samples analyzed. Although the water tends to be hard, it generally does not exceed the drinking-water standards for nitrate, fluoride, sodium, and chloride in at least 75 percent of the samples analyzed. Iron may exceed the standard, but probably not in more than 10 percent of the water-quality analyses.

EFFECTS OF LAND USE ON WATER QUALITY

Florida's unique hydrogeologic features of a thin soil layer, high water table, porous limestone, and large amounts of rainfall, coupled with its rapid population growth, result in a ground-water resource extremely vulnerable to contamination. Numerous structures resulting from human activities throughout Florida have the potential to contribute to ground-water contamination. There are tens of thousands of potential point sources such as surface-water impoundments, drainage wells, underground storage tanks, flowing saline artesian wells, hazardous-waste sites, powerplants, landfills, and cattle and dairy feedlots. Similarly, there are numerous septic tanks and urban and industrial-commercial areas that may recharge water of undesirable quality. Nonpoint sources, which have vast potential for contributory ground-water contamination, include coastal saltwater bodies, agricultural and silvicultural practices, and mining.

The distribution of selected types of waste-disposal sites and occurrences of ground-water contamination are shown in figure 3. Figure 3*A*2 shows the locations of the CERCLA, RCRA, IRP, and UIC sites and figure 3*A*1 shows a summary by county of potential hazardous-waste sites identified by the State. Reported cases of recent ground-water contamination summarized by county are shown in figure 3*B*. In many cases included in this summary, the principal aquifer was not directly affected; further, not all cases posed a significant threat to human health and welfare. The reported cases mainly represent recent information gathered from special State and Federal studies on drinking-water supplies, hazardous and nonhazardous waste-site monitoring, and underground storage tanks. Figure 3*B* is a very general portrayal and likely does not represent all recent contamination cases of ground water or supply wells. In particular, figure 3*B* does not include bacteriological data collected by the numerous county and local health agencies. Figure 3*C* shows the distribution of active and inactive municipal landfills in Florida.

A brief overview of some human activities affecting the environmental integrity of Florida's ground-water resource is presented below.

Hazardous-Waste Sites

As of February 1986, 413 potential hazardous-waste sites have been identified in Florida (Florida Department of Environmental Regulation, 1986b). Currently, six counties have more than 20 sites—Dade (48), Hillsborough (46), Duval (41), Broward (40), Polk (38), and Palm Beach (23) (fig. 3*A*1). Statewide, 185 of these sites had some type of water or soil contamination and 84 additional sites were suspected of contamination. Ground-water contamination was confirmed at 156 sites. Nearby supply wells at some of these sites have been contaminated, but thorough documentation is not available. Enforcement action requiring contamination assessment and necessary remedial action has been initiated at 118 sites (Florida Department of Environmental Regulation, 1986b).

Some of the more notable hazardous-waste sites are the 39 CERCLA (Superfund) sites (as of May 1986) shown in figure 3*A*2. Ground-water contamination was confirmed at 32 of these sites and was suspected, but unconfirmed, at the remaining 7 (Florida Department of Environmental Regulation, 1986b). The primary contaminants at most of these sites were a mix of industrial organic solvents. These sites represent disposal of hazardous waste that constitutes a major threat to the quality of underlying ground water. Because of the absence of a significant amount of relatively impermeable surficial material to retard downward movement of contaminants, leakage from many of the sites poses a direct threat to the principal aquifers, particularly in southern and western Florida.

As of September 1985, 160 hazardous-waste sites at 14 facilities in Florida have been identified by the U.S. Department of Defense (DOD) as part of IRP as having potential for contamination. The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 160 sites in the program, 8 contained contaminants but did not present a hazard to people or the environment. Twenty sites at 4 facilities (fig. 3*A*2) presented a hazard significant enough to warrant response action in accordance with CERCLA.

Gasoline Storage Tanks

The Florida Department of Environmental Regulation (1986a) had documented more than 400 instances of ground-water contamination from leaking gasoline pipes or storage tanks as of April 30, 1986. The greatest frequency of gasoline contamination occurred in Dade County (77 cases), Broward County (57 cases), and Palm Beach County (25 cases) (fig. 3*B*). In many of these cases the quality of water in the Biscayne aquifer was directly affected. Statewide, perhaps the most environmentally and financially significant incident was the leaking of 10,000 gal (gallons) of gasoline between October 1979 and March 1980, which contaminated the public-water supply for about 2,000 residents at Belleview (see fig. 1*A*). The contamination was extensive enough to result in abandonment of the city's well field. Other gasoline leaks in rural Marion County have caused contamination of about 20 supply wells in the unconfined Floridan aquifer system and are under special study by the Department of Environmental Regulation. A leaky gasoline pipeline in Duval County contaminated 14 wells in the Floridan aquifer system. Another gasoline leak of immediate concern to the State occurred in Cocoa Beach, Brevard County, where between 800 and 1,600 gal of gasoline is floating atop the underlying ground water.

Pesticides

Pesticide contamination of ground water has become a major environmental issue in Florida. Since 1983, water from more than 1,000 public and private supply wells, primarily in the Floridan aquifer system, have been found to contain levels of the soil fumigant EDB above the State regulation of 0.02 μg/L. Statewide, EDB has been detected in 50 community wells, 74 noncommunity wells, and 922 private wells as of May 1986 (G.M. Dykes, Florida Department of Environmental Regulation written commun., 1986). The distribution of EDB was extensive, with detections in ground water in 22 of the 66 counties tested. The most pervasive detections were in Jackson, Lake, Highlands, and Polk Counties (fig. 3*B*). Although the number of wells sampled per county differed, 10 counties had confirmed EDB in 10 percent or more of the wells tested. The State has taken, or assisted in, remedial measures using granular activated carbon; nonetheless, perhaps as many as 60,000 people were at least temporarily affected (G.M. Dykes, Florida Department of Environmental Regulation oral commun., 1986).

Aldicarb (Temik) has also been detected in ground water at seven agricultural study sites in Hillsborough, Martin, Polk, St. John, Seminole, and Volusia Counties. At one of the Polk County sites, aldicarb residues appeared to have migrated 300 feet laterally from the point of application (Florida Department of Environmental Regulation, 1984b).

Other recent studies have indicated trace concentrations of pesticides in 3 of 91 major public supplies in Florida (Irwin and others, 1985) and in shallow ground water near treatment-plant spray fields (Pruitt and others, 1985). None of these detections, however, exceeded State drinking-water standards. A reconnaissance of about 40 large springs (J.B. Pruitt, U.S. Geological Survey, written commun., 1986) indicated EDB in one spring in Orange County in concentrations exceeding the State drinking-water regulation of 0.02 μg/L. Pesticide compounds also are common contaminants near landfills.

Municipal Landfills

The State has about 300 active and 500 inactive landfill sites (fig. 3*C*). Most of the landfills are unlined. Six of Florida's CERCLA (Superfund) sites are landfills, and all have contaminated the underlying ground water. Three in southeastern Florida have directly contaminated the Biscayne aquifer. More than 50 additional landfills likely have contributed to ground-water contamination and have been identified for remedial action by the State. The statewide extent of public-supply well contamination from landfills presently is poorly documented. A recent landfill study concluded that "the potential for ground-water pollution from landfills is severe in Florida at the present time and will continue to get worse until regulations and practices catch up to existing technology" (Miller and others, 1985, p. viii).

Organic Compounds

Incidences of volatile organic compounds (VOC), aromatics, and trihalomethane in ground water, particularly in southern Florida, have become an issue of concern. A recent study of public supplies from the Biscayne aquifer in Broward, Dade, and Palm Beach Counties reported that four supplies serving about 290,000 people indicated VOC concentrations that slightly exceeded Florida drinking-water standards (Vincent, 1984). The primary compounds detected were trichloroethylene and vinyl chloride, which have maximum contaminant level concentrations of 3 and 1 μg/L, respectively. In all, 27 public supplies had detectable amounts of VOC, but at 23 of them the concentration did not exceed the standards. The report also indicated that the overall VOC quality of the three-county area has improved since 1982 when 1.3 million people were receiving drinking water with VOC exceeding State regulations. Additional study of 150 industrial facilities to identify possible sources of VOC contamination in the area is now underway. Recent incidents of VOC contamination in ground-water supplies have also occurred in other parts of the State. Several city supply wells for Pensacola and Gainesville were closed temporarily (1985–86) because of VOC contamination.

Public water-supply data collected as part of the EPA's national organics reconnaissance, the national organic monitoring survey, and the ground-water systems survey, indicate that 25 to 30 percent of the ground-water supplies tested in Florida may have some contamination from VOC and other synthetic organic compounds (G.M. Dykes, Florida Department of Environmental Regulation written commun., 1986). Further, 35 percent of the community systems supplying a population of 10,000 or more is likely to have detectable levels of trihalomethanes after chlorination.

POTENTIAL FOR WATER-QUALITY CHANGES

Currently, Florida is only moderately industrialized, but it has one of the fastest growing populations. Future population growth is projected to be most intensive in coastal-urban areas, although central and northern urban areas will also be affected (fig. 1*B*). Increased development in coastal areas may result in saltwater-intrusion problems, and agricultural stresses of today likely will give way to future water-quality effects associated with increased urban, commercial, and industrial development.

In many areas of Florida, the present degradation of water has occurred only in surficial deposits and not in the deeper principal aquifer, but downward movement of contamination is a possible threat. In other hydrogeologic settings such as in southeastern Florida, however, the principal aquifer has been directly contaminated.

GROUND-WATER-QUALITY MANAGEMENT

The Florida Department of Environmental Regulation, created by the Florida Environmental Reorganization Act of 1975, is the primary State agency responsible for water-quality management. The Department's activities are funded by State general revenue and Federal grants. The Department has regional offices throughout the State. The Florida Department of Natural Resources has jurisdiction over Class II Oil and Gas deep wells as specified under the UIC program. The Florida Department of Health and Rehabilitative Services has jurisdiction over the use of water withdrawn from private wells as mandated by the U.S. Environmental Protection Agency (1986a) and the Florida Department of Environmental Regulation (1985d). The Department of Environmental Regulation has jurisdiction over public supplies. The Department of Health and Rehabilitative Services also has jurisdiction over the regulation of domestic septic tanks. The Florida Department of Community Affairs is involved in the Development of Regional Impact documents, which in many instances involve water-quality issues. In addition to State agencies, the local county health departments and pollution control boards are involved to varying extents in water-quality issues. These program regulations and activities may occasionally overlap with those of the Department of Environmental Regulation. The local agency's regulations, however, may not be less stringent than the State's regulations.

Water-quantity management, under the Florida Water Resources Act of 1972, is the primary responsibility of the five Water Management Districts funded by property taxation and covering specifically delineated areas of the State. The five districts are the Northwest Florida Water Management District, the St. Johns River Water Management District, the South Florida Water Management District, the Southwest Florida Water Management District, and the Suwannee River Water Management District.

The Department of Environmental Regulation has assumed primacy for the protection of ground water mandated by Federal legislation. The appropriate State legislation primarily includes the Environmental Control Act of 1972, the Florida Environmental Reorganization Act of 1975, the Florida Resource Recovery and Management Act of 1980, and the Water Quality Assurance Act of 1983. New legislation mandated the State Underground Petroleum Environmental Response (SUPER) Act of 1986, which became effective in July 1986 and addresses the problem of leaking underground storage tanks.

A statewide water policy designed to bring a more consistent approach to water-management practices was adopted in 1981. The policy is designed to coordinate the water quality and quantity issues and to encourage preservation of natural systems through use of nonstructural water-management techniques. Florida has a comprehensive ground-water rule that became effective in 1983. Primarily under Chapters 17-3, 17-4, and 17-22 of the Florida Administrative Code, the State expanded ground-water classification, applied secondary drinking-water standards to Florida's aquifers, added minimum water-quality criteria, created more restrictive zones of discharge, encouraged recycling of wastewaters that are compatible with receiving ground water, and increased the authority of the Department of Environmental Regulation to prevent the introduction of dangerous toxic materials into drinking-water supplies.

The Water Quality Assurance Act of 1983 established the Department of Environmental Regulation as the central repository for water-resources data and authorized the Department to design an extensive ground-water monitoring network, which ultimately may include as many as 2,500 wells. A primary intent of this network will be to provide data useful to protect potable supplies from contamination. Much of this activity will be in cooperation with the U.S. Geological Survey and the five Water Management Districts. One aspect of the Water Quality Assurance Trust Act, established in 1983, was to coordinate emergency response operations and to clean or provide corrective action at hazardous-waste sites that threaten or have contaminated ground waters. Additional significant aspects of Florida's ground-water protection program include the Department's storage tank program designed to assure that above- and below-ground tanks are installed properly and do not leak gasoline or other toxic materials that can cause ground-water contamination. The Department of Environmental Regulation also has an underground injection-control regulatory program that applies specifically to injection wells. The program is designed to ensure that wastes injected underground are injected into the proper geologic layer and depth and that they stay confined in that area. The Department's ground-water monitoring and CERCLA site screening programs call for sampling of suspected contaminated ground water throughout the State.

The ultimate authority to preserve the State's environmental integrity and water quality is based on regulatory programs for permitting and enforcement. The State's regulatory program is designed to merge citizen complaints, departmental investigations, water analysis, and a variety of planning and management programs. Permitting protocol is the major tool used in the regulatory program and is administered chiefly through district offices of the Department of Environmental Regulation located throughout the State. Illegal pollution, operating without a permit, or violating permit conditions may, under Florida law, be grounds for enforcement action by the Department. Legal action, with criminal penalties or fines of as much as $10,000 a day for each separate violation, may be instituted. If hazardous-waste rules are violated, penalties can include fines of as much as $50,000 a day for each violation, in addition to any corrective or remedial action that may be required to halt illegal discharges.

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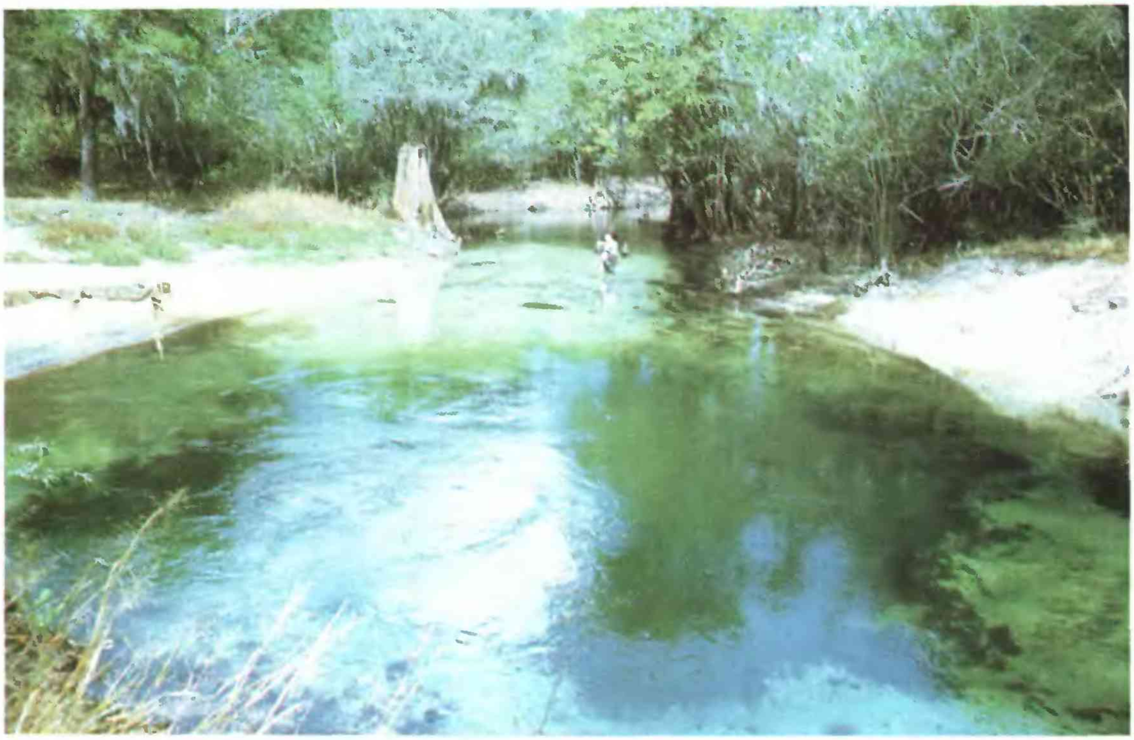

Fletcher Spring, in Lafayette County, Florida, discharges about 26 million gallons of ground water per day from the Floridan aquifer system. The 320 known springs in the Floridan aquifer system discharge more than 8 billion gallons per day and serve as points of concentrated discharge from tens to hundreds of square miles. Springs are used as an indication of general ground-water quality in the aquifer system. (Photograph by Jack C. Rosenau, U.S. Geological Survey.)

Prepared by George A. Irwin, U.S. Geological Survey, and Jacqueline L. Bonds, Florida Department of Environmental Regulation, Tallahassee, Florida

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GEORGIA
Ground-Water Quality

Ground water in Georgia is of good quality and is suitable for most uses. It provides drinking water to more than 2.6 million people, or almost one-half the total population of the State (fig. 1). About one-third of the 2.6 million people are supplied by domestic wells in rural areas, and two-thirds are supplied by public ground-water systems. Most ground-water withdrawals are in the southern part of the State, where the aquifers (fig. 2) are very productive.

Constituent concentrations in ground water generally do not exceed the maximum contaminant levels established for drinking water by the Georgia Department of Natural Resources (1977) and the U.S. Environmental Protection Agency (EPA). There is no evidence of any significant deterioration of public drinking-water supplies in the State. Only a few occurrences of human-related ground-water contamination have been detected, primarily in the more densely populated parts of the State (figs. 3, 4).

The Georgia Environmental Protection Division (GEPD) of the Department of Natural Resources and its branches are responsible for enforcing all State surface-water, ground-water, and water-quality laws. In 1984, the Division developed and implemented a comprehensive ground-water management plan for Georgia. The plan identified key activities already being performed to control and regulate potential pollution sources, and it included a monitoring program to provide water-quality and water-quantity data for the State's principal aquifers. Water quality in Georgia's aquifers is monitored through several networks. The GEPD has a cooperative program with the U.S. Geological Survey that provides data and interpretive information needed to manage the quality and quantity of ground water in the State.

WATER QUALITY IN PRINCIPAL AQUIFERS

Georgia has six principal aquifers—the Floridan aquifer system, the Claiborne and Clayton aquifers, the Cretaceous aquifer system, and the Paleozoic and crystalline rock aquifers (figs. 2*A*, 2*B*). The differing geologic character of the aquifers results in differences in natural ground-water quality from one part of the State to another.

The principal aquifers are overlain by water-table aquifers in surficial deposits that yield sufficient quantities of water for domestic supplies, primarily in rural areas. Most of the water is of good quality for most uses and can be used without treatment.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), chloride, and iron analyses of water samples collected from 1938 to 1985 from the principal aquifers in Georgia. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986 a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include maximum concentrations of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of

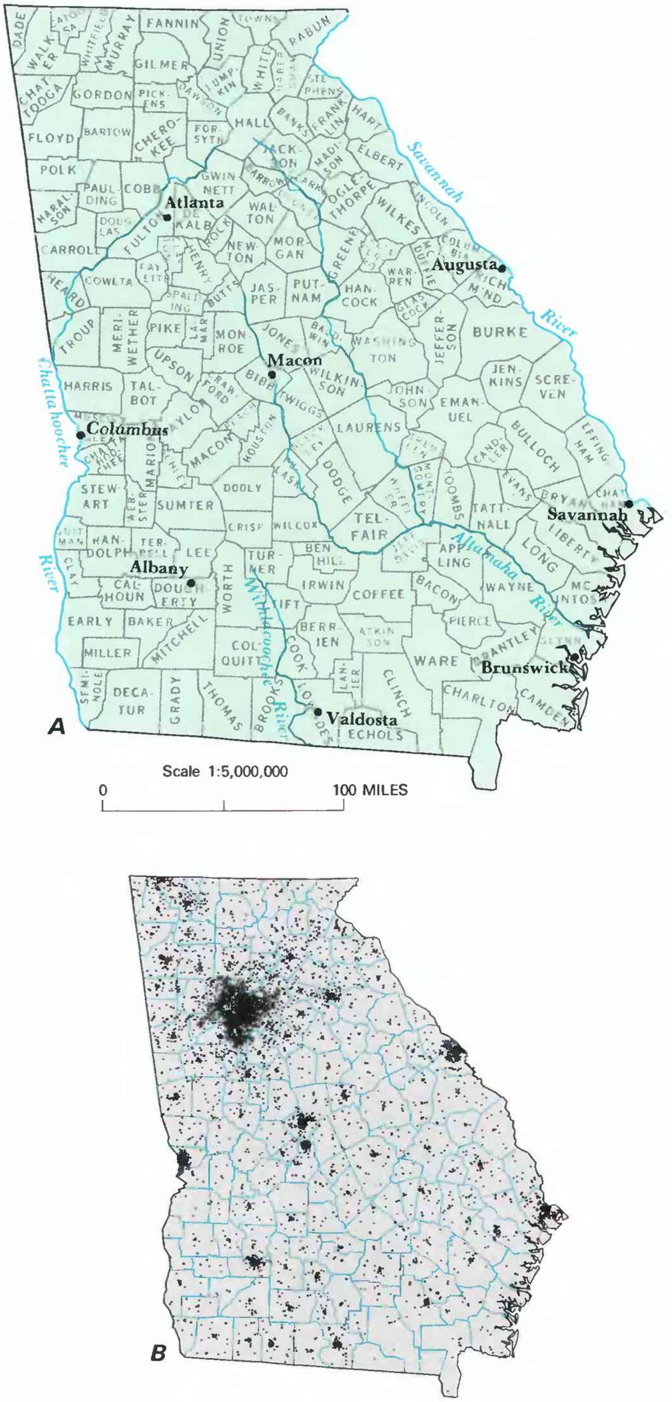


Figure 1. Selected geographic features and 1985 population distribution in Georgia. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

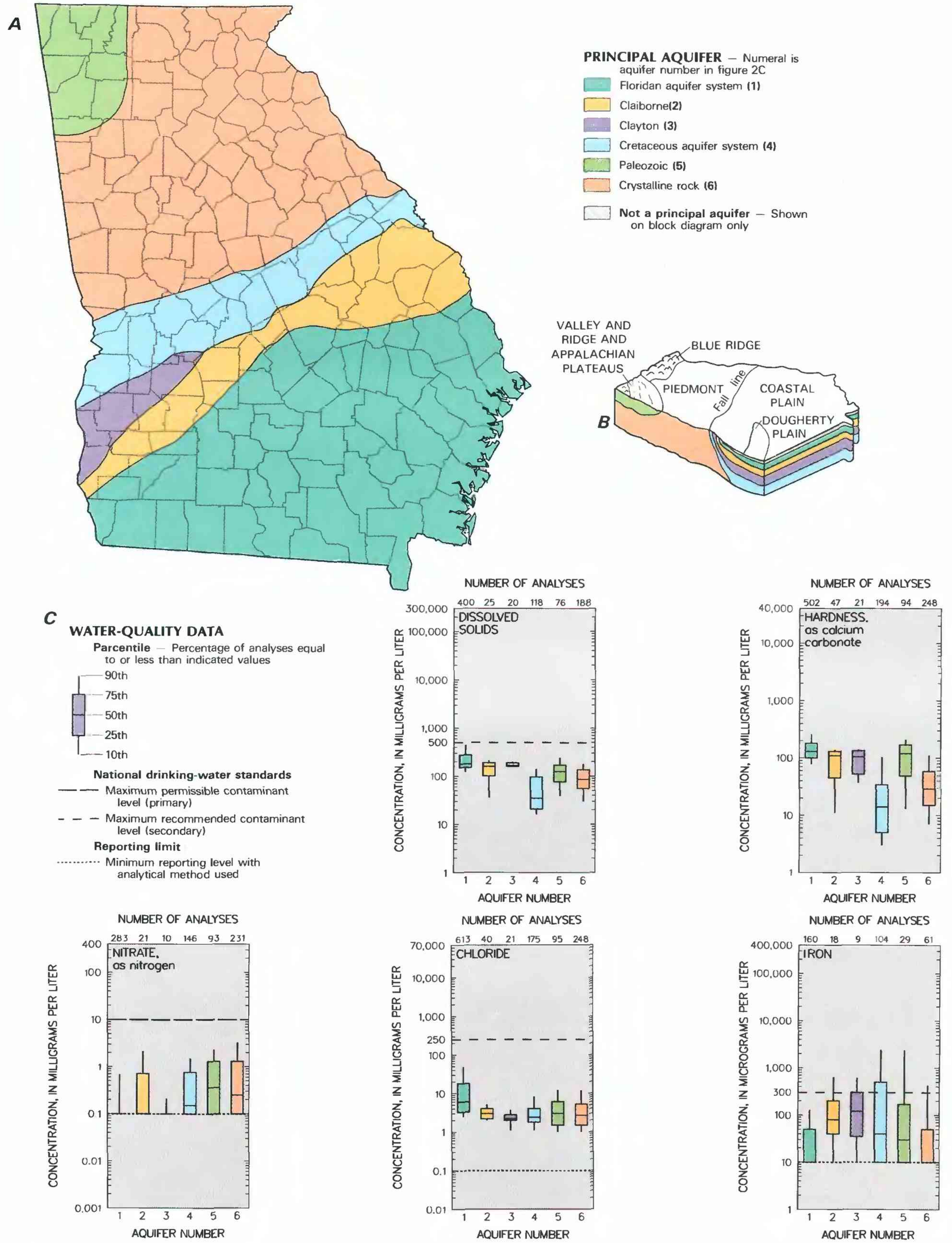


Figure 2. Principal aquifers and related water-quality data in Georgia. *A*, Principal aquifers. *B*, Block diagram showing principal aquifers and physiographic divisions. *C* Selected water-quality constituents and properties, as of 1985. (Sources: *A*, J.S. Clarke, U.S. Geological Survey, written commun., 1984. *B*, Modified from Pierce and others, 1984. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

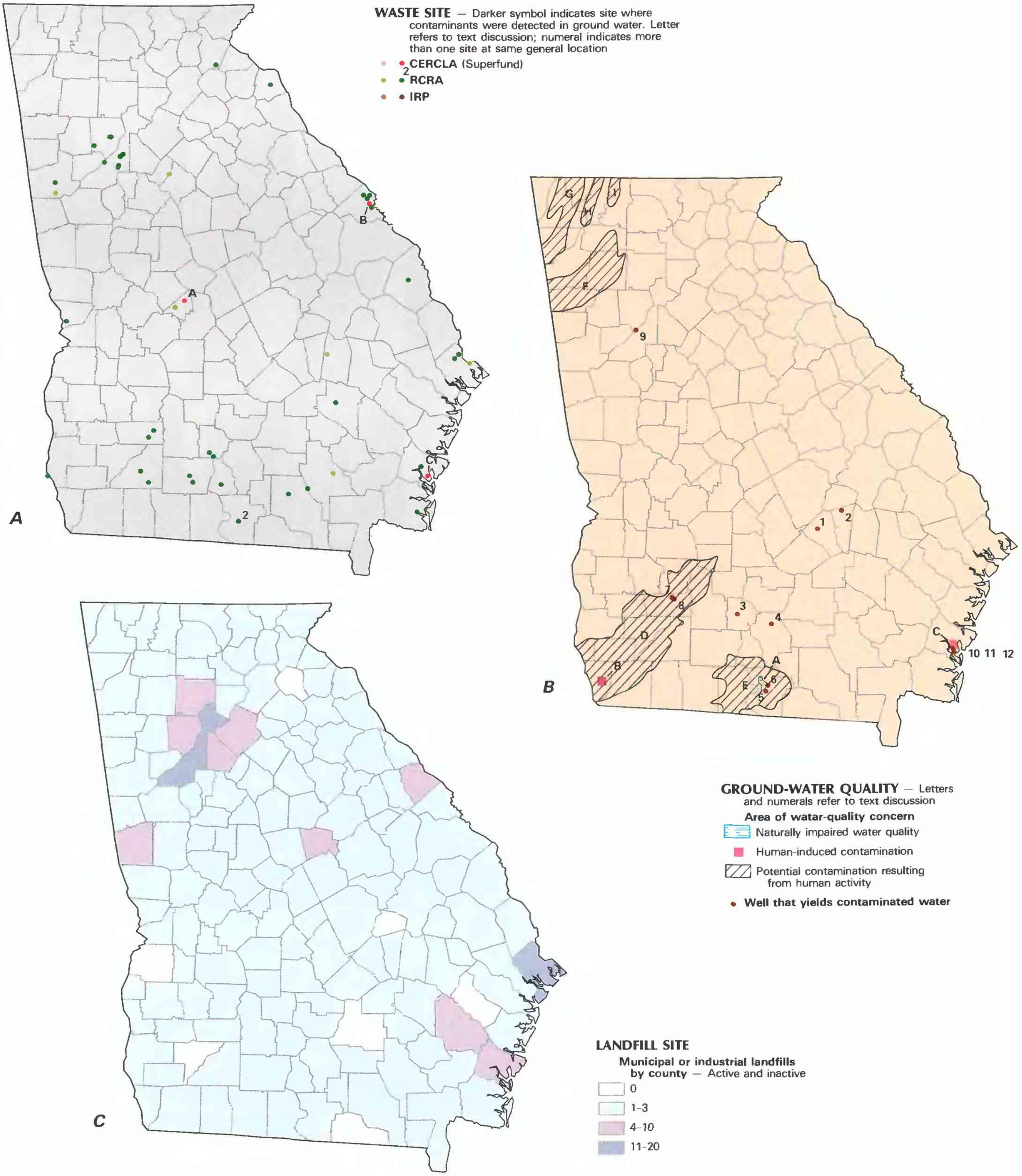


Figure 3. Selected waste sites and ground-water-quality information in Georgia. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of September 1986; Resource Conservation and Recovery Act (RCRA) sites, as of September 1986; Department of Defense Installation Restoration Program (IRP) sites, as of February 1986; and other selected waste sites, as of September 1986. *B*, Areas of naturally impaired water quality, areas of human-induced and potential contamination, as of September 1986. *C*, Municipal and industrial landfills, and distribution of wells that yield contaminated water, as of September 1986. (Sources: *A*, J.R. Kaduck, Georgia Environmental Protection Division, oral commun., 1986; U.S. Department of Defense, 1986. *B*, J.S. Clarke, U.S. Geological Survey, written commun., 1986. *C*, J.W. Dunbar, Georgia Environmental Protection Division, written commun., 1986.)

500 mg/L dissolved solids, 250 mg/L chloride, and 300 µg/L (micrograms per liter) iron.

The summary characterizes the variability of the chemical quality of water from the State's principal aquifers. The data are presented without distinction as to sample depth within the aquifers, and the median concentration for a site was used where more than one analysis was available. In each of the principal aquifers, median concentrations of these constituents are less than standards set by the GEPD and the EPA. Median concentrations of dissolved solids and hardness are smallest in the Cretaceous aquifer system and largest in the Floridan aquifer system.

Floridan Aquifer System

The Floridan aquifer system is one of the most productive ground-water reservoirs in the United States and is the principal source of ground water in southern Georgia. More than 600 Mgal/d (million gallons per day) is withdrawn from the aquifer system for irrigation, industrial, public, and rural-domestic supply (U.S. Geological Survey, 1985, p. 179). The aquifer system consists of limestone, dolomite, and calcareous sand, and yields a calcium bicarbonate type water. The water ranges from soft to very hard—about 4 to 2,550 mg/L as calcium carbonate. Among the six principal aquifers, the Floridan aquifer system has the largest median concentrations (fig. *2C*) of hardness (130 mg/L), dissolved solids (176 mg/L), and chloride (6.0 mg/L). Concentrations of nitrate shown in figure *2C* do not exceed the primary drinking-water standard of 10 mg/L, but in some analyses the concentrations were as large as 17.0 mg/L. The median concentration of iron (fig. *2C*) is less than the detection limit (10 µg/L); however, the water from some wells had concentrations as large as 1,200 µg/L.

Naturally occurring constituents in ground water have resulted in unsatisfactory water quality in a few small areas of the Floridan aquifer system. Between 1980 and 1985, community water-supply wells in Wheeler, Montgomery, Tift, and Berrien Counties (fig. *3B*, wells 1, 2, 3, and 4) were reconstructed to exclude water-bearing zones in the aquifer system in which the levels of natural radioactivity exceeded Georgia's drinking-water standards for combined radium-226 and radium-228 of 5 pCi/L (picocuries per liter) and gross alpha particle activity of 15 pCi/L (S.S. McFadden, Georgia Environmental Protection Division, oral commun., 1984).

North of Valdosta, Lowndes County, direct recharge of the aquifer by the Withlacoochee River has introduced significant levels of color and organic matter that, when combined with aquifer water, have produced hydrogen sulfide (fig. *3B*, area A). According to Krause (1979, p. 31), river water recharging the Floridan aquifer system generally exceeds secondary drinking-water standards for color (15 color units).

Although not a threat to public health, significant levels of color and hydrogen sulfide are present in water being withdrawn by some public supply, rural-domestic, and industrial wells in the Valdosta area. Since 1975, two city of Valdosta wells have been abandoned because the color intensity exceeded the drinking-water standard (fig. *3B*, wells 5 and 6). In 1975, the color intensity of the well water ranged from 0 to 90 platinum-cobalt units (color units), and the hydrogen sulfide concentration ranged from about 0.1 to 3.0 mg/L (Krause, 1976, p. 6; 1979, table 2). Results of a survey during 1982–85 indicate that water-quality conditions in the area have not changed appreciably since 1975.

Claiborne Aquifer

The Claiborne aquifer is an important source of water in southwestern Georgia, where it supplied an estimated 36 Mgal/d during 1980, primarily for irrigation. The sand and sandy limestone aquifer yields water that ranges from soft to hard (6 to about 160 mg/L). Median values (fig. *2C*) of dissolved solids (160 mg/L), chloride (3.0 mg/L), and iron (80 µg/L) do not exceed drinking-water standards established by the GEPD and the EPA. Concentrations of nitrate do not exceed the established primary drinking-water standard of 10 mg/L and range from the detection limit (0.1 mg/L) to about 3.6 mg/L.

Clayton Aquifer

The Clayton aquifer consists primarily of limestone and calcareous sand and is an important source of water in southwestern Georgia. During 1980, the aquifer supplied an estimated 20 Mgal/d, primarily for public supply and for irrigation (Clarke and others, 1984, sheet 6). Water from the aquifer generally is a calcium bicarbonate type and is classified as soft to hard (about 26 to 150 mg/L). Near the pumping center at Albany, Dougherty County, the water is a sodium bicarbonate type, which may indicate that water from the underlying Providence aquifer (Cretaceous aquifer system) is leaking upward into the Clayton aquifer (Clarke and others, 1984, sheet 6).

Concentrations of dissolved constituents generally do not exceed State and Federal drinking-water standards. Median values (fig. *2C*) are 165 mg/L dissolved solids, 2.2 mg/L chloride, and 120 µg/L iron. In part of Randolph County, however, concentrations of dissolved iron are as much as 620 µg/L, which exceeds the secondary drinking-water standard of 300 µg/L. The concentration of dissolved nitrate does not exceed the drinking-water standard and ranges from the detection limit (0.1 mg/L) to about 0.22 mg/L.

Cretaceous Aquifer System

The Cretaceous aquifer system is a major source of water in the northern one-third of the Coastal Plain where it supplied an estimated 128 Mgal/d during 1980, primarily for industrial and public-supply use. The aquifer system consists of sand and gravel and includes the Providence aquifer in the southwestern part of the State and the Dublin, Midville, and Dublin-Midville aquifer systems in the east-central part (Clarke and others, 1986, p. 32). Water from the aquifer system (fig. *2C*) is a soft (median hardness is 14 mg/L), sodium bicarbonate type that has little dissolved solids (median concentration is 35 mg/L). Concentrations of dissolved constituents generally do not exceed State and national drinking-water standards. Median concentrations of dissolved nitrate and chloride are 0.15 and 2.4 mg/L, respectively. Although the median value for iron is 40 µg/L, in much of east-central Georgia concentrations exceed the standard (300 µg/L) for drinking water (Clarke and others, 1985, p. 47). In part of the outcrop area, the water is naturally corrosive because it has low pH and a large dissolved-oxygen concentration.

Paleozoic Aquifers

The Paleozoic aquifers consist of sandstone, shale, limestone, and dolomite, and water is stored in joints, fractures, and solution openings in the bedrock. An estimated 33 Mgal/d was withdrawn from the aquifers during 1980, about half of which was for industrial supply. Water from wells and springs completed in the Paleozoic aquifers ranges from soft to very hard (6 to about 1,100 mg/L). Median dissolved-solids and chloride concentrations (fig. *2C*) are 126 and 3.0 mg/L, respectively. The median nitrate concentration is 0.36 mg/L. The median iron concentration is 30 µg/L but iron concentrations as large as 11,000 µg/L occur in water from some wells.

Crystalline Rock Aquifers

The crystalline rock aquifers of the Piedmont province (fig. *2B*) yielded an estimated 99 Mgal/d during 1980, primarily for rural supply (U.S. Geological Survey, 1985, p. 182). Water from the aquifers is a calcium bicarbonate type that is soft to very hard (about

1 to 855 mg/L). Median concentrations (fig. 2*C*) of dissolved solids and chloride are 87 and 2.7 mg/L, respectively. The median nitrate concentration is 0.25 mg/L. The median concentration of iron is 10 μg/L, but iron concentrations as large as 14,000 μg/L occur in some wells. Water-quality problems in the aquifers generally are limited to areas where naturally occurring iron concentrations are larger than the 300-μg/L standard for drinking water.

EFFECTS OF LAND USE ON WATER QUALITY

The State's ground water is of good quality overall; however, in a few small areas, ground-water-quality problems have resulted from agricultural practices, waste disposal, urbanization, and ground-water withdrawals. Water-quality changes attributed to agricultural practices (McConnell and others, 1984, p. 17) and ground-water withdrawals (Wait and Gregg, 1973, p. 65) have been documented by the U.S. Geological Survey in cooperation with the GEPD, EPA, and other agencies. Localized water-quality degradation attributed to waste disposal and urban activities has been detected.

Agricultural Practices

In a study conducted by the U.S. Geological Survey in cooperation with the EPA during August 1983, ethylene dibromide (EDB) was detected in a 4-square-mile area of the Floridan aquifer system in an intensively farmed part of central Seminole County (fig. 3*B*, area B). A soil fumigant, EDB was applied extensively until its use was banned by the EPA in September 1983. Results of the study indicate that EDB applied to the soils may have moved downward through the surficial material into the aquifer system. Water samples from 6 of 19 wells completed in the Floridan aquifer system contained EDB. Five of the samples that contained EDB were from irrigation wells, and one was from a rural-domestic well. Concentrations of EDB ranged from about 0.01 to 11.8 μg/L (McConnell and others, 1984, p. 15). Additional water samples collected during 1985 indicated that the area of contamination was approximately the same as in 1983 but that EDB concentrations had decreased. A survey conducted by the GEPD during October 1983 found no trace of EDB in any of the 21 community water systems sampled in Seminole County (John Fernstrom, Georgia Environmental Protection Division, oral commun., October 1986).

Waste Disposal

Hazardous waste is treated, stored, or disposed at 100 facilities regulated by the Federal Resource Conservation and Recovery Act (RCRA). As of September 1986, 37 land-disposal sites and 5 sites where spills or other waste releases have occurred were being monitored for ground-water quality (fig. 3*A*). The GEPD has determined that some contamination of shallow ground water has occurred at 35 of the 42 sites (J.R. Kaduck, Georgia Environmental Protection Division, oral commun., 1986). Five additional sites regulated by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 either have been proposed or have met requirements for the EPA's National Priorities List (NPL) of hazardous-waste sites (U.S. Environmental Protection Agency, 1986c). Contaminants have been detected in the shallow ground water at each of the five sites. The three CERCLA sites on the NPL are shown in figure 3*A*. No leachates from any of the RCRA or CERCLA sites have contaminated any public water-supply wells.

As of September 1985, 86 hazardous-waste sites at 6 facilities in Georgia had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. EPA presently ranks these sites under the hazard ranking system and may include them in the NPL. Of the 86 sites in the program, 22 sites contained contaminants but did not present a hazard to the environment. Eleven sites at 3 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required. No leachates from any of the IRP sites have contaminated any public water-supply wells.

Small concentrations of pesticides have been detected in one private well located downgradient from the Powersville, Peach County, CERCLA site (fig. 3*A*, site A) (D. Bracket, Georgia Environmental Protection Division, oral commun., 1986). This CERCLA site, which was a municipal landfill and a pesticide disposal area, is in a sparsely populated part of the recharge area of the Providence aquifer (Cretaceous aquifer system).

At Augusta (population 47,500), Richmond County, concentrations of arsenic that exceed the 0.05-mg/L primary drinking-water standard were detected (T.W. Watson, Georgia Environmental Protection Division, oral commun., 1986) beneath an industrial landfill (fig. 3*A*, site B). This CERCLA site is in the recharge area of the Dublin-Midville aquifer system (Cretaceous aquifer system). Because a corrective-action program has removed the source, arsenic concentrations can be expected to decrease.

At Brunswick, Glynn County, concentrations of toxaphene larger than the 5-μg/L primary drinking-water standard were detected in the surficial aquifer at an industrial landfill (D. Bracket, Georgia Environmental Protection Division, oral commun., 1986) that is included on the NPL list (fig. 3*A*, site C). The site is on the outskirts of the city of Brunswick (population 37,480) and overlies a surficial water-table aquifer that is not used as a source of drinking water.

In addition to the disposal sites described above, Georgia has about 265 municipal and industrial landfill sites (fig. 3*C*), of which about 50 are monitored for water-quality changes (J. W. Dunbar, Georgia Environmental Protection Division, written commun., 1986). As expected, most landfills are near the largest population centers of Atlanta, Fulton County, and Savannah, Chatham County. Monitoring, to date, does not indicate any significant ground-water contamination near any landfill in Georgia.

Urbanization

At Albany (population 73,900), Dougherty County, volatile organic compounds (VOC) were detected during late 1985 in two monitoring wells—one completed in the Floridan aquifer system and one completed in the underlying Claiborne aquifer (fig. 3*B*, wells 7 and 8). The wells are in the recharge area of the Floridan aquifer system. Concentrations of VOC did not exceed the EPA's proposed maximum contaminant levels, but the concentration of tetrachloroethylene exceeded their proposed recommended maximum contaminant level of zero for drinking water (K.R. Davis, Georgia Environmental Protection Division, written commun., 1986). A search of the area by GEPD revealed no likely source of contamination. Subsequent sampling and analysis during the summer of 1986 indicated small levels of contaminants in the Floridan well but did not show any in the Claiborne well (K.R. Davis, Georgia Environmental Protection Division, oral commun., 1986). There is no indication that the contaminants have affected any public water-supply wells.

In Fulton County, VOC were detected in a well completed in the crystalline rock aquifers (fig. 3*B*, well 9). Concentrations of the VOC trichloroethylene and 1,1-Dichloroethene exceeded the EPA's proposed maximum contaminant levels of 0 and 7 μg/L, respectively, for drinking water, and the concentration of tetrachloroethylene exceeded the proposed recommended maximum contaminant level of zero for drinking water (K.R. Davis, Georgia Environmental Protection Division, written commun., 1986). The well is near an industrial complex that may be the source of the contaminants. Ground water is not used for drinking in this area.

Ground-Water Withdrawals

The chloride concentration in water from the Floridan aquifer system in the Brunswick area has been monitored monthly or semiannually since the late 1950's. Since monitoring began, the chloride concentration has increased in part of Brunswick from about 20 mg/L to much more than the secondary drinking-water standard of 250 mg/L, largely as a result of movement of more saline water into the area due to ground-water withdrawals. Elsewhere in Brunswick, the chloride concentration does not exceed the drinking-water standard. Examples of the effects of ground-water withdrawals on chloride concentrations in the Floridan aquifer system in the Brunswick area are shown in figure 4.

Since pumping began in the late 1800's, the ground-water level in the Floridan aquifer system at Brunswick has declined as much as 65 feet. This water-level decline has allowed briny water from deep zones to migrate upward in the aquifer system at three known locations and move downgradient toward the centers of pumping. At two locations in Brunswick, the chloride concentration in the upper part of the aquifer system has increased to more than 2,000 mg/L (Clarke and others, 1986, p. 148). During the past 10 years, the city of Brunswick, whose water system serves a population of about 37,500, has abandoned three wells (fig. 3*B*, wells 10, 11, 12) because chloride concentrations exceeded the 250-mg/L drinking-water standard (fig. 3*B*, area C). Because saltwater intrusion is induced largely by pumping, the GEPD worked with local industries to achieve voluntary decreases in water use. The resulting 10-Mgal/d decrease in pumping caused a water-level rise that slowed the increase in chloride concentration (fig. 4). By 1984, the chloride concentration began to decrease (H.E. Gill, U.S. Geological Survey, oral commun., 1986).

POTENTIAL FOR WATER-QUALITY CHANGES

Georgia's aquifers are most susceptible to contamination from surface sources in recharge areas; the GEPD has taken the position that these areas warrant special protection efforts. Potential sources of contaminants include landfills and hazardous-waste sites, waste impoundments, and infiltration of agricultural chemicals applied to farmland. In the Coastal Plain and Valley and Ridge provinces (fig. 2*B*), the recharge areas of the various aquifers tend to be more areally extensive than in the Piedmont and Blue Ridge provinces. For this reason, the potential for contamination in the Coastal Plain and Valley and Ridge provinces is greater.

In recharge areas of the Cretaceous aquifer system, extremely permeable, sandy soils provide little protection against leakage from surface waste impoundments and landfills. The potential for contamination is greater near the urbanized areas of Columbus, Macon, and Augusta (fig. 1*A*) than in the rural parts of the Cretaceous recharge area. For the Floridan aquifer system, the risk of aquifer contamination is greatest in the intensely farmed Dougherty Plain District (fig. 3*B*, area D) where the soils are very permeable and sinkholes connect the aquifer with the land surface. The potential for aquifer contamination also is great in the Valdosta area (fig. 3*B*, area E), where sinkholes are numerous and where water from the Withlacoochee River directly recharges the Floridan aquifer system.

In the Valley and Ridge province, the Paleozoic aquifers are susceptable to contamination in limited areas where sinkholes have developed or where bedrock is exposed at the surface or is covered by a thin layer of soil (fig. 3*B*, areas F, G, H, and I). In the Piedmont province, the crystalline rock aquifers are vulnerable to contamination where they are exposed and where the protective layer of saprolite is thin and permeable.

Along the coast, the potential for saltwater intrusion in the Floridan aquifer system has been minimized by GEPD management practices that limit increases in ground-water withdrawals. However, if withdrawals were to increase in Georgia or in adjacent parts of Florida or South Carolina, the potential for saltwater intrusion would increase.

The use of agricultural chemicals has increased substantially in the last decade and probably will continue to increase. Irrigated farmland in Georgia increased from 300,000 acres during 1975 to 1,080,000 acres during 1985 (R.R. Pierce, U.S. Geological Survey, oral commun., 1986). Further, the demand for agricultural products is projected to increase through the end of the century (University of Georgia, 1986), and crop production likely will increase to meet the demand. As farming intensifies through the use of irrigation systems and the planting of several crops each year, ground-water contamination by agricultural chemicals could become a problem.

GROUND-WATER-QUALITY MANAGEMENT

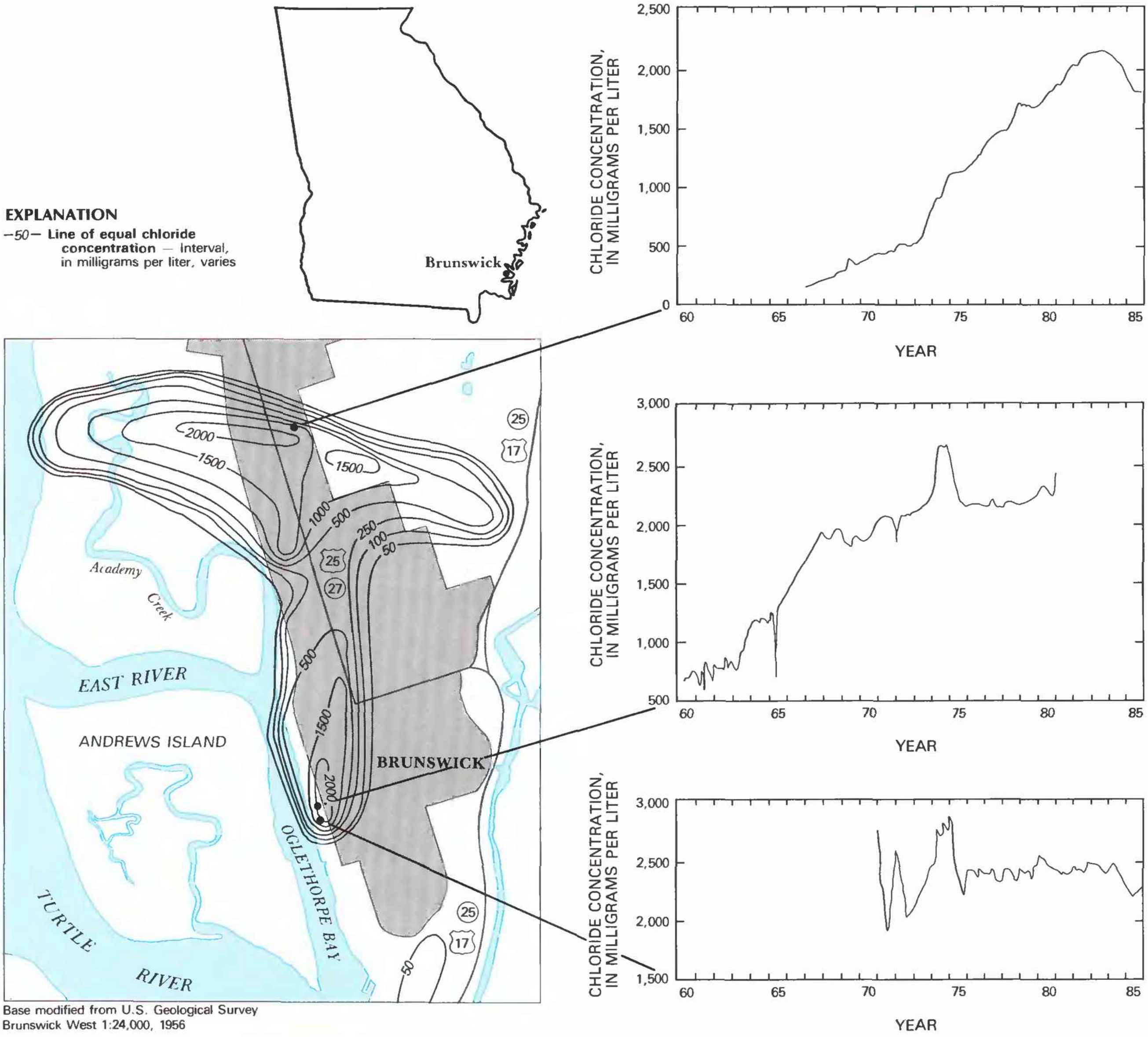
Through comprehensive laws and regulatory activities, the GEPD has significant control programs to prevent new ground-water contamination and to require remedial action in the few situations where contamination exists. Furthermore, the Division regulates municipal and industrial ground-water withdrawals exceeding 100,000 gal/d. Activities having the potential to affect ground water, such as wastewater treatment, landfill operation, hazardous-waste management, underground injection, surface mining, and oil and gas and other types of drilling, are all managed by the GEPD under existing laws. In addition, the Well Standards Act of 1985 provides for the licensing of drillers and for the proper construction, grouting, location, maintenance, operation, and abandonment of wells.

In 1984, a ground-water management plan for Georgia was developed and implemented by the GEPD. This plan provided for improved coordination of all the activities listed above, in addition to establishing a comprehensive ground-water-quality monitoring program. The Division also is preparing a recharge-area protection plan that will prevent degradation of the State's aquifers. The State's management strategy includes aquifer mapping, which has been completed through cooperative efforts between the GEPD and the U.S. Geological Survey and through the State's Underground Injection Control (UIC) program. Information on water-resource conditions in parts of the State, including ground-water contamination, is distributed to the public through the GEPD and local water-management plans.

The GEPD has long recognized that saltwater intrusion may be induced by pumping anywhere along the Georgia coast. To prevent more saltwater from moving into freshwater zones, the Division has instituted several comprehensive ground-water management practices. Ground-water management plans for the Savannah area will not permit future industrial withdrawals and will limit municipal withdrawals. A similar managment plan is in preparation for the Brunswick area. The GEPD, in cooperation with the U.S. Geological Survey, is conducting studies to assess the effect of increased water use on the quantity and quality of ground water in the coastal area of Georgia. The studies will use ground-water flow models to improve definition of the ground-water flow system and to assess the effect of geologic faults on that system.

Water quality in Georgia's aquifers is monitored through several networks:

- The GEPD has monitored more than 3,200 public-water systems statewide since the early 1970's on a frequency that varies from monthly to biannually.
- The U.S. Geological Survey has monitored the chloride concentration in the Floridan aquifer system at Brunswick, in cooperation with the city of Brunswick and with Glynn



Base modified from U.S. Geological Survey Brunswick West 1:24,000, 1956

Figure 4. Chloride concentration (October-November 1985) and change in chloride concentration (1960-85) in the Floridan aquifer system in the Brunswick area, Georgia. (Source: Modified from Clarke and others, 1986.)

County, since the late 1950's. At Savannah, the chloride concentration has been monitored by the U.S. Geological Survey from the late 1960's to 1984 in cooperation with the city of Savannah and Chatham County, and since 1984 in cooperation with the GEPD. Currently, 90 wells in the Brunswick area are monitored semiannually, and 11 in the Savannah area are monitored monthly.

- Water quality in 127 wells completed in the State's principal aquifers has been monitored by the GEPD since 1984 on an annual and semiannual basis. Samples are analyzed for standard constituents, organics, priority pollutants, and trace metals.

- Under the Hazardous Waste Management Act and the Georgia Solid Waste Management Act, the GEPD has overseen water-quality monitoring by operators at RCRA-regulated hazardous-waste sites, at CERCLA-regulated hazardous-waste sites, and at municipal and industrial landfills since the late 1970's. Samples are collected on schedules that range from monthly to annually.

In addition to the sampling networks described above, the GEPD has a cooperative program with the U.S Geological Survey that provides data and interpretive information needed to manage the quality and quantity of ground water in the State. Several studies conducted through this cooperative program have provided necessary information on the State's aquifers, including aquifer mapping, aquifer characteristics, flow characteristics and direction, and water quality. Although much information is known about the State's principal aquifers in the Coastal Plain (fig. 2*B*), additional information on these aquifers is needed, and significant additional information on aquifers in the Piedmont, Blue Ridge, and Valley and Ridge provinces is needed. The GEPD initiated in 1987 a 5-year plan to investigate the ground-water resources of northern Georgia. In addition, more data are needed for the shallow water-table aquifers (those less than 100 feet deep), which are the most vulnerable to contamination from the surface.

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HAWAII
Ground-Water Quality

Hawaii consists of 132 islands, shoals, and reefs (fig. 1). The State extends more than 1,600 miles across the central Pacific Ocean, and occupies 6,451 mi^2 (square miles) in a northwest to southeast orientation. The eight major islands, comprising 99.9 percent of the land, in decreasing size are: Hawaii (4,038 mi^2), Maui (729 mi^2), Oahu (608 mi^2), Kauai (553 mi^2), Molokai (261 mi^2), Lanai (139 mi^2), Niihau (73 mi^2), and Kahoolawe (45 mi^2) (U.S. Geological Survey, 1986, p. 201).

Ground water is the major source for public supply in Hawaii, and about 95 percent of the population (fig. 1*B*) depends on ground water. All ground water developed for public supplies does not exceed drinking-water standards recommended by the Hawaii State Department of Health (DOH) for dissolved solids, chloride, and nitrate. In the major areas of public-supply withdrawals, the median concentration of dissolved solids is smaller than 1,000 mg/L (milligrams per liter), and in all areas, the median nitrate concentration, reported as nitrogen, does not exceed the recommended maximum of 10 mg/L (fig. 2*C*). However, saltwater intrusion, on a regional or local scale, is a potential problem because most of Hawaii's ground water resides as a freshwater lens (referred to locally as basal water), floating on the underlying saltwater, in a highly permeable and porous aquifer. Two percent contamination of the aquifer by seawater will increase the chloride concentration of the water in the aquifer to exceed the secondary drinking water standard of 250 mg/L. Degradation of water quality in several areas is associated with use of organic compounds including ethylene dibromide (EDB), *dibromochloropropane* (DBCP), *trichloropropane* (TCP), trichloroethylene (TCE), perchloroethylene (PCE), and atrazine. Contamination of drinking-water sources by these synthetic chemicals has been confirmed by the DOH. At present, about 10 wells have been removed from service as a drinking-water supply because of contamination by EDB or DBCP at concentrations larger than 0.02 μg/L (micrograms per liter), and TCE at concentrations larger than 2.8 μg/L. These are the levels at which the DOH recommends a review for alternative sources or treatment of the water. In some instances, treatment plants have been installed to remove the contaminants before the water is used for public supply.

There are no active hazardous-materials disposal sites located in Hawaii. Three nonhazardous industrial sites (fig. 3) regulated under the Federal Resources Conservation and Recovery Act (RCRA) of 1976. Six well sites ("other" sites in fig. 3) on Oahu have been proposed for inclusion in the National Priorities List (NPL) for evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (U.S. En-

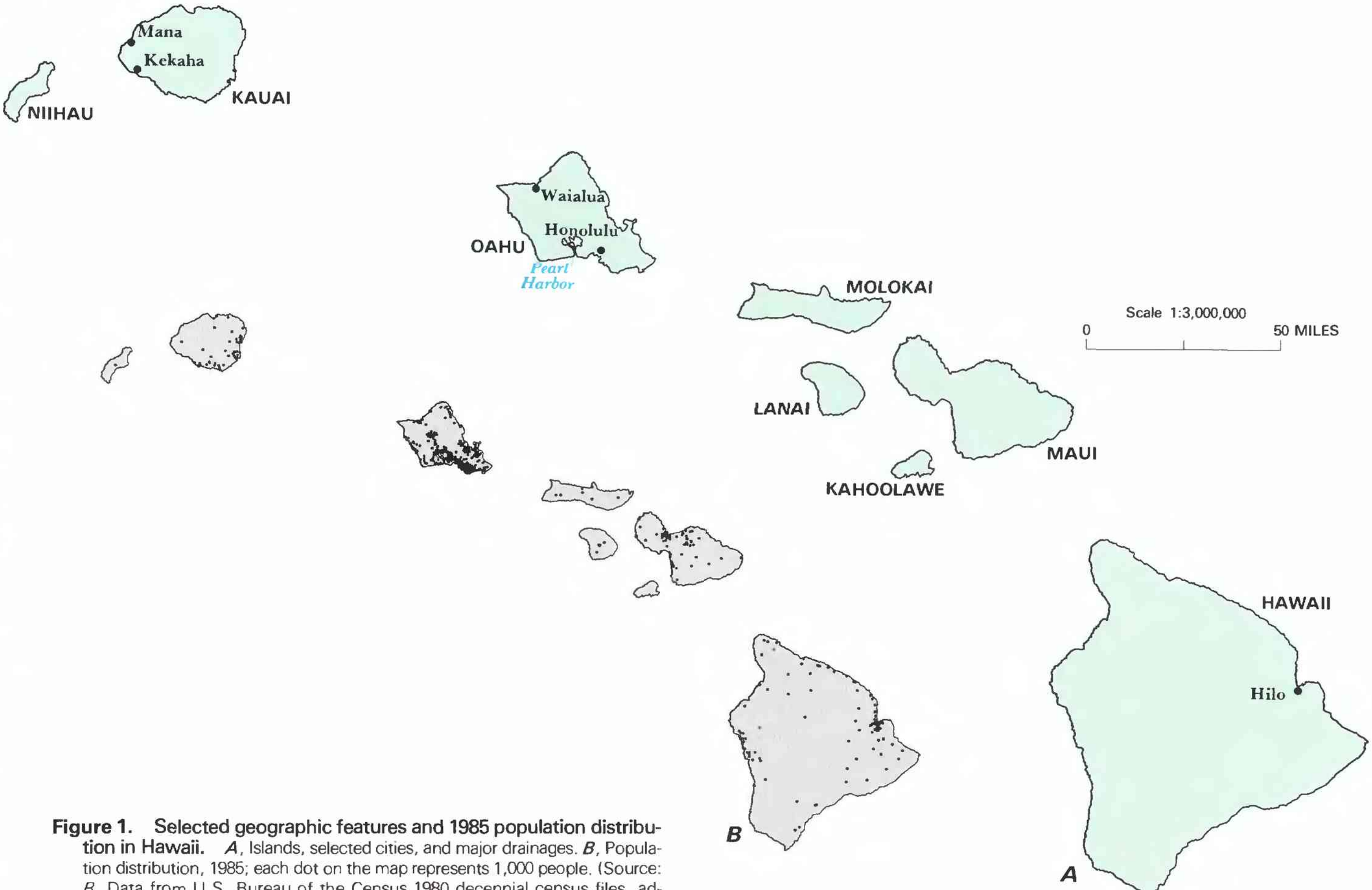

Figure 1. Selected geographic features and 1985 population distribution in Hawaii. *A*, Islands, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

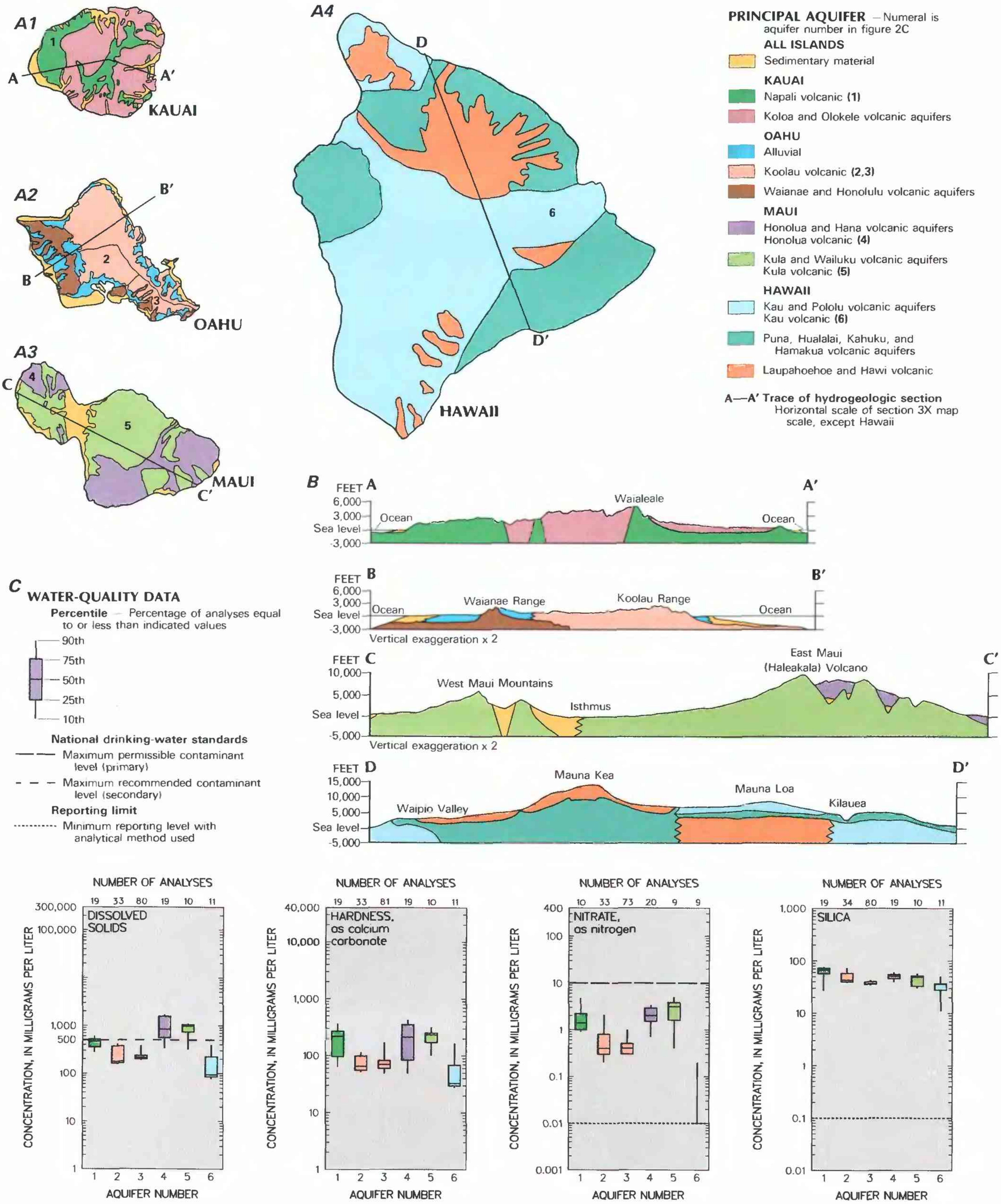

Figure 2. Principal aquifers and related water-quality data in Hawaii. *A*, Principal aquifers and generalized hydrogeologic sections: *A1*, Kauai; *A2*, Oahu; *A3*, Maui; *A4*, Hawaii. *B*, Selected water-quality constituents and properties, as of 1969-85. (Sources: *A*, U.S. Geological Survey, 1985; Stearns and Macdonald, 1942; modified from Takasaki, 1978. *B*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

vironmental Protection Agency, 1986c). In addition, the U.S. Department of Defense (DOD) has identified four sites at one facility where contamination has warranted remedial action.

In 1969, the U.S. Geological Survey, in cooperation with Hawaii State Department of Land and Natural Resources (DLNR), began a ground-water-quality observation program to monitor chloride concentration as a measure of saltwater intrusion into basal aquifers. By 1986, the program included measurements at more than 154 wells. In addition to monitoring chloride concentrations, the program has included limited data collection for inorganic and organic constituents. From 1984 to 1986, organic constituents were measured at 85 sites by the U.S. Geological Survey, in cooperation with the DOH, to determine organic priority pollutants in ground water. Organic constituents, however, have been measured at specific sites where presence of pesticides has prompted investigations by State and county agencies, and by the pineapple and sugar industries.

WATER QUALITY IN PRINCIPAL AQUIFERS

Eighteen aquifers have been identified on the six islands of Kauai, Oahu, Molokai, Lanai, Maui, and Hawaii (U.S. Geological Survey, 1985, p. 185). Among these are the principal volcanic aquifers that yield large quantities of water: Napali volcanic rocks in the Kekaha-Mana area, Kauai; Koolau volcanic rocks in central Oahu and Honolulu areas; East Molokai volcanic rocks in Molokai; Honolua volcanic rocks in west Maui; Kula volcanic rocks in central Maui; and Kau volcanic rocks in the Hilo area, Hawaii (fig. 2*A*).

Fresh ground water extends below sea level in porous volcanic rocks, floating as a freshwater lens in equilibrium with the underlying denser saline water. The lens is maintained by recharge. Whenever recharge is decreased, thinning of the lens occurs and subsequently seawater can encroach. In Hawaii, saltwater encroachment is the most common pollutant of freshwater. Many of Hawaii's ground-water problems are in some way connected to the encroachment of saline water induced by development and pumping of the aquifers (Takasaki, 1978, p. M1). Other ground-water bodies, small in comparison, are perched or isolated from the basal freshwater aquifers by intrusive dikes.

The freshest ground water in Hawaii, commonly containing less than 500 mg/L dissolved solids, occurs in the interior of the islands. At the outer rim of the islands, the dissolved-solids concentration in ground water exceeds 1,000 mg/L; below the freshwater lenses, dissolved-solids concentrations of the ground water approach those of seawater.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*B*. The summary is based on dissolved-solids, hardness (as calcium

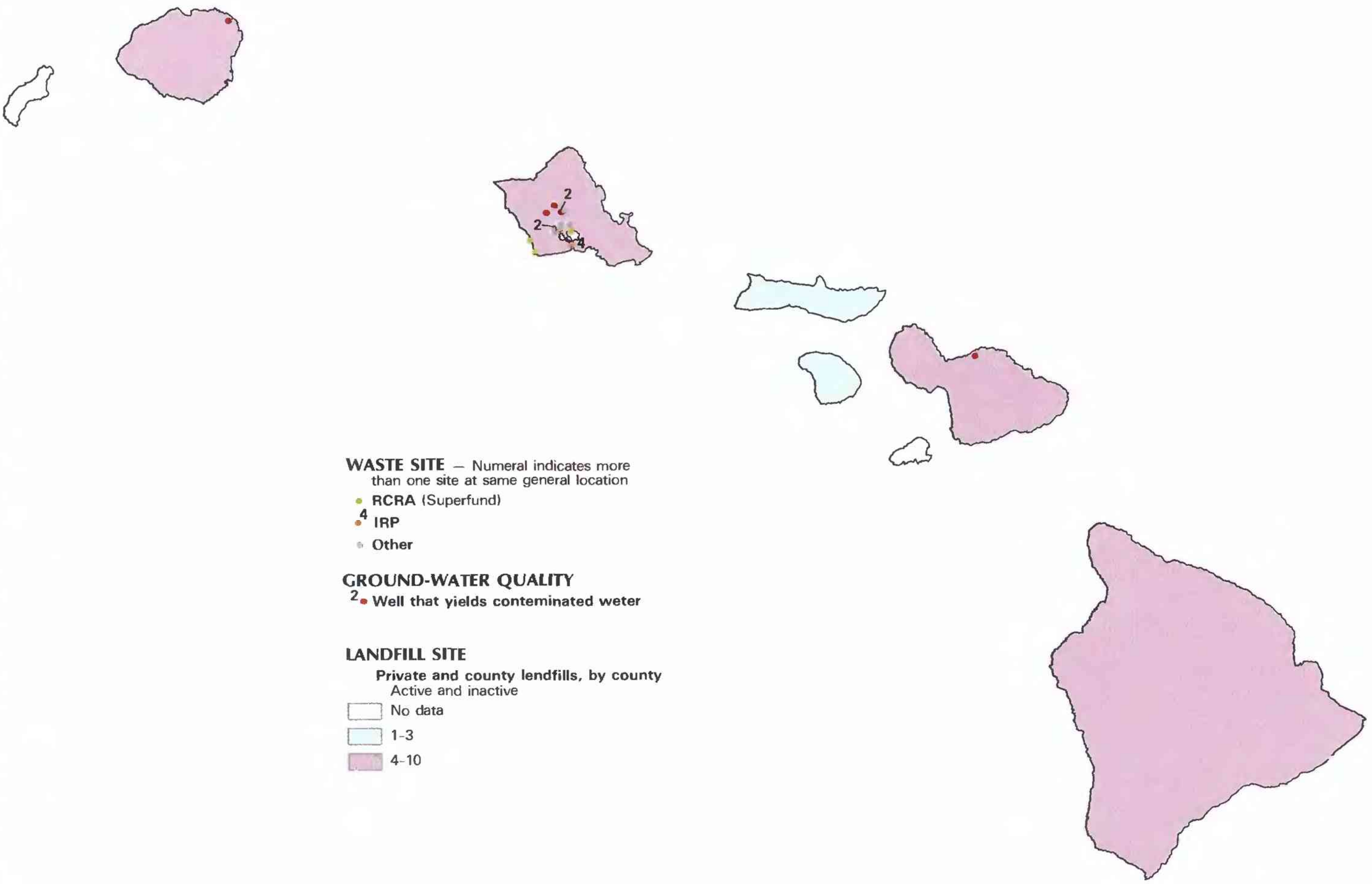

Figure 3. **Selected waste sites in Hawaii, 1986.** Resource Conservation and Recovery Act (RCRA) sites as of 1985; Department of Defense Installation Restoration Program (IRP) sites as of 1985 and other selected waste sites, as of 1986; distribution of wells that yield contaminated water, as of 1985; private and county landfills, as of 1985. (Sources: Hawaii State Department of Health records; U.S. Department of Defense, 1986; U.S. Environmental Protection Agency, 1986c.)

carbonate), nitrate (as nitrogen), and silica analyses of water samples collected from 1969 to 1985 from the principal aquifers in Hawaii. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include a maximum concentration of 500 mg/L for dissolved solids. The summary was limited to volcanic aquifers because of their importance as water supplies. The data base is not adequate to make statistical inferences for other aquifers. The data were interpreted without distinction as to sample depth within the aquifer, and where more than one analysis was available, the median concentration for a site was used.

Volcanic Aquifers

In the Koolau volcanic aquifers on Oahu (fig. *2B*, aquifers 2 and 3), where most water for public supply is withdrawn, the median concentration of dissolved solids does not exceed the secondary drinking-water standard of 500 mg/L. Although this limit does not apply to irrigation water, large concentrations of dissolved solids or salinity make the water less desirable for irrigation or other uses. Water from the Maui volcanic aquifers (fig. *2B*, aquifers 4 and 5) is used principally for irrigation; the median concentration of dissolved solids exceeds 500 mg/L.

Calcium and magnesium, which contribute to the hardness of water, are among the soluble minerals in water from volcanic aquifers. Generally, the larger the concentration of dissolved solids, the greater is the hardness (fig. *2B*). Hardness concentration is largest on Maui and Kauai, where the water is used mostly for irrigation. Hardness concentration for all public supplies is generally smaller than 120 mg/L, which is classified as moderately hard.

In water from all volcanic aquifers (fig. *2B*, aquifers 1–6), the median value of nitrate (as nitrogen) is smaller than 10 mg/L. No nitrate concentrations in ground water exceed this standard. In Hawaii, nitrate concentrations larger than about 1.1 mg/L (as nitrogen) indicate contamination by human activities (Swain, 1973, p. 5). Studies have indicated that increased nitrate concentrations in ground water are directly correlated with areas of irrigation.

The median concentration for silica is larger than 30 mg/L in all waters from the volcanic aquifers (fig. *2C*). Silica in water is undesirable for a number of industrial uses, because in the presence of calcium and magnesium it forms scale, especially in boilers and steam turbines.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has deteriorated in some areas because of the effects of urbanization, irrigation, and waste disposal. Investigation by the U.S. Geological Survey and interpretation of data collected by the Honolulu Board of Water Supply have documented declines in ground-water levels and increases in chloride concentration in Oahu's aquifers. Examples of the effects of urbanization on the chloride concentration in ground water are shown in figure 4.

Urbanization

Considerable ground-water development occurred, especially in southern Oahu, after the first successful well was drilled in 1879. During the 50 years that followed, water from wells near the coast in southern Oahu, once of good quality, became brackish. The ground-water level in the Honolulu area of Oahu, which once stood as high as 43 feet above sea level, steadily declined to about 25 feet above sea level (Takasaki, 1978). It is estimated from the Ghyben-Herzberg principle, that for the long-term loss of every foot of freshwater above sea level, there is a concurrent loss of about 40 feet of freshwater below sea level. The loss of freshwater is actually greater than 40 feet because of mixing of the fresh and saltwaters that causes a thickening of the transition zone between the two waters.

Among the major islands, Oahu has experienced unparalleled urban growth since statehood in 1959. To accommodate this growth, many agricultural lands were developed and urbanized. Because of this change in land use, much of the recharge from both irrigation and precipitation that normally would percolate into the water table in agricultural lands is now lost by evaporation or flows into storm drains away from the recharge area. The additional demands for water also led to increased pumping, which caused local upconing of the saline water and larger concentrations of dissolved solids.

Irrigation

The large use of ground water for irrigation in Hawaii has contributed to water-quality changes. Intensive pumping of the basal freshwater has caused local upconing of the underlying saline water, resulting in larger chloride concentrations. Irrigating with water containing larger chloride concentrations further increases the chloride concentration in the freshwater lens, as excess water percolates back to the water table. Eyre (1983) reported an increase of chloride concentration from 178 to 290 mg/L in water used as a potable supply in central Oahu. The increase of chloride concentration over a 7-year period was attributed to brackish irrigation-return water recharging the freshwater aquifer.

Application of fertilizer and other chemicals to the surface adds soluble products to the ground water, but at present, few chemicals have been detected in excess of the limits recommended for drinking water. However, pesticides and other organic compounds have reached the basal aquifers. The State has closed 10 wells that yield contaminated water (fig. *3B*) in central Oahu and has directed remedial action to eliminate DBCP and EDB in drinking water sources having concentrations larger than 0.02 μg/L. Two granulated active carbon (GAC) filtration units are operated by the Honolulu Board of Water Supply to remove DBCP, EDB, and TCP. The U.S. Army is operating an air-stripping unit to remove TCE in water pumped from the Schofield wells.

Waste Disposal

Waste sites in Hawaii are associated mainly with private and county landfills (fig. *3C*) that are used to dispose of industrial and domestic solid wastes. Most military waste sites have been discontinued and have been replaced with private-contracting disposal services. Very few data are being collected to evaluate the effects of active or inactive landfill sites on ground-water quality. Fortunately, most landfills are located away from ground-water recharge areas. Trace metals and organic chemicals commonly associated with landfills have not been detected in potable ground-water supplies. Hawaii lacks heavy urban and industrial densities that produce the type of heavy pollutant loads found in various parts of the continental United States. Furthermore, plans are being made to build and operate a garbage-to-energy plant in Honolulu that will further reduce the waste loading to landfills on Oahu.

There is no evidence that current surface impoundment activities are any threat to existing drinking water sources (Hawaii State Department of Health, 1980). This is due, in part, to the location of sites generally down-gradient and sufficient distances from drinking-water sources, and to the composition of the wastes going into impoundments.

As of September 1985, 32 hazardous-waste sites at 7 facilities in Hawaii had been identified by the U.S. Department of Defense

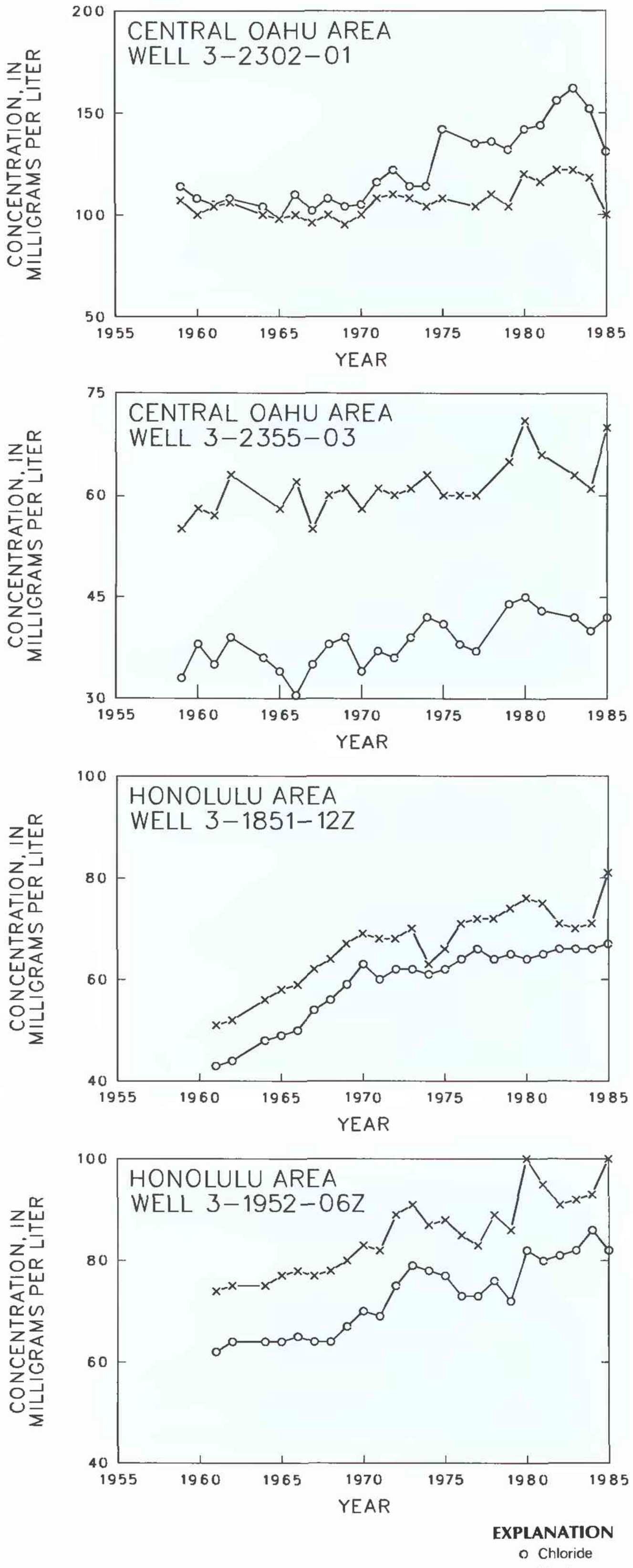

Figure 4. Long-term fluctuations of hardness and chloride concentrations in selected wells in Oahu, Hawaii, 1959-85. (Sources: C.E. Miyaji and S.E. Miyamoto, U.S. Geological Survey, written commun., 1986.)

(DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency's (EPA) Superfund program under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Four sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

There are no hazardous-waste disposal sites in Hawaii operating under RCRA regulations. All hazardous and toxic materials are currently transported by commercial contractors out of the state. RCRA sites are mainly industrial-related sites where chemicals are used for cooling or treating wastewater. There are two electric generating stations and one petroleum refinery on Oahu (fig. 3*A*) that are regulated by RCRA guidelines.

Six well sites ("other" sites in fig. 3*A*) have been proposed for inclusion on the NPL (U.S. Environmental Protection Agency, 1986c), because of contamination of the water by DBCP, EDB, TCE, and TCP. EPA has not made any final decisions on these CERCLA (Superfund) sites, and will retain them on its proposed list for future cleanup consideration. The sites are within the Koolau volcanic aquifer in central Oahu.

POTENTIAL FOR WATER-QUALITY CHANGES

Pesticides and chemicals have been reported in Hawaii's ground water other than those found in central Oahu's wells that yield contaminated water. Some are agricultural pesticides, and others may be decomposition products. Concentrations of many reported organic compounds, which have no established drinking-water standards, range from 0.02 to 0.20 μg/L. The potential danger of these chemicals has been recognized, and the DOH is developing strategies to monitor all frequently used and suspected compounds found in Hawaii's waters. Organic compounds detected and confirmed by the DOH in ground water include atrazine, carbon tetrachloride, DBCP, dichloropropane, dichloropropene, EDB, PCE, and TCP.

GROUND-WATER-QUALITY MANAGEMENT

The Hawaii DOH administers programs to protect the quality of ground water. Monitoring of ground-water quality for compliance with the Safe Drinking Water Act is performed by the State's Safe Drinking Water Program. This program monitors for those contaminants identified in Chapter 20, Title 11, Administrative Rules (Hawaii State Department of Health, 1981). The program attempts to ensure that water from public water systems meets all drinking-water standards. In the past, this program has monitored unregulated compounds in ground and surface waters, and in potable and nonpotable waters on a statewide basis.

Because of the agricultural activities in Hawaii, much of the emphasis in ground-water protection from pesticide usage is vested in the Pesticides Branch of the Hawaii State Department of Agriculture (DOA) for enforcement of rules for permit and application of pesticides. Monitoring of soils and water for the presence of pesticides has been undertaken by the Pesticides Branch with assistance from the Drinking Water Program and the Laboratories Branch of the DOH.

The Hawaii State Office of Environmental Quality Control (OEQC) has been directed by Act 127, Hawaii Session Law 1985, to coordinate and develop a systematic plan to monitor Hawaii's ground and surface waters. Short- and long-term strategies are being developed first to monitor drinking-water sources and then all other waters. The plan, to be completed by October 1, 1987, will report on which chemicals are frequently used, how toxic they are, how likely they are to enter into ground-water sources, and what efforts are needed to monitor the water resources.

The island character of the State, combined with the relatively fast population growth, requires that water quantity and availability be carefully monitored. This responsibility rests with the DLNR. The DLNR enforces Chapter 177, Hawaii Revised Statutes (HRS) which empowers it to control water withdrawals in areas of ground-water shortage. Currently, DLNR has designated areas in the Koolau volcanic aquifers of Waialua, Pearl Harbor, and Honolulu on Oahu as control areas to prevent depletion, waste pollution, or deterioration by saltwater encroachment. Permits for drilling wells on Oahu are required by the DLNR or the Honolulu Board of Water Supply.

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IDAHO
Ground-Water Quality

Idaho ranks as one of the top five States in the United States for volume of ground water used. Total ground-water pumpage was about 6.3 billion gallons per day in 1980 (U.S. Geological Survey, 1985, p. 193). Between 1980 and 1985, an increasing demand for ground water accompanied a statewide population growth of 6.4 percent (Allan Porter, Idaho Department of Commerce, oral commun., 1986). (See distribution of population in fig. 1.)

Although quantities of ground water for public and rural use are only about 3 percent of total ground-water pumpage, ground water is currently the principal source of more than 90 percent of public water supplies and 79 percent of rural-domestic and livestock supplies; these are large percentages compared to those of most other States. Many drinking-water supplies are pumped from relatively shallow aquifers (fig. 2), where the potential is large for degradation of ground water by land- and water-use activities.

Idaho's economy is dominated by agriculture and agriculture-related businesses such as food and meat processing, feedlots, dairies, aquaculture, and farm chemical, feed, fuel, or equipment supply. The most agriculturally developed and intensely populated areas in the State are valley lowlands and plains. These areas generally receive only 8 to 12 inches of precipitation per year. From about May to October, billions of gallons of both surface and ground water are applied to crops and pastureland each day to supplement infrequent rainfall.

Many potential sources of ground-water degradation are associated with agriculture or agriculture-related activities. Irrigation practices and land application of billions of gallons of wastewater from agriculture-related activities are major sources of recharge to many aquifers in the State and are direct or indirect sources of contaminants such as nitrate, iron, organic compounds, and bacteria. More importantly, recharge from land-use activities may transport contaminants from land surface to ground-water systems (fig. 3).

However, the most significant known and potential sources of ground-water contaminants are related to urban land use. The Idaho Department of Health and Welfare identified 17 land- and water-use activities as potential sources of ground-water contamination (Burr, 1986). Of these 17 activities, contamination is most frequently related to movement, storage, or transfer of petroleum or hazardous materials and land disposal of solid and liquid wastes.

Six hazardous-waste sites, including one commercial disposal facility near Grand View (Owyhee County), currently are regulated under the Resource Conservation and Recovery Act (RCRA) of 1976 (fig. 3*A*). Four additional sites have been included on the National Priorities List (NPL) of hazardous-waste sites (U.S. Environmental Protection Agency, 1986c) for assessment and cleanup action under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Known or potential ground-water contaminants at RCRA and CERCLA sites include solvents, wood preservatives, polychlorinated biphenyls (PCB's), petroleum products, and ore-processing wastes (lead and cadmium). An additional 39 sites, which currently are not subject to RCRA or CERCLA regulation, have received a preliminary site assessment, have potential or known ground-water contamination, or are awaiting further evaluation before monitoring or cleanup activities may be considered. In addition, the U.S. Department of Defense (DOD) has identified four sites at one facility where contamination has warranted response action.

Ground water in Idaho can be divided into two major types—nonthermal (temperature less than 26 °Celsius) and thermal (26 °Celsius or greater) (Wood and Low, 1987). Chemical characteristics and suitability for use of ground water differ throughout the State. In general, nonthermal ground water has good to excellent chemical quality, is suitable for most uses, and meets national drinking-water standards (U.S. Environmental Protection Agency, 1986a,b). In localized areas, use of very mineralized nonthermal water may be restricted for health, economic, or esthetic reasons. The quality of thermal ground water also is generally good for many uses, but concentrations of a few constituents in thermal water may exceed drinking-water standards or may be harmful to livestock or selected crops in some areas. Use of thermal water for crop and pasture irrigation can result in an accumulation of salts in soils.

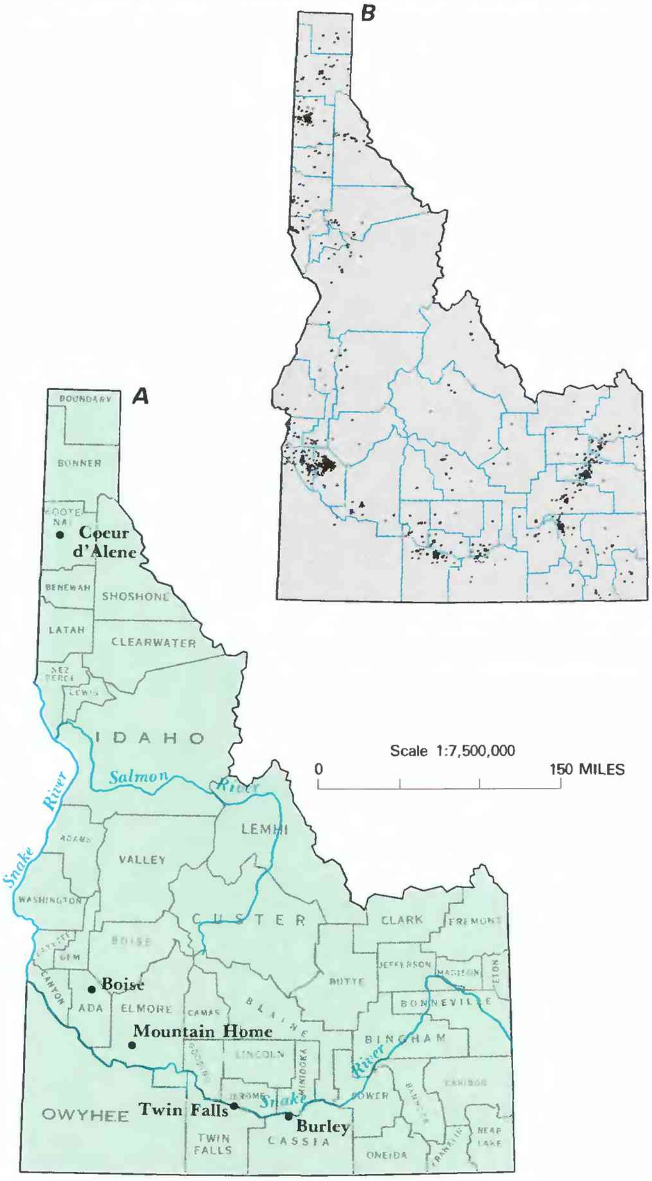

Figure 1. Selected geographic features and 1985 population distribution in Idaho. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Ground-water-quality data are sparse in most parts of the State, and few data are available to describe temporal variations of water quality in most aquifers. Although numerous local, State, and Federal agencies, as

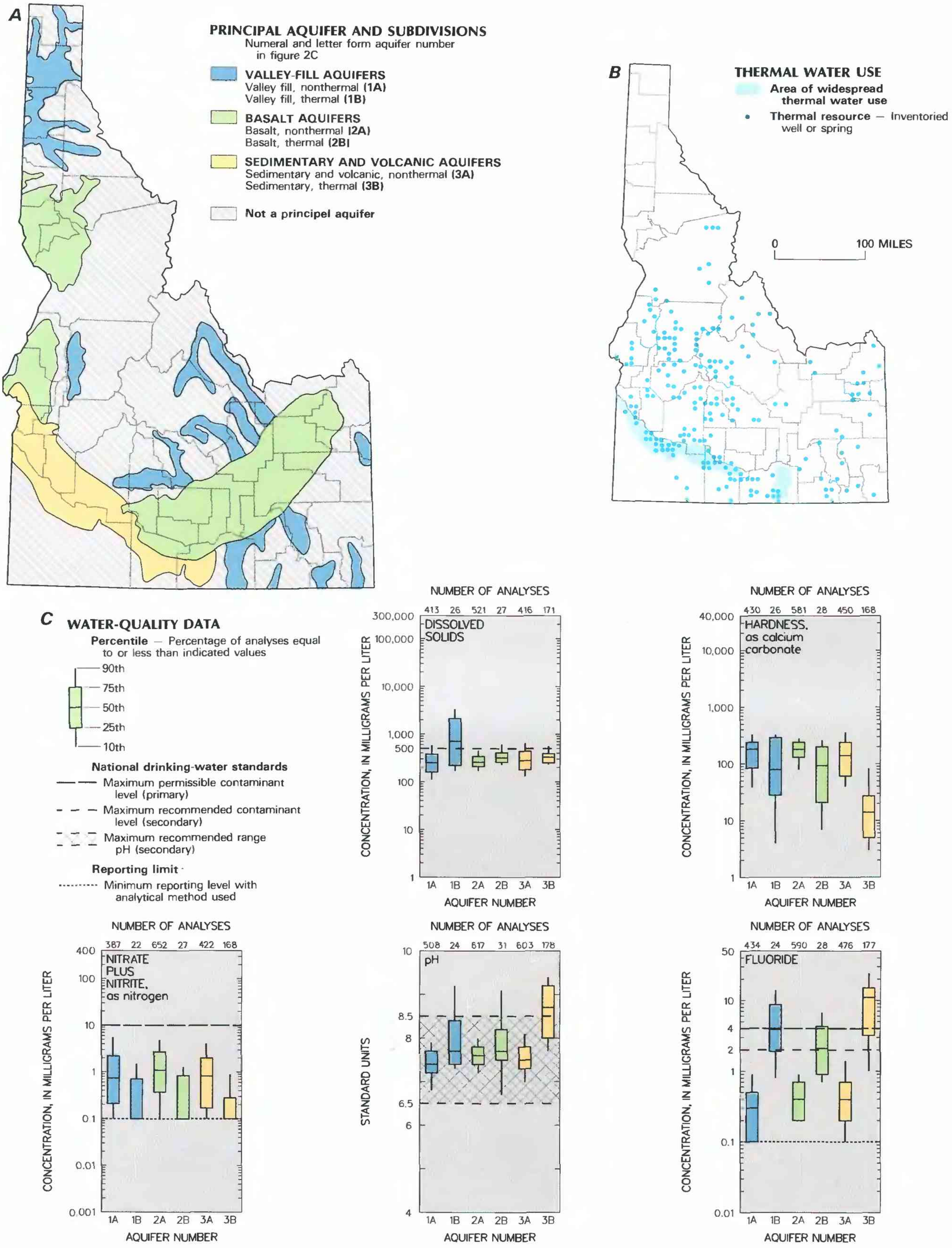

Figure 2. Principal aquifers and related water-quality data in Idaho. *A*, Principal aquifers. *B*, Thermal water-use areas. *C*, Selected water-quality constituents and properties, as of 1970-86. (Sources: *A*, U.S. Geological Survey, 1985; Burr, 1986. *B*, Yee and Souza, 1984. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

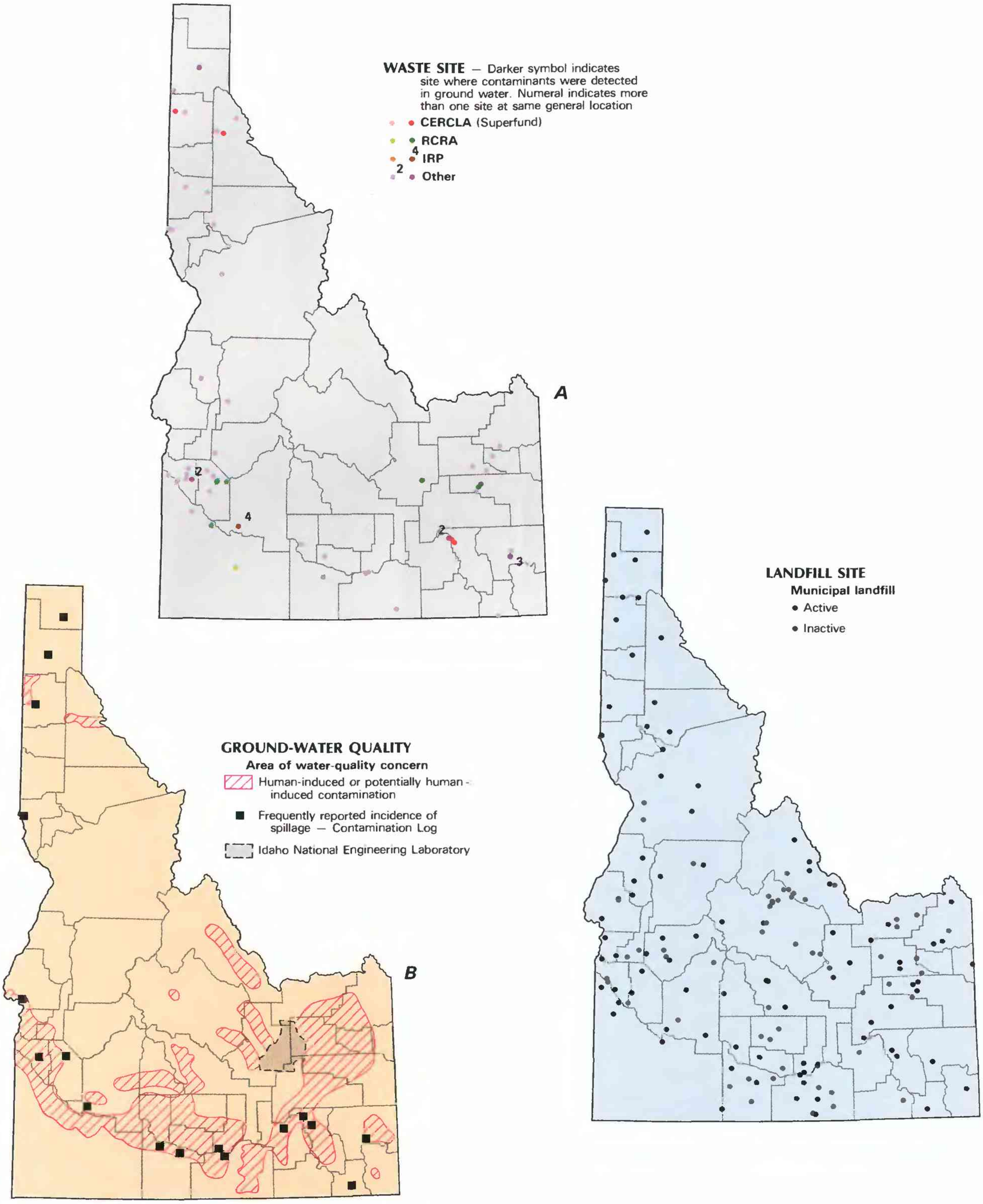

Figure 3. Selected waste sites and ground-water-quality information in Idaho. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of July 1986; Resource Conservation and Recovery Act (RCRA) sites, as of July 1986; Department of Defense Installation Restoration Program (IRP) sites, as of September 1985; and other selected waste sites, as of July 1986. *B*, Areas of human-induced or potential contamination and location of frequently reported incidences of spillage, as of July 1986. *C*, Municipal landfills, as of July 1986. (Sources: *A*, Cathy Ardakan, U.S. Environmental Protection Agency, written commun., 1986; Deborah Flood, U.S. Environmental Protection Agency, written commun., 1986; J.E. Jankowski, Idaho Department of Health and Welfare, written commun., 1986; S.L. Lund, Idaho Department of Health and Welfare, oral commun., 1986; U.S. Department of Defense, 1986. *B*, Yee and Souza, 1984; W.G. Graham, Idaho Department of Water Resources, written commun., 1986; Idaho Department of Health and Welfare, 1986b. *C*, J.E. Jankowski, Idaho Department of Health and Welfare, written commun., 1986.)

well as private organizations, collect and analyze hundreds of ground-water samples each year (Parliman and Brower, 1985), methods of data storage are different. Publication or distribution of data may be limited. Also, sampling methods and onsite sample preservation techniques are not standardized among the many agencies, and comparability of historical and current data may be questionable both within and among agencies. Analyses of synthetic organic, pesticide, and petroleum compounds are sparse, but a national survey by the U.S. Environmental Protection Agency (EPA) in 1981 indicated low-level contamination by synthetic organic compounds in 8 of 14 Idaho public water supplies (Westrick and others, 1984).

WATER QUALITY IN PRINCIPAL AQUIFERS

Seventy aquifers have been identified in Idaho, but some are limited in extent and yield insignificant amounts of water (U.S. Geological Survey, 1985, p. 193). Three principal aquifers have been defined and are characterized by their distinctive geology (fig. 2*A*)—valley-fill aquifers, basalt aquifers, and sedimentary and volcanic aquifers.

Valley-fill aquifers consist of unconsolidated sediments in intermontane valleys; water-yielding zones are most commonly unconfined. Recharge to valley-fill aquifers is primarily from infiltration of precipitation and leakage from surface-water sources. The chemical character of water in these aquifers is extremely varied, because of the diverse composition of aquifer materials. Principal valley-fill aquifers are located in northern and southeastern Idaho, and in the central Idaho mountains.

Basalt aquifers are characterized by numerous basalt flows and thin, interbedded sediments or pyroclastics. Water-yielding zones may be confined or unconfined. Major sources of recharge are infiltration of irrigation water; seepage from canals, streams, and rivers; and underflow from tributary basins. The principal basalt aquifer, which is the largest yielding aquifer in the State, underlies the eastern Snake River Plain (Sun, 1986).

Sedimentary and volcanic aquifers consist of unconsolidated sediment with basalt and felsic rock and interbedded shale and sandstone. Water-yielding zones may be confined or unconfined. Major sources of recharge are infiltration of irrigation water and seepage from canals and rivers. Principal aquifers of this group chiefly underlie the western Snake River Plain.

Each of these principal aquifers contains both nonthermal and thermal ground water. Generalized locations of inventoried thermal water resources are included in figure 2*B*. Nonthermal water may be from confined or unconfined water-yielding zones, commonly less than 400 feet below land surface. Nonthermal water is used mainly for domestic, irrigation, and industrial purposes. Thermal water is commonly from confined zones more than 400 feet below land surface and is used most commonly for irrigation, aquaculture, space heating, health spas, or recreation. Zones of mixed thermal and nonthermal water are common and can result from upward leakage of thermal water in open well boreholes or through faulted and fractured rock.

Significant thermal-water resources are associated with valley-fill aquifers in southeastern Idaho, basalt aquifers near Twin Falls and Burley, and all the sedimentary and volcanic aquifers in southwestern Idaho. Statewide, about 21,800 acres are designated as known geothermal resource areas and nearly 15 million acres (about 30 percent of the State) are classified as potentially valuable for geothermal exploration (Young and Mitchell, 1973). Although the potential volume of thermal water is relatively small compared with that of nonthermal water, water users in many parts of Idaho rely on thermal-water supplies for most nondrinking water needs, particularly for irrigation.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), fluoride, and pH analyses of water samples collected from 1970 to 1986 from the principal aquifers in Idaho. Data for both nonthermal and thermal water are shown for each principal aquifer. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen) and 4 mg/L fluoride; the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 6.5–8.5 units of pH, and 2 mg/L fluoride. In addition, a summary of the maximum values for selected water-quality properties or constituents in the principal aquifers is given as follows:

Maximum values for selected water-quality properties or constituents, 1970–86

(Data from U.S. Geological Survey water-quality files)

(Properties or dissolved constituents reported in degrees Celsius, °C; milligrams per liter, mg/L; or micrograms per liter, μg/L)

	PRINCIPAL AQUIFERS					
	Valley-fill		Basalt		Sedimentary and volcanic	
PROPERTY OR CONSTITUENTS	Nonthermal	Thermal	Nonthermal	Thermal	Nonthermal	Thermal
Temperature (°C)	25.5	95.0	25.5	76.0	25.5	84.5
Alkalinity, total (mg/L as $CaCO_3$)	810	430	520	630	1,580	830
Dissolved solids (calculated sum of constituents, mg/L)	6,600	3,600	1,500	1,000	2,400	1,000
Hardness (mg/L as $CaCO_3$)	1,600	330	610	280	1,700	250
pH	9.8	9.2	11.6	9.3	9.6	10.2
Chloride (mg/L as Cl)	3,900	2,100	830	83	430	88
Fluoride (mg/L as F)	11	14	7	13	17	30
Nitrate plus nitrite (mg/L as N)	25	1.5	22	2	29	3.8
Sodium (mg/L as Na)	2,000	1,300	470	330	570	330
Sulfate (mg/L as SO_4)	1,100	270	420	170	1,400	240
Arsenic (μg/L as As)	170	510	23	18	68	80
Boron (μg/L as B)	2,400	7,800	330	2,200	1,700	2,100
Iron (μg/L as Fe)	18,000	40	7,000	50	6,100	410
Manganese (μg/L as Mn)	3,200	520	5,100	10	7,700	110

Nonthermal Water

Chemical quality of nonthermal water generally is suitable for most uses and does not exceed the national drinking-water standards. Very mineralized ground water occurs naturally in localized areas statewide, particularly in sediments where nonthermal and thermal waters mix or where water is confined in organic-rich sediments. Very mineralized water may restrict water use because of health, economic, and esthetic reasons.

Nonthermal water in all aquifers contains predominantly calcium, magnesium, and bicarbonate ions or calcium, sodium, and bicarbonate ions. Where nonthermal water is very mineralized, pH or concentrations of dissolved solids, sulfate, chloride, fluoride, arsenic, iron, manganese, or selenium may be unusually large and may exceed primary and secondary drinking-water standards. Extremely hard water or anomalously large concentrations of alkalinity, sodium, or boron can make the water unsuitable for some domestic, industrial, or agricultural uses. Shallow, nonthermal water can become more mineralized by upward leakage of thermal water or by downward percolation of thermal water used for irrigation.

In most instances, very mineralized water is the result of natural geologic and hydrologic conditions in aquifers. Maximum concentrations of constituents generally are associated with nonthermal water in fine-grained lake or stream deposits in the valley-fill or sedimentary and volcanic aquifers. Anomalously large or restrictive concentrations of some trace metals, most commonly iron and manganese, may be related to land- and water-use activities. For example, maximum concentrations of iron and manganese in nonthermal water from basalt aquifers resulted from land application of food-processing wastewater (Parliman, 1986a).

Chemical characteristics of nonthermal water in principal aquifer groups (numbers 1*A*, 2*A*, and 3*A* in fig. 2*C*) were relatively uniform. At least 75 percent of dissolved-solids concentrations did not exceed the secondary drinking-water standard of 500 mg/L. Most nonthermal water was moderately hard to very hard; therefore, many consumers prefer to soften their water. More than 90 percent of the nitrate (as nitrogen) concentrations did not exceed the primary drinking-water standard of 10 mg/L, but many concentrations in nonthermal water were larger than the estimated natural background level of about 1 mg/L (few nonthermal water-quality data before intensive land use are available). More than 90 percent of the pH values for nonthermal water were within the established drinking-water range of 6.5 to 8.5. More than 75 percent of the fluoride concentrations in nonthermal water were smaller than 0.8 mg/L. Optimum State recommended limits for fluoride in public water supplies in Idaho, based on annual average maximum daily air temperatures, range from about 1.8 to 2.4 mg/L (Parliman 1983, 1986b).

Although nitrate plus nitrite (as nitrogen) concentrations commonly are smaller than 1 mg/L statewide, the median concentrations are largest in nonthermal water. Annual or seasonal increases in nitrate plus nitrite (as nitrogen) concentrations or concentrations that exceed about 2 mg/L probably indicate degradation of ground-water quality from land- and water-use activities. The largest median nitrate plus nitrite (as nitrogen) concentration was in nonthermal water from the basalt aquifers. Most of the basalt aquifer data were from the eastern Snake River Plain—an area of intensive and varied agricultural, industrial, and urban development.

Water-yielding zones that produce methane gas occur in areas with nonthermal and thermal water, principally in the sedimentary and volcanic aquifers of the western Snake River Plain and northern Owyhee County. Methane-producing wells are common throughout these areas, but areal and vertical distribution of ground-water related methane resources are generally unknown.

Thermal Water

Thermal water is suitable for many uses and contains predominantly sodium, bicarbonate, and sulfate ions or, rarely, sodium and chloride ions. In some areas, pH or concentrations of dissolved solids, sodium, fluoride, arsenic, or boron exceed primary and secondary drinking-water standards, and can be harmful to livestock or some crops, or can result in an accumulation of salts in soils.

In contrast to nonthermal ground water, chemical characteristics of thermal water in principal aquifers (numbers 1*B*, 2*B*, and 3*B* in fig. 2*C*) were diverse and often distinctive. Median values for dissolved solids, pH, and fluoride were larger in thermal water than in nonthermal water, but median values for hardness and nitrate (as nitrogen) were smaller in thermal water than in nonthermal water. The largest median dissolved-solids concentration was from thermal water in the valley-fill aquifers in southeastern Idaho. Hardness of thermal water in valley-fill and basalt aquifers ranged widely from soft to very hard; however, nearly 90 percent of the water in sedimentary and volcanic aquifers was soft. Nitrate plus nitrite (as nitrogen) concentrations were consistently small in thermal water. At least 50 percent of the nitrate plus nitrite (as nitrogen) concentrations from thermal waters in all aquifers were less than the detection limit of 0.1 mg/L, an indication that thermal water is not being degraded by land-use activities. The largest median pH and fluoride concentration were from thermal water in sedimentary and volcanic aquifers.

EFFECTS OF LAND USE ON WATER QUALITY

Most known and potential sources of ground-water contamination have been ranked on the basis of risk of harm and drinking-water standards (Idaho Department of Health and Welfare, 1985c). The ranking is as follows, from greatest to least risk: petroleum handling and storage; feedlots and dairies; landfills and hazardous-waste sites; land application of wastewater; hazardous-material handling; pesticide handling and use; land spreading of sludge and solid or liquid septic-tank pumpage; surface runoff; pits, ponds, and lagoons; radioactive substances; fertilizer application; septic-tank systems; mining, including oil and gas drilling; wells (injection, geothermal, domestic); and silviculture activities. Ground-water contamination from these land- or water-use activities can be caused by large concentrations of one or more of the following constituents: dissolved solids; sulfate; chloride; fluoride; sodium; nitrogen compounds; phosphate compounds; trace metals including iron, manganese, or zinc; radiochemicals; detergents; pesticides; toxic metals such as cadmium or chromium; petroleum products; or hazardous organic chemicals including solvents, wood preservatives, and PCB's (Yee and Souza, 1984; S.L. Lund, Idaho Department of Health and Welfare, oral commun., 1986). Biological contaminants include bacteria, viruses, and possibly giardia lamblia.

In 1985, the Idaho Department of Health and Welfare (1986b) established a Contamination Log to record occurrences of potential or known ground-water contamination. The log is a compilation of information about spills in nine categories of contaminants, including pesticides and releases of chemicals from mining, landfills, and other activities. As of January 1, 1986, 252 incidents of potential or known contamination were recorded; however, records before 1980 are sparse. Although documentation and reporting of incidents have not been consistent statewide, incidents reported since 1980 generally are located in urban areas and frequently are associated with movement, storage, or transfer of petroleum or hazardous materials and land disposal of solid and liquid wastes.

Waste-disposal sites and known or potential areas of ground-water contamination are shown in figure 3. Figure 3*A* shows locations of the following: (1) 4 CERCLA (Superfund) hazardous-waste sites; (2) 6 RCRA hazardous-waste sites; and (3) 51 other sites which include 12 industrial or municipal/industrial waste-disposal sites and 39 sites, not currently regulated under RCRA or CERCLA, that have potential or known hazardous-materials contamination. Contaminants commonly associated with waste- disposal sites are industrial solvents, wood preservatives (creosote, pentachlorophenol), PCB's, petroleum products, and ore-smelting wastes (lead and cadmium).

As of September 1985, 12 hazardous-waste sites at 2 facilities in Idaho had been identified by the U.S. Department of Defense as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA of 1980. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Four sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Ground water at 1 of the 12 sites at the U.S. Air Force Base near Mountain Home is being monitored and evaluated as part of the IRP.

Figure 3*B* shows major areas where the potential exists for degradation of ground-water quality because of nonsewered urban and industrial development, agricultural irrigation, drain-well use, Idaho National Engineering Laboratory activities, and major mining and related processing activities. Most contamination occurs in discrete locations; therefore, patterns in figure 3*B* represent those areas of the State with the greatest potential for or frequency of contamination from a particular source. Generalized areas where known and potential ground-water contamination are most frequently reported in the Department of Health and Welfare's Contamination Log are also shown in this figure. Naturally impaired water quality occurs locally in every part of the State, but in most instances, data on very mineralized water are most complete in areas with thermal, mixed thermal, and nonthermal water-yielding zones.

Contaminants associated with nonsewered urban and industrial development near Coeur d'Alene and Boise include the following: dissolved solids, nitrate, bacteria, iron, manganese, toxic organic wastes from household chemicals such as trichloroethylene (TCE), petroleum products (pesticides, solvents, wood-treatment products), and food-processing wastes (Jones and Lustig, 1977; Idaho Department of Health and Welfare, 1985b). Several hazardous-waste sites, currently regulated or being evaluated for RCRA action, are located in these areas (fig. 3*A*). Valley-fill aquifers in northern Idaho are particularly susceptible to contamination from surface sources. The largest valley-fill aquifer in northern Idaho was designated as a "sole source aquifer" (sole or principal source of drinking water) in 1976 under the Safe Drinking Water Act (Jones and Lustig, 1977).

The State's only commercial hazardous waste-disposal site, in northern Owyhee County, overlies numerous nonthermal and thermal water-yielding zones of the sedimentary and volcanic aquifer group. Some organic contaminants have been detected in ground water at the site (S.L. Lund, Idaho Department of Health and Welfare, oral commun., 1986). Concern exists not only for further contamination and migration of contaminants, but also for spillage of hazardous materials being transported to the site on highways.

Contaminants associated with irrigation and street or highway drain wells include suspended sediments, dissolved solids, bacteria, sodium, chloride, nitrate, phosphate, organic compounds (including pesticides), and lead. Of these constituents, suspended sediments, bacteria, and lead may pose a risk to some domestic ground-water supplies (Idaho Department of Health and Welfare, 1985a). Nearly 1,900 drain wells have been inventoried in Idaho, and of these, 1,590 are in use, primarily in the eastern Snake River Plain (W.G. Graham, Idaho Department of Water Resources, oral commun., 1986). All injection wells, authorized for construction and use within the area overlying the eastern Snake River Plain, are EPA subclass V (nonhazardous or nonradioactive fluid injection). Current injection wells probably present minimal hazards to regional ground-water quality. However, because the eastern Snake River Plain basalt aquifer is being considered for "sole source aquifer" designation, this widespread disposal practice is being closely monitored by the Idaho Department of Water Resources.

The Idaho National Engineering Laboratory encompasses about 980 square miles and overlies part of the eastern Snake River Plain basalt aquifer. The facility, which was established in 1949 to build and test nuclear reactors, currently stores chemical radioactive wastes from this and other sites across the United States. Contaminants associated with these activities include dissolved solids, sodium, sulfate, chloride, nitrate, chromium, solvents, and radionuclides including tritium, strontium-90, iodine-129, cobalt-60, cesium-137, and plutonium (Robertson and others, 1974; Leenheer and Bagby, 1982; Lewis and Jensen, 1984; Yee and Souza, 1984). Concern exists for both migration of contaminants from the site and spillage of materials being transported to the facility.

Known and potential contaminants from mining and related processing activities in northern and southeastern Idaho include phosphate compounds, fluoride, radiochemicals, and metallic trace elements such as arsenic, cadmium, chromium, iron, lead, manganese, and zinc (Parliman and others, 1980; Jacobson, 1982, 1984; Yee and Souza, 1984; and S.L. Lund, Idaho Department of Health and Welfare, oral commun., 1986). Cyanide, mercury, and arsenic also are potential contaminants in several mountain valleys, principally in central Idaho.

Locations of municipal landfill sites are shown in figure 3*C*. Landfills receive domestic, agricultural, and industrial-waste materials including aquaculture sludge, municipal waste-treatment sludge, liquid and solid septic-tank wastes, and probably small quantities of hazardous wastes. Effects of landfills on ground-water quality currently (1986) are not being monitored routinely.

POTENTIAL FOR WATER-QUALITY CHANGES

Degradation of water quality from migration of petroleum and hazardous wastes from numerous disposal, storage, transfer, or spillage sites is a primary concern in urban areas. In the basalt aquifer of the eastern Snake River Plain, water quality may also be affected by agricultural practices and the widespread use of drain wells, land spreading of wastes, and disposal of low-level radioactive and chemical waste at the Idaho National Engineering Laboratory. The potential exists for water quality to be affected by increased concentrations of trace metals in ground water in the mining district in northern Idaho and phosphate-ore and fertilizer processing areas in southeastern Idaho. Areas with the most intensive land-use activities and the greatest potential for land- or water-use effects on ground-water quality are in both the eastern and the western Snake River Plain and in the northern Idaho valleys.

Background water-quality data are sparse in Idaho, particularly in recharge areas. Few analyses are available on organic compounds, such as pesticides and toxic wastes from household and industrial chemicals. The potential effectiveness of some ground-water management activities may be affected by lack of long-term, comprehensive monitoring programs.

GROUND-WATER QUALITY MANAGEMENT

Management of ground-water resources and protection of these resources from contamination are the responsibilities of the Idaho Department of Water Resources (IDWR), Department of Lands; Department of Agriculture; and Department of Health and Welfare, Division of Environment (Bureau of Water Quality and Bureau of Hazardous Materials). Limited protection of ground-water resources presently (1986) is provided through statewide regulations for various activities.

Regulatory and administrative authority for ground-water protection is provided by State statutes and Federal regulations. The IDWR has authority to assess ground-water resources, including aquifer mapping and data collection of nonthermal and thermal resources, and federally delegated responsibility to regulate injection wells. The Idaho Department of Lands is responsible for protection of ground water from oil and gas drilling operations. This agency also directs State programs in surface mining, dredge mining, and rural forestry—activities that can result in ground-water contamination. The Idaho Department of Agriculture has been delegated responsibility for the Federal Pesticides Enforcement Program.

Most State statutes and federally delegated authority are the responsibility of the Idaho Department of Health and Welfare, including regulation of General Water Pollution Control and Public Water System programs. The Division of Environment, Water Quality Bureau, of the Idaho Department of Health and Welfare is the lead agency in managing the quality of Idaho's ground water. In 1983, the Water Quality Bureau published the State's first comprehensive Groundwater Quality Management Plan (Martin, 1983), which outlines a coordinated approach to ground-water quality management among several State agencies. Since 1983, a management strategy has been developed for the basalt aquifer of the eastern Snake River Plain (Idaho Department of Health and Welfare, 1986a). Regulations or guidelines have been revised or established for 16 potential contaminant sources, and 10 original program elements are ongoing or have been completed, including hazardous-waste regulations and the Contamination Log.

A second edition of the Groundwater Quality Management Plan was published in 1985 (Idaho Department of Health and Welfare, 1985c) to update work on ground-water-quality programs, assess the current status of the plan, and propose additional direction for Idaho's ground-water-quality management. Current ground-water management priorities include establishment of a management strategy for valley-fill aquifers in northern Idaho; ground-water policy and water-quality standards (selected inorganic and organic compounds); a dedicated statewide monitoring program; guidelines for cyanide leachates and feedlots; and regulations for underground storage tanks, land application of wastewater, and pesticide container and equipment rinse-water handling.

Ground-water-quality monitoring data are obtained primarily through the State's drinking-water program. This program consists of about 2,600 public-supply systems that are analyzed periodically for selected water-quality characteristics. From 1975 through 1982, the U.S. Geological Survey, in cooperation with the IDWR, established reconnaissance ground-water-quality data bases for areas where land and water-resource development was expected to increase, but the program was discontinued after studies in seven areas were completed. The U.S. Geological Survey, in cooperation with the IDWR, published a ground-water-quality monitoring network plan in 1979 (Whitehead and Parliman, 1979). Also, a project proposal for statewide ground-water-quality monitoring was developed by the U.S. Geological Survey and the Idaho Department of Health and Welfare in 1985, but the project has not been implemented. Current monitoring activities consist of water-level measurements and occasional ground-water analyses for site or areal studies by numerous local, State, and Federal agencies.

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Road cut near Kimberly, Idaho reveals a cross section of an open-hole well construction frequently used in Idaho. Surface casing is cement grouted to the well borehole to a shallow depth. The remaining borehole is left uncased, allowing mixing of water from aquifers throughout the depth of the well. (Photograph by D.J. Parliman, U.S. Geological Survey.)

Prepared by D.J. Parliman

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ILLINOIS
Ground-Water Quality

Illinois contains abundant water resources. About one-third of the water withdrawn in 1984 for public water-supply systems was from ground-water sources. Public water supplies furnish 88.7 percent (10.2 million) of the State's 11.5 million people (fig. 1) with potable water; ground water supplies about 3.7 million people. An additional 1.3 million people have their own supply of potable water, nearly all of which is ground water (Kirk and others, 1985). Ground-water quality in the principal withdrawal areas (fig. 2) of the State generally does not exceed the drinking-water standards established by the Illinois Pollution Control Board (1984a,b). Ground water in Illinois generally is very hard, and concentrations of iron and manganese commonly exceed the State standard. However, these conditions can be treated and water use is not impaired.

Ground-water quality has been degraded in several areas of the State (fig. 3). The degradation commonly has been associated with urbanization and waste-disposal practices. Although these are not the only sources of contamination in Illinois, they are the ones more readily observed and monitored. Waste disposal is a particularly serious concern, for it may affect all sectors of the State's population and economy. These sources of potential contamination include industrial wastes, municipal landfills, human and animal wastes, oil-field brine and impounded waste.

In 1984, the U.S. Geological Survey and the Illinois Environmental Protection Agency (IEPA), with assistance from the Illinois State Water Survey (ISWS) and Illinois State Geological Survey (ISGS), began a systematic approach to ground-water-quality data collection. The resultant ground-water-quality observation network includes the first statewide sampling for volatile organic compounds (VOC) of all public water-supply wells in Illinois. A smaller subset of wells is being sampled for pesticides. As of July 1986, 1,100 public water-supply wells had been sampled. Before this program, data were collected in response to State regulations requiring compliance with drinking-water standards and the collection did not always consider location or source aquifer. Changes and improvements in analytical procedures and differences in procedures between laboratories complicated data comparisons.

WATER QUALITY IN PRINCIPAL AQUIFERS

There are five principal aquifers in Illinois (fig. 2)—the sand-and-gravel, Pennsylvanian-Mississippian, shallow dolomite, Cambrian-Ordovician, and Mount Simon (U.S. Geological Survey, 1985, p. 199). More than half of the State's ground-water withdrawals are from the sand-and-gravel aquifers. Withdrawals from the combined Cambrian-Ordovician and Mount Simon aquifers account for about 28 percent of the ground-water withdrawal; the shallow dolomite aquifer about 16 percent; and the Pennsylvanian-Mississippian aquifers about 5 percent. In 1984, ground-water withdrawals in Illinois were estimated to be 1,100 Mgal/d (million gallons per day), and the largest percentage (43 percent) was withdrawn for public water supply. About 54 percent of all ground-water withdrawals in the State are for public supply and rural-domestic use (Kirk and others, 1985).

Natural water quality from some zones of some aquifers is undesirable in several parts of the State. The Cambrian-Ordovician and Mount Simon aquifers are not used in the southern two-thirds of the State because concentrations of dissolved solids are larger than 10,000 mg/L (milligrams per liter).

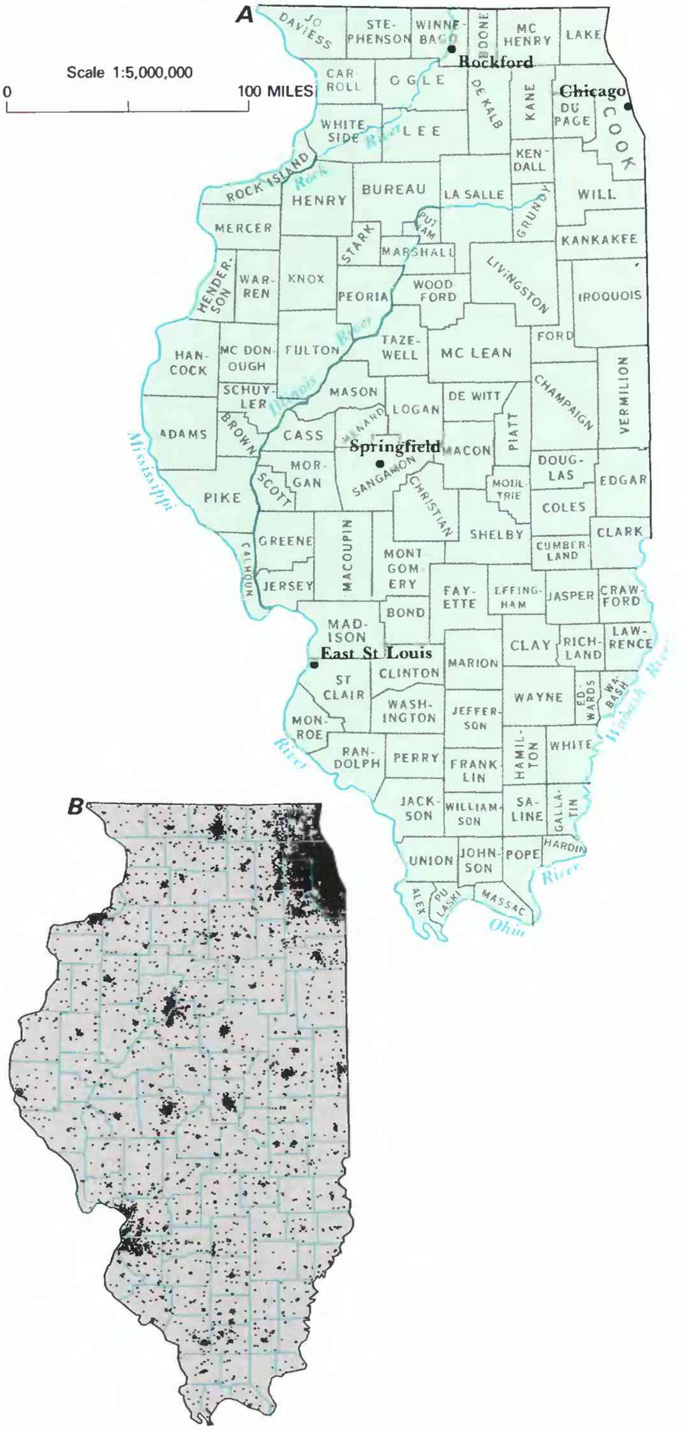

Figure 1. Selected geographic features and 1985 population distribution in Illinois. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

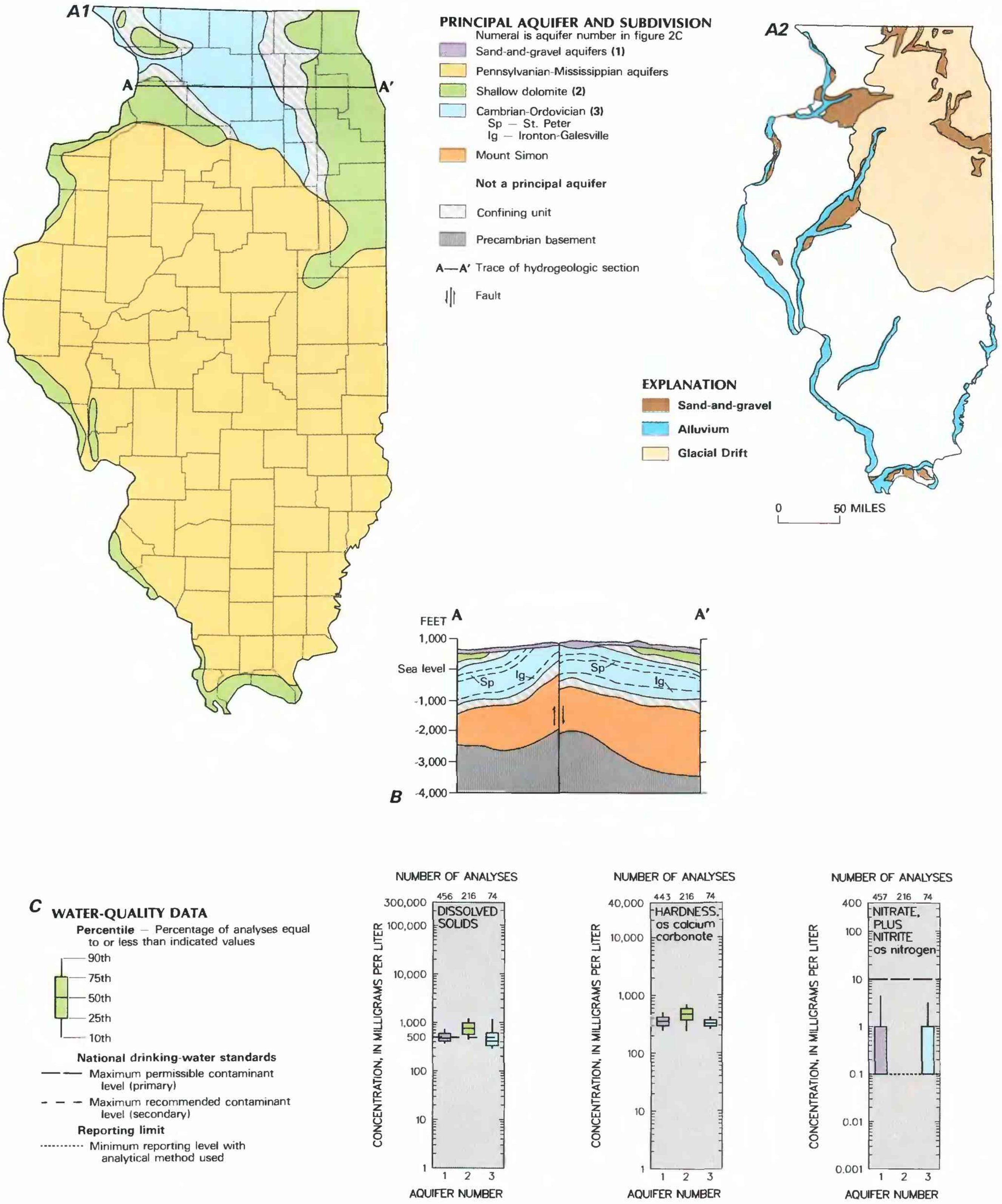

Figure 2. **Principal aquifers and related water-quality data in Illinois.** *A*1, Principal aquifers; *A*2, Surficial deposits. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of June 1986. (Sources: *A*1, Willman and others, 1967. *A*2, Willman and others, 1975. *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a, b.)

Radioactivity from naturally occurring radionuclides such as radium has been observed in the Cambrian-Ordovician and Mount Simon aquifers in parts of northern Illinois (Gilkeson and others, 1983, 1984) and in two smaller areas in the Pennsylvanian-Mississippian aquifer in southern Illinois (Illinois Environmental Protection Agency, 1986) (fig. 3*B*). The ISGS is continuing to study naturally occurring radioactive contaminants in the State.

Recently, attention has focused on arsenic in some drinking-water supplies in the central part of Illinois. Larger than average arsenic concentrations, some exceeding the State standard (0.05 mg/L), have been detected in the sand-and-gravel aquifers. Two public water supplies in Macon County and some private wells in Tazewell County have reported arsenic concentrations that may threaten use of the water. Investigations are currently (1986) underway to define the affected area and determine the source.

Historical ground-water-quality data before 1984 lacked documented quality assurance and have sampling bias. Except for compliance monitoring, ground-water-quality work generally was done in response to "problems"; wells producing "good" water were less likely to be sampled (Frost and others, 1984). Information about private domestic wells was mainly from voluntarily submitted samples, not always identified with regard to location, aquifer, or well sampled. In 1984, the U.S. Geological Survey in cooperation with the U.S. Environmental Protection Agency (EPA) initiated a ground-water sampling network that will include all 3,427 public water-supply wells in the State.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), iron, and sulfate analyses of water samples collected from 1984 to 1986 from the principal aquifers in Illinois as part of the ground-water-quality observation network. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a, b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include maximum concentrations of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter) iron, and 250 mg/L sulfate. For nitrate, dissolved solids, and sulfate the State drinking-water standards are the same as the national standards. The State standard for iron is 1,000 μg/L.

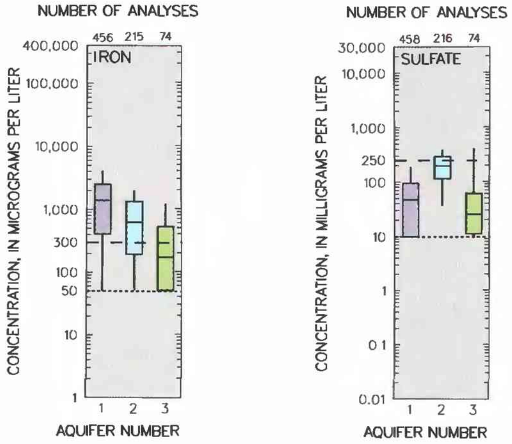

Figure 2. Principal aquifers and related water-quality data in Illinois—Continued.

Sand-and-Gravel Aquifers

Collectively, the sand-and-gravel aquifers in Illinois are the largest source of water for domestic supplies. Although extensively distributed throughout the State, individual aquifers can differ greatly in depth and yield. The largest yields generally are obtained from outwash sand and gravel in major glacial valleys (U.S. Geological Survey, 1985, p. 199–204). Water-quality data (fig. 2*C*) for the sand-and-gravel aquifers are not differentiated by sample depths, aquifer origins, or geographic locations but represent public water-supply wells open to various sand-and-gravel units throughout the State.

Water in these aquifers is of generally good quality for most uses. Dissolved-solids concentrations generally range from about 360 to 750 mg/L, and the median concentration does not exceed the 500-mg/L advisory level set by the State for drinking water (Illinois Pollution Control Board, 1985). In some areas of the State, historical data indicate dissolved-solids concentrations larger than 800 mg/L. Some of the smallest dissolved-solids concentrations are in areas with sandy soils where infiltration of precipitation is rapid (Gibb and O'Hearn, 1980). During the growing season, areas with sandy soils have a large amount of ground water withdrawn for irrigation.

The hardness of waters in the sand-and-gravel aquifers generally is about 250 to 510 mg/L as calcium carbonate. The median concentration of hardness is about 360 mg/L, which generally is considered to be very hard water.

Nitrate plus nitrite concentrations do not exceed the State standard of 10 mg/L throughout the sand-and-gravel aquifers, except for some isolated locations. Of more than 450 samples from public water-supply wells, only 2 samples exceeded the State standard for nitrate. Larger nitrate plus nitrite concentrations may be more common in shallow private wells that have inadequate protection from septic systems, fertilizer usage, or animal wastes. However, this information is not well documented.

Iron concentrations in the sand-and-gravel aquifers are extremely variable. Generally, iron concentrations range from about 50 to 4,100 μg/L. Gibb and O'Hearn (1980) indicate that iron concentrations are smallest in samples from the shallow drift wells in the northern part of the State and along the Illinois River valley, whereas concentrations are larger in southern Illinois. Most iron concentrations in water from the drift exceed the State drinking-water standard of 1,000 μg/L. However, current water-treatment practices make these waters usable for public water supplies. Manganese concentrations throughout the State follow a pattern similar to that for iron.

Sulfate concentrations generally do not exceed the State advisory level of 250 mg/L. The median concentration of sulfate is about 50 mg/L.

Pennsylvanian-Mississippian Aquifers

Four-fifths of the bedrock surface in Illnois is formed by sedimentary rocks of Pennsylvanian and Mississippian age (U.S. Geological Survey, 1985, p. 200). Although fairly extensive in area, this aquifer yields amounts of water that generally are sufficient only for small supplies. Very few data are available on the quality of water from this aquifer.

Dissolved-solids concentrations are extremely variable and range from about 500 to about 3,000 mg/L (Gibb and O'Hearn, 1980), well in excess of the State's advisory level. Some of the variability is attributable to increased mineralization with depth owing to longer residence times of water in the aquifer. Hardness also is extremely variable, ranging from 150 to 400 mg/L in north-central Illinois and from to 150 to 1,000 mg/L in southern Illinois. Hardness generally is similar to that in water from the overlying glacial drift. Iron concentrations generally range from 1,000 to 5,000 µg/L. Sulfate concentrations generally are less than 5 mg/L (Gibb and O'Hearn, 1980).

Shallow Dolomite Aquifer

The shallow dolomite aquifer of northeastern Illinois has been studied extensively. Dissolved-solids concentrations generally exceed the State advisory level, and the most recent analyses indicate a range of about 400 to 1,200 mg/L. Few nitrate plus nitrite concentrations exceed 6 mg/L. Hardness values have a relatively broad range; concentrations range from about 200 to almost 700 mg/L and the median is 470 mg/L. The median iron concentration in this aquifer is about 610 µg/L, although several samples had concentrations that exceeded the State standard. Sulfate concentrations range from about 35 to 380 mg/L (Gibb and O'Hearn, 1980).

Cambrian-Ordovician Aquifer

The Cambrian-Ordovician aquifer provides much of the ground-water supply in the northern one-third of Illinois. The water quality in this aquifer generally is suitable for most uses. Visocky and others (1985) analyzed the Cambrian-Ordovician system in Illinois. Their report presents information on the geology, hydrology, and water quality of this system in northern Illinois.

Water in the unconfined zone of this aquifer has relatively small dissolved-solids concentrations; however, in the confined units, concentration differences may occur either vertically or horizontally. Gibb and O'Hearn (1980) report that dissolved-solids concentrations range from 250 to 400 mg/L and increase downgradient in the aquifer. Analyses of samples collected from 1984 to 1986 indicate dissolved-solids concentrations in the Ironton and Galesville Sandstones of Cambrian age ranging from 290 to 1,180 mg/L.

Hardness generally ranges from 260 to 420 mg/L. Iron concentrations generally are smaller than 500 µg/L and appear to be regionally uniform. Sulfate concentrations generally do not exceed the 250-mg/L State advisory level.

Mount Simon Aquifer

The Mount Simon aquifer is overlain by and hydraulically connected to the lower Eau Claire Sandstone of Cambrian age. The upper part of the Mount Simon aquifer in most of northern Illinois contains water of quality similar to that in overlying units in the Cambrian-Ordovician aquifer. Generally, water-supply wells tapping the Mount Simon aquifer are also open to the overlying aquifers. Wells completed in the Mount Simon aquifer generally penetrate only the upper sections of the aquifer because dissolved-solids concentrations increase with depth.

EFFECTS OF LAND USE ON WATER QUALITY

Contaminants from several sources have affected ground-water quality in Illinois. Sources may include, but are not limited to, industrial wastes, municipal landfills, agricultural chemicals, septic-system effluents, oil and gasoline leaks, animal wastes, acid-mine drainage, oil-field-brine wastes, road salts, hazardous-waste disposal, and waste impoundments. Waste sites are shown in figures 3*A* and 3*C*, and human-induced contamination is shown in figure 3*B*. Figure 4 illustrates how trends in concentrations of dissolved solids have increased in three areas.

Waste Sites

Waste sites shown in figure 3*A* include 14 Comprehensive Environmental Response Compensation and Liability Act of 1980 (CERCLA) sites listed on the EPA's National Priority List (NPL) for 1986; 38 Resource Conservation and Recovery Act (RCRA) hazardous-waste disposal facilities; 3 U.S. Department of Defense (DOD) facilities; waste sites listed for cleanup through such programs as the State Remedial Action Priority List (SRAPL) and the Immediate Hazardous Waste Removal Program (IHWRP); and 4 sites at which deep-well injection of hazardous wastes is occurring through the Underground Injection Control (UIC) Program (U.S. Environmental Protection Agency, 1984). Although all these sites are considered to be potential sources of ground-water contamination, not all are known to have current contamination problems.

As of September 1985, 87 hazardous-waste sites at six facilities in Illinois had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 87 sites in the program, 38 contained contaminants but did not present a hazard to the environment. Six sites at three facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Urbanization and Industry

In northeastern Illinois (fig. 3*B*, area A), westward expansion of the Chicago suburbs has increased the demand for ground water. Increased pumpage in this area has lowered the regional water levels in the shallow dolomite and Cambrian-Ordovician aquifers, necessitating the drilling of wells to greater depths to obtain adequate water supplies. Concerns have been raised about the transfer of saline water between aquifers through the deeper wells, especially those open to both the Cambrian-Ordovician and the Mount Simon aquifers.

In north-central Illinois, several problems, including contamination by nitrate and VOC have been identified in the near-surface sand-and-gravel aquifers (fig. 3*B*, area B). Wehrmann (1983) studied an area north of Rockford, Ill., where nitrate concentrations exceeded State standards. The increased nitrate concentrations were associated with septic-tank wastewaters and areas of agricultural fertilizer usage.

VOC have also been detected in some wells in area B throughout Boone and Winnebago Counties. The city of Rockford has had a sampling program for monitoring organic constituents since 1983. Several wells have been closed, owing to contamination by VOC. VOC detected in ground-water samples from Winnebago County include tetrachloroethlyene, tribromomethane (bromoform), trichloromethane (chloroform), dichloroethane, dichlorobromomethane, trichloroethylene, and chlorodibromomethane. The area is densely populated (fig. 1*B*) and extensively industrialized, with accompanying activities that may contribute to ground-water contamination.

The area around East St. Louis, locally known as the American Bottoms (fig. 3*B*, area C), has long been favored for ground-water use. Because of plentiful ground water, the area became urbanized as a result of industry relocation there. Water use increased and water quality of the sand-and-gravel aquifer deteriorated, owing to the effects of urbanization and industrialization (fig. 4). Voelker (1984) reported that iron, sulfate, and dissolved-solids concentrations exceeded State standards in most of the area. Nitrate plus nitrite concentrations have increased in areas where rising water levels have intercepted and damaged sewer lines and septic systems that were installed during periods of lower water levels. Additionally, the vast amount of oil refining in the area has resulted in seepage of some petroleum by-products into

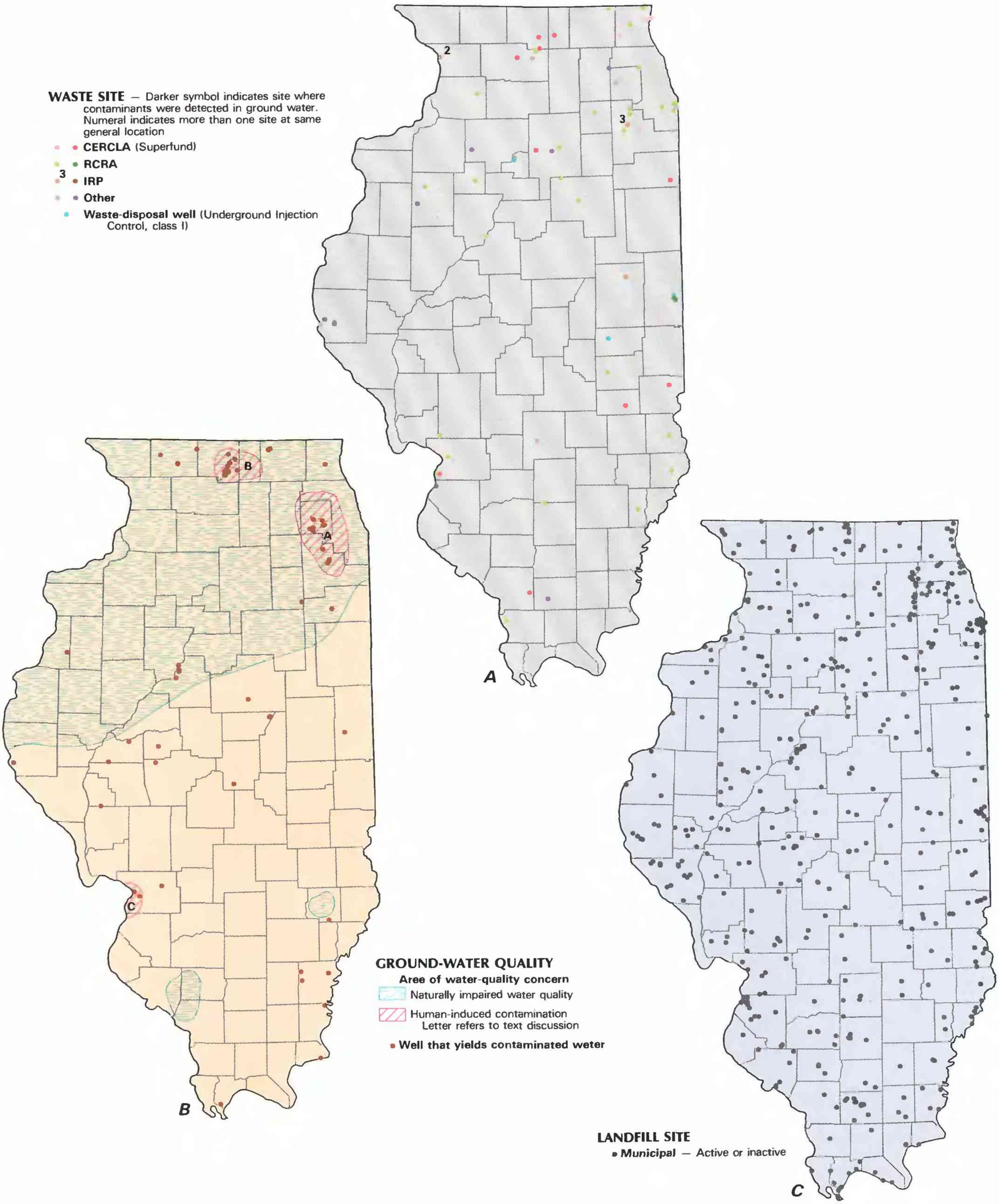

Figure 3. **Selected waste sites and ground-water-quality information in Illinois.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A*, Dixon and others, 1986; D.J. Yeskis, U.S. Environmental Protection Agency, written commun., 1986; U.S. Department of Defense, 1986. *B*, Voelker, 1984; R.P. Clarke, Illinois Environmental Protection Agency, oral commun., 1986. *C*, Dixon and others, 1986.)

the ground water. In an effort to remedy these potentially hazardous conditions, "skimmer" wells have been used in some areas to remove these compounds from the ground-water surface.

POTENTIAL FOR WATER-QUALITY CHANGES

The effects noted in the preceding section have generally been associated with urbanization and industrialization where the demand for ground water is large. Urbanized areas overlying relatively shallow aquifer systems such as the sand-and-gravel or shallow dolomite aquifers probably present the greatest potential for water-quality degradation. Areas most susceptible to ground-water contamination have been mapped by the Illinois State Geological Survey (Berg and others, 1984) in an attempt to delineate areas of the State where monitoring needs are greatest (Shafer, 1985).

In addition to waste disposal in the densely urbanized and industrialized areas of the State, most towns and cities have disposed of nearly all types of waste materials in municipal landfills (fig. 3*C*). Ground-water contamination has been detected at some sites adjacent to landfills. Some landfills are located in recharge areas and have the potential for contaminating some downgradient parts of underlying aquifers.

Agriculture is of major economic importance within the State and has the potential for affecting water quality over wide geographic areas. Fertilizers, herbicides, and insecticides are stored, transported, and applied over large areas that include recharge areas. In addition to potential contamination by these agricultural chemicals, surficial aquifers of the State also are susceptible to changes caused by irrigation and to contamination by animal wastes and effluent from inadequate septic systems. An estimated 97 percent of rural-domestic water systems are supplied from shallow aquifers.

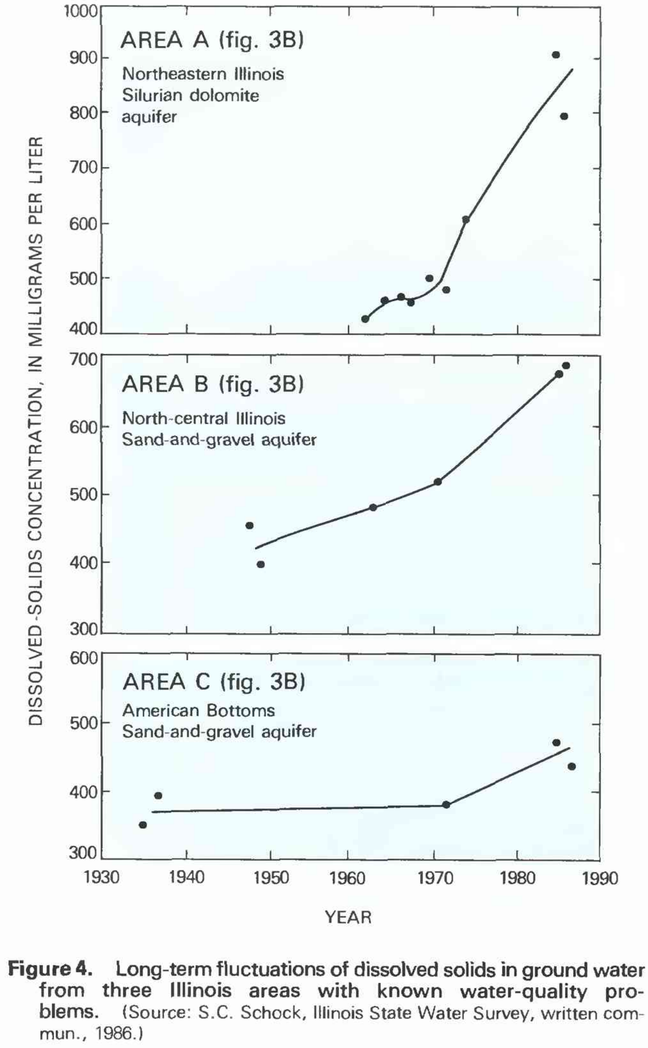

Figure 4. Long-term fluctuations of dissolved solids in ground water from three Illinois areas with known water-quality problems. (Source: S.C. Schock, Illinois State Water Survey, written commun., 1986.)

Illinois also is a major producer of oil, gas, and coal. Thousands of oil and gas wells are located throughout Illinois, with most being in the southern one-third of the State. Brine-waste impoundments have been associated with many of the production wells, and salinity has increased in nearby water-supply wells, but documentation is scarce. These impoundments are now banned in Illinois, and wastes presently are being injected below current and potential water supplies through disposal wells.

Coal production has resulted in surface-mined areas in much of southern, western, and east-central Illinois that may also be a threat to shallow aquifers. Investigations such as that by Borghese and Klinger (1984) have identified some of the effects of mining on ground-water quality, but additional work is needed. Acid-mine drainage also may be a threat to ground-water quality.

GROUND-WATER QUALITY MANAGEMENT

The issue of ground-water protection was brought to the attention of the Illinois State Water Plan Task Force in 1981. The Task Force issued a report (Illinois State Water Plan Task Force, 1984) that recommended a coordinated, multiagency policy and framework for action. The Illinois General Assembly recognized the need for a statewide problem assessment and for an action plan. Public Act 83–1268 was passed to respond to the need for monitoring, assessing, and resolving ground-water problems, and for developing a unified, statewide, ground-water protection plan. The IEPA (1986) proposed a core program to prevent future ground-water contamination and to correct current problems. Additionally, Public Act 83–1268 directed the Illinois Department of Energy and Natural Resources to prepare a study on ground-water quality by July 1985; the IEPA was directed to conduct a statewide monitoring program and develop a ground-water protection plan by January 1986.

The IEPA developed "A Plan for Protecting Illinois Groundwater" in 1986, and submitted it to the Governor, General Assembly, and Pollution Control Board. Governor James R. Thompson established a task force under the guidance of his Subcabinet for Natural Resources. This ground-water task force was scheduled to submit its findings for legislative, budgetary, and regulatory initiatives to the Governor by January 1, 1987.

Part of the IEPA's plan was a 5-year program to address ground-water protection. This time frame was suggested because several important and related programs would be operating concurrently. These programs include (1) the recently reauthorized Federal RCRA program, (2) the Build Illinois program, and (3) the Federal CERCLA (Superfund) program. The time frame is sufficient to anticipate significant progress within existing programs and to establish new programs where necessary.

Within this time, the IEPA recommends the following five-part plan:

1. Clarify goals and objectives for ground-water protection in Illinois including legislative and regulatory actions. This part would focus on application of standards and determination of differential or uniform protection needs.

2. Operate appropriate ground-water monitoring programs including the first statewide sampling of VOC in public water-supply wells and networks for pesticide monitoring.

3. Continue to address suspected and (or) known contamination problems by taking advantage of the "Build Illinois" initiative.

4. Implement technology based on programs for land pollution control that focus on waste decrease and reuse. A special program on leaking underground storage tanks will be initiated.

5. Establish a statewide program for ground-water source protection that requires legislation to do the following:

    - Designate potential ground-water contamination sources;
    - Establish a well-site protection effort including siting prohibitions;
    - Establish a local plan for recharge-area protection;
    - Require new potential-contamination sources to be reported to the IEPA; and
    - Assure continued water supply or replacement thereof if contamination occurs.

The current focus is to finalize the proposed program, thereby providing information and protection in support of current and future ground-water programs. In addition, considerable effort will be made to assure that all Federal Safe Drinking Water Act amendments are incorporated in the new Illinois ground-water-protection programs.

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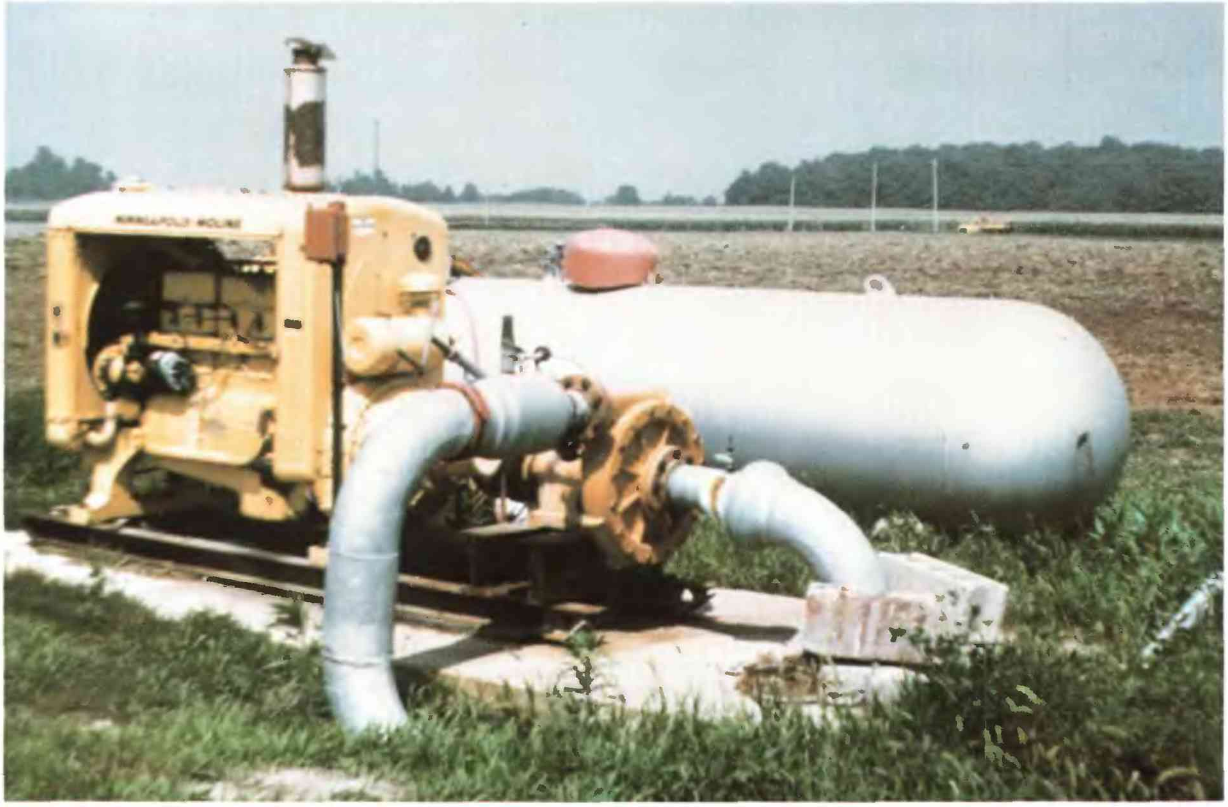

Natural gas powered centrifugal pump used to irrigate crops in Mason County, Illinois. The County has extensive pumpage for irrigation from the shallow sand and gravel aquifer in the area. (Photograph by Walter Lembke, Department of Agricultural Engineering Sciences, University of Illinois.)

Prepared by David C. Voelker, U.S. Geological Survey, ''Ground-Water-Quality Management'' section by Robert P. Clarke, Illinois Environmental Protection Agency

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INDIANA
Ground-Water Quality

Ground water provides drinking water for nearly 60 percent of the population in Indiana (fig. 1*B*); of this percentage, about one-half get their water from domestic wells (Indiana Department of Environmental Management, 1986, p. 152). Five principal aquifers have been identified in the State; of these five, the glaciofluvial and the glacial-outwash aquifers are the most productive (fig. 2*A*). Some ground water is obtained from other less-productive aquifers in areas where the principal aquifers are not present.

Ground water in Indiana is usually very hard—with hardness concentrations greater than 180 mg/L (milligrams per liter) as calcium carbonate—and has an average median dissolved-solids concentration of about 465 mg/L. Large concentrations of iron are common. However, most ground water in the State is potable. Water from 67 percent of the public water-supply wells has been analyzed for organic compounds, and water from about 8 percent of those wells contained at least one detectable organic compound (Indiana Department of Environmental Management, 1986).

The U.S. Environmental Protection Agency (1986c) has identified 23 hazardous-waste sites in Indiana (fig. 3*A*) for inclusion on the National Priorities List (NPL), or "Superfund", Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 . The Interagency Groundwater Task Force (1986, p. 52) has estimated that as many as 50 of the 853 sites now undergoing evaluation for inclusion on the NPL will be listed. The U.S. Department of Defense (DOD) has identified 32 hazardous-waste sites at 3 facilities as having potential for contamination. Six sites at two facilities (fig. 3*A*) present a hazard significant enough to warrant response action in accordance with CERCLA. Hazardous wastes are disposed of at 28 Resources Conservation and Recovery Act (RCRA) sites. Indiana has 113 solid-waste landfills that are permitted by the State (fig. 3*C*) and 687 abandoned landfills. Ninty-six of the 1,774 public water-supply wells (serving more than 25 people) have water with detectable concentrations of volatile organic compounds (fig. 4).

WATER QUALITY IN PRINCIPAL AQUIFERS

Indiana has five principal aquifers (fig. 2*A*). In order from youngest to oldest, they are the glaciofluvial, glacial-outwash, Wisconsin till, Mississippian, and Silurian-Devonian aquifers. These five principal aquifers are of two principal types—glaciofluvial and glacial deposits, and carbonate bedrock. Water is stored and transmitted through interconnected pores in the glaciofluvial and glacial deposits and through fractures and solution openings in the carbonate bedrock (U.S. Geological Survey, 1985, p. 207). Parts of the State are underlain by less-productive aquifers of limited extent, which are shown in figures 2*A* and 2*B* as "other aquifer." Small, but locally significant, withdrawals are made from these other aquifers.

In some areas of Indiana, large concentrations of iron [as much as 3,000 μg/L (micrograms per liter)] and manganese (as much as 1,000 μg/L) are present in the ground water (Clark, 1980, v. I, p. 80). The only other commonly occurring constituent of some concern is sulfate, which exceeds the 250-mg/L drinking-water standard (U.S. Environmental Protection Agency, 1986b) in some less productive aquifers in the coal-producing area of southwestern Indiana.

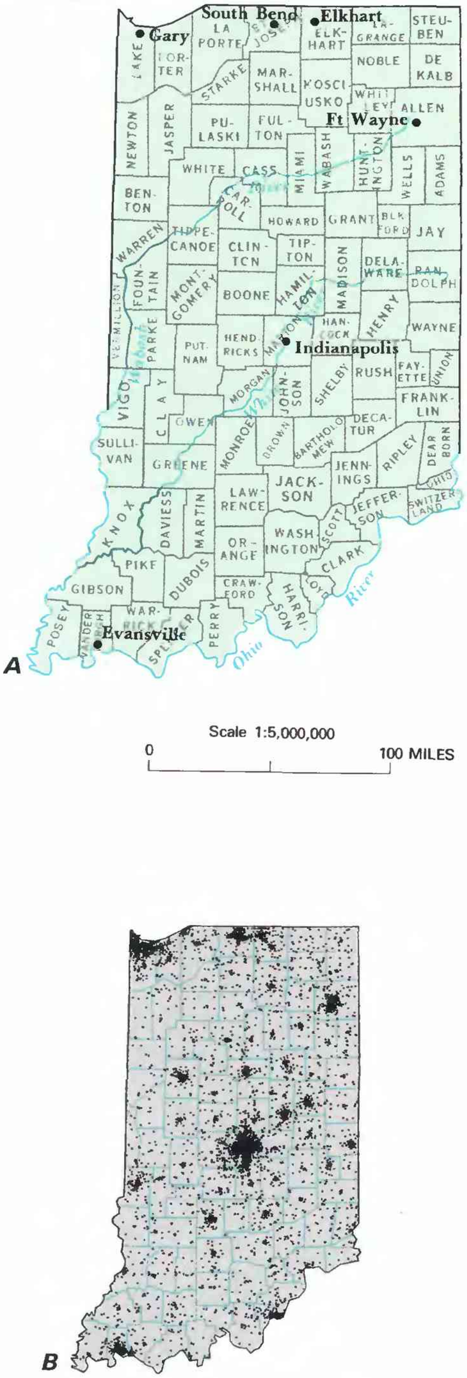

Figure 1. Selected geographic features and 1985 population distribution in Indiana. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985, each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

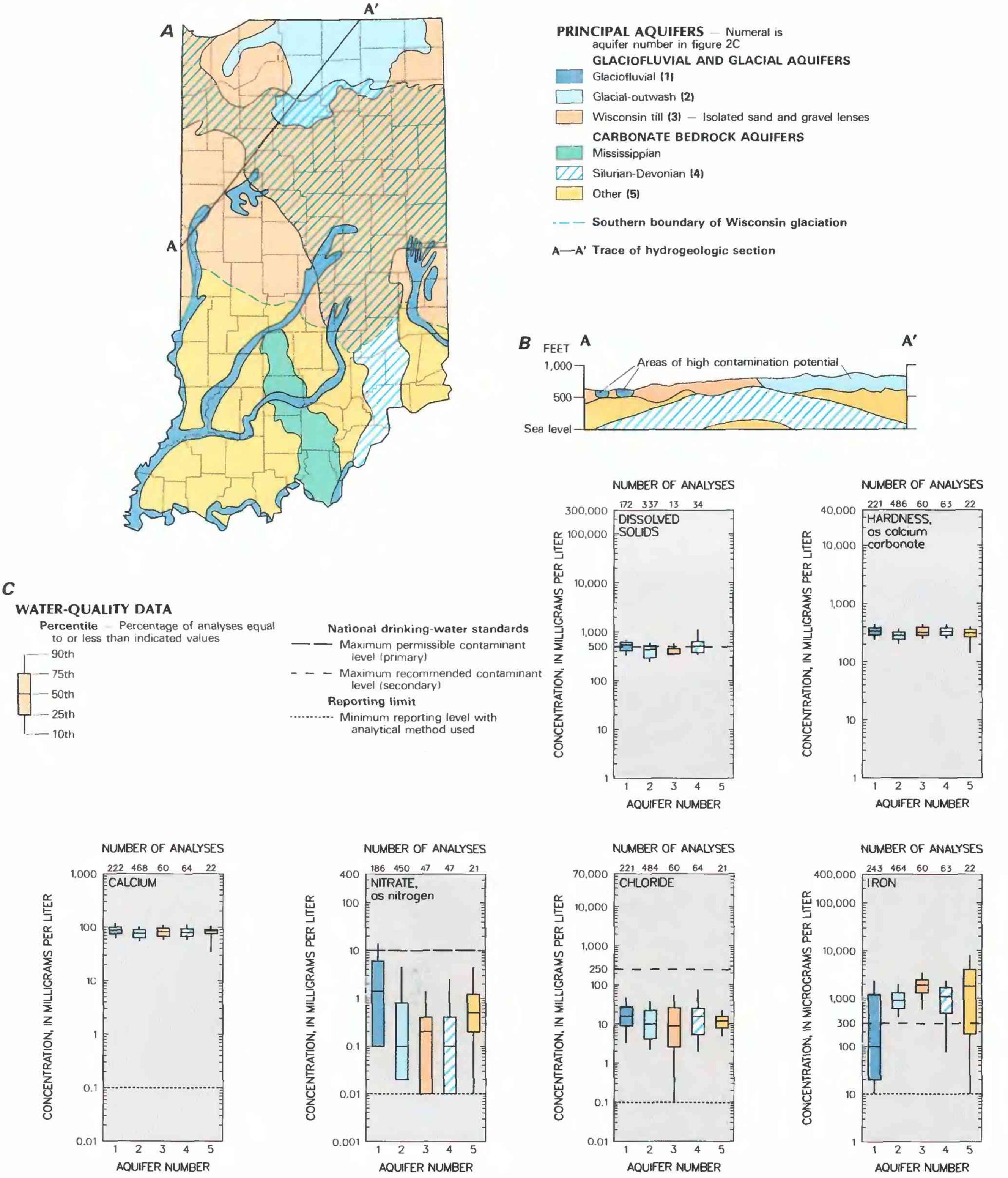

Figure 2. Principal aquifers and related water-quality data in Indiana. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1986. (Sources: *A* and *B*, Aten and others, 1982; U.S. Geological Survey, 1985; Indiana Department of Environmental Management, 1986. *C*, Analyses complied from Indiana State Board of Health, 1984, unpublished data from the Division of Water of the Indiana Department of Natural Resources; and from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

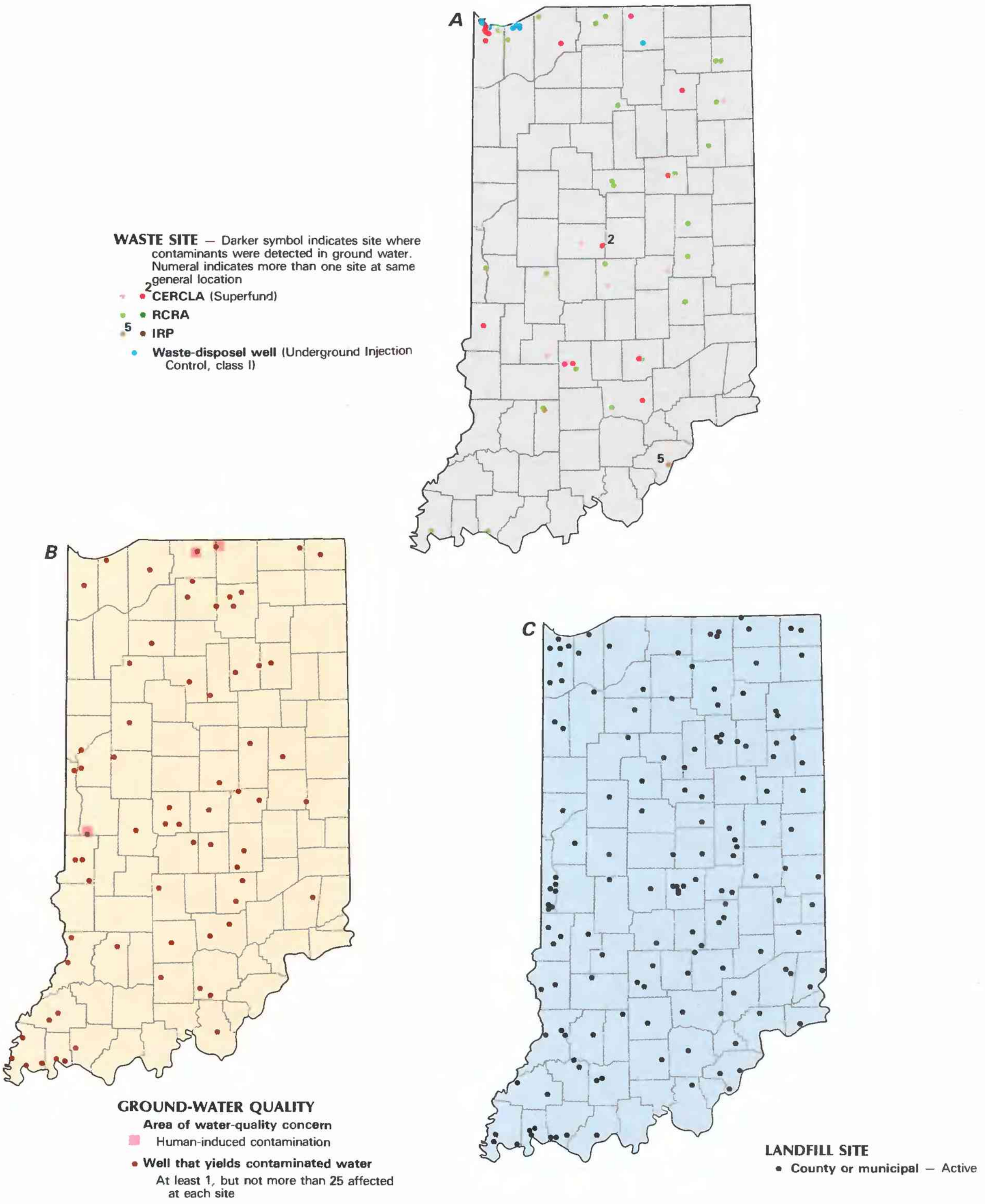

Figure 3. **Selected waste sites and ground-water-quality information in Indiana.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986, Department of Defense Installation Restoration Program (IRP) sites, as of 1986, and other selected waste sites, as of 1986. *B*, Areas of human induced contamination and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, Indiana Department of Environmental Management files. *B*, Indiana Department of Environmental Management, 1986. *C*, Indiana Department of Environmental Management, written communication, 1986.)

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from (1) the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE), (2) unpublished data from the Indiana Department of Natural Resources (IDNR) for the St. Joseph River and Whitewater River basins Division of Water and (3) 1984 data from the Indiana State Board of Health (ISBH) for 169 public water-supply wells is presented in figure 2*C*. The summary is based on analyses of dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), chloride, and iron in water samples collected from aquifer units in Indiana. Percentiles of these variables (except hardness) are compared to national standards that specify the maximum concentration or level of a constituent in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L iron.

Differences in water quality of the principal aquifers occur throughout Indiana and are related to the mineral characteristics of the aquifers. Most of the State's ground water is potable but very hard with median hardness ranging from 286 to 340 mg/L as calcium carbonate. Although not shown in figure 2*C*, the median calcium concentration ranged only from 77 to 88 mg/L for all aquifer units. The average median dissolved-solids concentration was about 465 mg/L, which is less than secondary drinking-water standards of 500 mg/L (U.S. Environmental Protection Agency, 1986b).

Glaciofluvial and Glacial Aquifers

GLACIOFLUVIAL AQUIFERS

Glaciofluvial aquifers are the most productive in the State. They consist of sand-and-gravel deposits in glacial channels and along river systems (fig. 2*A*, aquifer 1). These aquifers typically are unconfined. The depth to water is commonly from 10 to 25 feet, and usually wells are constructed 20 to 60 feet in depth. Median concentrations of 546 mg/L dissolved solids and 340 mg/L hardness (as calcium carbonate) were found in water from the glaciofluvial aquifers. Of the aquifers represented in figure 2*C*, water in the glaciofluvial aquifers had the largest median nitrate concentration (1.4 mg/L as nitrogen), the largest median chloride concentration (16 mg/L of the glaciofluvial and glacial aquifers), and the smallest median iron concentration (100 μg/L). Large chloride concentrations may reflect road-salting and waste-disposal activities. The small iron concentrations may result from oxidizing conditions typical of these aquifers.

GLACIAL-OUTWASH AQUIFERS

The glacial-outwash aquifers consist of sand and gravel that are more areally extensive than the glaciofluvial aquifers (fig. 2*A*, aquifer 2). These aquifers are generally unconfined, although units of small permeability, such as till, commonly restrict vertical flow between the permeable parts of these aquifers. The depth to water is commonly 10 to 25 feet below land surface, and most wells are from 20 to 100 feet deep.

The water in these aquifers is suitable for most uses and had median concentrations of 440 mg/L dissolved solids; 286 mg/L hardness (as calcium carbonate) and iron, 900 μg/L. Concentrations of some constituents were small, however, such as median concentrations of 0.1 mg/L for nitrate (as nitrogen), and 10 mg/L for chloride.

WISCONSIN TILL AQUIFERS

The Wisconsin till aquifers (fig. 2*A*, aquifer 3) consist of isolated sand and gravel lenses that are usually enclosed by silty clay and clay till; therefore, the aquifers tend to be confined. From 5 to 100 feet of confining material may overlie the water-bearing zone.

Wells are commonly 20 to 100 feet deep. Water in Wisconsin till aquifers had median concentrations of 358 mg/L dissolved solids and 320 mg/L hardness (as calcium carbonate). Nitrate concentrations were small with a median of 0.2 mg/L as nitrogen. The water in till aquifers had a median chloride concentration of 9 mg/L, which is similar to that of precipitation. Water from the Wisconsin till aquifers however, contained the largest median iron concentration (1,900 μg/L). This may be due to the abundance of iron-rich materials in the aquifers and to the thick confining materials in which reducing conditions may prevail and through which water must flow.

Carbonate Bedrock Aquifers

MISSISSIPPIAN AQUIFERS

The Mississippian aquifers (fig. 2*A*) are fractured limestones characterized by solution channels that enhance permeability. Most wells drilled into these aquifers are shallow (from 20 to 150 feet deep). Unfortunately, data from only four water-quality sites (all public-supply wells) are available. For water samples from these four wells, the maximum concentrations were 640 mg/L hardness (as calcium carbonate), 1.2 mg/L nitrate (as nitrogen), 28 mg/L chloride, and 530 μg/L iron. No dissolved-solids data were available.

SILURIAN-DEVONIAN AQUIFERS

The Silurian-Devonian aquifers consist of fractured limestone not known to contain solution channels. These aquifers (fig. 2*A*, aquifer 4) usually are confined by overlying glacial till. Where the limestones are unconfined (in the southeastern part of the State), well yields are small (Greeman, 1981). Wells completed in these aquifers are 50 to 200 feet deep. The general water quality is similar to that in the overlying Wisconsin till aquifers with median concentrations of 513 mg/L dissolved solids and 333 mg/L hardness (as calcium carbonate). The median dissolved-solids concentration in these aquifers was much larger than for water in the Wisconsin till. However, the median chloride concentration, 16 mg/L, was the largest for any of the carbonate bedrock aquifers. The large chloride concentration may reflect the depth of wells in this principal aquifer. Nitrate and iron concentrations in the Silurian-Devonian aquifers were smaller than for water in the Wisconsin till, with medians of 0.1 mg/L and 1,100 μg/L, respectively.

Other Aquifers

Other aquifers (fig. 2*A*, aquifer 5) include pre-Wisconsin till and loess, Pennsylvanian coal-bearing rocks, Mississippian clastic rocks, and Devonian shale. In general, these aquifers are not areally extensive and cannot support large withdrawals. Quality of water from these aquifers, statewide, generally is similar to that of the more extensive aquifers, with median concentrations of 314 mg/L hardness and 12 mg/L chloride. The median nitrate concentration (as nitrogen) was 0.5 mg/L, or about one-third of the median for water from glaciofluvial aquifers. However, the median iron concentration was 1,800 μg/L, which was only 100 μg/L below the largest median concentration (which occurred in the Wisconsin till aquifers). The coal-bearing rocks and the Devonian shale contain significant amounts of iron. Analysis of the data suggests that these rocks are the probable sources for the large iron concentrations in these other aquifers.

EFFECTS OF LAND USE ON WATER QUALITY

The quality of Indiana's ground water is degraded mainly by the handling, storage, spillage, and eventual disposal of hazardous materials. In addition, mining, production of brines associated with oil and gas drilling (Shedlock, 1980), and agriculture probably have degraded ground-water quality to some extent.

Waste Disposal and Spills

The Indiana Department of Environmental Management (IDEM) has identified 146 sites and three areas where ground-water contamination has occurred (fig. 3*B*). Contamination is defined as "concentrations of chemicals in excess of public drinking-water standards, proposed standards or health protection guidance from the EPA" (Indiana Department of Environmental Management, 1986, p. 159). Of these sites, 29 have no confirmed source of contamination. Of the 117 remaining sites, about one-third were affected by spills of hazardous materials. After spills, the sources of contamination in order of declining importance are leaks from underground storage tanks; solid- and hazardous-waste disposal; leaks from above-ground storage; and disposal pits, ponds, and lagoons (Indiana Department of Environmental Management, 1986, p. 161). Of the 146 sites, 48 percent contained detectable volatile organic compounds, about 25 percent contained petroleum or petroleum-related products, and 27 percent of the sites contained metals, trace metals, chloride, and nitrate (Indiana Department of Environmental Management, 1986, p. 162).

The IDEM and the EPA have identified 23 CERCLA (Superfund) sites (fig. 3*A*). Ground-water contamination has been detected at 16 of the sites. An additional five sites have been proposed for inclusion on the EPA's NPL. Hazardous wastes are disposed at 28 RCRA sites (fig. 3*A*). Eight class-I injection wells (fig. 3*A*) currently are regulated by the Underground Injection Control (UIC) Program (U.S. Environmental Protection Agency, 1984). The EPA administers the UIC program in Indiana. Seven of the eight injection wells are located in Lake and Porter Counties in the far northwest corner of the State. The other well is located in Elkhart County.

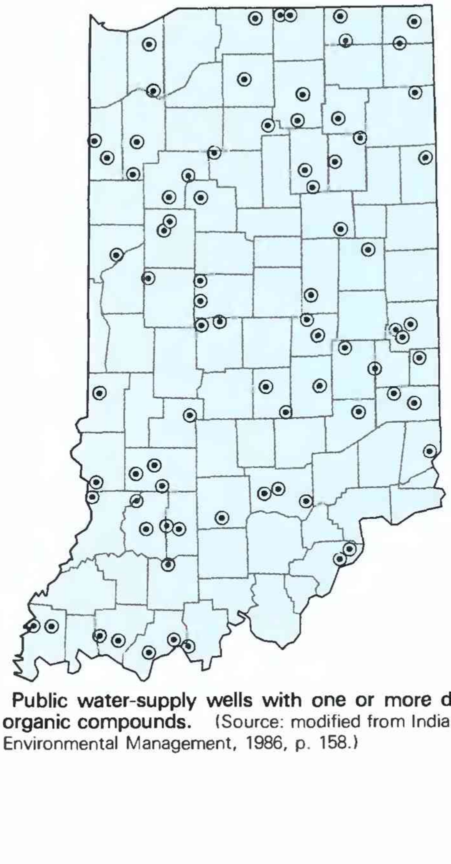

Figure 4. Public water-supply wells with one or more detectable volatile organic compounds. (Source: modified from Indiana Department of Environmental Management, 1986, p. 158.)

As of September 1985, 32 hazardous-waste sites at 3 facilities in Indiana have been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazardous-ranking system and may include them in the NPL. Of the 32 sites evaluated under the program, 6 sites contained contaminants, but they did not present a hazard to people or to the environment. Six sites at two facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Indiana has 113 operating county or municipal solid-waste landfills permitted by the State (fig. 3*C*) and 687 abandoned landfills (Indiana Department of Environmental Management, 1986).

The EPA has been assessing the 1,774 public water-supply wells in Indiana that serve more than 25 people for the possible the presence of 26 volatile organic compounds. As of March 31, 1986, the EPA reported that 96 of the 1,198 wells sampled had detectable levels of at least one volatile organic compound (Indiana Department of Environmental Management, 1986, p. 157). Seventy-nine of these well locations, which include multiple wells at some locations, are shown in figure 4. As a result of the survey, fifteen of the 96 wells were abandoned permanently or temporarily and four water-supply systems are now using treatment systems. In order to reduce the concentrations of volatile organic compounds in the water, some water suppliers are mixing uncontaminated water with contaminated water.

Agriculture

The effects of agricultural chemicals on the quality of ground water in Indiana are not well understood. The occurrence of some large nitrate concentrations in water from glaciofluvial aquifers may be related to agricultural activity. IDEM (1986) has identified 12 sites throughout the State with known nitrate contamination, 10 are located near fertilizer storage or manufacturing or are near known spills of fertilizer. Two sites have no identified contamination source.

POTENTIAL FOR WATER-QUALITY CHANGES

Three of the five principal aquifers have a relatively significant potential for contamination—the glaciofluvial aquifers, the glacial-outwash aquifers, and the Mississippian aquifers. The glaciofluvial and glacial-outwash aquifers are the most important water-supply aquifers for the State. However, water from these two aquifers had the largest 90th-percentile nitrate concentration of the five principal aquifers (fig. 2*A*, aquifers 1 and 2), indicating that they are contaminated more easily than the others. Furthermore, the glaciolfluvial and glacial-outwash aquifers underlie the majority of the contamination sites, as evidenced by the fact that most of the public-supply wells that yield water with detectable concentrations of volatile organic compounds (fig. 4) tap these aquifers. Additionally, much of the population (fig. 1*B*) resides above or near these aquifers. Ground-water flow paths in the limestones of the Mississippian aquifers are short, which reduces the time available for adsorption of contaminants by aquifer materials. The Wisconsin till and Silurian-Devonian aquifers are protected in direct proportion to the thickness of the overlying confining units.

Recognizing the potential for contamination of ground water and the ranking of that potential for the various aquifers, the State is developing a program to protect ground-water quality. These steps and greater public awareness should reduce the likelihood of ground-water contamination in the future.

GROUND-WATER QUALITY MANAGEMENT

Three agencies have primary responsibility for ground water. The Indiana Department of Natural Resources (IDNR) has responsibility for protecting the quantity of ground water by (1) registering facilities capable of withdrawing 100,000 gallons per day or more; (2) assessing the availability of water; and (3) planning for the development, conservation, and use of water for beneficial uses. The IDNR derives its authority from the Water Resources Management Act (IC 13-2-6.1), which makes no distinction between ground and surface water. The Indiana State Board of Health (ISBH) has responsibility for monitoring water quality of public-water supplies for selected inorganic constituents and derives its authority from the Water Sanitary Regulation (320 IAC 3) and the Environmental Management Act (IC 13-7-7-5). The Indiana Department of Environmental Management (IDEM) has responsibility for the quality of ground water and can set standards specifying maximum permissible concentrations of contaminants. The IDEM derives its authority from the Environmental Management Act (IC 13-7-7-5) and from the Stream Pollution Control Law (IC 13-1-3-7), which applies both to surface and ground water.

The IDNR Division of Reclamation has responsibility for the effects of mining on ground-water quality under the Surface Mining Reclamation Act (IC-13-4). The Office of the State Fire Marshall and the Office of the State Chemist have responsibility for regulating the storage and handling of flammable liquids and agricultural chemicals. Local authorities also have the power to protect ground water. Several local governments, notably the City of Elkhart and Elkhart County, and Indianapolis and Marion County, have been actively delineating ground-water contamination areas.

The inadequacy of existing ground-water data bases has been recognized as a major issue in the Draft Strategy for Ground Water (Interagency Groundwater Task Force, 1986, p. 18-20.) The U.S. Geological Survey and the IDNR Division of Water maintain the only significant computerized data bases within the State. The Interagency Groundwater Task Force (1986) lists several alternatives for improving the ground-water data bases for the State.

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IOWA
Ground-Water Quality

The population served by ground-water supplies in Iowa (fig. 1*A*) is estimated to be about 2,392,000, or 82 percent of the total population (U.S. Geological Survey, 1985, p. 211). The population of Iowa is distributed fairly uniformly throughout the State (fig. 1*B*), with 59 percent residing in rural areas or towns of less than 10,000 (U.S. Bureau of the Census, 1982). Surficial aquifers, the Jordan aquifer, and aquifers that form the uppermost bedrock aquifer in a particular area are most commonly used for drinking-water supplies and usually provide ample amounts of good quality water. However, naturally occurring properties or substances such as hardness, dissolved solids, and radioactivity limit the use of water for drinking purposes in some areas of each of the five principal aquifers (fig. 2*A*). Median concentrations of nitrate in all aquifers and radium-226 in all aquifers except the Jordan are within the primary drinking-water standards established by the U.S. Environmental Protection Agency (1986a). Median concentrations for dissolved solids in the surficial, Dakota, and Jordan aquifers exceed secondary drinking-water standards established by the U.S. Environmental Protection Agency (1986b).

Ground water in Iowa, however, has been affected by human-induced contamination. Water from some wells in surficial and the uppermost bedrock aquifers contains nitrate concentrations exceeding the primary drinking-water standard of 10 mg/L (milligrams per liter) as nitrogen. Surficial aquifers also contain detectable concentrations of pesticides and other organic substances. Standards have not been established for many of the organic substances detected, and water supplies containing these substances may continue to be used. The long-term health consequences of exposure to these substances are not known; however, the estimated number of people in Iowa exposed to pesticide contaminants is believed to exceed 750,000 or 25 percent of the population (Kelley and others, 1986.)

Land-use and waste-disposal practices are believed to be responsible for most human-induced contamination in Iowa. About 33 million acres, or nearly 93 percent of the land area of Iowa, is farmed (Skow and Halley, 1986). About 56 million pounds of herbicides was used for agriculture during 1979 (Becker and Stockdale, 1980) and about 2.7 million tons of fertilizer products was used during 1985 (Skow and Halley, 1986). Additionally, 30 hazardous-waste sites are under authority of the Federal Resource Conservation and Recovery Act (RCRA) of 1976; six other sites have been listed in the National Priorities List (NPL) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (U.S. Environmental Protection Agency, 1986c). As of September 1985, two Federal sites at one facility under the U.S. Department of Defense Installation Restoration Program (IRP) were designated for remedial response in accordance with CERCLA. In addition to the above sites, Iowa has 90 active municipal landfills (fig. 3*C*).

The U.S. Geological Survey, in cooperation with the University of Iowa Hygienic Laboratory, the Iowa Department of Natural Resources, and several counties in Iowa, currently (1986) is monitoring about 1,500 public and private wells for inorganic and organic constituents. The principal objective of this program, begun in 1982, is to collect water-quality data that will describe the long-term chemical quality of the surficial and major bedrock aquifer systems in Iowa (Detroy, 1985).

WATER QUALITY IN PRINCIPAL AQUIFERS

Five principal aquifers are used in Iowa—surficial aquifers, the Dakota aquifer, the Mississippian aquifer, the Silurian-Devonian aquifer, and the Jordan aquifer (fig. 2*A*). All aquifers except the surficial aquifers are bedrock. The surficial aquifers are present

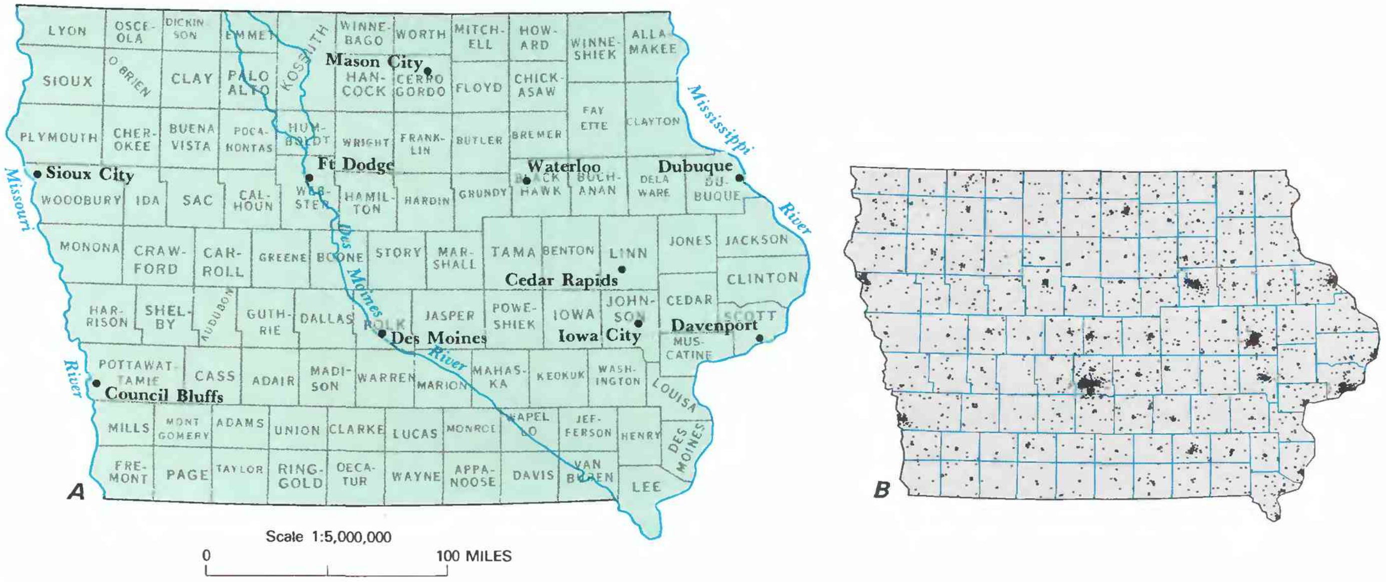

Figure 1. Selected geographic features and 1985 population distribution in Iowa. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

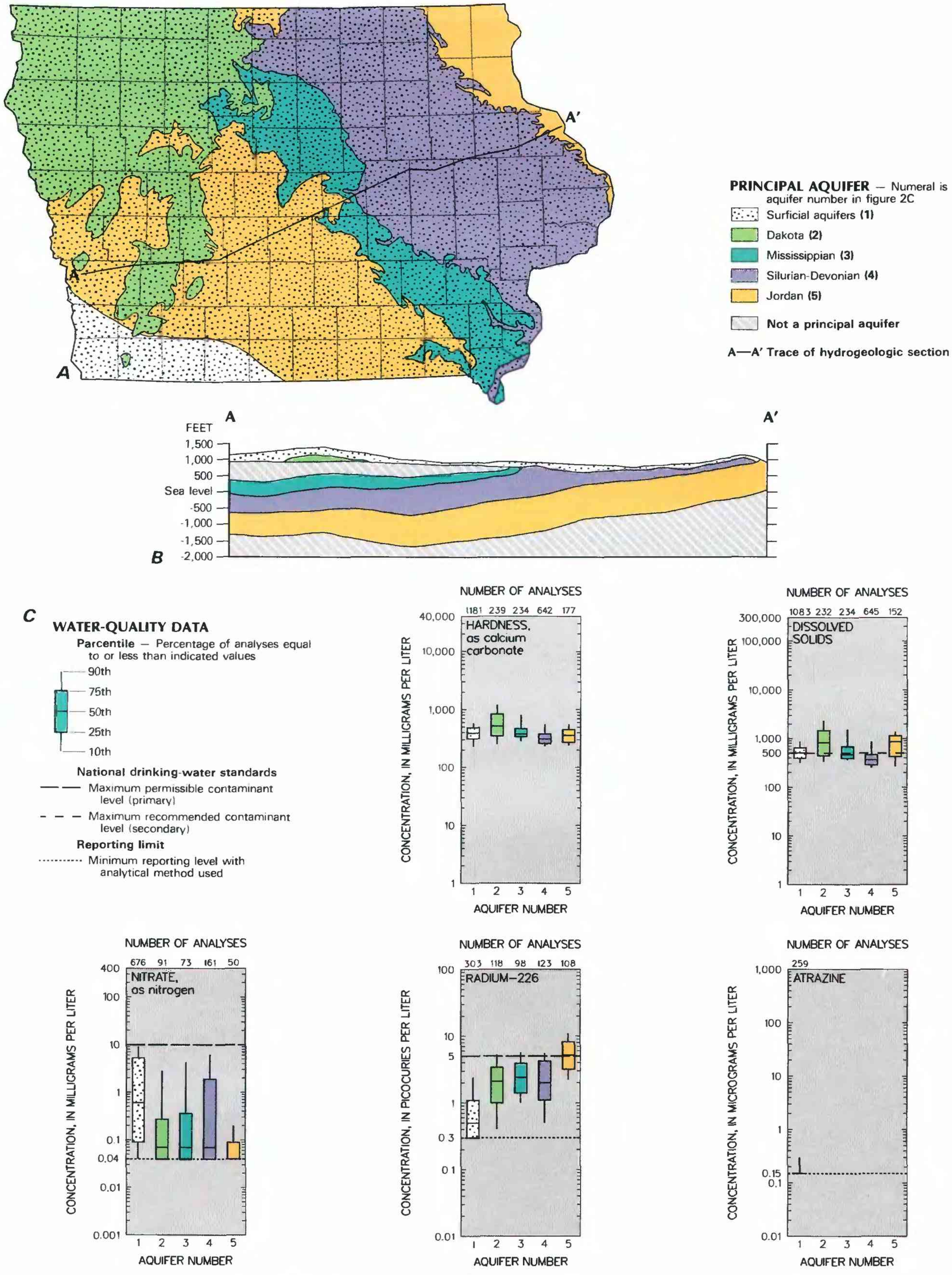

Figure 2. Principal aquifers and related water-quality data in Iowa. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1975-85. (Sources: *A*, Modified from Hershey, 1969, and Horick and Steinhilber, 1978. *B*, Modified from Horick and Steinhilber, 1978. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a, b.)

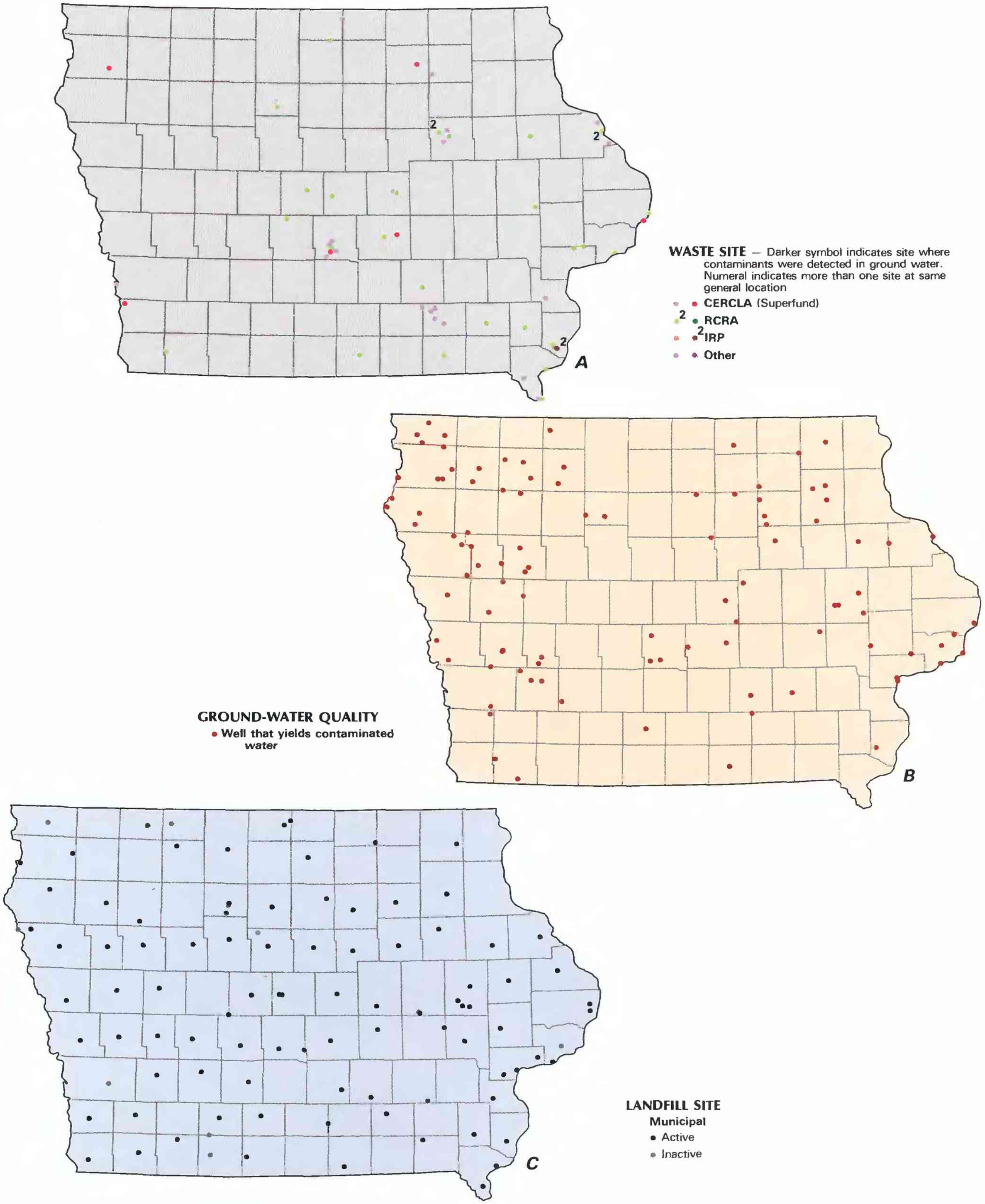

Figure 3. Selected waste sites and ground-water-quality information in Iowa. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, Bruce Henning, Iowa Department of Water, Air and Waste Management, written commun., 1986; Peter Culver and David Doyle, U.S. Environmental Protection Agency, written commun., 1986; U.S. Environmental Protection Agency, 1986c. *B*, Kelley, 1985; Kelley and Wnuk, 1986; G.R. Hallberg, Iowa Geological Survey, written commun., 1986. *C*, Bruce Henning, Iowa Department of Water, Air and Waste Management, written commun., 1986.)

throughout Iowa but are limited to the valleys of major streams in extreme northeastern Iowa because of thin or nonexistant unconsolidated glacial material in this area. The bedrock aquifers beneath the Dakota aquifer dip gently to the south and southwest (fig. 2*B*). In most areas of Iowa, more than one aquifer is available as a potential water supply. The population served by each aquifer has not been determined because many of the municipal wells derive water from more than one aquifer or several wells may tap different aquifers.

In Iowa, the concentration of dissolved solids in ground water typically increases with depth and with the distance from recharge areas. Shallow aquifers usually are preferred for drinking-water supplies, especially in areas where alternative aquifers are deeply buried and contain more mineralized water. However, shallow aquifers are more susceptible to human-induced contamination than more deeply buried aquifers that are protected from activities on the land surface by relatively thick overlying deposits. This susceptibility of the surficial aquifers is demonstrated by the number of water samples from wells completed in shallow aquifers that contain detectable concentrations of synthetic organic chemicals and pesticides and substantial concentrations of nitrate.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), radium-226, and atrazine analyses of water samples collected from 1975 to 1985 from the principal aquifers in Iowa. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). Primary maximum contaminant level standards are health related and are legally enforceable. Secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary standards for the variables shown in figure 2*C* are 10.0 mg/L nitrate (as nitrogen) and 5.0 pCi/L (picocuries per liter) radium-226 plus radium-228. Primary drinking-water standards require that samples having concentrations of radium-226 in excess of 3.0 pCi/L be analyzed additionally for radium-228. The secondary standard for dissolved solids is 500 mg/L. At present (1986), no primary or secondary standard has been established for atrazine in drinking water.

Surficial Aquifers

The surficial aquifers in Iowa (fig. 2*A*) are the water-yielding strata within the unconsolidated deposits overlying the bedrock surface. The three general types of surficial aquifers in Iowa are buried-channel aquifers, glacial-drift aquifers, and alluvial aquifers. Preglacial depressions and valleys in the buried bedrock surface that contain sand and gravel compose the buried-channel aquifers. Glacial-drift aquifers consist of lenses of sand and gravel distributed within the silt and clay deposited by Pleistocene glaciers. Alluvial aquifers consist of sand and gravel deposits along present-day streams.

The naturally occurring quality of water within surficial aquifers generally is suitable for most uses. Buried-channel aquifers that occur beneath a substantial thickness of glacial drift or that fill valleys deeply incised into the bedrock may have water-quality characteristics similar to those of water in the bedrock aquifers, particularly if the buried channel is in hydraulic contact with the bedrock aquifer. Glacial-drift aquifers generally yield a limited quantity of water because of their limited hydraulic connection to other sources of water and their limited areal extent. Glacial-drift aquifers usually are considered to be unreliable for public or industrial water supplies. Alluvial aquifers typically yield large quantities of water and may have water-quality characteristics similar to those of adjacent streams.

The median dissolved-solids concentration approximately equaled the drinking-water standard (fig. 2*C*); concentrations in 10 percent of the samples were larger than 870 mg/L. Nearly all water sampled was very hard. The median for hardness was 390 mg/L and the hardness was larger than 230 mg/L as calcium carbonate ($CaCO_3$) in 90 percent of the samples. The median nitrate concentration was 0.6 mg/L as nitrogen, but the concentration in nearly 10 percent of the samples exceeded the drinking-water standard. Radium-226 was present in concentrations smaller than 3.0 pCi/L in 90 percent of the samples. Atrazine, a herbicide used in the production of corn, was detected in about 10 percent of the samples.

Dakota Aquifer

The Dakota aquifer consists of sandstone of Cretaceous age and occurs mainly in the western one-half of Iowa (fig. 2*A*). This aquifer lies unconformably on the other bedrock aquifers and is overlain throughout its extent by unconsolidated deposits that contain surficial aquifers. The Dakota aquifer is important in northwestern Iowa as a source of public, industrial, irrigation, and rural-domestic water. In some areas, large concentrations of dissolved solids limit the use of the water for some purposes. Water in some areas of the aquifer also contains naturally occurring radium-226 and radium-228 in concentrations that may limit the use of the water. The areal extent of naturally occurring contaminants such as radium has not been determined.

The median dissolved-solids concentration of 824 mg/L exceeded the drinking-water standard (fig. 2*C*). The median dissolved-solids and hardness concentrations were among the largest in water from the five principal aquifers. Nitrate does not occur in significant concentrations in water from the Dakota aquifer. Radium-226 exceeded 3.0 pCi/L in about 25 percent of the samples. Water samples from wells more than 150 feet deep commonly are not tested for atrazine because there probably is little likelihood of atrazine percolating below that depth. Because most wells completed in the Dakota aquifer exceed this depth, few analyses of atrazine are available for this aquifer and other deep aquifers.

Mississippian Aquifer

The Mississippian aquifer, which consists of limestone and dolomite, is the uppermost bedrock aquifer in parts of central Iowa (fig. 2*A*), although in parts of western Iowa it is overlain by the Dakota aquifer. In much of southwestern and south-central Iowa, the Mississippian aquifer is overlain by rocks of Pennsylvanian age, which usually are not considered to be aquifer materials. Large concentrations of naturally occurring dissolved solids limit the use of water from the Mississippian aquifer in many areas. Furthermore, because of the large concentrations of dissolved solids and small yields from the the Mississippian aquifer, the aquifer usually is neglected as a drinking-water source in areas where it is the uppermost bedrock aquifer. Instead, supplies are obtained from surface water, surficial aquifers, or the deeper Jordan aquifer.

Data for the Mississippian aquifer (fig. 2*C*) indicate that the water had a median dissolved-solids concentration of 470 mg/L and was very hard. Concentrations of nitrate were not significant in this aquifer, based on 73 samples. Radium-226 concentrations exceeded 3.0 pCi/L in more than 25 percent of the samples analyzed.

Silurian-Devonian Aquifer

The Silurian-Devonian aquifer, consisting of limestone and dolomite, is the uppermost bedrock aquifer in most of north-central

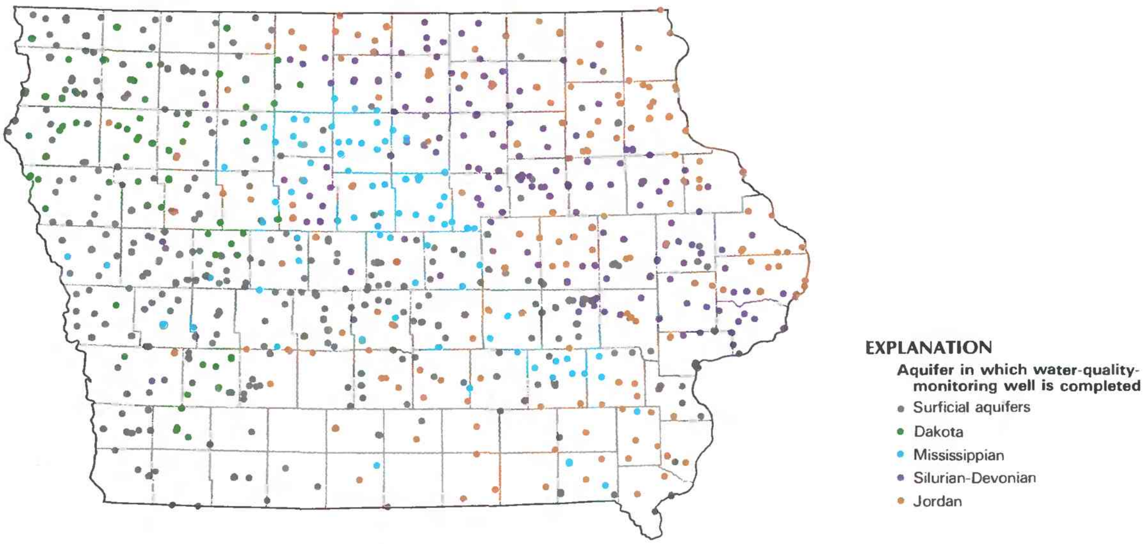

Figure 4. Location of ground-water-monitoring network wells in Iowa, 1986. (Source: U.S. Geological Survey files; Detroy, 1985.)

and eastern Iowa (fig. 2*A*). Where it forms the bedrock surface, the Silurian-Devonian aquifer provides a readily available source of water for most uses. Where overlain by younger bedrock units, water from the aquifer may not be suitable for drinking because of undesirable concentrations of naturally occurring sulfate and dissolved solids. As a result, these parts of the aquifer usually are bypassed as a source of water supply in the same manner as the Mississippian aquifer. The aquifer is near or at the land surface in much of northeastern Iowa and, because of solution-enlarged fractures and thin soil cover, is particularly susceptible to surface contamination.

Water from this aquifer contains the smallest median concentrations of dissolved solids and hardness of the five principal aquifers (fig. 2*C*). Nitrate and atrazine are known to be contaminants in parts of Iowa where the Silurian-Devonian aquifer is susceptible to surface-water contamination or to the leaching of contaminants from shallow ground water (Hallberg and others, 1984). However, data from those areas are not contained in the data base used to prepare this report. Nitrate and atrazine, in analyses of 18 samples from other areas of the Silurian-Devonian aquifer, do not appear to be significant problems at the present time. Radium-226 concentrations exceeded 3.0 pCi/L in more than 25 percent of the samples tested.

Jordan Aquifer

The Jordan aquifer consists of sandstone and dolomite of Ordovician and Cambrian age. It is the most extensively used aquifer in Iowa and is present throughout the State except for an area in northwestern Iowa. This aquifer is a source for many large-capacity water systems in Iowa because of its large yields and the suitability of the water for most uses. Large concentrations of naturally occurring dissolved solids and the greater depth to the aquifer limit the use of the Jordan aquifer in southwestern Iowa; however, in many areas of southwestern Iowa the Jordan aquifer is the best source of drinking water despite large dissolved-solids concentrations. Radium also is a naturally occurring constituent in water from parts of the Jordan aquifer, but the extent of this problem has not been determined.

Median concentrations of dissolved solids and radium-226 in water from the Jordan aquifer exceeded drinking-water standards (fig. 2*C*). More than 90 percent of the samples had a hardness exceeding 260 mg/L, which is very hard. In the samples analyzed, no nitrate concentrations exceeded the drinking-water standard. Analysis for atrazine in water from Jordan wells was uncommon because the depth to the Jordan in most parts of Iowa was considered to be a significant barrier to pesticide contamination. About 75 percent of the samples analyzed for radium-226 had concentrations larger than 3.0 pCi/L and required additional analysis for radium-228. Concentrations in about 50 percent of the samples exceeded the drinking-water standard for radium without consideration of radium-228.

An additional deeper, and possibly separate, aquifer exists in eastern Iowa below the Jordan aquifer (not shown in fig. 2). This aquifer, locally known as the Dresbach aquifer, is composed of a Cambrian sandstone that has not been extensively mapped; detailed information on the hydraulic and water-quality characteristics of the aquifer is not available. The Dresbach aquifer is used by several public water systems and industries along the eastern border of Iowa; however, many of these wells also are open to the Jordan aquifer and obtain some water from that source.

EFFECTS OF LAND USE ON WATER QUALITY

The monitoring of ground-water quality within Iowa has been conducted mainly by Federal and State agencies as part of the Safe Drinking Water Act (Public Law 93–523) and as part of the environmental responsibilities of public-health agencies. Four types of human-induced ground-water contamination routinely occur in Iowa—nitrate, bacteria, pesticides, and synthetic organic compounds other than pesticides. Agricultural and waste-disposal activities currently (1986) are receiving the most attention as potential sources of these contaminants. The location of the CERCLA, RCRA, IRP, and other waste-disposal sites in Iowa is shown in figure 3*A*. The last category consists primarily of privately owned landfills and disposal sites.

As of September 1985, 28 hazardous-waste sites at 2 facilities in Iowa had been identified by the U.S. Department of Defense (DOD) as part of their IRP as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under CERCLA. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Two sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

The locations of 104 public water-well systems in Iowa that consistently contain nitrate concentrations in excess of the drinking-water standard or have been determined to contain detectable concentrations of pesticides or synthetic organic substances other than pesticides are shown in figure 3*B*. Many of the 104 systems shown contain more than 1 contaminant. The estimated population potentially served by these systems is 739,000 or about 25 percent of the total State population. The number of private wells that are contaminated and the population served by them are not known.

The location of municipal landfills in Iowa is shown in figure 3*C*. The effect of many of these landfills on local ground-water quality has not been determined.

Nitrate

In Iowa, large nitrate concentrations in shallow ground water were detected as early as the 1940's (McDonald and Splinter, 1982). From 1978 to 1981, the University of Iowa Hygienic Laboratory analyzed 13,625 water samples from private wells less than 100 feet deep. Twenty-eight percent of these samples exceeded the drinking-water standard of 10 mg/L nitrate as nitrogen (Hallberg, 1985).

The correlation of increasing nitrate with decreasing well depth has been apparent for some time. However, Detroy (1986) has more specifically defined the vertical distribution of nitrate in an alluvial aquifer in Iowa County, Iowa. Nitrate concentrations in shallow aquifers also typically have a seasonal fluctuation, with the concentrations being largest during the early part of the growing season. As a result, the concentrations of nitrate in water from many wells do not consistently exceed the drinking-water standard throughout the year. Complexities of the shallow ground-water-flow system, as well as chemical transformation occuring within the aquifer, may affect the quantity and form of nitrogen present at any particular location and time.

Bacteria

Most of the water-quality data available are for public water supplies that are required to be free of bacteria. However, bacteria have been relatively common contaminants in shallow private wells. Many times this problem is caused by faulty well construction, which has allowed surface runoff and bacterial contaminants to enter the well. Remedial measures, such as chlorination, may decontaminate a well; however, additional measures would be needed to prevent renewed contamination. Conditions within the aquifer may prevent a total decontamination of affected wells.

Pesticides

Agricultural pesticides have been detected in water from both public and private wells in Iowa (Hallberg and others, 1984; Kelley, 1985; Kelley and Wnuk, 1986; and data from U.S. Geological Survey files). Pesticides usually are detected in water that also contains substantial concentrations of nitrate. Recent investigations by the U.S. Geological Survey have detected commonly used pesticides in public water-supply wells; however, samples are not routinely analyzed for every pesticide used in Iowa. Atrazine is the most commonly detected pesticide in ground water.

Pesticide occurrence in ground water is similar to nitrate occurrence in that it commonly is detected shortly after application. Modern agricultural pesticides are not as persistent as the early chlorinated pesticides like DDT. This condition may help explain why in many wells, pesticides are detected in the water only during the growing season. Recent investigations, however, have found detectable quantities of atrazine throughout the year in ground water (Hallberg and others, 1984). There is also an uncertainty concerning the prevalence and health effects of the pesticide degradation products. The chemistry of the degradation of these pesticides is complex and water samples from monitoring activities have not been analyzed for the degradation products.

Synthetic Organic Substances

Synthetic organic substances other than pesticides have been detected in water from public and private wells in Iowa (Kelley, 1985; Kelley and Wnuk, 1986). These substances commonly are associated with commercial or industrial uses, or chemical storage and disposal areas. Many of the detected substances such as trichloroethylene (TCE) are among those identified as potential carcinogens, although drinking-water standards have not yet been established for them (U.S. Environmental Protection Agency, 1979; 1986a).

POTENTIAL FOR WATER-QUALITY CHANGES

Iowa predominantly is an agricultural State and most land use is related to agriculture. Iowa ranks first in the Nation in the production of corn and second in the production of soybeans (Skow and Halley,1986). This national leadership in row-crop production has been bolstered by the use of modern agricultural practices and chemicals.The correlation between increases in agricultural-chemical use and ground-water contamination has been apparent for some time (McDonald and Splinter, 1982). In 1982, the U.S. Geological Survey in cooperation with the University of Iowa Hygienic Laboratory and the Iowa Geological Survey began a program of long-term monitoring of wells in Iowa. The network currently (1986) contains about 1,500 wells. The location of each well and the aquifers monitored at each well site are shown in figure 4. About 300 of the network wells are sampled each year for a variety of water-quality properties and constituents, including nitrate, trace metals, pesticides, and synthetic organic substances. Shallow wells are monitored more frequently because of the vulnerability of shallow aquifers to point and nonpoint source contamination.

Data collected thus far indicate that pesticide residues in ground water probably are increasing (Kelley and others, 1986, p. 2). Contaminants entering shallow aquifers likely will continue unless land-use or agricultural practices are changed significantly. Deeper aquifers also may begin to be affected as water from shallow aquifers moves downward within the recharge areas to the deeper aquifers. Increased efforts are needed to define the extent and magnitude of detected or suspected contamination; to determine the physical, chemical, and biological mechanisms that affect the movement and degradation of contaminants; and to determine alternatives to decrease or eliminate the cause of contamination.

Waste-disposal sites in Iowa (figs. 3*A* and 3*C*) also may present a long-term threat to ground-water quality. Not included in the sites shown in figures 3*A* and 3*C* are the location of wells used for the gravity draining of agricultural lands or the areas within Iowa where municipal sewage sludge is being applied to the land. Agricultural-drainage wells transport surface water and shallow ground water and their associated contaminants into deeper aquifers in north-central Iowa (Baker and Austin, 1982). The extent and potential of this contamination are not known.

GROUND-WATER-QUALITY MANAGEMENT

The Iowa Department of Natural Resources has primary responsibility for managing ground-water quality in Iowa. Regulatory functions related to ground-water quality are conducted by the Department's Environmental Protection Division. These functions include implementing the Federal Safe Drinking Water Act, managing a water allocation permit system, and regulating solid-waste disposal. For the most part the RCRA program is administered by the EPA; however, EPA is involved with certain hazardous-waste programs. It administers the State Superfund program, which primarily is a registry of uncontrolled or abandoned waste sites in the State. The State also has an established administrative procedure for obtaining State and local approval of sites for any hazardous-waste disposal facility. In addition, the Iowa Department of Natural Resources provides technical assistance for control of hazardous spills and participates with the EPA in CERCLA investigations and cleanups.

Various divisions of the Iowa Department of Natural Resources become involved in ground-water studies, commonly supported by grants from the EPA. The Geological Survey Bureau of the Department's Energy and Geological Resources Division performs ground-water investigations, research, and service work. Ground-water-monitoring programs and special studies commonly are cooperative efforts between the Geological Survey Bureau, the University of Iowa Hygienic Laboratory, and the U.S. Geological Survey. Such studies have included surveys of the occurrence of synthetic organic compounds, including commonly used pesticides, in public water supplies.

The Iowa Department of Agriculture and Land Stewardship administers rules for pesticide handling and storage facilities, which attempt to prevent ground-water contamination. The Department also administers the Federal Insecticide, Fungicide, and Rodenticide Act in Iowa. This act involves the registration and use of pesticides.

The Planning Bureau of the Iowa Department of Natural Resources' Coordination and Information Division prepared a legislatively mandated ground-water-protection plan for presentation to the 1987 Iowa Legislature. The plan was to identify sources of ground-water pollution, provide policy options, and recommend legal and program changes. In addition, the plan was to be reviewed and a status report provided to the Legislature every 5 years. The plan resulted in the passage of a ground-water protection act that emphasizes a nondegradation policy.

The State has passed numerous items of legislation related to the protection of ground-water quality in the past few years in addition to the ground-water-protection plan mandate. This recent legislation can be divided into three general catagories: hazardous waste, landfills, and preventive measures.

Legislation has required the development of a State hazardous-waste-management plan. This development will be followed by a more specific plan for the establishment of a State-owned facility for the long-term, above-ground storage of hazardous waste. New legislation requires registration of underground tanks used for the storage of petroleum products or other hazardous chemicals with the Iowa Department of Natural Resources. The Department also was directed to establish rules regarding detection, prevention, and correction of leaking tanks. There is a hazardous-waste fee and remedial fund (State Superfund) that has been recently established. "Toxic cleanup days" demonstration projects are created to promote the proper disposal of household and farm-generated hazardous wastes.

A fee was established for solid-waste disposal in landfills, with the revenue to be used to develop alternative waste-disposal methods and methods for preventing ground-water contamination. Rules also were developed for improved monitoring of ground water at landfills. Other new legislation requires that alternative means of waste disposal, other than landfills, be considered and given preference if determined to be economically feasible. This legislation attempts to phase out landfills by 1997.

Legislation that may aid in the prevention of water-quality problems includes the establishment of an Agricultural Energy Management Fund to be used for education and demonstration projects which result in management practices that, among other things, decrease the potential for ground-water contamination. Municipal water suppliers have been mandated to conduct a one-time sampling for certain synthetic organic compounds including commonly used pesticides. A provision was passed enabling the designation of protected water sources and restriction of water use from such sources to protect the long-term quantity and quality of ground water. Also, the registration of well drillers is now required.

The recent legislation listed above primarily has addressed ground-water quality with respect to potential point-sources of contaminants. However, studies have identified degradation of ground-water quality from nonpoint agricultural chemicals. Thirty-three percent of the samples from water-supply wells, sampled in various environments, contained pesticide residues (Kelley and others, 1986, p. 1). These nonpoint sources may constitute the major ground-water-quality problem in Iowa. Research in this regard is being done by the Iowa Geological Survey Bureau of the Energy and Geological Resources Division, in cooperation with numerous Federal and other State, local, and private agencies.

Past efforts involving ground-water data collection in Iowa focused on regional, deep bedrock aquifers and naturally occurring constituents that affect water quality. As a result, these aquifers have been well characterized. Recently, emphasis has shifted to shallow aquifers and the effects of human activities on water quality. However, the data base for such information is still small and continued efforts to expand it are needed. For effective management of ground-water quality, information also is needed on the hydraulic and chemical factors affecting contaminant movement, effective means for preventing ground-water contamination, and the effects of various contaminants on human health.

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KANSAS
Ground-Water Quality

Ground water is the principal source of supply for more than 500 public-water-supply systems in Kansas, including that of the largest city, Wichita. Ground water also is the primary source of self-supplied rural-domestic water. About 60 percent of the State's 2.45 million people drink ground water. (See population distribution in figure 1.) About 90 percent of the irrigation water and about 75 percent of the self-supplied industrial water used in the State is ground water.

Most ground water in Kansas contains less than 1,000 mg/L (milligrams per liter) dissolved solids and does not exceed the drinking-water standards established by the State in 1982 (Kansas Administrative Regulations 28–15–11 through 28–15–20). Locally, each of the aquifers may yield water with dissolved-solids concentrations that exceed 1,000 mg/L. Nearly all the ground water in the State is hard to very hard (hardness more than 120 mg/L as calcium carbonate). (See figure 2*C*.)

Changes in ground-water quality in several areas of the State can be associated with human activities—mineral extraction, oil production, waste disposal, and agriculture. Problems with contamination of ground water associated with the production of oil and gas are widespread. Contamination of ground water from waste disposal has been identified chiefly in and near the major population centers. (See figures 2 and 3.) Adverse effects from agricultural practices have not been studied extensively; however, investigations (Spruill, 1985) indicate increased concentrations of inorganic compounds in water from alluvial aquifers in north-central Kansas as a result of irrigation return flows. Pesticides have been detected in ground water in at least one area in northern Sedgwick County. In addition, some alluvial aquifers are affected by natural sources of saline water and brine.

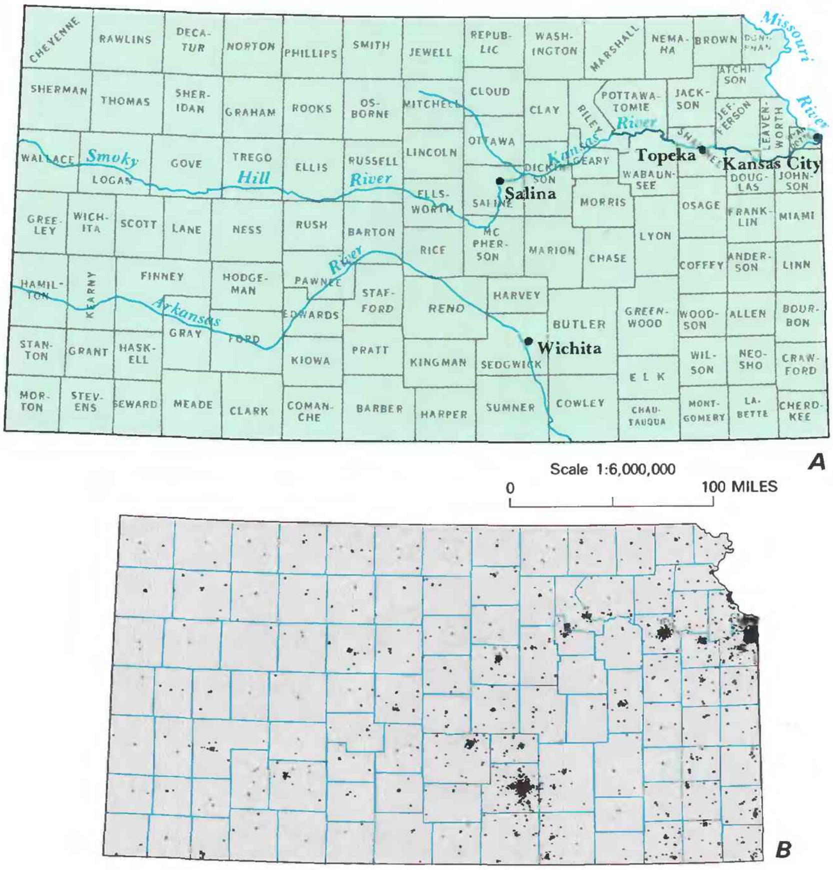

Figure 1. Selected geographic features and 1985 population distribution in Kansas. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

During 1976, Kansas agencies established a ground-water-quality monitoring network in cooperation with the U.S. Geological Survey. The network now (1986) includes 250 wells that are sampled annually. The sampling program includes routine analysis for major ions and analysis of selected samples for trace elements, organic compounds, and radionuclides.

WATER QUALITY IN PRINCIPAL AQUIFERS

Kansas has seven principal aquifers, all with differing water quality. These principal aquifers can be divided into two groups—unconsolidated deposits of Cenozoic age (alluvial, glacial-drift, and High Plains aquifers) and consolidated rocks of Mesozoic and Paleozoic age (Great Plains, Chase and Council Grove, Douglas, and Ozark aquifers). The geographic distribution of the seven aquifers is shown in figure 2*A*; a description of each aquifer is given by the U.S. Geological Survey (1985, p. 217–220). Vertical relations among the principal aquifers are shown by the hydrogeologic section (fig. 2*B*). About 95 percent of the ground water used in Kansas is from the aquifers in unconsolidated deposits, and about 90 percent of the withdrawal is from the High Plains aquifer.

BACKGROUND WATER QUALITY

A statistical summary of concentration of dissolved solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), fluoride, and chloride in water from the principal aquifers is shown in figure 2*C*. The water samples were collected during the period 1965 to 1985 from a variety of wells and test holes; no distinction was made between samples collected from different depth intervals within the same aquifer.

Figure 2*C* is based on selected chemical data available in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Percentiles of the variables are compared to national standards established by the U.S. Environmental Protection Agency (1986a,b) that specify the maximum concentration or level of a contaminant in a drinking-water supply. The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines.

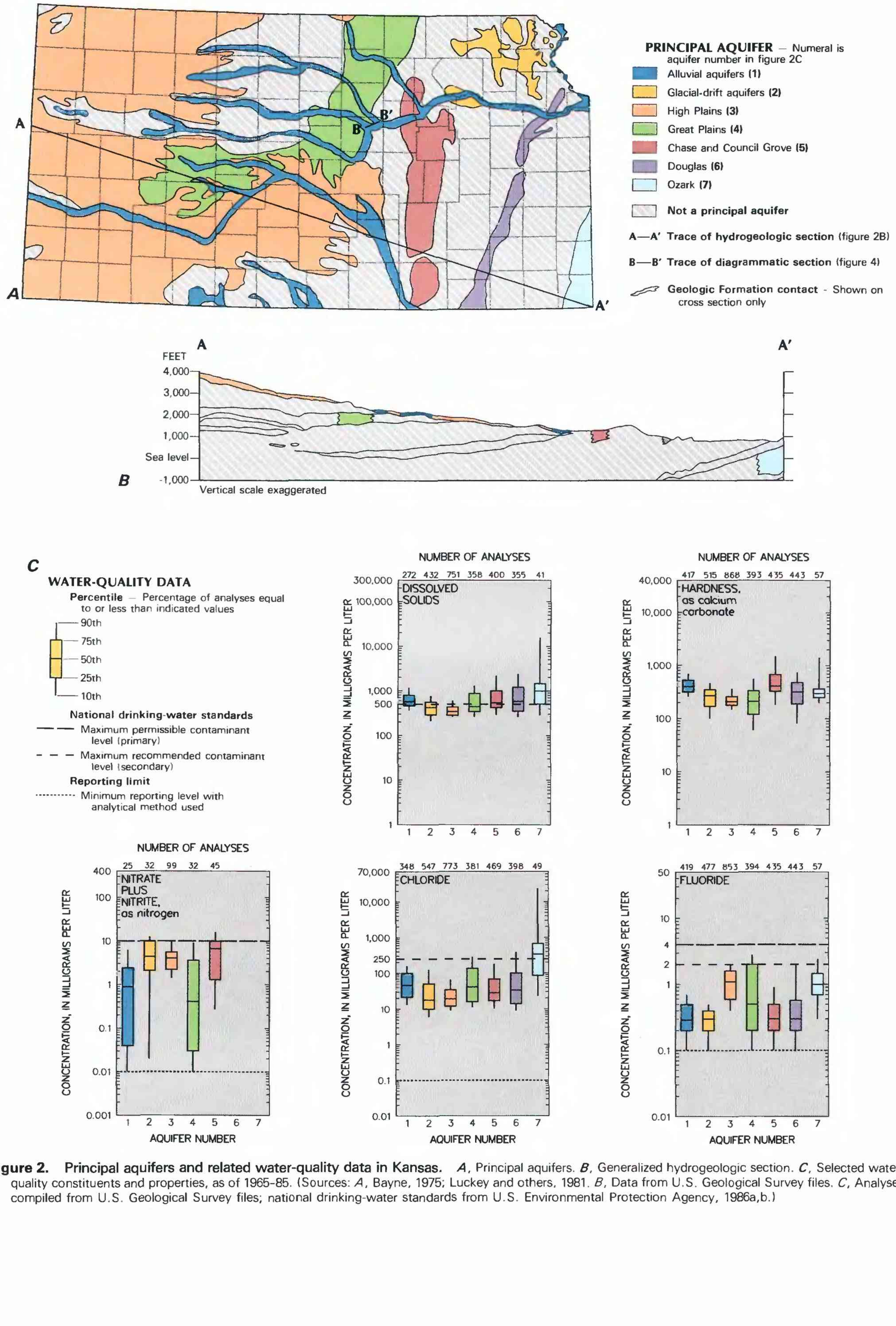

Figure 2. Principal aquifers and related water-quality data in Kansas. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1965-85. (Sources: *A*, Bayne, 1975; Luckey and others, 1981. *B*, Data from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

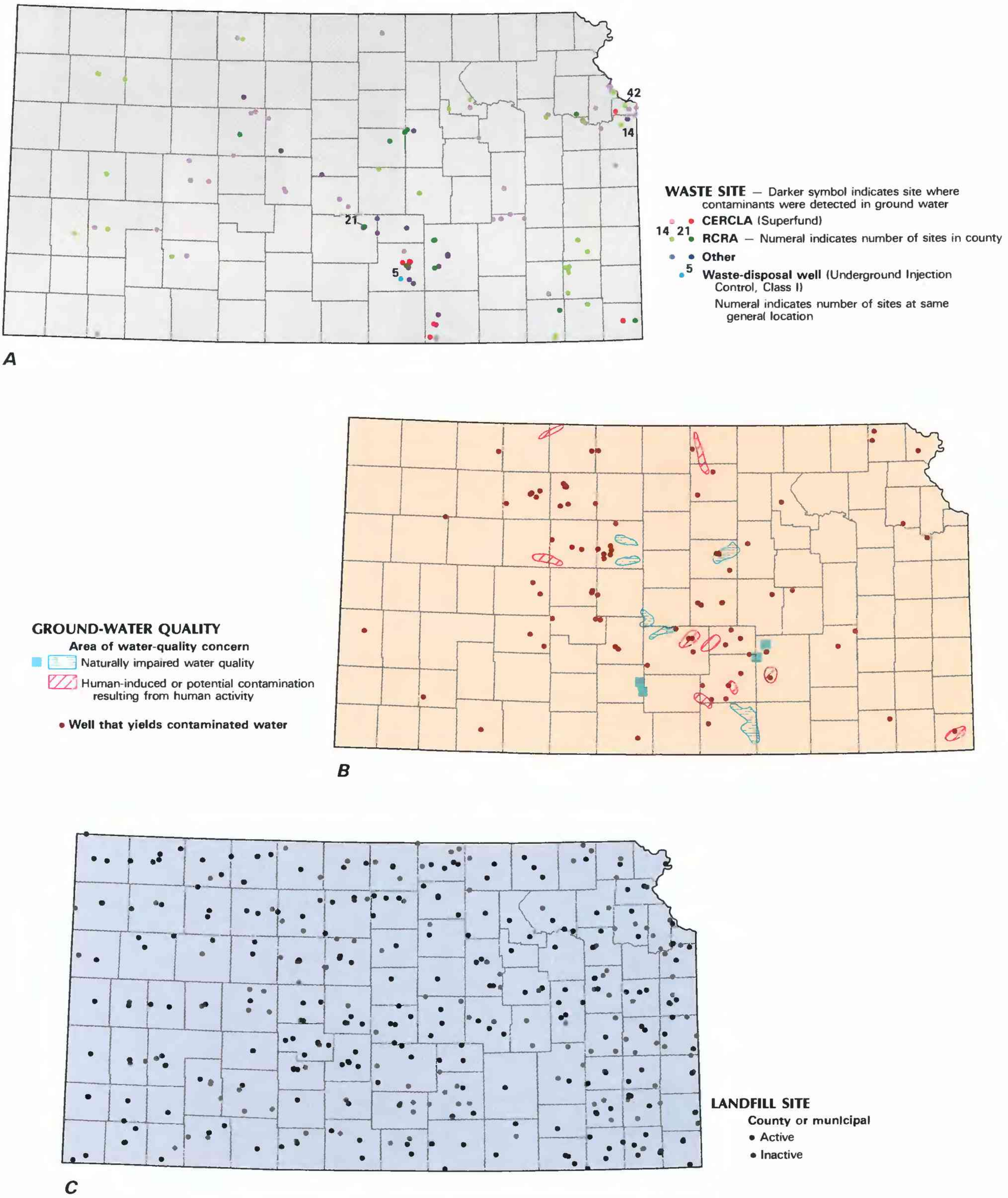

Figure 3. Selected waste sites and ground-water-quality information in Kansas. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource, Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, areas of human-induced or potential contamination, and distribution of wells that yield contaminated water, as 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Kansas Department of Health and Environment, unpublished data. *B*, Kansas Department of Health and Environment, unpublished data; Gillespie and Hargadine, 1981; Gogel, 1981; Spruill, 1985. *C*, Kansas Department of Health and Environment, 1985, and unpublished data.)

Alluvial Aquifers

Most water from the alluvial aquifers contained less than 1,000 mg/L dissolved solids. Locally, concentrations of dissolved solids larger than 9,000 mg/L may be caused by inflow of saline water from underlying consolidated rocks. Typically, the water was very hard; the median concentration of hardness was 400 mg/L. Maximum concentrations of nitrate plus nitrite and fluoride did not exceed the primary drinking-water standards, whereas the maximum chloride concentration exceeded the secondary standard. Water from these aquifers is used primarily for public supplies and industry.

The quality of water in several of the alluvial aquifers is impaired by inflow of saline or briny water from underlying consolidated rocks (fig. 3*B*) (Hargadine and others, 1978; Gillespie and Hargadine, 1981; Gogel, 1981). Locally, confined water that contains significantly large concentrations of calcium, sodium, sulfate, and chloride is under higher hydraulic head than that in the overlying alluvium. In these areas, the saline or briny water may move upward through the confining layer and enter the alluvial aquifers. An example of such degradation in the Smoky Hill River valley near Salina is shown in figure 4. Water withdrawals from the alluvial aquifers may lower the hydraulic head in these aquifers causing upwelling of saline water and aggravation of the problem.

Glacial-Drift Aquifers

Water from the glacial-drift aquifers contained smaller concentrations of dissolved solids and chloride and slightly larger concentrations of fluoride than water from the alluvial aquifers. The water was very hard (median hardness was 270 mg/L), and nitrate plus nitrite concentrations in 10 percent of the samples analyzed were larger than 10 mg/L. The principal withdrawal of water from the aquifers is from shallow wells for self-supplied rural-domestic use. Water from deep wells may have concentrations of dissolved solids larger than 700 mg/L.

High Plains Aquifer

The High Plains aquifer yields water with the smallest concentrations of dissolved solids in Kansas; the median concentration of dissolved solids was 340 mg/L. Water from the High Plains aquifer typically is hard to very hard; only 25 percent of the samples had hardness concentrations less than 180 mg/L. Most concentrations of nitrate plus nitrite and fluoride do not exceed the drinking-water standards. Although samples from a few wells had large concentrations of chloride (the maximum for 773 samples was 440 mg/L), fewer than 10 percent of the samples contained more than 70 mg/L. Most of the water pumped from the High Plains aquifer is used for irrigation, but the aquifer also supplies water for public supply and industrial use in the Wichita area as well as for many smaller cities and rural domestic users.

Great Plains Aquifer

Water from the Great Plains aquifer is more variable in quality than water from unconsolidated deposits. Where the aquifer crops out at the land surface or is directly overlain by unconsolidated Cenozoic deposits, the water contains less than 500 mg/L dissolved solids and is used for irrigation, public, and rural-domestic supplies. Concentrations of all constituents, particularly chloride and sodium, increase with depth or increase where the aquifer is overlain by younger Cretaceous rocks; water from the aquifer in the northwest part of the area shown in figure 2*A* commonly is too saline for human use.

Chase and Council Grove Aquifer

Water from the Chase and Council Grove aquifer is suitable for most uses but is very hard (90 percent of samples had hardness concentrations larger than 180 mg/L). Most nitrate plus nitrite concentrations were within the acceptable range for drinking water. Fluoride concentrations generally were less than 1 mg/L. The water in the aquifer is used primarily for rural-domestic and public supplies. Some wells in the southern part of the area yield water with more than 2,000 mg/L dissolved solids; locally, sulfate concentrations are undesirably large. West of the area shown in figure 2*A* the aquifer water is unused because it is briny, with chloride concentrations larger than 10,000 mg/L.

Douglas Aquifer

Water from the Douglas aquifer is used for rural-domestic and public supplies by a few communities where the aquifer is at or near land surface. Dissolved-solids concentrations in these areas were smaller than 500 mg/L, but hardness typically exceeded 180 mg/L. Nitrate-plus-nitrite concentrations were variable; too few data are available to include a summary of nitrate plus nitrite in figure 2*C*, but the concentration exceeded 30 mg/L in 1 sample. Away from the outcrop area, water from the Douglas aquifer is likely to be saline, with dissolved-solids concentrations larger than 2,000 mg/L.

Ozark Aquifer

Water from the Ozark aquifer is variable in quality. The median concentration of dissolved solids in 41 samples was 1,000 mg/L. Locally in southeastern Kansas, the water is used for rural-domestic and public supplies. As is most ground water in Kansas, the water from this aquifer is very hard (hardness exceeded 200 mg/L in 90 percent of the samples). No exceptionally large concentrations of nitrate plus nitrite were reported, but the number of samples available (7) was considered too small to summarize in figure 2*C*. Fluoride concentrations in most samples were less than 2 mg/L. Northwest of the area shown in figure 2*A*, chloride concentrations in excess of 20,000 mg/L have been noted.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has changed in some areas of Kansas because of the effects of mineral extraction, waste disposal, and agricultural practices. In addition, shallow aquifers have been contaminated locally by spills and by leaks from pipelines and storage tanks. Most of the sites in the "other site" category shown in figure 3*A* are of this type; where ground water has been contaminated from these sites, the area of contamination rarely exceeds 1 or 2 square miles.

Mineral Extraction

Drainage from abandoned lead-zinc and coal mines has caused water-quality changes in southeastern Kansas. Water in the mine shafts contains large concentrations of iron, manganese, zinc, and other trace elements and large concentrations of dissolved solids (principally sulfate). Values of pH as low as 2.2 were reported by Spruill (1984). Surface-water supplies and shallow alluvial aquifers (too small to show in figure 2*A*) have been affected. The entire area of Cherokee County is included in the National Priorities List of hazardous-waste sites under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) (U.S. Environmental Protection Agency, 1986c). Although the Ozark aquifer, which underlies this area, probably has not been affected by mine drainage because it is deeply buried, the potential exists for contamination by leakage through drill holes and fractures.

Brines associated with the production of oil and gas have caused local contamination of freshwater aquifers in several areas in Kansas. Principal sources of contamination are leakage from brine-retention ponds and interaquifer movement of brines through improperly abandoned wells or test holes. Contamination by chloride is associated with oil production in Harvey County northwest of Wichita.

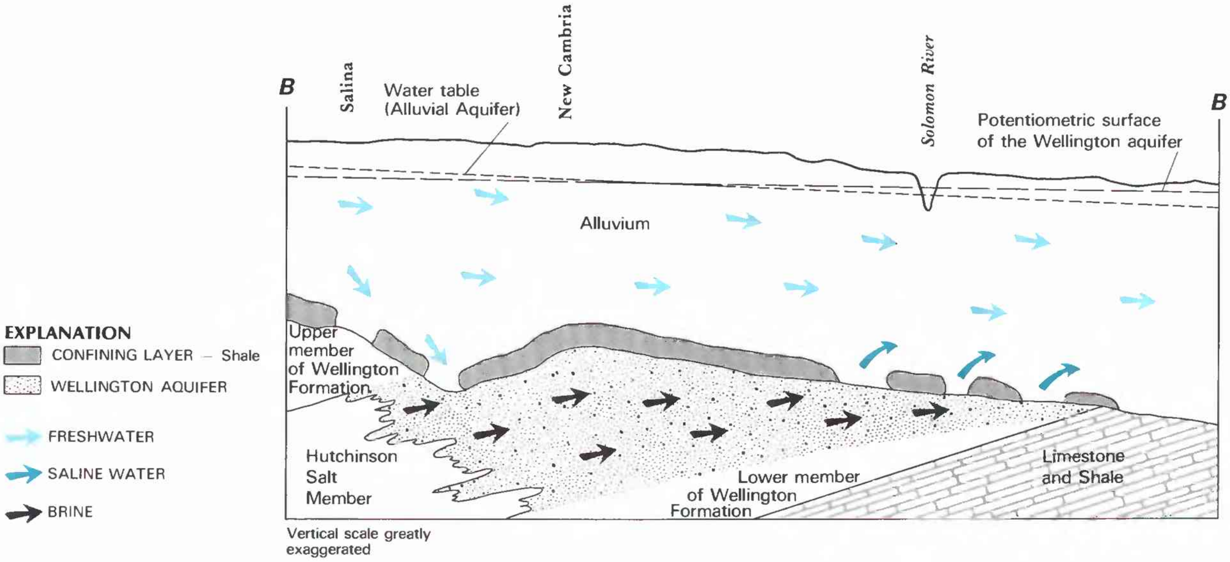

Figure 4. Diagrammatic section along the Smoky Hill River valley showing patterns of ground-water flow that introduce saline water into the alluvial aquifer. (Source: modified from Gillespie and Hargadine, 1981, fig. 10.)

Waste Disposal

Six CERCLA (Superfund) sites, 113 sites investigated by the Kansas Department of Health and Environment under the Resource Conservation and Recovery Act (RCRA), and 5 Underground Injection Control (UIC) wells are shown in figure 3*A*. Most of these sites involve disposal of industrial wastes. RCRA sites are concentrated near the major population and industrial centers of Wichita (Sedgwick County), Topeka (Shawnee County), and Kansas City (Johnson, Leavenworth, and Wyandotte Counties). Wastes present at the CERCLA and RCRA sites include arsenic, chromium, lead, and other trace elements; petroleum products; volatile organic compounds (VOC); and agricultural chemicals. Areas of known and potential ground-water contamination from these sources are shown in figure 3*B*. Kansas has 5 UIC wells using on-site deep-well disposal of hazardous waste. Waste disposed of in these wells consists of ignitables, cooling water blow-down containing chromium, spent antimony catalyst from fluoromethane production, aqueous solution containing methylene chloride, and chloroform. No known contamination problems exist at these sites.

In addition to industrial waste-disposal sites, 104 active county and municipal landfills in Kansas that are monitored by the Kansas Department of Health and Environment are shown in figure 3*C*. Also shown are 281 closed and abandoned landfills that were identified from county highway maps. Few data are available to evaluate the effects of these closed landfills on local ground-water quality.

Agriculture

Few studies have been conducted to determine the effect of irrigation on ground-water quality in Kansas. Irrigation is not practiced extensively in the eastern one-third of the State, and water quality in the glacial-drift, Chase and Council Grove, Douglas, and Ozark aquifers is unlikely to be affected by irrigation. The Ozark aquifer also is protected by the thickness of the overlying units.

Spruill (1985) attributed increased concentrations of calcium, sodium, sulfate, chloride, and dissolved solids in alluvial aquifers in north-central Kansas to irrigation return flows. However, analyses for pesticides for which primary drinking-water standards have been established indicated no contamination of ground water by these compounds.

Investigations to determine the effect of agricultural practices on the quality of water in the High Plains aquifer in western Kansas began in 1984. Although concentrations of sodium and bicarbonate have increased as a result of irrigation, insecticides and herbicides were not detected or were detected in only trace concentrations (J.K. Stamer, U.S. Geological Survey, oral commun., 1986).

Recent investigations have detected herbicides in water from the High Plains aquifer in north-central Sedgwick County (H.E. Bevans, U.S. Geological Survey, oral commun., 1986). These findings are of concern to State and local officials because the city of Wichita uses water from this aquifer as a principal source of public supply.

POTENTIAL FOR WATER-QUALITY CHANGES

Available water supplies in most of the irrigated areas of Kansas are almost completely appropriated, and irrigation is unlikely to increase greatly. However, the potential for additional contamination of ground water from agricultural practices remains. The movement of pesticides through the unsaturated zone is poorly understood, and investigations to determine their effect on ground-water quality continue. Declining water levels caused by withdrawals for irrigation also offer the potential for contamination of freshwater aquifers by underlying brines. Disposal and management of oil and gas production wastes are regulated by the State, but such regulation is sometimes difficult to enforce, particularly where large areas are involved. Disposal of oil-field brines remains a potential source of contamination.

GROUND-WATER-QUALITY MANAGEMENT

The principal State agencies with regulatory authority over matters of ground-water quality are the Kansas Corporation Commission (KCC) and the Kansas Department of Health and Environment (KDHE). The KCC enforces regulation of oil and gas exploration and production, with a statutory mandate [Kansas Statutes Annotated (KSA) 55–115 and the following] to protect the quality of fresh ground-water supplies. It also is responsible for locating and plugging abandoned oil and gas wells (KSA 55–1003 and the following).

The KDHE is responsible for developing water-quality-management plans, monitoring waste-disposal sites, monitoring public-water supplies, licensing well drillers, and responding to emergency water-contamination problems (KSA 65-161 and the following, 82a-1035 through 1038, 82a-1201 and the following).

The Kansas State Board of Agriculture, Division of Water Resources, is responsible for the administration of water rights. The Division of Water Resources and the five local Groundwater Management Districts have authority to instigate controls on withdrawals in areas where ground-water quality is deteriorating. The Board of Agriculture also regulates and monitors the use of agricultural chemicals. The Kansas Geological Survey conducts studies and research on ground-water availability and quality, and performs ground-water investigations on a service or contractual basis for other State agencies.

Kansas has established State drinking-water standards that are used in the assessment of ground-water quality (Kansas Administrative Regulations 28-15-11 through 28-15-20). A ground-water-quality monitoring network was established in 1976, in cooperation with the U.S. Geological Survey, to monitor background quality. About 250 wells in the network are sampled each year and analyzed for major ions, trace elements, radionuclides, and selected organic compounds. In addition, the KDHE obtains a sample annually from the distribution systems of each of the 525 public supplies that use ground water. These samples are analyzed for major ions and bacterial content, and every 3 years a sample is analyzed for trace elements and radionuclides. The Department also conducts studies of specific areas of known or potential ground-water contamination in cooperation with the Kansas Geological Survey and the U.S. Geological Survey.

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KENTUCKY
Ground-Water Quality

In the Commonwealth of Kentucky (fig. 1*A*) ground water supplies 22 percent of the total water withdrawn for all uses excluding thermoelectric power. About 31 percent of the total population is served by ground water (U.S. Geological Survey, 1985, p. 223). In the extensive karst areas of central Kentucky and in the coal-mining regions of the Commonwealth, ground water is the primary source of drinking water. The more densely populated urban areas (fig. 1*B*) are not as dependent upon ground water for drinking water because of the general availability of reliable surface water.

Generally, a thin veneer of freshwater in shallow aquifers overlies deep reservoirs that contain brackish water or brine at varying depths. Most shallow ground water is relatively unmineralized. Concentrations of dissolved solids, nitrate, and chloride in ground water generally are small, but iron concentrations in water from some shallow aquifers exceed the recommended standards for public water supplies. Also, water from some shallow aquifers is hard to very hard (fig. 2).

Locally, human activities have degraded the natural quality of ground water; the extent of this degradation is unknown. There are, however, several known and potential sources of ground-water contamination in Kentucky (fig. 3). Parts of the karstified limestone aquifers, which underlie about 50 percent of the Commonwealth, are contaminated; the contaminants are derived from both point and nonpoint sources. In karst topography, contaminated surface flows can enter the ground-water system directly through open sinkholes and solution openings. Such features make these aquifers very vulnerable to contamination. Septic systems that are improperly sited, designed, constructed, or maintained have been identified by the Kentucky Natural Resources and Environmental Protection Cabinet (1986, p. 50) as the most significant source of ground-water contamination statewide.

As of February 1987, there were 29 hazardous-waste management facilities in Kentucky that use a land unit for storage, treatment, or disposal of hazardous waste (Lori Johnson, Kentucky Natural Resources and Environmental Protection Cabinet, oral commun., 1987). The operators of these facilities are required to monitor ground-water quality under the Resource Conservation and Recovery Act (RCRA). However, "no contamination of drinking water wells or supplies by a hazardous waste facility has been documented to date" (Kentucky Natural Resources and Environmental Protection Cabinet, 1986, p. 83). An additional nine abandoned toxic-waste sites are listed on the National Priorities List (NPL), and the State has proposed the inclusion of one additional site (U.S. Environmental Protection Agency, 1986c). These sites require additional evaluation as part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly referred to as "Superfund." Ground-water contamination has been reported at 12 RCRA sites and 4 CERCLA sites.

Other known or potential sources of ground-water degradation in Kentucky include agricultural activities, underground storage tanks, municipal and radiological-waste landfills, and surface impoundments (Kentucky Natural Resources and Environmental Protection Cabinet, 1986). Also, coal mining and brine disposal by the oil and gas industry may be affecting extensive areas of the ground-water resource in south-central Kentucky and in the coal fields of eastern and western Kentucky. In addition, the effects of urbanization on ground-water quality have not been adequately

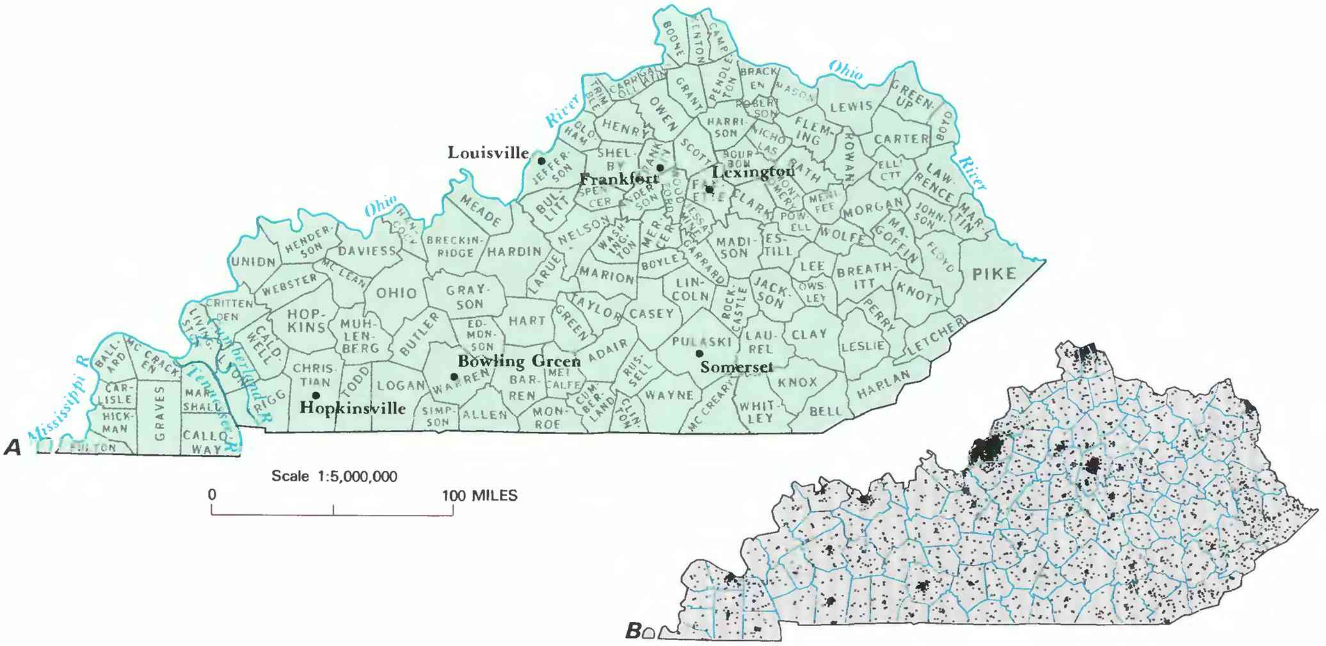

Figure 1. Selected geographic features and 1985 population distribution in Kentucky. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

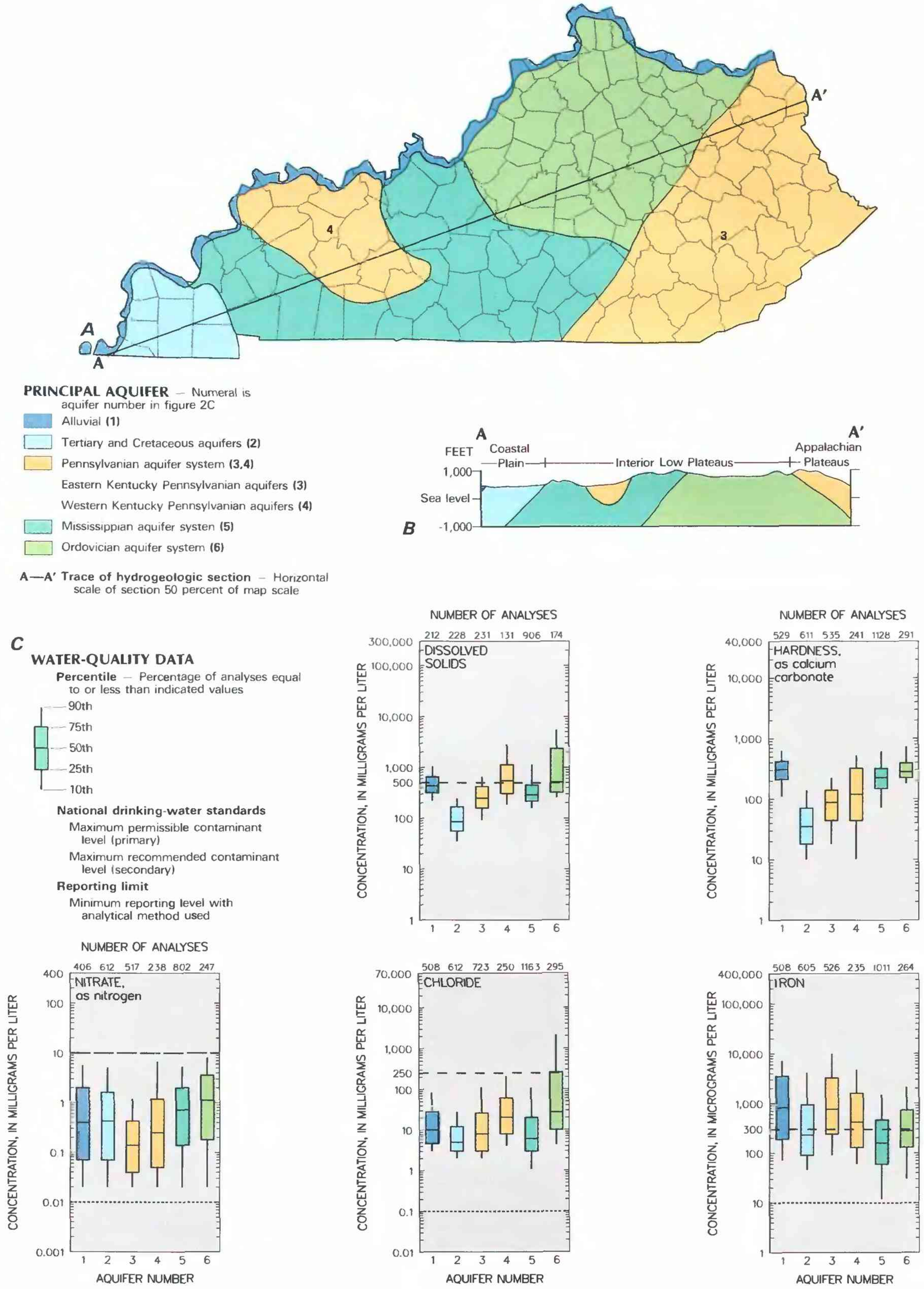

Figure 2. Principal aquifers and related water-quality data in Kentucky. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1930-86. (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

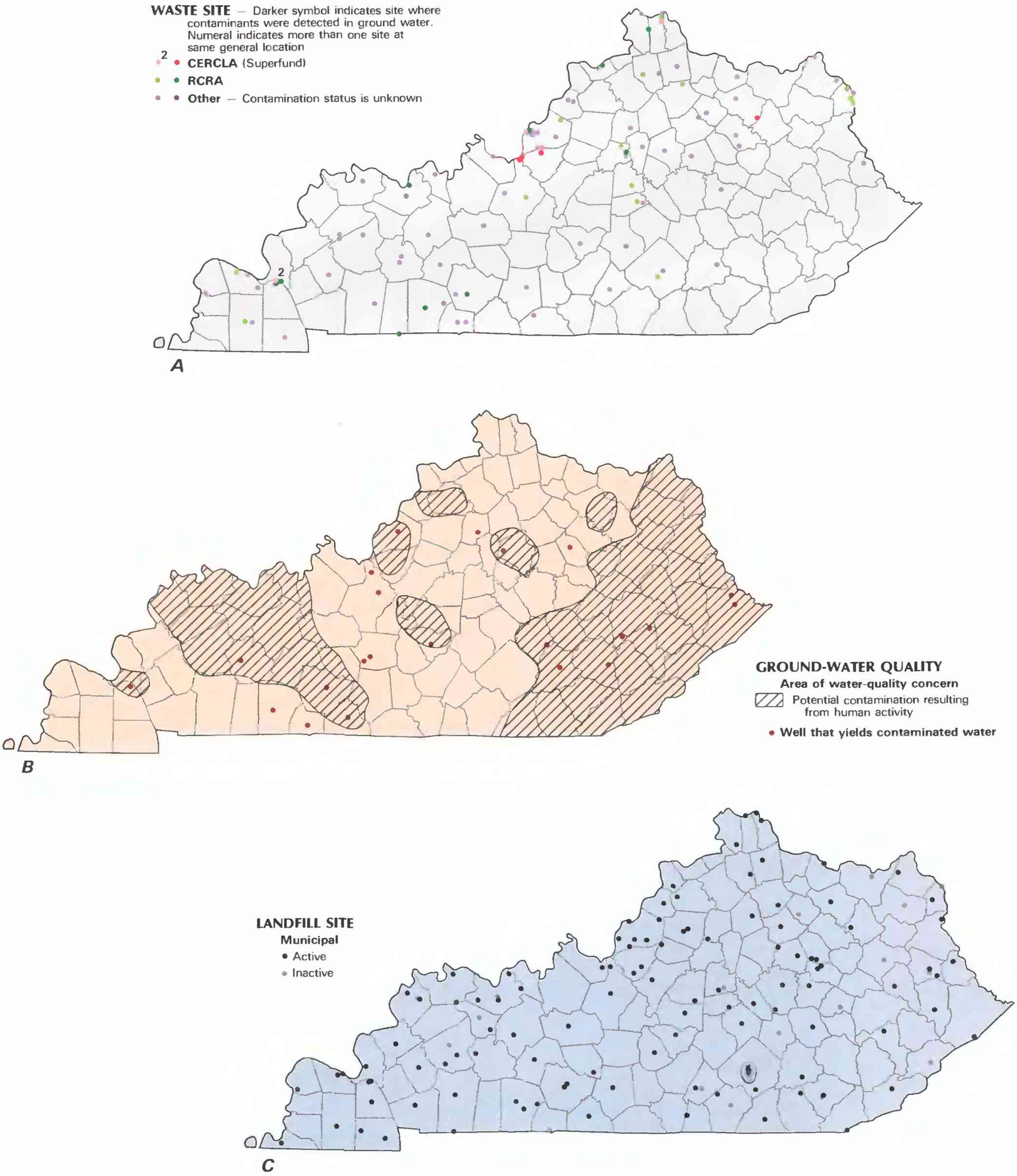

Figure 3. Selected waste sites and ground-water-quality information in Kentucky. *A*, Comprehensive Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of February 1987. *B*, Areas of potential contamination and distribution of wells that yield contaminated water, as of July 1986. *C*, Municipal landfills, as of July 1986. (Sources: *A*, *B*, *C*, Kentucky Natural Resources and Environmental Protection Cabinet files.)

defined. Isolated contamination incidents have been associated with pesticides and other organics, metals, radionuclides, chloride, fluoride, and nitrate.

WATER QUALITY IN PRINCIPAL AQUIFERS

Kentucky has five principal aquifers—the alluvial aquifer, the Tertiary and Cretaceous aquifers, the Pennsylvanian aquifer system, the Mississippian aquifer system, and the Ordovician aquifer system (figs. 2*A*,*B*). The aquifer types are unconsolidated sand and gravel in the alluvial aquifer along the Ohio, the Mississippi, and the downstream parts of the Cumberland and Tennessee Rivers; unconsolidated sand of the Tertiary and Cretaceous aquifers in extreme western Kentucky; fractured sandstone in the Pennsylvanian aquifer system in the eastern and western coal fields; and solution openings and fractures in the limestone in the Mississippian and the Ordovician aquifer systems in the north-central part of the Commonwealth. Of the State's total ground-water withdrawals, 63 percent is from the alluvial aquifer and the remaining 37 percent is withdrawn about equally from the other four aquifers (U.S. Geological Survey, 1985, p. 224).

Ground water generally is fresh—less than 1,000 mg/L (milligrams per liter) of dissolved solids—near the outcrop of the rocks that form the aquifers. However, the depth of the freshwater zone ranges from 25 to 2,000 feet below the land surface (Sprinkle and others, 1983, p. 13). The freshest ground water in Kentucky occurs in the Tertiary and Cretaceous aquifers; dissolved-solids concentrations in water from these aquifers generally are smaller than 170 mg/L. Water from the alluvium, Mississippian, and eastern Kentucky Pennsylvanian aquifer systems is fresh. Water from the western Kentucky Pennsylvanian aquifers and the Ordovician aquifer system have median dissolved-solids concentrations of 551 and 516 mg/L, respectively. Although water from the western Kentucky Pennsylvanian sandstone and Ordovician limestone aquifers generally is fresh, the chance of obtaining slightly saline water (1,000 to 3,000 mg/L dissolved solids) from these aquifers is greater than elsewhere in the State.

Concentrations of nitrate (as nitrogen) across Kentucky generally do not exceed the 10 mg/L national primary drinking-water standard. Nitrate data indicate that the largest concentrations are in the Mississippian and Ordovician aquifer systems, with median concentrations of 0.7 and 1.1 mg/L, respectively. The geographical area comprising these aquifers contains most of the metropolitan Louisville area, all the Lexington, Frankfort, Bowling Green, Somerset, and Hopkinsville metropolitan areas, and many other smaller, densely populated areas.

BACKGROUND WATER QUALITY

Samples of ground water have been collected in Kentucky since the 1930's. The U.S. Geological Survey maintained a network of wells and springs from 1967 to 1982 and most of the samples were collected from that network. Samples collected as part of this network were analyzed for several variables including common ions, nitrate, pH, and dissolved solids.

As the Commonwealth implements its ground-water protection strategy and continues to respond to incidents of contamination, data collected by the Kentucky Natural Resources and Environmental Protection Cabinet, U.S. Environmental Protection Agency, U.S. Geological Survey, and Kentucky Geological Survey, local governments, and facility operators will be added to the data base. These data will be used to document and analyze the effects of contamination incidents. Also, limited chemical data collected at public and private ground-water supply wells and springs, before the water is stored or treated, will be added to the data base. Ground-water-quality data for Kentucky were compiled by Faust and others (1980), and evaluated by Sprinkle and others (1983). The range of ground-water quality in Kentucky is illustrated by the graphical summary for dissolved solids, hardness (as calcium carbonate), nitrate (as nitrogen), chloride, and iron in figure 2*C*. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of contamination in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L (micrograms per liter) iron.

The ground-water-quality data base for Kentucky includes data from wells and springs sampled only once. The constituent values from those analyses have been used to define water quality at a location. Where multiple analyses were available at a site, the median constituent values were used to define the ground-water quality at the site. The summary shown in figure 2*C* represents about 94 percent of the 7,563 analyses of ground water in Kentucky. These analyses are stored in the U.S. Geological Survey's National Water-Data Storage and Retrieval System (WATSTORE). Those analyses containing concentrations of dissolved solids larger than 10,000 mg/L were assumed to have been taken from the extremely mineralized zone of water below the shallow freshwater zone and therefore, were not used in the summary shown in figure 2*C*.

Alluvial Aquifer

The alluvial aquifer along the Ohio, the Mississippi, the lower Tennessee, and the lower Cumberland River valleys yields large quantities of water and is the most intensively used aquifer in Kentucky (fig. 2*A*, aquifer 1). Numerous public supplies and industrial users withdraw water from shallow wells completed in the alluvium. In Louisville several commercial buildings use ground water for heating and cooling.

The quality of water in the alluvial aquifer generally is good for most uses, and only about 10 percent of the dissolved-solids concentrations are larger than 1,000 mg/L. However, between 25 and 50 percent of the dissolved-solids concentrations (fig. 2*C*, aquifer 1) exceed the national drinking-water standard of 500 mg/L. Water from the alluvial aquifer generally is very hard, with 75 percent of the values of hardness being larger than 210 mg/L. Between 50 and 75 percent of the iron concentrations exceed the national drinking-water standard of 300 μg/L. Chloride concentrations normally are smaller than 90 mg/L.

Concentrations of nitrate generally are small, with only 25 percent of the nitrate concentrations being larger than 2.0 mg/L. Examination of the nitrate data indicates that 20 samples from the alluvial aquifer contained nitrate concentrations larger than 11 mg/L, which slightly exceeds the national primary drinking-water standard of 10 mg/L. Further examination of the data showed that 10 of these samples were taken from locations in the six-county metropolitan Louisville area.

Increased concentrations of nitrate may indicate contamination from sources such as septic-tank leach fields and applications of fertilizers. Other investigations have revealed that contamination by oil-field brines, industrial waste and spills, and municipal waste may have locally affected the water quality of the alluvial aquifers (Hopkins, 1963; Davis and Matthews, 1983).

Tertiary and Cretaceous Aquifers

The Tertiary and Cretaceous aquifers are west of the Tennessee River in Kentucky (fig. 2*A*, aquifer 2). Both aquifers are relatively shallow, and supply water for public, industrial, and domestic purposes. However, these aquifers have not been fully developed as a water supply.

Water from these aquifers is very fresh and soft. Dissolved-solids concentrations rarely are larger than 250 mg/L and 75 percent of the values of hardness are smaller than 70 mg/L (fig. 2*C*, aquifer 2). The median iron concentration in these aquifers is 230 μg/L, but iron concentrations in the Cretaceous aquifer commonly exceed the drinking-water standard. Concentrations of chloride generally are smaller than 30 mg/L and 75 percent of the nitrate concentrations are smaller than 1.6 mg/L.

Pennsylvanian Aquifer System

The Pennsylvanian aquifer system is in the coal-mining regions of eastern and west-central Kentucky (fig. 2*A*, aquifers 3 and 4). Wells tapping these aquifers are used for domestic and stock supplies.

Concentrations of dissolved solids in water from the shallow ground-water circulation zone of the Pennsylvanian aquifer system in eastern Kentucky generally do not exceed the drinking-water standard (fig. 2*C*, aquifer 3). The water is moderately hard, with only about 25 percent of the hardness values being larger than 120 mg/L, and generally contains iron in excess of the secondary drinking-water standard. Concentrations of chloride generally are smaller than 110 mg/L, and 90 percent of the nitrate concentrations are smaller than 1.2 mg/L.

Water from the Pennsylvanian aquifer system in west-central Kentucky (fig. 2*C*, aquifer 4) generally contains dissolved-solids concentrations larger than 500 mg/L. Water from these aquifers is hard to very hard—the median hardness is 120 mg/L. Concentrations of iron generally are larger than 300 μg/L, and chloride concentrations normally are smaller than 60 mg/L. Concentrations of nitrate are larger in the western Kentucky Pennsylvanian aquifers than in the eastern Kentucky Pennsylvanian aquifers. In the western Kentucky aquifers, 25 percent of the nitrate concentrations are larger than 1.2 mg/L, compared to 10 percent for the eastern Kentucky Pennsylvanian aquifers.

The coal-mining regions of eastern and western Kentucky are being mined and extensively explored for oil and gas reserves. Water samples from deep oil-test wells commonly are briny.

Mississippian Aquifer System

The karst aquifer system in Mississippian age rocks is in the north-central part of Kentucky (fig. 2*A*, aquifer 5). Water from the Mississippian aquifer system is used as a public supply for several communities.

Water from the Mississippian aquifer system generally is fresh and concentrations of dissolved solids normally do not exceed the drinking-water standard (fig. 2*C*, aquifer 5). Water from this aquifer system is very hard—the median hardness is 226 mg/L. Iron concentrations generally do not exceed the secondary drinking-water standard (300 μg/L). Concentrations of chloride generally are smaller than 110 mg/L, and 75 percent of the nitrate concentrations are smaller than 2 mg/L.

Ordovician Aquifer System

The karst Ordovician aquifer system is in the north-central part of Kentucky (fig. 2*A*, aquifer 6). The ground water primarily is used for rural-domestic and stock purposes.

Water from this aquifer system generally is fresh and dissolved-solids concentrations commonly are larger than 500 mg/L (fig. 2*C*, aquifer 6). The water is very hard, with 90 percent of the values of hardness exceeding 178 mg/L. Iron concentrations commonly do not exceed the secondary drinking-water standard—the median concentration is 280 μg/L. About 25 percent of the chloride concentrations exceed the secondary drinking-water standard. Concentrations of nitrate generally are larger in the Ordovician aquifer system than in any other aquifer system in Kentucky; however, only about 10 percent of the nitrate concentrations are larger than 8.0 mg/L.

EFFECTS OF LAND USE ON WATER QUALITY

Although the general quality of shallow ground water is good for most uses, Kentucky is faced with ground-water degradation problems on a statewide basis. Some incidents have been reported and investigated on a localized basis by the Kentucky Natural Resources and Environmental Protection Cabinet, the U.S. Environmental Protection Agency (EPA), the U.S. Geological Survey, the Kentucky Geological Survey, and other agencies, but the total extent of any degradation is undefined.

Waste Management and Chemical Storage

Waste management and chemical storage include the following major sources: RCRA-regulated facilities that use a land unit for storage, treatment, or disposal of hazardous waste; NPL listed or nominated abandoned toxic-waste disposal sites; nonhazardous waste-disposal facilities; and underground storage tanks.

As of February 1987, there were 29 RCRA-regulated hazardous waste facilities in Kentucky (fig. 3*A*), which are required to monitor ground-water quality (Lori Johnson, Kentucky Natural Resources and Environmental Protection Cabinet, oral commun., 1987). These facilities use landfills, surface impoundments, and waste piles for the storage, treatment, or disposal of hazardous waste. Because of the nature of the waste involved and the possibility of liner failure, these facilities constitute a potential hazard to the quality of ground water. Ground-water contamination has been reported at 12 sites (Lori Johnson, Kentucky Natural Resources and Environmental Protection Cabinet, oral commun., 1986).

Abandoned toxic-waste sites are a serious threat to ground-water quality. In Kentucky, nine such CERCLA sites (fig. 3*A*) are listed on the NPL (U.S. Environmental Protection Agency, 1986c). The one site shown in Marshall County actually represents two individual sites. One of the sites located in Hardin County, shown as an "other site" in figure 3*A*, has been proposed for addition to the NPL. Four of the CERCLA sites are reported to have created measurable, localized ground-water contamination (Nancy Redgate, U.S. Environmental Protection Agency, oral commun., 1986). Many of the CERCLA and RCRA sites are in the vicinity of populated areas along the Ohio and the Tennessee Rivers.

Nonhazardous waste is defined as solid waste not regulated as a hazardous waste under RCRA. Primarily, landfills and landfarms are used for nonhazardous waste disposal in Kentucky. Figure 3*A* shows the location of industrial landfills and landfarming sites (designated as "other" sites) and figure 3*C* shows the location of municipal landfills.

Landfarming is a common practice for the disposal of municipal wastewater treatment sludge. The practice involves the spreading of digested sludge, which is excellent soil additive and fertilizer, on agricultural plots with subsequent mixing of the sludge into the soil layer. Limited data are available to document the potential effect of these sites on the quality of ground water in Kentucky; however, the EPA has issued new sludge-management standards that include ground-water protection standards for landfarming.

Kentucky has more than 100 municipal landfills. Minimal data exist to document the effects, if any, of each landfill on ground-water quality; however, an improperly sited, designed, constructed, or operated facility can allow contaminants to infiltrate the ground-water system. The EPA is reassessing its solid-waste management criteria and guidelines to determine if increased protection of ground water is warranted, particularly for those landfills that receive household hazardous and toxic chemicals.

Underground storage tanks are used in Kentucky to store hazardous and toxic substances and petrochemical products. Consequently, they represent a potentially serious threat to ground-water quality if leakage occurs. As a result of this potential threat, the State is implementing a program to regulate such tanks. As of September 1986, the State had inventoried more than 18,000 tanks, with an estimated 25 percent of them possibly leaking contaminants (A.L. Smothers, Kentucky Natural Resources and Environmental Protection Cabinet, oral commun., 1986).

Mineral Development

Coal mining in Kentucky, which started in the early 1800's, affects the area of the Pennsylvanian aquifers. Many ground-water problems have occurred in these regions of Kentucky. The reasons for these problems include improper mining and reclamation techniques, and improperly constructed and abandoned wells and exploratory holes (Kentucky Natural Resources and Environmental Protection Cabinet, 1986). Sloane and Warner (1984) reported that dewatering of an aquifer can affect the quality of ground water by exposing materials containing pyrite to oxygen. When water percolates through the oxidized material, the resulting chemical reactions can make available for transport increased concentrations of iron and other heavy metals.

Surface mining also can affect the quality of ground water. Collier and others (1964; 1970) reported that water in spoil material is more highly mineralized than water from the bedrock aquifers, and its composition is dependent on the chemical composition of the spoil material. Water in spoil material has infiltrated the ground-water system and increased sulfate concentrations in bedrock aquifers. Where mining is or has been intense, such as in the Evarts, Cranks Creek, and the Clover Fork areas of Harlan County, ground water is considerably mineralized (Kentucky Natural Resources and Environmental Protection Cabinet, 1986).

Oil and gas development in the Pennsylvanian and Mississippian aquifers also affects the quality of ground water. Oil was first discovered in Kentucky in 1819 and most wells today are stripper wells, which produce both brine and oil. Brine brought to the surface by stripper wells is injected, under EPA regulation, into a suitable formation or discharged under Kentucky Natural Resources and Environmental Protection Cabinet regulation, to streams, sinkholes, or evaporation pits. However, brines injected into improperly constructed wells, or illegally discharged to streams, sinkholes,or evaporation pits can infiltrate the shallow ground-water system. The extent of such contamination has not been defined.

By far the most serious cause of ground-water contamination problems associated with oil and gas wells is the improper casing and plugging of exploration and production wells. Many old holes have deteriorated plugs, and other holes have been left unplugged. Such holes serve as connections between fresh and briny aquifers (Kentucky Natural Resources and Environmental Protection Cabinet, 1986).

Urbanization

The effect of urbanization on the quality of ground water within Kentucky is not well documented. Ground-water quality can be affected by leaking septic tanks and sewers, as well as inadequately sited and designed leach fields, increased densities of waste disposal and underground storage facilities, and the covering of recharge areas by roads and buildings. The fluctuations of ground-water quality and water levels in a well in urban Jefferson County, Kentucky, are shown in figure 4. Analysis of these data did not conclusively show that urbanization was the cause of the changes. However, increased concentrations of dissolved solids, chloride, nitrate, or bacteria are indications of ground-water contamination by septic-tank leach fields. Also, in northern Jefferson County, at least 15 percent of the septic systems have failed to function as waste-disposal systems, but only limited data are available to document the effects of septic seepage on ground-water quality (U.S. Environmental Protection Agency, 1983a).

Perhaps the best example of the effects of urbanization on ground-water quality occurs in Bowling Green, Kentucky. The city, located in an environmentally vulnerable karst plain, has a history of ground-water contamination by point and nonpoint sources. To date, storm-water runoff has contributed oil, grease, metals, and bacteria to the ground water; gasoline leakage has resulted in fumes forming in caverns and moving upward into at least 30 homes, 2 elementary schools, a business, and a church; and point-source discharges to sinkholes have created significant problems (Kentucky Natural Resources and Environmental Protection Cabinet, 1986).

POTENTIAL FOR WATER-QUALITY CHANGES

The largest potential for changes in the quality of Kentucky's ground water exists in karst areas. About 50 percent of Kentucky is karst terrane, and ground-water recharge in karst areas occurs,

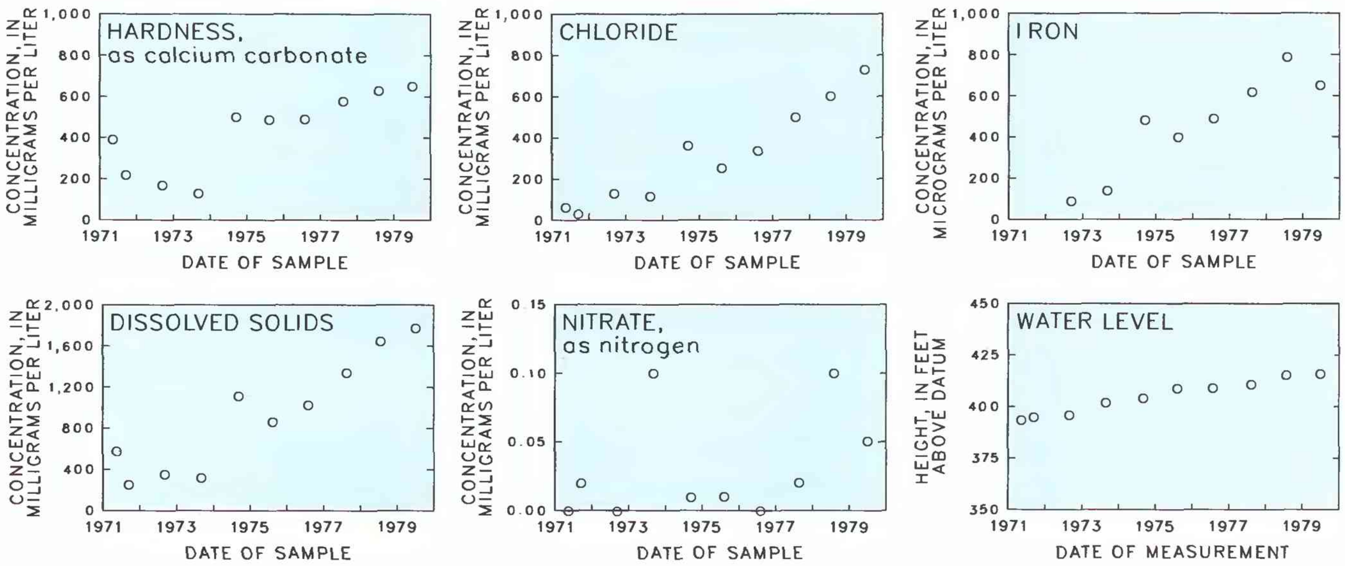

Figure 4. Fluctuations in ground-water quality and water level in the alluvial aquifer at Louisville. (Source: U.S. Geological Survey files.)

in most instances, as direct flow from the surface through solution openings, such as sinkholes or swallets, in the limestone. Underground drainage can consolidate to a few well-developed conduits, as indicated by well and spring yields ranging from gallons to thousands of gallons per minute. Where caves are present, the water table may occur below the level of streambeds, and water may be lost to the subsurface. In such instances, underground streams that are created have flow and water-quality characteristics somewhat similar to surface streams, particularly in their potential to assimilate organic wastes.

Owing to the availability of open conduits to the ground-water system, aquifers in karst terrane are extremely vulnerable to contamination. Surface flows, such as contaminated storm-water runoff from urban and agricultural areas, can directly discharge to the ground-water system. It is not uncommon for sinkholes in urban areas to be converted to drainage wells for storm-water runoff control and disposal. The EPA has not developed regulatory standards for drainage wells (Class V injection wells). Therefore, the wells are unregulated by this agency and the Kentucky Natural Resources and Environmental Protection Cabinet, unless a specific well can be demonstrated to be adversely affecting public health.

When a contaminant enters a karst conduit, it can reach a discharge point, either a spring, well, or surface stream, in a short time. Ground-water velocities have been observed to range from 1.5 to 23 miles per day (Mull and Lyverse, 1984, p. 24). Throughout Kentucky, springs and wells in karst terrane are contaminated by bacteria, nutrients, metals, and a variety of organics. Consequently, proper land-use planning, waste management, chemical-product management, and storm-water management are critical to continued reliance on ground water as a potable water supply in the karst terrane of Kentucky.

Except for a limited number of localized watersheds, such as in Elizabethtown in Hardin County (Mull and Lyverse, 1984), the hydrogeology of the karst aquifers of Kentucky have not been studied in detail. Many of these areas are experiencing both long-term and emergency-incident ground-water contamination problems. For example, in 1982, at Buttermilk Spring in Meade County, a serious outbreak of viral hepatitis-A was reported. This outbreak resulted in 1 fatality and 110 cases of reported illness (Kentucky Natural Resources and Environmental Protection Cabinet, 1984). Water from many wells in this karst area also contained levels of fecal and total coliform greater than the highest desirable concentrations recommended by the State (0 and 4 colonies per 100 milliliters, respectively) for private water supplies (Russell Barnett, Kentucky Natural Resources and Environmental Protection Cabinet, written commun., 1987). The source of the contamination is still undetermined and the recharge area providing water to this spring has not been mapped.

Perhaps just as significant is the unknown number of leaking underground storage tanks that contain hazardous and toxic substances and petrochemical products. Kentucky has initiated a program to inventory all existing tanks and to determine which tanks may be leaking contaminants to the ground water, requiring corrective action.

GROUND-WATER-QUALITY MANAGEMENT

In November 1984, the Kentucky Water Management Plan was adopted, calling for the development of a ground-water management program. In August 1985, a Ground-Water Advisory Council was appointed to oversee the development and implementation of this program. The council consists of representatives from each of the State agencies responsible for the management and protection of ground water, as well as the State and Federal Geological Surveys.

Five State agencies are responsible for enactment of the 10 State statutes that address ground water in Kentucky:

Division of Water is the primary agency responsible for developing and implementing a comprehensive ground-water management program. The Division's Ground-Water Branch is responsible for developing a statewide ground-water protection strategy, maintaining a ground-water data base, administering a water-well drillers certification program, and other protection efforts.

Division of Waste Management's Solid and Hazardous Waste Management Program is responsible for regulating waste treatment, storage, and disposal facilities under RCRA and the State solid-waste statute. Ground-water monitoring is required at some solid and all hazardous waste land treatment, storage, and disposal facilities. The Division cooperates with the EPA in their efforts to implement the provisions of CERCLA, and has initiated a program to regulate underground storage tanks.

Department for Health Services is responsible for monitoring the quality of private ground-water supplies and regulating the use of individual waste disposal systems, such as septic tanks.

Division of Oil and Gas administers a program designed to protect freshwater during drilling, plugging, and waste-injection operations (Class II injection wells) associated with the oil and gas industry. The Division is seeking primacy from the EPA for administering the Federal regulatory program for Class II injection wells.

Department of Surface Mining Reclamation and Enforcement is responsible for regulating the mining industry, including monitoring the effects of surface and underground mining on the ground-water resource.

In addition, the Kentucky Geological Survey, in cooperaton with the U.S. Geological Survey, collects and compiles ground-water-level and water-quality data for the Commonwealth.

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LOUISIANA
Ground-Water Quality

Ground water is the principal source of water for domestic use for almost 69 percent of the population of Louisiana. About two-thirds of the total ground water withdrawn for domestic use is delivered by public-supply systems in populous areas; the remaining one-third is delivered by self-supply systems in rural areas (fig. 1). As of 1985, about 1,450 Mgal/d (million gallons per day) of ground water was withdrawn in Louisiana for irrigation, industry, public-supply, rural and domestic livestock, and power generation. The Chicot aquifer system is the major source of ground water in Louisiana (D.L. Lurry, U.S. Geological Survey, written commun., 1986).

The quality of ground water in Louisiana is generally suitable for public supply, except where dissolved-solids concentrations are larger than 1,000 mg/L (milligrams per liter). Additionally, in some areas of the Pleistocene and Pliocene-Miocene aquifers, saltwater contamination of freshwater aquifers degrades ground-water quality. Water color and hardness or iron concentration can also render ground water locally unsuitable for public supply without treatment. Some areas, primarily coastal, have no fresh ground water at any depth.

Saltwater encroachment into freshwater aquifers (fig. 2) is not an immediate threat to public supply. However, saltwater encroachment is a potential threat to public supply in the Chicot aquifer, the "400- and 600-foot" sands of the southeastern Pleistocene aquifers, and the "1,200-foot" and deeper sands near Baton Rouge. At current pumping rates, saltwater encroachment probably will not degrade any major water supply in the State for about 30 years. Upconing of saltwater locally affects ground-water quality.

Louisiana contains 5 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; 50 Resource Conservation and Recovery Act (RCRA) sites; 29 active industrial landfill sites; 71 Class I hazardous-waste injection sites; 138 parish and municipal solid-waste landfill sites; and an unknown number of oil-field waste-disposal pits (fig. 3). In addition, 14 sites at 2 U.S. Department of Defense (DOD) facilities had required response action in accordance with CERCLA as of September 1985. Shallow ground-water contamination has been documented at 23 RCRA, 3 industrial landfill, and the 5 CERCLA (Superfund) sites. Saltwater contamination in the terrace aquifers has been partly attributed to oil and gas production activities, which includes oil-field waste disposal. Industrial waste has contaminated shallow sands in the area of some disposal sites and is a potential threat to the quality of potable ground water in Louisiana. Efforts are currently underway to define the distribution and concentration of organic chemicals in the ground water.

WATER QUALITY IN PRINCIPAL AQUIFERS

The principal aquifer groups of Louisiana, from youngest to oldest, are the alluvial, Pleistocene, Pliocene-Miocene, Cockfield and Sparta, and Carrizo-Wilcox aquifers (figs. 2*A*,*B*). Major concerns about the quality of ground water in Louisiana are (1) excessive concentrations of dissolved solids, iron, and hardness in the alluvial aquifers, (2) large concentrations of iron in the Chicot aquifer of the Pleistocene aquifers group and the Cockfield and Sparta aquifers, and (3) saltwater contamination of aquifers in coastal areas. Also, concern is increasing about contamination of ground water by surface waste disposal and use of agricultural chemicals.

Ground-water-quality information is collected through a cooperative program with the State of Louisiana. These cooperative efforts include areal ground-water and water-quality studies as well as a statewide water-quality monitoring system.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data

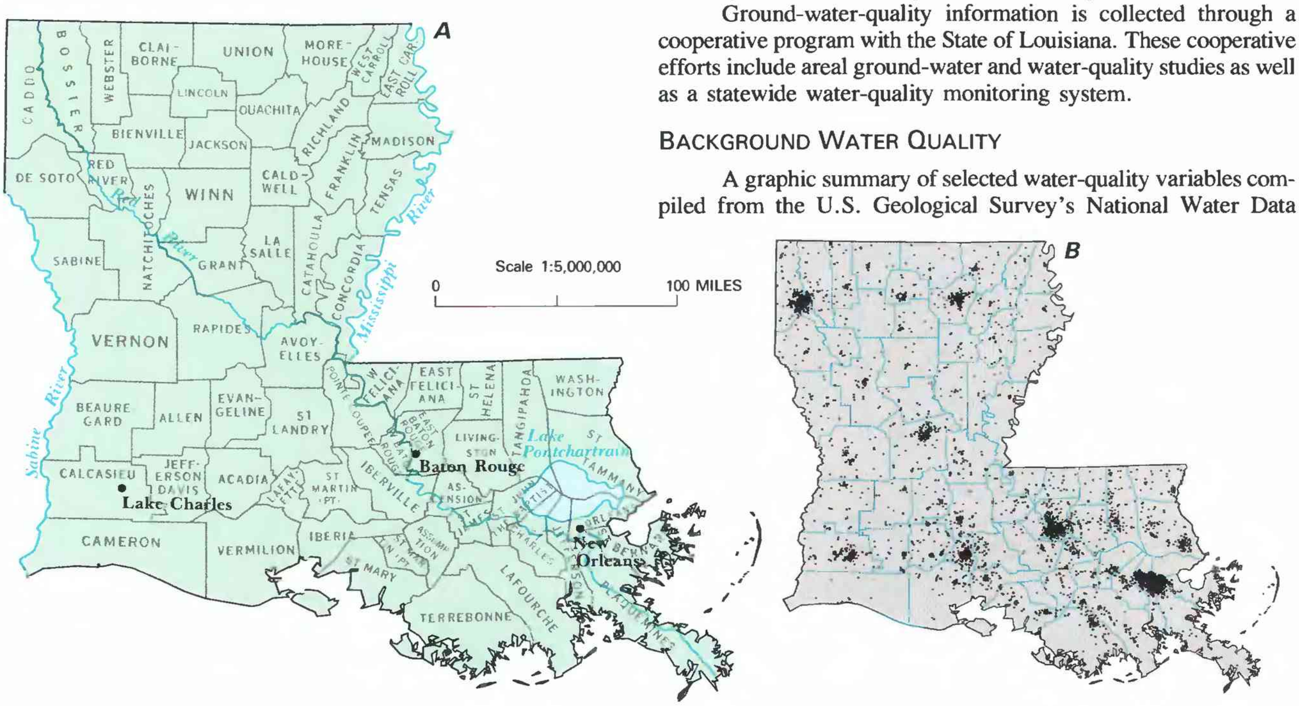

Figure 1. **Selected geographic features and 1985 population distribution in Louisiana.** *A*, Parishes, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

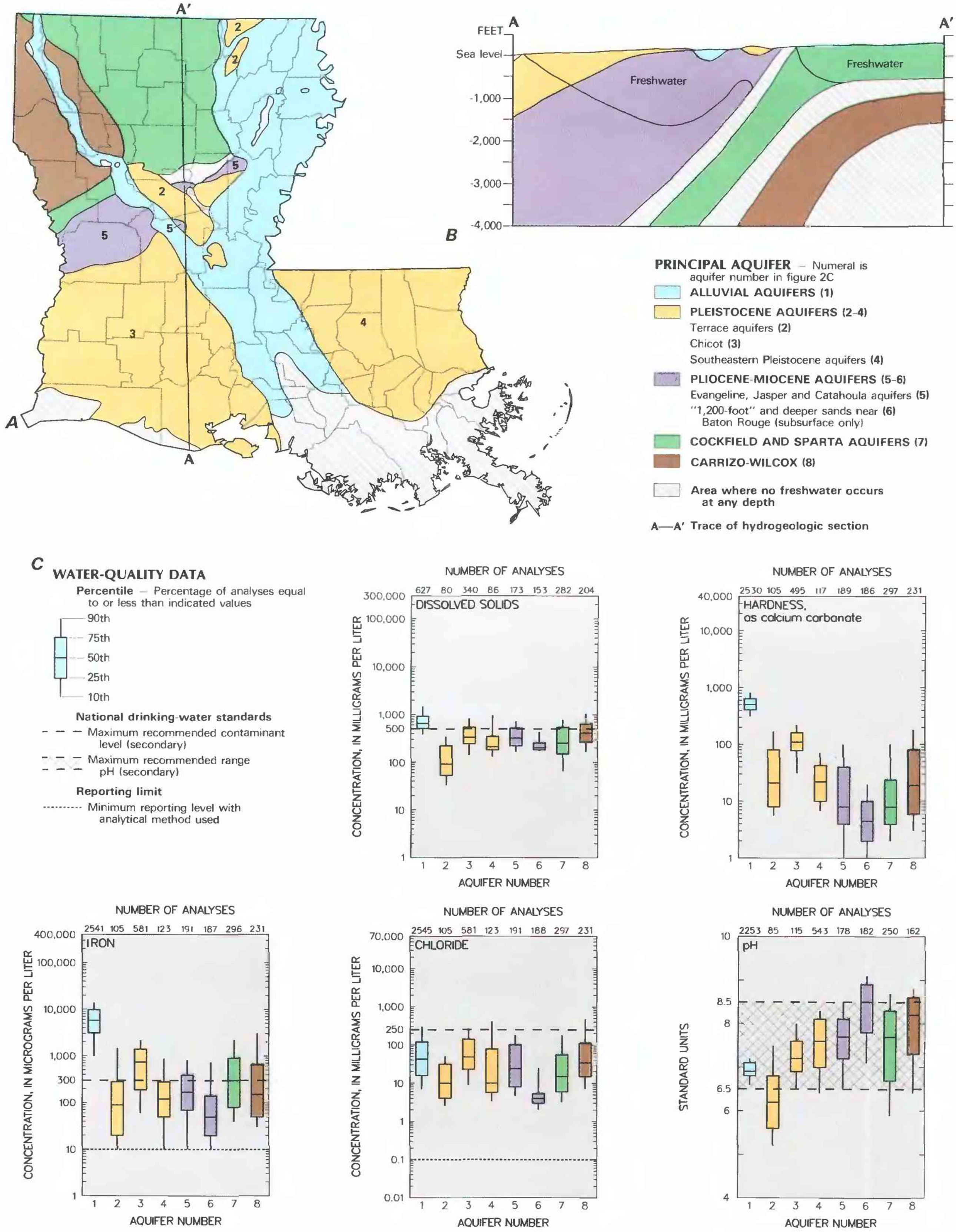

Figure 2. Principal aquifers and related water-quality data in Louisiana. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1970-86. (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

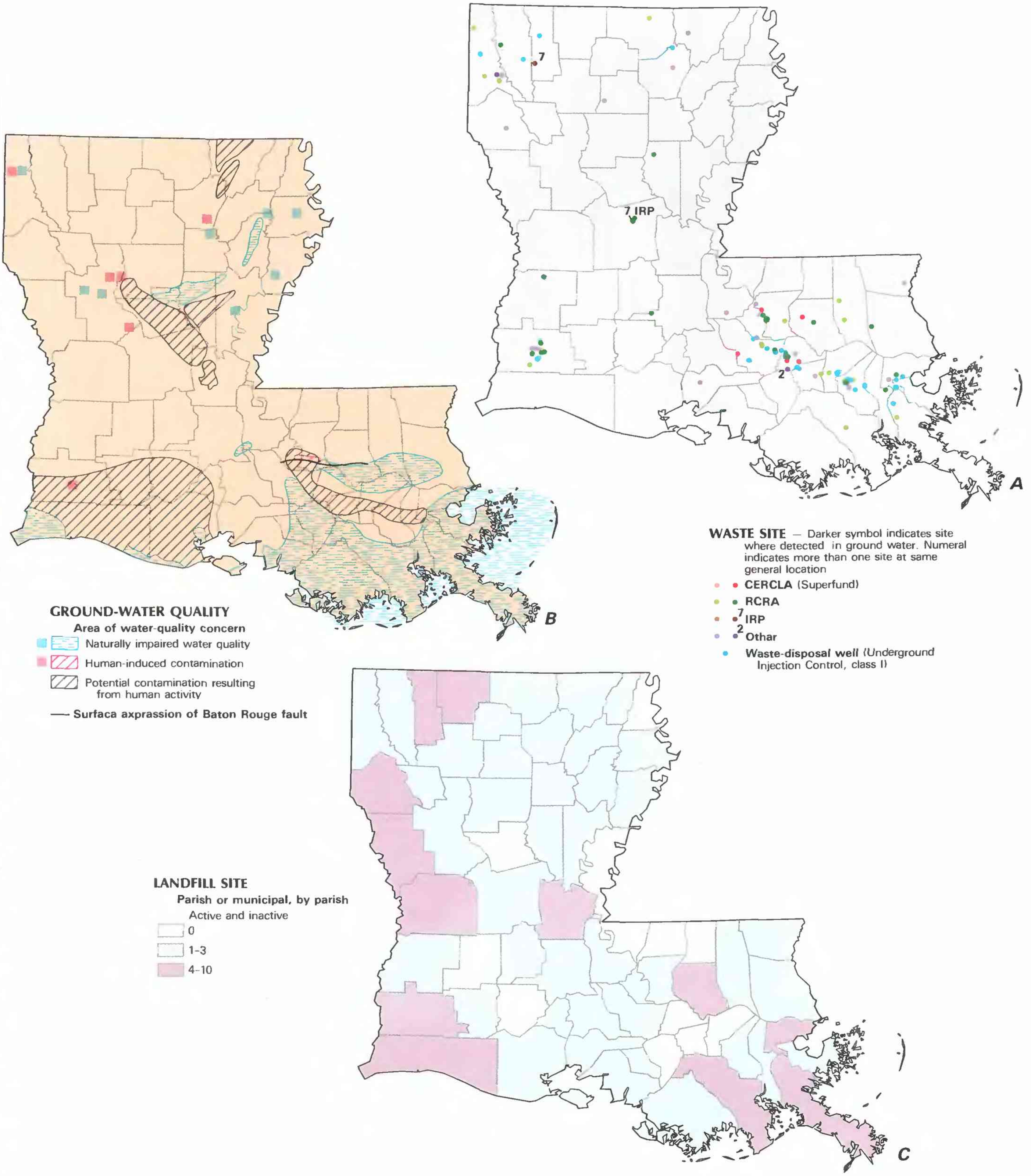

Figure 3. Selected waste sites and ground-water-quality information in Louisiana. *A*, Comprehensive Environmental response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, and areas of human-induced and potential contamination, as of 1986. *C*, Parish and municipal landfills, as of 1986. (Sources: *A*, Louisiana Department of Environmental Quality files; Joyce Lehe, U.S. Environmental Protection Agency, written commun., 1986; U.S. Environmental Protection Agency, 1984; U.S. Department of Defense, 1986. *B*, U.S. Geological Survey, 1985; Nyman, 1984; C.W. Smoot, U.S. Geological Survey, written commun., 1986; Snider and Sanford, 1981; Whiteman, 1979; Whitfield, 1975a, 1980. *C*, Louisiana Department of Environmental Quality files.)

Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, iron, chloride, and pH analyses of water samples collected from 1970 to 1986 from the principal aquifers in Louisiana. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986b). Primary maximum contaminant level standards are health related and are legally enforceable. Secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter) iron, and 250 mg/L chloride, and a range of 6.5–8.5 for pH.

Alluvial Aquifers

The alluvial aquifers (fig. 2*A*) grade from silt and clay at the surface to poorly to moderately well-sorted sand and gravel at the base (Whitfield, 1975a, 1980). Fresh ground water is typically a calcium or magnesium bicarbonate type. Excessive concentrations of dissolved solids, hardness, iron, or localized salinity limit ground water to primarily industrial and agricultural use (U.S. Geological Survey, 1985, p. 229–235). Dissolved solids and hardness are less near the surface, owing to mixing of fresh recharge water from precipitation with older ground water, but generally increase and have less temporal fluctuation with depth. The pH is as low as 5.2 standard units and iron concentration is as large as 49,000 μg/L where recharge is through thick organic-rich sediments. Large concentrations of chloride accompanying large concentrations of dissolved solids (as much as 8,000 and 14,000 mg/L, respectively) indicate saltwater contamination (Whitfield, 1975a, 1980).

Pleistocene Aquifers

The major Pleistocene aquifers of Louisiana include the terrace aquifers, the Chicot aquifer, and the southeastern Pleistocene aquifers (including the "400- and 600-foot" sands at Baton Rouge, the upper Ponchatoula aquifer, and the Gonzales-New Orleans aquifer) (fig. 2*A*) (U.S. Geological Survey, 1985).

The terrace aquifers generally are unconsolidated, poorly to well sorted, and grade from very fine sand near the surface to coarse sand and gravel in the lower three-fourths of the aquifer. The small saturated thickness of the aquifer limits its use in some areas (Snider and Sanford, 1981). Fresh ground water is generally a soft calcium or sodium bicarbonate type, but locally is very hard (as much as 450 mg/L as calcium carbonate). Low values of pH are attributed to large concentrations of dissolved carbon dioxide (Snider and Sanford, 1981). Anomalously large chloride concentrations have been partly attributed to oil and gas activities (Snider and Sanford, 1981).

The Chicot aquifer is a stratigraphically complex series of fluvial deposits characterized by thick sequences of sand and gravel separated by clay layers (Jones and others, 1956). Fresh ground water is dominantly a calcium bicarbonate type (D.J. Nyman, U.S. Geological Survey, written commun., 1986). Ground water is generally suitable for irrigation but, because of locally large iron concentrations, may require treatment for public supply (U.S. Geological Survey, 1985). Large concentrations of iron are spatially related to Pleistocene channel sands of the Red River (D.J. Nyman, U.S. Geological Survey, written commun., 1986). Large concentrations of chloride and dissolved solids (as much as 3,000 and 4,900 mg/L, respectively) indicate saltwater contamination (Nyman, 1984).

The southeastern Pleistocene aquifers are generally confined and range from the well-sorted, fine-grained "400- and 600-foot" sands at Baton Rouge to the moderately well-sorted, medium to coarse sands and gravel of the upper Ponchatoula aquifer (Meyer and Turcan, 1955; Nyman and Fayard, 1978). Fresh ground water is generally a moderately hard, sodium bicarbonate type. Locally, saltwater contamination (dissolved solids and chloride as much as 6,600 and 3,800 mg/L, respectively) and color problems make ground water unsuitable for public supply (Rollo, 1966; Whiteman, 1979). Ground-water use is primarily industrial (U.S. Geological Survey, 1985).

Pliocene-Miocene Aquifers

The Pliocene-Miocene aquifers include the Evangeline, Jasper, and Catahoula aquifers and the "1,200-foot" and deeper sands near Baton Rouge (fig. 2*A*). The Evangeline, Jasper, and Catahoula aquifers are composed of unconsolidated, moderately well to well-sorted, fine to medium sands. All are confined by extensive clays. Freshwater in the aquifer is a soft, sodium bicarbonate type. Large concentrations of fluoride (more than 1.6 mg/L) and high color make ground water locally unsuitable for public supply

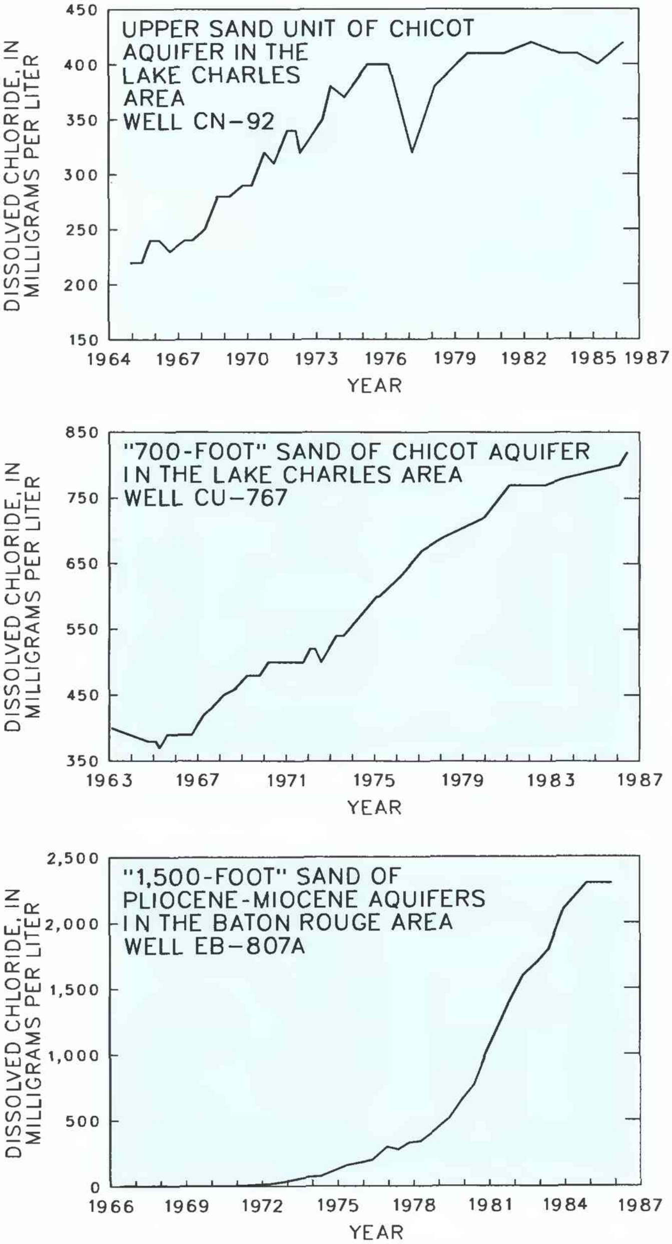

Figure 4. Change in chloride concentration for three wells in the Lake Charles and Baton Rouge areas, Louisiana (Source: U.S. Geological Survey files.)

(Whitfield, 1975b). The lower part of each of these aquifers contains saltwater.

The "1,200-foot" and deeper sands near Baton Rouge consist of the Pliocene "1,200-, 1,500-, and 1,700-foot" sands and the Miocene "2,000-, 2,400-, and 2,800-foot" sands. The Pliocene sediments are fine- to medium-grained and moderately to well-sorted sands. The Miocene sediments are fine sand to gravel. Grain size increases and degree of sorting decreases with depth in the Miocene sediments. Both Pliocene and Miocene aquifers are confined and typically contain a soft, sodium bicarbonate type water with moderately alkaline pH in areas of fresh ground water (Buono, 1983; Meyer and Turcan, 1955). The "1,500-, 2,000-, and 2,800-foot" sands contain some saltwater north of the Baton Rouge fault (fig. 3*B*) (Whiteman, 1979).

Cockfield and Sparta Aquifers

The Cockfield aquifer is composed of fine, commonly massive or cross-bedded sand, silty clay, and lignite. The Sparta aquifer consists of very fine to medium sand, silty clay, and lignite. The lithology of the Sparta ranges widely, both vertically and laterally. The Cockfield and Sparta aquifers (fig. 2*A*) are generally confined and are separated by the Cook Mountain Formation. Freshwater in the Cockfield and Sparta aquifers is typically a soft, sodium bicarbonate type. Large iron concentrations (as much as 44,000 μg/L) and color problems occur locally. Dissolved-solids and chloride concentrations generally increase with depth in the Sparta aquifer (Payne, 1968, 1970; Rogers and others, 1972).

Carrizo-Wilcox Aquifer

The Carrizo-Wilcox aquifer includes the Eocene Carrizo sand and the sands of the Eocene-Paleocene Wilcox Group (fig. 2*A*). The Carrizo sand is well-sorted fine to medium sand. The Wilcox Group is composed of interbedded fine sand, silt, clay, and variable amounts of lignite. The Carrizo sand and the Wilcox aquifer are hydrologically connected and form a generally confined hydrologic system which typically contains a soft, sodium bicarbonate type water. Iron concentrations are locally as much as 40,000 μg/L (U.S. Geological Survey, 1985; Ryals, 1983; Payne, 1975).

EFFECTS OF LAND USE ON WATER QUALITY

The quality of ground water in Louisiana has changed in some areas because of surface waste disposal and the encroachment of saltwater into freshwater aquifers. Waste disposal has contaminated ground water primarily by organic compounds. saltwater degradation has resulted primarily from withdrawal of ground water near the coast and from oil and gas activities.

Waste-Disposal Sites

Petrochemical wastes including benzene, toluene, xylene, and many chlorinated organics are disposed, treated, or stored at 5 CERCLA sites and 50 RCRA sites in Louisiana (fig. 3*A*). The five CERCLA sites are included by the U.S. Environmental Protection Agency (1986c) in the National Priorities List (NPL). Other types of industrial wastes are only a small part of the total waste processed. Materials from 23 of the RCRA sites have contaminated shallow ground water (fig. 3*A*). An unknown number of oil-field waste-disposal pits exist in Louisiana. These pits contain organic chemicals, drilling fluids, and brines. Also, aqueous industrial waste is injected below the base of the deepest underground source of drinking water in 71 class I wells in Louisiana (fig. 3*A*). In addition, Louisiana has 29 active industrial landfill sites (other sites) (fig. 3*A*), 3 of which have contaminated shallow ground water, and 138 parish and municipal solid-waste landfill sites (fig. 3*C*).

As of September 1985, 52 hazardous-waste sites at 4 facilities in Louisiana had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 52 sites in the IRP program, 15 sites contained contaminants but did not present a hazard to the environment. Fourteen sites at two facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at two of these sites has been completed under the program. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Saltwater Encroachment

Naturally occurring saltwater occupies the entire water column in some, primarily coastal, areas. In other areas, saltwater sands overlie freshwater sands. Saltwater contamination is caused by pumping from freshwater aquifers and oil and gas activities.

Saltwater encroachment into the Chicot aquifer has occurred along the southwestern coast of Louisiana (not shown in fig. 3*B*). Northward movement of saltwater from about 1968 to 1984 was indicated by increasing chloride concentrations in areas south and east of Lake Charles (fig. 4). However, as of 1984, the net effect on public supply was minimal (Nyman, 1984). Recent data from continuing saltwater-monitoring efforts show no significant increase in chloride since 1984 in the area of concern. Saltwater upconing affects the quality of water in southwestern Louisiana near major pumping centers.

Contamination in the "1,200-foot" and deeper sands near Baton Rouge includes saltwater in the "1,500-, 2,000-, and 2,800-foot" sands north of the Baton Rouge fault (fig. 3*B*). The increase in chloride, from 1971-85, in the "1,500-foot" sand north of the Baton Rouge fault is shown in figure 4. Recent data show no significant increase in chloride since 1985. Given the present rate of withdrawal, the current model of the aquifer indicates that saltwater will not effect the Baton Rouge public supply for about 30 years (Whiteman, 1979).

Saltwater contamination in the alluvial aquifers from oil and gas activities has been documented (Whitfield, 1975a, 1980). Saltwater contamination in the terrace aquifers was caused by oil and gas activities and intrusion of saltwater from underlying Tertiary sediments (Snider and Sanford, 1981).

POTENTIAL FOR WATER-QUALITY CHANGES

Detrimental changes in the quality of ground water in Louisiana could be caused by increased saltwater encroachment, contamination by hazardous chemicals from surface waste-disposal facilities, and agricultural chemicals.

Increased pumping from the "1,200-foot" and deeper sands or the Chicot aquifer could cause more rapid encroachment of saltwater. Pumping from these aquifers has decreased in recent years, but long-term trends are difficult to predict (D.L. Lurry, U.S. Geological Survey, oral commun., 1986).

Both active and abandoned surface industrial waste-disposal facilities (fig. 3*A*), many of which are located along the densely populated industrial Baton Rouge-New Orleans corridor (fig. 1*B*), are a potential threat to ground-water quality. No contamination traceable to surface waste-disposal facilities or to solid-waste landfill sites has been documented in ground water used for public supply.

An analysis of selected organic pesticides in 1981 showed no detectable levels in ground water from the terrace aquifers. However, because of rapid recharge from surface water, the shallow terrace aquifers are particularly susceptible to contamination from surface waste disposal and agricultural chemicals (Snider and Sanford, 1981).

GROUND-WATER-QUALITY MANAGEMENT

The Ground Water Protection Division of the Louisiana Department of Environmental Quality is responsible for developing ground-water protection strategy. The responsibility for ground-water-quality management is divided among five agencies within the State government. The agencies and their areas of principal responsibility are:

Department of Environmental Quality	CERCLA, RCRA, and State protection plans
Department of Natural Resources	Underground injection-control program
Department of Transportation and Development	Water-well construction and licensing of drillers
Department of Health and Human Resources	Safe Drinking Water Act and public water supply regulation
Department of Agriculture	Federal Insecticide, Fungicide, and Rodenticide Action and pesticide control

Ground-water-protection strategy is in the developmental stage. Information is still needed on which to base future decisions. Work is underway to delineate the recharge areas and to determine background water quality in the major aquifers of the State. More data are needed to determine the distribution of organic constituents in ground water. All cleanup efforts are directed toward restoration of the ground water to background water-quality conditions.

State law and practice call for an antidegradation standard for all ground water above the lowest level of ground-water sources of drinking water. However, injection of hazardous waste is allowed below sources of drinking water.

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MAINE
Ground-Water Quality

The ground-water resources of Maine are used to supply 57 percent of the State's population. The population is concentrated largely in the southwestern quarter of the State (fig. 1). Water quality in the State's aquifers (fig. 2) is generally excellent and suitable for most uses, but water use in some areas is limited by excessive hardness or naturally occurring large concentrations of iron, manganese, sulfur, sodium chloride, and radon. Water quality in several areas has been degraded by urbanization, agriculture, and industrial- and municipal-waste disposal (fig.3).

Ground-water quality has been monitored since 1968 as part of a cooperative program between the U.S. Geological Survey and the State. This program provides information on background levels of inorganic constituents and total organic carbon. State agencies and private industry have sampled for organic compounds at specific sites where hazardous-waste contamination is suspected. In 1985, Maine instituted a 3-year program to determine the effect of pesticide use on the State's ground-water supplies.

Each of the aquifers is vulnerable to contamination, but the stratified-drift and bedrock aquifers tend to be the most severely effected. The large permeability of the stratified-drift aquifers allows contaminants to percolate readily from land surface to the water table (Tolman and others, 1983). Pollutants that reach the bedrock aquifers can travel along secondary openings such as cleavage and bedding planes, joints, fractures and solution openings, and contaminate the aquifer over a large area.

The Maine Department of Environmental Protection (MDEP) has identified 32 hazardous-waste sites that threaten ground-water quality (fig. 3). Eighteen of these sites require monitoring under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Five sites have been identified as Superfund sites in the National Priorities List (NPL) of the U.S. Environmental Protection Agency (1986c). These sites receive additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. The MDEP is evaluating the remaining nine sites under the Maine Hazardous Waste Fund and Uncontrolled Substance Act. The types of waste generators in this group of nine sites include metal finishing, chemical and photochemical companies, salvage operations, and military installations. Ground-water contamination is suspected at many other sites and these sites will be included in the State's program if evidence of contamination becomes available. Contamination of ground water is documented at six of the RCRA sites, two of the CERCLA sites, and eight of the State program sites. At the remaining 16 sites, either no contamination has been detected or monitoring data have not been evaluated. In addition, the U.S. Department of Defense (DOD) has identified one site at one facility where contamination has warranted remedial action.

WATER QUALITY IN PRINCIPAL AQUIFERS

Maine has four principal types of aquifers (fig. 2)—stratified drift (glaciofluvial deposits), till, carbonate rock, and metamorphic and igneous crystalline bedrock (U.S. Geological Survey, 1985, p. 237–240). The areal extent of each aquifer type, except till, is shown in figure 2*A* and the typical stratigraphic sequence is shown by the block diagram, figure 2*B*. Till forms a discontinuous cover over bedrock in upland areas, and, in valleys, it is usually located between stratified-drift deposits and bedrock. Thick, stratified-drift (ice-contact) sand and gravel is located along some valley walls as kame deposits or as eskers in the center of valleys. Silts and clays deposited in marine or lacustrine environments usually is interspersed with the coarse sand and gravel.

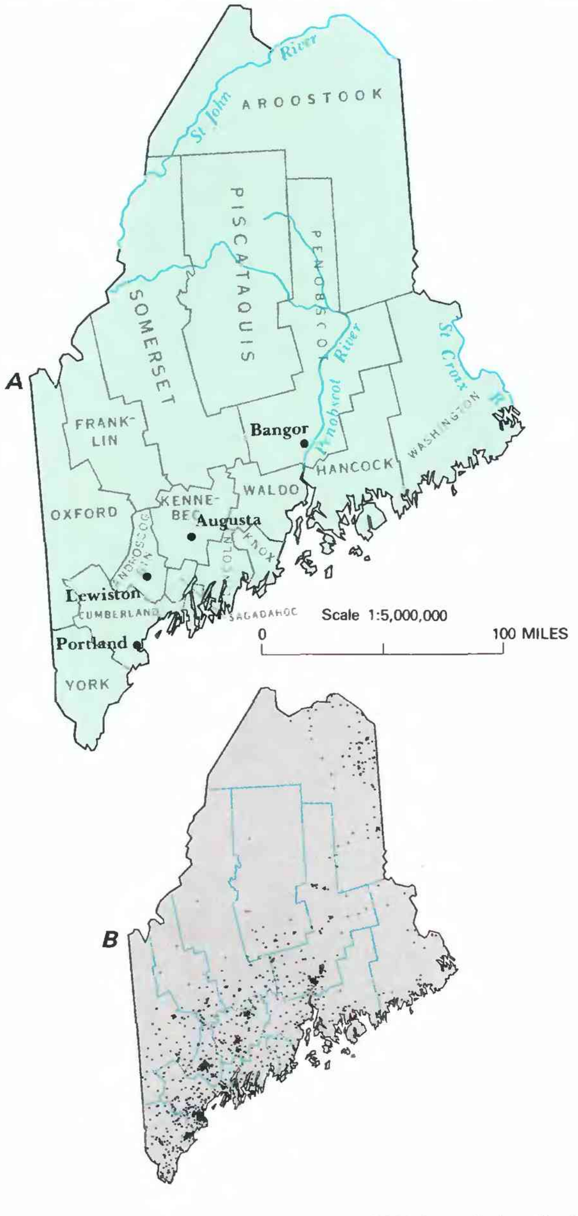

Figure 1. Selected geographic features and 1985 population distribution in Maine. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Sources: *B*, Data from the U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

The chemical quality of ground water is determined by several natural factors. In the stratified-drift and till aquifers the primary control is the chemical composition of the sand and gravel and associated marine clay. Most of the sand and gravel is derived from noncalcareous, crystalline bedrock, which generally consists of silicate minerals that are relatively insoluble. Ground water in

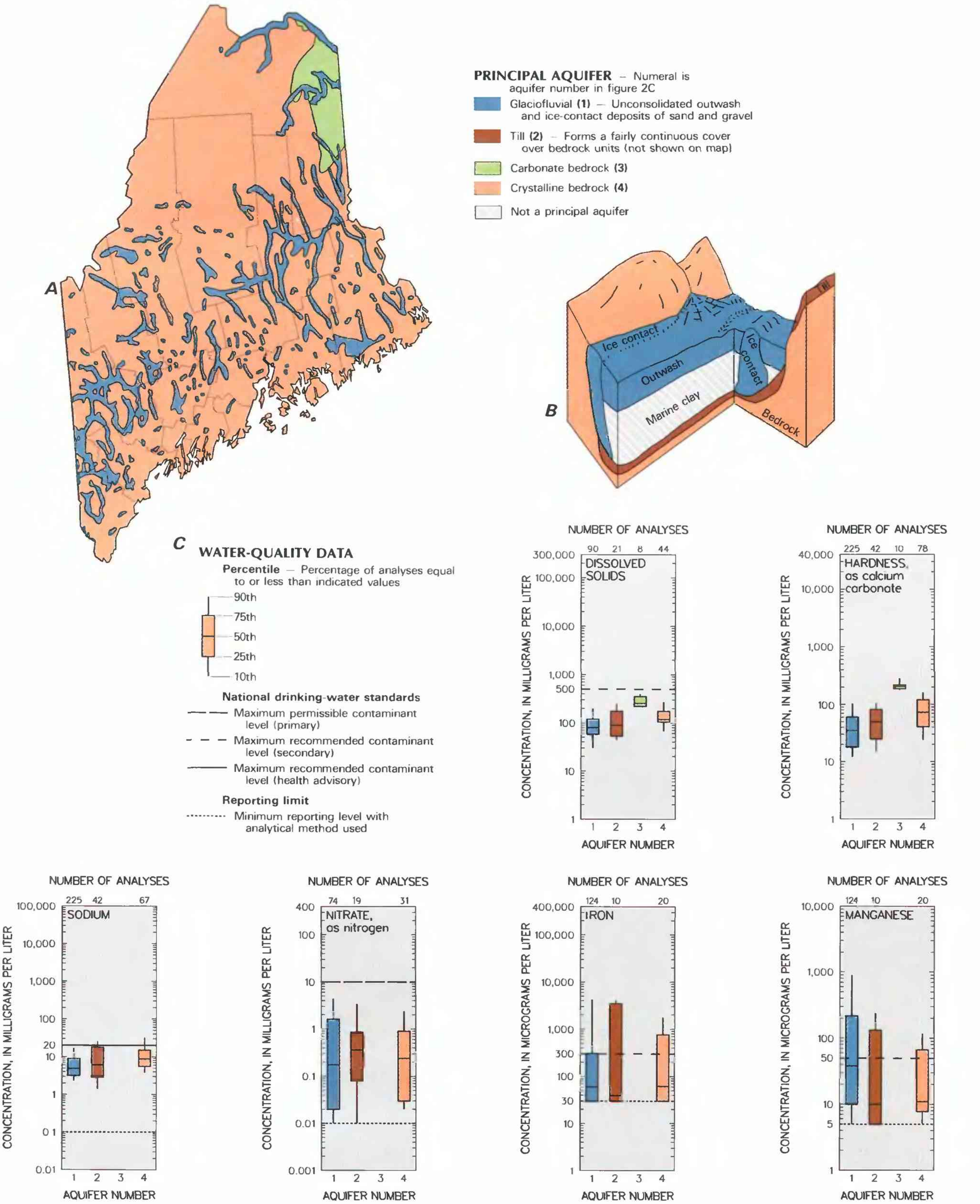

Figure 2. Principal aquifers and related water-quality data in Maine. *A*, Principal aquifers. *B*, Generalized block diagram. *C*, Selected water-quality constituents and properties, as of 1960-85. (Sources: *A*, Modified from Adamik, 1984. *B*, Compiled by T.J. Maloney from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

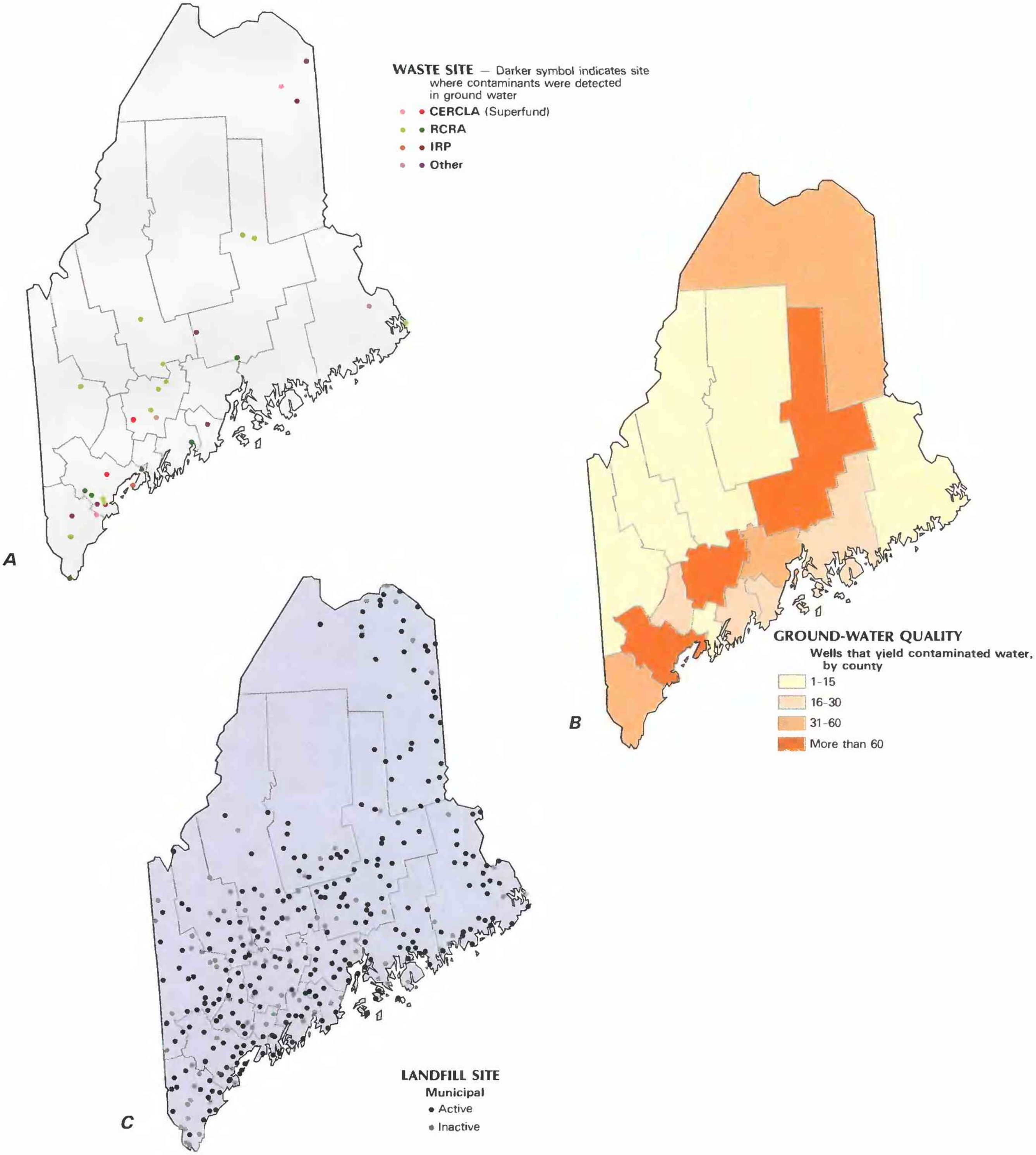

Figure 3. Selected waste sites and ground-water-quality information in Maine. *A*, Comprehensive Environmental Response, Compensation, and Liability Action (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1985. *B*, Distribution of wells that yield contaminated water, as of 1985. *C*. Municipal landfills, as of 1985. (Sources: *A*, Maine Department of Environmental Protection, Bureau of Hazardous Materials Control files: *B*, Maine Department of Environmental Protection, Bureau of Water Quality Control files; National Governors Association, 1985; Scudder and Anderson, 1986; and U.S. Department of Defense, 1986. *C*, Maine Department of Environmental Protection, Bureau of Land Quality Control files.)

regions with this type of bedrock tends to have a small dissolved-solids concentration compared to water in regions with carbonate bedrock. Chemical reactions that occur as infiltrating water passes through the soil zone can also affect ground-water chemistry. Where the saturated thickness is great, the flow paths are long and the water may have a long time to dissolve soluble material in the aquifer (Caswell, 1978). The chemistry of precipitation can also affect ground-water quality. In coastal regions where precipitation contains sea salt, the concentrations of sodium and chloride in ground water are typically larger than in inland areas. Elevated concentrations of sodium and chloride can also result from saltwater intrusion in coastal areas or from the entrapment of seawater in regions of relatively stagnant ground-water flow, which occurred during the late Wisconsinan marine submergence (Tepper, 1980).

Public suppliers that use ground water as a source serve about 12 percent of the population. These suppliers rely almost exclusively on large-yield screened wells located in stratified-drift aquifers. A few large-yield—greater than 200 gal/min (gallons per minute)—supply wells are located in bedrock aquifers.

About 45 percent of the population obtains water from individual private wells. All four aquifer types can yield sufficient quantities of water (2 gal/min) for individual households. The quality of water from each of the aquifers generally is suitable for most uses, but increased concentrations of some constituents can limit use.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure *2C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), sodium, nitrate (as nitrogen), iron, and manganese analyses of water samples collected from 1960 to 1985 from the four principal aquifer types in Maine. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter) iron, and 50 μg/L manganese. Although a national maximum concentration level for sodium has not been set by the U.S. Environmental Protection Agency (EPA), a concentration smaller than 20 mg/L is recommended for people on sodium restricted diets (U.S. Environmental Protection Agency, 1976). The "very hard" classification of hardness (180 mg/L as calcium carbonate) as defined by Durfor and Becker (1964, p. 27) is used as the upper limit for general water use.

Stratified-Drift and Till Aquifers

The water-quality characteristics of the stratified-drift and till aquifer types are similar, as shown in figure *2C*. Water from the aquifers typically had small concentrations of dissolved solids and was soft. The median dissolved-solids concentrations for water from the stratified-drift and till aquifer types are 80 and 90 mg/L, respectively. Likewise, the median hardness concentrations (as calcium carbonate) for water from the stratified-drift and till aquifer types were 35 and 50 mg/L, respectively. The 90th-percentile concentration of dissolved solids does not exceed the national drinking-water standard in either aquifer (fig. *2C*).

Median concentrations of naturally occurring sodium in water in the stratified-drift and till aquifers are small, 4.9 and 6.1 mg/L, respectively. Although the median background concentrations in water in both aquifers did not exceed health advisory levels, these aquifer types are particularly susceptible to sodium contamination from storage and application of road deicing salt. Another source of sodium contamination is from saltwater intrusion induced by overpumping of an aquifer in coastal areas.

Background concentrations of nitrate (as nitrogen) were small, with median concentrations of 0.18 and 0.36 mg/L in the stratified-drift and till aquifers, respectively. The 90th-percentile concentrations in these two aquifers are less than one-half the national maximum standard of 10 mg/L (fig. *2C*). Drainage from barnyards or septic tanks is a source of nitrate contamination, which can severely degrade water quality.

Concentrations of iron and manganese in more than 25 percent of the analyses of water from the stratified-drift and till aquifers (fig. *2C*) exceed drinking-water standards 300 and 50 μg/L, respectively. These metals are the products of weathering of minerals and dissolution of oxide coatings on aquifer materials. They are easily dissolved in acidic water in the absence of oxygen. Water in the stratified drift is almost always acidic, but commonly contains enough dissolved oxygen to inhibit the solution of iron and manganese. However, ground water may lose some of its dissolved oxygen as it passes through organic deposits, such as peat or river-bottom sediments, and begin to dissolve and mobilize iron and manganese. Wells that initially yield water with small concentrations of these metals may yield water with larger concentrations and become less efficient as ground-water gradients are reversed by pumping, causing iron- and manganese-bearing water to flow to the well (Gay and Frimpter, 1985).

Carbonate-Bedrock Aquifer

The carbonate-bedrock aquifer types are limestone, calcareous shale, and calcareous siltstone deposits located primarily in the northeastern corner of the State in Aroostook County. The Carys Mills Formation—a bluish-gray limestone—is fairly widespread and constitutes the principal carbonate aquifer. Recoverable water is contained primarily in secondary openings, such as bedding planes, joints, fractures, and solution openings. Most wells completed in the carbonate aquifers are for domestic or farm use; however, some large-yielding wells (500 gal/min) have been developed for industry, public supply, and irrigation.

The quality of water in the carbonate aquifers is suitable for most uses. The few available samples indicate that the water had a moderately large dissolved-solids concentration and was very hard. The median concentrations were 256 mg/L dissolved solids and 204 mg/L (as calcium carbonate) hardness. Concentrations of sodium (four analyses) range from 4.4 mg/L to 9.2 mg/L.

Crystalline-Bedrock Aquifers

The crystalline-bedrock aquifer in Maine consists of a variety of igneous and metamorphic rocks. Igneous rocks include granite, gabbro, diorite, granodiorite, and pegmatite; metamorphic rocks include schist, gneiss, quartzite, slate, and argillite. These rocks are dense and relatively impermeable, but contain recoverable water in secondary openings such as joints, fractures, and bedding or cleavage planes. These aquifers are an important source of water for many rural domestic water users in Maine, and provide public supplies in some areas where other supplies are limited. Communities located on islands and peninsulas along Maine's coast often must depend on bedrock aquifers for water supplies.

Water in crystalline-bedrock aquifers was suitable for most uses. It had small concentrations of dissolved solids, with a median hardness of 119 mg/L, and was moderately hard, with a median hardness of 73 mg/L (as calcium carbonate). The median concentration of sodium is small, 8.8 mg/L, but was the largest for water from any of the four aquifer types. Increased sodium concentrations have been observed when the recharge zones of these aquifers are contaminated by deicing salts. Some wells drilled in coastal zones yield brackish or salty water (Prescott, 1973; Tepper, 1980). Nitrate concentrations in water from crystalline bedrock are typically small, with a median concentration of 0.24 mg/L. Water from some recharge areas that receive drainage from barnyards or septic fields has nitrate concentrations that exceed the drinking-water standard of 10 mg/L. The median concentrations for iron and manganese are 62 and 11 μg/L, respectively. The concentrations of iron and manganese in ground water from many localities statewide far exceed the drinking-water standards, thus requiring treatment prior to use.

Radon-222 in ground water has been recognized as a problem in Maine since the late 1950's. Several studies have been undertaken to determine the magnitude of the problem. Radon-222 is a radioactive-decay product of uranium. It is a colorless, odorless, inert gas and has been associated with the incidence of lung cancer among metal-ore miners (National Council on Radiation Protection and Measurements, 1984). One important source of radon in Maine is well water from crystalline bedrock. When this water is heated and agitated, as in a shower or dishwasher, the radon is released into the air where it becomes a health risk. A second source is "soil gas"—a mixture of vapors and gases including radon. High-permeability soils, such as sand and gravel, facilitate migration of radon. Because radon does not combine chemically with other elements, it can migrate to the ground surface and seep into homes through cracks, pore spaces, and utility openings in basements.

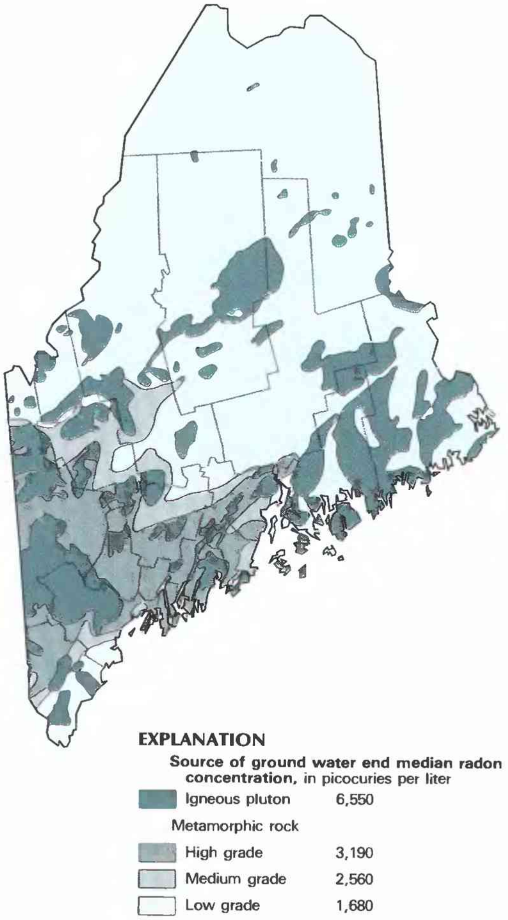

Figure 4. Median radon concentration in water from bedrock and geographic distribution of bedrock types in Maine. (Source: Lanctot, 1985.)

Analysis of data collected by the University of Maine at Orono (Penobscot County) indicates that radon levels in ground water increase with increasing depth of bedrock wells and decrease with increasing yield (Hess and others, 1979). On the average, radon levels in water from wells completed in sand and gravel, unless capped by clay, did not exceed the Maine Department of Human Services' (MDHS) suggested limit of 20,000 pCi/L (picocuries per liter).

In Maine, the greatest levels of radon have been found in water pumped from igneous plutons, which contain water with a median radon level of 6,550 pCi/L. Water from granites containing the micas muscovite and biotite have especially large radon levels. Increased radon levels also have been found in high-grade metamorphic rock. The median concentrations of radon in water obtained from wells drilled into various rock types in Maine and the areal distribution of these rocks are shown in figure 4. Data used to produce this map came from files of the Maine Geological Survey and Maine Department of Human Services.

The health risks associated with the radon levels commonly found in homes are a subject of debate. The EPA recommends that remedial action be taken when indoor-air radon levels reach 4 pCi/L (U.S. Environmental Protection Agency, 1986e). Based on extrapolation from mining data, a person who lives in his home for 70 years and was exposed to 4 pCi/L for 75 percent of the time, faces an increased risk of lung cancer of from 1 to 5 chances in 100. Aerators and carbon filters are highly effective in removing radon from water and various ventilation techniques have been used to remove radon from indoor air (U.S. Environmental Protection Agency and U.S. Department of Health and Human Services, 1986).

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has deteriorated in some areas because of the effects of urbanization, agriculture, and waste disposal. State agencies have instituted programs to determine the extent of contamination from these factors and to remedy situations that threaten the public health.

Urbanization

Three factors responsible for contamination of the greatest number of wells (fig. 3*B*) are highway-deicing chemicals, petroleum or heating oil from leaking underground storage tanks, and underground waste disposal through septic systems. The number of wells abandoned as a result of contamination from leakage of stored fuel has increased sharply during the past 10 years. Reports of contamination caused by deicing compounds and septic systems have remained fairly constant during the same period.

Well contamination by deicing salts has resulted from storage and spreading procedures. During the 1984–86 period, 16 claims were settled by the Maine Department of Transportation (MDOT) that concerned salt contamination of wells resulting from MDOT operations. Of the 16 claims, 14 were attributed to contamination from storage facilities (A.C. Olson, Maine Department of Transportation, written commun., 1986).

In Maine, the general practice for operation of a salt-storage facility has been to place an uncovered salt pile at the location of a readily accessible sand supply, so that the materials could be mixed before spreading. This practice has two major drawbacks. First, many supplies of sand are parts of or are recharge areas for the largely permeable stratified-drift aquifers. Second, because the salt piles are uncovered, rain dissolves some of the salt, and the contaminated water then enters the underlying aquifer. The MDEP, Bureau of Water Quality Control, has examined each of the 800 registered salt-storage sites in the State to determine their effects on water quality and to prioritize construction of covered shelters. Well contamination has been documented at about 50 of the sites

(D.L. Locke, Maine Department of Environmental Protection, oral commun., 1986).

Salt-spreading procedures typically are responsible for contamination of wells located near highways. Maine law 23 MRSA (Maine Revised Statute Annotated) 652 provides that no well can be located within the public right-of-way. As a further measure to prevent contamination from salt spreading procedures, it is recommended that wells be constructed at least 50 feet from the edge of highway pavement (A.C. Olson, Maine Department of Transportation, oral commun., 1986). The quantity of salt spread by the MDOT has been greatly decreased from 110,000 tons in 1968 to 60,000 tons in 1986 (J.E. Dority, Maine Department of Transportation, oral commun., 1986).

Contamination of ground water by leaking underground petroleum-storage tanks has been documented in 215 wells statewide, and many more wells that have been contaminated may exist but have not been reported (Scudder and Anderson, 1986). Towns with six or more wells that have been contaminated by petroleum are Boothbay (Lincoln County), Easton (Aroostook County), Friendship (Knox County), Lee (Penobscot County), North Berwick (York County), Penobscot (Hancock County), Readfield (Kennebec County), and Waterboro (York County). When tank leaks develop, they may go undetected for years, while the tank continues to be used or after a partly filled tank has been abandoned. The locations of many abandoned tanks are not known. The 1986 MDEP tank-registration files show more than 20,000 tanks statewide. The petroleum industry estimates that 20 to 40 percent of these tanks may be leaking (Garrett, 1986). The amount of product leaking to ground water statewide is estimated to be 6 million gallons per year (Moreau, 1983).

About 250,000 housing units in Maine use septic systems for waste disposal (D.C. Hoxie, Maine Department of Human Services, oral commun., 1986). Even a properly designed system can contribute some contaminants, such as nitrates, chlorides, bacteria, metals, and solvents, to ground water, (Garrett, 1986). In 1974, a more stringent State Plumbing Code was implemented that required use of soil-horizon information in the design of septic systems. This code has resulted in improved function and efficiency of the systems and has helped curb ground-water contamination (D.C. Hoxie, oral commun., 1986).

Agriculture

The use of insecticides and herbicides in Maine's agriculture has raised concern about adverse effects on ground water. The National Governors Association (1985) reports restricted use of water from 30 wells in Aroostook and Penobscot Counties resulting from pesticide contamination. In 1985, the State began a 3-year statewide program to determine concentrations of pesticides and herbicides in ground water, to document the extent of contamination, and to assess the health risks of drinking the contaminated water. During the first year of this investigation, detectable concentrations of pesticides were not observed; however, the results were considered inconclusive because of questions regarding sample-collection and analytical techniques (Tolman, 1986).

Manure storage and spreading and application of commercial fertilizers are agricultural practices that can contaminate ground water with nitrates. The Maine Department of Agriculture, Food and Rural Resources, has determined that there are 3,000 cattle farms that annually produce 1.7 million tons of manure, and 1,700 poultry farms that produce 0.4 million ton of manure. As part of the pesticide and herbicide test program mentioned above, samples have been collected to determine the extent of nitrate ground-water contamination. One-quarter of the wells sampled during the first year of the monitoring program had nitrate concentrations that exceeded the drinking-water standard of 10 mg/L (as nitrogen) (Tolman, 1986).

Waste Disposal

A variety of industries in Maine, including shipbuilding, munitions, photo-chemicals, tanneries, plastics, electronics, and metal finishing, generate hazardous waste. Types of chemicals involved include trace metals, polychlorinated biphenyls, trichloroethylene, and other volatile organics. Many industries have developed their own waste-disposal sites (Garrett, 1986). Military installations in Limestone (Aroostook County), Brunswick (Cumberland County), and Kittery (York County) also have waste-disposal sites that have resulted from their operations.

The paper industry in Maine disposes of waste at eight sites, which are included on the RCRA list. Caustics and acids are used extensively by the paper industry, but no ground-water contamination has been documented at any of these locations.

Most of the 32 hazardous-waste sites MDEP has identified are located in the populous areas of southern and central Maine (fig. 3*A*). Ground-water contamination has been documented at 16 of these sites. Of the 36 drinking-water wells contaminated by these sites, 34 are attributed to two CERCLA sites in Gray (Cumberland County) and in Winthrop (Kennebeck County).

Also, as of September 1985, 28 hazardous-waste sites at 4 facilities in Maine have been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under the hazardous ranking system and may include them in the NPL. Of the 28 sites evaluated under the program only one site at one facility (fig. 3*A*) was considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

In addition to the hazardous-waste sites, the MDEP, Bureau of Land Quality Control, has identified 379 active and inactive municipal-landfill sites. The locations are known for 371 of these sites (fig. 3*C*); 114 of these landfills overlie stratified-drift deposits. These typically are conventional landfills that may allow leachate to percolate to the water table. Salt and hazardous-waste compounds are common in landfill leachate (Garrett, 1986). Of the 379 sites, 270 are active. Many municipalities are becoming members of waste-to-energy projects, and an additional 125 towns are expected to close existing landfills. The volume of solid waste will be greatly reduced by waste-to-energy projects; however, the substantial quantities of ash generated need to be placed in a secure landfill, one which has an impervious liner and a collection system so that the leachate can be recovered and treated.

POTENTIAL FOR WATER-QUALITY CHANGES

The potential for water-quality changes is greatest in high-population-growth areas, including southern Maine, resort areas, and the corridor along Interstate 95 from Portland to Bangor. Increased pumping to meet the demands of the growing population may change ground-water flow patterns, increase the concentrations of iron and manganese, or cause saltwater intrusion in coastal areas. The increased population also is expected to cause additional contamination as a result of urbanization effects.

The number of wells contaminated by leaking underground petroleum-storage tanks is expected to increase steadily until existing petroleum facilities are replaced, using proper installation and handling practices.

GROUND-WATER-QUALITY MANAGEMENT

Management of ground-water quality in Maine is shared by several State agencies with statutory responsibility. The MDEP reviews and licenses land-use activities that affect ground water. The Department also conducts research into effects of petroleum leaks and contamination from highway-deicing compounds on ground water, provides ground-water-quality assessments, investigates sites of spills, and provides emergency response and cleanup services.

The Maine Department of Human Services is responsible for ground-water-quality management through its Drinking Water Program, Environmental Health Unit, and Public Health Laboratories. The Department reviews and approves new public water-supply sources, monitors the quality of existing sources, does research on ground-water-transmitted diseases, and analyzes private water supplies, including determination of petroleum contamination. It also is active in determining the health risks associated with radon.

The Maine Department of Conservation, through the Maine Geological Survey and the Land Use Regulation Commission, coordinates ground-water research, performs research into permit-related ground-water problems, and regulates activities that impact ground water in areas of sparse population. The Department also coordinates a statewide ground-water-quality sampling network and conducts a program to determine the affects of pesticide use on ground water.

The "Maine Ground Water Policy" was issued June 1985, by executive order of the Governor. This order states: "It is the policy of the State of Maine to allocate, protect, and monitor Maine's ground-water resources, through measures which expand our knowledge of ground water hydrogeology, protect public and environmental health, meet future water supply needs, and encourage a sound economy." The Maine Land and Water Resources Council of the State Planning Office was given responsibility to oversee implementation of the policy through formation of a Ground Water Standing Committee. The committee is chaired by the Commissioner of the MDEP and has representatives from other member agencies of the Land and Water Resources Council. The committee's day-to-day activities are carried out by the State Groundwater Coordinator at the State Planning Office. The coordinator serves as a ground-water consultant to the State; provides a State focus for communication on ground-water issues with Federal agencies, local governments, regional planning agencies, and the public; assesses State ground-water priorities; assures cost-effective allocation of State funding and staffing resources; and coordinates the efforts of the Ground Water Standing Committee member agencies.

Six subcommittees of the Ground Water Standing Committee were established to focus on the ground-water issues of Resource Use, Resource Protection, Groundwater Classification, Health Risk Assessment, Interagency Coordination, and Ground Water Education. The subcommittees made their reports and recommendations on July 1, 1986. A Ground-Water Policy Subcommittee has been formed to set priorities and review allocation of resources. Many of the recommendations have been implemented, and pilot projects in ground-water data management and ground-water classification have been undertaken. Other recommendations, such as protection for essential public and private ground-water supplies, requiring a well-information report for new wells, salt-storage site regulations, and regulations for petroleum tank installation, operation, and abandonment, will require legislation. This planning effort has been well coordinated and is expected to improve ground-water management in the State of Maine significantly (Maine State Planning Office, 1986).

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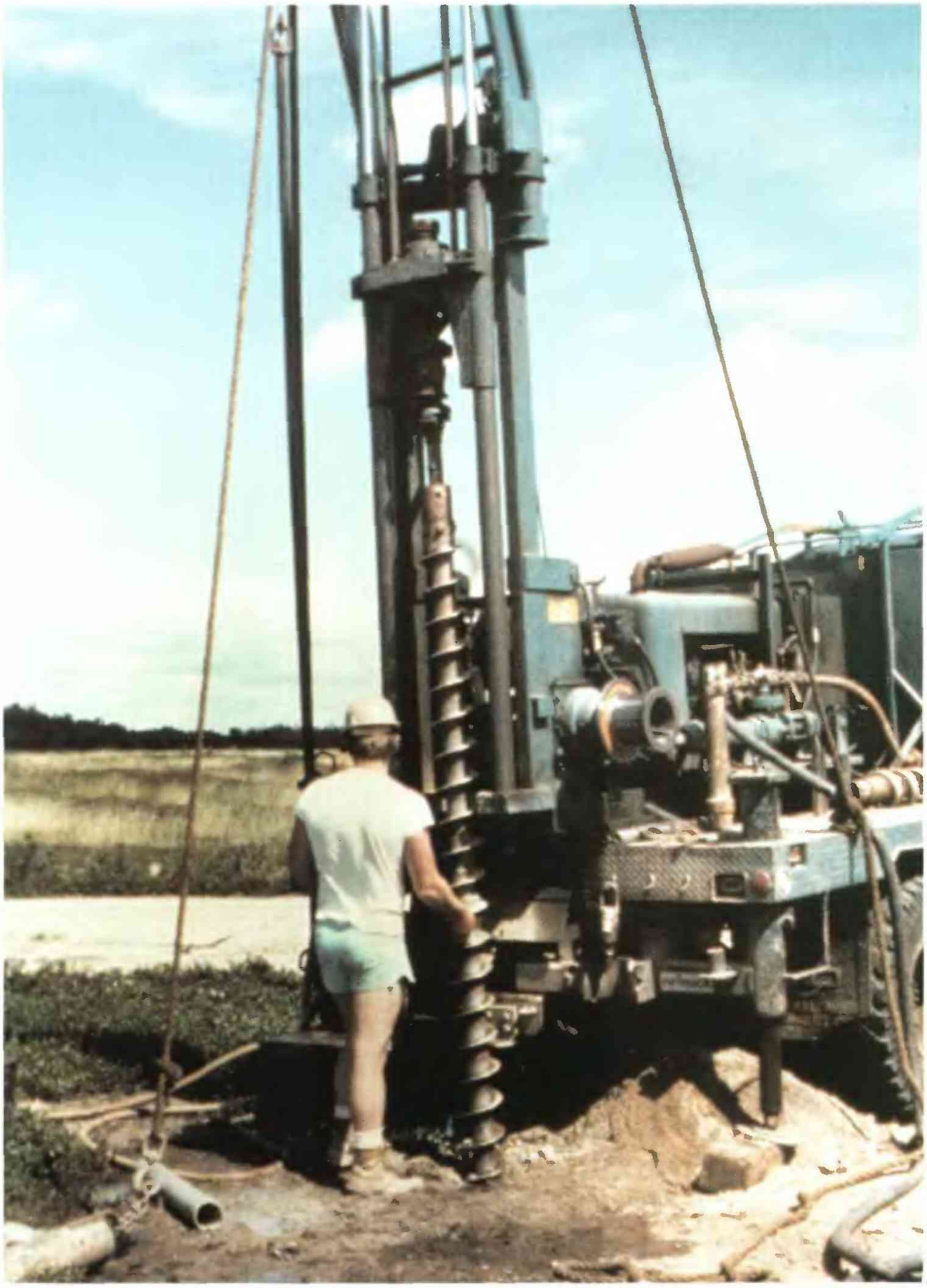

Installation of an aquifer test well in southeastern Maine. Test drilling by the U.S. Geological Survey, the Maine Geological Survey and the Maine Department of Environmental Protection determined thickness, lithology, yield, and water quality of the sand and gravel aquifers in Maine. (Photograph by John Poisson, Maine Geological Survey.)

Prepared by T.J. Maloney, U.S. Geological Survey; radon discussion in "Crystalline-Bedrock Aquifers" part of "Background Water Quality" section by E.M. Lanctot, Maine Department of Human Services

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MARYLAND AND THE DISTRICT OF COLUMBIA
Ground-Water Quality

Maryland and the District of Columbia (fig. 1) lie in five distinct physiographic provinces—the Coastal Plain, the Piedmont, the Blue Ridge, the Valley and Ridge, and the Appalachian Plateaus (fig. 2). Differences in physiography affect the State's climate, soils, land use, and water use. Ground water is an abundant natural resource in Maryland. Although it constitutes only 13 percent of total water used in the State, it is of substantial socioeconomic significance. Most freshwater withdrawals are from the Coastal Plain, and the area east of Chesapeake Bay depends almost entirely on ground water for supply. The District of Columbia depends almost entirely on surface-water supplies, although ground water is used for some industries and for emergency backup for several hospitals, government facilities, and embassies (U.S. Geological Survey, 1985, p. 243).

Maryland's aquifers provide water for about 30 percent of the State's population—13 percent from public supplies and 17 percent from rural self-supplied systems. (See population distribution in fig. 1*B*.) Population growth has increased the demand for potable ground water. The resulting need to dispose of increasing quantities of wastewater, sewage sludge, refuse, and many other wastes has increased the potential threat to ground-water quality.

The ground water used in Maryland generally is suitable for most purposes. With few exceptions, ground water used by public-supply systems meets U.S. Environmental Protection Agency (EPA) drinking-water standards (1986a,b). Natural water-quality problems, however, do occur; the most common are iron and manganese concentrations that exceed national drinking-water standards, excessive hardness as calcium carbonate, naturally occurring saltwater (sodium chloride), and low pH (less than 5.0 units in some places).

Human activities that contribute to present or potential sources of contamination include septic systems, landfills and open dumps, underground oil and gasoline storage tanks, saltwater intrusion due to pumping, agriculture, mining, surface impoundments, road salting, chemical spills, and improper storage and disposal of hazardous substances. The contaminants from these activities include nitrates, chloride, toxic organic and inorganic compounds, petroleum, and bacteria. Some of these contaminants have the potential to threaten human health and ecological systems; others are merely nuisances. Most ground-water contamination in Maryland occurs in widely scattered but localized areas around specific sources (fig. 3). However, some larger "clusters" of wells that yield contaminated water occur where hydrogeologic conditions can promote expansion of ground-water contamination or where potential ground-water-polluting activities are concentrated (Maryland Office of Environmental Programs, 1984a, p. 41).

The Maryland Department of the Environment, Hazardous and Solid Waste Management Administration, through its Maryland Superfund Program has identified 168 sites where hazardous substances may affect public health and the environment. Seventy-four of these sites are regulated also by the Federal Resource Conservation and Recovery Act (RCRA) of 1976 and six sites are included in the National Priorities List (NPL) of hazardous waste sites (U.S. Environmental Protection Agency, 1986c) (fig. 3*A*). These six sites require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Within the District of Columbia, the Department of Consumer and Regulatory Affairs has identified one RCRA site; no CERCLA sites have been designated. In addition, the U.S. Department of Defense has identified three sites at two facilities where contamination has warranted remedial action.

Maryland and the District of Columbia do not have statewide or district-wide routine ground-water-quality monitoring programs. However, such a program is now being considered by Maryland's Ground-Water Steering Committee.

WATER QUALITY IN PRINCIPAL AQUIFERS

The aquifers in Maryland and the District of Columbia generally are of two distinct types—unconsolidated aquifers of the

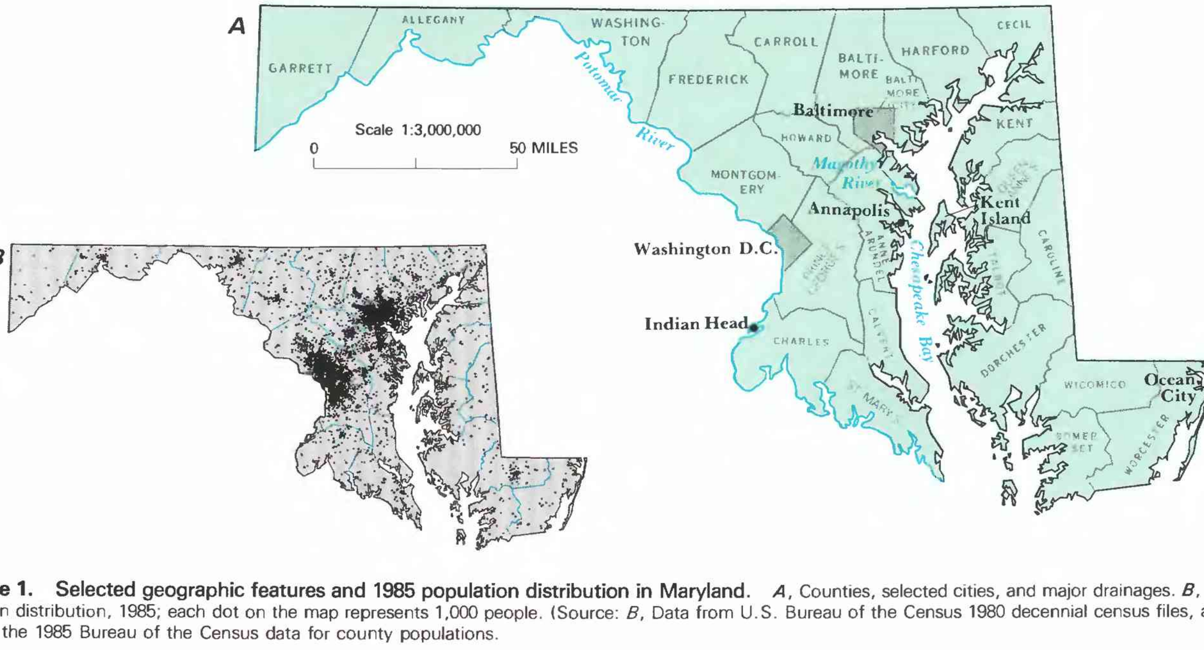

Figure 1. Selected geographic features and 1985 population distribution in Maryland. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 Bureau of the Census data for county populations.

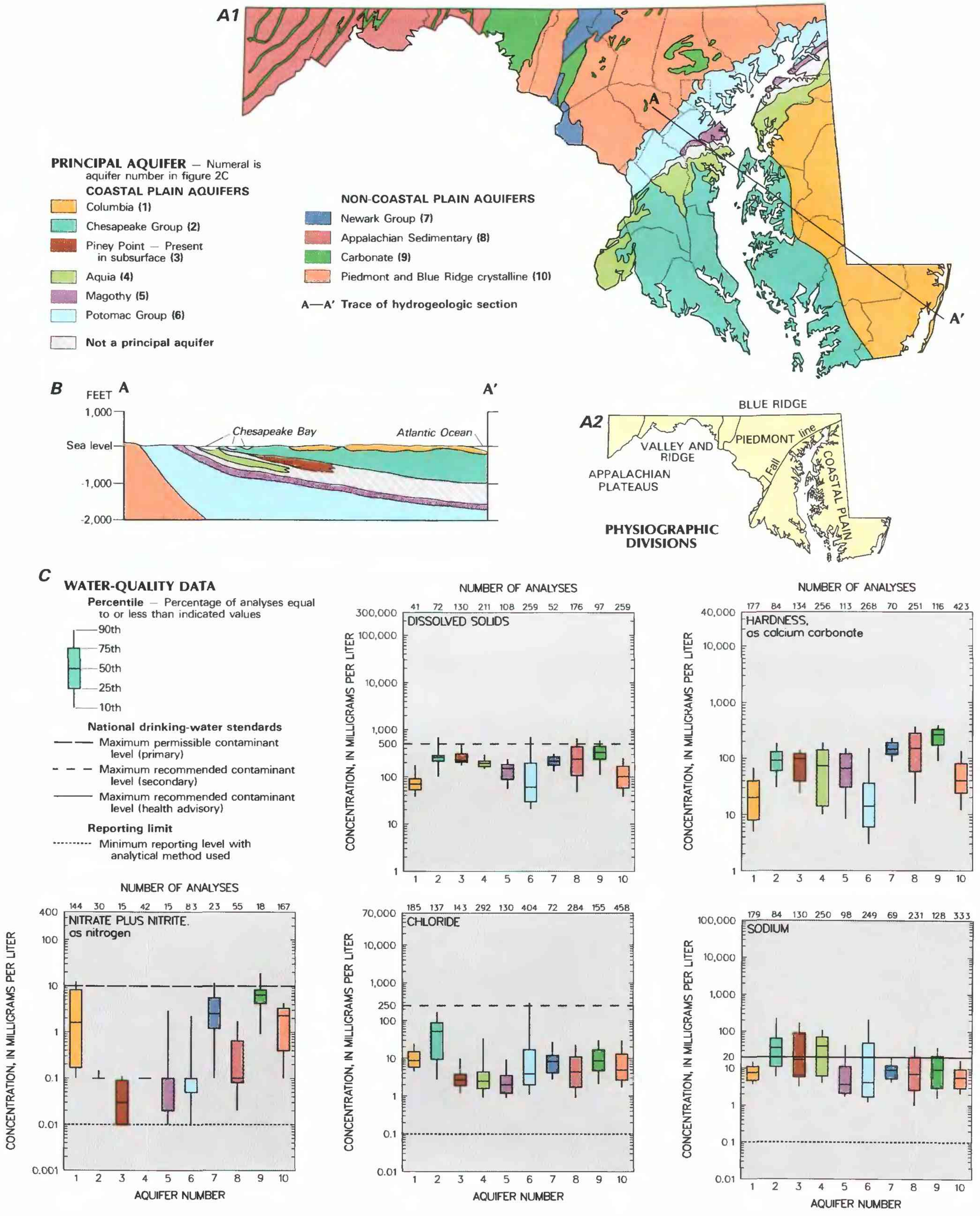

Figure 2. Principal aquifers and related water-quality data in Maryland. *A1*, Principal aquifers; *A2*, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1938-86. (Sources: *A1*, Otton and Richardson, 1958; Maryland Geological Survey, 1967; Cleaves and others, 1968; Hansen, 1972. *A2*, Fenneman, 1946. *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled by L.B. Maclin from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

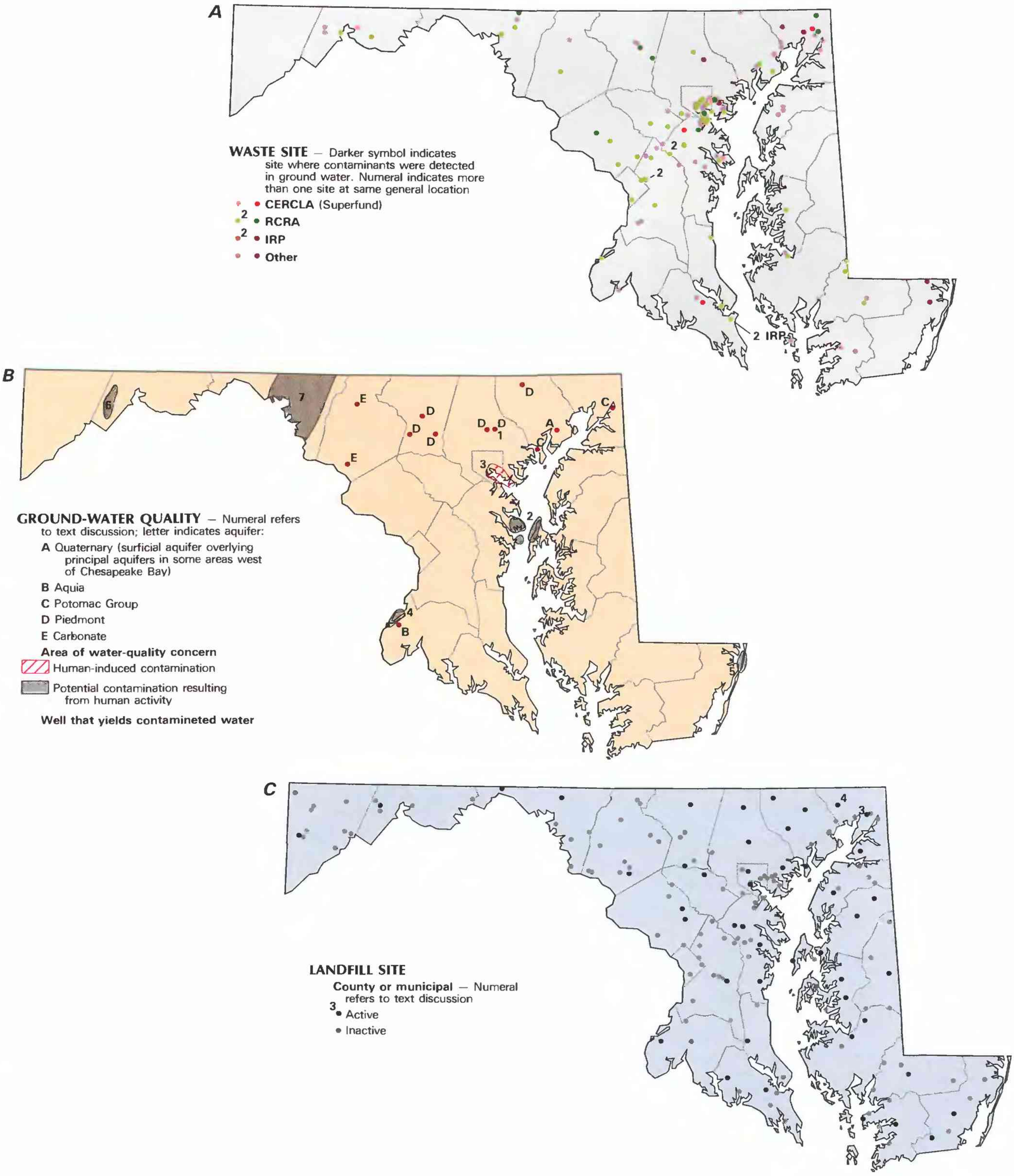

Figure 3. Selected waste sites and ground-water-quality information in Maryland. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of July 1986. *B*, Areas of human-induced and potential contamination, and distribution of wells that yield contaminated water, as of July 1986. *C*, County and municipal landfills, as of July 1986. (Sources: *A*, Maryland Office of Environmental Programs, 1984a,b; 1985; 1986a,b; U.S. Department of Defense, 1986. *B*, Maryland Department of Natural Resources and Maryland Department of Health and Mental Hygiene, 1983a; Maryland Water Resources Administration, 1984, Maryland Department of Natural Resources files. *C*, Maryland Office of Environmental Programs, 1984a; Maryland Office of Environmental Programs files.)

Coastal Plain and consolidated sedimentary and crystalline aquifers of the other physiographic provinces, termed non-Coastal Plain aquifers. The principal aquifers, their geographic distribution, physiographic divisions, and a generalized hydrogeologic section (A–A′) are shown in figure 2. A description of the aquifers is given by the U.S. Geological Survey (1985, p. 243–248). More than 90 percent of the State's total ground-water withdrawals are from Coastal Plain aquifers (Herring, 1983, p. 39).

Natural water quality in freshwater aquifers of the Coastal Plain is suitable for most uses, although quality varies with the composition of the rocks through which the water moves. Water that has been drawn from limey (calcareous) formations may have a greater carbonate content and will be harder than water from other formations. Most public water supplies with hardness that exceeds 150 mg/L (milligrams per liter) are treated to soften the water. Water of Coastal Plain aquifers ranges from soft to very hard, with the average being in the moderately hard range (61 to 120 mg/L as calcium carbonate). The concentration of dissolved solids in the Coastal Plain aquifers varies greatly; largest concentrations (median of more than 200 mg/L) are in the Chesapeake Group and Piney Point aquifers. Dissolved iron concentrations also vary greatly; generally, they are smaller than 200 μg/L (micrograms per liter); however, locally they may be larger than 300 μg/L.

One of the most common problems in Coastal Plain aquifers is saltwater intrusion. The position of the freshwater–saltwater boundary depends not only on the amount of inflow to the aquifer but also the amount of freshwater discharging from the aquifer. Any change in freshwater discharge can change the location of the boundary. Minor variations occur naturally as a result of tidal action and seasonal and annual changes in freshwater discharge.

In the non-Coastal Plain aquifers, natural water quality is satisfactory for most uses, but may vary greatly depending on the type of rock with which the water comes into contact. Water is relatively soft (median of 40 mg/L as calcium carbonate) in most of the Piedmont and Blue Ridge crystalline aquifers. Water in the Carbonate aquifer may be harder—in some areas in excess of 400 mg/L as calcium carbonate. In most non-Coastal Plain aquifers the pH ranges from 6.0 to 8.0, although in some areas the water may be acidic, with pH values smaller than 5.0. Iron concentrations larger than 300 μg/L also are a common problem.

BACKGROUND WATER QUALITY

A graphic summary of water-quality analyses for dissolved solids, hardness as calcium carbonate, nitrate plus nitrite (as nitrogen), chloride, and sodium is shown in figure 2*C* to characterize the variability of the background chemical quality of water in the principal aquifers in Maryland. The data were interpreted without distinction as to either the date of sample collection or the depth within the aquifer from which the sample was collected.

The summary (fig. 2*C*) is based on selected chemical data available in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Percentiles of the variables are compared to national standards established by the U.S. Environmental Protection Agency (1986a,b) that specify the maximum concentration or level of a contaminant in a drinking-water supply. The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines.

Coastal Plain Aquifers

COLUMBIA AQUIFER

The Columbia aquifer crops out over much of the Maryland Eastern Shore (fig. 2*A*1). This aquifer primarily is a water-table aquifer that is recharged by infiltration of precipitation; however, in eastern Worcester County, the aquifer is semiconfined. Natural water quality of the Columbia aquifer generally is suitable for most purposes. Dissolved-solids concentration, a secondary drinking-water standard, commonly is small (median of 70 mg/L). The water usually is soft, with hardness commonly less than 35 mg/L. Nitrate plus nitrite concentration, a primary drinking-water standard, has a median value of 1.6 mg/L. Although chloride concentration, a secondary drinking-water standard, is small (median of 8.7 mg/L), saltwater intrusion is a potential problem, particularly in coastal areas along the Chesapeake Bay and Atlantic Ocean. Sodium concentrations generally are smaller than 10 mg/L.

CHESAPEAKE GROUP AQUIFERS

The aquifers of the Chesapeake Group are major sources of water for several counties of the Eastern Shore of Maryland (fig. 2*A*1). Overall water quality is sufficient for most uses. Salinity, however, generally increases downdip and toward the Chesapeake Bay. Dissolved-solids concentrations generally range from 100 to about 690 mg/L, with the median being 259 mg/L. The average hardness is about 92 mg/L, which is moderately hard. Median chloride and sodium concentrations are 52 and 36 mg/L, respectively.

PINEY POINT AQUIFER

The Piney Point aquifer is a major source of water for public supply, rural-domestic, and small self-supplied commercial uses in Calvert, St. Marys, Queen Annes, Caroline, Talbot, and Dorchester Counties. This aquifer does not crop out (fig. 2*B*); therefore, recharge to the aquifer is by leakage from overlying and underlying aquifers. Quality of water is suitable for most uses and is relatively uniform. In most areas of the aquifer, dissolved-solids concentrations are smaller than 250 mg/L, but they are commonly larger east of the Chesapeake Bay. The water naturally becomes increasingly brackish downdip (toward the southern edge of Dorchester County). Hardness ranges greatly throughout the aquifer, generally from 23 to 140 mg/L (soft to hard). Chloride and sodium concentrations have median values of 2.7 and 17 mg/L, respectively.

AQUIA AQUIFER

The natural water quality of the Aquia aquifer is suitable for most public supply and rural-domestic uses without treatment. The median dissolved-solids concentration is 194 mg/L. In the outcrop area, water usually is soft because much of the fossil shell material and calcite cement commonly found in the aquifer material has been removed by leaching. However, in the rest of the aquifer, water hardness generally ranges from 10 to 190 mg/L (soft to very hard) with the median at 73 mg/L. The median concentrations for chloride and sodium are 2.5 and 40 mg/L, respectively.

MAGOTHY AQUIFER

The Magothy aquifer is one of the most extensive aquifers beneath the Maryland Coastal Plain. Its natural water quality is acceptable for most uses, but in some updip areas the water is excessively acidic and contains undesirably large concentrations of iron (more than 300 μg/L). To the southeast, in parts of Caroline and Somerset Counties, water becomes brackish and is unsuitable for most uses. Median dissolved-solids concentration is 151 mg/L, which is considerably smaller than the drinking-water standard of 500 mg/L. Hardness averages about 70 mg/L (moderately hard) and median chloride and sodium concentrations are small—2.0 and 3.6 mg/L, respectively.

POTOMAC GROUP AQUIFERS

The Potomac Group aquifers supply the largest quantity of ground water for public supplies. Overall, the natural water quality is satisfactory for most uses. The median concentration of dissolved solids (61 mg/L) is considerably smaller than the drinking-water standard. However, iron content may exceed the standard (300 μg/L) in updip areas of the aquifers. Median hardness is about 14 mg/L (soft). Chloride concentrations generally are small (less than 10 mg/L) in the updip areas, and sodium concentrations average 4.1 mg/L. Farther downdip, the water tends to become harder and more alkaline, and contain less iron, more chloride (greater than 250 mg/L), and more dissolved solids until the water becomes too brackish for potable use.

All the principal Coastal Plain aquifers have median values of nitrate plus nitrite (as nitrogen) that are considerably smaller than the drinking-water standard (10 mg/L). The majority of the samples from the Piney Point, Magothy, and Aquia aquifers have nitrate plus nitrite concentrations smaller than 0.1 mg/L.

Non-Coastal Plain Aquifers

Non-Coastal Plain aquifers, which are west of the Fall Line (fig. 2*A2*), usually have natural water quality that is suitable for most uses, although problems of hardness and large iron concentrations are evident. Dissolved-solids concentrations may vary depending on the rock type with which the water comes into contact; concentrations generally range from 38 to about 600 mg/L for the different non-Coastal Plain aquifers. Water hardness also varies widely, generally from about 12 to 390 mg/L (soft to very hard). Brine underlies freshwater in the Appalachian sedimentary aquifers.

The median concentrations of nitrate plus nitrite (as nitrogen) for the principal non-Coastal Plain aquifers are considerably smaller than the drinking-water standard of 10 mg/L. Median chloride and sodium concentrations for the aquifers average about 10 mg/L.

EFFECTS OF LAND USE ON WATER QUALITY

In some areas of Maryland, ground-water quality has deteriorated because of the effects of malfunctioning septic systems, landfills and open dumps, military facilities, leaking underground oil and gasoline storage tanks, saltwater intrusion due to pumping, agricultural practices, surface impoundments, and mining. Locations of documented areas or points of known ground-water contamination, as well as hazardous-waste sites and municipal landfills, are shown in figure 3.

Septic Tank Systems

Approximately 20 percent of the State's population is dependent on individual septic systems for waste disposal. A properly installed and operated septic system is not a threat to ground water; however, a system that malfunctions because of improper installation or maintenance, poor soil conditions (either relatively impermeable or poorly drained), or a high water table may pollute ground water with nitrate, chloride, and bacteria. Septic systems are the most commonly reported source of ground-water contamination in the State. Malfunctioning systems occur in all physiographic areas but are more prevalent in many low-lying shoreline communities where soils are poorly drained and the water table is near the land surface.

Ground-water contamination from septic-system failure usually is localized around communities with numerous failing systems. Many of the existing malfunctioning septic systems were installed before present State Department of the Environment regulatory procedures were in effect, and, in most problem areas, remedies currently are being sought through the EPA Construction Grant Program under the national Clean Water Act (Maryland Department of Natural Resources and Maryland Department of Health and Mental Hygiene, 1983a, p. 209).

Landfills and Open Dumps

Landfilling is the most commonly used method of solid-waste disposal in Maryland. Water that leaches solid wastes at a landfill may contain large concentrations of organic-carbon compounds, chloride, iron, lead, copper, and sodium. Formation of leachate can continue for years after closure of a landfill. As of 1986, new landfills are sited well above maximum ground-water levels and are required to have a liner, an underdrain system to collect leachate for treatment, and monitoring wells to detect and to minimize the potential for contamination of ground water (Maryland Office of Environmental Programs, 1986a). With no such protection at older landfills, the potential for leachate to travel through the soil to ground water is much greater. As of July 1986, 46 municipal land and rubble fills are permitted to operate in the State. However, more than 100 closed or abandoned landfills and open dumps pose potential hazards to ground-water quality; forty two of these sites are on the Maryland Superfund list. (See fig. 3*C* for location of active and inactive landfills.) Ground-water contamination has been detected at several of these landfills (fig. 3*C*, sites 1–4), but monitoring wells have been installed and remedial action to prevent further contamination has been taken (Maryland Office of Environmental Programs, 1986b, p. 1059–1089).

In the District of Columbia, no landfills are in operation, but about 80 sites were used in the past as landfills or open dumps. Several of the abandoned sites are shown in figure 3*C*.

Military Facilities

As of September 1985, 62 hazardous-waste sites at 8 facilities in Maryland had been identified by the U.S. Department of Defense as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 62 sites in the program, 30 contained contaminants but did not present a hazard to the environment. Three sites at two facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Underground Oil and Gasoline Storage Tanks

Petroleum products can enter ground water in two ways—as surface spills that percolate through the soil or as leaks from underground tanks and pipes. Once in the ground water, hydrocarbons may remain for a long time because they can be very resistant to degradation. Small concentrations of hydrocarbons generally are not acutely toxic, but even slight concentrations can render water unpotable because of unpleasant taste or odor (Maryland Department of Natural Resources and Maryland Department of Health and Mental Hygiene, 1983a, p. 237).

The magnitude of ground-water pollution caused by leaking oil and gasoline storage tanks is difficult to assess. Although the incidents of contamination usually are localized, many instances are reported—250 in fiscal year 1986 (Maryland Water Resources Administration, 1986). Most counties report one or more instances each year. The areal extent of the ground-water contamination from a leaky buried storage tank may not be large, but the impact is severe for those directly affected. One site in Baltimore County (fig. 3*B*, site 1) is typical of many instances of petroleum contamination. At this site, one family and five businesses were forced to abandon use of their wells and have water delivered. However, the problem of underground storage tanks is being addressed by the Maryland Department of the Environment. Prevention and detection of underground spills were addressed in regulations promulgated in

1985 for controlling the installation, testing, lining, and abandonment of underground storage tanks. Current efforts are directed toward an evaluation of the feasibility and necessity of complete restoration of contaminated ground water.

Saltwater Intrusion

Saltwater occurs naturally in downdip areas of most Coastal Plain aquifers. Under certain hydrogeologic conditions, saltwater also can be drawn into freshwater aquifers from the Chesapeake Bay or the Atlantic Ocean. (See section on "Background Water Quality.") The problem of saltwater intrusion into freshwater aquifers is associated most commonly with excessive withdrawals of water from aquifers. When saltwater is drawn in, the affected part of the aquifer is no longer suitable for water supply. A public water supply in Harford County experienced saltwater intrusion in the late 1960's when excessive withdrawals from one of the Potomac Group aquifers drew in brackish water from a nearby tidal river that is tributary to Chesapeake Bay. Withdrawal levels were decreased until the hydraulic gradient in the aquifer reversed and the chloride concentrations decreased to acceptable levels (Maryland Department of Natural Resources and Maryland Department of Health and Mental Hygiene, 1983a).

The northwestern corner of Kent Island in Queen Annes County (fig. 3*B*, area 2) is experiencing a saltwater-intrusion problem in the Aquia aquifer. Since 1983, the U.S. Geological Survey and the Maryland Geological Survey, in cooperation with Queen Annes County and the Maryland Water Resources Administration, have been conducting a comprehensive evaluation of the problem. In the meantime, the Maryland Water Resources Administration has prohibited increased pumpage from the affected part of the Aquia aquifer.

The Potomac Group aquifers under south-central Baltimore city (fig. 3*B*, area 3) became contaminated with saltwater as a result of large withdrawals of ground water for industrial use in the first half of this century. Most industries in the city now use the public supply, which is a surface-water reservoir system. A recently completed investigation of the status of ground water in the Baltimore city area concluded water quality was unlikely to improve significantly even if all ground-water pumpage in the Baltimore area were stopped; and significant pumping stress in the northeastern corner of Anne Arundel County could cause the chloride plume to migrate toward that pumping center (Chapelle, 1985).

Saltwater intrusion in the Indian Head area of Charles County (fig. 3*B*, area 4) has been recognized as a potential threat to local water supplies for many years, but until recently, little indication of saltwater intrusion had been found. The town of Indian Head has experienced increased concentrations of dissolved solids in the drinking water drawn from Potomac Group aquifers. Before 1964, dissolved-solids concentrations in the town's water supply typically ranged from 200 to 250 mg/L; however, by 1982, the concentrations had increased to about 424 mg/L. In 1983, brominated compounds, which may be associated with brackish water, also were detected. A preliminary investigation by the Water Resources Administration indicates the possibility of intrusion of brackish water from the Potomac River (Maryland Water Resources Administration, 1984, p. 211–235).

Increased withdrawals of ground water by Maryland's largest coastal resort town, Ocean City, Worcester County (fig. 3*B*, area 5), have caused the development of large cones of depression in the aquifers pumped. In addition, Ocean City is located on an island surrounded by the ocean, thus increasing the potential for saltwater intrusion. Since 1974, chloride concentrations in some supply wells of the 44th Street cluster have increased from 75 mg/L during November 1974 to 197 mg/L during February 1986 (fig. 4).

Two major ground-water studies currently are underway in the Ocean City area. One study by the U.S. Geological Survey, in cooperation with Maryland and Delaware agencies, is investigating water levels, chloride concentrations, and water use in coastal Maryland and Delaware. The other study is a multistate management planning effort between Maryland and Delaware, which is expected to result in the formation of a State water-supply strategy for resolving several issues in the region, including the saltwater-intrusion problem in the Ocean City area.

Agricultural Practices

Agriculture affects the State's ground-water quality primarily by the misapplication of pesticides and fertilizers. Some classes of pesticides, including organic botanicals such as rotenone and pyrethrin, are biodegradable and in most situations present little threat to ground water. However, other classes, including organometallic compounds, have toxic and (or) heavy metals as part of their structure and present a real threat to ground water. Of greatest concern are the metallic arsenates, which contain extremely toxic arsenic. Under ideal circumstances, arsenic reacts with iron, aluminum, and calcium present in soils and forms compounds that are insoluble in water. Areas most vulnerable to ground-water contamination by arsenic compounds are those where the soil layer is thin or excessively permeable.

In 1983, the Maryland Office of Environmental Programs conducted a statewide study of selected wells to evaluate whether increased use of pesticides had affected ground-water quality. For most of the wells tested (at 28 agricultural sites), pesticides were not detected in the water, and in the few samples in which pesticides were present, concentrations were considerably smaller than established "alert" levels (Maryland Office of Environmental Programs, 1986a, p. 101).

Agricultural fertilizers usually contain one or more of the three major nutrients required for plant growth—nitrogen, phosphorus, and potassium. The most significant of these, from a drinking-water standpoint, is nitrogen. Excessive use of nitrogen fertilizers is suspected to be a factor in increased levels of nitrate in ground water in several areas of the State. A statewide study evaluated nitrate levels in 1,521 wells (Maryland Office of Environmental Programs, 1986a). Nearly 7 percent of the wells tested had nitrate concentrations that exceeded the national drinking-water standard of 10 mg/L as nitrogen. Twenty-two percent of the wells had concentrations ranging from 3 to 10 mg/L, whereas the remaining 71 percent had less than 0.3 mg/L.

A study completed in 1983 (Bachman, 1984) focused on describing the factors that affect nitrate variability in the Columbia aquifer in Maryland. A major finding of that report was that of 604 water-quality samples analyzed from randomly selected wells, 25 percent had nitrate concentrations that ranged from 0 to about 0.42 mg/L as nitrogen and that more than half had concentrations greater than 3 mg/L, which is larger than the median concentrations of 144 analyses shown here in figure 2*C*. In that study about 15 percent of the samples had nitrate concentrations that exceeded the drinking-water standard. The overall median concentration was about 3.5 mg/L. Concentration of nitrate tended to be larger at sites with urban and agricultural land uses and moderately well drained soils.

Surface Impoundments

Pits, ponds, and lagoons are surface impoundments widely used in Maryland for the treatment, disposal, or storage of wastes. In 1978–79, the Maryland Surface Impoundment Assessment Group identified 855 impoundments throughout the State. Approximately 75 percent of all sites were unlined and were possible sources of ground-water contamination. However, very little ground-water-quality monitoring had been done at the sites to determine the extent and severity of contamination (McGlincy and others, 1980).

About 82 percent of the surface impoundments were used for waste treatment rather than storage or disposal. Municipal impoundments were mostly sewage-treatment lagoons designed to discharge to surface water. Agricultural impoundments typically were used for storage or treatment of swine or dairy wastes. Mining ponds commonly were unlined basins used to settle and neutralize acid water with lime. Industries primarily used impoundments for waste treatment by settling or seepage. Of the 132 industrial impoundments assessed by the Surface Impoundment Assessment Group, 40 contained hazardous wastes as defined by State regulations. Leaking industrial impoundments are the most well-known sources of severe ground-water contamination in the State. Many of the RCRA sites shown in figure 3*A* are surface impoundments, and several have documented ground-water contamination, including a CERCLA site located in St. Marys County.

Mining

Acid mine drainage from abandoned coal mines is western Maryland's most critical water-contamination problem. The large number of abandoned mines, the method of mining commonly employed, and the extent of many underground workings render acid mine drainage difficult to decrease. Coal-bearing sedimentary rocks usually contain sulfide minerals. When rocks are exposed to surface conditions, as in mining, weathering begins. Sulfides, water, and atmospheric oxygen react to produce large quantities of sulfuric acid-bearing water. This acid water, in turn, can dissolve considerable amounts of metals from surrounding rocks. The result is ground water that may exceed national standards for pH, sulfate, iron, and trace metals.

Several areas in western Maryland are known to have degraded ground-water quality that may be attributed to mine drainage. Water from several springs in western Allegany County (fig. 3*B*, area 6) contains excessive hardness, acidity, large concentrations of iron (more than 300 μg/L), and bacterial contamination. Similar water-quality problems occur in the coal mining areas of Garrett County. Information is insufficient to determine the degree to which mining has contributed to the problem.

POTENTIAL FOR WATER-QUALITY CHANGES

Some aquifers or geographic regions are more susceptible than others or are particularly at risk of becoming contaminated because they are more exposed to potential surface sources of contamination. Unconfined aquifers typically have greater potential for contamination than confined aquifers for these reasons. The effect of land-use activities on these vulnerable areas may be substantial. Deeper confined aquifers may also become contaminated by infiltration of contaminated water from unconfined aquifers or by direct access through wells.

Aquifers that underlie coastal areas are susceptible to salt-water intrusion as a result of excessive withdrawals of water from the aquifer. A few locations where such problems already exist are shown in figure 3*B* (areas 2–5). A particular area of concern is the Broadneck Peninsula in Anne Arundel County (fig. 1*A*), where a decline in the potentiometric surface of the Magothy aquifer is creating a potential for salt-water intrusion. In this area, the potentiometric surface is below sea level about a mile from the aquifer's outcrop/subcrop, which is under the salt-water tidal zone of the Magothy River. If the hydraulic gradient at the saltwater source is landward toward the aquifer, the possibility for salt-water intrusion is present. Since 1983, the Maryland Water Resources Administration has placed restrictions on further increases in withdrawals from the Magothy aquifer in the Broadneck Peninsula, as well as the upper sand zone of the hydrologically connected Potomac Group aquifers. Despite these actions, the potentiometric surface continues to decline, although at a slower rate. As a result, the Water Resources Administration has encouraged the Anne

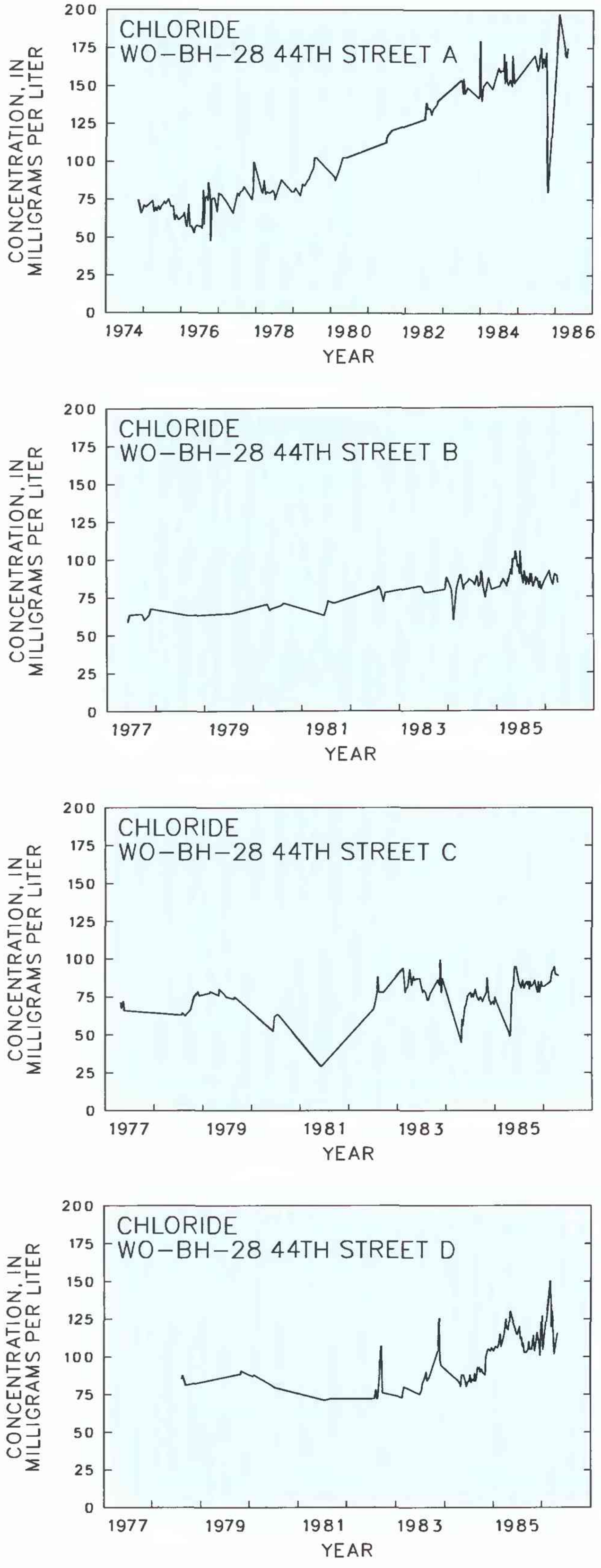

Figure 4. Chloride concentrations in samples from four wells, 44th Street, Ocean City, Md., November 1974 through February 1986. (Source: Worcester County Sanitary Commission files, July 1986.)

Arundel County Department of Utilities to drill into the lower zones of the Potomac Group aquifers to meet future public-supply demands.

The large region of Maryland underlain by carbonate aquifers (fig. 2*A*1) has distinct problems regarding waste disposal and ground-water quality. Like other bedrock types found west of the Fall Line (fig. 2*A*2), the carbonate rocks may contain cavernous passages through which large volumes of ground water can move. The Hagerstown Valley in Washington County is representative of this phenomenon and is the largest area underlain by carbonate aquifers in the State (fig. 3*B*, area 7). Although some of the carbonate aquifers of the Hagerstown Valley are capable of yielding large quantities of water to wells, any contaminant introduced into the ground water can spread quickly and over great distances. In some areas, the subterranean passages intersect with the land surface as sinkholes, giving contamination direct access to ground water. Long-standing concern about ground-water quality in the Valley has increased as residential development with individual wells and septic systems has accelerated. Ground-water quality has already deteriorated in some locations. Conclusions of studies by the State and Washington County indicated that this contamination was the result of constructing numerous septic systems on sites where soil thickness was insufficient to attenuate the effluent before it reached the carbonate aquifer. These problems may increase, because thousands of such systems are already in place and hundreds more are proposed each year. The county responded to the problem by formulating a comprehensive quality management plan, which, in part, addresses and regulates point and nonpoint sources of contamination, as well as requiring appropriate well siting and construction standards (Maryland Department of Natural Resources and Maryland Department of Health and Mental Hygiene, 1983a, p. 245).

The Columbia aquifer also is extremely susceptible to ground-water contamination. This unconfined aquifer underlies much of the Eastern Shore area of Maryland (fig. 2*A*1) where it is a major source of potable water. The aquifer is vulnerable to contamination because water occurs close to the land surface under unconfined conditions and because the aquifer consists largely of permeable sand and gravel, and lacks sufficient clay and organic matter to provide effective filtration. Because land use is mostly agricultural, risk of contamination from industrial sources is small. However, problems can occur because this aquifer serves as a potable water supply and also receives potential contaminants from septic systems and agricultural activities. Although this risk is present in all areas of the State underlain by unconfined aquifers, it is especially significant on the Eastern Shore because of the weak attenuating capacity of the soil/sediment material.

The use of infiltration techniques to manage storm water may affect ground-water quality. In 1985, the U.S. Geological Survey, in cooperation with the Maryland Geological Survey and the Water Resources Administration, began a 5-year study to evaluate effects of infiltration structures on ground-water quality. Depending on results of the study, the State may incorporate additional design specifications or restrict the use of infiltration structures in vulnerable areas (Maryland Water Resources Administration, 1986).

GROUND-WATER-QUALITY MANAGEMENT

The strategy of Maryland State and local regulatory agencies is to prevent ground-water contamination by concentrating on the potential sources of the contamination. This prevention-based approach allows each regulatory group to develop expertise in dealing with the source of contamination for which it is responsible and to establish programs that are compatible with Federal laws. Currently, the U.S. Environmental Protection Agency is emphasizing the development of a comprehensive ground-water-protection program. In response, the State legislature assigned the primary responsibility to develop, coordinate, and plan ground-water-protection policies, programs, and strategies for the State to the Ground-water Steering Committee, composed of representatives from the Maryland Department of the Environment (lead agency), the Department of Natural Resources, and the Department of Agriculture.

The Department of the Environment, through a number of different divisions, is the primary regulatory agency responsible for ground-water-quality protection:

- Division of Planning reviews and approves county water and sewerage plans.
- Division of Residential Sanitation issues ground-water-discharge permits for land treatment systems that apply municipal wastewater; issues well construction permits for rural-domestic and public-water systems, and dairy farm wells; and assists local health departments with regulation of septic systems.
- Division of Water Supply implements provisions of the Federal Safe Drinking Water Act of 1974 and activities related to the quality of "finished" potable water (treated and delivered water) rather than quality of "raw" water within the aquifer, including monitoring community water systems and sampling treated water for bacteriological, radiological, physical, and chemical analysis.
- Hazardous and Solid Waste Management Administration, in addition to administering RCRA and CERCLA, issues permits for and monitors ground-water discharges; landfills; sewage sludge; and the treatment, transport, and disposal of hazardous and nonhazardous industrial wastes. The administration also regulates oil operations, vehicle operators, and terminal facilities, and responds to spill emergencies for both surface spills and leaking underground storage tanks; administers State regulations pertaining to the installation, testing, lining, and abandonment of underground storage tanks.
- Stormwater Management Administration directs the State Erosion and Sediment Control Program through enforcement and monitoring of sediment control plans and a statewide program to decrease stream-channel erosion, pollution, siltation, and sedimentation.

The Department of Natural Resources, through the Water Resources Administration, is responsible for the protection, management, and development of the State's water resources. These goals are accomplished primarily through the Water Management and Resource Protection Programs and Bureau of Mines:

- Water Management Program directs the development, management, and conservation of the State's water-supply resources by regulating water withdrawals through the issuance of appropriation permits and by analyzing areawide effects of collective water appropriation in view of future supply and demand needs.
- Resource Protection Program is responsible for assuring compliance with environmental safeguards in the operation and reclamation of non-fossil fuel surface mines.
- Bureau of Mines ensures adherence of environmental safeguards and proper reclamation of coal mines in western Maryland.

The Hazardous Waste Facilities Siting Board is an independent board created in 1980 to ensure that the State has a means of locating new hazardous-waste management facilities. The Board's program includes maintaining the statutory authority to locate needed facilities for hazardous and low-level radioactive waste; conducting studies as needed at proposed sites; establishing and maintaining a level of awareness by citizens, government, and commerce that will permit informed response to a proposed facility; and conducting periodic reviews of the State's hazardous-waste treatment and disposal needs. An important aspect of the State's experience since 1980 is that facilities have not been developed as expected.

In addition to State-level agencies concerned with ground-water quality, local health departments are responsible for overseeing the proper siting and installation of private wells and septic systems, verifying quantity and quality of well water for new dwellings or before reconveyance of already developed property, reviewing subdivision plans with respect to their effect on ground water, sampling monitoring wells at landfills, sampling private rural-domestic wells on request for bacterial and chemical quality, and requiring septic system repairs or maintenance when failures become evident.

The State has a continuing commitment to improve programs that address ground-water quality with greater emphasis on inspection, compliance, and enforcement and with better quality control to ensure their effectiveness. However, more information is needed on other sources of ground-water contamination including agricultural and residential uses of fertilizers, herbicides, and pesticides and uses of unregulated toxic chemicals including domestic cleaners and other household chemical products (Maryland Office of Environmental Programs, 1984a). Evaluation of the effects of these sources may indicate a need for additional regulations to minimize contamination problems.

The District of Columbia relies mainly on surface water and has no specific legislation directed at ground-water management. However, the Environmental Control Division of the Department of Consumer and Regulatory Affairs is responsible for ground-water-quality protection through two branches. The Water Hygiene Branch manages the ground- and surface-water needs of the District, and the Hazardous Wastes and Pesticides Branch is responsible for regulations that pertain to pesticides; leaking underground storage tanks; and the treatment, storage, and disposal of hazardous wastes, as well as administering RCRA and CERCLA.

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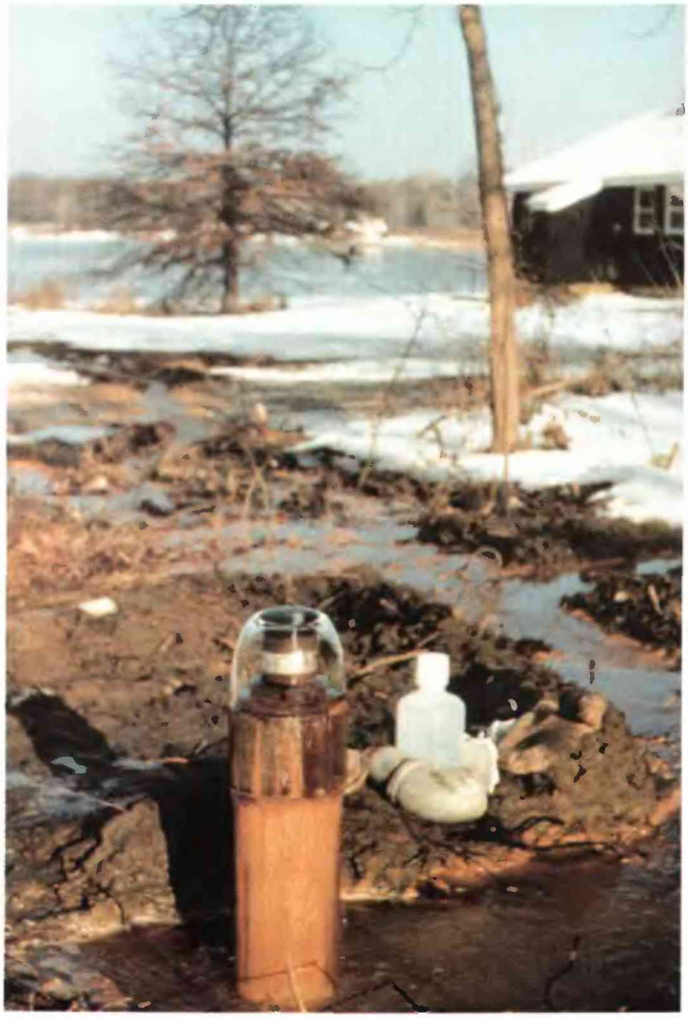

Flowing well on Thomas Point in Anne Arundel County, Maryland. This well, near Chesapeake Bay, is completed in the Magothy aquifer. (Photograph by Frederick K. Mack, Maryland Geological Survey.)

Prepared by Judith C. Wheeler and Lillian B. Maclin

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MASSACHUSETTS
Ground-Water Quality

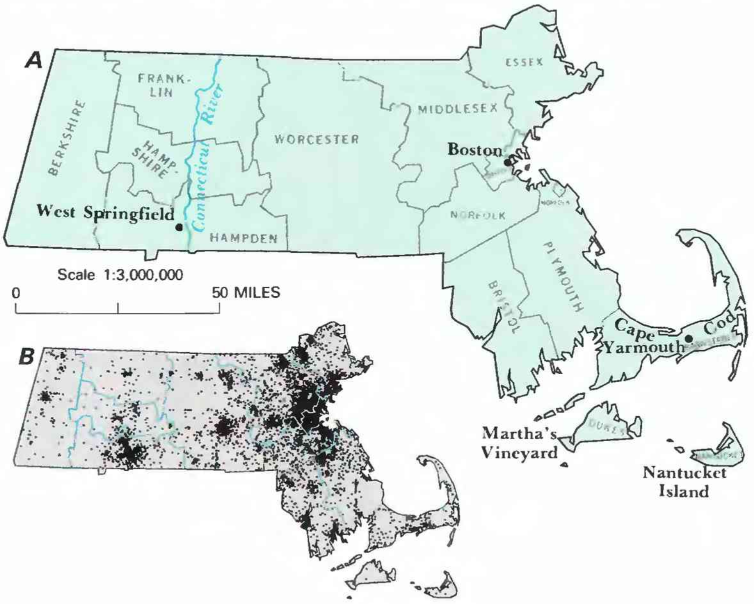

Figure 1. **Selected geographic features and 1985 population distribution in Massachusetts.** *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

In Massachusetts, ground water supplies about 2 million people, one-third of the State's population (fig. 1). Most ground water throughout the State meets the drinking-water standards established by the Massachusetts Department of Environmental Quality Engineering (MDEQE) and the U.S. Environmental Protection Agency (EPA); however, concentrations of iron and manganese can exceed drinking-water standards. Most ground water contains small concentrations of dissolved solids and is soft, acidic, and corrosive to pipes and plumbing.

Nearly all public ground-water supplies are derived from unconfined stratified-drift aquifers that are less than 100 feet thick. Because of the permeable nature of these deposits, water from these aquifers and from the bedrock aquifers is extremely susceptible to contamination from activities on the land surface. Degradation is associated with urbanization, agriculture, and waste disposal. Since 1960, more than 100 public wells or well fields out of about 1,400 have been closed because of contamination. Nearly all the wells that yield contaminated water were identified through a monitoring network operated by the MDEQE. Most commonly, initial identification of private well contamination has been through detection of unpleasant or unnatural taste and odor.

Sixteen hazardous-waste sites have been included on the National Priorities (NPL) by EPA. Thirty-one sites are regulated under the Resource Conservation and Recovery Act (RCRA) of 1976. In addition, five sites at one facility were identified by the U.S. Department of Defense for remedial cleanup action.

Contamination of the ground water with organic compounds is the primary cause of well closures in Massachusetts. Sixty public wells or well fields have been closed because of contamination with waste organics, mostly solvents. Several of these wells have been reopened, but the water must be treated by air stripping and activated carbon filtration. Some wells have been closed because of pesticide contamination. At least six public-supply wells and an uncounted number of private wells have been closed because of contamination from the State's 484 active and inactive landfills. As a result, a program has been initiated for closing, capping, and monitoring landfills. Wastewater disposal through municipal sewage-treatment facilities and private septic systems is a source of degradation and a cause for closure of several private wells and one public-supply well. Storage and application of road salt has contaminated nine public-supply wells and an uncounted number of private wells, causing them to be closed. The Massachusetts Department of Public Works has responded by covering salt storage piles to prevent leaching, by decreasing the amount of salt applied to highways in watersheds of public supplies, by experimenting with calcium magnesium acetate as an alternative deicing chemical, and by evaluating experimental paving materials.

The prevention of contamination is paramount in the State's ground-water protection strategy, which has three major elements. First, all public water supplies and waste-disposal facilities are regulated by the State. Second, a program of technical assistance and information provides guidance for local and regional agencies to apply their land-use controls and for other authorities to protect public and private water supplies. Third, an economic assistance program motivates the implementation of ground-water quality planning and management at the town and municipal level.

WATER QUALITY IN PRINCIPAL AQUIFERS

Massachusetts has four principal types of aquifers (fig. 2*A*)—stratified drift; sedimentary-bedrock; crystalline, metamorphic and igneous bedrock; and carbonate rock (U.S. Geological Survey, 1985, p. 249–252). Virtually all the State's ground-water withdrawals for public water supply are from the stratified-drift aquifers. In southeastern Massachusetts, on Cape Cod, and on the islands of Martha's Vineyard and Nantucket the stratified-drift aquifers are the only water source for both public and domestic supply. However, in other parts of the State, about 300,000 people rely on domestic wells in the bedrock aquifer.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) and the MDEQE is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, pH, sodium, and sulfate analyses of water samples collected from 1979 to 1985 from the principal aquifers in Massachusetts. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The secondary drinking-water standards include maximum concentrations of 500 mg/L (milligrams per liter) dissolved solids, 6.5-8.5 units of pH, and 250 mg/L sulfate.

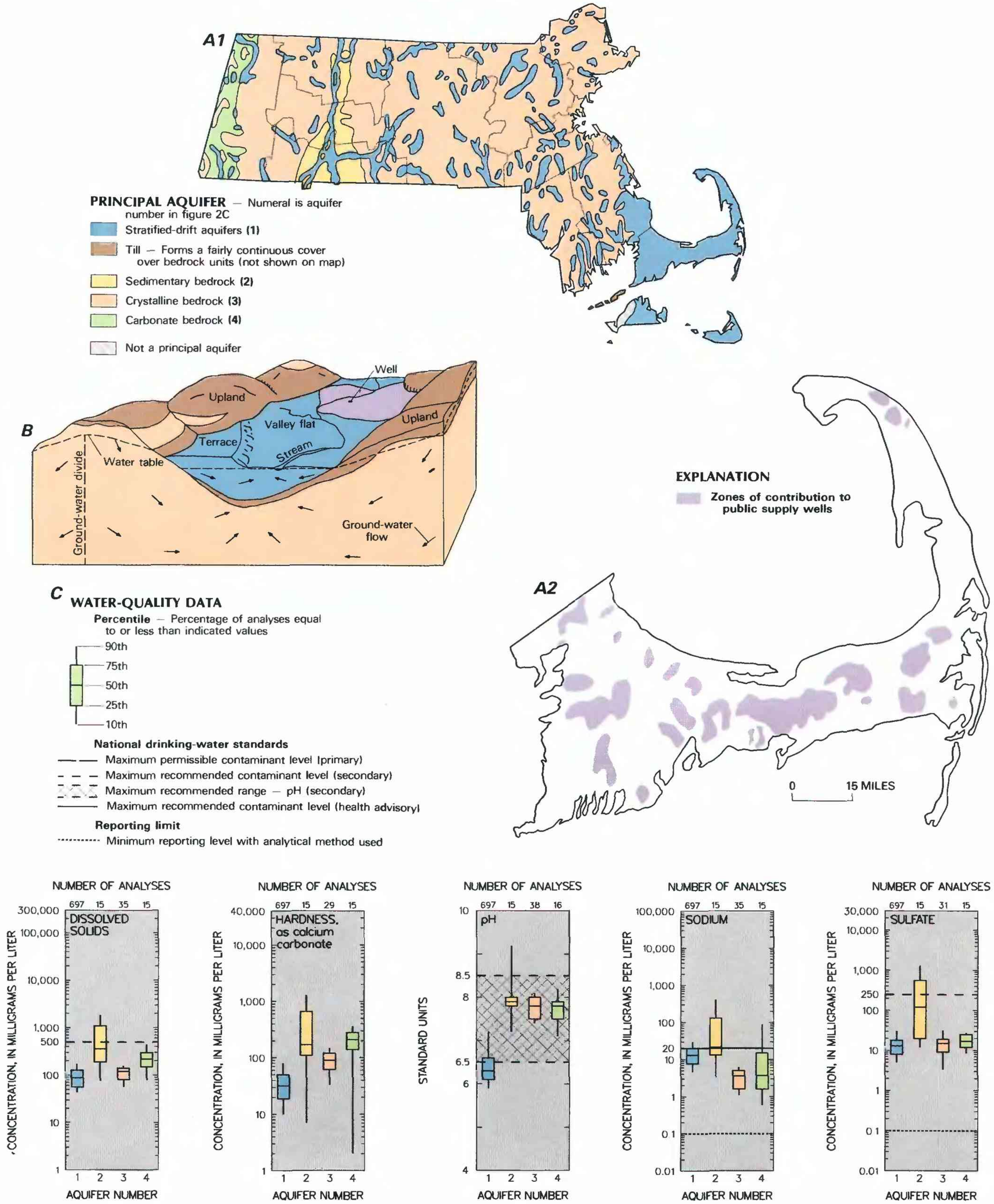

Figure 2. Principal aquifers and related water-quality data in Massachusetts. *A1*, Principal aquifers; *A2*, Map of Cape Cod showing zones of contribution to public supply wells. *B*, Block diagram showing typical characteristics of valley-fill stratified-drift aquifers and the zone of contribution (shaded) to a public supply well. *C*, Selected water-quality constituents and properties, as of 1979–85. (Sources: *A1*, *A2*, U.S. Geological Survey, 1985, p. 251; modified from Cape Cod Planning and Economic Development Commission, 1983. *B*, Frimpter, 1981. *C*, Analyses compiled from U.S. Geological Survey and Massachusetts Department of Environmental Quality Engineering files; national drinking-water standards from U.S. Environmental Protection Agency, 1986b.)

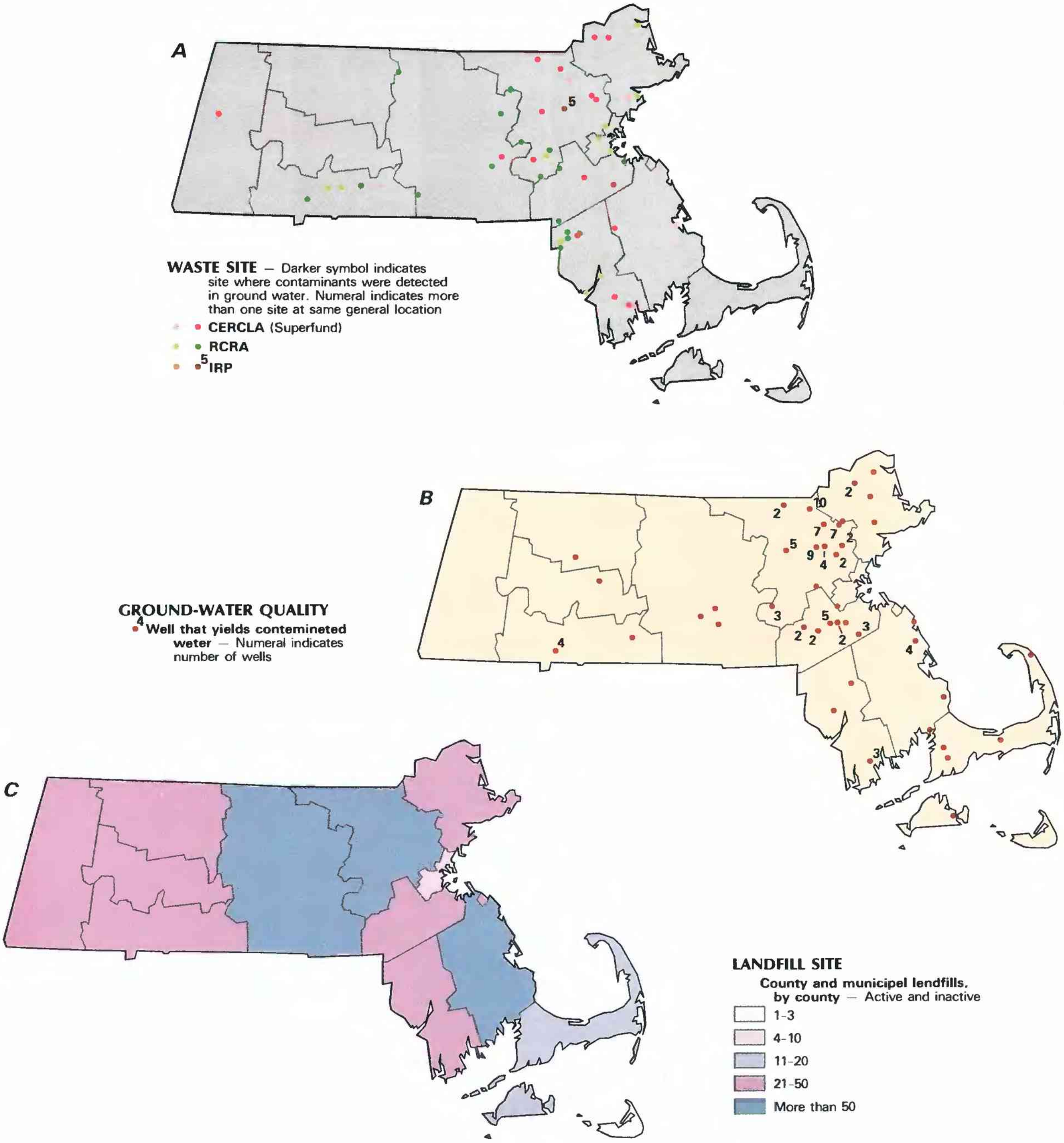

Figure 3. **Selected waste sites and ground-water-quality information in Massachusetts.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act, (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985. *B*, Distribution of wells that yield contaminated water, as of 1960-86. *C*, County and municipal landfills, as of 1986. (Sources: *A*, Massachusetts Department of Environmental Quality Engineering files; U.S. Environmental Protection Agency, 1986c; U.S. Department of Defense, 1986. *B*, Massachusetts Department of Environmental Quality Engineering files. *C*, Massachusetts Division of Water Supply files.

Stratified-Drift Aquifers

The stratified drift consists of layers of unconsolidated sand and gravel, whose mineral composition is commonly more than 99 percent quartz and feldspar, which are chemically stable, nonreactive, and virtually insoluble in water. Because of the chemical composition of both the aquifer and precipitation, water from the stratified-drift aquifers generally has small concentrations of dissolved solids and is soft and slightly acidic (fig. 2*C*). In the western part of Massachusetts, the stratified drift locally derived from carbonate rocks has a mineral composition similar to local bedrock and, therefore, possesses water chemistry similar to that described here for the carbonate rock aquifer. The median dissolved-solids concentration was 88 mg/L based on 697 samples of water from public-supply wells in the stratified-drift aquifers analyzed by the MDEQE in 1984, and the median hardness as calcium carbonate was 32 mg/L. Most public and private wells in this aquifer are less than 100 feet deep, and the aquifer generally is unconfined. The water is commonly nearly saturated with dissolved oxygen and has a relatively constant temperature of about 11°C (degrees Celsius). Eighty-five percent of the 697 analyses had a pH of less than 7; the median pH was 6.3. Because the water has a small dissolved-solids concentration and is soft and acidic, it is corrosive to metal and cement pipe. Of 697 analyses of water from public-supply wells, 75 percent had negative Langelier indexes of -2.5 or lower; and the median index was -3.23. Water with a negative Langelier Index (Hem, 1970, p. 24) is undersaturated with respect to calcium carbonate and, therefore, may dissolve metals and cement releasing lead, copper, zinc, and perhaps other metals. Sodium hydroxide or other chemicals are added to some public-water supplies to increase the pH and decrease corrosivity. In 1986, plumbing codes were changed to limit the lead content of solder to less than 0.02 percent, thereby decreasing the potential for dissolution of lead from plumbing. Consumers are advised to flush water which has been in domestic copper plumbing or lead service lines before drawing water for drinking or cooking. The metals may impart an acerbic taste to the water and copper causes blue-green staining of white porcelain sinks and tubs.

Iron and manganese may occur in concentrations requiring treatment before distribution in public supplies. These elements are the products of the weathering of minerals and dissolution of oxide coatings on aquifer materials. They are easily dissolved in acidic water in the absence of oxygen. Water in the stratified drift is almost always acidic, but commonly contains dissolved oxygen, which precludes the solution of iron and manganese. However, dissolved oxygen may be depleted when ground water passes through organic deposits, such as peat or river-bottom sediments, thereby allowing the water to dissolve and mobilize iron and manganese. For example, in Middlesex County, a test well located in an aquifer below a 5-foot thick layer of peat yielded water with 19,000 μg/L (micrograms per liter) dissolved iron. In addition to causing taste, color, and staining problems, iron and manganese can form encrustations on well screens, thereby decreasing well efficiency. Wells, which initially yield water with small concentrations of these metals, may show a trend toward increasing concentrations and decreased well efficiency as a result of reversing ground-water gradients and causing iron- and manganese-bearing water to flow to the well (Gay and Frimpter, 1981, p. 18-23). Aquifers that previously had been bypassed because of large concentrations of iron and manganese are now being developed and the water treated because of increased demand and limited resources.

Organic deposits can cause other problems in addition to large concentrations of iron and manganese. In Provincetown, on the northern tip of Cape Cod, decomposition of organic material in marsh deposits that have been buried by postglacial sand dunes, produces dissolved ammonia, hydrogen sulfide, and iron in the ground water (Frimpter and Gay, 1979, p. 7-9).

Saltwater intrusion into the stratified-drift aquifers has been caused by overpumping in some coastal areas of Massachusetts, but no public-supply well fields have been closed and only one has been affected. Public-supply wells for Provincetown (Barnstable County) draw freshwater from the upper 100 feet of the stratified-drift aquifer, but overpumping has caused gradual upward migration of saltwater that underlies the shallow freshwater lens in this area. Sodium concentrations have increased from less than 25 to 150 mg/L at one well field. The intrusion has been controlled by decreasing pumping rates in the well field and by areally distributing withdrawal from the aquifer. Massachusetts, which has a 20-mg/L guideline for sodium in public drinking water, requires that suppliers notify all their customers if that guideline is violated.

Sedimentary-Bedrock Aquifer

The Triassic sedimentary-bedrock aquifer in the Connecticut River valley has been developed for private domestic supplies and a few industrial supplies. It consists of sandstone, shale, conglomerate, and interbedded lava flows (traprock). Deposited in a continental basin environment, these rocks contain traces of gypsum, a mineral characteristic of evaporite deposits. Localized ore deposits and prospects contain copper, lead and zinc sulfides, fluoride, and secondary uranium-bearing minerals. The ground water is slightly alkaline and has a median pH of 7.9. Water from the upper 200 feet of this aquifer generally contains moderate levels of dissolved solids and is moderately hard, but water from deeper parts of the aquifer commonly has large concentrations of dissolved solids and is hard. The median dissolved-solids concentration of 15 samples was 360 mg/L, but one 510-foot deep well yielded water with 1,600 mg/L dissolved solids. The water in this aquifer contains larger median concentrations of sulfate (120 mg/L), sodium (21 mg/L), and fluoride (0.2 mg/L) than any other aquifer in Massachusetts.

Carbonate-Rock Aquifer

The carbonate-rock aquifer consists of limestone, dolomite, and marble interbedded with schist and quartzite in the valleys of Berkshire County in western Massachusetts. This aquifer has been developed for domestic supplies and for large-yield wells by industry. Water from this aquifer characteristically is very hard (median 210 mg/L as calcium carbonate) and has moderately large dissolved-solids concentrations (median 220 mg/L), but unlike the sedimentary-bedrock aquifer has little sodium (median 3.7 mg/L), sulfate (median 17 mg/L), and less than 0.1 mg/L fluoride. The water is also slightly alkaline and has a median pH of 7.8

Crystalline-Bedrock Aquifer

The crystalline-bedrock aquifer is composed predominantly of granite, gneiss, and schist, and is relied upon for domestic water supplies, for which only a few gallons per minute are needed and where there are no other easily accessible aquifers. Virtually all water in this aquifer has small dissolved-solids concentrations, with a median concentration of 120 mg/L. It is moderately hard, with a median concentration of 90 mg/L (as calcium carbonate) and is slightly alkaline, with a median pH of 7.8. Iron in concentrations requiring treatment before use is common in those rocks known as "rusty" schist or gneiss which contain an abundance of ferromagnesian minerals or small amounts of pyrite or pyrrhotite. Arsenic, possibly derived from sulfide minerals, has also been found in concentrations between 1 and 560 μg/L in a few wells in Hampden, Worcester, and Middlesex Counties. The median arsenic concentration in 33 samples was 11.5 μg/L. The primary drinking-water standard for arsenic is 50 μg/L. Local variations of bedrock mineralogy affect ground-water quality, particularly where carbonate lenses and sulfide-bearing zones occur in the bedrock of Middlesex County. Radon concentrations larger than 10,000 picocuries per liter have been detected in water from crystalline-bedrock aquifers elsewhere in New England, New York, and Pennsylvania, and in the Triassic sediments of Connecticut and New Jersey. The gas is likely to be present in similar concentrations in some locations in Massachusetts.

EFFECTS OF LAND USE ON WATER QUALITY

Most of Massachusetts' population and water-quality problems are located in the eastern one-third of the State (figs. 1 and 3). Water quality has been degraded mainly because of the effects of waste disposal, urbanization, and agriculture. Slightly more than 100 of about 1,400 public-supply wells or well fields have been closed since 1960 because of contamination (fig. 3*B*). The total pumping capacity of these closed wells was 54 Mgal/d (million gallons per day), about 7 percent of the State's 765 million gallon average daily demand. Nearly all of the contaminated public-supply wells were identified through programs of periodic water-quality analyses and special organics testing to protect public health by the MDEQE. About 1,400 public-supply wells constitute an extensive ground-water-quality monitoring network in Massachusetts. Sampling consists of frequent bacterial tests, annual analyses for common inorganic constituents and properties, and for metals and organic compounds testing on a 3-year cycle at a minimum.

Waste Disposal

Hazardous waste, which is treated, stored, or disposed of at 31 sites identified under RCRA constitutes a known or possible potential hazard to the quality of ground water (fig. 3*A*). The Massachusetts Division of Solid and Hazardous Waste has determined that some contamination of ground water has been detected at 19 of these sites. Sixteen sites have been included and 5 additional sites have been proposed for inclusion on the U.S. Environmental Protection Agency's NPL under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Contaminants have been detected in ground water at 16 of the CERCLA sites. Many of the hazardous materials sites are located in populous eastern Massachusetts (fig. 3*A*).

As of September 1985, 37 hazardous-waste sites at 6 facilities in Massachusetts had been identified by the U.S. Department of Defense as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Five sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Organic compounds from industrial waste, mostly solvents, are the major ground-water contaminants in the State—56 public-supply wells have been closed because of contamination with organics. A few wells have been reopened, but require treatment of the water by both air stripping and activated-carbon filtration. Waste lagoons, pits, landfills, transfer stations, improper storage, and illegal discharge are the major avenues of contamination for extremely mobile and persistent organic compounds. Organic wastes are commonly associated with chemical and electronic industries, machine and electroplating works, aircraft engine cleaning, tank-truck and drum washing, and leaking sewer lines. Many of the public-supply wells contaminated with organic compounds are in or near industrial parks. The most common contaminants are trichloroethylene, methyl chloride, and tetrachloroethylene, but additional compounds that have also been identified include 1,1 dichloroethylene, 1,2 dichloroethylene, 1,1 dichlorethane, 1,1,1 trichloroethylene, methyl ethyl ketone, methyl isobutyl ketone, trichlorofluoromethane, dioxane, carbon tetrachloride, chloroform, acetone, benzene, toluene, and phenols.

Disposal of domestic sewage in the ground has been favored by sanitary engineers and regulatory agencies. Land disposal through septic systems and municipal facilities is still the method of choice on the State's two sole-source aquifers, Cape Cod and Nantucket, partly as a consequence of the State's Ocean Sanctuaries Act which prohibits new discharges of wastewater to the ocean. Municipal wastewater recharges the ground through seepage lagoons at several sewage-treatment facilities. About one-third of the State's housing is serviced by septic systems that discharge underground. Numerous private wells and some public-supply wells have been contaminated by wastewater containing nitrates or organics or both. One public-supply well, located 7,500 feet downgradient from sewage-treatment plant lagoons, has been contaminated with organics and showed increased concentrations of nitrate, detergents, boron, and dissolved solids (LeBlanc, 1984, p. 11–22; Thurman and others, 1984 p. 58–63).

The Massachusetts Division of Water Supply estimates that there are 241 active and 243 closed municipal landfills in Massachusetts (fig. 3*C*). At least six public-supply well fields and an uncounted number of private wells have been closed as a result of contamination attributed to landfills. Leachates from landfills commonly cause ground water to contain large concentrations of iron, dissolved solids, and nitrogen (as ammonia or nitrate), but most well closures have resulted from contamination by organics. Inappropriate disposal of waste organics and septic-system degreasing solvents in landfills are the sources of these persistent contaminants. Since 1971, capping of landfills with a relatively impermeable material has been part of the closure requirements. The MDEQE now requires ground-water protection systems, such as liners, leachate-collection systems, and ground-water quality monitoring, for all new landfills and all expansions of landfills.

Urbanization

Twenty of about 1,400 public-supply wells in Massachusetts have been closed in response to unsatisfactory water-quality conditions that can be attributed to the effects of urbanization. The causes of closures may be divided into three major groups—road salt, oils and fuels, and sewage.

Road salt stored and applied to roads for ice and snow control has contaminated nine public wells and an uncounted number of private wells. Three public-supply wells in Weston (Middlesex County) have been closed because of contamination by road salt. Two of these wells were located in the stratified-drift aquifer near a major superhighway intersection including two large toll plazas where "bare pavement" is a highway maintenance policy. In Yarmouth on Cape Cod, a public-supply well in the stratified-drift aquifer was closed because of large concentrations of salt that had been leached by rain from an uncovered salt-storage pile. A scavenger well pumped to remove salt from the site was estimated to have removed 835 tons of salt during 29 months (Frimpter and Gay, 1979, p. 7) . In 1967 the Massachusetts Department of Public Works (MDPW) began covering all of it's stored salt to prevent leaching. Also, in 1978 the Department began providing financial assistance to towns and municipalities for the purpose of covering salt stockpiles. By February of 1987, the MDPW built, or provided financial assistance for building, 395 salt-storage sheds. The salt to sand mixture ratios have been decreased on selected highways, experiments with calcium magnesium acetate as an alternative deicing chemical have begun, and evaluation of pavements which contain encapsulated calcium chloride or rubber particles is planned.

Private wells along highways also are susceptible to road-salt contamination, particularly where more than average amounts of salt are applied at dangerous intersections. For example, near an intersection on a hill in rural Pelham (Hampshire County), a private domestic-supply well was drilled to a depth of 121 feet deep into the crystalline-bedrock aquifer to replace a 25-foot deep well in till that had become contaminated with salt. Soon, that well became contaminated and a new 740-foot deep well was drilled, but that too became contaminated with salt and the property was abandoned as a homesite and the house was removed. Drilling deeper to avoid road-salt contamination has not been a dependable solution in Massachusetts.

Private and public wells have been contaminated by fuel oil or gasoline in several widely scattered locations. A public-supply well field in the stratified-drift aquifer in Truro, which serves Provincetown on Cape Cod, was closed because of a gasoline leak from a nearby underground storage tank. This closing required the development of a temporary emergency-supply well and created increased demands on other well fields where withdrawals must be limited to prevent saltwater intrusion. Domestic wells have also been affected by fuel leaks and spills. For example, 68 domestic wells, more than 95 percent of which are in the crystalline-rock aquifer in Walpole and Dover (both in Norfolk County), were affected by a gasoline leak from an underground storage tank. The leak was stopped and the immediate water-quality problem was solved when the oil company, on it's own initiative, provided public water to the homes.

The MDEQE has established a 400-foot radius for sanitary protection about a public-supply well which successfully protects against biological contamination. Degradation of private and public supplies by sewage from leaking sewers, cesspools, and septic systems occurs mainly in the form of large nitrate levels and organic compounds. Of 5,118 chemical analyses of private-supply wells in Barnstable County from 1979 to 1986, 130 wells had nitrate (as nitrogen) concentrations that equaled or exceeded the primary drinking standard of 10 mg/L (U.S. Environmental Protection Agency, 1986a), and 294 had from 5 to 10 mg/L nitrate (as nitrogen). Most of these occurrences are most easily explained as caused by septic systems and lawn fertilizers. Increasing levels of nitrate have been observed in some public-supply wells and attributed to urban congestion and domestic wastewater (Frimpter and Gay, 1979, p. 9–10), but this condition has not been identified as a cause of recent public-supply well closures.

Agricultural Practices

Agricultural pesticides have been detected in ground-water supplies in the farming areas of the Connecticut River valley in central Massachusetts. Public-supply wells in Southwick (Hampton County) and Deerfield (Franklin County) have been closed because of contamination by ethylene dibromide, which was used as a soil fumigant in the growing of tobacco. The four closed wells in Southwick represent two-thirds of the West Springfield water supply, which serves 27,000 people. The closed well in Deerfield was a standby well and not used, but water from 52 private wells in the Connecticut River valley has been identified as exceeding the standards for a number of pesticides including ethylene dibromide, 1-2 dichloropropane, aldicarb, alachlor, carbofuran, and dinoseb. Also, in southern Bristol County, where potatoes are grown, eight private wells contained aldicarb and one other well contained alachlor at levels exceeding the standards. Of the 556 suspect wells tested by the MEDQE, 28 percent contained detectable amounts of pesticides and 11 percent exceeded the drinking-water standards. Although an actual count is not available, most of the affected wells draw water from shallow water-table aquifers in unconsolidated glacial drift.

POTENTIAL FOR WATER-QUALITY CHANGES

For public water supplies, there are generally no deeper aquifers that can be used as alternatives to the unconfined and shallow unconsolidated stratified-drift aquifers. A 1-Mgal/d public-supply well may draw water from a recharge zone as large as 1 square mile around the wellhead. These zones, where water table is commonly less than 25 feet below land surface, are extremely susceptible to contamination (figs. 2*A*,*B*).

Because the small aquifers are recharged within a short time (Knott and Olimpio, 1986, p. 15–24), they are able to sustain the large withdrawals necessary for public supplies. These conditions also allow relatively rapid flow of contaminants, making restoration a more rapid process (tens of years) than is typical (centuries) in many of the aquifers in the rest of the Nation (James, 1986, p. 4–6).

Because of continued urbanization and land disposal of wastes (fig. 3*C*), water demand will continue to increase and ground-water quality may be expected to be further degraded. As a result, there may be continued demand for longer and larger water diversions to the urbanizing areas, and ground-water-treatment plants may become common, rather than exceptional. State and local governments, as part of the management of ground-water quality, are now designating zones of degraded water to increase identification and protection of supply.

GROUND-WATER-QUALITY MANAGEMENT

In 1983, the MDEQE adopted a ground-water protection strategy, "to protect the quality and quantity of groundwaters to the levels necessary for projected future use." The MDEQE has developed, and is continuing to develop, a program to prevent ground water from being degraded to a quality less than its intended use, and to manage known or suspected contamination. The responsibility for assuring the protection of ground-water quality is shared between local government and the State. Towns and cities have primary responsibility for ground-water quality because they are the only government entities with authority to control land use. The State has regulatory control of all public water supplies, sanitary landfills, hazardous waste, underground storage tanks, industrial wastewater discharges of any size, and sanitary wastewater discharge facilities of 15,000 gallons per day or more. Local government has control of land use, of sanitary wastewater disposal of as much as 15,000 gallons per day, and of private wells. The State Fire Marshall regulates underground storage tanks and the regulations are enforced by local Fire Chiefs.

State regulatory guidance is provided through public water-supply regulations, sanitary-landfill regulations, hazardous-waste-management regulations, land application of sludge regulations, wetlands regulations, onsite and municipal wastewater treatment regulations, and ground-water discharge permitting and classification (S. Roy and D. Terry, Massachusetts Division of Water Supply, written commun., 1986). All discharges to the ground water of the State must meet Massachusetts drinking-water standards and health advisories established by the EPA, except discharges to ground water specifically identified and permitted to be degraded.

A second major element of the program is technical assistance and information. Publication of handbooks and a newsletter and presentation of numerous educational and information workshops are part of this element. Technical assistance is provided for the implementation of local ground-water protection through a series of 1:25,000-scale map overlays containing geographic information for aquifers, public-water supplies, waste-disposal sites, and surface-water drainage divides. A long-range program of water-resources appraisal and aquifer mapping by the U.S. Geological Survey in cooperation with the Massachusetts Division of Water Resources is now nearly statewide in scope, and results are contained in a series of 24 U.S. Geological Survey Hydrologic Investigations Atlases.

In addition to regulatory guidance and technical assistance, Massachusetts is encouraging local management and protection of water supplies by providing economic assistance. Under Chapter 286 of the Acts of 1982, funds are provided to communities for immediate response to the emergency and remedial cleanup of contaminated public water supplies. This Act also provides funds to communities for the delineation of zones of contribution (that part of an aquifer which contributes water to a public supply well) and the purchase of land, development rights, or easements necessary to implement long-range protection of ground-water supplies. This economic incentive is a step that encourages towns and cities to develop measures to help ensure adequate supplies of good-quality ground water for their future and for the future of the State.

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Multilevel observation wells at US Geological Survey study site, Cape Cod, Massachusetts. Research on contaminant transport and dispersion in an aquifer is being conducted using this array of 640 observation wells. Water samples can be obtained from 15 different depths in each of the wells. (Photograph by Denis R. LeBlanc, U.S. Geological Survey.)

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MICHIGAN
Ground-Water Quality

Ground water is the source of 17 percent of public-water supplies and almost 100 percent of the rural-domestic water supplies in Michigan (Bedell, 1982) (fig. 1.) About 43 percent of Michigan's residents depend on ground-water supplies (U.S. Geological Survey, 1985). Most natural ground water contains dissolved constituents in amounts that do not exceed the U.S. Environmental Protection Agency's national drinking-water standards (1986a,b); at some locations, however, the concentrations of dissolved solids, iron, manganese, and lead equal or exceed the standards (fig. 2). Ground water in the southeastern part of the State tends to have larger concentrations of dissolved solids, hardness, ammonia, barium, sodium, sulfate, and chloride than elsewhere. Statewide, the dissolved-solids concentrations of water are larger in bedrock aquifers than in glacial aquifers (Cummings, 1980). Ground-water quality is affected by waste disposal and spills, agricultural activities, storage and use of road salts, brine disposal, and pumping-induced movement of deeper lying saline waters (Deutsch 1961a,b; 1962; 1963).

The U.S. Environmental Protection Agency (1986c) has identified 56 National Priorities List (NPL) sites that require evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (fig. 3). At 42 sites, disposal of hazardous materials requires ground-water monitoring under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. The U.S. Department of Defense (DOD) has identified 49 sites at 6 federally owned facilities as having potential for contamination. In addition, the Michigan Department of Natural Resources (1986b) has identified more than 1,000 sites with environmental contamination. Ground-water contamination has been detected at 49 of the NPL sites and at more than 700 of the State-identified locations.

WATER QUALITY IN PRINCIPAL AQUIFERS

BACKGROUND WATER QUALITY

In a discussion of Michigan's ground-water resources, the U.S. Geological Survey (1985, p. 255–260) identified three glacial aquifers and five bedrock aquifers that yield significant quantities of water to wells (figs. 2*A*,*B*). Of the glacial aquifers, yields generally are largest from outwash and glaciofluvial deposits, although yields range from 1 to 1,000 gal/min (gallons per minute). Lacustrine sand aquifers typically yield less water (80 to 500 gal/min), and till aquifers (5 to 200 gal/min) still less. Among bedrock aquifers the Saginaw and Marshall Formations in the Lower Peninsula are the most productive; yields commonly range from 100 to 500 gal/min. In the Upper Peninsula, Silurian-Devonian rocks (10 to 300 gal/min), Cambrian-Ordovician rocks (10 to 100 gal/min), and Precambrian sandstone (5 to 50 gal/min) are important sources of water.

In 1974, the Geological Survey Division of the Michigan Department of Natural Resources (MDNR) and the U.S. Geological Survey began a cooperative program to investigate the natural

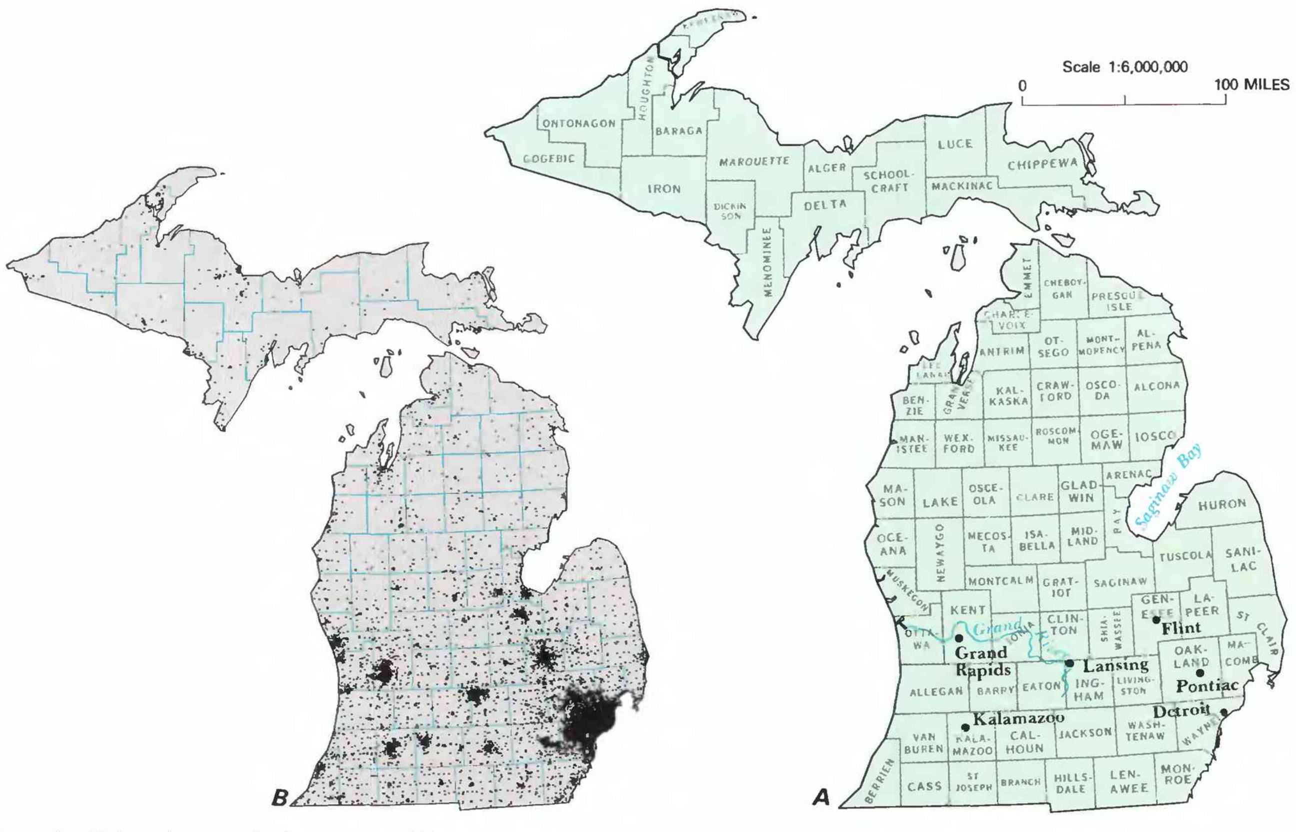

Figure 1. Selected geographic features and 1985 population distribution in Michigan. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

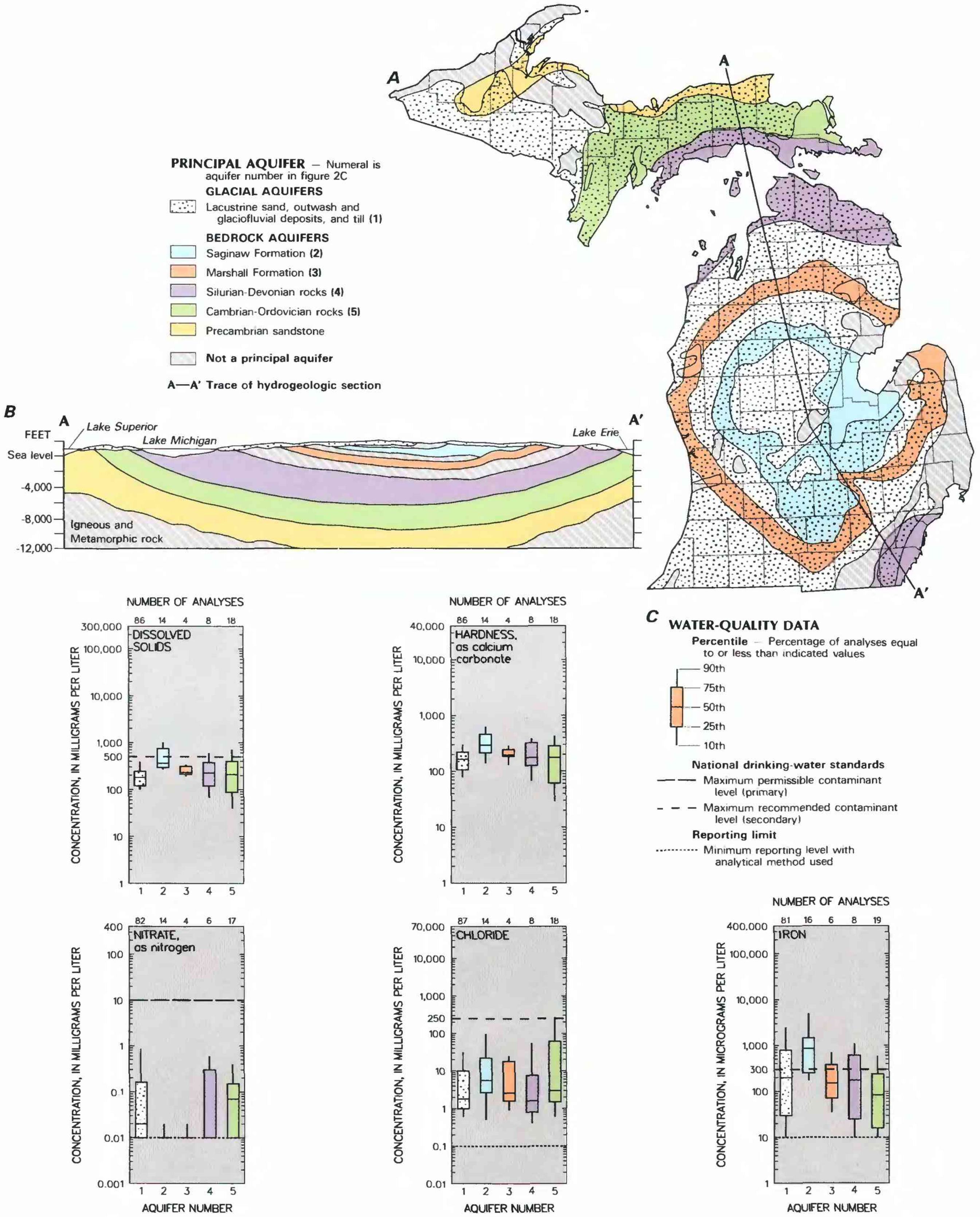

Figure 2. Principal aquifers and related water-quality data in Michigan. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1965-85. (Sources: *A*, Farrand, 1982. *B*, Compiled by N.G. Grannemann from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

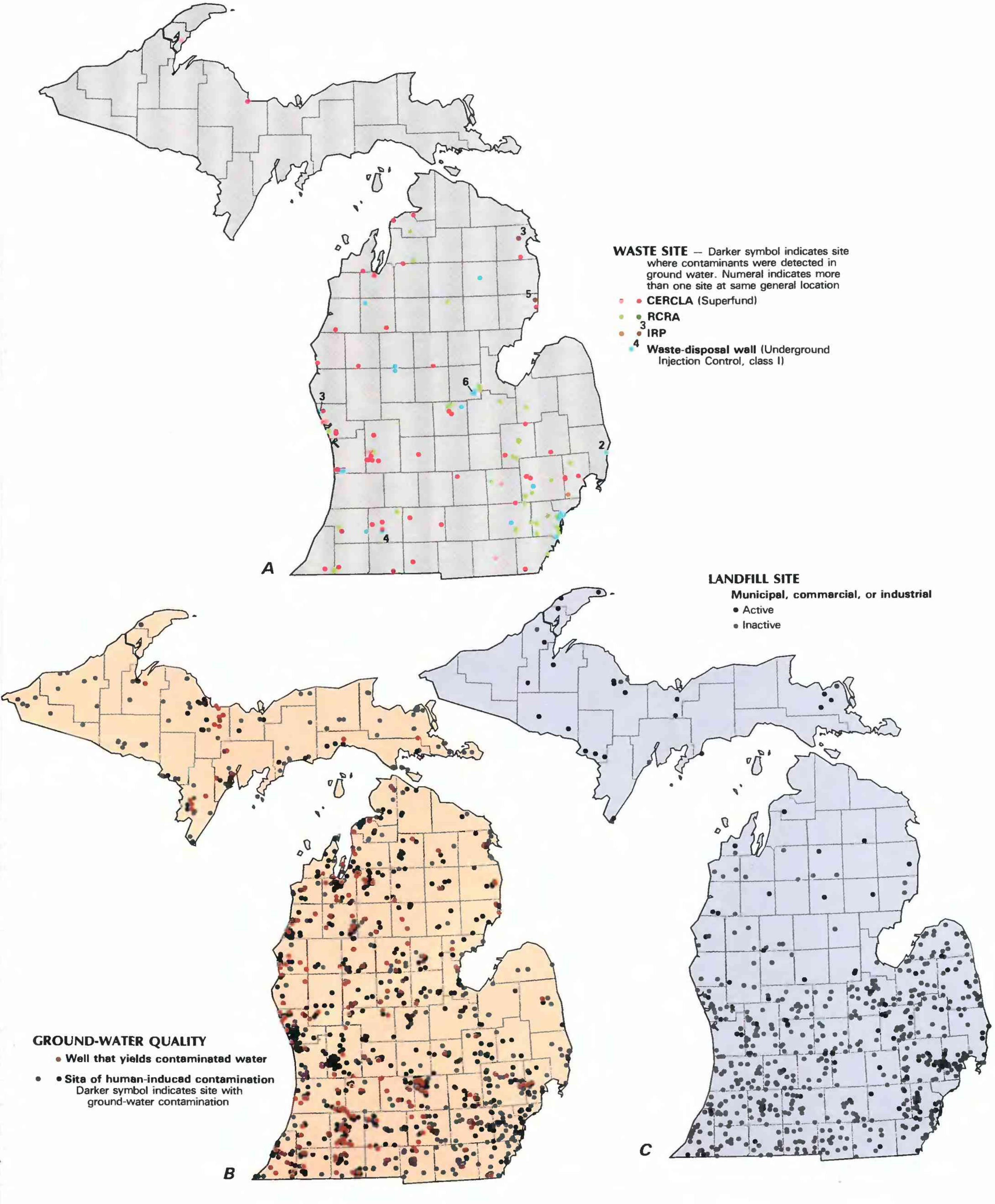

Figure 3. **Selected waste sites and ground-water-quality information in Michigan.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; and Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1985. *B*, Sites of human-induced contamination, and distribution of wells that yield contaminated water as of July 1986. *C*, Municipal, commercial, and industrial landfills, as of July 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Michigan Department of Natural Resources, 1986b; U.S. Department of Defense, 1986. *B*, Michigan Department of Natural Resources, 1986b. *C*, Michigan Department of Natural Resources, 1986a.)

characteristics of water in aquifers in the State. The program is a continuing one in which carefully selected wells are sampled each year. New wells also have been drilled in some of the principal aquifers to monitor both water quality and water levels. Laboratory analyses normally are made for more than 60 naturally occurring substances and properties. In addition, analyses are made for synthetic substances to determine their presence or absence. Frequency data for some of the substances and properties, based on the analyses of 113 samples collected statewide (Cummings, 1980), are given in the following table.

Constituent or property (µg/L, micrograms per liter; mg/L, milligrams per liter; °C, degrees Celcius)	Maximum constituent or property value occuring for the indicated percentile				
	10	25	50	75	90
Aluminum, total recoverable (µg/L as Al)	7	19	31	56	150
Arsenic, total (µg/L as As)	0	0	1	2	5
Barium, total recoverable (µg/L as Ba)	0	0	0	84	127
Cadmium, total recoverable (µg/L as Cd)	0	0	1	2	9
Calcium, dissolved (mg/L as Ca)	20	34	48	64	97
Chloride, dissolved (mg/L as Cl)	.7	1.1	2.2	14	54
Chromium, total recoverable (µg/L as Cr)	2	8	9	10	11
Cobalt, total recoverable (µg/L as Co)	0	0	1	2	5
Copper, total recoverable (µg/L as Cu)	1	2	5	10	20
Cyanide, total (mg/L as CN)	.00	.00	.00	.00	.00
Fluoride, dissolved (mg/L as F)	.0	.0	.1	.3	.6
Germanium, total (µ g/L as Ge)	<2	<3	<4	< 10	<23
Hardness (mg/L as $CaCO_3$)	75	119	17B	244	375
Iron, total recoverable (µg/L as Fe)	51	160	740	2,400	4,300
Lead, total recoverable (µg/L as Pb)	2	5	11	21	78
Manganese, total recoverable (µg/L as Mn)	6.5	9.8	36	120	200
Mercury, total recoverable (µg/L as Hg)	.0	.0	.4	.5	.5
Nickel, total recoverable (µg/L as Ni)	0	2	5	9	16
Nitrogen, Ammonia, total (mg/L as N)	.00	.00	.04	.16	.37
Nitrogen, Nitrate, total (mg/L as N)	.00	.00	.00	.07	.24
pH (units)	7.3	7.5	7.7	7.9	8.1
Phenols (µg/L)	0	0	0	0	2
Phosphorus, total (mg/L as P)	.00	.00	01	.03	.07
Selenium, total (µg/L as Se)	0	0	0	0	0
Silver, total recoverable (µg/L as Ag)	0	0	0	0	1
Sodium, dissolved (mg/L as Na)	1.1	1.9	3.4	12	55
Solids, residue at 180° C, dissolved (mg/L)	106	145	223	360	630
Sulfate, dissolved (mg/L as SO_4)	3.1	6.5	12	35	170
Titanium, total (µg/L as Ti)	1	2	5	14	120
Uranium, dissolved (µg/L as Ur)	.00	.03	.11	.24	.46
Zinc, total recoverable (µg/L as Zn)	6	13	65	240	710

The table indicates how often values of a given magnitude may be expected in natural waters of Michigan. For example, 10 percent of the chloride concentrations are equal to or less than 0.7 mg/L (milligrams per liter); 90 percent of the concentrations are equal to or less than 54 mg/L.

Concentrations of most substances are within the range common for ground water, with the exception of the concentrations of iron, aluminum, and titanium. Maximum concentrations of these substances were: iron, 29,000 µg/L (micrograms per liter); aluminum, 44,000 µg/L; and titanium, 3,600 µg/L.

National standards that specify the maximum concentration or level of a contaminant in a drinking-water supply have been established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. A comparison of the frequency data for natural water quality to these national drinking-water standards indicates that most substances and properties do not exceed the standards. However, there are exceptions. For example, 15 percent of the dissolved-solids concentrations equaled or exceeded the standard. Similarly, 44 percent of the iron concentrations, 30 percent of the manganese concentrations, and 13 percent of the lead concentrations did also.

Geologic conditions are a principal factor determining the areal variation in the natural quality of ground water throughout the State, although differences can also be due to hydrologic conditions. Data are inadequate, however, to establish the chemical characteristics of water in each glacial and bedrock aquifer or to permit conclusions regarding differences in quality. In general, chemical characteristics seem to be related more to mineralization than to a specific aquifer; however, areal variations in the concentrations of some substances are evident.

Some of the chemical characteristics of water of each aquifer are shown in figure 2*C*, which is a statistical summary of concentrations of dissolved solids, hardness, nitrate, chloride, and iron. The summary is based on selected chemical data available in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Water of the Saginaw Formation has larger concentrations of dissolved solids, iron, and hardness than water from glacial deposits or other bedrock aquifers. This condition may be attributed to the fact that the Saginaw Formation contains considerable shale and coal and, at places, may contain saline water. A comparison of water from glacial deposits with that in bedrock aquifers by Cummings (1980) indicated that the mean dissolved-solids concentration of water from bedrock aquifers was 535 mg/L, whereas the mean dissolved-solids concentration of water from glacial deposits was 241 mg/L.

Analyses of data (Cummings, 1980) indicated that water-quality characteristics—such as iron, dissolved solids, lead, hardness, barium, and ammonia—exhibited distinguishable areal variations. For example, the variation in total recoverable iron concentrations statewide is shown in figure 4. In general, ground water has a larger iron concentration in the southeastern part of the Lower Peninsula and in the western and eastern parts of the Upper Peninsula than in other parts of the State. For other constituents, with the exception of lead, concentrations generally are larger in the southeastern part of the State. Many wells in this area obtain water from bedrock, which normally contains water that is more extensively mineralized. In addition to the characteristics cited, sodium, sulfate, and chloride concentrations also tend to be larger in the southeastern part of the State than elsewhere.

Statewide, waters having a small dissolved-solids concentration generally are calcium bicarbonate waters; that is, the calcium constitutes more than 50 percent of the cations and bicarbonate constitutes more than 50 percent of the anions if concentrations are converted to milliequivalents per liter. As the dissolved-solids concentration of a typical water increases, the proportion of sodium, sulfate, and chloride increases. Sulfate increases most rapidly when dissolved solids increase and that increase is accompanied by a proportional decrease in bicarbonate. A decrease in calcium is balanced by a corresponding increase in sodium. Magnesium does not change appreciably. In general, the concentrations of major dissolved substances increase as dissolved-solids concentration increases. Concentrations of most trace substances, however, seem to be unrelated to the dissolved-solids concentration of the water.

EFFECTS OF LAND USE ON WATER QUALITY

The chemical characteristics of ground water in Michigan are modified chiefly by industrial and municipal waste-disposal activities or accidental spills of hazardous materials, agricultural activities, use and storage of road salts, pumping-induced movement of deeper lying saltwaters into shallow freshwater aquifers, and improper handling of brines produced during oil drilling. Early studies by Deutsch (1961a,b; 1962; 1963) documented several instances of ground-water contamination in Michigan.

Waste Disposal and Spills

Fifty-six (CERCLA) sites (fig. 3*A*) have been identified and included on the NPL in Michigan by the U.S. Environmental Protection Agency (1986c). Ground-water contamination has been detected at 49 of these sites. An additional six sites are proposed for inclusion on the NPL. Hazardous wastes are disposed in 42 RCRA sites (fig. 3*A*), most of which are located in the southeastern part of the Lower Peninsula. Ground water near older RCRA sites may be contaminated.

As of September 1985, 49 hazardous-waste sites at 6 federal facilities in Michigan have been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under the CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 49 sites evaluated under the program, 9 contained contaminants but did not present a hazard to people or the environment. Nine sites at 3 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA.

The MDNR has identified more than 1,000 sites where air, soil, or water has been contaminated (fig. 3*B*) (Michigan Department of Natural Resources, 1986b). Many of the sites are located near major cities such as Detroit, Grand Rapids, Kalamazoo, Lansing, and Pontiac. Ground-water contamination has been detected at 739 sites; the principal causes of the contamination (Michigan Department of Natural Resources, 1986b) are identified:

Cause of ground-water contamination	Percentage of contamination (739 sites)
Petroleum-related	26
Landfills	15
Metal plating and production	9
Chemical production—manufacturing	7
Salt storage	3
Agricultural and food-related	3
Laundromats	2
Hazardous-waste handling	1
Unknown	24
Other (miscellaneous industrial products)	10

Causes identified as petroleum related include, but are not limited to, brines, gasoline, and fuel-oil contamination. Metal plating wastes include trace metals such as copper, chromium, nickel, mercury, and arsenic. The other wastes consist of a wide variety of contaminants including trace metals, organics, nitrates, phenols, paints, polychlorinated biphenols (PCB's), polybrominated biphenols (PBB's), oils, and solvents. Sources of contaminants (Michigan Department of Natural Resources, 1986b) are:

Source of ground-water contamination	Percentage of contamination (739 sites)
Underground tanks	17
Landfills	16
Lagoons	14
Surface discharges	11
Above-ground tanks	6
Barrels	5
Unknown	27
Other (containers, movement of water from deep geologic formations, piles, pipelines, and pits)	4

In addition to the 1,000 sites where air, soil, or water has been contaminated, the MDNR has also identified more than 600 municipal, commercial, and industrial landfills (fig. 3*C*), most of which are located in the more populated Lower Peninsula. Some of these landfills may also be State-identified contamination sites. Only 95 landfills currently are active. There also are 133 demolition debris landfills, some of which may contain hazardous wastes (Michigan Department of Natural Resources, 1986a).

Agricultural Practices

Studies of the effect of agricultural activities on ground-water resources in Michigan have largely described the fate of applied fertilizers and the increase in nitrate concentrations in shallow aquifers. Unpublished data in State and county files have indicated that concentrations of nitrate exceeding the U.S. Environmental Protection Agency (1986a) primary drinking-water standard occur at sites throughout the State, although most commonly in areas of intensive agriculture. Cummings and others (1984), in a study of Van Buren County, concluded that nitrate concentrations of ground water were related to the amount of fertilizer applied but that equally important was the amount of irrigation water used. About 22 percent of the wells sampled in the southern part of the county yielded water having a nitrate concentration exceeding the primary standard of 10 mg/L as nitrogen. Rajagopal (1978), in a study of nitrate concentrations in ground water of Grand Traverse County in the northern part of Michigan's Lower Peninsula, found an average nitrate concentration of 18 mg/L in an area of intensely fertilized cherry orchards. He concluded that permeable soil, along with years of fertilizer application, were principal reasons for the large concentrations detected. D'Itri and others (1985), using nitrate data from the Michigan Department of Public Health (MDPH), studied concentration trends in ground water in the Lower Peninsula. Three periods (1933–70, 1971–74, and 1975–84) were separately considered. Average concentrations during 1975–84 exceeded those of earlier periods; large concentrations were evident in the west-central, southwestern, northwestern, and northeastern parts of the Lower Peninsula.

Salt Storage and Use

Among States spreading rock salt (sodium chloride) for road deicing, Michigan ranks in the top five in quantity used (VanderMeulen, 1984). Storage of rock salt has caused ground-water contamination, particularly when it has been stored unprotected from rain and without runoff controls. The Michigan Department of Natural Resources (1986b) has identified 29 salt-storage facilities that have caused ground-water contamination, or about 3 percent of the known sites in the State (fig. 3*B*). In one instance, the contamination plume was 350 feet wide and about 3,000 feet long and was moving at a rate of 350 to 400 feet per year (Curry, 1972). The maximum chloride concentration in ground water at the site was 2,800 mg/L; water from at least 8 wells had chloride concentrations exceeding the standard of 250 mg/L for drinking water.

In Michigan, only a few studies link highway salt applications to ground-water contamination. One Michigan Department of Transportation (MDOT) study found chloride levels in ground water increasing, then stabilizing, adjacent to deiced highways. The stabilized chloride concentrations rarely exceeded 250 mg/L (D. Malotte, Michigan Department of Transportation, oral commun., 1986).

Water Withdrawal

Bedrock formations underlying glacial deposits in Michigan commonly contain very mineralized water. U.S. Geological Survey data indicate that near Lakes Erie, St. Clair, and Huron, and near Saginaw Bay, saline water lies at an average depth below land surface of about 200 feet. At a few locations near Saginaw Bay, very mineralized water has been detected near the land surface. Twenter and Cummings (1985) found the water of one well to have a dissolved-solids concentration larger than 80,000 mg/L; depth to water below land surface was only 29 feet. In smaller areas in southwestern Michigan, saline water is also within 200 feet of land surface. In the northwestern part of the Lower Peninsula, however, the depth to saline water is as much as 900 feet. In much of the Upper Peninsula, the depth to saline water is about 400 feet.

Extremely mineralized water has been induced into freshwater aquifers in several areas by excessive pumping. When pumping decreases the hydraulic head in the freshwater aquifer, saline water may migrate toward the well. In the Flint area, upward migration of saline water increased the chloride concentration of water from a well by 300 percent, requiring abandonment of the Saginaw Formation as a water source (Deutsch, 1963). Intensive pumping near the city of Pontiac caused water in the Coldwater Shale, which contained a large sulfate concentration, to migrate into the glacial drift aquifer. Changing the pumping pattern decreased the sulfate concentrations.

Saline water has also migrated through unplugged wells or leaky casings when pumping was intensive. In 1956, the city of Lansing drilled a water-supply well into the Saginaw Formation. After 2 months of pumping, the chloride concentration of the water had increased from less than 100 mg/L to about 900 mg/L. The source of the chloride was a brine well drilled in 1867 which had been abandoned and buried. (The brine well had produced water containing more than 4,500 mg/L of chloride.) After plugging the brine well, the chloride concentration of water in the aquifer began to decrease (Deutsch, 1963).

Oil and gas test wells are drilled through bedrock formations that commonly contain brines. Brines have been disposed by injection into rock formations, by surface impoundment, or by spreading on unpaved roads. Surface disposal of brines has resulted in ground-water contamination, and old unplugged abandoned wells have provided avenues of migration. Although the plugging of wells is now regulated (Michigan Department of Public Health, 1984), corrosion of casings may still allow leakage.

POTENTIAL FOR WATER-QUALITY CHANGES

Development of ground-water protection strategies by State and local units of government, as well as closer monitoring of the use, storage, and disposal of hazardous materials, probably will decrease the potential for contamination of freshwater aquifers in the future. Inevitably, accidental spills will continue, but prompt reporting and remedial response will eliminate some of the problems of the past. The potential for contamination of aquifers will remain greatest in those areas where sandy, permeable materials form unconfined surficial glacial deposits. Unconfined aquifers in the northern and western parts of the Lower Peninsula and in the eastern half of the Upper Peninsula, where outwash and glaciofluvial deposits are the principal surficial deposits, are most susceptible to contamination from surface sources. Similar deposits of smaller areal extent occur along the Lake Huron shoreline as well as in southeastern and south-central Michigan. About one-half of the State's aquifers are susceptible to contamination because fine-grained till or glaciolacustrine clay, which tends to restrict downward movement of contaminants, is absent. In these areas, contaminants can percolate directly to the water table. In addition, the unconfined aquifers commonly consist of coarse-grained deposits in which the relatively rapid rate of water movement contributes to the spread of any contaminant that reaches the water table.

Excessive pumping of public water-supply and irrigation wells, primarily in the southern part of the Lower Peninsula, could cause saline water to migrate upward, contaminating freshwater supplies. Where natural fractures or improperly plugged old wells exist, upward movement could be accelerated. In counties surrounding Saginaw Bay, upward migration of saline water could develop without drastic changes in current withdrawals because saline water occurs at shallow depths.

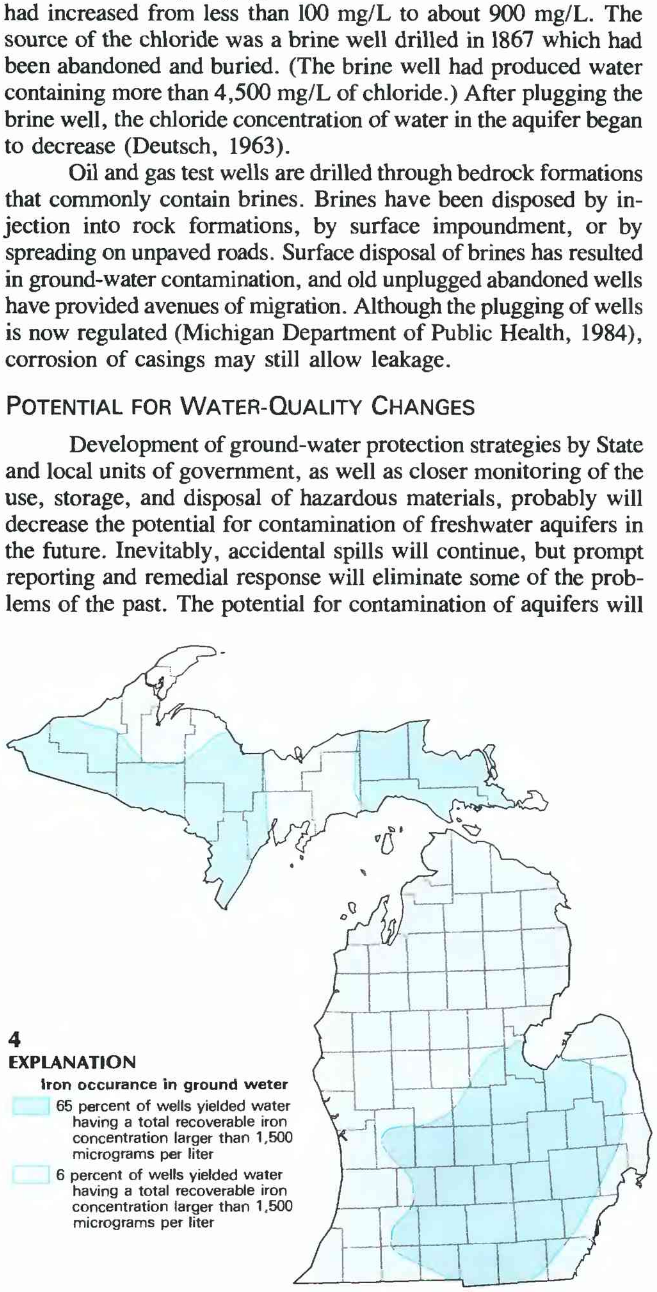

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Figure 4. Areal predominance of total recoverable iron in ground water in Michigan. (Source: Cummings, 1980.)

GROUND-WATER-QUALITY MANAGEMENT

Recognizing existing and potential problems, Governor Blanchard, in his 1984 State of the State message, identified protection of the State's drinking-water supply as a priority activity and directed his Cabinet Council on Environmental Protection to develop a State policy on ground water and an initiative for implementing that policy. This initiative advanced ground-water management by supplementing cleanup efforts with an enhanced prevention program. It proposes ground-water management goals, a policy aimed at achieving those goals, and a specific strategy that identifies areas where legal authority or programs can be improved. The keys to this policy are:

- Controlling surface and underground storage of chemicals;
- Isolating high-risk activities from underground sources of drinking water;
- Working intensively with individual small businesses, local governments, and their associations to provide information on proper storage and handling of potentially polluting materials;
- Educating the public; and
- Developing comprehensive data on the quality, quantity, and movement of ground water.

Authority for the State's ground-water-quality program is derived from several State laws. State legislation includes the Water Resources Commission Act (Act 245, P.A. 1929), the Solid Waste Management Act (Act 641, P.A. 1978), the Hazardous Waste Management Act (Act 64, P.A. 1979), the Environmental Response Act (Act 307, P.A. 1982), and Servicing of Septic Tanks, Seepage Pits, or Cesspools Act (Act 243, P.A. 1951). These Acts are administered primarily by the MDNR.

Some ground-water-management activities are conducted as part of the Public Water Supply Program under the regulations of the Federal Safe Drinking Water Act (Public Law 93–523) and the State Safe Drinking Water Act (Act 399, P.A. 1976). The MDPH, under the authority of Act 399, has been granted primary enforcement responsibility by the EPA for the implementation of the Federal Safe Drinking Water Act.

The MDNR, Environmental Response Division, responds to contamination problems by taking the lead for compliance with ground-water pollution control statutes, implementation of CERCLA, and compliance with the Michigan Environmental Response Act (Act 307, P.A. 1982). The Waste Management Division is also responsible for issuing State ground-water discharge permits under Act 245, P.A. 1929, as amended.

The serious nature of some contamination problems caused the State to focus on cleanups and other remedial actions. Maximum advantage has been taken of CERCLA; in addition, Michigan has created a similar fund, under its own Environmental Response Act (Act 307), to prioritize sites to receive State funding.

Ground-water-quality management practices in the State are governed by several factors:

- A nondegradation policy for proposed ground-water discharges;
- A very heterogeneous hydrogeologic setting; policies and commitments to the protection of aquifers for existing and potential use as drinking-water supplies;
- Protection of public health by limiting, to the extent possible, exposures to critical materials through water supplies; and
- A policy of assuring that insofar as possible those who may be liable for causing ground-water contamination will bear the cost of remedial action.

As a result, decisions regarding activities potentially affecting ground water and the correction of existing ground-water contamination problems usually require the development of substantial on-site ground-water-quality data. Existing data are commonly helpful in designing specific studies but rarely are sufficient for decision making. A statewide ground-water data base system is being developed to improve the use of ground-water-quality data generated throughout the State.

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Geophysical well logging being conducted by U.S. Geological Survey personnel in southeastern Michigan. Information about the thickness, lithology, and properties of the strata penetrated by a well can be obtained using a variety of geophysical well-logging probes. (Photograph by Steve Rheaume, U.S. Geological Survey.)

Prepared by D.H. Dumouchelle and T.R. Cummings, U.S. Geological Survey, and G.R. Klepper, Michigan Department of Natural Resources

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MINNESOTA
Ground-Water Quality

Nearly one-half the population of Minnesota (fig. 1) depends on wells for drinking water. Virtually all the rural population and 94 percent of the public-water systems use ground water. In general, the quality of Minnesota's ground water is satisfactory for most uses, such as for domestic, public, and industrial supplies and for irrigation. Most of the water can be classified, on the basis of predominant ions, as a calcium-magnesium-bicarbonate type with less than 1,000 mg/L (milligrams per liter) dissolved solids (Adolphson and others, 1981). However, naturally occurring saline water (exceeding 1,000 mg/L dissolved solids) is common along the western border, the northern shore of Lake Superior, and below depths of about 1,000 feet in the southeastern part of the State. Statewide concentrations of iron and manganese commonly exceed 300 μg/L (micrograms per liter) and 50 μg/L, respectively, which are the maximum recommended concentrations for these constituents in drinking water (U.S. Environmental Protection Agency, 1986b). Concentrations of sulfate in water from Cretaceous rocks and overlying glacial drift in southwestern Minnesota commonly exceed the U.S. Environmental Protection Agency's (EPA) secondary drinking-water standard of 250 mg/L (fig. 2).

Ground-water quality in Minnesota has been degraded by contamination, with the most serious problems being in local areas. Major sources of contamination in the State, according to the Minnesota Pollution Control Agency (1986a, p. 47), include: (1) spills or improper disposal of industrial or manufacturing chemicals, (2) leachate from solid-waste landfills, (3) spills and leaks from petroleum-product storage areas and pipelines, and (4) feedlots and agricultural chemicals. A total of 132 sites have been identified, as of November 1986, by the Minnesota Pollution Control Agency (MPCA) and the EPA as priority sites for cleanup. Included in these priority sites are 36 hazardous-waste sites on the National Priorities List (NPL), and 6 sites at two U.S. Department of Defense facilities (fig. 3*A*). In addition, two principal aquifers in the State—the surficial-drift aquifers, which underlie much of the State (fig. 2*A*2), and the upper carbonate aquifer, which underlies karst-type terrain in the southeastern part of the State (fig. 2*A*1)—are very susceptible to contamination from land-surface sources, such as spills, leachates from landfills, infiltration of runoff from feedlots, and widespread application of agricultural chemicals.

A survey of 887 community water systems, which included about 1,800 wells, was made by Minnesota Department of Health (MDH) (1985) for the purpose of detecting volatile organic compounds (VOC) in drinking water. The survey showed detectable VOC concentrations in 109 wells (fig. 3*B*). In 15 communities, the concentration of VOC in water from some of the public-supply wells exceeded limits considered acceptable by the MDH. Various actions have been taken by the MDH to ensure safe drinking water for the approximately 100,000 persons in those communities (Minnesota Department of Health, 1985).

WATER QUALITY IN PRINCIPAL AQUIFERS

The 14 principal aquifers in Minnesota (Adolphson and others, 1981) can be grouped by general rock type into unconsolidated glacial drift, sedimentary rocks, and crystalline rocks (fig.

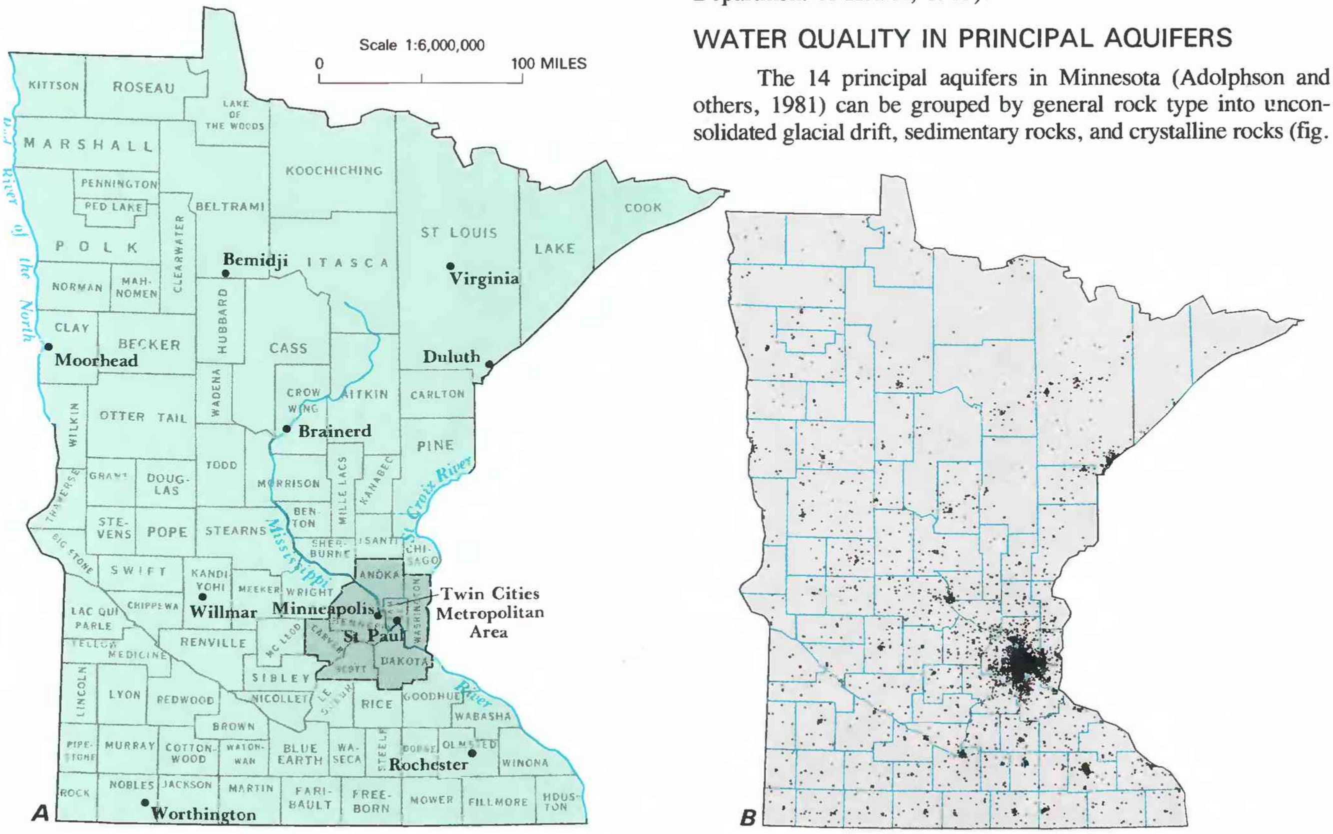

Figure 1. Selected geographic features and 1985 population distribution in Minnesota. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

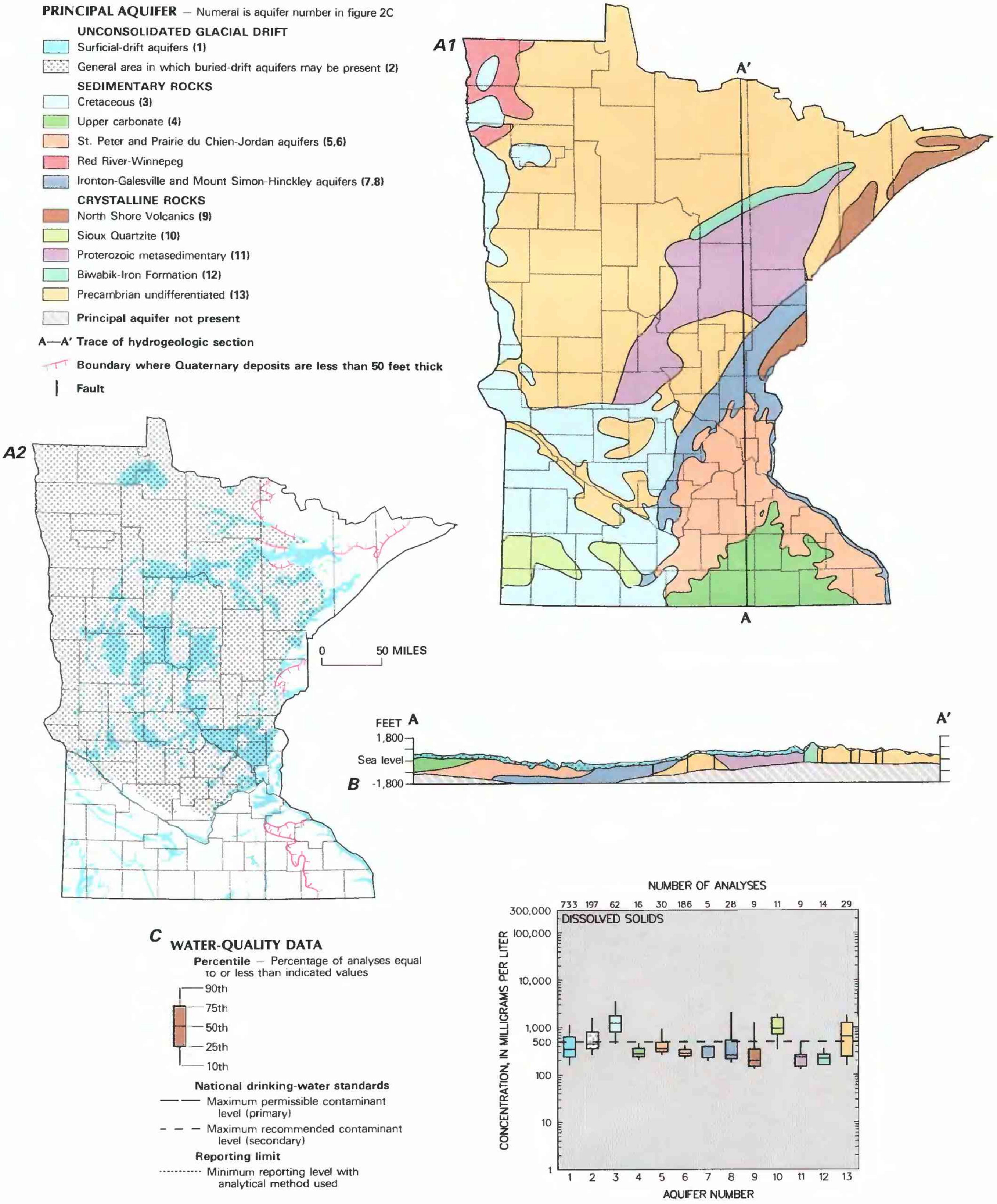

Figure 2. Principal aquifers and related water-quality data in Minnesota. *A1*, Principal aquifers; *A2*, Surficial- and buried-drift aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, from 1965 to 1985. (Sources: *A1*, *A2*, U.S. Geological Survey, 1985. *B*, Kanivetsky, 1978. *C*, Analyses complied from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

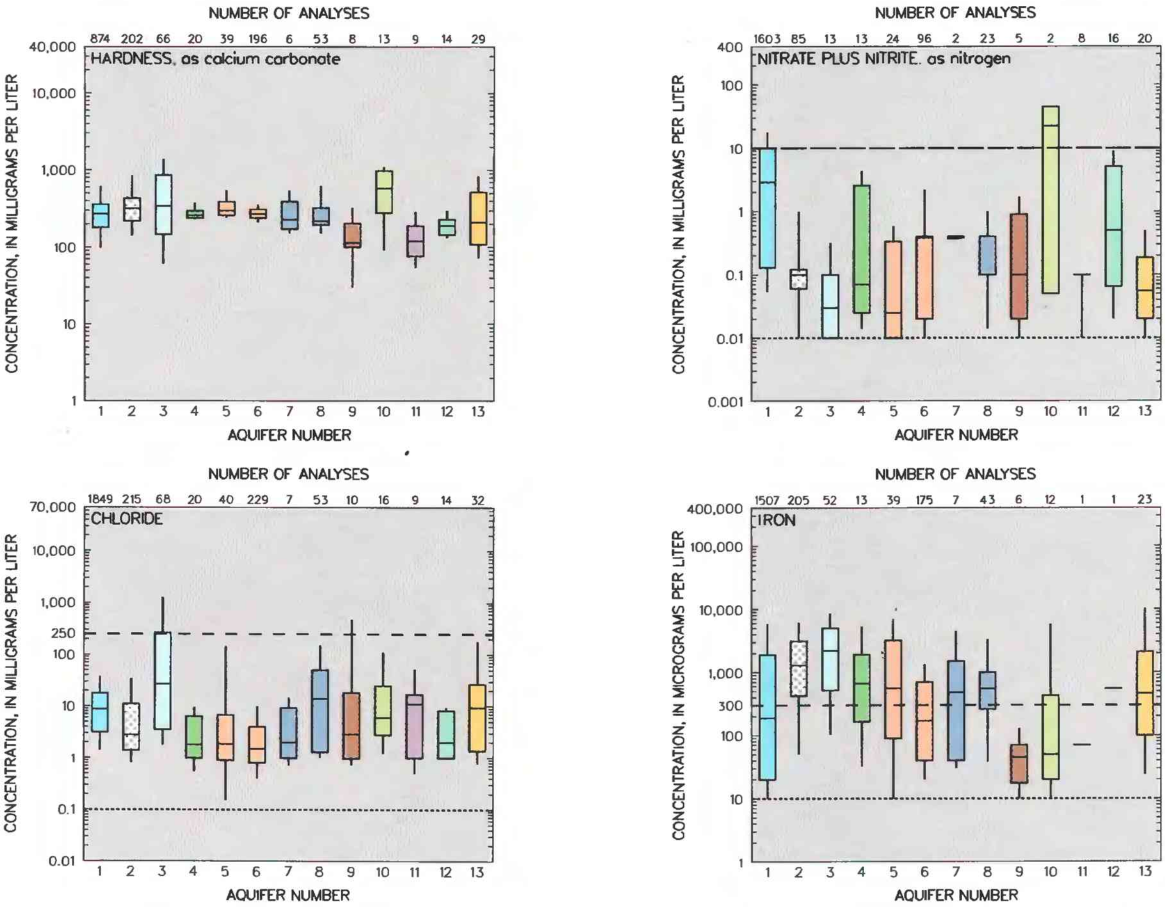

Figure 2. Principal aquifers and related water-quality data in Minnesota—Continued.

2*A*1). Glacial drift overlies much of Minnesota, and many water supplies have been developed from these unconsolidated deposits. Wells completed in outwash sand and gravel (surficial-drift aquifers) commonly yield 500 to 1,500 gal/min (gallons per minute) for irrigation and for public and industrial or commercial supplies. Sedimentary rocks consist mostly of sandstone, dolomite, and some limestone, and support large withdrawals of water for public supply and industrial or commercial use in southeastern Minnesota. Well yields of 500 to 1,000 gal/min are common. Crystalline igneous and metamorphic rocks form the basement complex in Minnesota and generally do not yield large amounts of water to wells. The rocks, however, are important as a source of water for many rural domestic supplies where no other aquifers occur. A summary of aquifer characteristics and ground-water use in Minnesota is given in "National Water Summary 1984" (U.S. Geological Survey, 1985, p. 261–268).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), chloride, and iron analyses of water samples collected from 1965 to 1985 from the principal aquifers in Minnesota. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate plus nitrite (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L iron.

Unconsolidated Glacial Drift

SURFICIAL-DRIFT AQUIFERS

Glacial drift underlies the land surface in most of Minnesota. In the central and western parts of the State, surficial-drift aquifers commonly consist of outwash sand and gravel (fig. 2*A*2 aquifer 1). Many water supplies, including large supplies for irrigation, have been developed in these aquifers. The water generally is a calcium-magnesium-bicarbonate type (Adolphson and others, 1981), but a mixed calcium magnesium bicarbonate sulfate type is present in places along the western border of the State. The quality of water from wells in the surficial-drift aquifers generally is suitable for most uses in relation to drinking-water standards. Dissolved-solids concentrations generally range from about 160 to 1,170 mg/L, with a median concentration of about 350 mg/L.

BURIED-DRIFT AQUIFERS

Buried-drift aquifers (fig. 2*A*2, aquifer 2) are present in glacial-drift deposits throughout most of the State, except in the northeast and southeast where the drift is thin or absent. These aquifers consist mainly of discontinuous layers of sand and gravel separated by till and are present commonly in areas of thick (200 to 600 feet) glacial drift. These "buried" sand and gravel deposits are being increasingly tapped by irrigation and public-supply wells. Water in the buried-drift aquifers generally is confined by till, which impedes the infiltration and downward percolation of contaminants from the land surface.

The water in the buried-drift aquifers generally is a calcium-magnesium-bicarbonate type, but water that contains significant concentrations of sulfate and chloride ions is present in the southwestern and northwestern parts of the State. In northwestern Minnesota, the buried-drift aquifers are underlain by rocks of Ordovician and Cretaceous age. Upward discharge of more mineralized water from the Ordovician and Cretaceous rocks affects the quality of water in the overlying buried-drift aquifers. Dissolved-soilds concentrations in the buried-drift aquifers generally range from about 260 to 1,600 mg/L, with a median concentration of about 450 mg/L.

Sedimentary Rock

CRETACEOUS AQUIFER

The Cretaceous aquifer (fig. 2*A*1, aquifer 3), which is present mainly in southwestern and western Minnesota, consists of shale and sandstone. The aquifer is not usually a water-supply source, except in areas where the surficial-and buried-drift aquifers are thin or absent. Many rural-domestic wells tap the Cretaceous aquifer in southwestern Minnesota, but the aquifer is seldom used for public-water supplies (Adolphson and others, 1981). Water from the Cretaceous aquifer, which generally is more mineralized than water from most other aquifers in Minnesota, commonly contains 450 to 3,600 mg/L dissolved solids. Water quality differs considerably from place to place; significant concentrations of sodium and chloride are present in ground water in northwestern Minnesota, and sodium and sulfate are present in the southwestern part. The widespread presence of large sodium concentrations (100 to 1,000 mg/L) is attributed to ion exchange and to the influx of sodium-bearing water from Cretaceous rocks to the west (Woodward and Anderson, 1986).

UPPER CARBONATE AQUIFER

The upper carbonate aquifer (fig. 2*A*1 , aquifer 4) consists primarily of limestone and dolomite and occurs in southeastern Minnesota. The aquifer yields adequate quantities of water to wells for most public-supply, industrial, and domestic uses. The water generally is a calcium-magnesium-bicarbonate type with a median dissolved-solids concentration of about 280 mg/L. Concentrations of sodium and sulfate increase to the southwest, where the aquifer is in contact with thick glacial drift and, possibly, with Cretaceous rocks (Ruhl and Wolf, 1984).

ST. PETER AQUIFER

The St. Peter aquifer (fig. 2*A*1, aquifer 5) is composed mainly of sandstone; it includes all but the basal silty part of the St. Peter Sandstone and extends throughout most of southeastern Minnesota. The St. Peter aquifer is seldom used for water supplies because larger well yields can be obtained from other aquifers. Water from the St. Peter aquifer generally is a calcium magnesium bicarbonate type that is suitable for most uses (Ruhl and Wolf, 1983). Dissolved-solids concentrations generally range from about 260 to 950 mg/L, with a median concentration of about 360 mg/L (fig. 2*C*).

The St. Peter aquifer is overlain by rocks of Cretaceous age in the southwestern part of its subcrop area. In this area, water from the St. Peter is a calcium sulfate type with a concentration of dissolved solids ranging from about 500 to 900 mg/L. This mineralized water is of limited use for public and industrial supplies (Ruhl and Wolf, 1983).

PRAIRIE DU CHIEN-JORDAN AQUIFER

The Prairie du Chien-Jordan aquifer (fig. 2*A*1, aquifer 6) consists mainly of sandstone (lower part) and dolomite (upper part). The aquifer extends throughout most of southeastern Minnesota and is the principal aquifer in the area. The Prairie du Chien-Jordan aquifer supplies about one-third of all ground water used in the State and 80 percent of the ground water used in the Twin Cities metropolitan area (Horn, 1983). About 54 billion gallons were withdrawn from the aquifer in 1980 in the metropolitan area. The water generally is suitable for most uses; it is a calcium magnesium bicarbonate type with a median dissolved-solids concentration of about 250 mg/L in most of southeastern Minnesota (Ruhl and others, 1983). However, dissolved-solids concentrations in the western part of the aquifer range from about 500 to 1,000 mg/L.

RED RIVER-WINNIPEG AQUIFER

The Red River-Winnipeg aquifer (fig. 2*A*1) consists of dolomitic limestone, mudstone, and sandstone. The aquifer underlies the extreme northwest corner of Minnesota and extends westward into a structural basin in North Dakota. Water from the aquifer is a very mineralized sodium chloride type in which dissolved-solids concentrations range from about 1,100 to 60,000 mg/L. (Selected water-quality constituents and properties are not shown in figure 2*C* because few samples were analyzed.) The only known uses of the water are for livestock and fire fighting (Ruhl and Adolphson, 1986). The naturally occurring saline water in the aquifer discharges upward into overlying alluvial deposits and to the Red River of the North, degrading the quality of both ground and surface water.

IRONTON-GALESVILLE AQUIFER

The Ironton-Galesville aquifer consists of sandstone and underlies southeastern Minnesota (fig. 2*A*1, aquifer 7). In part of the area, the aquifer includes part of the overlying Franconia Formation. Water from the aquifer generally is suitable for most uses; it is a calcium magnesium bicarbonate type, with dissolved-solids concentrations generally less than 400 mg/L. About 7 Mgal/d (million gallons per day) were being withdrawn from the aquifer in the 1970's, mostly for industrial and public supplies (Horn, 1983).

MOUNT SIMON-HINCKLEY AQUIFER

The Mount Simon-Hinckley aquifer (fig. 2*A*1, aquifer 8) consists of sandstone and is the most extensive of the sedimentary-rock aquifers underlying southeastern Minnesota. North of the Twin Cities metropolitan area, the aquifer also includes sandstone of the underlying Fond du Lac Formation (Wolf and others, 1983). Many wells have been completed in the aquifer north of the Twin Cities metropolitan area where it is the shallowest bedrock aquifer and, locally, the only aquifer. Withdrawals from the aquifer averaged about 19 Mgal/d in 1980, mostly for public and industrial supplies. The withdrawals represent about 10 percent of the total ground water used in the Twin Cities metropolitan area (Horn, 1983).

Water from the Mount Simon-Hinckley aquifer generally is suitable for most uses; it is a calcium magnesium bicarbonate type throughout most of the area, and concentrations of dissolved solids generally are less than 500 mg/L (Wolf and others, 1983). In part of southeastern Minnesota, sodium chloride type water is present in the aquifer below depths of about 1,000 feet. In the southwestern part of the area, where the aquifer is overlain by and receives recharge from rocks of Cretaceous age, the water contains significant concentrations of magnesium and sulfate. The aquifer is well protected from surface contamination throughout most of the area by overlying confining beds.

Crystalline Rock

NORTH SHORE VOLCANICS AQUIFER

The North Shore Volcanics aquifer (fig. 2*A*1, aquifer 9) consists of a thick series of basaltic lava flows that are exposed along the north shore of Lake Superior and the upper part of the St. Croix River valley. Water from the aquifer generally is a calcium magnesium bicarbonate type that is used mostly for domestic and

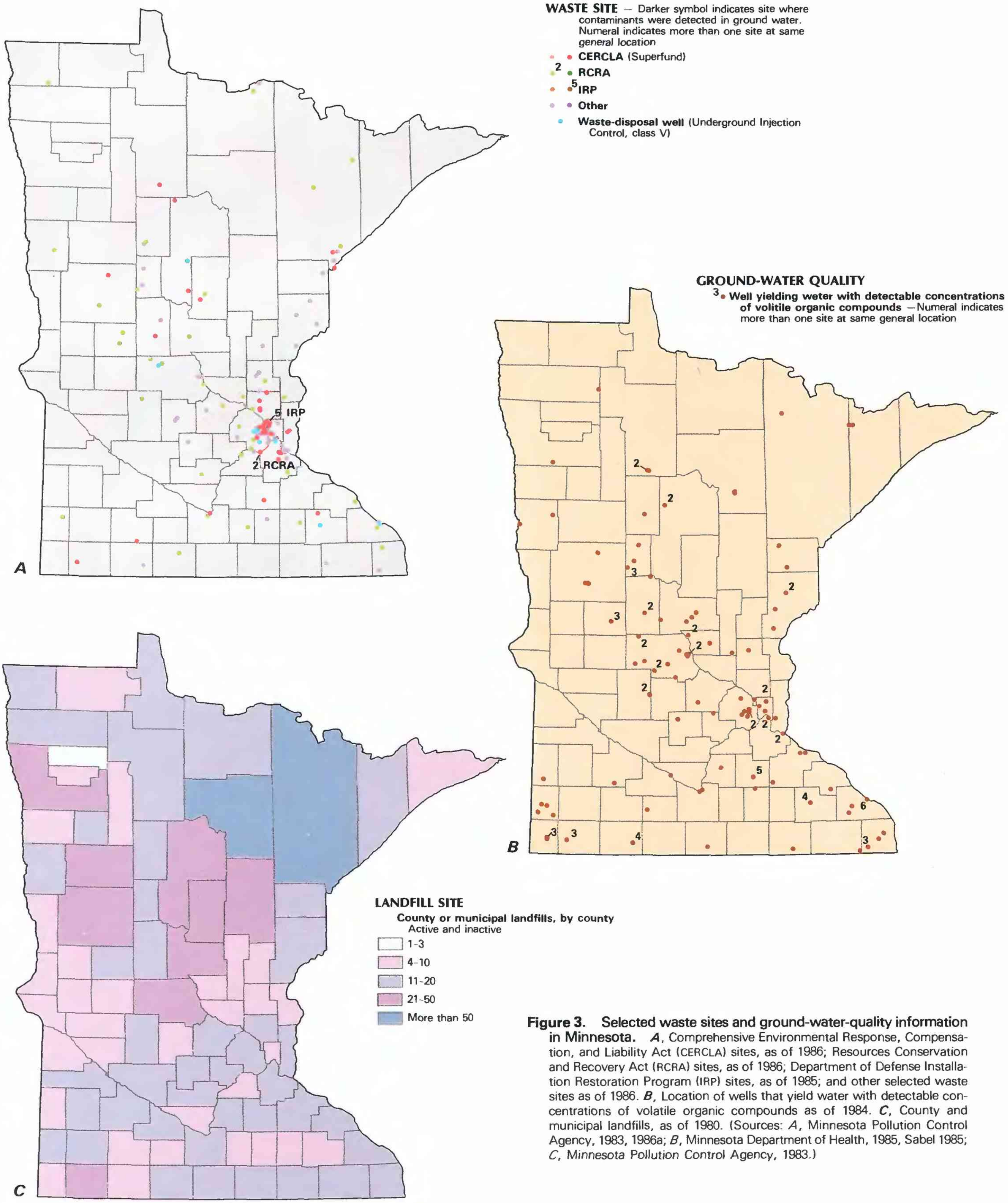

Figure 3. Selected waste sites and ground-water-quality information in Minnesota. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resources Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites as of 1986. *B*, Location of wells that yield water with detectable concentrations of volatile organic compounds as of 1984. *C*, County and municipal landfills, as of 1980. (Sources: *A*, Minnesota Pollution Control Agency, 1983, 1986a; *B*, Minnesota Department of Health, 1985, Sabel 1985; *C*, Minnesota Pollution Control Agency, 1983.)

stock supplies, and dissolved-solids concentrations generally are less than 500 mg/L. Sodium-chloride type water is present locally along the north shore. Dissolved-solids and chloride concentrations in these local areas are as large as 74,300 mg/L and 46,000 mg/L, respectively (Anderson, 1986). This naturally occurring, very mineralized water is not used.

SIOUX QUARTZITE AQUIFER

The Sioux Quartzite aquifer (fig. 2*A*1, aquifer 10), which is present in southwestern Minnesota, consists of orthoquartzite with interbedded layers of mudstone and poorly cemented sandstone. The upper part of the aquifer typically is fractured and deeply weathered and yields from 1 to 450 gal/min to wells (Anderson, 1986). Water from the aquifer commonly is hard and is a mixed calcium-magnesium-bicarbonate-sulfate type. Dissolved-solids concentrations generally exceed 500 mg/L (fig. 2*C*) and are as large as 2,300 mg/L in areas where the aquifer is overlain by rocks of Cretaceous age (U.S. Environmental Protection Agency files).

PROTEROZOIC METASEDIMENTARY AQUIFER

The Proterozoic metasedimentary aquifer (fig. 2*A*1, aquifer 11) consists of argillite, slate, and metagraywacke (Anderson, 1986). The aquifer underlies central and northeastern Minnesota where it is used mostly for domestic water supplies. Water from the aquifer generally is suitable for domestic use because dissolved-solids concentrations typically are less than 500 mg/L. The water is a calcium-magnesium-bicarbonate type that generally is of better quality than water from most of the other crystalline-rock aquifers (Anderson, 1986). Although susceptible to contamination from land surface, contamination is not a serious problem in the Proterozoic metasedimentary aquifer.

BIWABIK-IRON FORMATION AQUIFER

The Biwabik-Iron Formation aquifer (fig. 2*A*1, aquifer 12) consists of ferruginous chert (Adolphson and others, 1981) that crops out in a narrow northeast-trending band in northeastern Minnesota. The aquifer yields as much as 1,000 gal/min of water to public-supply and industrial wells; largest yields are in areas where the aquifer has been altered by faulting and by the leaching of iron minerals (Anderson, 1986). Water from the aquifer is a calcium-magnesium-bicarbonate type that is suitable for most uses. Concentrations of iron, however, generally exceed the secondary drinking-water standard of 300 μg/L. Because the aquifer crops out at land surface, the water is susceptible to contamination from spills, landfills, septic systems, leaking tanks, and other such sources; however, contamination is not a widespread problem.

PRECAMBRIAN UNDIFFERENTIATED AQUIFER

Undifferentiated rocks of Precambrian age (fig. 2*A*1, aquifer 13) are tapped for rural domestic and livestock supplies in parts of southwestern and central Minnesota and in much of northern Minnesota. The aquifer consists of a variety of igneous and metamorphic rocks—mostly granite, greenstone, and slate (Adolphson and others, 1981). Water from the aquifer generally is a calcium-magnesium-bicarbonate type, but significant concentrations of sulfate are present in southwestern Minnesota. Sodium-chloride type water is present locally in the aquifer in the northeastern part of the State (Anderson, 1986). Dissolved-solids concentrations generally exceed 500 mg/L, and concentrations of 1,000 to 2,000 mg/L are relatively common.

EFFECTS OF LAND USE ON WATER QUALITY

Ground water is known to be contaminated at many of the sites shown in figures 3*A* and 3*B*, at many of the landfills and dumps shown in figure 3*C*, and in parts of southeastern and southwestern Minnesota. Contamination from the use of fertilizers and pesticides is suspected and may be increasing in the agricultural areas of Minnesota, but few data currently (1986) support this conclusion.

Thirty-six sites (fig. 3*A*) have been included in the NPL of Hazardous Waste Sites (U.S. Environmental Protection Agency, 1986c) for evaluation and cleanup under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Ground-water contamination is present at all 36 of these CERCLA sites. Forty-three hazardous-waste sites are included under the Resource Conservation and Recovery Act (RCRA) of 1976 (fig. 3*A*). The general distribution of the nearly 1,400 county or municipal landfills and dumps in Minnesota is shown in figure 3*C*. The number of landfills per county ranges from 2 in Pennington County to 180 in St. Louis County.

As of September 1985, 34 hazardous-waste sites at four facilities in Minnesota have been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazardous ranking system and may include them in the NPL. Of the 34 sites evaluated under the program, 10 sites contained contaminants but did not present a hazard to people or the environment. Six sites at two facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at one of these sites has been completed under the program.

"Other sites" on figure 3*A* include sites identified by MPCA on the Minnesota Permanent List of Priorities and wells identified by EPA as Class-V injection wells in the Underground Injection Control (UIC) program, (U.S. Environmental Protection Agency, 1984).

In addition to individual sites, two principal aquifers (the surficial-drift and the upper carbonate aquifers areas) in the State are known or suspected to have widespread ground-water contamination from "nonpoint" sources, and principal aquifers in several areas have been affected locally.

Much of Minnesota is underlain by glacial drift (fig. 2*A*2) that consists, in part, of outwash deposits of sand and gravel. These outwash deposits, the surficial-drift aquifers, are at or near land surface in many parts of central and western Minnesota (fig. 2*A*) and generally contain large quantities of water at shallow (less than 200 feet) depths. Water in the surficial-drift aquifers is susceptible to contamination from land-use activities such as irrigated agriculture. Concentrations of nitrate plus nitrite (as nitrogen) beneath or adjacent to irrigated fields have exceeded 10 mg/L (Myette, 1984), which is the primary drinking-water standard. Nitrate concentrations that exceed this limit are common in ground water in glacial drift or alluvium in parts of southwestern Minnesota where feedlots are numerous (Minnesota Pollution Control Agency, 1986a, p. 47). Residual concentrations of commonly used pesticides have been found in water from a few wells that tap the surficial-drift aquifer (H.W. Anderson, Jr., U.S. Geological Survey, written commun., 1986).

Widespread contamination also occurs in southeastern Minnesota where karst topography has developed on carbonate rocks that are at or near land surface. The hydraulic connection between the streams and the shallow ground-water system in the karst area allows rapid movement of contaminants from feedlots and septic systems into the ground water. Runoff from croplands that have been fertilized and treated with pesticides also can readily enter the ground-water system and contribute to the contamination. Concentrations of nitrate plus nitrite in the karst area commonly exceed the primary drinking-water standard of 10 mg/L (Adolphson and others, 1981).

Aquifers that have been affected by contamination in local areas include the St. Peter, Prairie du Chien-Jordan, Ironton-

Galesville, and Sioux Quartzite aquifers. In the St. Peter aquifer, water-quality problems occur mainly in the Twin Cities metropolitan area, where layers of shale that normally overlie and protect the aquifer from contamination were breeched and eroded by glacial streams. In this area, the St. Peter aquifer commonly is in direct contact with glacial-drift or valley-fill deposits and is susceptible to contaminants percolating through these materials from the land surface. Locally, the aquifer has been affected by contaminants moving through multiaquifer wells and along deteriorated or improperly grouted well casings (Ruhl and Wolf, 1983).

Water in the Prairie du Chien-Jordan aquifer has been seriously contaminated in parts of the Twin Cities metropolitan area by downward movement of organic compounds through multiaquifer wells and through glacial-drift deposits where confining beds were breeched and eroded by glacial streams. This contamination is of concern because (1) some of the organic compounds are known carcinogens and (2) most public supplies in the metropolitan area are derived from wells completed in the Prairie du Chien-Jordan aquifer. Water in the aquifer also has been contaminated in places as a result of land uses such as landfills, salt storage, and agriculture.

The Ironton-Galesville aquifer also has been contaminated locally in the Twin Cities metropolitan area, even though this aquifer is generally well protected from surface contamination throughout most of the area by overlying confining beds.

The Sioux Quartzite aquifer is susceptible to contamination from land surface in areas where it crops out or where overlying glacial drift is thin. In these areas, concentrations of nitrate plus nitrite commonly exceed 10 mg/L.

POTENTIAL FOR WATER-QUALITY CHANGES

Additional sites where ground water has been contaminated by organic compounds are likely to be found in Minnesota, particularly as attention is given to the problem of the 40,000 to 50,000 underground storage tanks estimated by MPCA to be in place and subject to regulation by the State. The quality of water in aquifers contaminated by organic compounds should improve over the next several years as contamination sites are identified and remedial actions are taken. There is a growing awareness in Minnesota (Minnesota Pollution Control Agency, 1986b) of the effect of agricultural chemicals on water quality in the surficial-drift and upper carbonate aquifers. This awareness may lead to changes in land-use practices that could result in improved ground-water quality. Further deterioration in ground-water quality from new sources is less likely because of the State's awareness of contamination problems and the various regulatory and management programs that have been implemented.

A program for monitoring temporal and areal variations in the quality of Minnesota's ground water was begun in 1978 by the MPCA. Results of the program are summarized in a report by Sabel (1985), which includes data on the annual minimum, mean, and maximum concentrations of iron, chloride, nitrate, total organic carbon, dissolved solids, and pH of samples collected from the surficial-drift, buried-drift, Prairie du Chien-Jordan, and Ironton-Galesville aquifers from 1978 to 1984. The data indicate that chemical concentrations and properties fluctuate from year to year, but no trend is readily apparent. Mean and median concentrations of nitrate plus nitrite (as nitrogen) in water from the surficial-drift aquifers are shown in figure 4 for all samples collected since 1976 as part of the U.S. Geological Survey's program of water-resources investigations in Minnesota. Although the annual mean and median concentrations vary, the nitrate-plus-nitrite concentrations seem to be increasing, which may reflect the widespread application of agricultural fertilizers. However, the apparent trend may be biased because the Geological Survey's sampling programs have placed greater emphasis in recent years on water-quality investigations in agricultural areas.

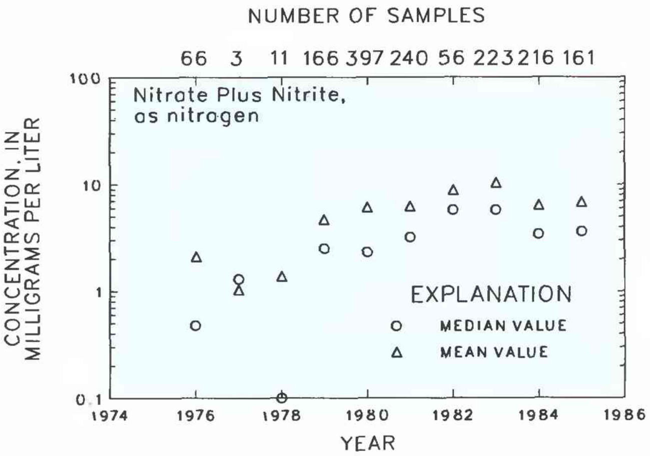

Figure 4. Mean and median concentrations of nitrate plus nitrite (as nitrogen) in the surficial-drift aquifers, 1976–85. (Source: U.S. Geological Survey files.)

GROUND-WATER-QUALITY MANAGEMENT

Management of ground-water quality in Minnesota potentially may involve one or more of five levels of government—Federal, interstate, State, regional, and local. Federal involvement generally is related to the Clean Water Act, the Safe Drinking Water Act, the Resource Conservation and Recovery Act, the Toxic Substances Control Act, or the Comprehensive Environmental Response, Compensation, and Liability Act. These Federal programs complement State authority and promote consistency in water-quality management among the States. Interstate involvement is through various Commissions and Boards that function by agreement between Minnesota and neighboring States and the Canadian and Provincial governments. Regional and local involvement is through Regional Development Commissions, the Metropolitan Council of the Twin Cities, Soil and Water Conservation Districts, Watershed Districts, counties, and cities.

Most of the responsibility for management of ground water and its quality in Minnesota rests with three agencies—the Minnesota Department of Natural Resources (MDNR), the Minnesota Department of Health (MDH), and the Minnesota Pollution Control Agency (MPCA). The responsibility is divided by placing control of (1) water appropriations, which can be affected by water quality, with MDNR, (2) health-related and domestic-supply matters with MDH, and (3) water quality and pollution control with MPCA (Bruemmer and Clark, 1984).

Protection of ground-water quality by MPCA includes (1) regulating the land application of wastewater, (2) regulating construction and operation of feedlots, (3) administering a nonpoint-source-control program, (4) responding to contamination incidents, (5) regulating disposal of solid and hazardous wastes, and (6) comprehensive planning for prevention of contamination. Under the Minnesota Environmental Response and Liability Act, the MPCA has a $5-million fund to finance cleanup of hazardous-waste sites.

In 1986, the Minnesota Legislature amended Minnesota Statutes Chapter 115 to establish potable-water supply as the highest-priority use of water in the State. The amendment prohibits the location of hazardous- or radioactive-waste facilities where they might cause pollution of potable water. The comprehensive Local Water Planning Act, Minnesota Statutes 110B, 1986, enables counties to prepare water-management plans and to regulate water resources. The Legislature also passed a law directing the MPCA to authorize projects for testing controlled injection of oxygen-bearing material and microbiological systems into contaminated sites as a possible remedial measure. The State currently is surveying the occurrence of pesticides in ground water.

Minnesota's goal in managing the ground-water resource is to assure an adequate supply of sufficient quality to meet reasonable demands for use. The strategy for achieving the goal includes:

1. Improved management of water and land resources,
2. identification of areas where additional ground-water development would be feasible and beneficial and where it would not, and
3. protection of ground water from contamination to assure safe drinking-water supplies.

The goal can be achieved through enhancement of existing programs, particularly those with the objective of preventing ground-water contamination. Minnesota does not, for example, agree with a policy that would allow intentional degradation of water quality in selected aquifers. As stated by Bruemmer and Clark (1984), "...efforts should be directed at managing information needs for evaluating environmental and health risks; assessing ground water resources in terms of quality and quantity; developing effective monitoring and remedial strategies; investigating contaminant movement and behavior in soil and ground water systems (transport and fate); expanding the presently limited and hard-pressed analytical capabilities and capacities; providing technical assistance and training to state and local authorities; and disseminating information efficiently and effectively to those directly involved with water resource management and to the general public."

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MISSISSIPPI
Ground-Water Quality

Ground water constitutes 54 percent of all the freshwater used in Mississippi and serves the water-supply needs of 93 percent of the population (fig. 1). Wells capable of producing 200 gal/min (gallons per minute) of water with quality suitable for most uses can be obtained in all but a few areas of the State. Wells producing more than 2,000 gal/min are common in northwestern Mississippi and are not unusual in the coastal area. The nearly exclusive use of ground water for public and industrial water supplies is the result of the statewide availability of aquifers (fig. 2) that are capable of supplying large yields of water containing dissolved-solids concentrations generally less than 400 mg/L (milligrams per liter). The ground-water quality in most of the aquifers does not exceed the national drinking-water standards established by the U.S. Environmental Protection Agency (1986a,b); however, wells in some aquifers in some localities produce water that contains objectionable concentrations of iron or has natural properties, such as excessive hardness, low pH, or color, that may limit its use for some purposes.

The largest use of ground water in the State is for irrigation of crops in the Mississippi River alluvial plain of northwestern Mississippi. Public-water supply constitutes the second largest use of ground water, and pumping for public supplies is concentrated in the more intensely populated areas. The public water-supply systems in Jackson (Hinds County), Meridian (Lauderdale County), and Columbus (Lowndes County) use ground water and surface water conjunctively and are the only systems in the State that use surface water.

Because Mississippi, in general, is a sparsely populated agricultural State and is not intensely industrialized, ground-water contamination is not a major problem at this time. However, ground-water contamination has been documented in some areas (fig. 3). Localized saltwater contamination of freshwater aquifers by oilfield-brine disposal has been documented at several sites, primarily in the central and southern parts of the State. Two hazardous-material National Priorities List (NPL) sites are being studied under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, and ground water is being monitored at 23 hazardous-waste sites under the Federal Resources Conservation and Recovery Act (RCRA) of 1976. Contamination of shallow ground water has been detected at 1 of the NPL sites and at 13 of the RCRA sites. In addition, the U.S. Department of Defense (DOD) has identified one site at one facility where contamination has warranted remedial action.

Although ground-water-quality contamination has been documented at only a few sites, the combination of very permeable soils, shallow ground water, and large annual rainfall makes the State's ground water susceptible to contamination. Consequently, ground-water monitoring is important to early detection of contamination.

The U.S. Geological Survey, in cooperation with the Mississippi Department of Natural Resources, and other local, State, and Federal agencies, has collected a significant amount of ground-water-quality information. Even though effective monitoring programs have been implemented for public water supplies and for sites of known and potential contamination, much of the water-quality information for other areas of the State has been limited to a small number of inorganic and organic constituents. This information is inadequate to assess the nature and occurrence of many of the hazardous organic compounds and agricultural chemicals that may affect the ground-water quality of the principal aquifers in Mississippi.

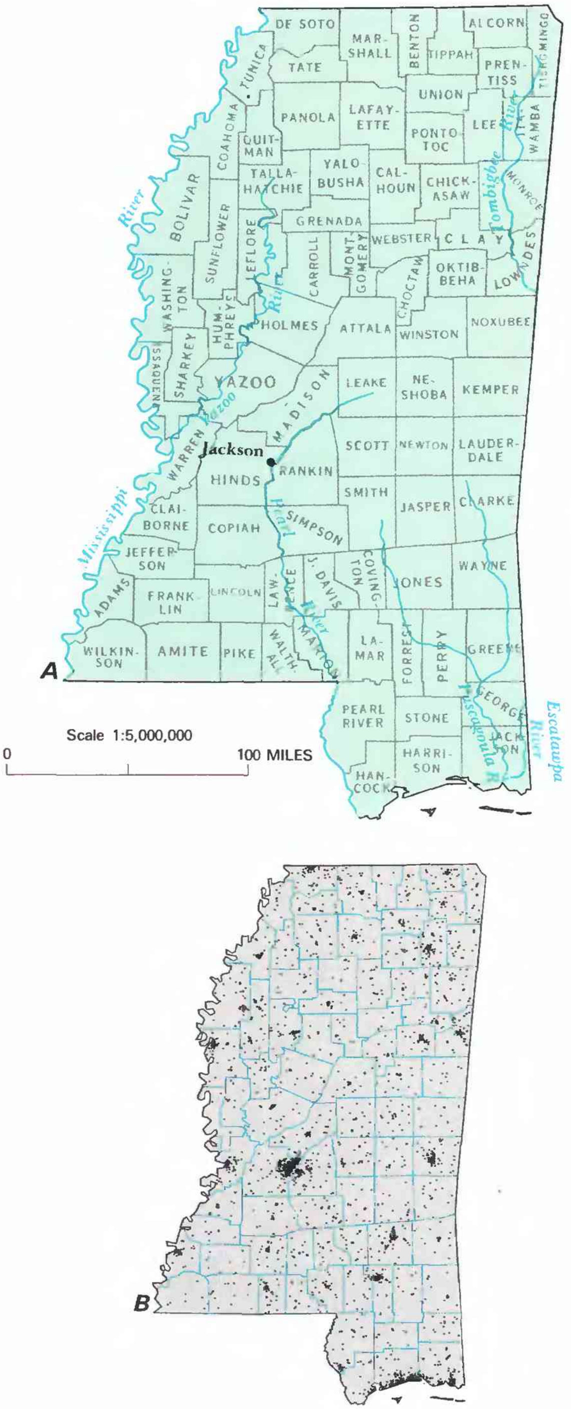

Figure 1. Selected geographic features and 1985 population distribution in Mississippi. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

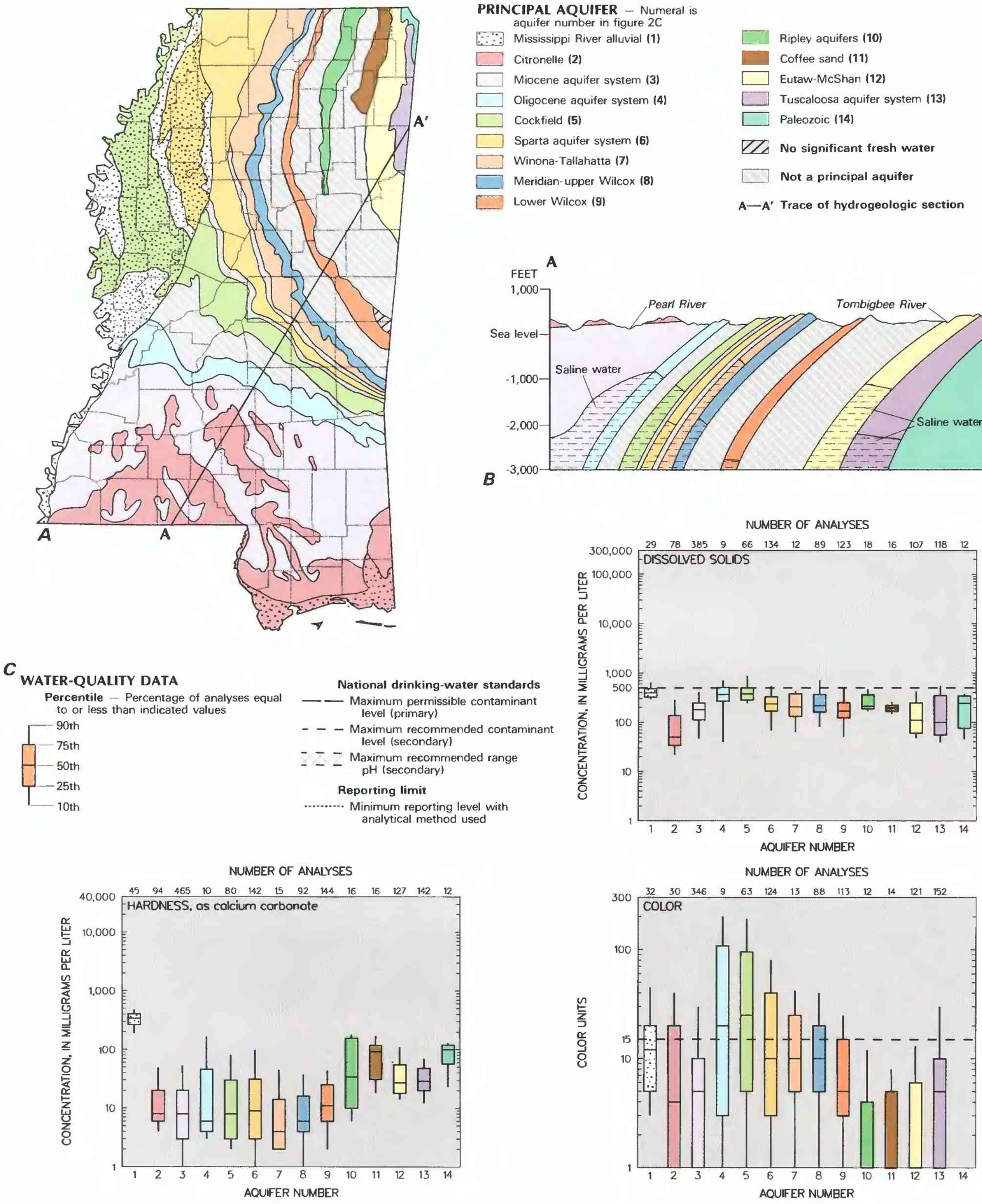

Figure 2. Principal aquifers and related water-quality data in Mississippi. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1970–85. (Sources: *A*, Modified from Bicker, 1969. *B*, Compiled by E.H. Boswell from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Almost all water wells in Mississippi obtain water from 1 or more of the 14 principal aquifers. The principal aquifers that crop out in the State are shown in figure 2*A*. Much of the water that reaches the water table moves downdip to the west-southwest into confined aquifers (fig. 2*B*). Although most of the State is underlain by one or more excellent freshwater aquifers, water-level declines are locally large as the result of large withdrawals. Slightly-saline water (dissolved-solids concentrations between 1,000 and 3,000 mg/L), which is plentiful in most confined aquifers beyond the downdip limit of freshwater, is an important resource for future use. Geohydrologic data indicate that most of the principal aquifers at one time were filled with saline water. Later, the saline water was displaced, at least partly, by freshwater (Wasson, 1980, p. 15).

In 1980, 74 percent or about 1,140 Mgal/d (million gallons per day) of all ground water used was from wells completed in the Mississippi River alluvial aquifer (U.S. Geological Survey, 1985, p. 274). About 70 percent of the water from the alluvial aquifer was used, without treatment, for aquaculture and agricultural purposes. Pumpage from the Tuscaloosa, Meridian-upper Wilcox, Sparta, Cockfield, and Miocene aquifers or aquifer systems represented 22 percent (330 Mgal/d) of the total ground water used whereas freshwater from the other eight aquifers represented 4 percent (65 Mgal/d). About 13 percent of all fresh ground water used in 1980 was for public and domestic water supplies. Water withdrawn from most deeper confined aquifers for public supplies generally needs little or no treatment, but water from the Mississippi River alluvial aquifer generally needs treatment for the removal of hardness and iron. About 14 percent of all ground water used is for industrial purposes. Most (11 percent) of the water is withdrawn from the Miocene and Tuscaloosa aquifer systems for self-supplied industrial use.

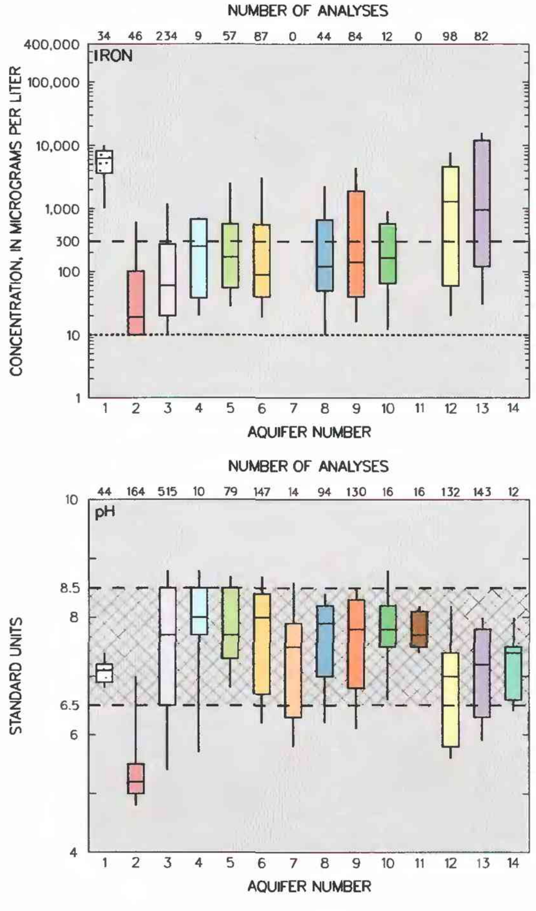

Figure 2. Principal aquifers and related water-quality data in Mississippi—Continued.

The chemical characteristics of water in the shallow (less than 200 feet below land surface) Mississippi River alluvial aquifer are fairly uniform throughout the aquifer. The base of freshwater in the confined aquifers ranges from about 200 to 3,000 feet in depth. A chemical-quality change occurs gradually with depth as the result of ion exchange and other natural geochemical processes. Dissolved-solids concentrations and pH values of water at depths of about 100 feet or less in recharge areas may be much smaller than 100 mg/L and 7 standard units, respectively. The dissolved-solids concentration and pH of water increase as water moves downdip. Ground water that is generally soft to moderately hard and a calcium-magnesium-bicarbonate type at shallow depths changes to a sodium-bicarbonate type deeper in the aquifer and eventually becomes a sodium-chloride-bicarbonate type. At greater depths, the water becomes very saline and dissolved-solids concentrations are larger than 10,000 mg/L. Local conditions, such as hydrologic connection between aquifers and streams, geologic structures and anomalies in aquifers, and recharge from estuaries and tidal marshes, also will affect ground-water quality.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, color, iron, and pH analyses of water samples collected from 1970 to 1985 from the principal aquifers in Mississippi. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant permissible in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 15 units color, 300 μg/L (micrograms per liter) iron, and 6.5–8.5 units pH.

Where more than one analysis from a site was available, the median concentration for the site was used. The data were interpreted without regard to sample depth within the aquifer. Dissolved-solids concentrations of water at depths in the principal aquifers are described on maps by Wasson (1980, p. 23–107).

Dissolved Solids

The concentration of dissolved solids describes the total mineral content of water and characterizes the general ground-water quality of an aquifer. The median dissolved-solids concentration of water from wells in all aquifers was 400 mg/L or less, which does not exceed the 500-mg/L drinking-water standard. Median values for dissolved-solids concentrations are largest (393 mg/L) for water in the Mississippi River alluvial aquifer and smallest (50 mg/L) for water in the Citronelle aquifer. The differences in the amounts of dissolved solids in the water in these two shallow aquifers reflect the differences in weathering and mineralogy of the sediments that constitute the two aquifers. Also, the alluvial aquifer is recharged primarily by the Mississippi River (Sumner and Wasson, 1984, p. 47), whereas the Citronelle aquifer is recharged by rainfall. The confined aquifers contain naturally occurring saline water at depth, and wells screened near or below the base of freshwater or downdip from the freshwater-saltwater interface can produce water with much larger dissolved-solids concentrations than those shown in figure 2*C*.

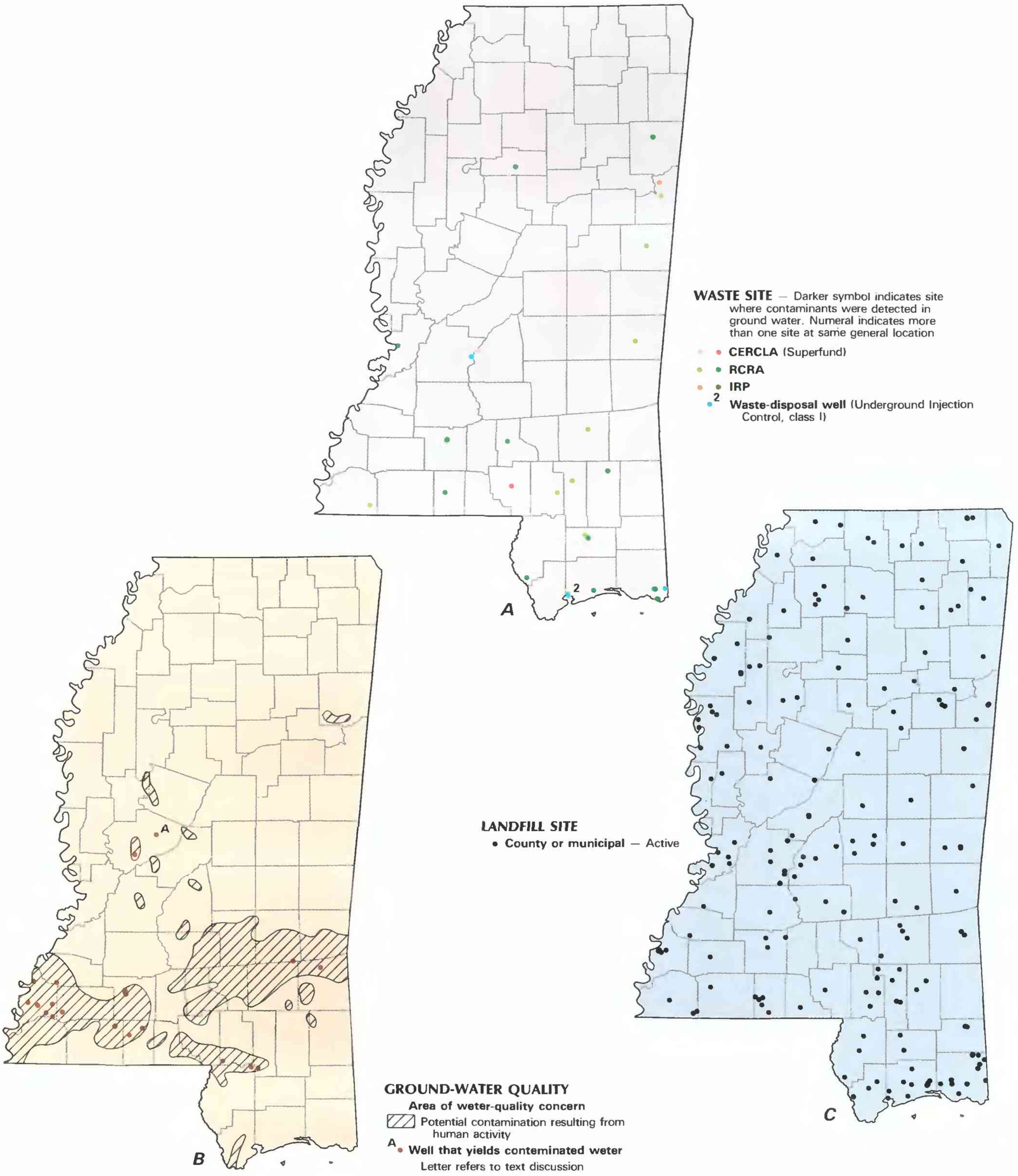

Figure 3. **Selected waste sites and ground-water-quality information in Mississippi.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of potential contamination, and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1984. (Sources: *A*, Mississippi Department of Natural Resources files; U.S. Department of Defense, 1986; U.S. Geological Survey files. *B*, Modified from Gandl, 1982, p. 6; Mississippi Department of Natural Resources, and U.S. Geological Survey files. *C*, Mississippi Department of Natural Resources and U.S. Geological Survey files.)

Hardness

Calcium and magnesium, which contribute to the hardness of water, are among the principal constituents in the water of the Mississippi River alluvial aquifer and water at shallow depths in the other aquifers. Water in the alluvial aquifer generally is very hard, with values larger than 340 mg/L. Median hardness values for water from the Coffee Sand and Paleozoic aquifers are 92 and 100 mg/L, respectively. The water in the other aquifers is soft and rarely exceeds a hardness of 60 mg/L.

Color

Color of water in most aquifers increases as the water contacts and dissolves color-producing organic materials. The color of water in the principal aquifers rarely exceeds 40 color units but locally may exceed 100 units. Median color values exceed the standard for drinking-water supplies (15 units) only in the Oligocene aquifer system and the Cockfield aquifer, where median color values are 20 and 25 units, respectively. Color is visible in this range but generally does not limit its use for most purposes.

Iron

Iron occurs least commonly in water from the Citronelle aquifer and the Miocene aquifer system and most commonly in the water from the Mississippi River alluvial aquifer, Eutaw-McShan aquifer, and Tuscaloosa aquifer system. Iron concentrations commonly are largest in water in the Mississippi River alluvial aquifer, where iron concentrations seldom are smaller than 4,000 μg/L and generally are larger than 6,000 μg/L. In the confined aquifers, iron concentrations tend to be larger in and near the outcrop areas. Median iron concentrations exceed the standard for drinking water in the Mississippi River alluval aquifer, Eutaw-McShan aquifer, and Tuscaloosa aquifer system. Data for the Eutaw-McShan aquifer may be biased toward larger iron concentrations, owing to the predominance of water samples obtained at shallow depths in the outcrop area. Iron concentrations are not shown for some of the aquifers (fig. 2*C*) because of the limited amount of data.

pH

Except for the Citronelle aquifer, median pH values for water in the principal aquifers do not exceed the drinking-water standards. The pH of water in the Citronelle aquifer generally is acidic and rarely exceeds 5.5 units. In the Mississippi River alluvial aquifer, the pH of water generally ranges from 6.9 to 7.2 units. In other aquifers, the pH of the water generally has a greater range with depth and commonly is larger than 7.5 units.

EFFECTS OF LAND USE ON WATER QUALITY

Current ground-water-quality concerns include the effects of mining, urbanization, surface and underground waste disposal, saltwater intrusion, and agricultural activites. Many of these land-use factors are under investigation, and others are to be investigated soon.

Mining

Mining has had little known effect on ground-water quality. Sand and gravel quarries are common, and economically important minerals, such as lime, clay, sulfur, and some trace metals have been mined for several years. Extensive mining of large lignite deposits in the State is not economically feasible (1986). Surface mining of lignite in the future may affect the ground-water quality of some aquifers in the northern and east-central parts of the State.

Urbanization

Considerable urban development has occurred since 1970 in areas along the Gulf Coast and in the Jackson metropolitan area. With this urban growth and development, there is potential for ground-water contamination from runoff from streets during excessive rains and from fertilizers, pesticides, and other chemicals applied to lawns.

There also are concerns about possible shallow ground-water contamination related to septic-tank systems in rural communities and some urban areas. These concerns are focused on bacterial and nitrate contamination, and more recently on synthetic organic chemicals used for septic-tank cleaners. Many systems are operated for periods that exceed their design life and leakage of hazardous substances is a possibility.

Waste Disposal

Hazardous wastes are treated, stored, or disposed at 23 RCRA sites that constitute a known or potential hazard to the quality of ground water (fig. 3*A*). The shallow ground water has been contaminated to some degree at 13 of the RCRA sites. The detected contamination is attributed to wood-treatment preservatives, such as pentachlorophenol or creosote, at nine of the RCRA sites; to organic chemicals, such as nitrobenzene, dinitrobutyl phenol, and phenolic compounds, at three sites; and nickel at one site.

Shallow ground water has been contaminated at an inactive waste site located near the Centreville RCRA site in Wilkinson County. The primary source of the contamination appears to be rubber-product wastes placed on a 35-acre tract of land since the 1970's. Carbon tetrachloride, chloroform, and acetone were detected in ground water at depths of less than 15 feet. The site may be designated a CERCLA site after assessments are completed.

An assessment also is being conducted to determine the source of organic compounds that have contaminated several public and private water-supply wells at Benton in Yazoo County (fig. 3*B*, site A). The suspected cause of the contamination is leakage from an underground storage tank (Seal, 1986, p. 1–4). Some of the compounds detected in the shallow wells included benzene, acetone, toluene, methylethylketone, and isopropylether.

Disposal of hazardous materials at Columbia (Marion County) and Flowood (Rankin County) has met requirements for inclusion of those sites on the NPL. Toxic volatile organic compounds (benzene, toluene, and xylene) have been detected in the water from two shallow wells (103 and 142 feet deep) in the Columbia water-supply system. Although ground-water contamination has been detected at Columbia NPL site (fig. 3*A*), studies now indicate that the source of the contaminants may have been from leaking gasoline storage tanks and not from waste materials at the NPL site (Jim McDonald, Mississippi Board of Health, oral commun., 1986). After the storage tanks were removed, the ground-water quality improved; the public-supply wells currently (1986) meet drinking-water standards (U.S. Environmental Protection Agency, 1986b). Analyses of water samples collected during April 1986 detected only benzene (1 μg/L) in one of the public-supply wells. Contamination of shallow ground water at the Flowood NPL site has not been detected.

Military installations generally have underground storage tanks and a variety of waste-disposal areas that include surface impoundments, evaporation ponds, chemical disposal pits, active and buried landfills, and beds for drying sludge from wastewater treatment. The types of potential contaminants are many and include oils, organic solvents, degreasing agents, defoliants, and trace metals. As of September 1985, 31 hazardous-waste sites at 3 facilities in Mississippi had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under the CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. One site at one facilitiy (fig. 3*A*) was considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites are scheduled for confirmation studies to determine if remedial action is required.

There are three facilities in the State with a total of six active industrial Class-I injection wells permitted under the Underground Injection Control (UIC) program (fig. 3*A*). These wells were all drilled within the past decade and are used to dispose of wastewater generated within these facilities (U.S. Environmental Protection Agency, 1984b). The facility near Pascagoula (Jackson County) injects waste that is composed primarily of polysulfide compounds and is classified as hazardous. The other two facilities at DeLisle (Harrison County) and Jackson (Hinds County) inject waste that is considered to be nonhazardous. Although each Class-I well is designed to inject the maximum waste generated at each plant, only one well at each of the three facilities is needed to dispose of the approximately 500,000 gal (gallons) of waste per day. Ground-water contamination has not been detected in any freshwater sections of aquifers in areas of Class-I waste-injection well operation. Commercial hazardous-waste underground injection wells designed or intended to dispose of wastes from sources other than the owner of the well are prohibited in the State of Mississippi.

There are 179 active county and municipal landfill sites (fig. 3*C*) and 125 unlicensed landfills (not shown) that are potential sources of contamination (U.S. Environmental Protection Agency, 1984a). Only a few data are available to evaluate the effects of landfills on the environment in Mississippi. An assessment of the effects of these landfills on ground-water quality is expected to be a major part of the ground-water protection program currently (1986) being developed by the Bureau of Pollution Control of the Department of Natural Resources. The U.S. Geological Survey is assisting the Bureau of Pollution Control in the identification of shallow public-supply wells that may be susceptible to contamination.

Since the discovery of oil in Mississippi in 1939, thousands of oil and gas exploration and production wells have been drilled. Most producing areas are in the southern part of the State. Petroleum production is accompanied by brine production that commonly ranges from 1 to about 20 barrels of brine per barrel of oil produced (Kalkhoff, 1986, p. 3). Although the injection of brine and drilling-fluid wastes into freshwater aquifers is prohibited by State and Federal law, the past use of leaky disposal pits and improper waste-injection methods has resulted in local contamination of several freshwater aquifers.

The aquifers most susceptible to surface contamination are the shallow aquifers that are not separated from the surface by layers of clay. The largest areas of oil and gas production and the location of 20 areas where water wells are known to be contaminated by oil-field brine are shown in figure 3*B*. The contaminated wells contain water with chloride concentrations that exceed the secondary drinking-water standard (250 mg/L). Chloride concentrations in many other wells are significantly larger than the background concentrations (20 mg/L) typical of uncontaminated water in shallow aquifers.

Saltwater contamination from surface disposal of oil-field brine usually is confined to shallow aquifers; however, contamination of water wells in deeper aquifers has been documented. Gandl (1982, p. 46) and Bicker (1972, p. 25) describe one instance of improper injection of oil-field wastes that contaminated the water in the lower Wilcox aquifer. Although numerous shallow wells have been abandoned because of saltwater contamination, only a few of the deeper public-supply wells have been affected. For example, wells in a confined aquifer owned by a rural water association in the Natchez (Adams County) area are no longer used because of saltwater contamination (Boswell and Bednar, 1985, p. 45).

Ground-Water Withdrawals

The aquifers along the Mississippi Gulf Coast are composed of interbedded layers of sand and clay. Saltwater intrusion near the coast is evident in a small area (not shown) in Jackson County, which extends southeastward from Pascagoula. The shallowest aquifer has a saltwater-freshwater interface along the coast and inland along the tidal reaches of the Pascagoula and Escatawpa Rivers. The "400-foot," "600-foot," and "800-foot" sands at Pascagoula contain freshwater, but there is evidence that freshwater-saltwater interfaces occur in all of these aquifers within short distances southeastward from Pascagoula. The deeper aquifers at Pascagoula contain saltwater.

Although there is some evidence of saltwater intrusion into the "400-foot," "600-foot," and "800-foot" aquifers at Pascagoula, the source of the saltwater has not been identified. Hydraulic-head differences could cause saltwater to move upward into the "800-foot" aquifer. Potentiometric surfaces in the three aquifers indicate that saltwater could be moving updip from the south toward the pumping centers at Pascagoula. The "400-foot" sand is vulnerable to leakage of saltwater from the overlying shallow aquifers that are hydraulically connected to the saltwater bays and estuaries.

Agricultural Practices

Agricultural chemicals are used extensively on about 6.6 million acres of cropland in the State. A 7,000-mi^2 (square mile) area of fertile farmland in the alluvial plain of northwestern Mississippi, commonly referred to as the "Delta", is the most intensively cultivated region in the State. The Delta comprises more than 50 percent of cropland acreage and accounts for most of the agricultural chemicals used. The Mississippi River alluvial aquifer, which averages between 80 and 200 feet in thickness, underlies the Delta and normally is saturated to within about 25 feet of the land surface. The shallow depth to water, the intensive use of agricultural chemicals, and the abundant rainfall are conditions in the Delta that make the shallow ground water susceptible to contamination.

The annual areal recharge of the alluvial aquifer by direct infiltration of rainfall is about 0.5 inch, or 180 Mgal/d (Sumner and Wasson, 1984, p. 46). However, recharge along streams and oxbow lakes in the Delta offers a greater potential for the transport of contaminants into the alluvial aquifer because the streams and lakes often penetrate the more than 20 feet of surficial clay that confines the aquifer in most places.

During 1983, about 8,000 tons of pesticides were applied to 2 million acres of crops in the Delta, primarily cotton, soybeans, and rice (R. Morgan, Mississippi Cooperative Extension Service, oral commun., 1986). During previous years, the application of agricultural chemicals was even more intensive; for example, during 1978, almost 10,000 tons of 55 kinds of pesticides and 500 tons of sodium chlorate were applied to crops. Other agricultural chemicals, such as fungicides, defoliants, emulsifiers, pesticide solvents, and many tons of lime and fertilizers, are applied annually to crops and soils.

Data collected by the U.S. Geological Survey indicate that some of the more persistent pesticides, such as DDT, endrin, and toxaphene, are present in the water and bottom sediments of the Yazoo River. The Mississippi Department of Wildlife Conservation (1980) reported significant quantities of DDT, DDD, DDE, and toxaphene in surface water and in fish tissue. The lakes and streams in the Delta are hydraulically connected in varying degrees with the alluvial aquifer. Where recharge occurs, the pesticides may be transported into the aquifer. However, data are not available to evaluate any suspected widespread deterioration of ground-water quality caused by agricultural chemicals in the Delta or in any of the other agricultural areas of the State.

POTENTIAL FOR WATER-QUALITY CHANGES

Localized contamination of freshwater aquifers by saltwater from oil and gas operations has been documented at many sites in the State. The extent of this problem may be greater than presently known and may not be fully realized for many years. Contamination from old brine-disposal pits eventually may be discharged horizontally to streams in some areas, but may continue to move downward into deeper aquifers in other areas. Regulation of the brine-disposal practices within the oil and gas industry has decreased, but not eliminated, the potential of ground-water contamination from brine. At present, brine-injection wells are being permitted and monitored where possible, but failure of these wells, improper well construction, and other factors could still threaten ground-water resources. Future ground-water contamination may be expected when some of the older, abandoned wells begin to fail. In intensely pumped areas, hydraulic-head differences could force saltwater into freshwater aquifers.

Because much of the State is underlain by shallow aquifers that are susceptible to contamination, leaking underground storage tanks, surface-disposal sites, and improperly operated septic-tank systems are a potential threat to ground-water quality. Recharge areas of the major aquifers are the most vulnerable to contamination, and the effect on ground-water quality is dependent on the aquifer characteristics and the quantity, solubility, and persistence of the contaminants.

The continued use of agricultural chemicals in the Mississippi River alluvial plain eventually may lead to ground-water contamination in the Delta. The extent of present and potential contamination of water in the alluvial aquifer will require further study and may take many years to define.

GROUND-WATER-QUALITY MANAGEMENT

In recent years, water-quality management has increased rapidly and has undergone substantial change. Legislative action in 1978 restructured State offices into various departments with clearly defined water-quality management and regulatory responsibilities. The Mississippi Air and Water Pollution Control Act in 1966 first established a regulatory program to protect "waters of the State", both surface and ground water. Primary pollution control efforts at that time were affected by Federal legislation predominantly directed toward surface-water protection. Little or no effort was made to develop specific regulatory programs for ground-water protection until 1970, when the Mississippi Oil and Gas Board adopted specific rules and regulations for saltwater disposal pits and began to issue permits for underground injection wells operated by the oil and gas industry. The Mississippi Air and Water Pollution Control Commission, which became the Bureau of Pollution Control of the Department of Natural Resources in 1978, retained regulatory authority for all aspects of stream and aquifer contamination.

State programs pertaining to the underground injection of wastes have been implemented as part of the UIC program of the Safe Drinking Water Act (SDWA) of 1974. The Bureau of Pollution Control has responsibility for these programs except for Class-II UIC wells. Primacy for permitting Class-II UIC wells has not been delegated by the EPA. The application of the Mississippi Oil and Gas Board for this authority is pending. The Bureau of Pollution Control also has full authority to administer regulatory controls for RCRA surface impoundments and landfills. As amended in 1984, RCRA increased ground-water protection by placing additional regulatory controls on existing hazardous-waste facilities and addressed program needs for small-quantity waste generators and underground storage tanks.

To continue an effective monitoring program for public water supplies and to enforce regulations required under the SDWA of 1974, the Mississippi Legislature passed the Mississippi Safe Drinking Water Act in 1976 and also designated the State Board of Health as the regulatory agency. The State Board of Health systematically monitors public water-supply systems that serve at least 25 people or have at least 15 service connections to comply with the primary drinking-water regulations (U.S. Environmental Protection Agency, 1986a) as amended. In addition to the 25 contaminants currently with standards, the SDWA, as amended in 1986, requires 83 additional primary drinking-water standards by 1991. A program to monitor the estimated 4,000 wells in 1,400 community public water-supply systems is under study and will be initiated under the statutory mandates. The State Board of Health and the Bureau of Pollution Control coordinate efforts to locate and eliminate the source in the event that contamination of a public water supply is detected. Where sewers are not feasible and soils meet acceptable percolation standards, septic tanks are approved by the Board of Health upon request. Engineering studies of 20 or more lots are reviewed by the Bureau of Pollution Control.

The Mississippi Department of Agriculture and Commerce, Division of Plant Industry, was created in 1972 to protect State agricultural and horticultural interests. The Division is responsible for a program to register pesticides, to license dealers and aerial applicators, and to regulate the application of restricted pesticides.

The Mississippi Water Management Council, created by State Legislature in 1983, reexamined completely all State laws pertaining to surface and subsurface water and reported recommended amendments to the 1985 legislative session. As the result of this action, legislation was passed in 1985 and signed into law by the Governor. Included was House Bill 762, which gives the State powers "to effectively and efficiently manage, protect, and utilize the water resources of Mississippi" and to require permits for the beneficial use of all water resources of the State. House Bill 149 authorized the creation of joint local government water-management districts.

In 1985, the Governor designated the Department of Natural Resources as the lead agency responsible for ground-water protection. Within the Department, the Bureau of Geology and the Bureau of Land and Water Resources have vital ground-water roles. The Bureau of Geology provides data for geologic and ground-water resources and serves as advisor during investigation of possible ground-water contamination. The Bureau of Land and Water Resources ensures that surface water and ground water are managed to the greatest benefit and also conducts ground-water quantity and quality investigations in cooperation with the U.S. Geological Survey. The Ground-Water Division of the Bureau of Pollution Control was created in 1985 to strengthen and develop an overall ground-water protection strategy. The Division also assumed responsibility for all ground-water activities within the Bureau of Pollution Control.

Nonregulatory support for ground-water programs are provided by other State agencies. The Mississippi State University Chemical Laboratory conducts ground-water related research in addition to a cooperative water-analysis program with the Department of Natural Resources. The Mississippi Water Resources Research Institute was designated as a State research institute by the State Legislature in 1983. The Institute receives support from the State and the U.S. Department of the Interior for water-resources research projects.

The current ground-water-quality management issues of most concern are the extent of aquifer contamination caused by disposal of oil-field brine and the sparsity of chemical-quality data, particularly concerning toxic substances and organic compounds in unmonitored aquifers. Other problems or potential problems that have been identified include aquifer contamination from agricultural chemical use, leaking storage tanks, industrial and municipal landfills and lagoons, septic tanks, and radioactive wastes.

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MISSOURI
Ground-Water Quality

In Missouri, about 34 percent of the population (fig. 1) obtains water supplies from ground-water sources. Ground water is the source of 74 percent of all rural domestic self-supplied water, 75 percent of all irrigation water, and 39 percent of all industrial self-supplied water, excluding water for thermoelectric power generation (U.S. Geological Survey, 1985). Ground water (fig. 2) generally is suitable for most uses except where it is saline. Median concentrations of dissolved solids, hardness, nitrate, fluoride, and sulfate (fig. 2) are less than the primary and secondary national drinking water regulations established by the U.S. Environmental Protection Agency (1986a,b); however, localized contamination from manufactured organic compounds (fig. 3) has been recognized in four principal aquifers in Missouri, including both shallow and deep aquifers.

WATER QUALITY IN PRINCIPAL AQUIFERS

The six principal aquifers in Missouri are: (1) Major river valleys, (2) alluvial (in southeastern Missouri), (3) Wilcox and Claiborne, (4) McNairy, (5) Ozark and (6) Kimmswick-Potosi (fig. 2). These aquifers, which underlie about 60 percent of the State, have differing water quality.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality constituents compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate, fluoride, and sulfate analyses of water samples collected from 1930 to 1986 from principal aquifers in Missouri. Percentiles of these constituents are compared to national standards that specify the maximum concentration or level of a contaminant in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include maximum concentrations of 10 mg/L (milligrams per liter) nitrate (as nitrogen) and 4.0 mg/L fluoride, and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L sulfate and 2.0 mg/L fluoride. The summary (fig. 2*C*) indicates that median dissolved-solids concentrations in ground water from all six principal aquifers are less than 500 mg/L; median hardness concentrations are less than 400 mg/L as calcium carbonate; median concentrations of nitrate are less than 0.10 mg/L as nitrogen; median concentrations of fluoride are 0.30 mg/L or less (except the Kimmswick-Potosi aquifer which is 1.0 mg/L); and median concentrations of sulfate are less than 60 mg/L.

About 40 percent of the aquifer systems in the State contain saline water, that is unusable for most purposes. Concentrations of dissolved-solids, chloride, sulfate, and other constituents in this saline water greatly exceed the national drinking water standards. Generally, saline water is located in northern, western, and southeastern Missouri (fig. 3*B*). The saline water-freshwater transition zone, defined as the zone where dissolved-solids concentration is larger than 1,000 mg/L, is located at the northwestern and southwestern margins of the Ozark and Kimmswick-Potosi aquifers (fig. 3*B*).

Along the transition zone, use of ground water for irrigation has increased rapidly during the past 20 years, causing water levels to decline about 100 feet in the Ozark aquifer in western

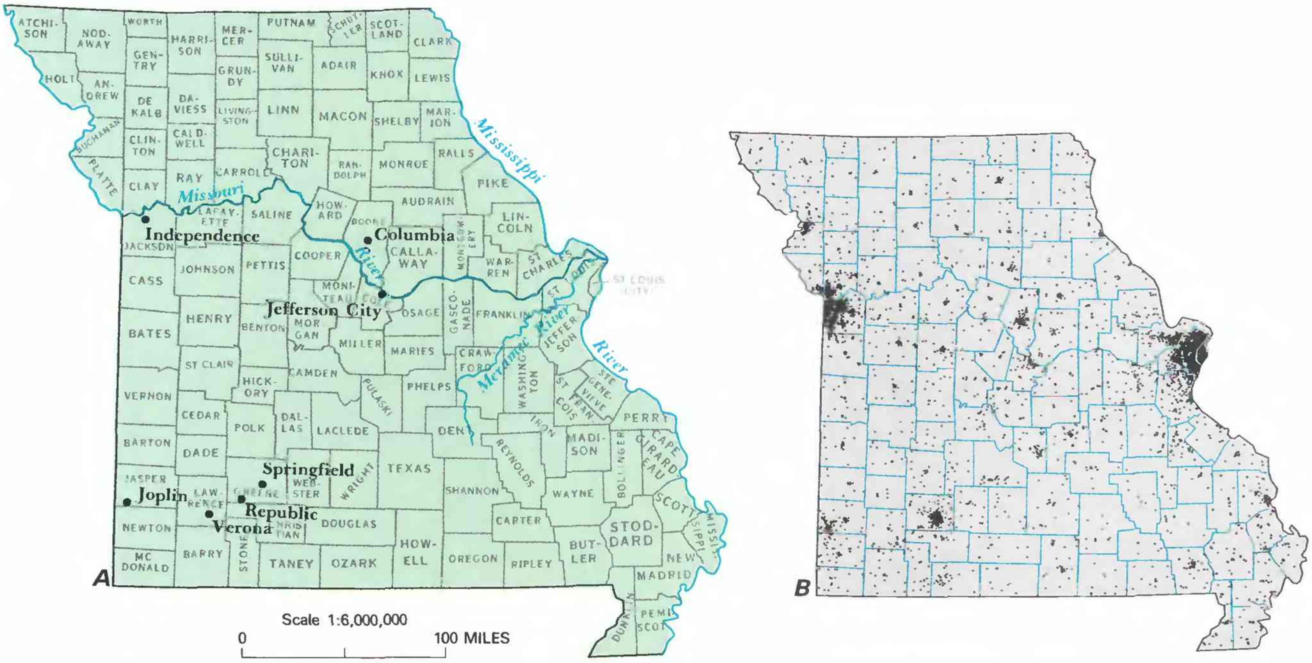

Figure 1. Selected geographic features and 1985 population distribution in Missouri. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

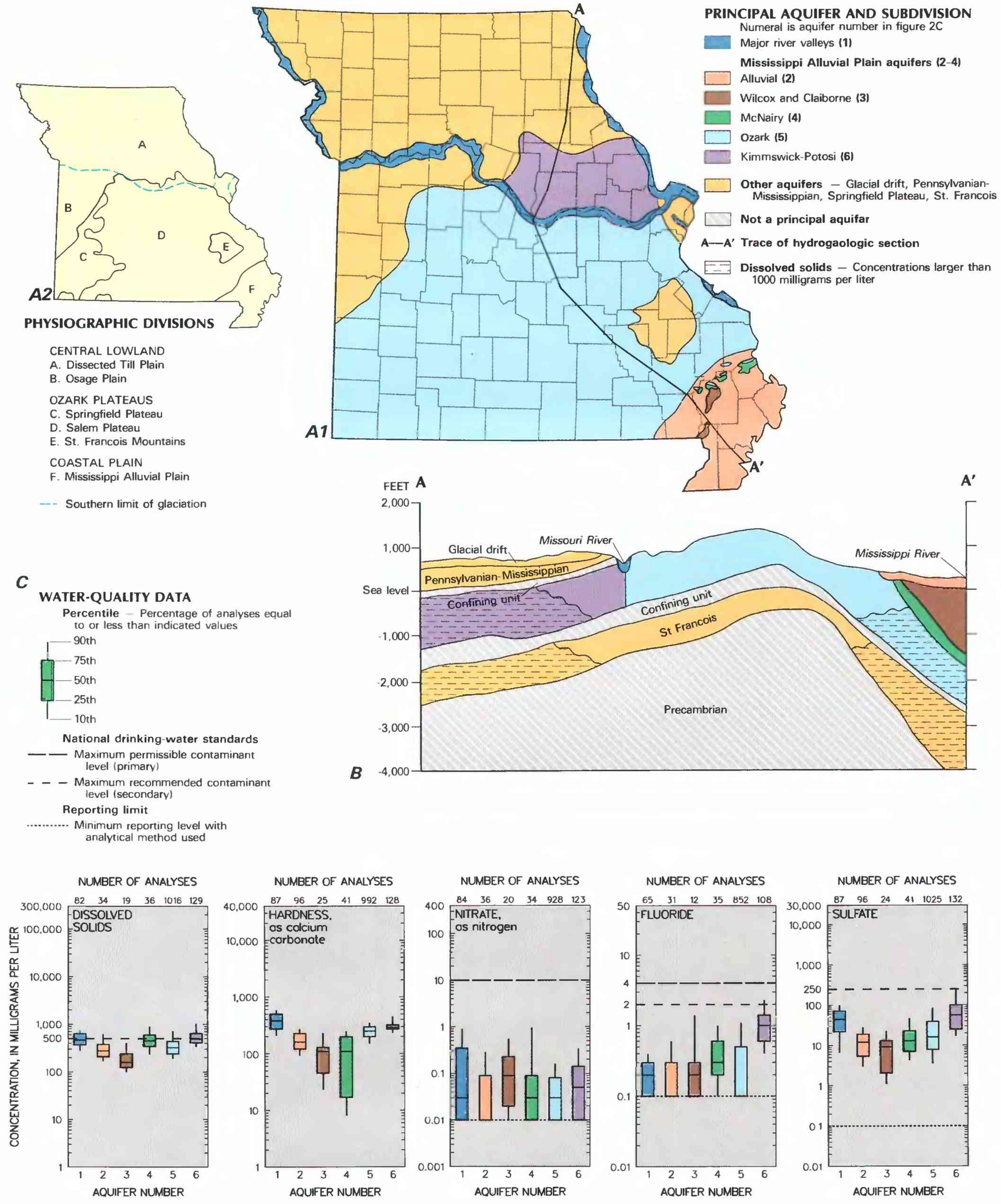

Figure 2. Principal aquifers and related water-quality data in Missouri; *A*1, Principal aquifers; *A*2, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1930-86. (Sources: *A*1, U.S. Geological Survey, 1985. *A*2, Fenneman, 1938; Raisz, 1954. *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a, b.)

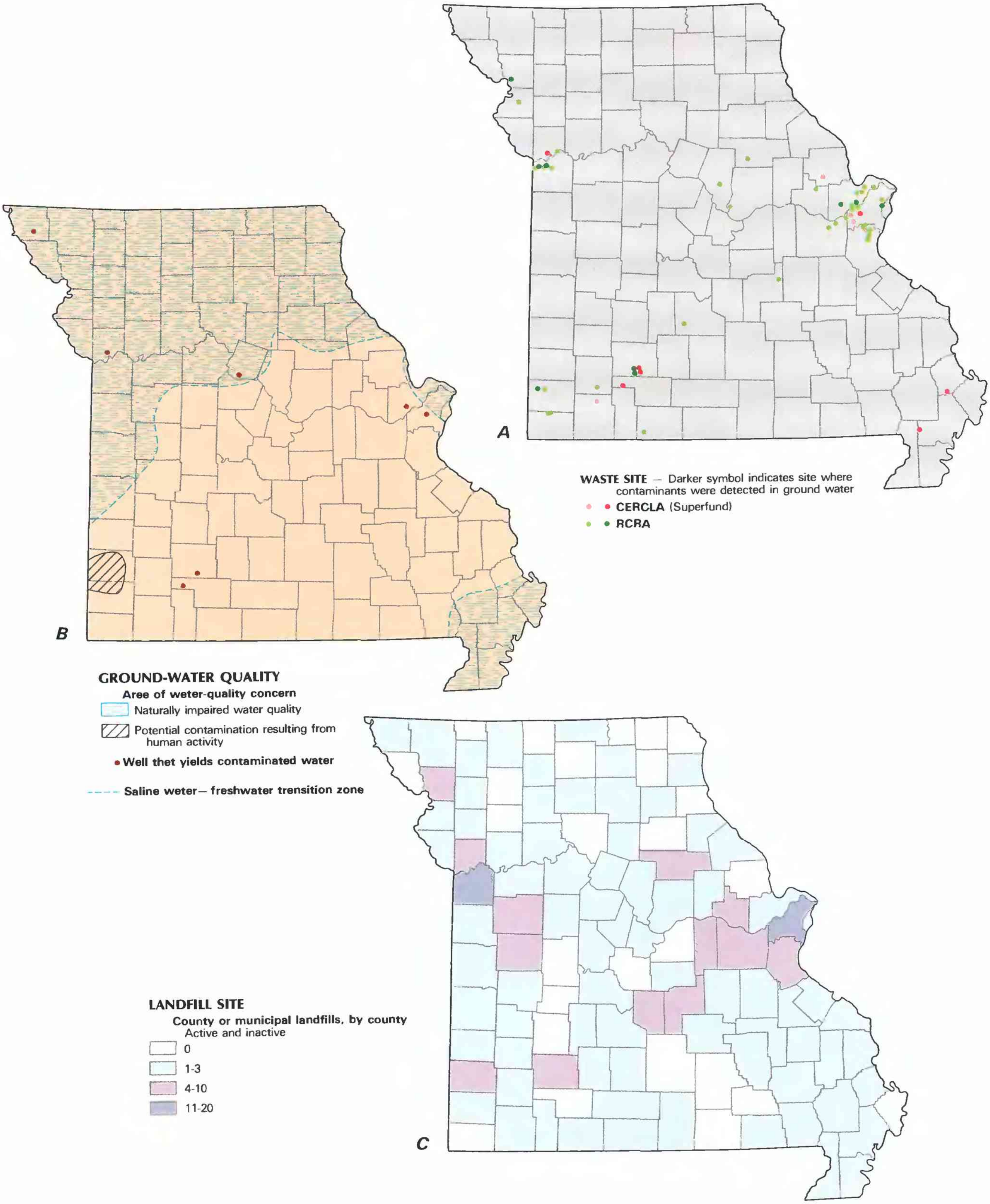

Figure 3. Selected waste sites and ground-water-quality information in Missouri. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; and Resource Conservation and Recovery Act (RCRA) sites, as of 1986. *B*, Areas of naturally impaired water quality, area of potential contamination, and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Missouri Department of Natural Resources, 1986d. *B*, Missouri Department of Natural Resources, 1986b. *C*, Missouri Department of Natural Resources, 1986c.)

Missouri (Kleeschulte and others, 1985), and in the Kimmswick-Potosi aquifer in northern Missouri (Emmett and Imes, 1984). Use of several irrigation wells in western Missouri was discontinued because of salt build-up in the soil. Also, the use of ground water for several public supplies in western Missouri was discontinued because the concentration of dissolved-solids was larger than 2,000 mg/L, even though the quality of water has not changed substantially in recent years (Kleeschulte and others, 1985).

Naturally occurring radioactivity in ground water also is associated with the saline water-freshwater transition zone. Deeply buried geologic units release radionuclides to the groundwater. These releases have been noted in regular monitoring of public water-supply wells (Missouri Department of Natural Resources, 1986b).

The karst nature of the Ozarks area makes it susceptible to contamination from many sources. Karst conduits may transmit contaminants rapidly, and interbasin flow has been documented in many areas. Dye-trace studies at Logan Creek, in south-central Missouri, indicate a dye velocity of more than 1 mi/d (mile per day). Other dye-trace studies in eastern Missouri in Jefferson County indicate velocity of ground water through karst conduits may be as much as 1,860 ft/d (feet per day) and historic studies indicate some dye travel-times as much as 2,500 ft/d (Kleeschulte and Duley, 1985). Dye-trace studies in southwestern Missouri indicate a greater range of travel times. Dye moving through a karst conduit had a velocity of about 1.3 mi/d, but dye moving through alluvial material had a velocity of about 54 ft/d (Barks and others, 1983).

Stream-aquifer interaction affects almost all stream channels. This interaction can vary seasonally and from site to site along a single stream. Ground water may discharge to a stream, or if the stream-bed elevation is sufficiently high or the geology permits, water may be lost from the stream into the ground-water system. A prominent example of flow loss to the subsurface was cited by Harvey (1980). Logan Creek was determined to have lost about 200 cubic feet per second of water between its upstream and downstream reaches. Kleeschulte and Duley (1985) reported streams in Jefferson County may lose or gain water from the ground-water system. Other examples of losing streams have been documented by Barks and others (1983) in southwestern Missouri.

Major River Valleys Aquifers

Aquifers of the major river valleys consist of unconsolidated gravel, sand, silt, and clay located along the Missouri, Mississippi, and lower Meramec Rivers (fig. 2). Recharge occurs by upward movement from underlying bedrock, stream-aquifer interaction, and precipitation. These aquifers are the surficial units along these rivers, are very permeable, and have shallow water levels. The median dissolved-solids concentration was 467 mg/L (fig. 2*C*); the maximum concentration was about 2,100 mg/L. The median sulfate concentration was 45 mg/L, which is the second largest of principal aquifers. Localized human-induced contamination of these aquifers has occurred at more than 30 sites (fig. 3). Primary use of water from this aquifer is for public supply at Independence and Columbia, and in St. Charles County.

Alluvial Aquifer

The alluvial aquifer consists of unconsolidated gravel, sand, silt, and clay located in the Mississippi Alluvial Plain of southeastern Missouri (fig. 2). Recharge occurs by upward movement from underlying bedrock near the margin of the Mississippi Alluvial Plain, stream-aquifer interaction, and precipitation. This aquifer is a surficial unit that is very permeable and has shallow water levels that range from 5 to 10 feet below land surface (Luckey, 1985). The median dissolved-solids concentration was 275 mg/L (fig. 2*C*); maximum concentration was about 1,100 mg/L. The median concentration of nitrate (as nitrogen) was less than 0.01 mg/L, which is the minimum detection limit. The area has been intensively developed for agricultural purposes and the aquifer is the principal source of water for irrigation. Localized human-induced contamination has occurred at two sites in southeastern Missouri (fig. 3).

Wilcox and Claiborne Aquifers

The Wilcox and Claiborne aquifers function as a multiaquifer unit and consist of interbedded layers of unconsolidated sand and clay located beneath the alluvial aquifer in southeastern Missouri (fig. 2). These aquifers are unconfined in and near outcrop areas, but are confined near the Mississippi River. Recharge occurs from the overlying alluvial aquifer, from precipitation, and possibly from the upward movement of water from the underlying McNairy and Ozark aquifers through localized fracture zones. These aquifers are exposed in parts of southeastern Missouri, but generally are covered by several hundred feet of alluvium. These aquifers have moderate permeability. The median dissolved-solids concentration was 159 mg/L (fig. 2*C*); maximum concentration was about 660 mg/L. The median concentration of sulfate was 9.2 mg/L, which was the smallest value for all six principal aquifers. This unit has not been intensively developed; however, some water for public supplies is pumped from these aquifers. No human-induced contamination has been recognized in these aquifers.

McNairy Aquifer

The McNairy aquifer consists of poorly consolidated sandstone, sand, and interbedded clay. The aquifer is confined except where it is exposed at the land surface or directly underlies the alluvial aquifer. The top of this aquifer is about 2,100 feet below land surface in extreme southeastern Missouri (Mesko, 1987). Recharge occurs from the underlying Ozark aquifer and from precipitation falling on outcrop areas. The aquifer has low permeability. The median dissolved-solids concentration was 448 mg/L (fig. 2*C*); the maximum concentration was about 2,200 mg/L in areas where saline water from the Ozark aquifer (fig. 2*B*) discharges upward. The median concentration of hardness as calcium carbonate was 110 mg/L, which was the same for the overlying Wilcox and Claiborne aquifers. Substantial quantities of water for public supplies are pumped from this aquifer. Only rare occurrences of human-induced contamination caused by coliform bacteria in public-supply wells have been recognized in this aquifer.

Ozark Aquifer

The Ozark aquifer consists of consolidated dolomite and minor layers of sandstone. This aquifer is confined except where it is exposed at the land surface. The top of this aquifer is about 1,000 feet below land surface in western Missouri (Imes, 1987). Recharge occurs from precipitation, from overlying and underlying aquifers, and from stream-aquifer interaction south of the Missouri River. The permeability varies considerably where solution activity has created karst conditions that allow rapid movement of water. The median dissolved-solids concentration was 322 mg/L (fig. 2*C*). In southeastern, western, and northern Missouri, water in this aquifer becomes saline, with a maximum dissolved-solids concentration larger than 5,000 mg/L. Substantial quantities of water for public, irrigation, industrial, and domestic supplies are pumped from this aquifer. Localized human-induced contamination occurs in this aquifer (fig. 3) from hazardous waste, landfills, and other sources.

Kimmswick-Potosi Aquifer

The Kimmswick-Potosi aquifer consists of consolidated dolomite and some sandstone that are generally confined. The top of this aquifer is about 1,800 feet below land surface (U.S. Geological Survey, 1985). This aquifer is a primary source of water in a seven-county area north of the Missouri River. Recharge occurs primarily from precipitation infiltrating overlying aquifers. The aquifer has low permeability. The median dissolved-solids concentration was 489 mg/L (fig. 2*C*). The maximum dissolved-solids concentration was about 4,700 mg/L to the north where water becomes saline. The median concentration of fluoride was 1.0 mg/L and sulfate was 56.0 mg/L, which were the largest median values of all six principal aquifers. No human-induced contamination has been recognized in this aquifer.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water concerns in Missouri have been identified by the Missouri Department of Natural Resources (MDNR) (1986a,b). MDNR (1986b) ranked the most important sources of ground-water contamination in the State, in order of decreasing importance as follows: abandoned hazardous waste sites (including radioactive waste sites), surface impoundments, underground storage tanks, and septic systems. Other major sources that have the potential to contaminate ground water are: solid-waste landfills, surface and underground mining, wells, transport, and agriculture. Human-related activities appear to be the most significant source of current (1986) and potential changes to ground-water quality.

Hazardous-Waste Sites

Twelve sites in Missouri (fig. 3*A*) have been evaluated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 and have been included in the National Priorities List (NPL) (U.S. Environmental Protection Agency, 1986c). Ground water is contaminated at seven of these sites. Also, 44 sites have been evaluated under the Resource Conservation and Recovery Act (RCRA) of 1982 (fig. 3*A*). Ground water has been contaminated at nine of these sites. The MDNR annually compiles a registry of confirmed, abandoned, or uncontrolled hazardous-waste sites in the State which include some, but not necessarily all, CERCLA and RCRA sites. A total of 81 sites has been proposed for the State registry, and currently (1986) 50 sites are listed in this registry (Missouri Department of Natural Resources, 1986d). Of these 50 sites, 23 are contaminated with dioxin (2, 3, 7, 8-tetrachlorodibenzo-p-dioxin).

Dioxin was formed as a byproduct in the manufacture of the herbicide Agent Orange, and the antiseptic hexachlorophene. Dioxin-contaminated waste oil was spread on roads and in horse stables for dust control at 45 sites in the state (Catherine Barrett, U.S. Environmental Protection Agency, oral commun., 1986).

During 1973, roads in the city of Times Beach (St. Louis County) were contaminated with dioxin. Subsequently, starting in 1983, the U.S. Environmental Protection Agency (EPA) relocated residents and purchased property in the affected areas (Catherine Barrett, U.S. Environmental Protection Agency, oral commun., 1986). Other major areas in Missouri affected by dioxin include facilities at Verona and Springfield where the byproduct was manufactured or stored, and areas in and near St. Louis County. Excavated material contaminated with dioxin was used as fill-dirt in some residential areas.

The city of Republic's well 1 was removed from service after being contaminated with trichloroethylene (TCE). Concentrations of this chemical were as much as 140 μg/L (Missouri Department of Natural Resources, 1986d), exceeding the national drinking-water standard of 27 μg/L.

Ground water at two sites in Missouri has been contaminated with low-level radioactive waste. Four pits and a quarry located at Weldon Spring (St. Charles County) were used to dispose waste generated by a uranium processing plant (Kleeschulte and Emmett, 1986). Locally, the bedrock aquifer (fig. 3) and Burgermeister Spring (St. Charles County) have been found to be contaminated with nitrates, lithium, and uranium (Kleeschulte and others, 1986).

Surface Impoundments

Storage and treatment lagoons are used to contain chemical byproducts and residues, and allow natural biodegradation of sanitation waste. Privately owned lagoons are not required to be licensed or inspected; therefore, no estimates are available on the total number of privately owned lagoons in the State. Operators of lagoons that discharge treated animal or human waste into streams must obtain a permit under the National Pollutant Discharge Elimination System (NPDES). About 1,200 lagoons have been permitted by the MDNR under NPDES. In addition, the Department estimates that 1,300 lagoons are used as nondischarging storage facilities for wastes. The Department estimates that another 1,300 lagoons are operated for purposes that do not require permits. About 30 surface impoundments are used to store liquid chemical waste (John Ford, Missouri Department of Natural Resources, Division of Environmental Quality, oral commun., 1986).

Sudden formation of sinkholes may cause surface-impoundment failures. During 1966, a major lagoon operated by the city of West Plains (Howell County) collapsed and leaked about 136 acre-feet of effluent in 52 hours, or an average rate of about 30 cubic feet per second (Aley and others, 1972). Later data indicated that the effluent was traced to Mammoth Spring, Arkansas, about 25 miles distant (James E. Vandike, Missouri Department of Natural Resources, oral commun., 1986).

A sewage lagoon operated by the city of Republic suddenly collapsed in 1968. An estimated 4 million gallons of sewage entered the ground-water system. Dye and effluent were traced 1 to 1.5 miles from the lagoon, reappearing in two domestic wells (Aley and others, 1972).

Underground Storage Tanks

Leakage from underground storage tanks is a relatively new and potentially widespread problem. Estimates indicate that as many as 25 percent of underground storage tanks may leak (Missouri Department of Natural Resources, 1986a). The Department currently (1986) is compiling an inventory of all underground storage tanks in Missouri, excluding those used for private-home heating oil. A total of 23,000 tanks have been inventoried, about one-half of the estimated total based on studies in other parts of the country (Gordon Ackley, Missouri Department of Natural Resources, written commun., 1986). About 90 percent of these tanks contain petroleum-related products and the remainder contain chemicals. The Department's Emergency Response Team has investigated about 135 reports of leaking underground storage tanks from 1980 to 1986.

Septic Tanks

Waste from septic-tank leach fields can contaminate ground-water systems with untreated sewage. In urban areas, this problem is compounded by closely spaced homes, each utilizing private septic systems. Wells withdrawing water may induce a more rapid downward infiltration of leachate from overlying surficial material. Where water levels are shallow, as in alluvial aquifers, leachate may have to travel only 5 to 10 feet downward before reaching ground water. Shallow wells, used as drinking-water supplies, may be affected by this relatively unfiltered leachate.

Solid-Waste Landfills

Missouri's Solid Waste Management Law (1972) requires that all solid-waste landfills operated since 1972 must be operated under a permit and inspected periodically. No information is available to determine the location of landfills operated before 1972 or the type of waste that landfills have received. Currently (1986), 220 permitted solid-waste landfills (fig. 3*C*) are in the State, of which 128 are active and 92 are inactive. The MDNR classifies landfills according to the type of facility and waste received. The largest category is sanitary landfills, of which there are 101 active and 65 inactive sites (Miles Stotts, Missouri Department of Natural Resources, written commun., 1986).

No estimates are available on the total number of private or non-permitted landfills; however, the MDNR currently is compiling an inventory of these types of landfills. Landfills that are not operated under permits represent a potential source of contamination to ground-water systems. Several examples of non-permitted landfills containing toxic materials have been documented (Missouri Department of Natural Resources, 1986d).

Fullbright landfill, located near Springfield, has been placed on the National Priorities List of CERCLA sites. This non-permitted site contains cyanide, acid, plating residues, trichloroethylene (TCE), paint, waste oil, and pesticide residue (Missouri Department of Natural Resources, 1986d). In 1967, one person died from cyanide poisoning and another person was overcome by fumes at the site (Missouri Department of Natural Resources, 1986d).

Westlake landfill, located in St. Louis County, accepted solvents, pesticides, acids, and material containing radionuclides. The site has been contaminated with 4,000 tons of chlordane, trichloroethylene, and toluene, as well as 7,000 tons of low-level uranium-ore waste. The shallow water surface in the alluvium along the Missouri River may provide an easy path for these contaminants to enter the river (Missouri Department of Natural Resources, 1986d).

Surface and Underground Mining

Surface mining of coal and mineral resources occurs in northern, western, and southeastern Missouri. Underground mining of lead and zinc occurs in southcentral Missouri and has been discontinued in southwestern Missouri.

Ground water at coal strip mines, located in western and northern Missouri, is acidic and generally contains large concentrations of dissolved metals. Acid drainage from these mines may contaminate surface- and ground-water supplies. The MDNR Land Reclamation Program has undertaken reclamation projects at several abandoned sites in the State. At an abandoned coal strip mine and processing plant in western Missouri, before reclamation, ground water had a dissolved-solids concentration of 10,000 mg/L and pH values as small as 2.3. The concentration of total iron was 1,800,000 μg/L (micrograms per liter) and sulfate was 6,300 mg/L (data from U.S. Geological Survey files). A spring discharging from the mine site had a dissolved-solids concentration of about 8,500 mg/L. After reclamation, dissolved-solids concentration in the spring discharge decreased to about 3,800 mg/L. Ground water in the Macon County area of northern Missouri has been locally affected by coal strip mining. In this area, the reported concentrations of selected constituents were: dissolved-solids, 18,000 mg/L; iron, 29,000 μg/L; and sulfate, 400 mg/L. The pH values were as small as 4.2 (Hall and Davis, 1986). Ground water in this area generally is not used; however, water from springs and seeps at these sites can flow into streams that are used as public supplies.

Missouri has been a leading producer of lead and zinc ore since the 1800's. Numerous abandoned lead and zinc mines that are now flooded are located in southwestern Missouri near the Joplin and Webb City (Jasper County) areas. Water in these mines typically contains larger than normal concentrations of dissolved solids and metals. The average dissolved-solids concentration was reported to be more than 1,000 mg/L, dissolved lead was reported to be 10 μg/L, and zinc was reported to be about 9,400 μg/L (Barks, 1977). Webb City, which obtains water from the Ozark aquifer underlying the abandoned mine area, removed a well from service because the water contained excessive dissolved solids. Lead and zinc ore also is produced in southeastern Missouri. Two ground-water samples collected from the Ozark aquifer in this area had lead concentrations of 59 and 106 μg/L, which exceed national drinking-water standards of 50 μg/L.

Wells

Water wells and test wells that have been abandoned or were improperly constructed may allow contamination of potable water supplies. Water-well drillers must now be licensed in the State, which will decrease the occurrence of well-casing failure because of improper construction. Public-supply wells and exploratory holes for oil, gas, and minerals must be plugged if abandoned; however, numerous abandoned private wells and old exploration holes that were not plugged have been documented (Missouri Department of Natural Resources, 1986b). Surface contamination may enter the ground-water system through these wells and open holes. Also, these wells and open holes may provide an interaquifer path for contaminated water to enter adjacent freshwater aquifers. Injection wells regulated under the Underground Injection Control Program (U.S. Environmental Protection Agency, 1984) may allow contamination of water supplies. In the State, no wells are used to inject hazardous, industrial, or municipal wastes underground that have been categorized by the EPA (1984) as Class I wells. Currently (1986), there are a total of 542 Class II wells used for recovery of oil and gas, 447 Class V wells used for ground-water heat pumps, 250 Class V storm drainage wells which use sinkholes to accept storm runoff, and 4,326 Class V wells and shafts associated with mine back fill (K.L. Deason, Missouri Department of Natural Resources, written commun., 1986).

Transport

Crude oil, refined petroleum products, liquified propane gas, and bulk fertilizers are transported through Missouri by a network of pipelines. Numerous other materials are transported by railroad and highway. Pipeline breaks, train derailments, and trucking mishaps can cause contaminants to "locally" enter ground-water systems. In Missouri, about 2,000 miles of pipeline transport crude oil and about 2,600 miles of pipeline transport refined petroleum products, liquified propane gas, and bulk fertilizers (Missouri Department of Natural Resources, 1982). Contamination of ground water by pipeline leaks has occurred in Missouri. One such leak occurred in central Missouri during 1981, when fertilizer leaked from a pipeline, traveled down a stream, and entered the ground-water system through a losing section of stream. About 8 days later, fertilizer appeared in a major spring about 13 miles from the original spill, damaging aquatic life. A dye-trace study after the spill indicated a flow velocity of about 1.1 mi/d (J.E. Vandike, Missouri Department of Natural Resources, written commun., 1986). Also, spills during railroad and highway transport can cause ground-water contamination in Missouri.

Agriculture

Use of insecticides, herbicides, and fungicides has increased throughout the State for both regulated and non-restricted categories of pesticides. Based on 1984 crop-acreage data (Tauchen, 1985) and an average rate of application for the most commonly used pesticides, an estimated 500,000 pounds of dry and 1 million gallons of liquid pesticides were applied to crops grown in southeastern Missouri. Few data currently (1986) are available on the regional occurrence of pesticides in ground water, and water from only a few test wells in southeastern Missouri has been documented as being contaminated with pesticides (James Burris, Missouri Department of Natural Resources, written commun., 1986). Currently (1986), no agency or program in the State monitors the sale or use of non-restricted pesticides.

A system of drainage ditches was constructed during the early 1900's in southeastern Missouri to drain swamp lands for agricultural use. Water from the shallow alluvial aquifer discharges into

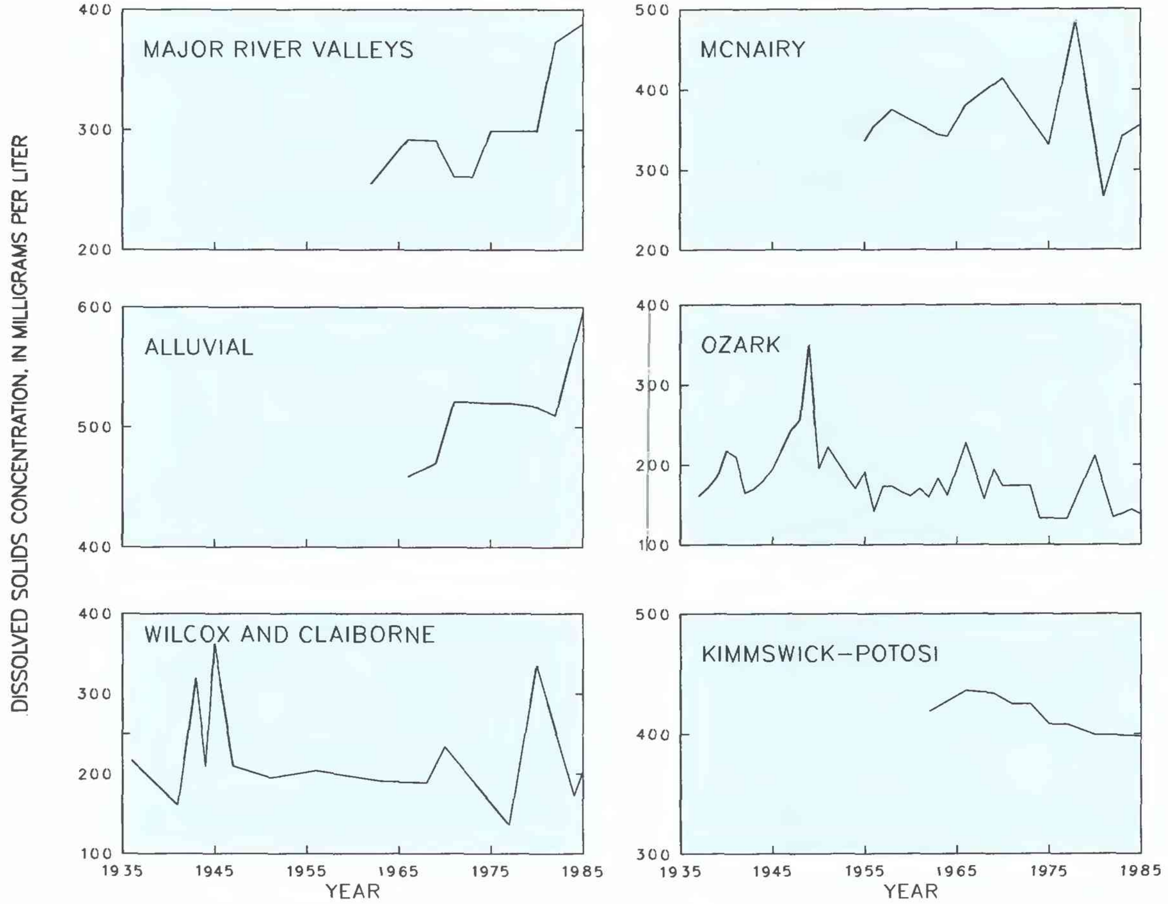

Figure 4. Long-term fluctuations of dissolved-solids concentration in selected wells in the principal aquifers of Missouri, 1936-85. (Source: Missouri Department of Natural Resources, Census of Missouri Public Water Supplies.)

the ditches, and sediment eroded from the surficial material is transported in these ditches. Water, bottom-sediment, and fish-tissue samples collected by the U.S. Army Corps of Engineers (1980) from ditches in Mississippi County indicate "...pesticides dieldrin, diazinon, DDT, benzene hexachloride (BHC), heptachlor, aldrin, DDD, and Lindane were all detected in water at concentrations above the maximum levels for protection of aquatic life. Toxaphene was detected at levels up to 3 μg/L, far above the maximum acceptable level defined by EPA for fish and wildlife."

Luckey (1985) detected aldrin, chlordane, DDD, and DDE in bottom sediments from major rivers and ditches draining southeastern Missouri. The EPA sampled major drainage ditches in southeastern Missouri during 1986 and detected concentrations of atrazine, alachlor, metoalachlor, and parathion in water samples (Norm Crisp, U.S. Environmental Protection Agency, written commun., 1986).

Water-Quality Trends

Water quality in the six principal aquifers fluctuates (fig. 4); however, no long-term degradation has been noted. Dissolved-solids concentrations in water from the alluvial aquifers (major river valleys and southeastern Missouri) have increased slightly since the 1960's, but the duration of data is not sufficient to prove degradation is occurring. Water from the Wilcox, Claiborne, and McNairy aquifers is used primarily for public supplies. Dissolved-solids concentrations have varied about 200 mg/L, but data are insufficient to indicate that water quality is being degraded in these aquifers. Data shown for the Ozark aquifer were compiled for a public water supply in western Missouri located near the saline water-freshwater transition zone. Almost 50 years of data indicate that the water quality has remained relatively constant. Data for other sites near the transition zone (Kleeschulte and others, 1985) indicate that the water quality has not changed since the late 1800's, even though the Ozark aquifer is intensively pumped for public and irrigation water supplies. The Kimmswick-Potosi aquifer is intensively used for public and irrigation supply; however, since the early 1900's water quality in this aquifer has not changed appreciably (Emmett and Imes, 1984).

POTENTIAL FOR WATER-QUALITY CHANGES

Densely populated areas of Missouri are located adjacent to the Missouri and Mississippi Rivers (fig. 1). The shallow water levels, characteristic of the major river valley aquifers, make these aquifers susceptible to contamination from landfills and accidental industrial spills. Although modern methods of waste disposal are improving, the large quantities of waste from metropolitan areas increase the potential for ground-water contamination.

The shallow water levels in the alluvial aquifer in southeastern Missouri make it susceptible to contamination. This aquifer is used for public, domestic, and irrigation supplies. Contamination can occur because of the large volumes of pesticides used annually on land in the region.

The karst nature of the Ozark aquifer makes it susceptible to contamination from many sources. Once in the ground-water system, rapid flow through the karst conduits provides little filtering of water. Surficial soils and residuum provide some filtering of water; however, in many places these materials may be thin or absent. Also, sinkholes may provide a direct path for contaminants to enter the ground-water system.

A saline water-freshwater transition zone is located along the northwestern boundary of the Ozark aquifer and along the northern boundary of the Kimmswick-Potosi aquifer. Although this transition zone has not moved a substantial distance during recent years, increased pumpage along the freshwater side of the transition zone may result in saline water moving into previously freshwater areas.

In Jasper and Newton counties in southwestern Missouri (fig. 3*B*), past lead and zinc mining has occurred in the Mississippian-age rocks that overlie the Ozark aquifer. Water in these abandoned mines has large concentrations of dissolved solids (Barks, 1977; Harvey and Emmett, 1980) and a potential to migrate downward, thereby contaminating the Ozark aquifer. A confining layer separates the two units; however, in places it is thin and locally may be fractured. Increased withdrawals of water from the Ozark aquifer could increase the potential for downward flow of water and contamination of this aquifer.

GROUND-WATER-QUALITY MANAGEMENT

The Missouri Department of Natural Resources (1986a) has proposed a ground-water protection strategy for the State. This strategy will coordinate existing legal and regulatory authority toward maintaining or restoring ground-water quality. The two agencies within the Department that currently (1986) are and will continue to be responsible for monitoring ground-water quality are the Division of Environmental Quality and the Division of Geology and Land Survey.

The Division of Environmental Quality, through its five programs, currently is responsible for protecting and enhancing the quality of the environment in Missouri. These programs are the Public Drinking Water Program, the Water Pollution Control Program, the Waste Management Program, the Land Reclamation Program, and the Laboratory Services Program.

Under the Public Drinking Water Program, about 985 public water supplies are monitored for bacteriological, chemical, and radiological constituents and properties. Monitoring of public water supplies began in 1919 under the direction of the Missouri Board of Health. Currently (1986) this program enforces the Missouri Safe Drinking Water Standard in accordance with the Federal Safe Drinking Water Act. This standard sets the acceptable levels of various constituents in raw surface and ground water that is used for public water supplies.

Under the Water Pollution Control Program, the policies of the Clean Water Commission and State and Federal clean water laws are implemented. Also, the quality of surface and ground water entering the State is monitored. This program enforces the Missouri Water-Quality Standard, which sets the maximum allowable concentrations of contaminants with respect to the intended use of the water. For example, if a leachate from a coal-spoil pile degrades the quality of nearby ground water that is used for public or domestic drinking supplies, the owners of the spoil pile must improve the ground-water quality so that it meets the Missouri Water-Quality Standard.

Under the Waste Management Program, solid and hazardous waste is regulated to ensure that storage or disposal does not adversely affect ground-water quality. As part of this program, permits are issued to transporters of hazardous waste and to operators of hazardous- and solid-waste disposal facilities. The program inspects these facilities to insure they are properly operated. Under this program, the Division also implements the policies of the Missouri Waste Management Commission, which sets regulations for the transportation, treatment, storage, and disposal of hazardous and non-hazardous wastes.

The Land Reclamation Program implements the policies of the Land Reclamation Commission, which regulates surface mining and reclamation of abandoned coal mined lands. Also, this program issues permits to surface mines and inspects mining and reclamation projects.

The Laboratory Services Program provides technical support to the other programs within the Division of Environmental Quality. As part of this program, the Division maintains an environmental response unit that coordinates Federal, State, and local agencies after accidental spills of hazardous material.

The Division of Geology and Land Survey is responsible for identifying the potential use and development of mineral, land, energy, and water resources in Missouri. The Geological Survey and Water Resources Program is the only program within the Division that is involved with ground-water resources. The responsibilities of this program are to identify ground-water resources, document ground-water quality and use, provide technical support to other agencies and programs, and monitor underground injection control wells.

Although the principal function of the Geological Survey and Water Resources Program is data and information gathering, the program also currently (1986) is writing regulations on water-well construction to accompany a recently passed Well Drillers Licensing Law. These regulations will require that certain standards be used when constructing a well. As part of the Geological Survey and Water Resources Program, policies set forth by the Oil and Gas Council are enforced which indirectly affect ground-water quality. The Council regulates the drilling, spacing, producing, and plugging of oil and gas wells and also has jurisdiction over illegal, malfunctioning, and unplugged wells.

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Greer Spring in southern Missouri. Greer Spring is the second largest spring in Missouri. (Photograph by James E. Vandike, Missouri Department of Natural Resources.)

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MONTANA
Ground-Water Quality

About 54 percent of Montana's 786,000 population (fig. 1) uses ground water for domestic purposes. However, the quantity of ground water withdrawn for domestic use is less than 0.5 percent of total statewide surface- and ground-water withdrawals (Montana Department of Natural Resources and Conservation, 1986). Remaining ground-water withdrawals for irrigation, livestock, and industry are about 1.5 percent of total water withdrawals (Solley and others, 1983). Although ground-water quality in Montana is not thought to be threatened by contamination (Montana Department of Health and Environmental Sciences, 1984) and the overall quality is suitable for many uses, ground-water supplies at several locations in the State have been degraded.

Concentrations of dissolved solids in ground water commonly exceed the national secondary drinking-water standards of the U.S. Environmental Protection Agency (1986b), particularly in principal aquifer groups of eastern Montana (fig. 2). A statistical analysis of computer-accessible ground-water-quality data in Montana indicates that the median dissolved-solids concentration for aquifer groups in the eastern part of the State ranged from about 400 to 5,000 mg/L (milligrams per liter) (Davis and Rogers, 1984). For aquifer groups in the western part, the median dissolved-solids concentration ranged from about 100 to 200 mg/L. Concentrations of trace constituents generally do not exceed the national primary drinking-water standards of the U.S. Environmental Protection Agency (1986a). Few computer-accessible data are available for organic constituents in ground water.

Several areas of ground-water contamination in Montana have inhibited the intended use of wells and required alternative supplies of water (fig. 3*A*, 3*B*). Sources of ground-water contamination as a result of human activity include saline seeps, mining, accidental spills, septic tanks and drain fields, oil and gas exploration, solid-waste-disposal landfills, municipal and industrial wastewater disposal, and leaking petroleum-storage tanks and delivery systems (Montana Department of Health and Environmental Sciences, 1984). A comprehensive ground-water-quality monitoring network has not been developed and ground-water-quality data generally have been collected in response to specific problems. Consequently, statewide ground-water-quality conditions and trends have not been well established.

Montana has seven sites (fig. 3*A*) on the National Priorities List for evaluation of hazardous waste under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

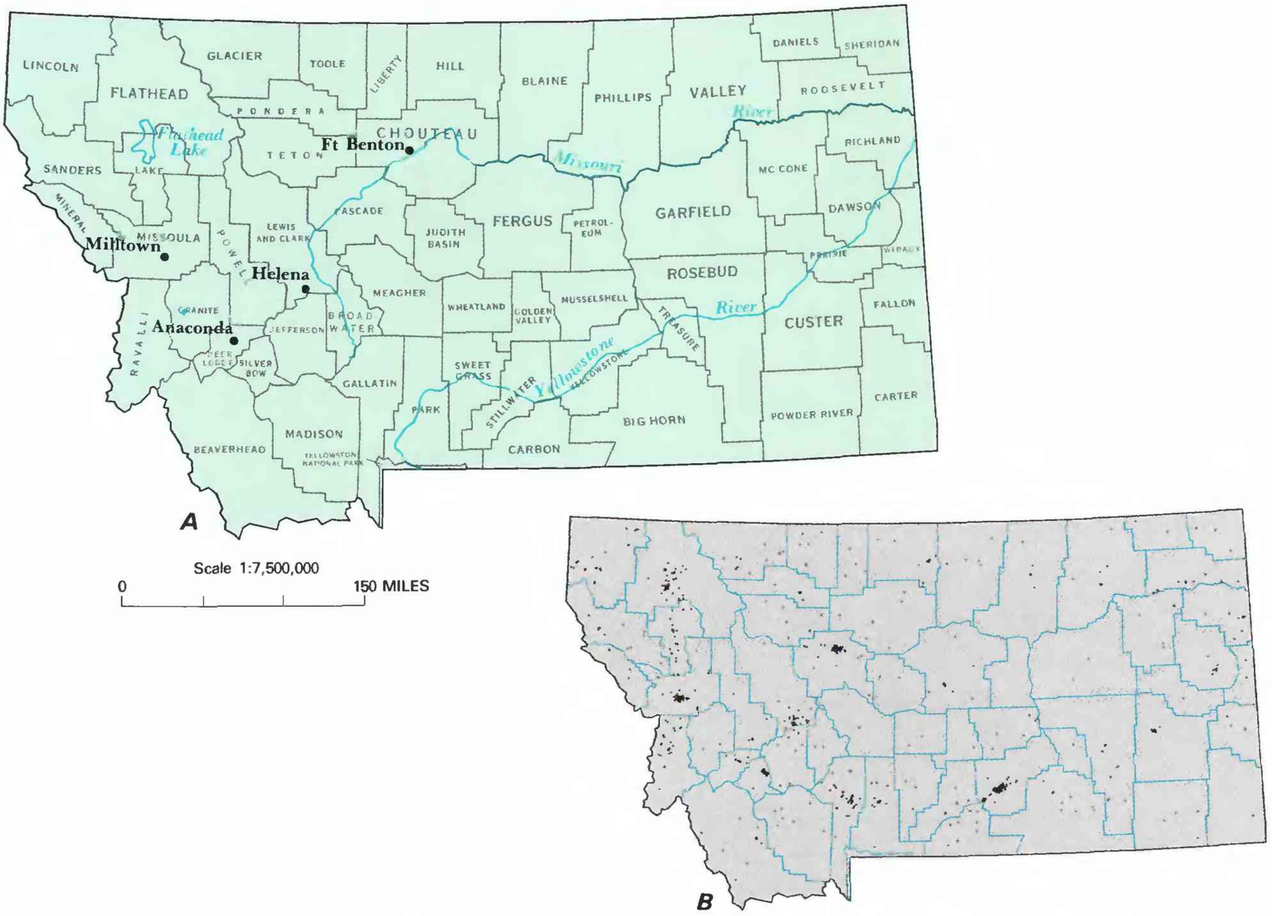

Figure 1. Selected geographic features and 1985 population distribution in Montana. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

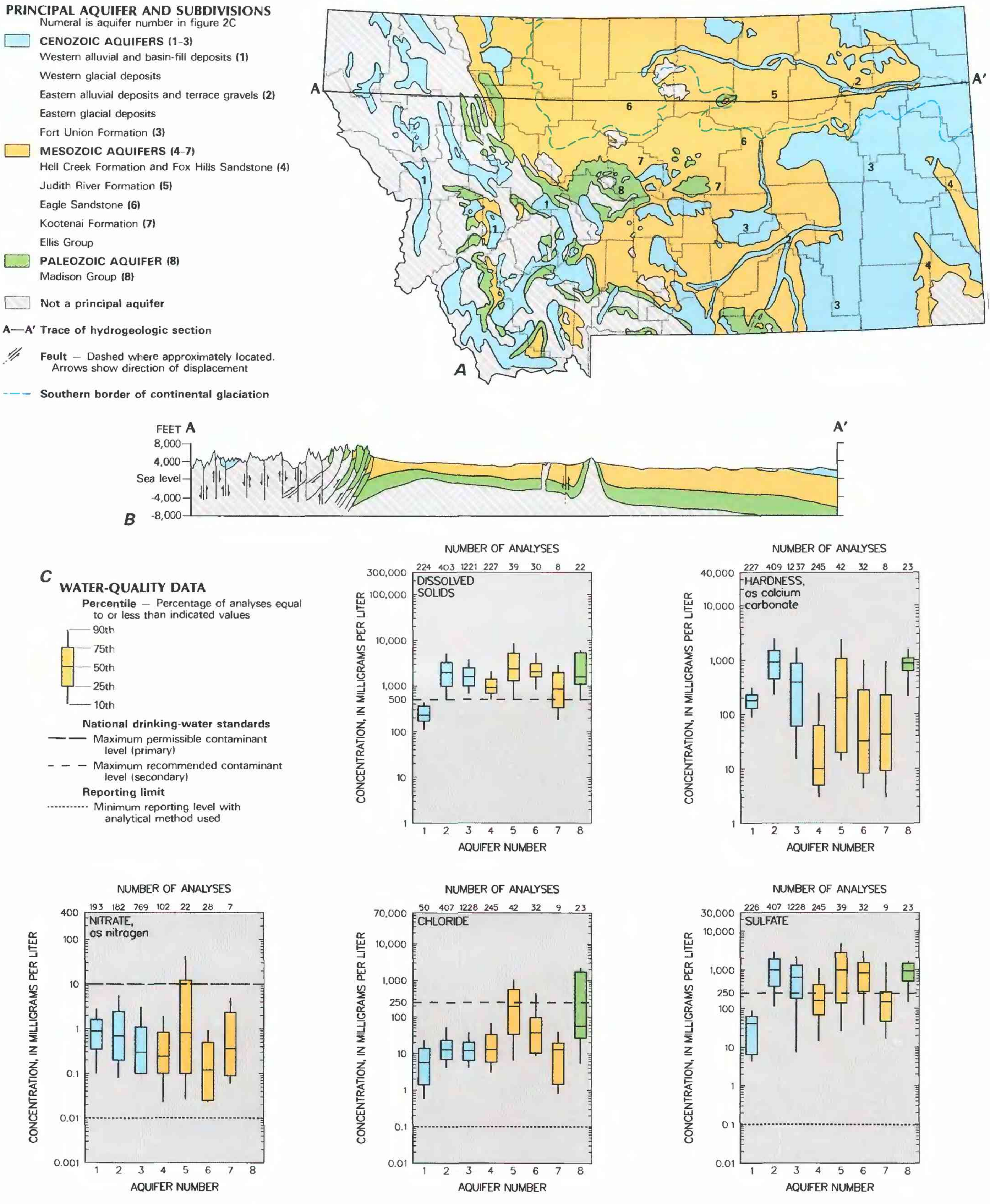

Figure 2. Principal aquifers and related water-quality data in Montana. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1965-85. (Sources: *A*, Ross and others, 1955. *B*, American Association of Petroleum Geologists, 1972. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

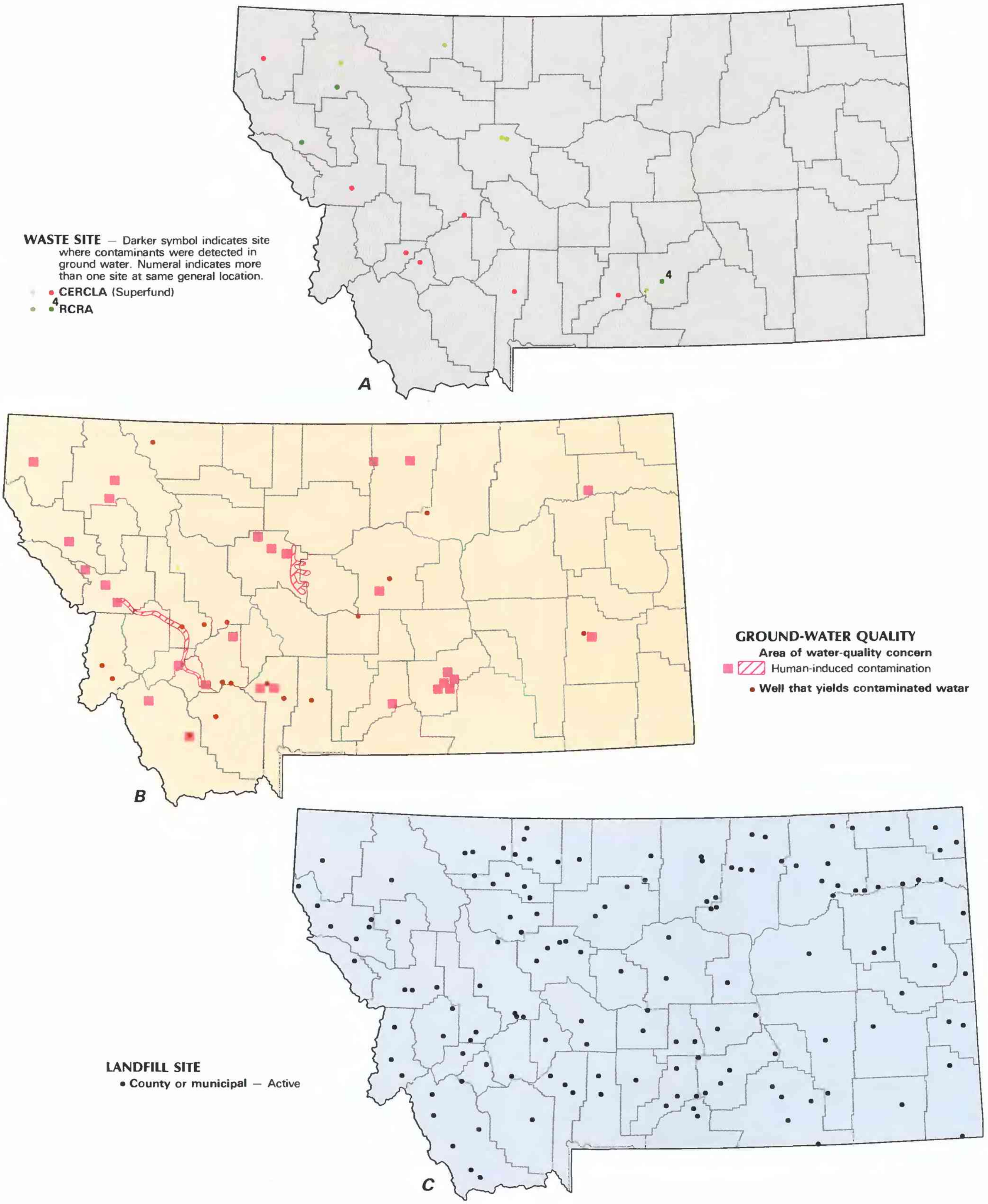

Figure 3. Selected waste sites and ground-water-quality information in Montana. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites and Resource Conservation and Recovery Act (RCRA) sites, as of 1986. *B*, Areas of human-induced contamination and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, R.C. Thorvilson, Montana Department of Health and Environmental Sciences, written commun., 1986; U.S. Environmental Protection Agency, 1986c. *B*, J.L. Arrigo, Montana Department of Health and Environmental Sciences, written commun., 1986; modified from Montana Department of Health and Environmental Sciences, 1986. *C*, J.E. Leiter, Montana Department of Health and Environmental Sciences, written commun., 1986.)

of 1980. An additional site, proposed to be included as a CERCLA site, is included with 11 sites that require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 (fig. 3*A*). Several additional sites are being investigated (1986) for potential ground-water contamination and possible inclusion in the CERCLA program. Some of these sites include landfills (fig. 3*C*) and other areas of human-induced contamination (fig. 3*B*).

WATER QUALITY IN PRINCIPAL AQUIFERS

Montana has two distinct hydrogeologic regimes that generally coincide with the western and south-central parts of the State and the eastern and north-central parts of the State (fig. 2*A*). Rocks in western and south-central Montana are severely faulted (fig. 2*B*); principal aquifer groups consist of Cenozoic alluvial and basin-fill deposits and glacial deposits. Principal aquifer groups in the eastern and north-central parts consist of Cenozoic alluvial deposits and terrace gravels, glacial deposits, and the Fort Union Formation; the Mesozoic Hell Creek Formation and Fox Hills Sandstone, Judith River Formation, Eagle Sandstone, Kootenai Formation, and Ellis Group; and the Paleozoic Madison Group. The Cenozoic aquifers primarily are unconsolidated to semiconsolidated gravel, sand, silt, and clay. Water in these aquifers generally is unconfined. The Mesozoic aquifers primarily are sandstone, siltstone, shale, and limestone. The Paleozoic aquifer primarily is limestone with some dolomite, anhydrite, and halite. Water in the Mesozoic and Paleozoic aquifers generally is confined except in outcrop areas.

Recharge to the ground-water systems mainly is from infiltration of precipitation in outcrop areas, although recharge also occurs by infiltration of streamflow in some areas and by leakage between aquifers. The annual rate of recharge is estimated to range from less than 1 inch in parts of the eastern plains to several inches in the western mountains.

Discharge from ground-water systems is variable. Generally, shallow ground water flows from topographically high areas toward local surface drainages, and deeper ground water flows toward major surface drainages.

Most ground-water withdrawals in Montana are from the near-surface Cenozoic aquifers, although water from all aquifers is used to some extent. A more complete description of aquifers and withdrawals is contained in a report by the U.S. Geological Survey (1985, p. 285–290).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved solids, hardness, nitrate (as nitrogen), chloride, and sulfate analyses of water samples collected from 1965 through 1985 from principal aquifers in Montana. Percentiles of these variables are compared to national primary and secondary drinking-water standards of the U.S. Environmental Protection Agency (1986a,b) that specify the maximum concentration or level of a contaminant in a drinking-water supply. The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary standards include a maximum concentration of 10 mg/L for nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L for dissolved solids, 250 mg/L for chloride, and 250 mg/L for sulfate.

Water from the principal aquifers generally can be classified as calcium bicarbonate in the western and south-central parts of Montana and as sodium bicarbonate or sodium sulfate in the eastern and north-central parts. The summary shows considerable ranges in values. Most dissolved-solids concentrations exceed the standard, and figure 2*C* indicates that hardness varies considerably; many areas yield water that is hard or very hard (Durfor and Becker, 1964). Dissolved nitrate and chloride seldom occur in concentrations that exceed the drinking-water standards. However, sulfate concentrations commonly exceed the drinking-water standard in most aquifers except in the western alluvial and basin-fill deposits, the Hell Creek Formation and Fox Hills Sandstone, and the Kootenai Formation. Following are detailed descriptions of water quality in each of the principal aquifer groups of Montana.

Cenozoic Aquifers

WESTERN ALLUVIAL AND BASIN-FILL DEPOSITS

Generally, the western alluvial and basin-fill deposits are located along streams, and adequate water supplies for stock, rural-domestic, and some irrigation uses can be obtained within several hundred feet of land surface. Water in the deposits generally is unconfined, although clay lenses may result in locally confined conditions.

The alluvial deposits are one of the most widely used sources of ground water because of favorable water-yielding characteristics. In most areas, the quality of water from the deposits is suitable for many uses. On the basis of median values of major dissolved constituents, calcium and bicarbonate ions are predominant (Davis and Rogers, 1984).

Fifty percent of the water samples collected from these deposits from 1965 through 1985 had dissolved-solids concentrations less than 230 mg/L, the smallest median dissolved-solids concentration among the principal aquifers in Montana (fig. 2*C*). The median hardness value was 180 mg/L, which classifies about one-half of the ground-water samples as being very hard. The median concentrations for nitrate (0.89 mg/L), chloride (5.7 mg/L), and sulfate (41 mg/L) did not exceed the drinking-water standards.

WESTERN GLACIAL DEPOSITS

The western glacial deposits consist of two units: glacial till and glaciolacustrine deposits. The deposits generally are less than several hundred feet thick and can transmit substantial quantities of water. Water in the deposits generally is unconfined, although locally may be confined.

Water from the western glacial deposits probably is suitable for most uses, although few data are available in WATSTORE for this aquifer. On the basis of median values of major dissolved constituents, calcium and bicarbonate ions are predominant (Davis and Rogers, 1984). Ground-water-quality data in WATSTORE for 1965 through 1985 were insufficient to determine median values of dissolved solids, hardness, nitrate, chloride, and sulfate.

EASTERN ALLUVIAL DEPOSITS AND TERRACE GRAVELS

Water in the eastern alluvial deposits and terrace gravels generally is unconfined, although clay lenses locally may cause confinement. The alluvial deposits and terrace gravels produce the most substantial quantities of ground water in eastern Montana. However, use may be limited in localized areas because of the quality.

Water from the eastern alluvial deposits and terrace gravels is used for many purposes, even though the dissolved-solids concentration commonly exceeds the drinking-water standard. On the basis of median values, sodium, magnesium, and sulfate ions are predominant (Davis and Rogers, 1984).

The median dissolved-solids concentration of 2,000 mg/L indicates that most samples collected from 1965 through 1985 had concentrations that exceeded the drinking-water standard. In addition, 50 percent of the samples had hardness values larger than 920 mg/L, indicating that the water is very hard. The median concentrations of nitrate (0.70 mg/L) and chloride (13 mg/L) did not exceed the drinking-water standards. The median concentration for sulfate was 1,000 mg/L, which considerably exceeded the drinking-water standard.

EASTERN GLACIAL DEPOSITS

The eastern glacial deposits include several units. Water in the deposits generally is unconfined, although locally it may be confined. In some areas, the deposits can transmit significant quantities of water.

On the basis of median values of major dissolved constituents, calcium, magnesium, sodium, and sulfate ions are predominant (Davis and Rogers, 1984). Ground-water-quality data for 1965 through 1985 were insufficient to determine median values of dissolved solids, hardness, nitrate, chloride, and sulfate.

FORT UNION FORMATION

The Fort Union Formation is composed of several members. Water in the formation can be unconfined or confined, with flow toward local or major surface drainages. Water from the formation is used for domestic and livestock purposes, even though the dissolved-solids concentration commonly exceeds the drinking-water standard. Chemical characteristics of water in the formation tend to change with depth. For well depths of 200 feet or less, median concentrations of common ions indicate that sodium and sulfate ions are predominant. For well depths of more than 200 feet, sodium and bicarbonate ions predominate (Davis and Rogers, 1984).

Fifty percent of the ground-water samples collected from 1965 through 1985 had dissolved-solids concentrations larger than 1,600 mg/L. The median hardness concentration was 390 mg/L, which indicates that the water generally is very hard. The median concentrations for nitrate (0.30 mg/L) and chloride (12 mg/L) did not exceed the drinking-water standards. The median concentration for sulfate was 640 mg/L, which exceeded the drinking-water standard.

Mesozoic Aquifers

HELL CREEK FORMATION AND FOX HILLS SANDSTONE

Water in the basal sandstone of the Hell Creek Formation and the underlying Fox Hills Sandstone is either unconfined or confined. Wells completed in the aquifer can yield as much as 200 gal/min (gallons per minute), although most yields are about 20 gal/min or less. Water from wells completed in this aquifer is used mainly for livestock, rural-domestic, and public supply, even though the dissolved-solids concentration commonly exceeds the drinking-water standard. Chemical characteristics of water in the aquifer tend to change with depth. On the basis of median concentrations for well depths of 200 feet or less, sodium, bicarbonate, and sulfate ions are predominant. For well depths more than 200 feet deep, sodium and bicarbonate ions predominate (Davis and Rogers, 1984).

Fifty percent of the ground-water samples collected from 1965 through 1985 had dissolved-solids concentrations larger than 910 mg/L. The median concentration for hardness was 10 mg/L, which indicates that the water generally is soft. The median concentrations for nitrate (0.24 mg/L), chloride (13 mg/L), and sulfate (160 mg/L) did not exceed the drinking-water standards.

JUDITH RIVER FORMATION

Water in the Judith River Formation is both unconfined and confined. Yields of wells completed in the formation range from 1 to 100 gal/min and average about 10 gal/min.

The water is used for many purposes, even though the dissolved-solids concentration commonly exceeds the drinking-water standard. Chemical characterisics of water in the aquifer tend to change with depth. On the basis of median concentrations of common ions for well depths of 200 feet or less, sodium and sulfate ions are predominant. For well depths more than 200 feet, sodium, bicarbonate, and sulfate ions predominate (Davis and Rogers, 1984).

Fifty percent of the ground-water samples collected from 1965 through 1985 had dissolved-solids concentrations more than 2,400 mg/L, the largest median dissolved-solids concentration among the principal aquifers. The median hardness concentration was 200 mg/L, which indicates that much of the water is very hard. The median concentration for nitrate was 0.81 mg/L, but more than 25 percent of the samples exceeded the drinking-water standard. The median concentration for chloride was 195 mg/L, which did not exceed the drinking-water standard. The median concentration for sulfate was 1,000 mg/L, which substantially exceeded the drinking-water standard.

EAGLE SANDSTONE

Water is both unconfined and confined in the Eagle Sandstone. Yields of wells completed in the Eagle range from 0.5 to 200 gal/min and average about 20 gal/min.

Water from the Eagle Sandstone is used for many purposes, although the dissolved-solids concentration commonly exceeds the drinking-water standard. Chemical characteristics of water in the aquifer change with depth. On the basis of median concentrations for well depths of 200 feet or less, sodium and sulfate ions are predominant. For well depths more than 200 feet, sodium and bicarbonate ions predominate (Davis and Rogers, 1984).

Fifty percent of the ground-water samples collected from 1965 through 1985 had dissolved-solids concentrations larger than 2,050 mg/L. The median concentration for hardness was 32 mg/L, which indicates that the water generally is soft. The median concentrations for nitrate (0.12 mg/L) and chloride (37 mg/L) did not exceed the drinking-water standards. The median concentration for sulfate was 835 mg/L, which substantially exceeded the drinking-water standard.

KOOTENAI FORMATION

Water is both unconfined and confined in the Kootenai Formation, although confined conditions predominate. Yields from wells completed in the Kootenai Formation range from 1 to about 90 gal/min and average about 30 gal/min.

Water from the Kootenai Formation is used for many purposes, although dissolved-solids concentrations commonly exceed the drinking-water standard. Chemical characteristics of water in the aquifer tend to change with depth. On the basis of median concentrations for well depths of 200 feet or less, calcium, magnesium, and bicarbonate ions are predominant. For well depths more than 200 feet, calcium, sodium, and bicarbonate ions predominate (Davis and Rogers, 1984).

Fifty percent of the ground-water samples collected from 1965 through 1985 had dissolved-solids concentrations larger than 850 mg/L. The median hardness concentration was 43 mg/L, which indicates that the water generally is soft. The median concentrations of nitrate (0.36 mg/L), chloride (13 mg/L), and sulfate (150 mg/L) did not exceed the drinking-water standards.

ELLIS GROUP

The Ellis Group includes several formations. Water in the aquifer is both unconfined and confined.

Water from the Ellis Group is used for many purposes. On the basis of median concentrations, calcium and bicarbonate ions are predominant (Davis and Rogers, 1984). Ground-water-quality data from 1965 through 1985 were insufficient to determine median concentrations of dissolved solids, hardness, nitrate, chloride, and sulfate.

Paleozoic Aquifer

MADISON GROUP

The Madison Group includes several formations. Water in this aquifer is both unconfined and confined.

Water from the Madison Group is not used extensively because of the deep drilling generally required. The water is fresh near outcrops but increases in salinity with distance from outcrops (Feltis, 1980). On the basis of median concentrations, calcium and sulfate ions are predominant (Davis and Rogers, 1984).

Fifty percent of the ground-water samples collected from 1965 through 1985 had dissolved-solids concentrations larger than 1,600 mg/L. The median hardness concentration was 890 mg/L, which indicates that the water is very hard. The median concentration for nitrate was not determined because only two water samples were available. The median concentration for chloride was 57 mg/L, which did not exceed the drinking-water standard. The median concentration for sulfate was 960 mg/L, which substantially exceeded the drinking-water standard.

EFFECTS OF LAND USE ON WATER-QUALITY

Ground-water-quality problems in Montana are varied. Ground-water quality is affected by agricultural practices, leachates from mine spoils and tailings, and disposal or spills of wastes and petroleum products. Major contaminants that have entered some of Montana's ground-water-flow systems include hydrocarbons, trace metals, salts, pesticides, and fertilizers. Sites where ground-water quality has been affected, or has the potential to be affected, by human activity are shown in figures 3*A*, 3*B*, and 3*C*.

Contamination of ground water has caused the closure of some private and public wells in Montana. Estimates by the Montana Department of Health and Environmental Sciences indicate that 57 private wells and 5 public wells have been contaminated since 1975. On the basis of those estimates, about 172 people that obtain water from private wells and 263 people that obtain water from public wells have been using contaminated well water (J.L. Arrigo, Montana Department of Health and Environmental Sciences, written commun., 1986).

Agricultural Practices

Agricultural practices in the dryland crop areas of the central and eastern Montana plains have resulted in the widespread and rapidly expanding problem of saline seeps. Saline seeps are characterized by wet salty areas that are discharge zones for shallow water-table aquifers. The crop and fallow system used for much of the plains area promotes recharge from precipitation, which in turn causes the water tables to rise and to discharge saline water at the land surface. In 1969, 28 counties in Montana contained saline seeps that affected about 51,200 acres. In 1983, the affected area had increased to about 280,000 acres (Montana Department of Health and Environmental Sciences, 1984). The development of saline seeps near Fort Benton during 1941, 1951, 1956, 1966, and 1971 is shown in figure 4. Water from saline seeps generally is characterized as a sodium-magnesium sulfate type having dissolved-solids concentrations of 4,000 to 60,000 mg/L (Miller and others, 1980). Saline seeps have affected the quality of water in some domestic and livestock wells.

Degradation of ground water by pesticides and other chemicals has been studied by the Montana Department of Agriculture. Although no widespread contamination of ground water by application of fertilizers and pesticides has been documented, localized problems are known to exist. Some of these problems were caused by improper disposal of contaminated wash from spray equipment and spillage from aerial pesticide applicators.

Mining and Related Activities

Surface mining of coal from the Fort Union Formation in the eastern part of Montana has removed areas of coal and sandstone aquifers and replaced them with mine spoils. Where mine spoils have become saturated, they contain water generally having a dissolved-solids concentration larger than that of water from nearby stock and domestic wells (Van Voast and others, 1978). Water from the mine spoils has a large range of dissolved-solids concentrations, and some of the spoils water is unsuitable for use by livestock. Water-quality changes at the mines have affected few people or wells because of the sparse population of the area, the slow rate of ground-water movement from the mine spoils, and the availability of alternative water supplies.

Mine tailings, mine operations, and smelting have caused local contamination of ground water in several areas. In a mining area about 20 miles south of Helena, cadmium concentrations in water from domestic water wells exceed the drinking-water standard (Montana Department of Health and Environmental Sciences, 1984). Mine tailings in sediments at a reservoir near Milltown caused arsenic contamination of ground water in nearby downgradient areas. As a result, some wells of a public-supply well system that supplied water to 33 residences in Milltown were abandoned and replaced. Smelting operations in East Helena (5 miles east of Helena) and Anaconda are sources of trace-metal contaminants. At East Helena, arsenic and sulfate contamination was found in shallow ground water (Montana Department of Health and Environmental Sciences, 1986); however, drinking-water supplies for nearby residences have not been affected.

Waste Disposal and Spillage

Hazardous waste is treated, stored, or disposed at 11 RCRA sites that constitute a known or potential hazard to the quality of ground water (fig. 3*A*). The Montana Department of Health and Environmental Sciences has determined that contamination of shallow ground water has occurred at four of these sites. At the other seven sites, either no contamination has been detected or monitoring data have not been evaluated. Known or potential contaminants at the sites include sludges from petroleum refining wastewater at six sites, creosote sludge at two sites, solvents and related chemicals at two sites, and pesticide-formulating wastes at one site.

The seven sites in Montana listed by the U.S. Environmental Protection Agency as CERCLA (Superfund) sites are shown in figure 3*A*. Contaminants have been detected in shallow ground water at each of these sites. At five of these sites, metals (arsenic, cadmium, copper, iron, lead, and zinc) from ore processing or smelting are the source of contamination. At the other two sites, pentachlorophenol and other petroleum derivatives from wood-treating operations have entered the ground water.

Contamination of ground water by petroleum products from spills or leaking storage tanks is a significant problem. Petroleum-contamination problems have varied from a few gallons of gasoline leaking into a developed spring to hundreds of thousands of gallons of diesel fuel spread by ground-water flow beneath major railroad centers. From April 1982 to May 1986, 81 instances that relate to petroleum contamination were reported to the Water Quality Bureau of the Montana Department of Health and Environmental Sciences. Petroleum leaks and spills have degraded the quality of water in springs and rural-domestic and public water-supply wells and have caused gasoline vapors to enter storm drains, sewers, and buildings. Currently (1986), 15 locations of reported fuel leaks are being investigated by the Montana Department of Health and Environmental Sciences.

POTENTIAL FOR WATER-QUALITY CHANGES

The potential for contamination of ground-water supplies in Montana is difficult to assess. Although the estimated number of ground-water analyses for Montana exceeds 25,000, the data base is not sufficiently complete, centralized, or organized to allow analysis, identification, and quantification of contamination prob-

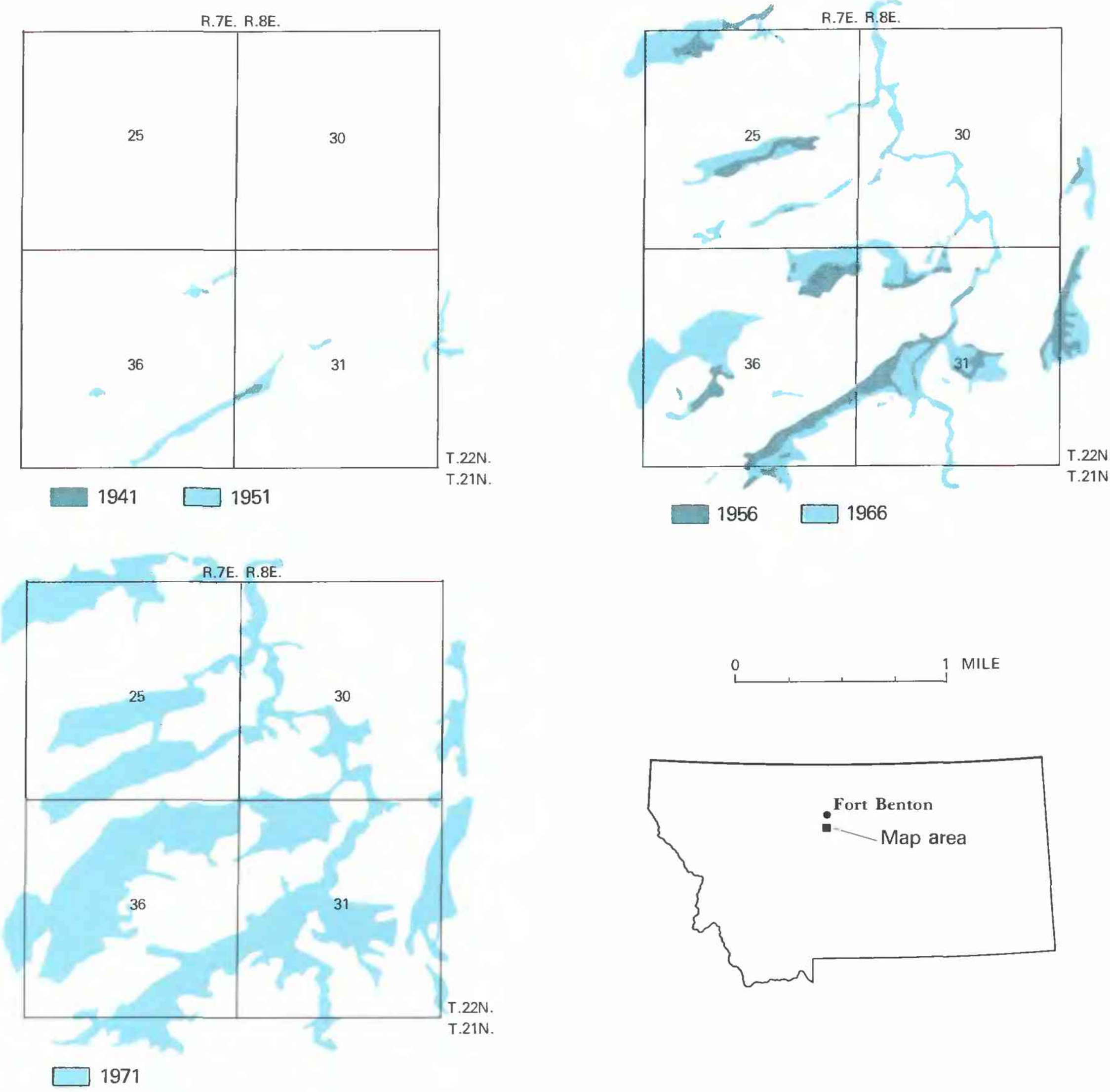

Figure 4. Saline-seep development in a 4-square-mile area near Fort Benton, Montana, 1941, 1951, 1956, 1966, and 1971. (Source: Miller and others, 1980.)

lems and trends (Davis and Rogers, 1984; Montana Department of Health and Environmental Sciences, 1984). A trend of increasing ground-water contamination in Montana is implied by the increasing number of reports of sites where hazardous materials have affected or have the potential to affect ground water. However, the increasing number of reports of sites could reflect the increased vigilance of governmental agencies and concerned citizens.

Saline seeps are considered by some to be most threatening to ground-water quality in the State (Montana Department of Health and Environmental Sciences, 1982). With present cropping practices, the areas affected by saline seeps could continue to expand at a rate of 10 percent per year (Miller and others, 1980).

Mined areas account for additional sources of ground-water contamination. Mining increases dissolved-solids and trace-metals concentrations locally. Because ground-water movement is slow in most areas, the effects of mining on ground-water quality are considered to be long term.

Petroleum contamination is becoming a major problem in near-surface ground water throughout Montana and even deeper ground water in some areas (Montana Department of Health and Environmental Sciences, 1984). As storage and transmission systems related to the petroleum industry become older, the potential for leaks increases. Because several years may elapse before detection of petroleum leaks, ground water under a large number of acres possibly is being contaminated each year.

GROUND-WATER-QUALITY MANAGEMENT

State ground-water regulations, termed the Montana Ground Water Pollution Control System, were promulgated by the Montana Department of Health and Environmental Sciences on October 29, 1982. The regulations include a ground-water classification system, ground-water-quality regulations, a nondegradation policy, and a permit system. The regulations also provide the Water Quality Bureau of the Department of Health and Environmental Sciences with emergency powers to protect the quality of existing and future beneficial uses of ground water.

The Montana Ground Water Pollution Control System primarily addresses the protection of ground water from potential pollution sources such as surface impoundments, waste piles, landfills, disposal systems, and releases from spills or unanticipated discharges. Operators of any of these potential pollution sources (except spills) are required to obtain a ground-water pollution-control permit as outlined under the system. Most of the approximately 30 existing permit sites under the system are gold-leach operations and industrial nonhazardous-waste storage and disposal facilities. A permit is not required for operations that were in existence before October 29, 1982. However, ground-water-quality regulatory objectives still must be maintained at these sites.

Montana Ground Water Pollution Control System rules do not require additional permitting for potential sources of ground-water pollution that are reviewed and approved or permitted under other regulations. They simply require compliance with the State's ground-water-quality regulations as outlined under the system. This situation results in joint review by the Water Quality Bureau and other State agencies on many projects that are excluded from the system's permitting requirements. Compliance with the regulations then is addressed within the approval or permit from the other agencies. Examples of these joint reviews are Major Facility Siting Act projects under the Department of Natural Resources and Conservation, permitting of mining and milling operations under the Department of State Lands, approval of subdivision and other public or private waste-treatment systems by the Water Quality Bureau, and review of CERCLA activities by the Department of Health and Environmental Sciences.

The management of regulated wastes in Montana is overseen by the Solid and Hazardous Waste Bureau of the Department of Health and Environmental Sciences. Because all waste-management sites have the potential to contaminate ground water, hazardous-waste treatment, storage, and disposal facilities are regulated under the Montana Hazardous Waste Act and are subject to regulations that generally are more stringent than those of the Montana Ground Water Pollution Control System. Permits for hazardous-waste treatment, storage, or disposal facilities are issued almost entirely by the staff of the Solid and Hazardous Waste Bureau. The Water Quality Bureau participates in the review and oversight of all CERCLA activities administered by Solid and Hazardous Waste Bureau or the U.S. Environmental Protection Agency. The Water Quality Bureau also is involved in locating, investigating, and evaluating sites where hazardous materials have been improperly managed or disposed or where they threaten ground-water quality.

The Montana Department of Agriculture has surveyed ground-water quality at several locations where mismanagement of pesticides is documented or suspected. If beneficial uses of ground water have been affected by the improper handling of pesticides, the Water Quality Bureau assists the Montana Department of Agriculture in formulating appropriate remedial actions. Corrective actions or compliance plans to maintain ground-water quality usually are administered by the Water Quality Bureau in situations involving pesticides that contaminate ground water.

The Montana Bureau of Mines and Geology is the primary ground-water research organization for the State of Montana. It is a source of ground-water information and data, including results of studies of specific ground-water problem areas; it also participates in the review of some CERCLA sites. Coordination between the Water Quality Bureau and the Montana Bureau of Mines and Geology is expected to increase in response to the Montana Ground-Water Information Center, which currently (1986) is being developed by the Montana Bureau of Mines and Geology.

The Water Quality Bureau also coordinates with Federal agencies involved in ground-water protection. Federal agencies such as the U.S. Geological Survey are a source of ground-water data and other information that result from data-collection activities and ground-water studies. The U.S. Geological Survey also participates in the review of CERCLA studies in cooperation with the Montana Department of Health and Environmental Sciences and the U.S. Environmental Protection Agency. Water Quality Bureau personnel commonly conduct joint inspections and review of ore-processing and storage facilities on Federal lands in cooperation with personnel from the U.S. Forest Service, the U.S. Bureau of Land Management, or the U.S. Bureau of Indian Affairs.

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NEBRASKA
Ground-Water Quality

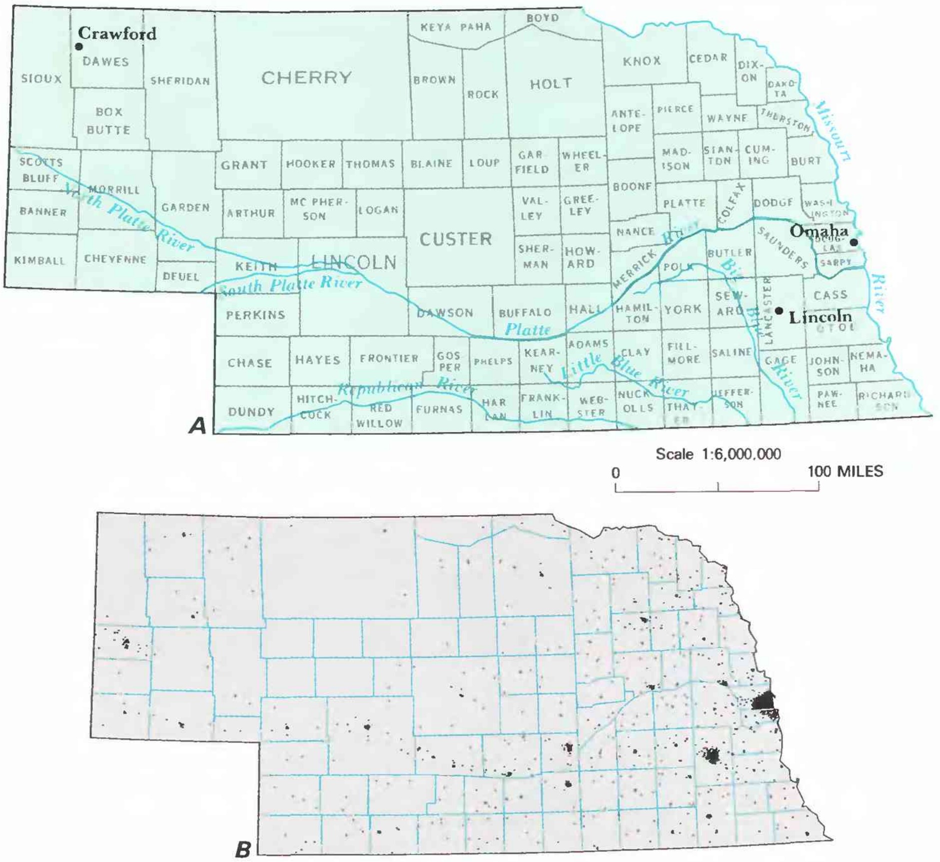

Figure 1. Selected geographic features and 1985 population distribution in Nebraska. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Ground water is the major source of drinking water for about 82 percent of the population in Nebraska (fig. 1), but this use accounts for only about 4 percent of the total water use in the State. Irrigation is the principal use of ground water, accounting for 94 percent of the total ground water used in the State (U.S. Geological Survey, 1985, p. 291); many water-quality changes during the past 40 years have been associated with the development of the resource for irrigation. In some areas of the State, nitrate concentrations in ground water exceed the standard of 10 mg/L (milligrams per liter) as nitrogen (Nebraska Department of Environmental Control, 1978, p. 10), although median nitrate concentrations for all aquifers are less than the standard. Median dissolved-solids concentrations are less than the recommended concentration of 500 mg/L (U.S. Environmental Protection Agency, 1986b) for most water except that produced from the Niobrara aquifer, the Dakota aquifer system, and the undifferentiated aquifers in Paleozoic rocks in eastern Nebraska (fig. 2). Small concentrations of the pesticide atrazine have been detected in about one-third of the water samples from agricultural areas analyzed for pesticides by the U.S. Geological Survey during 1984–85. Contamination from several other organic compounds has been found in ground water at industrial sites or at locations where underground storage tanks have leaked.

Eleven hazardous-waste sites in Nebraska require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Two additional sites have been included in the National Priorities List of hazardous-waste sites (Superfund program) by the U.S. Environmental Protection Agency (1986c) and three other sites have been proposed and are under consideration. "Superfund" sites require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. At eight of the RCRA and CERCLA (Superfund) sites, contamination of ground water has been detected (see fig. 3). The Department of Defense has identified 137 hazardous-waste sites as having potential for contamination at 2 facilities in Nebraska.

WATER QUALITY IN PRINCIPAL AQUIFERS

The High Plains aquifer system is the most important aquifer in Nebraska (fig. 2*A*1 and 2*B*). This system underlies 64,770 mi^2 (square miles) (Pettijohn and Chen, 1983) or about 85 percent of the State. The High Plains aquifer system consists of: Quaternary-age alluvium, valley fill, and eolian sand and gravel; the Tertiary-age Ogallala Formation and Arikaree Group; and the fractured upper part of the Tertiary-age Brule Formation. The Tertiary-age deposits generally are composed of slightly consolidated gravel, sand, silt, and clay. About 96 percent of the irrigation wells in Nebraska are completed in the High Plains aquifer system, and an estimated 95 percent of the total withdrawals of ground water in the State are from this aquifer system.

Other aquifer systems are Quaternary-age sand and gravel in present stream valleys and in principal paleovalleys outside the areal extent of the High Plains aquifer system. In addition, the Cretaceous-age Niobrara Formation and the Dakota Sandstone are developed for water supplies in parts of eastern Nebraska. Sedimentary rocks of Paleozoic age underlie all but a small area of northern Nebraska but are used for water supplies only in southeastern Nebraska. Some Paleozoic rocks of Permian, Pennsylvanian, Devonian, Ordovician, and Cambrian age provide water to domestic and industrial wells.

Water in that part of the High Plains aquifer system located beneath the Nebraska Sand Hills (fig. 2*A*2), an area of about 20,000 mi^2 in north-central Nebraska, contains less than 250 mg/L dissolved solids. In some areas, principally in Brown County, dissolved solids are less than 100 mg/L. With the exception of small areas, principally in eastern Nebraska, dissolved solids in ground water in the rest of the High Plains aquifer system, the valley and principal paleovalley alluvial aquifers, and the Niobrara aquifer are less than 750 mg/L (Engberg, 1984). All but about 400 of the 70,701 registered irrigation wells in Nebraska, as of December 31, 1984, were completed in the High Plains aquifer system, the valley and principal paleovalley alluvial aquifers, and the Niobrara aquifer.

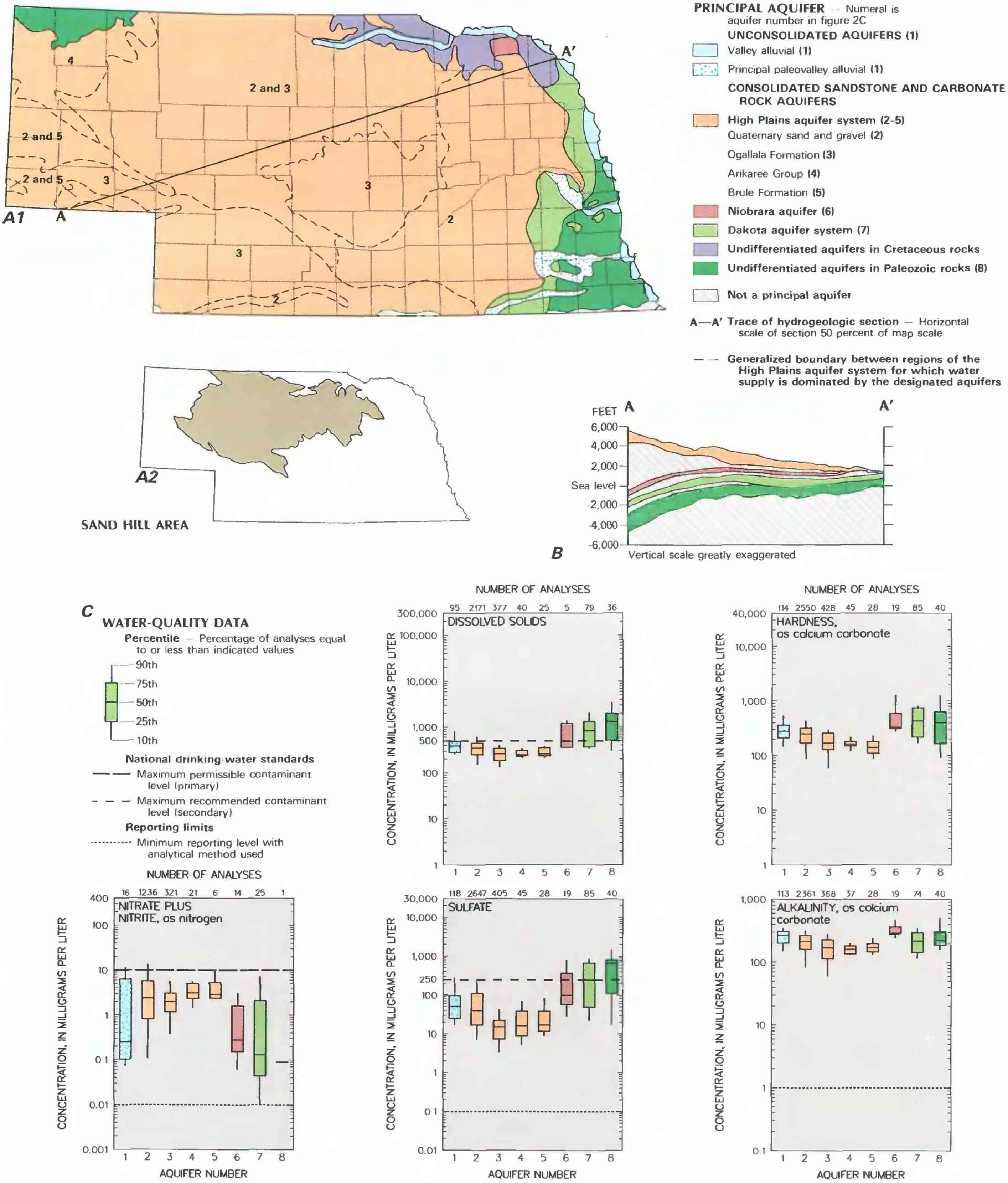

Figure 2. Principal aquifers and related water-quality data in Nebraska. *A1*, Principal aquifers; *A2*, Sand hill area. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, 1935-85. (Sources: *A*, U.S. Geological Survey, 1985. *B*, M.J. Ellis, U.S. Geological Survey, written commun. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

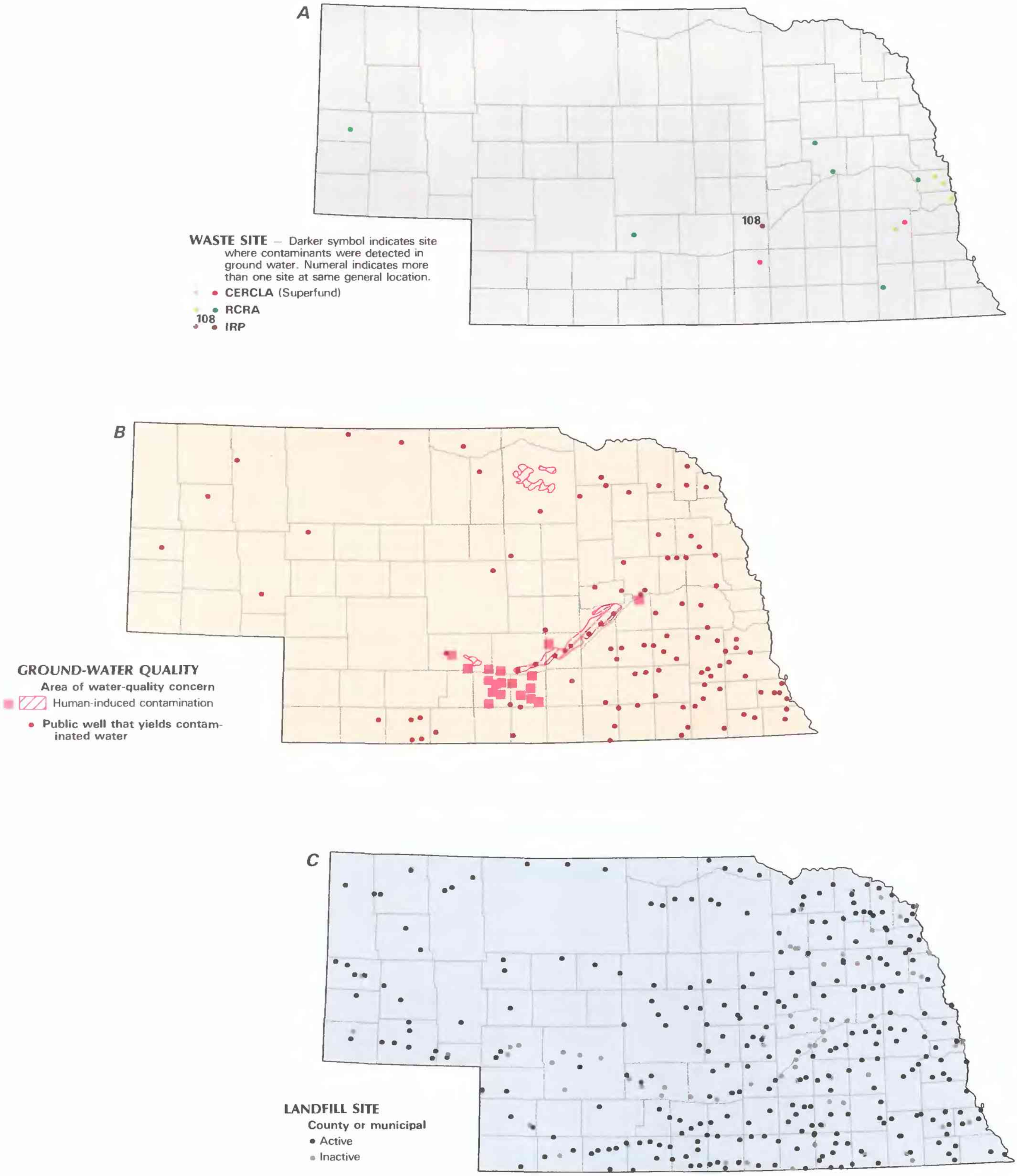

Figure 3. **Selected waste sites and ground-water-quality information in Nebraska.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of July 1986; Resource Conservation and Recovery Act (RCRA) sites, as of July 1986; and Department of Defense Installation Restoration Program (IRP) sites, as of 1985. *B*, Areas of human-induced contamination, and distribution of public wells that yield contaminated water, as of May 1986. *C*, County and municipal landfills, as of 1983. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Michael Steffensmeier, Nebraska Department of Environmental Control, oral commun., 1986. *B*, Exner, 1985; Exner and Spalding, 1976, 1979; Nebraska Department of Health, unpublished list of contaminated public wells, 1986; Spalding and others, 1978. *C*, Nebraska Department of Environmental Control, 1983.)

Because the dissolved solids are less than 1,000 mg/L, the water in these aquifers generally can be used for all crops grown in the State.

Slightly more saline water generally is found in the Dakota aquifer system and in the undifferentiated aquifers in Cretaceous and Paleozoic rocks. Except for areas in eastern Nebraska where the Dakota aquifer system is near the land surface and receives local recharge, dissolved solids in water exceed 750 mg/L. For water samples from 36 wells completed in undifferentiated aquifers in Paleozoic rocks, the median dissolved-solids concentration is about 1,300 mg/L.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) for principal aquifers in Nebraska from 1935 through 1985 is shown in figure 2*C*. Dissolved solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), total alkalinity (as calcium carbonate) and sulfate concentrations are illustrated to characterize the variability of the chemical quality of water from eight aquifer groups. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 250 mg/L sulfate.

Data for valley and principal paleovalley alluvial aquifers are combined into one group because the chemical quality of water from each is similar and because insufficient data were available to make statistical inferences for the principal paleovalley aquifers. Because the data base is large, data from the High Plains aquifer system are divided into four groups by geologic age, from youngest to oldest: Quaternary sand and gravel; the Ogallala Formation; the Arikaree Group; and the Brule Formation. Other groups are the Niobrara aquifer, the Dakota aquifer system, and undifferentiated aquifers in Paleozoic rocks.

Valley and Principal Paleovalley Alluvial Aquifers

Valley alluvial aquifers are located along the Missouri River and downstream reaches of the Platte River in eastern Nebraska, and along the downstream reaches of the Niobrara River in northern Nebraska. The principal paleovalley alluvial aquifers include the aquifer underlying Todd Valley in Saunders County, and the aquifers in several east-trending paleovalleys in southeastern Nebraska. Water from the alluvial and principal paleovalley alluvial aquifers is used for public supply, irrigation, and domestic purposes. No numerical standard for dissolved solids in drinking water has been established by Nebraska, but the median dissolved-solids concentration of 390 mg/L (aquifer 1, fig. 2*C*) for water from valley and principal paleovalley alluvial aquifers was less than the 500 mg/L concentration for public supply established by the U.S. Environmental Protection Agency (1986b).

Calcium and magnesium, the principal components of hardness of water, were the principal cations generally present in water from valley and principal paleovalley alluvial aquifers. The median hardness concentration was 280 mg/L, which indicates that the water was very hard.

The median nitrate-plus-nitrite concentration of 0.25 mg/L as nitrogen was much less than the State established standard for nitrate of 10 mg/L as nitrogen. However, the median is for only 16 analyses.

Bicarbonate, the principal component of alkalinity, was the predominant anion in water from these aquifers. The median alkalinity for 113 analyses was 268 mg/L. Sulfate, another significant anion, had a median concentration of 50 mg/L, which is much less than the proposed State standard of 250 mg/L (Nebraska Department of Environmental Control, 1986).

High Plains Aquifer System

QUATERNARY SAND AND GRAVEL

Quaternary deposits of sand and gravel that are part of the High Plains aquifer system in the Big Blue and Little Blue River basins, in the Central Platte River basin, and in the loess hills southeast of the Sand Hills yield abundant supplies of water for all uses. An estimated 70 percent of the ground water pumped for irrigation in Nebraska comes from these deposits. In the Sand Hills (fig. 2*A2*), Quaternary sand and gravel and the Ogallala Formation constitute an aquifer that provides about 7 percent of the ground water pumped for irrigation in the State.

The quality of water from the Quaternary deposits is variable. Water quality is affected by recharge from surface-water irrigation projects and recharge from streams. In some places where the water table is shallow, the quality of ground water is affected largely by nonpoint sources, such as fertilizers, but it also is affected locally by point sources, such as feedlots. The median dissolved-solids concentration for 2,171 water samples collected from Quaternary deposits was 350 mg/L (aquifer 2, fig. 2*C*); dissolved solids exceeded 630 mg/L in only 10 percent of the samples. The areas from which this 10 percent were collected receive recharge from a three-county (Gosper, Phelps, and Kearney) surface-water irrigation project in central Nebraska or directly from the Platte River.

Water in Quaternary deposits associated with the High Plains aquifer system generally was very hard; the median hardness was 250 mg/L. Calcium was the principal cation. The median nitrate-plus-nitrite concentration for 1,236 samples from Quaternary deposits was 2.4 mg/L as nitrogen. However, the State standard of 10 mg/L as nitrogen was exceeded in more than 10 percent of all samples; in some areas where the water table is shallow and soils are sandy, nitrate-plus-nitrite concentrations were several times the limit. The median alkalinity for Quaternary deposits was 211 mg/L. Bicarbonate was the predominant anion. The median sulfate concentration was 40 mg/L. However, sulfate concentrations in ground water were greatest in areas where the Quaternary deposits receive recharge from irrigation projects or from the Platte River, and nearly equaled or exceeded bicarbonate concentrations.

OGALLALA FORMATION

The Ogallala Formation underlies most of central and western Nebraska, except for the west-central and northern parts of the panhandle. The Ogallala, which consists of loosely cemented sandstone, caliche, sand, gravel, and volcanic ash, ranges in thickness from 0 to 600 feet. In general, recharge to the Ogallala is derived locally. Together with Quaternary deposits, the Ogallala is the principal aquifer in the Sand Hills. About 16 percent of the ground water pumped for irrigation is solely from the Ogallala, predominantly from southwestern Nebraska, the southern part of the panhandle, and north-central Nebraska near the northeast border of the Sand Hills. Likewise, in these areas, the Ogallala Formation provides water for all other uses.

Water quality of the Ogallala Formation is similar to that of Quaternary alluvial sand and gravel, but the water generally is less mineralized and less variable. The median dissolved-solids concentration was 260 mg/L (aquifer 3, fig. 2*C*); dissolved solids exceeded 400 mg/L in water from only 10 percent of the 377 samples analyzed. Water in the Ogallala Formation generally was hard; the median hardness was 170 mg/L. Calcium was the principal cation. The median nitrate-plus-nitrite concentration was 2.0 mg/L as nitrogen for 321 water samples from the Ogallala Formation. The State standard of 10 mg/L as nitrogen was exceeded in only a few of the water samples from the Ogallala. The median alkalinity was 170 mg/L, and bicarbonate was the predominant anion. The median sulfate concentration was 15 mg/L, and sulfate concentrations rarely were of the same magnitude as bicarbonate concentrations (Engberg, 1984).

ARIKAREE GROUP

The Arikaree Group in the northern part of the panhandle of Nebraska consists of sand interlayered with sandy silt and concretions, and may be as thick as 500 feet (Engberg, 1984). Like recharge to the Ogallala Formation, recharge to the Arikaree generally is local. The Arikaree supplies abundant water for irrigation and all other uses. About 4 percent of the ground water pumped for irrigation in Nebraska is from the Arikaree.

Water quality in the Arikaree is nearly the same as that in the Ogallala Formation because soluble materials in deposits overlying and within both geologic units are similar. The median dissolved-solids concentration in water from the Arikaree was 245 mg/L (aquifer 4, fig. 2*A*) and dissolved solids exceeded 350 mg/L in only 10 percent of the 40 samples analyzed. Water in the Arikaree Group generally was hard; the median hardness was 160 mg/L. Calcium was the principal cation. Only 21 analyses were available for nitrate-plus-nitrite concentrations in water from the Arikaree Group. The median concentration was 3.1 mg/L as nitrogen, and the maximum concentration observed was 7.8 mg/L as nitrogen. Median alkalinity was 160 mg/L, and bicarbonate was the predominant anion. The median sulfate concentration was 16 mg/L. Sulfate concentrations were not of the same magnitude as bicarbonate concentrations.

BRULE FORMATION

The Brule Formation is used as water supply in the panhandle of Nebraska and is composed principally of silty clay as much as 600 feet thick. In some areas, as a result of fracturing of the upper 100 feet, the Brule Formation may yield water in sufficient quantities for irrigation, but it generally supplies water sufficient only for domestic use (Engberg, 1984).

Water quality in the Brule Formation is similar to that in the Arikaree Group. The median dissolved-solids concentration in water from 25 samples from the Brule was 260 mg/L (aquifer 5, fig. 2*C*), and the maximum concentration was 540 mg/L.

Water from the Brule Formation was hard; the median hardness was 140 mg/L. Calcium was the predominant cation. Few data are available for nitrate-plus-nitrite concentrations in water from the Brule Formation. Concentrations ranged from 2.3 to 9.9 mg/L in analyses of six water samples. The median alkalinity was 169 mg/L, and bicarbonate was the predominant anion. The median sulfate concentration was 17 mg/L.

Niobrara Aquifer

The Niobrara Formation of Cretaceous age ranges from 0 to 300 feet thick and underlies the Cretaceous-age Pierre Shale in most places, which in turn underlies the High Plains aquifer system. The Niobrara Formation, which is composed of shaley chalk and limestone, subcrops beneath Quaternary-age sand and gravel in south-central Nebraska, and beneath glacial drift in northeastern Nebraska. For much of its areal extent, the Niobrara Formation is not an aquifer, but in some areas where fracturing has occurred or solution channels have formed, it yields sufficient water for irrigation, public-supply, and domestic wells (Engberg, 1984).

In northeastern Nebraska, the Niobrara aquifer is recharged locally through glacial drift or directly in outcrop areas. In northern Cedar County (fig. 2*A*) the Niobrara aquifer, together with overlying saturated sand and gravel, is the principal aquifer.

Water in the Niobrara aquifer generally is more mineralized than water in the High Plains aquifer system. Dissolved-solids data for the Niobrara aquifer are few, but a median dissolved-solids concentration of 489 mg/L was estimated from specific-conductance data in five analyses (aquifer 6, fig. 2*C*) water from the Niobrara aquifer is considerably harder than water in the High Plains aquifer system. The median hardness was 330 mg/L, and calcium was the predominant cation. Limited data for nitrate plus nitrite are available for water from the Niobrara aquifer; the median was 0.28 mg/L as nitrogen for 14 available water analyses. Where the Niobrara aquifer is near the land surface, a potential for contamination of the aquifer by nitrate exists. The median alkalinity for the Niobrara aquifer, based on 19 water samples, was 287 mg/L. Bicarbonate was the predominant anion in water from areas where the aquifer is recharged locally. The median sulfate concentration was 100 mg/L.

Dakota Aquifer System

The Dakota Sandstone crops out in eastern Nebraska but is nearly 8,000 feet beneath land surface in the panhandle. The Dakota Sandstone ranges from 0 to more than 800 feet thick. In eastern Nebraska, where the Dakota extends from the land surface to a depth of 1,500 feet, it is an important aquifer. Farther west, with few exceptions, it is not used for water supply. The Dakota aquifer system is used for public supply by 38 communities in nine counties in eastern Nebraska, and for numerous domestic supplies (U.S. Geological Survey, 1985, p. 294). The Dakota supplies water to about 400, or less than 1 percent, of the irrigation wells in Nebraska.

The quality of water in the Dakota aquifer system is different depending on whether the aquifer system is recharged locally, whether the aquifer system has been leached, and residence time of the water in the aquifer system. The median dissolved-solids concentration for 79 water samples was 840 mg/L (aquifer 7, fig. 2*C*), but dissolved solids exceeded 1,300 mg/L in water from 25 percent of the samples.

Water from the Dakota aquifer system is harder than water from other aquifers in Nebraska. The median hardness was 430 mg/L. In areas where the Dakota aquifer system is recharged locally, calcium was the principal cation. In areas where the Dakota is at greater depth, the sodium concentration was almost equivalent to the calcium concentration.

The median nitrate-plus-nitrite concentration (0.13 mg/L) in water from the Dakota aquifer system was less than that of all other aquifers in Nebraska for which data are available. Where the Dakota is near the land surface and receives local recharge, a potential exists for contamination by nitrate. However, where the Dakota occurs at a depth of several hundred feet and is not recharged locally, the chances of detecting substantial concentrations of nitrate are slight.

The median alkalinity for water from the Dakota aquifer system was 218 mg/L, and bicarbonate was the principal source of alkalinity. The median sulfate concentration was 250 mg/L. Sulfate generally was the principal anion in water from the Dakota aquifer, but near outcrop areas where water is derived largely from local recharge, bicarbonate was the principal anion.

Undifferentiated Aquifers in Cretaceous Rocks

Undifferentiated aquifers in Cretaceous rocks serve as minor aquifers in northern Nebraska. They consist of chalk and sandstone and range from 75 to 1,300 feet in depth. In most cases, the Niobrara aquifer and the Dakota aquifer system are overlain locally by Quaternary sand and gravel deposits.

Few water-quality analyses are available for the undifferentiated aquifers in Cretaceous rocks; therefore, discussion of water quality for these aquifers was not attempted.

Undifferentiated Aquifers in Paleozoic Rocks

Paleozoic rocks ranging in thickness from 1,000 to 4,000 feet underlie nearly all of the State but are aquifers only in small areas of southeastern Nebraska. Some of the rocks crop out in these areas and are recharged locally. Water from Permian and Pennsylvanian rocks of Paleozoic age is used for domestic, industrial, and public supplies in 10 counties. Some deep industrial wells in or near the Omaha area are developed in older rocks and may produce water that is a mixture derived from Paleozoic rocks ranging in age from Mississippian to Cambrian.

Water quality from undifferentiated aquifers in Paleozoic rocks differs greatly. The few available data indicate that water produced from Devonian rocks is considerably more mineralized than water from underlying Ordovician and Cambrian rocks (Engberg, 1984). In areas where Pennsylvanian rocks are recharged locally, the quality of water is similar to that from nearby paleovalley alluvial aquifers, which also are recharged locally. The median dissolved-solids concentration in 36 samples of water from the undifferentiated aquifers in Paleozoic rocks was 1,300 mg/L (aquifer 8, fig. 2*C*); dissolved solids were greater than 3,450 mg/L in 10 percent of the samples.

A wide range of hardness characterizes water from the undifferentiated aquifers in Paleozoic rocks; 40 samples had a median of 402 mg/L. Calcium was the principal cation in water from Pennsylvanian rocks, which are recharged locally. Sodium was the principal cation in saline water from Devonian rocks.

Data for nitrate plus nitrite are not available for water from the undifferentiated aquifers in Paleozoic rocks. The median alkalinity was 221 mg/L in water from the undifferentiated aquifers in Paleozoic rocks, and the median sulfate concentration was 668 mg/L. Sulfate was the principal anion in water from the aquifers with two exceptions. Bicarbonate was the principal anion in the area where Pennsylvanian rocks are recharged locally. Chloride concentrations were nearly equivalent to those of sulfate in water from Devonian rocks.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has changed in many areas of the State principally because of human activities. Treatment and disposal of hazardous wastes and changes in land and water use, especially in response to the rapid development of the High Plains aquifer system for irrigation, have contributed to water-quality changes and possible ground-water contamination.

Hazardous Waste

In Nebraska, hazardous waste is treated, stored, or disposed of at 11 sites identified under RCRA. These RCRA sites constitute known or potential hazards to the quality of ground water (fig. 3*A*). The Nebraska Department of Environmental Control has detected ground-water contamination at six of the RCRA sites (Michael Steffensmeier, oral commun., 1986). Two hazardous-waste sites in Nebraska (fig. 3*A*) are included on the National Priorities List (CERCLA sites) of the U.S. Environmental Protection Agency (EPA). Volatile organic compounds have been detected in ground water at these sites located in Adams and Lancaster Counties. Three RCRA sites in Hall, Dawson, and northwest Platte Counties have been proposed for inclusion on the National Priorities List (NPL) and are still under consideration. Most of the RCRA and CERCLA sites are located near major population centers.

As of September 1985, 137 hazardous-waste sites at two facilities in Nebraska had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. The EPA presently ranks these sites under a hazard-ranking system and may include them in the NPL. One-hundred eight sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Areas that Yield Contaminated Water

Areas of water-quality concern and wells that yield contaminated water are shown in figure 3*B*. The 103 known wells that yield contaminated water are located in cities and towns with public ground-water supplies having one or more constituents that exceed U.S. Environmental Protection Agency (1986a,b) or Nebraska Department of Environmental Control (1978) maximum contaminant levels. In some instances, the entire water system of a community is represented by a single well site because analyses were determined for finished water delivered to customers rather than for individual public-supply wells. Many of the communities are, or have been, operating their water systems under Nebraska State Health Department administrative orders that specify remedial measures. Point sources are responsible for contamination of the ground water at many of these sites.

Nonpoint sources are responsible for the contaminated areas shown in figure 3*B* and for the wells that yield contaminated water included in these areas. Many of the sampled wells in which atrazine has been detected are located in these areas.

Present or previous military installations have, or have had, a variety of waste-disposal areas, including surface impoundments, evaporation ponds, and active or buried landfills. The munitions products 2,4,6 trinitrotoluene (TNT) and hexahydro-trinitro-triazine (RDX) have been detected in ground water at and downgradient from the former Cornhusker Army Ammunitions Plant in northeastern Hall County.

Active and inactive county and municipal landfills in Nebraska are shown in figure 3*C*. Insufficient data have been collected to evaluate the effects of these landfills on the quality of ground water in Nebraska.

Land Use

Cultivated land accounts for more than 40 percent of all land use in Nebraska (Engberg, 1984). More than one-third of all cropland is irrigated and more than 80 percent is irrigated by ground water (Engberg, 1984).

Temporal changes in ground-water quality are related indirectly to land use. Conversion of pastureland and nonirrigated cropland to irrigated cropland is accompanied by increased use of agricultural chemicals, which increases the possibility that residues of these chemicals may move into the ground water.

Water Use and Irrigation

Ground-water use in Nebraska increased 129 percent from about 3,100 Mgal/d (million gallons per day) during 1970 (Engberg, 1984) to 7,100 Mgal/d during 1980 (U.S. Geological Survey, 1985). Eighty-five percent of the ground water pumped in 1970 was used for irrigation, compared to 94 percent of the water pumped in 1980. For the same period, domestic, public, and industrial uses increased by less than 23 percent, from 357 to 438 Mgal/d.

The large increase in ground-water use for irrigation has affected the quality of ground water in some areas. Large increases in the use of fertilizers and pesticides have accompanied irrigation development and have provided the potential for widespread nitrate and pesticide nonpoint-source contamination of shallow ground water.

The area north of the Platte River in central Nebraska has the greatest density of irrigation wells in the State (Ellis and Pederson, 1985). For example, an average density of 7.7 registered irrigation wells per square mile has been reported in Merrick County (Engberg, 1984). From 1958 to 1982, the U.S. Geological Survey sampled six wells located north of the Platte River in Buffalo and Hall Counties in central Nebraska. Nitrate concentrations in water from these six wells are shown in figure 4. Water in three of the wells, located in lowlands near the river, showed substantial increases in nitrate concentrations with time. These wells were drilled in sandy soils, and the depth to water in the lowlands generally is less than 20 feet. Nitrate concentrations in water from the other three wells have remained nearly the same through time. These wells are located at greater distances from the Platte River in terrace deposits that are characterized by soils that contain some clay. Depth to water in the terrace deposits generally is more than 20 feet.

Exner and Spalding (1976) prepared a map showing the distribution of nitrate concentrations in 1974 for an extensive area north of the Platte River in central Nebraska. The map indicated that nitrate concentrations exceeded 10 mg/L as nitrogen in an area of about 340 mi^2. Seventy-eight percent of the wells sampled in 1974 were resampled in 1984 (Exner, 1985). A new map showed that the area in which nitrate concentrations exceeded 10 mg/L as nitrogen had increased by about 45 percent to about 490 mi^2. In Merrick County alone, the mean nitrate concentration for 36 wells increased from 22 to 26 mg/L as nitrogen.

Similar increases in nitrate have been detected in other parts of the State where large-scale development of ground water for irrigation has occurred more recently. Areas of nonpoint-source-derived nitrate in concentrations greater than 10 mg/L as nitrogen have been found in Holt, Kearney, and Phelps Counties (Hsiu-Hsiung Chen, U.S. Geological Survey, oral commun., 1986).

Pesticides in ground water are being detected in measurable concentrations. Measurable concentrations (greater than 0.04 microgram per liter) of the herbicide atrazine were detected in 43 of 132 water samples collected during 1984–85 by the U.S. Geological Survey from wells completed in the High Plains aquifer system in Nebraska.

Water-level rises as a result of surface-water irrigation may be accompanied by changes in ground-water quality. Infiltration from canal seepage and surface application supplements natural recharge and has caused substantial water-level rises in some areas of the State. If the infiltrating surface water is less mineralized than the ground water, the quality of the ground water improves. This has occurred in Howard and Sherman Counties in areas irrigated by surface water. If the infiltrating surface water is more mineralized than the ground water, the quality of ground water is degraded. This has occurred in Gosper, Kearney, and Phelps Counties and elsewhere in areas irrigated by surface water diverted from the Platte River.

POTENTIAL FOR WATER-QUALITY CHANGES

Because Nebraska is primarily an agricultural State, the potential for most changes in water quality is related to agriculture and to nonpoint sources of ground-water contamination. Nitrate and pesticide contamination of ground water from nonpoint sources is expected to increase. Areas especially susceptible are adjacent to those where contamination presently exists (fig. 3*B*). Other areas where nitrate may cause changes in ground-water quality include the Big Blue and Little Blue River basins, the western part of the Republican River basin, and most of Box Butte County (fig. 1). These areas all have large-scale development of ground water for irrigation, and all have had water-level declines. Recharge, derived locally and enriched with agricultural chemicals, may cause gradual increases in nitrate and pesticide concentrations in ground water. If further irrigation development takes place in the Sand Hills, rapid contamination of the ground water from agricultural chemicals, such as documented in Holt County (Exner and Spalding, 1979), may be expected.

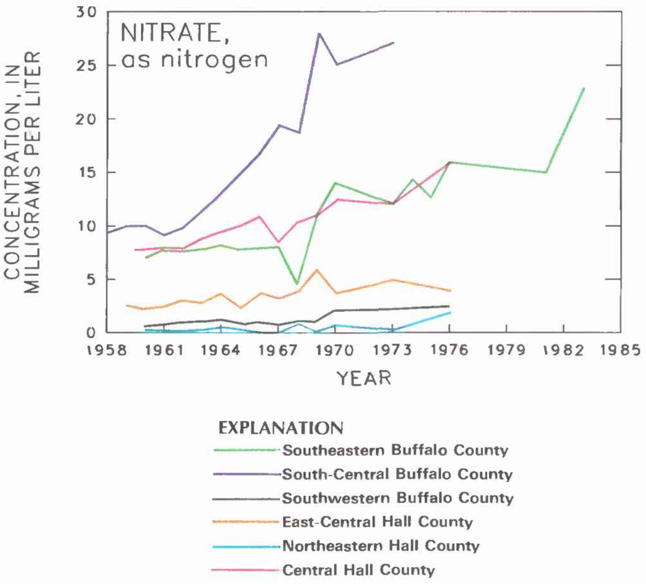

Figure 4. Trends in nitrate concentrations in water from six wells north of Platte River, central Nebraska. (Source: U.S. Geological Survey files.)

Radioactive constituents may change ground-water quality in Dawes and Sioux Counties, northwestern Nebraska. Extensive deposits of uranium are found in the White River Group at depths of 400 to 600 feet below land surface. A pilot plant has been constructed in Dawes County near Crawford, to recover uranium by in-situ solution-mining techniques. If these efforts prove feasible, large-scale mining may start in a few years. The deposits in which the uranium are found are virtually undeveloped as a source of water supply but do serve a few users for stock watering.

GROUND-WATER-QUALITY MANAGEMENT

The Nebraska Ground-Water-Quality Protection Strategy prepared by the Nebraska Department of Environmental Control (NDEC) (1985) provides an assessment of ground-water contamination in Nebraska and contains proposals to control, manage, or mitigate existing or potential contamination. The strategy has been accepted by the administration of Governor Robert Kerrey as a basis for upgrading State regulatory measures related to ground-water quality or to create new programs to address ground-water quality issues.

As an outgrowth of the strategy, four legislative bills designed to implement ground-water-quality protection were passed by the Legislature in 1986. Bill LB217 applies to underground chemical and fuel storage tanks. The law, administered by the NDEC (for ground-water-quality protection) and the State Fire Marshall (for public safety), requires the issuance of installation permits and registration of underground storage tanks and represents an effort to regulate leaky tanks.

Bill LB284, the Nebraska Chemigation Act, requires that all irrigation systems into which chemicals are injected must have, at the minimum, check valves in both the delivery pipe and injection line; a low-pressure drain, and vacuum-relief valve, and an inspection port between the check valve and the pump; and an interlock device between the chemigation unit and the irrigation pump in the event of pump or power failure. The law requires an operating permit and training and certification of operators, and provides for system inspections by representatives of the Natural Resources District in which the system is located.

Bill LB310 provides for the certification of all well drillers in Nebraska. The law further defines standards for well construction and includes penalties for noncompliance with the standards.

Bill LB894 authorizes the establishment of ground-water-quality protection areas by the local Natural Resources District or by the NDEC. Area designations are restricted to nonpoint sources of ground-water contamination. Local action toward protecting ground-water quality may include education of land users on nonpoint sources of contamination and regulated agricultural-management practices. This law will enable local groups to protect localized ground-water sources affected by land use, aquifer characteristics, and soil types unique to the area.

Several State and local agencies are involved in the administration of existing Federal and State regulations pertaining to ground-water-quality management:

1. The NDEC administers ground-water-quality protection standards for Nebraska. The NDEC also administers a hazardous-waste-management program in Nebraska that complies with RCRA. Permits are required for onsite storage of hazardous waste for periods longer than 90 days. Disposal of hazardous waste by underground injection also is regulated by the NDEC under a permitting program. Underground injection is prohibited above or into sources of drinking water. The NDEC is responsible for licensing solid-waste disposal sites for municipalities with populations greater than 5,000, provided that hazardous wastes regulated by RCRA are not disposed of at the sites. Lagoons and surface impoundments used for storing or treating wastewater also are regulated by the NDEC. The operators of these facilities may be required to obtain effluent-discharge-limitation permits from the NDEC if there is a potential for leakage that will reach the ground-water system. The NDEC also regulates exploration for minerals other than gas and oil and processes such as solution mining. Regulations include monitoring ground-water restoration and proper plugging of abandoned wells or test holes.

2. The Nebraska Oil and Gas Conservation Commission (NOGCC) regulates gas and oil exploration and production wells. Regulations include plugging requirements but include no provisions for monitoring or cleanup.

3. The Nebraska Department of Health (NDH) regulates a safe drinking-water program in Nebraska patterned after the Federal Safe Drinking-Water Act. Public drinking-water supplies are monitored by the NDH, and suppliers are issued permits. If contaminant concentrations exceed "maximum contaminant levels" contained in the National Drinking-Water Regulations, wells may be closed or use of the water restricted. The NDH establishes compliance schedules for decreasing contaminants to safe concentrations. The NDH also may regulate siting of new wells to avoid contamination by existing or potential sources. In addition, the Department regulates construction standards for new wells and public-supply distribution systems.

4. The Nebraska Department of Water Resources (NDWR) is responsible for registration of all water wells drilled in the State except those used solely for domestic and stock purposes. The NDWR also is responsible for enforcing well-spacing regulations and well-abandonment requirements, both of which may affect ground-water quality. The Director of the NDWR presides over public hearings conducted by the Natural Resources Districts to consider creation of ground-water control areas, and the Director also has sole authority to decide whether a control area is to be established. None of the three control areas presently authorized have been established because of ground-water contamination.

5. The 24 Natural Resources Districts in Nebraska were mandated by the 1984 Nebraska Legislature to prepare ground-water-management plans. These plans were to be submitted for approval to the Director of the NDWR of by January 1, 1986. Several plans have been approved, and others are undergoing revisions. Although they differ considerably, ground-water-quality monitoring programs are key elements in many District plans.

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NEVADA
Ground-Water Quality

In Nevada (fig. 1), about 50 percent of the population, 30 percent of light industry including thermoelectric power, and 17 percent of irrigated agriculture are supplied by ground water. Of the total ground-water withdrawals, irrigation accounts for about 74 percent; public and rural supplies, about 15 percent; and industrial use, about 10 percent (U.S. Geological Survey, 1985, p. 297).

The quality of water from most aquifers in Nevada is suitable, or marginally suitable, for most uses. Most aquifers contain water with constituent concentrations (fig. 2) that do not exceed State and national drinking-water standards. However, parts of some aquifers contain water having constituent concentrations that exceed these standards. Excessive concentrations in ground water result from both natural processes and human activities (fig. 3). Natural impairment occurs in: (1) areas of shallow ground water with large evapotranspiration rates, (2) geothermal areas, and (3) aquifers containing sufficient amounts of soluble material. Human-induced contamination occurs in areas of downward percolating wastes from: (1) disposal ponds and pits associated with industrial, mining, milling, explosives-handling, and oil-production activities; (2) coal-slurry storage-ponds and process-water evaporation ponds at electric-generating stations; (3) gasoline, aviation-fuel, and diesel-fuel spills or storage-tank leaks; and (4) septic tanks. In addition, areas of potential contamination are associated with irrigation, feedlots, dairy farms, and nuclear-bomb testing sites.

The most populated areas of Nevada (fig. 1*B*), which have the greatest potential for industrial development, urbanization, and waste-disposal problems, are Las Vegas Valley in the south and the Reno-Carson City area in the west. Human-induced contamination has been documented in parts of the shallow basin-fill aquifers in Truckee Meadows and the Las Vegas, Mason, Antelope, Washoe, Carson, Colorado River, and Eagle Valleys; the Whiskey Flat-Hawthorne subarea adjacent to Walker Lake; the Incline Village area in the Lake Tahoe basin; and the Marys Creek area and Winnemucca segment of the Humboldt River basin (fig. 3*B*).

WATER QUALITY IN PRINCIPAL AQUIFERS

Principal aquifers in Nevada are basin-fill deposits, carbonate rocks, and to a lesser extent, volcanic rocks (fig. 2*A*). Virtually all ground-water withdrawals have been from the upper 500 feet of the basin-fill aquifers. Carbonate-rock aquifers in eastern Nevada have not been significantly developed as a water supply, but are an important source of water. About 50 springs, discharging a combined total of about 90 Mgal/d (million gallons per day) from the carbonate-rock aquifers, are used for irrigation and drinking-water supplies. Volcanic-rock aquifers extend over hundreds of square miles, but only one volcanic-rock aquifer, in the Carson Desert (Churchill County) of west-central Nevada, has been developed. The quality of most water from the volcanic-rock aquifers is suitable or marginally suitable for most uses.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) and files of the Nevada Division of Environmental Protection (NDEP) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), fluoride, and arsenic analyses of

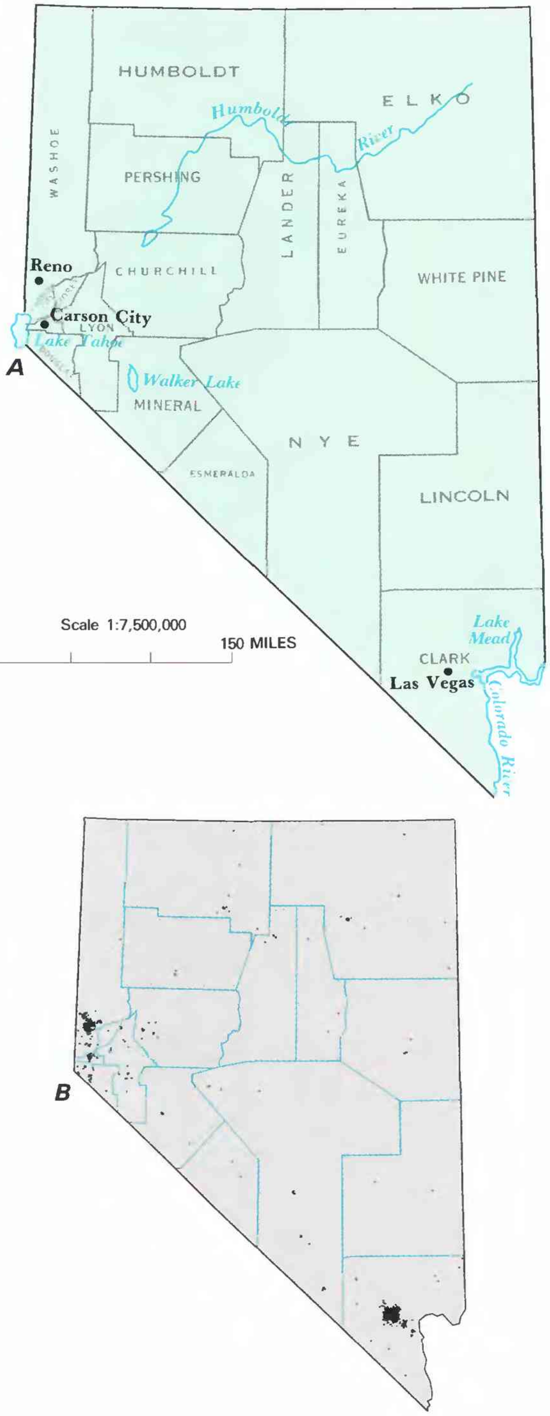

Figure 1. Selected geographic features and 1985 population distribution in Nevada. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

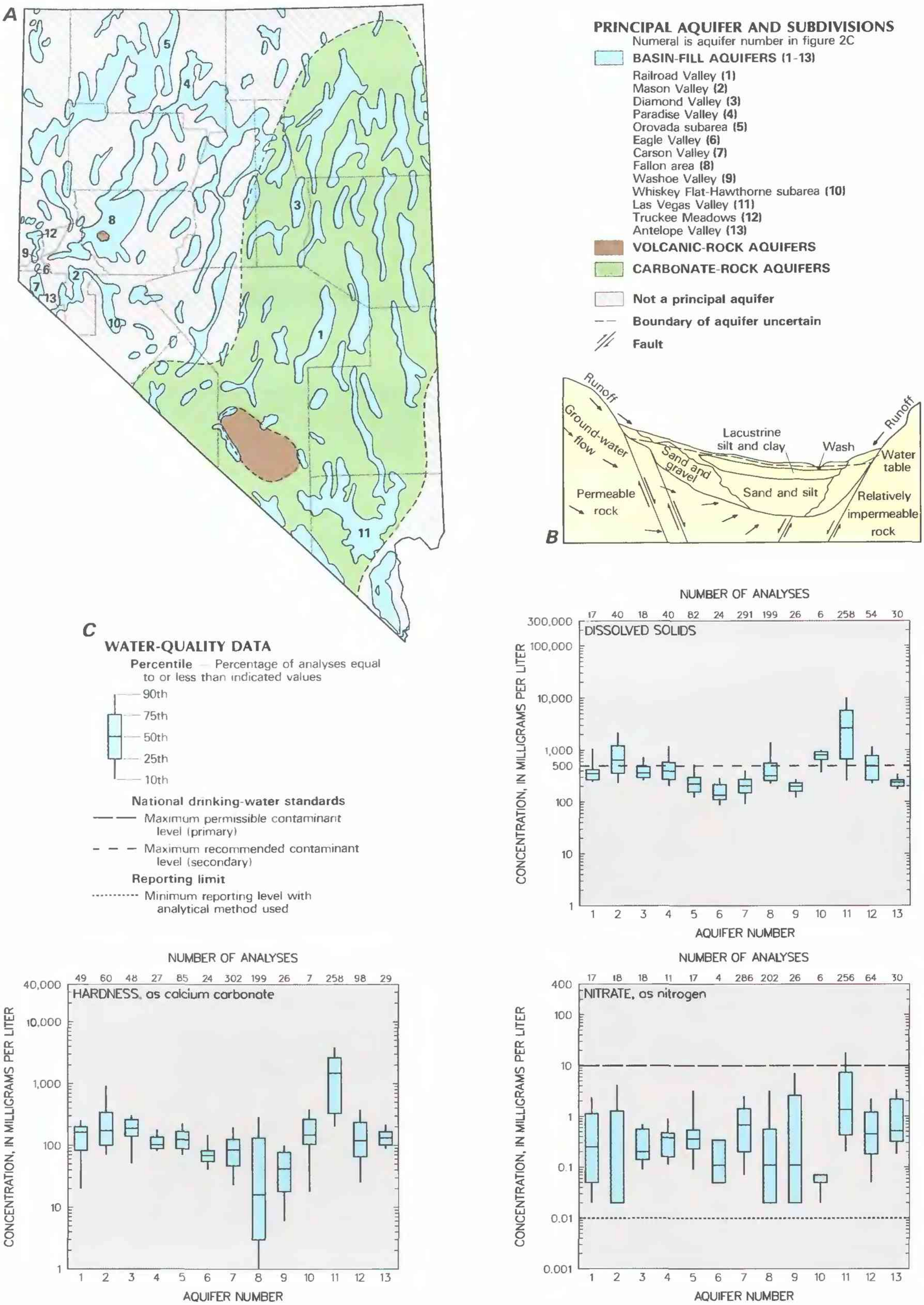

Figure 2. Principal aquifers and related water-quality data in Nevada. *A*, Principal aquifers. *B*, Generalized hydrogeologic section showing typical distribution of unconsolidated deposits in a basin-fill aquifer. *C*. Selected water-quality constituents and properties, 1950-86. (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Cohen and Loeltz, 1964; Huxel and others, 1966; Worts and Malmberg, 1966; Everett and Rush, 1967; Harrill and Lamke, 1968; Huxel and Harris, 1969; Van Denburgh and Rush, 1974; Kaufmann, 1976; Patt and Hess, 1976; Armstrong and Fordham, 1977; Nowlin, 1982; Seitz and others, 1982; Van Denburgh and Schaefer, 1986; U.S. Geological Survey, U.S. Bureau of Reclamation, and Nevada Division of Environmental Protection files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

water samples collected from 1950 to 1986 from the basin-fill aquifers in Nevada. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant allowed in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include maximum concentrations of 10 mg/L (milligrams per liter) nitrate (as nitrogen), 4.0 mg/L fluoride, and 50 µg/L (micrograms per liter) arsenic. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 2.0 mg/L fluoride. The State drinking-water standards include maximum concentrations of 1,000 mg/L dissolved solids, 10 mg/L nitrate (as nitrogen), 1.4 to 2.4 mg/L fluoride (depending on air temperature), and 50 µg/L arsenic, and a recommended maximum concentration for dissolved solids of 500 mg/L (Nevada Division of Health, 1977).

The summary (fig. 2*C*) contains water-quality data for 13 of the basin-fill aquifers. The data are limited to the basin-fill aquifers because virtually all withdrawals of ground water and water-quality analyses have been from these aquifers. Limited data preclude the interpretation of lateral or vertical chemical changes within the basin-fill aquifers. If more than one analysis for a well was available, the mean values of constituents were used in plotting the data.

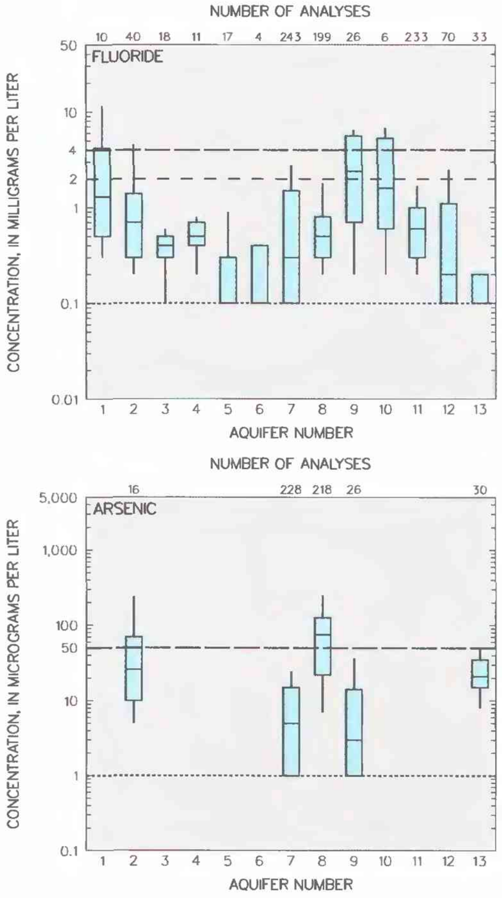

Figure 2. Principal aquifers and related water-quality data in Nevada—Continued

Basin-Fill Aquifers

Median dissolved-solids concentrations for the basin-fill aquifers generally do not exceed the national or State drinking-water standards. However, in local areas the water commonly contains more than 1,000 mg/L dissolved solids and constituent concentrations exceed the standards (figs. 2*C*, 3*B*). Generally, this exceedance occurs where deposits naturally contain significant amounts of soluble minerals, where ground water is discharged by evapotranspiration, or where ground water is affected by geothermal activity.

In the southeast part of the Las Vegas Valley basin-fill aquifer, naturally occurring dissolved-solids concentrations are large, generally greater than 2,000 mg/L, resulting principally from the dissolution of gypsum and evaporite salts. Large concentrations of naturally occurring arsenic, sulfate, nitrate, and fluoride are prevalent in many of the basin-fill aquifers. The large concentrations are derived from dissolution of (1) arsenic-containing volcanic rocks, mineral coating on the grains of detrital rocks, or sedimentary organic matter, (2) gypsum, (3) nitrogen-bearing sediments or spring deposits, and (4) fluoride minerals.

Areas of ground-water evapotranspiration, which can encompass hundreds of square miles, generally contain water that is slightly saline (1,000–3,000 mg/L dissolved solids) to brine (more than 35,000 mg/L dissolved solids). Water with a dissolved-solids concentration smaller than 500 mg/L typically recharges basin-fill aquifers on alluvial fans around the margins of the aquifers. The water then becomes more mineralized by dissolving minerals as it flows through the basin-fill deposits (fig. 2*B*). In areas of shallow ground water, evapotranspiration can further concentrate constituents in the water, resulting in areas with naturally occurring large dissolved-solids concentrations.

Ground water in areas of geothermal activity commonly contained more than 1,000 mg/L dissolved solids. This water also can contain fluoride concentrations that exceed national drinking-water standards, and excessive concentrations of arsenic and boron.

Hardness of water in the basin-fill aquifers ranged from soft (less than 60 mg/L) to very hard (more than 180 mg/L; fig. 2*C*). Water hardness, a function of calcium and magnesium concentrations, is derived primarily from natural processes, such as dissolution of limestone, dolomite, or calcium-rich volcanic rocks.

No median concentrations of nitrate exceeded the national drinking-water standard. However, nitrate concentrations in ground water have been increased locally by natural sources, such as solution of minerals that contain nitrogen, or percolation of water through organic material (Patt and Hess, 1976). The Las Vegas Valley basin-fill aquifer contains water suitable for most uses. However, in the southeastern part and in a small area (7 square miles) in the north-central part of the aquifer (fig. 3*B*), naturally occurring nitrate concentrations exceed 300 mg/L (Patt and Hess, 1976).

Median fluoride concentrations, which range from 0.1 to 2.4 mg/L in the basin-fill aquifers, do not exceed the national drinking-water standard (4.0 mg/L). However, maximum concentrations did exceed the drinking-water standard in some water from 8 of the 13 basin-fill aquifers. Most of the fluoride is probably from dissolution of fluoride-bearing rocks.

Arsenic concentrations exceeded the drinking-water standard (50 µg/L) in parts of all the basin-fill aquifers sampled (fig. 2*C*). Naturally occurring arsenic concentrations exceeding 50 µg/L commonly are associated with geothermal waters and alluvial-lacustrine and volcanic deposits.

Carbonate-Rock Aquifers

Water quality in the carbonate-rock aquifers is suitable for most uses. Water from the springs in eastern Nevada generally is hard (121–180 mg/L as calcium carbonate) to very hard (more than

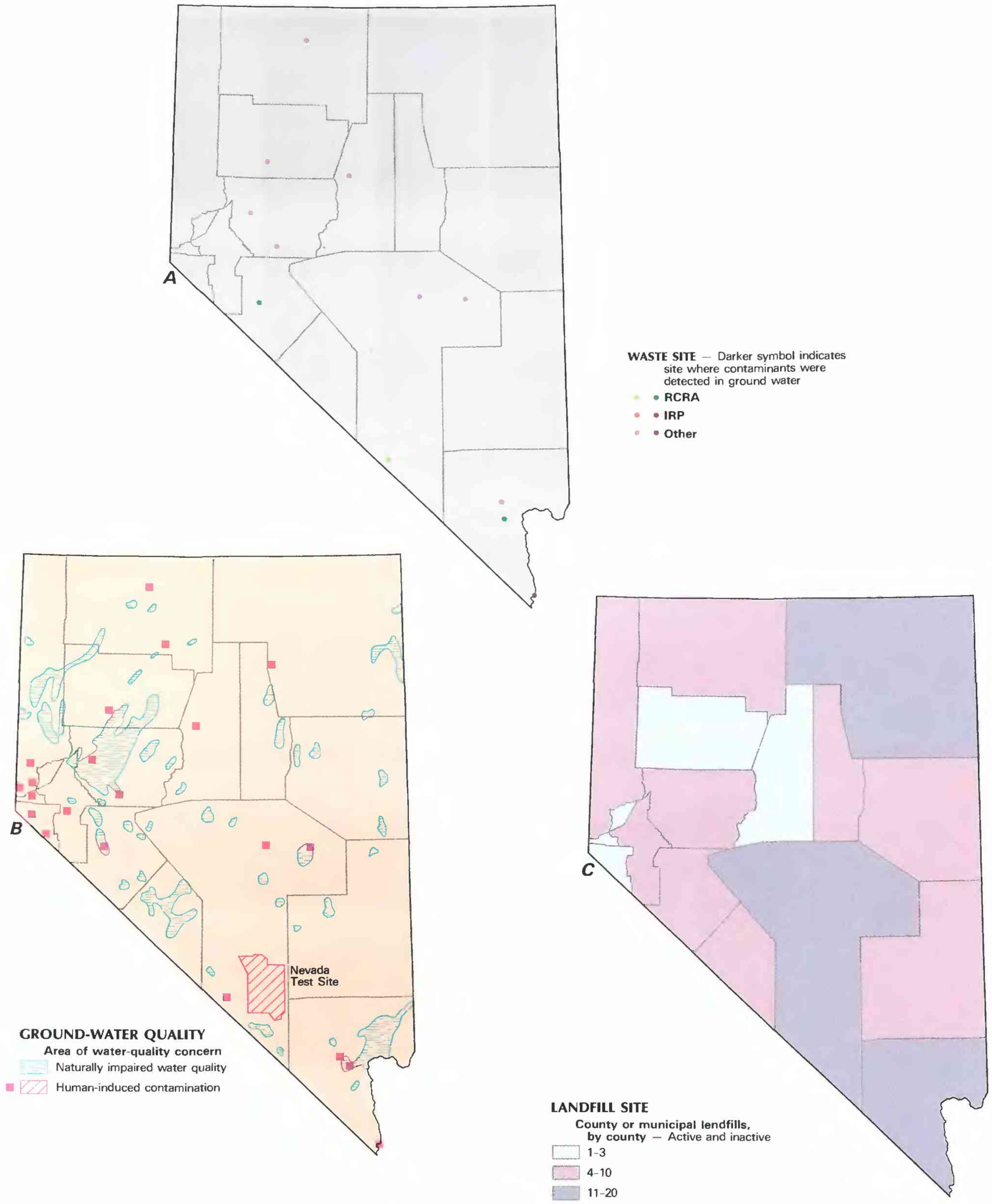

Figure 3. Selected waste sites and ground-water-quality information in Nevada. *A*, Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, and areas of human-induced contamination, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, Van Denburgh and Rush, 1974; Nevada Division of Environmental Protection, 1979; Geraghty and Miller, Inc., 1980; Seitz and others, 1982; Nowlin, 1986; U.S. Department of Defense, 1986; Van Denburgh and Schaefer, 1986; James Thompson, U.S. Environmental Protection Agency, written commun., 1986. *B*, Van Denburgh and Rush, 1974; Patt and Hess, 1976; Garside and Schilling, 1979; Geraghty and Miller, Inc., 1980; Nowlin, 1982; Seitz and others, 1982; Nowlin, 1986; Van Denburgh and Schaefer, 1986; and Nevada Division of Environmental Protection files. *C*, Dan Gross, Nevada Division of Environmental Protection, written commun., 1986.)

180 mg/L), owing to the dissolution of carbonate minerals. Dissolved-solids concentrations in carbonate-rock aquifers do not exceed the State drinking-water standard of 1,000 mg/L.

Volcanic-Rock Aquifers

Water in the volcanic-rock aquifer in the Carson Desert of west-central Nevada is suitable for most uses. However, arsenic concentrations are large, ranging from 73 to 140 µg/L. These concentrations exceed the national primary drinking-water standard of 50 µg/L.

EFFECTS OF LAND USE ON WATER QUALITY

Water in some of the basin-fill aquifers has been contaminated by downward percolation of industrial wastes, milling-waste fluids, explosives wastes, possibly oil-well brines from disposal ponds or pits, coal-slurry storage ponds, and process-water evaporation ponds at electric-generating stations. Excessive leakage or spills of gasoline, diesel fuel, and aviation fuel from storage tanks and contamination by effluents from septic-tank systems have contributed to the contamination of water in some of the basin-fill aquifers.

Waste Disposal

Nevada has one operating low-level waste-disposal site near Beatty (Nye County), three commercial facilities at an industrial complex near Henderson (Clark County) that are either closed or in the process of being closed, and an Army ammunition plant at Hawthorne (Mineral County) that require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 (James Thompson, U.S. Environmental Protection Agency, written commun., 1986). In addition, the State has: a military hazardous-waste area at Nellis Air Force Base in Las Vegas Valley (U.S. Department of Defense, 1986), the Nevada Test Site for nuclear-bomb testing in southern Nevada (fig. 3*B*), two sites in central Nevada where underground nuclear tests were conducted, four pesticide-disposal sites, industrial waste-disposal sites in the Las Vegas and Carson Valleys, previously used settling ponds for oil-well brine in Railroad Valley, an electric-generating station with process-water evaporation ponds and coal-slurry storage ponds in the Colorado River valley, and 107 landfills (figs. 3*A*, 3*C*). For these areas, minimal information is available on the quality of ground water, mainly because of a lack of wells. As a result, only the industrial sites in southeastern Las Vegas Valley and Carson Valley; the fluid-disposal pits for explosives wastes associated with shell- and bomb-casing cleaning in the Whiskey Flat-Hawthorne subarea near Walker Lake; and the process-water evaporation ponds and coal-slurry storage ponds in the Colorado River valley have documented ground-water contamination (Geraghty and Miller, Inc., 1980; Harding-Lawson Associates, 1986; Dan Gross and Doug Zimmerman, Nevada Division of Environmental Protection, written commun., 1986; and U.S. Bureau of Reclamation, unpublished data on file in the U.S. Geological Survey office, Carson City, Nevada).

As of September 1985, 16 hazardous-waste sites at 2 facilities in Nevada, including the site at Nellis Air Force Base, had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. The EPA presently ranks these sites under the hazard ranking system and may include them in the National Priorities List (NPL). Of the 16 sites in the program, 5 sites contained contaminants but did not present a hazard to the environment. One IRP site at one facility (fig. 3*A*) was considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Contamination from an industrial site at Henderson near Las Vegas has increased the dissolved-solids concentrations in the Las Vegas Valley basin-fill aquifer to about 10,000 mg/L near the site (Dave Hemphill, U.S. Bureau of Reclamation, written commun., 1986). The increase is due mainly to leakage of industrial organic compounds—primarily benzene, chlorinated benzene compounds, trichloromethane (chloroform), and organophosphates—from the industrial site into the aquifer. Dithioic acids and hexachlorocyclohexane (BHC) also have been detected in the ground water at the site (Geraghty and Miller, Inc., 1980). In addition, organic compounds, primarily benzene with dissolved organophosphates, are present—both floating at the top of the water table and at the bottom of wells because of the differences in densities of the associated fluids. The layer of organic compounds is about 2 to 5 feet thick in three wells near the organophosphate waste ponds and contains as much as 530,000 mg/L benzene and 54,000 mg/L carbophenothion (Geraghty and Miller, Inc., 1980). The compounds are principally from a 30,000-gallon leak of benzene from an underground storage tank that occurred in 1976. The benzene subsequently migrated downgradient beneath the organophosphate waste ponds, dissolving the downward-percolating organophosphate compounds. By 1980, the benzene had migrated between 3,000 and 5,000 feet downgradient from the tank (Geraghty and Miller, Inc., 1980). Chromium concentrations as large as 90,000 µg/L also are present at the site from leakage of processing fluids (Dan Gross, Nevada Division of Environmental Protection, written commun., 1986).

Traces of trichloroethylene (TCE); 1,1,1 trichloroethane (1,1,1-TCA); 1,1,2 trichloroethane and 1,2,2 trifluoroethane (Freon 113); and 1,1 dichloroethylene (1,1-DCE) have been detected in water in the Carson Valley basin-fill aquifer (Dan Gross, Nevada Division of Environmental Protection, written commun., 1986). These organic compounds apparently have percolated into the aquifer from a nearby industrial site.

Explosives—principally ammonium picrate, ammonium nitrate, and trinitrotoluene (TNT) from fluid-disposal pits associated with shell- and bomb-casing cleanout—have percolated into the basin-fill aquifer between Hawthorne and Walker Lake in Mineral County. Dissolved solids have increased from natural concentrations of 1,000–2,000 mg/L to 2,000–3,000 mg/L, and nitrate (as nitrogen) has increased from natural concentrations of less than 2 mg/L to 130 mg/L between 1952 and 1979 (Van Denburgh and Schaefer, 1986). Nitrate had migrated at least 3,200 feet from the fluid-disposal pits, whereas ammonium nitrate and TNT had moved about 1,200 feet by 1979.

Coal-slurry storage ponds and process-water evaporation ponds at the Mohave Electric-Generating Plant in the Colorado River valley have contaminated the shallow basin-fill aquifer. Natural dissolved-solids concentrations of less than 1,000 mg/L in the ground water had increased to a maximum of 3,620 mg/L by 1985 in the contaminated areas (Harding-Lawson Associates, 1986).

Percolation of oil-well brines from previously used settling ponds may have contaminated the basin-fill aquifer in Railroad Valley, according to Van Denburgh and Rush (1974, p. 31).

Mining

Ground water in the Weed Heights area of Mason Valley has been contaminated downgradient from dumps and ponds used for disposal of brine and tailings fluid and gangue from copper ore-milling operations. Copper was mined and milled in the area from 1953 to 1978. A study by Seitz and others (1982) indicated the following maximum concentrations of constituents in two shallow wells nearest the dumps and ponds: 38,000 mg/L dissolved solids; 8,360 mg/L hardness (as calcium carbonate); 6,500 µg/L boron; 26,000 mg/L sulfate; 340 µg/L arsenic; 6,800 µg/L cobalt; 24,000 µg/L copper; 6,300,000 µg/L iron; 88,000 µg/L manganese; 6,200 µg/L nickel; and 13,000 µg/L zinc.

Copper also was mined and smelted in the Ruth and McGill areas (White Pine County) of Steptoe Valley and mined and milled in the Mountain City area (Elko County) of the Owyhee River valley. Ground-water-quality data are too sparse to determine if these areas are being affected.

Urbanization

Water in the basin-fill aquifers along the northwest shore of Topaz Lake in Antelope Valley (Nowlin, 1982) and in Washoe Valley (Armstrong and Fordham, 1977) has been contaminated by septic-tank effluent. However, concentrations of nitrate, the principal effluent contaminant, generally do not exceed the 10-mg/L drinking-water standard (fig. 2*C*); water from one well in these two valleys exceeded the standard.

Contamination by petroleum products has been documented at 10 sites in the urbanized areas of Las Vegas, Reno, Carson City, Yerington (Lyon County), Winnemucca (Humboldt County), Carlin (Elko County), and Incline Village (Washoe County), as of 1985. Leakage and spillage of gasoline, aviation fuel, and diesel fuel from underground and surficial storage tanks have resulted in localized contamination of the shallow basin-fill aquifers. In places, layers of petroleum products more than 7 feet thick, but generally less than 1 foot thick, have been measured floating on top of the water table. Overall, of the 10 sites with documented petroleum-product contamination in Nevada, 3 have contaminant-recovery programs in progress, 1 has contaminant recovery planned, and 6 have contaminant recovery completed or not needed. In addition, four areas of suspected contamination currently (1986) are being evaluated to determine the effect on the subsurface environment (Dan Gross, Nevada Division of Environmental Protection, written commun., 1986).

POTENTIAL FOR WATER-QUALITY CHANGES

Waste-disposal, industrial, urbanized, nuclear-bomb testing, mining, and irrigation areas are all possible sites for present and future contamination. However, because of the limited information available on the quality of ground water in these areas, the nature and extent of contamination may go undetected. Some areas of known contamination are no longer active disposal sites, and some facilities used for storing wastes have been upgraded. Existing contaminant plumes, however, will continue to migrate and affect larger parts of the aquifer unless the contaminants are removed or contained.

Most areas of documented human-induced contamination have active ground-water restoration programs. Others are being studied to determine the nature and extent of contamination and the methods that will be needed to mitigate the problem. Organic contamination in the basin-fill aquifer near Henderson in Las Vegas Valley probably will decrease in the future because contaminants are being removed from the affected ground water. Localized contamination of the Carson Valley basin-fill aquifer by organic solvents currently (1986) is being studied to define the extent of contamination and to determine what future actions are needed. A program to remove contamination from a copper ore-milling operation in the Weed Heights area (Lyon County) also has been implemented. Continued use of septic tanks in the Antelope and Washoe Valley areas, as well as future development, probably will result in a continued increase in the concentration of nitrate from these effluents. Oil-well brines now are disposed in injection wells in Railroad Valley, so possible future contamination of the basin-fill aquifer from downward migrating brines is not anticipated (Dan Gross and Doug Zimmerman, Nevada Division of Environmental Protection, oral commun., 1986).

Possible sources of presently undetected or potential contamination include chemical- and petroleum-product storage tanks, mine and milling wastes, irrigation water that percolates to the water table, feedlots, dairy farms, and radionuclides. Chemical, gasoline, diesel-fuel, and aviation-fuel contamination will continue to be a problem as old storage tanks develop leaks and because spills of chemicals and fuels are likely to occur. However, starting in February 1987, all new petroleum-product underground storage tanks will be constructed of noncorrosive material and will be monitored for releases. Hazardous-chemical storage tanks will have similar requirements starting in 1988 (U.S. Environmental Protection Agency, 1985). In addition, there is the potential for contamination from fuel spills associated with fire-fighting training at the Naval Air Station in Fallon (Dan Gross, Nevada Division of Environmental Protection, oral commun., 1986).

Mining activities have produced and will continue to produce tailings piles and milling wastes that are susceptible to leaching of contaminants. More than 300 mining districts throughout Nevada may be adversely affecting ground-water quality. Ground-water contamination in these areas depends mainly on the amount of waste materials produced, type of ores mined, method of mining, amount of precipitation, depth to ground water, and presence or absence of surface water (Resource Concepts, Inc., 1980). Furthermore, cyanide solutions and mercury used in gold-ore processing may be a problem as they are toxic, even in small concentrations.

Contamination from agricultural activities is possible from: (1) water used for irrigation that either has dissolved an undesirable constituent or has been concentrated by evaporation; (2) infiltration of contaminated water from feedlots or dairy farms; and (3) downward percolation of water containing agricultural chemicals (insecticides, herbicides, or fertilizers). For example, shallow ground-water samples from subsurface drains beneath an irrigated field at Fallon (Churchill County) contain large arsenic concentrations (maximum of 950 μg/L) derived from the soil as the irrigation water percolated to the shallow water table (Doug Zimmerman, Nevada Division of Environmental Protection, written commun., 1986).

Radionuclides from nuclear-weapon detonations beneath the Nevada Test Site in southern Nevada, Hot Creek valley (Nye County), and the Sand Springs Range (Churchill and Mineral Counties) in central Nevada may migrate into the basin-fill aquifers in the future. In addition, the Nevada Test Site is one of the areas that is being considered as a national repository for the underground storage of high-level radioactive wastes.

GROUND-WATER-QUALITY MANAGEMENT

Ground-water quality is regulated by the NDEP, but is monitored by several State and Federal agencies. The Department may require ground-water monitoring for ground-water permits issued for industrial plants, land applications of sewage effluent, and geothermal injection wells. In addition, in 1987 the Department will assume responsibility for oil and gas injection wells, which currently are monitored by the EPA, and for issuing permits for zero-discharge heap-leaching operations. Ground-water monitoring also may be required in response to suspected contamination, such as mining sites or leaking fuel tanks (Dan Gross, Nevada Division of Environmental Protection, oral commun., 1986).

The State Health Division, Bureau of Consumer Health Protection Services, monitors ground-water quality for public and rural systems, and also monitors quality with regard to the approval of water supply and waste-water disposal facilities for subdivisions and developments, in all counties except Clark and Washoe. Clark and Washoe Counties have their own monitoring programs. All community water systems are required to monitor system water periodically for contaminants regulated under the Federal Safe Drinking Water Act and State law. Amendments to the Safe Drinking Water Act in 1986 will require monitoring of 83 additional constituents, including 14 volatile organic compounds, 29 synthetic organic chemicals, 13 inorganic chemicals, 4 microbiological contaminants, and 2 radiological contaminants (Thompson, 1986).

Radionuclide migration and ground-water quality are being monitored where underground nuclear device testing has been conducted in Nevada. These locations include the Nevada Test Site and surrounding areas, the Hot Creek Valley area, and the Sand Springs Range area. The monitoring program was initiated in 1972. Under a Memorandum of Understanding with the DOD, the EPA's laboratory in Las Vegas has operated the monitoring program to evaluate possible movement of radionuclides from the nuclear-test sites. The network consists of 22 monthly, 23 semi-annual, and 22 annual stations (Nowlin, 1986).

The U.S. Department of Agriculture makes random checks on pesticide disposal during use inspections, and any violations of pesticide-management laws are referred to the NDEP. The Nevada Department of Minerals regulates permitting for well construction relating to oil, gas, and geothermal wells. The Nevada Division of Water Resources regulates geothermal wells with regard to water rights and well construction (Dan Gross, Nevada Division of Environmental Protection, oral commun., 1986).

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Exploratory well installation by the U.S. Geological Survey near Hawthorne, Nevada, September 1977. The study, at a military ammunition plant, indicated that liquid explosives wastes had percolated into the shallow basin-fill aquifer beneath disposal pits (Van Denburgh and Schaefer, 1986). (Photograph by A.S. Van Denburgh, U.S. Geological Survey.)

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NEW HAMPSHIRE
Ground-Water Quality

Ground water is a major source for public supply in New Hampshire; about 57 percent of the population (fig. 1) depends on ground water. Water from principal aquifers in the State (fig. 2) does not exceed the drinking-water standards developed by the New Hampshire Department of Environmental Services (1984) for dissolved solids, hardness, and nitrate, which are important indicators of water quality. Subsurface waste disposal (fig. 3) and urbanization have caused contamination in some areas, and highway deicing has affected ground-water quality along roads throughout the State. Upland areas away from highways have not been affected by road salting.

Fifty-four hazardous-waste sites require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. In addition to these 54 RCRA sites, 13 others have been proposed or included in the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c) and will be evaluated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. In addition, the U.S. Department of Defense (DOD) has identified two sites at two facilities where contamination has warranted further investigation.

Ground-water quality currently is monitored by the Water Supply and Pollution Control Division (WSPCD) and Waste Management Division (WMD) of the New Hampshire Department of Environmental Services (NHDES). The U.S. Geological Survey has been monitoring background water quality in stratified-drift aquifers since 1983 as part of a cooperative program with the NHDES to identify important stratified-drift aquifers in the State.

WATER QUALITY IN PRINCIPAL AQUIFERS

Stratified drift and crystalline bedrock comprise the principal aquifers in New Hampshire (U.S. Geological Survey, 1985, p. 303). Water from stratified-drift aquifers generally can be classified as having small concentrations of dissolved solids and being slightly acidic and soft. Stratified-drift aquifers consist of unconsolidated sand and gravel deposits that are usually less than 100 feet thick. These aquifers are commonly located along river valleys and in broad outwash plains and are bordered by till or bedrock uplands as shown by the block diagram, figure *2B*. Water in stratified drift is generally unconfined, and depth to the water table is usually less than 20 feet. Yields from public-supply wells in stratified-drift aquifers may be as much as 1,500 gal/min (gallons per minute).

Although most of the State's ground-water withdrawals for public supply are from stratified-drift aquifers, most domestic and small public-supply wells are completed in bedrock aquifers. Water in bedrock aquifers, which consist of igneous and metamorphic rocks such as granite, gneiss, and schist, is present in fractures. Water from the bedrock aquifer can be classified as having moderate levels of dissolved solids and being slightly acidic and moderately hard to hard. Yields from wells in these aquifers typically are less than 10 gal/min, although some large-yield community and public-supply wells are located in areas where bedrock is extensively fractured.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from analyses in the files of the NHDES laboratory is presented in figure 2*C*. The summary is based on specific conductance, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), iron, and sodium analyses of water samples collected from 1980 to 1985 from the principal aquifers in New Hampshire. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 300 μg/L (micrograms per liter) iron.

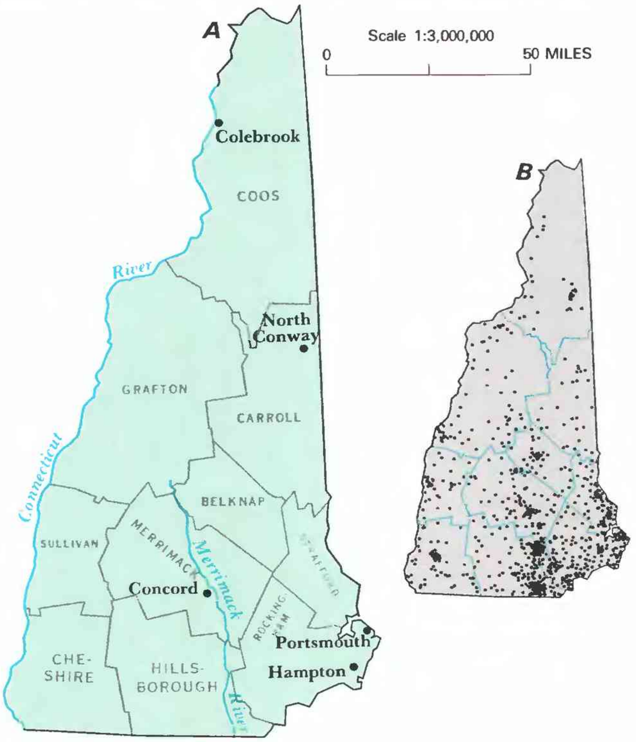

Figure 1. Selected geographic features and 1985 population distribution in New Hampshire. *A*, Counties, selected communities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Stratified-Drift Aquifers

Analyses of water from public-supply wells completed in the stratified-drift aquifers (aquifer 1) are summarized in figure 2*C*. The data are for towns with public-supply wells that pump at least 100,000 gal/d (gallons per day).

The median value of specific conductance for water in stratified-drift aquifers was 132 μS/cm (microsiemens per centimeter at 25° Celsius). Using conversion factors given by Hem (1985), this median value is equivalent to 75 to 100 mg/L of dissolved solids. The maximum observed specific conductance of water from these data was 469 μS/cm, which is equivalent to 260 to 350 mg/L of dissolved solids. The small concentrations of dissolved solids in water from stratified-drift aquifers are related to the relative insolubility of the aquifer matrix and the relatively short time that water is in contact with the aquifer.

Because calcium and magnesium, which contribute to the hardness of water, are widely distributed in the rocks and soil, they are the principal cations in most natural freshwater (Hem, 1985).

The median concentration of hardness in the stratified-drift aquifers of New Hampshire was 37 mg/L (fig. 2*C*); 75 percent of the samples mentioned in this summary had hardness concentrations of 60 mg/L or less. Water with hardness less than 60 mg/L is termed "soft".

Nitrate plus nitrite (as nitrogen) was usually less than 1 mg/L in stratified-drift aquifers (fig. 2*C*). The largest observed concentration, 3.4 mg/L, was in water from a well in Hampton and was probably caused by fertilizers and (or) septic wastes associated with nearby residential development (Bernard Lucy, New Hampshire Department of Environmental Services, written commun., 1987).

The median iron concentration for water from stratified-drift aquifers was 100 μg/L (fig. 2*C*). About 25 percent of the wells tested had iron concentrations that exceeded the 300-μg/L limit recommended by the New Hampshire Department of Environmental Services. The largest concentration was 1,200 μg/L. Increased concentrations of iron are not known to be harmful to humans. However, increased concentrations of iron can cause staining of clothes and plumbing fixtures and can impart an objectionable taste to water.

The New Hampshire Department of Environmental Services (1984) recommended that sodium concentrations in drinking water not exceed 250 mg/L for healthy people and 20 mg/L for people with cardiac or kidney problems or hypertension. Sodium concentrations in the wells sampled ranged from 1 to 58 mg/L, with a median concentration of 11 mg/L. Increased concentrations of sodium in ground water usually are caused by salt that is used for road deicing and stored in piles near roadways or by saltwater intrusion in coastal areas.

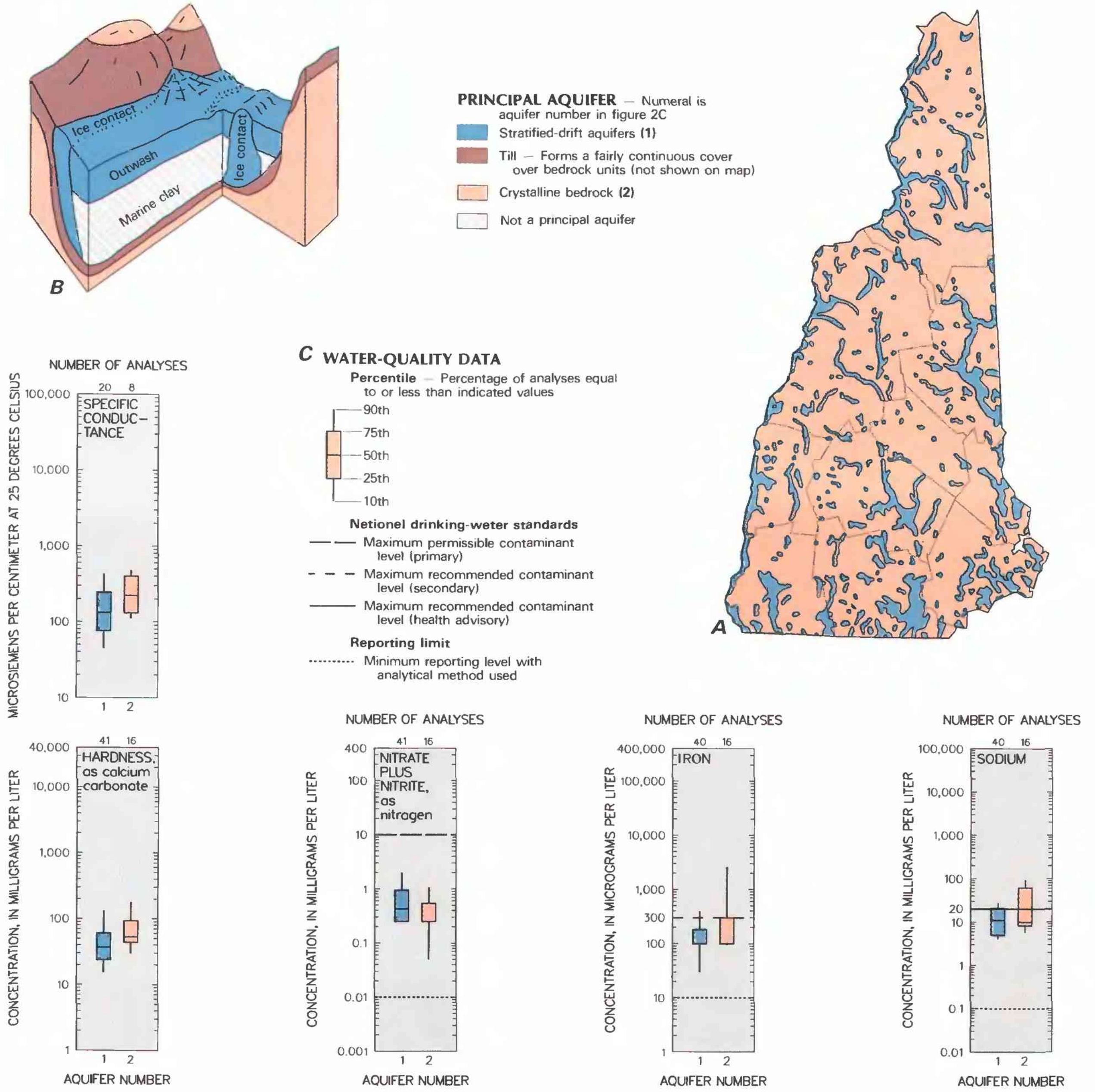

Figure 2. **Principal aquifers and related water-quality data in New Hampshire.** *A*, Principal aquifers; *B*, Generalized block diagram. *C*, Selected water-quality constituents and properties, as of 1980-85. (Sources: *A*, *B*, Compiled by R.E. Hammond and J.E. Cotton from U.S. Geological Survey files. *C*, Analyses compiled from New Hampshire Department of Environmental Services Laboratory files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

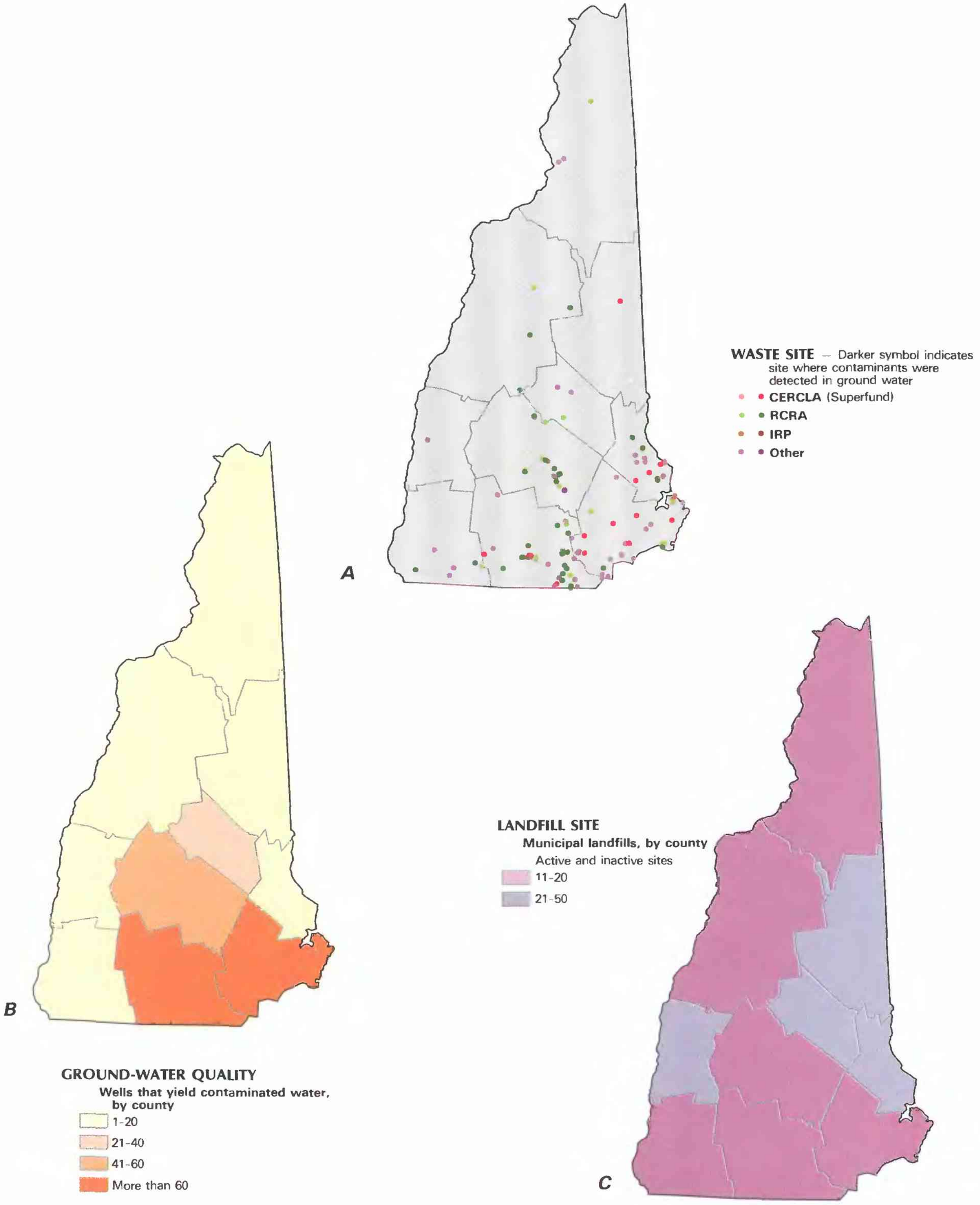

Figure 3. **Selected waste sites and ground-water-quality information in New Hampshire.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites, as of January 1987; and other selected waste sites, as of January 1987. *B*, Distribution of wells that yield contaminated water, as of January 1987. *C*, Municipal landfills, as of January 1987. (Sources: *A*, New Hampshire Department of Environmental Services, Waste Management Division files; U.S. Department of Defense, 1986. *B*, New Hampshire Departments of Environmental Services and Transportation files. *C*, New Hampshire Department of Environmental Services, Waste Management Division files.)

Crystalline-Bedrock Aquifers

Analyses of water from public-supply wells completed in bedrock (aquifer 2) are summarized in figure 2*C*. The yields of these wells range from 40,000 to 1,500,000 gal/d.

Water from bedrock aquifers had larger specific conductances and, therefore, more dissolved solids than water from stratified drift (fig. 2*C*). The median specific conductance is 222 μS/cm in bedrock, which is equivalent to 120 to 170 mg/L dissolved solids.

The hardness of water from bedrock ranges from 24 to 182 mg/L, with a median value of 53 mg/L. This water was generally harder than water from stratified drift, and about 50 percent of the samples are moderately hard to very hard (fig. 2*C*).

Water from the crystalline-bedrock aquifer had nitrate plus nitrite as nitrogen concentrations that are slightly smaller than those in stratified-drift aquifers, ranging from 0.05 to 1.5 mg/L with a median value of 0.25 mg/L. The most common sources of increased concentrations of nitrogen in ground water are faulty septic systems and fertilizers.

Iron is found in ground water that is in contact with iron-rich crystalline rocks. The median value was 100 μg/L, but almost one-third of all wells sampled had iron concentrations at or larger than 300 μg/L, the recommended limit for drinking water. Filtration is commonly used to control elevated concentrations of iron in drinking water and water used in trout and salmon hatcheries. Sodium in bedrock aquifers ranged from 1 to 97 mg/L with a median concentration of 10 mg/L.

Levels of arsenic in excess of the State and Federal maximum contaminant level of 50 μg/L were detected in 10 to 15 percent of the bedrock wells tested in private, State, and municipal programs. Arsenic can have as its source sulfide minerals in bedrock, such as pyrite (U.S. Environmental Protection Agency, 1981) or detergents present in septic waste (Boudette and others, 1985).

Radon-222, which may be carcinogenic when inhaled, has been found in water from bedrock wells in New Hampshire. Radon levels generally were largest in water from granites containing the micas muscovite and biotite. Other sources include quartz monzonite, granite, high- and low-grade metamorphic rocks, and diorite (Hall and others, 1985). Other radionuclides found in bedrock wells include uranium, radium-222, and radium-228. The NHDES estimates that significant concentrations of these constituents occur in 5 percent of bedrock wells.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has deteriorated in some areas, especially urban areas, mostly because of road salting and salt storage, leaking underground petroleum storage tanks, and underground disposal of septic waste. In addition, ground-water contamination has occurred near hazardous-waste disposal sites and landfills. Except for contamination by road salt, only localized ground-water contamination has occurred in New Hampshire.

Waste Disposal

New Hampshire currently has 13 hazardous-waste sites that are included on the NPL of CERCLA (U.S. Environmental Protection Agency, 1986c). Most of these sites are located in southern and southeastern New Hampshire in Hillsborough, Rockingham, and Strafford Counties (fig. 3*A*). At least 3 public-supply wells and more than 30 private wells near these CERCLA sites have been contaminated. In addition, hazardous wastes are treated, stored, or disposed of at 54 RCRA sites within New Hampshire (fig. 3*A*). Ground-water contamination has been detected at 35 of these RCRA sites (K. Marschner, New Hampshire Department of Environmental Services, written commun., 1987).

As of September 1985, 22 hazardous-waste sites at 4 facilities in New Hampshire had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under the CERCLA of 1980. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Two sites at two facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Organic compounds, mostly solvents from industrial waste, are some of the major ground-water contaminants in the State. Landfills, transfer stations, waste lagoons, drum-storage sites, and illegal discharge are the most common sources of organic contaminants. The most common organic contaminants are dichloroethane, trichloroethylene, tetrachloroethane, benzene, ethylbenzene, and toluene. Inorganic contaminants include hydrochloric acid and trace metals, such as chromium, cadmium, copper, and lead.

Septic Waste

About 50 percent of the State's population uses septic systems that discharge underground. The State also contains 95 sludge-disposal sites and 50 sites with lagoons for disposal of septic wastes. Contamination of public wells with septic waste is not a major problem in New Hampshire. However, in areas with many underground septic systems such as North Conway (Carroll County), increased concentrations of nitrate have been detected in ground water (Johnson and others, 1986).

Solid-Waste Landfills

In 1980, the annual generation of solid waste in New Hampshire was more than 927,000 tons (2.3 million cubic yards) (New Hampshire Office of State Planning, 1981). This waste has been disposed of at 246 sites (fig. 3*C*), 83 of which remain active in 1987. Four of these landfill sites were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Leachate produced by rain seeping through solid waste commonly contains increased concentrations of calcium, sodium, iron, sulfate, and chloride. Trace metals, such as lead, nickel, and cadmium, and organic compounds, such as phenols, trichloroethylene, and tetrahydrofuran also are commonly detected in landfill leachate. The four landfill sites included on the CERCLA list have caused contamination of many private wells.

Urbanization

New Hampshire's population grew 25 percent from 1970 to 1980 (U.S. Bureau of the Census, 1982). Much of this growth has been in the southern part of the State in Hillsborough, Merrimack, and Rockingham Counties. However, some areas in northern New Hampshire near recreation areas, such as Lake Winnipesaukee and the White Mountains, also have been developed in recent years.

The use of salt, mostly sodium chloride, for deicing roads began in the 1940's and increased steadily until the 1970's. In the early to mid-1960's, the annual salt usage on State highways was about 85,000 tons, but in the late 1960's and early 1970's, about 150,000 tons of salt was used annually (Hall, 1975). Examples of increases in chloride in public-supply well water from 1915 to 1970 are shown in figure 4 for the towns of Portsmouth, Colebrook, and Hampton. Before road salting began, natural (background) concentrations of chloride in ground water appear to have been smaller than 10 mg/L at each of these locations. Chloride increases have occurred mainly in urban areas and along highways; upland areas above highways have been unaffected.

Since 1979, the New Hampshire Department of Transportation has replaced 267 wells contaminated by road salt, but funds have not been available to replace all contaminated wells (W. Campbell, New Hampshire Department of Transportation, written commun., 1986). Wells contaminated by road salt are represented by about 79 percent of all wells that yield contaminated water shown in figure 3*B*.

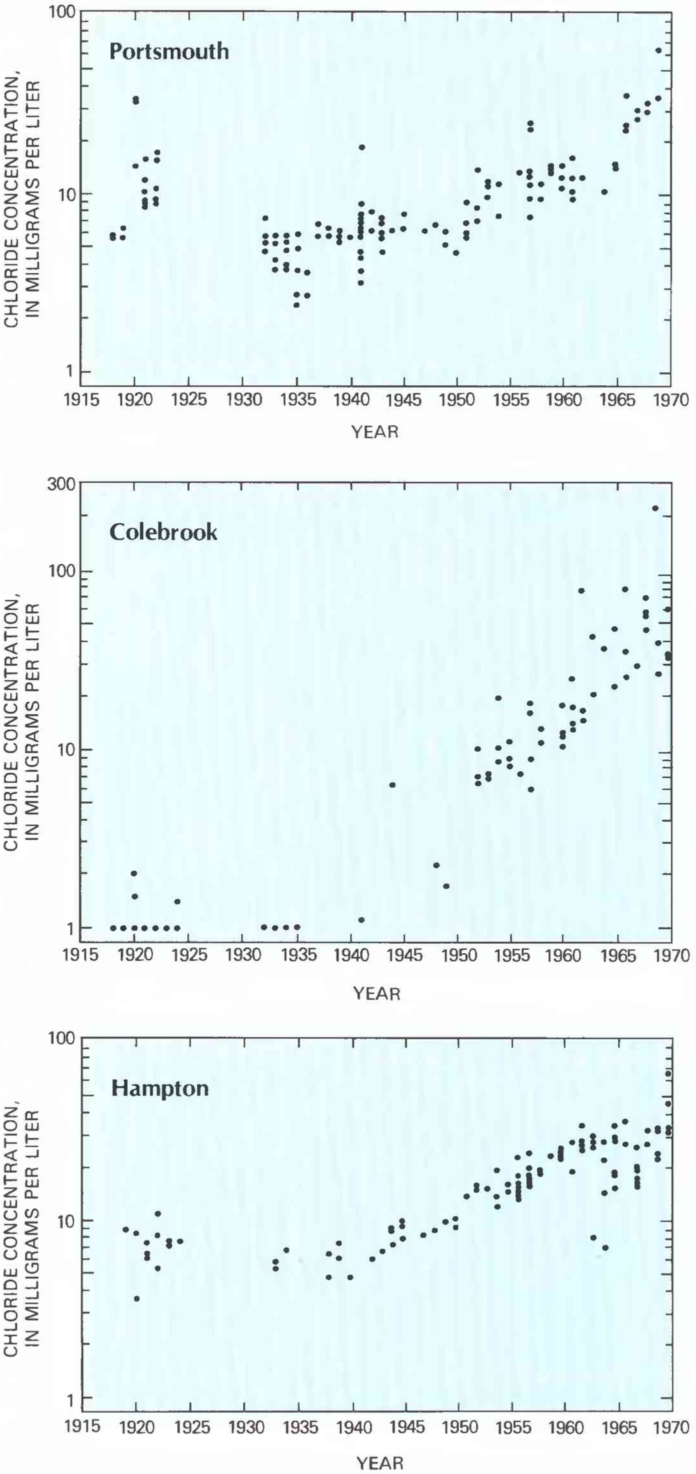

Figure 4. Variations in chloride concentrations in water from the Portsmouth, Colebrook, and Hampton public-supply wells, 1918-70. (Source: Modified from Hall, 1975.)

Some vegetation, such as elms, maples and grasses, that has little tolerance to salt and that is located near salted highways has been killed or damaged. Water that contains salt is corrosive to home water systems; corrosion may result in increased concentrations of iron, copper, zinc, and cadmium in drinking water. Ingestion of sodium also can create complications for people with heart, kidney, and liver ailments and especially for those with hypertension who are on sodium-restricted diets (Hall, 1975).

In New Hampshire, at least 20 incidences are reported annually of gasoline and petroleum products leaking from storage tanks; more than 35 major water supplies have been contaminated (Sills and others, 1985). The Water Supply and Pollution Control Division of NHDES estimates that at least 70 private wells have been contaminated by gasoline in the past few years (B. Foster, New Hampshire Department of Environmental Services, written commun., 1986). Several chemicals that are present in gasoline, such as benzene and ethylene dibromide, are carcinogenic. Because technology to clean ground water is relatively new and expensive, the standard remedy has been to provide alternative water supplies to affected residents.

POTENTIAL FOR CHANGES IN WATER QUALITY

Stratified-drift aquifers in New Hampshire are susceptible to contamination because they are usually less than 100 feet thick, unconfined, and have permeable materials in the thin unsaturated zones above the water table. A well that pumps 1,000,000 gal/d in such an aquifer may draw water from an area as large as 1.7 square miles (Morrissey, 1986). If contaminants enter the ground within this contributing area, they may eventually contaminate water from the well. Protection zones around public-supply wells in New Hampshire are usually 400 feet in diameter—an area much smaller than the contributing area. Under the 1986 amendments to the Federal Safe Drinking Water Act, the NHDES plans to protect the contributing areas of supply wells. State regulations for protecting areas that contribute ground water to wells probably will be developed by 1990.

Continued increases in population will increase the demand for water and will result in increased waste disposal, which has the potential to threaten ground-water quality. The quality of water from wells that obtain significant amounts of water from infiltration through river and lake beds may actually improve if the chemical quality of the surface water improves. Ground-water-protection ordinances for entire aquifers, and especially for contributing areas to wells, will help to preserve the quality of ground water.

GROUND-WATER-QUALITY MANAGEMENT

The New Hampshire Legislature recently established the Department of Environmental Services as the agency responsible for coordinating and managing water and waste. This new agency has four divisions that previously were independent agencies. The Commissioner of the Department is appointed by the Governor. The four divisions are:

Water Resources Division (WRD) (formerly Water Resources Board)
Water Supply and Pollution Control Division (WSPCD) (formerly Water Supply and Pollution Control Commission)
Waste Management Division (WMD) (formerly Division of Public Health Services)
Air Resources Division (ARD) (formerly Air Resources Agency)

The WSPCD has responsibility for water quality and related water-supply aspects of ground-water protection, whereas the WRD will manage water quantity by collecting data for water use, mapping ground-water resources, licensing well drillers, and collecting and assessing well-completion reports. The WMD is responsible for permitting facilities for solid- and hazardous-waste disposal and the Environmental Health Risk Assessment Unit of the New Hampshire Department of Public Health Services is responsible for assessing health risks related to ground-water use.

The Geological Survey, in cooperation with the New Hampshire Water Resources Division, completed the reconnaissance or "availability" mapping of the State's sand and gravel aquifers in 1977. The WSPCD has used these preliminary ground-water maps to construct "Non-Point Pollution Source Maps" for each municipality in New Hampshire. These maps show landfills, disposal sites, salt piles, areas of pesticide use, and areas of numerous septic tanks. Surface-water resources and areas with private and public wells are also shown. A document titled "Ground Water Protection Manual—A Guide for Local Action" also was published.

Although preliminary maps may be adequate for planning, implementing plans and policies requires more detailed information about the ground-water resource. Therefore, the U.S. Geological Survey, in cooperation with the WRD, started a program, which began in 1983 and is expected to be completed in 1993, to provide detailed maps of sand and gravel aquifers in New Hampshire. These maps will be the basis for future ground-water-management planning for State and local officials.

The WSPCD enforces the State Groundwater Protection Rules, Ws410, which require that the ground-water quality in the State not be degraded below background quality. These rules require a permit for discharges that may adversely affect ground-water quality and outline the requirements for monitoring and hydrogeologic studies. The WSPCD also regulates all septic systems in the State and administers the Federal Underground Injection Control (UIC) program, which includes a survey of potential sources of ground-water contamination.

The WMD issues permits for waste-disposal sites in the State and is responsible for siting all new hazardous-waste treatment and disposal facilities in New Hampshire. The issues concerning ground-water impact and permitting of these facilities are coordinated with the WSPCD.

The WSPCD has developed rules (Ws411) for storing petroleum products in underground tanks that apply to all nonresidential tanks with a capacity greater than 1,100 gallons; the rules apply to the registration, maintenance, inventory, leak detection, and installation of new equipment and include reporting requirements.

Ground-water quality is currently controlled by the State permitting system, the Federal Clean Water Act, the Federal UIC program, Safe Drinking Water Act, CERCLA, and RCRA. The NHDES maintains a laboratory for testing water for State and Federal programs in accordance with the quality-assurance quality-control requirements of each program. The NHDES laboratory also analyzes water from private wells and public-water supplies.

Although State and Federal efforts to protect ground water are important to management strategies, local ordinances and initiatives also are important. A few towns have adopted aquifer-protection ordinances that include regulations for underground storage tanks, zoning above aquifers, purchases of land to protect aquifers, and tax incentives to discourage development of open land over sensitive aquifers. Many other towns are considering similar ordinances to protect ground-water quality. The New Hampshire Office of State Planning is establishing rules governing local water-resource management and protection planning.

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NEW JERSEY
Ground-Water Quality

New Jersey (fig. 1*A*) historically has had, and continues to have, a sufficient supply of ground water for much of the State that is suitable for most uses. In fact, about 50 percent of the 7.56 million people in New Jersey (fig. 1*B*) obtain their drinking water from ground-water supplies—about 39 percent from public-supply wells and 11 percent from domestic-supply wells.

Of the 622 public water-supply systems in the State, which include more than 1,900 wells, 90 percent obtain all or part of their supplies from ground-water sources (fig. 2). An additional 16,000 self-supply irrigation, industrial and commercial wells and about 400,000 rural domestic-supply wells are used in the State (Robinson, 1986). In 1985, about 442 Mgal/d (million gallons per day) of ground water was pumped for public-supply use, 157 Mgal/d for self-supplied industrial/commercial use, 97 Mgal/d for irrigation use, and 64 Mgal/d for rural domestic-supply use (Charles Qualls, U.S. Geological Survey, written commun., 1986).

The scientific literature before 1970 indicated that New Jersey's ground water was regionally suitable for most uses, although locally saltwater intrusion, toxic metal or other inorganic contamination, objectionable odor and taste, and excessive iron content were problems. These studies had focused only on inorganic quality because an awareness of organic ground-water contamination was not realized until the advent of improved organic analytical capability in the 1970's. By 1977, reports on incidents of organic contamination resulting from chemical-waste storage, production, disposal, or spills were reaching the New Jersey Department of Environmental Protection with some regularity.

In 1986, New Jersey had 1,224 known or suspected hazardous-waste sites (fig. 3*A*) at which at least a site inspection or preliminary assessment had been made in response to suspected ground-water contamination (Robert Kunze, New Jersey Department of Environmental Protection, written commun., 1986). More than 650 of these sites are known to need some remedial measures, and about 60 of the sites have been cleaned (Robinson, 1986). As of May 1986, 91 sites were on the "Superfund" or National Priorities List for cleanup (U.S. Environmental Protection Agency, 1986c), as part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, and another 6 sites were proposed for inclusion. Also, 196 sites require monitoring under the Federal Resource Conservation and Recovery Act of 1976 (RCRA) program (Robert Kunze, New Jersey Department of Environmental Protection, written commun., 1986). A total of 205 county and municipal landfills (fig. 3*C*) are known to exist in New Jersey as of July 1986 (John Castner, New Jersey Department of Environmental Protection, written commun., 1986), most of which are not included in the 1,224 sites noted above.

WATER QUALITY IN PRINCIPAL AQUIFERS

New Jersey's principal aquifers (fig. 2*A*1) are classified into two groups—Coastal Plain aquifers south of the Fall Line and non-Coastal Plain aquifers north of the Fall Line (U.S. Geological Survey, 1985 p. 309). Depending on location, these aquifers are recharged by precipitation, soil-moisture drainage, seepage from surface-water systems, or leakage through confining beds. Three major areas of the State (fig. 2*A*2) have special State regulations protecting ground water. The Pinelands Region has stringent controls on development and removal of ground water from the region in order to protect the ecology of it's wetlands. The two Water Supply Critical Areas have controls (reductions) on pumpage to allow water levels to recover and to reduce the potential for saltwater intrusion and other water-quality problems.

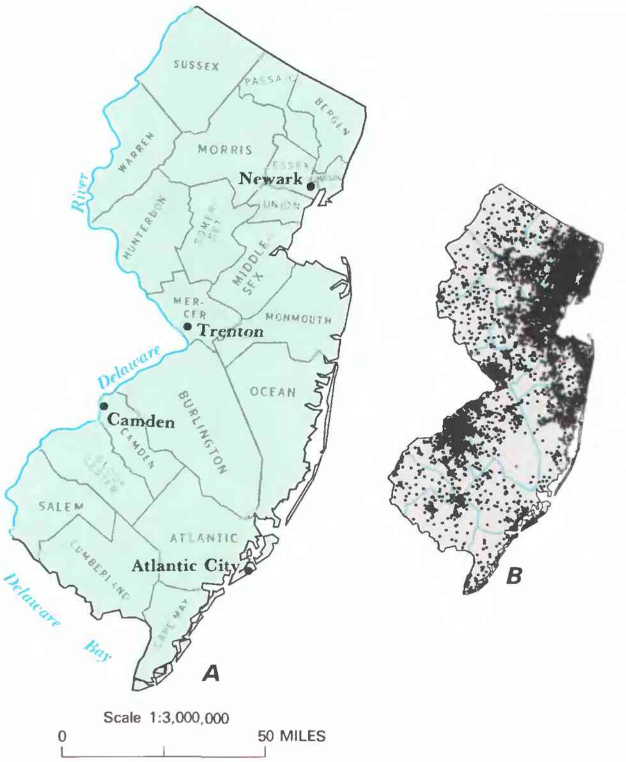

Figure 1. Selected geographic features and 1985 population distribution in New Jersey. *A,* Counties, selected cities, and major drainages. *B,* Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B,* Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

The five principal Coastal Plain aquifers or aquifer systems (from youngest to oldest) are the Kirkwood-Cohansey aquifer system, the Atlantic City 800-foot sand aquifer of the Kirkwood Formation, the Wenonah–Mount Laurel aquifer, the Englishtown aquifer, and the Potomac-Raritan-Magothy aquifer system (fig. 2*A*1). In general, extremely permeable beds of unconsolidated sand and gravel form the aquifers and slightly permeable interbeds of silt and clay form the confining beds. These interbedded, unconsolidated sediments differ in areal extent and thickness, but the entire Coastal Plain system dips to the southeast and thickens seaward (fig. 2*B*). All the aquifers except the Kirkwood-Cohansey aquifer system are confined except where they crop out. These aquifers supply more than 70 percent of the freshwater used in the 4,400-mi^2 (square mile) Coastal Plain area.

North of the Fall Line, the principal aquifers are associated with the glacial valley-fill deposits (narrow, beltlike deposits scattered throughout northern New Jersey and too small in areal extent to be shown in figure 2*A*1), the fractured shale and sandstone units of the Newark Group, the Valley and Ridge sedimentary units, and the weathered and fractured zones of the Highlands crystalline units. These aquifers are important locally and commonly are inter-

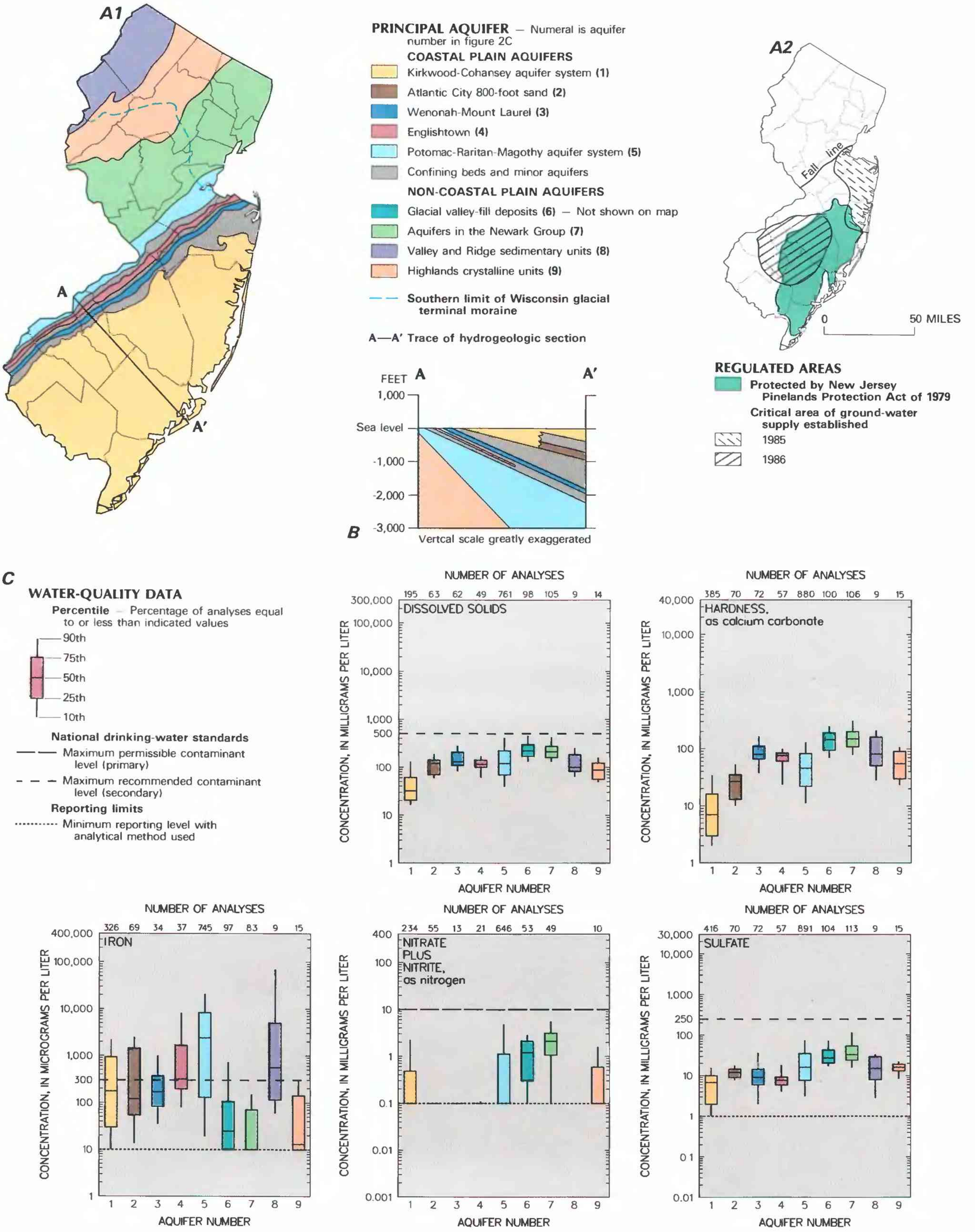

Figure 2. Principal aquifers and related water-quality data in New Jersey. *A1*, Principal aquifers; *A2*, Pinelands region and water-supply critical areas. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1923-86. (Sources: *A1*, Compiled by O.S. Zapecza from U.S. Geological Survey files; *A2*, Unpublished documents of the New Jersey Department of Environmental Protection and the New Jersey Pineland Commission. *B*, Compiled by O.S. Zapecza from U.S. Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S Environmental Protection Agency, 1986a,b)

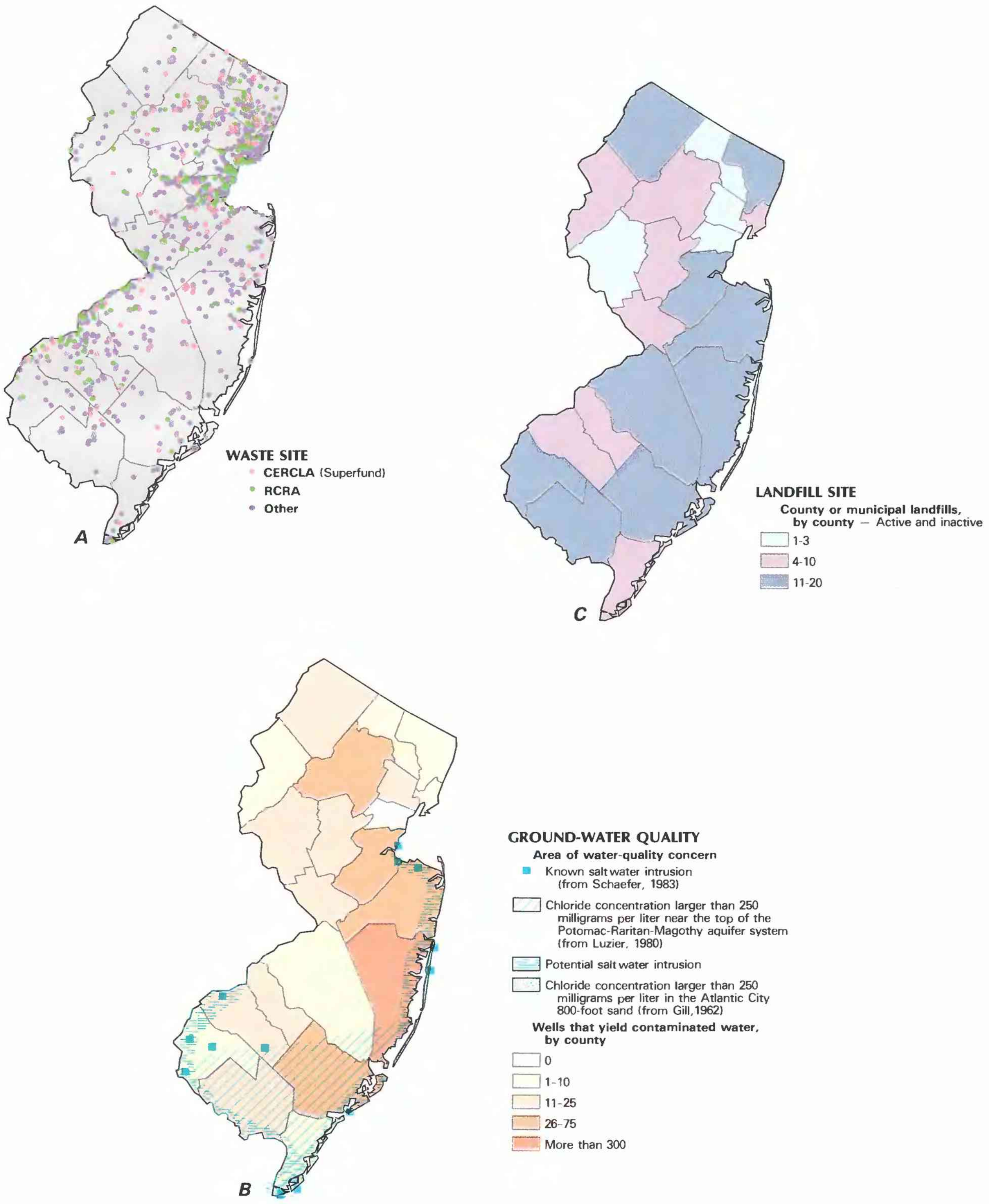

Figure 3. Selected waste sites and ground-water-quality information in New Jersey. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of August 1986. *B*, Areas of human-induced and potential saltwater contamination, and distribution of wells that yield contaminated water, as of 1985. *C*, County and municipal landfills, as of July 1986. (Sources: *A*, Robert Kunze, New Jersey Department of Environmental Protection. *B*, Compiled from Association of State and Interstate Water Pollution Control Administrators, 1985; Gill, 1962; Luzier, 1980; Schaefer, 1983. *C*, John Castner, New Jersey Department of Environmental Protection.)

connected with surface-water sources in most northern New Jersey public water-supply systems. Ground water provides about 20 percent of the freshwater supply north of the Fall Line, an area of 3,080 mi².

The New Jersey Geological Survey and U.S. Geological Survey have investigated ground-water conditions in the Coastal Plain since the late 1800's. In cooperation with the State, the U.S. Geological Survey formally began a saltwater-intrusion monitoring program in 1923. Nearly 9,000 chloride analyses were performed on water samples from 884 wells between 1923 and 1961 (Seaber, 1963). Since 1961, about 225 wells of a network of about 500 wells have been sampled each year for chloride, specific conductance, temperature, and, more recently, sodium and pH. Thirteen areas of the Coastal Plain (fig. *3B*) have well-defined occurrences of saltwater intrusion (Schaefer, 1983).

In 1961, the cooperative program began "network" coverage of inorganic ground-water quality by sampling 15 to 50 different wells per year, largely in the Coastal Plain. By 1982, the sampling had been expanded to include trace metals and various organics, and the sampling network had been redirected toward 20 different wells in the water-level observation-well network each year. The water-quality and water-level networks are being further expanded into the less-studied non-Coastal Plain aquifers in northern New Jersey. The water-quality network will sample about 30 wells annually and the intensive basin-assessment program will sample another 20 wells.

U.S. Geological Survey cooperative studies with the State that assess the quantity and inorganic quality of New Jersey's water-supply sources also started in 1923 (Seaber, 1963). Since 1980, the New Jersey and U.S. Geological Surveys have undertaken many ground-water-quality studies around the State, emphasizing trace-metal and organic analyses. More than 1,750 wells have been sampled for major ions since 1980; about 55 percent (977 wells) also have been analyzed for trace metals and organic constituents. Of the 1,750 wells, 90 percent were sampled in regional studies and 10 percent were sampled as part of a network.

BACKGROUND WATER QUALITY

The inorganic water quality of the nine major aquifer systems in New Jersey is summarized by graphs (fig. 2*C*) compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). The graphs show dissolved-solids, hardness, iron, nitrate plus nitrite (as nitrogen), and sulfate of water samples collected from 1923 to 1986. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards, which are health related and are legally enforceable, include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen). The secondary maximum contaminant level standards, which apply to esthetic qualities and are recommended guidelines, include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter) iron, and 250 mg/L sulfate. The data in figure 2*C* are presented without distinction as to sample depth or whether the aquifer is confined or unconfined. Where more than one sample was analyzed per site, the median value of the constituent was used.

Median dissolved-solids concentrations (fig. 2*C*) ranged from 32 to 219 mg/L, which did not exceed the national drinking-water standard. In the Coastal Plain the dissolved-solids concentrations for aquifers 2, 3, and 4 reflect the longer residence time of water expected under predominantly confined conditions and show less variation than aquifers 1 and 5, which are under predominantly unconfined conditions.

The predominant ions in most New Jersey ground waters are calcium, magnesium, and bicarbonate. A gradual change to sodium bicarbonate dominance is observed about 30 to 40 miles downdip in the confined Coastal Plain aquifer systems as a result of cation-exchange mechanisms (Leroy Knobel, U.S. Geological Survey, written commun., 1986). The Atlantic City 800-foot sand aquifer is a sodium bicarbonate dominated system except where it is salty south of the tip of Cape May County (fig. *3B*). The Potomac-Raritan-Mogothy aquifer system is salty in the southern part of the Coastal Plain (fig. *3B*).

The soils overlying the Kirkwood-Cohansey aquifer system are very sandy and permeable, leaving little time and potential for mineralization of recharge water. Consequently, dissolved-solids concentrations near that of rainfall occur in ground water of this system. Water in this aquifer system also is poorly buffered (median alkalinity is 3 mg/L) and naturally acidic (median pH is 5.2). Ion dominance in this aquifer system is variable, depending on depth and location relative to wetlands (Rhodehamel, 1979).

The Potomac-Raritan-Magothy, the glacial valley-fill, and the Newark Group aquifer systems have median chloride concentrations of 11.6, 30.5, and 16.0 mg/L, respectively. All other aquifers have median chloride concentrations smaller than 7.0 mg/L. Chloride is a problem only in some coastal areas (fig. *3B*) where extensive ground-water withdrawals have induced saltwater intrusion (Schaefer, 1983).

Using Hem's (1985, p. 159) classification ranges for hardness, the Kirkwood-Cohansey, Atlantic City 800-foot sand, Potomac-Raritan-Magothy, and Highlands crystalline aquifer systems have "soft" ground water (0–60 mg/L as calcium carbonate); the Wenonah-Mount Laurel, Englishtown, and Valley and Ridge aquifer systems have "moderately hard" ground water (61–120 mg/L); and the glacial valley-fill and Newark Group aquifers have "hard" ground water (121–180 mg/L) (fig. 2*C*). Hardness is easily treatable for those ground waters with concentrations larger than 100 mg/L.

Median iron concentrations (fig. 2*C*) commonly exceed the national drinking-water standard of 300 μg/L in all aquifers except the glacial valley-fill deposits, the Newark Group, and the Highlands crystalline systems. Iron concentrations are extremely variable within each aquifer system because of large variations in local conditions controlling the dissolution of iron minerals. Iron is a local or subregional problem and usually is treatable.

Sulfate (fig. 2*C*) follows a pattern similar to dissolved solids, as does chloride. Sulfate is not perceived to be a water-quality problem in New Jersey ground water. However, certain soils in the Coastal Plain appear to be saturated with respect to sulfate and present research indicates that sulfate mobility through soils to shallow ground-water and surface-water systems may be increasing the mobilization of aluminum (Paul Schuster, U.S. Geological Survey, written commun., 1986). Increased aluminum, if in the ionic form, can be toxic to some plants (Ulrich and others, 1980) and fish (Driscoll and others, 1980).

Median concentrations of nitrate plus nitrite (fig. 2*C*) in the confined Coastal Plain aquifer systems are consistently 0.11 mg/L or less, which is considerably smaller than the national drinking-water standard of 10 mg/L. Although median concentrations in the Kirkwood-Cohansey and Potomac-Raritan-Magothy aquifer systems are small, 0.1 mg/L, the data set is extremely variable because of the large number of samples from unconfined wells, which are more susceptible than confined wells to the effects of different land uses. The glacial valley-fill and Newark Group aquifer systems generally are water-table systems overlain by soils more fertile than soils overlying the other New Jersey aquifer systems; therefore, the median concentrations of nitrate plus nitrite are larger than in the other systems.

Several dozen rural-domestic wells have been closed statewide because of increased nitrate levels resulting from the intensity of agricultural practices or septic systems in some areas (Haig

Kasabach, New Jersey State Geologist, oral commun., 1986). Furthermore, the New Jersey Department of Environmental Protection recently has received loan requests from six Coastal Plain communities to correct nitrate-contamination problems in their water supplies (Joseph Miri, New Jersey Department of Environmental Protection, written commun., 1986).

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality in some areas of New Jersey has been degraded, in some instances severely, owing to the effects of urbanization, transportation, industrialization, agriculture, land disposal of wastes, ground-water pumpage, and perhaps atmospheric deposition. New Jersey has between 10,000 and 15,000 firms engaged in the manufacture of chemical and petrochemical products. New Jersey also generates about 8 percent of the Nation's hazardous waste—more than 40 million pounds annually, which is the largest of any State (Stevenson and others, 1986). The use, transport, and storage of organic and other hazardous chemicals is pervasive throughout much of the State. Consequently, aquifers have been contaminated in many locations through poor industrial housekeeping, spills and accidents of all types, deliberate dumping, illegal discharges, leaks from subsurface storage tanks, landfills, and other factors.

In retrospect, the permitting process of the 1970's and before did not consider ground water to be so vulnerable, and, consequently, ground-water protection did not receive sufficient consideration. In fact, State and Federal laws passed in the 1970's concentrated on "fishable and swimmable" goals for surface waters and, lacking comprehensiveness with respect to ground water, inadvertently increased ground-water contaminant discharges. Many surface-water discharges were replaced by lagoons, spray irrigation, and landfills that accepted chemical wastes (Kasabach and Althoff, 1983), thereby increasing contaminant movement to ground water. Later, the seriousness of ground-water contamination was brought into focus and, important steps in the late 1970's led to development of comprehensive legislation in the early 1980's to both identify and deal with existing problems and to greatly aid prevention of further ground-water degradation.

Roux and Althoff (1980) described the hydrogeologic complexity associated with ground-water supplies that became contaminated by multiple industrial sources of volatile organic compounds (voc). This study, which indicates how industrial-plant procedures of the 1970's contributed to the degradation of ground-water quality, is an example of how a detailed hydrogeologic analysis was used to define sources of contamination and to provide solutions for abatement.

In two regional ground-water studies of toxic contaminants (metals, pesticides, and voc), researchers found that voc present the most serious and pervasive contamination threat to New Jersey's ground water (Tucker, 1981; Fusillo and Hochreiter, 1982). Testing for 22 organic compounds, Tucker (1981) found one or more of eight voc with a concentration larger than 10 μg/L in 16.6 percent of the 670 wells sampled statewide. The most common compounds were 1,1,1-trichloroethane, trichloroethylene, and trichloromethane (chloroform). Fusillo and others (1985) found one or more of 27 voc with a concentration larger than 1 μg/L in about 20 percent of the 315 Coastal Plain wells sampled. The three most common contaminants were trichloroethylene, tetrachloroethylene, and benzene.

An overview report on the State's ground-water-quality program (Kasabach and Althoff, 1983) reported nearly 70 percent of the ground-water-contamination cases involved industrial solvents. The principal contaminants were trichloromethane, 1,1,1-trichloroethane, tetrachloroethylene, trichloroethylene, carbon tetrachloride, and methylene chloride. Where gasoline discharges had occurred, dissolved benzene, toluene, and xylene were common ground-water contaminants.

Results of the State Safe Drinking Water Testing Program (A-280) for the spring of 1985 indicate that about 18 percent of the New Jersey public water supplies ("finished water") had detectable concentrations (more than 1 μg/L) of one or more organic contaminants (New Jersey Department of Environmental Protection, 1986a). Interestingly, all public-water systems where samples contained detectable levels of organic contaminants use ground water as either the sole or partial source of supply. The most frequently detected contaminants were trichloroethylene, 1,1,1-trichloroethane, and tetrachloroethylene. More importantly, though, only 1 percent of the suppliers had contamination levels large enough that they were required to take some remedial action within 1 year or face closure. At least 17 wells that yield contaminated water have been closed as a result of this Safe Drinking Water Testing Program.

Since 1970, about 200 wells in the State have been closed because of chloride, arsenic, nitrate, mercury, lead, hexavalent chromium, biological, or radiological (both natural and human-caused) contamination (John Preczewski, New Jersey Department of Environmental Protection, oral commun., 1986). Also, since 1970, nearly 1,200 wells have been closed because of contamination from organic compounds. Most of these closures, 80 to 90 percent, were private wells.

The New Jersey experiences with ground-water contamination indicate that wells located in unconsolidated, water-table aquifers near population and industrial centers are most likely to have contamination problems. Organic compounds, especially volatile organic compounds, are the most common and pose the most serious human-induced contamination threats to ground-water supplies. Furthermore, as indicated by Kish and others (1987), an association exists between specific groups of contaminants and land uses, at least for the outcrop of the Potomac-Raritan-Magothy aquifer system.

POTENTIAL FOR WATER-QUALITY CHANGES

In response to severe water-level declines (about 90 feet) and continued development, two major areas of the Potomac-Raritan-Magothy aquifer system are being delineated as water-supply critical areas (fig. 2*A2*). Decreases in pumpage from 35 to 50 percent of 1983 pumpage will be required of all critical area ground-water users by 1990. This mandate is forcing most users to rigorously search for alternative sources such as importation of water; increased surface-water use, such as high-flow skimming and increased surface-water storage; or use of shallower, generally water-table ground-water systems. It follows from past experiences that a potential increase in the identification of water-quality problems, especially organic contamination, is to be expected where usage of shallow ground water increases.

Furthermore, ground-water-contamination problems with respect to nonpoint sources in New Jersey are not delineated or well understood. For example, the effects of agricultural practices, especially the use of pesticides, and the effects of atmospheric deposition on ground-water quality are not well documented. Also, natural radioactivity in ground water may be a problem in some non-Coastal Plain aquifers (Otto Zapecza, U.S. Geological Survey, written commun., 1986). Increasing sampling and use of ground water will uncover more existing problems. Undoubtedly, expected growth outward from populous areas shown in figure 1*B* will cause additional problems. However, New Jersey appears not to be growing in chemical or heavy manufacturing industries, but rather is growing in the lighter industrial, commercial corporate, and research and development activities, and also in suburban residential development. This trend, along with the more active implementation of comprehensive and stringent State and Federal protective and cleanup legislation, likely will minimize New Jersey's future ground-water-contamination problems.

GROUND-WATER-QUALITY MANAGEMENT

New Jersey considers ground-water protection and pollution control to be extremely important and, by legislative guides and mandates, has made major commitments towards progressive, often innovative, approaches to ground-water management. The New Jersey Department of Environmental Protection (NJDEP) is the agency delegated with primary responsibility for ground-water management and regulation in New Jersey. The State has taken a comprehensive resource management approach to ground-water protection. Virtually every State law dealing with ground-water protection requires certain groups of facilities or users to self-monitor, for State review, all uses of the resource and all activities suspected or known to be a contamination source. New Jersey's laws and regulations are broad based in that they control potential, as well as actual, discharges to ground water.

The Delaware River Basin Commission also has an active ground-water management program for the part of New Jersey in the basin. Included in the program's 27 recommendations are a comprehensive ground-water data base and computer management system, and new well registration and metering regulations.

On the resource assessment side, the thorough evaluation of the State's ground-water resources, both in quantity and quality, has been established to be critical to effective management. Identification of significant resource problems during the last 10 years has further stimulated resource assessment. Increased activities include major ongoing and planned regional ground-water studies in problem areas, a statewide aquifer-mapping project, redirection of the statewide monitoring networks, development of county/State cooperative ground-water monitoring, "A-280" mandated monitoring of public water supplies (see later in this section), revision of State ground-water-quality standards, improved coordination between data-collection agencies, a growing and better informed enforcement program, and development of an aquifer classification system based on the evaluation of potability, hydraulic properties, use, and susceptibility to contamination. The New Jersey Geological Survey and the U.S. Geological Survey are providing technical support to the ground-water regulatory programs, particularly through development of the resource data bases, interpretive resource and modeling studies, and studies of ground-water contamination processes.

On the regulatory side, New Jersey Law 1947, further strengthened by the Water Supply Management Act of 1981, requires all ground-water users to obtain NJDEP certification for irrigation withdrawals or diversion permits for all other withdrawals of 0.1 Mgal/d or more, and well permits for all public or private water-supply well installations before drilling a well. More than 1,000 diversion permits have been granted and about 10,000 well permit applications are processed annually (Robinson, 1986). New Jersey also requires that all water-well drillers be licensed.

The 1981 Act also provides for the designation of water-supply critical areas if severe water-supply problems exist, thereby empowering the State to exercise regional water-management controls not otherwise applicable. The NJDEP responded to severe ground-water-level declines as a result of pumpage and increased development in the Coastal Plain by establishing the first water-supply critical area in 1985 and a second in 1986 (fig. 2*A*2).

The direction and activities of water-quality management programs are outlined in the Statewide Water Quality Management Plan (New Jersey Department of Environmental Protection, 1986b). One direction is through the New Jersey Pollutant Discharge Elimination System (NJPDES) program, proposed as a State program in 1975 and officially approved for State primacy by the U.S. Environmental Protection Agency in 1981, whereby both surface- and ground-water dischargers are issued permits. Ground-water discharges include surface impoundments or lagoons, injection wells, spray irrigation, land application of residuals, and landfills for both hazardous and nonhazardous materials. An important requirement is that all ground-water permitted facilities must perform routine discharge and aquifer water-quality monitoring (Robinson, 1986).

The State had issued 618 final NJPDES ground-water discharge permits through July 1986—314 for land application of wastewaters and 304 for landfills (Robert Berg, New Jersey Department of Environmental Protection, written commun., 1986). Another 762 draft NJPDES permits had been issued and several hundred more permits are expected to be issued over the next few years.

Pursuant to the New Jersey Solid Waste Management Act of 1970, the State is revising the standards for installation and construction of onsite disposal systems, and transferring to the local health agencies some onsite system review and control of sludge disposal.

Under the NJPDES permit program and the provisions of the Federal RCRA, the State has taken an active role in registration and identification of underground storage tanks (UST) in excess of 1,100 gallons. About 14,000 UST facilities have registered so far. On September 3, 1986, the Governor signed into law the New Jersey Underground Storage Tank legislation to provide for the registration, annual certification, systematic testing, and monitoring of UST's. The State UST law will increase the number of facilities to be registered by an estimated 50,000 to 70,000 owing to the broader scope of the State law (Robert Nugent, New Jersey Department of Environmental Protection, written commun., 1986).

In addition to Federal RCRA and Superfund cleanup activities, the State has initiated private (that is, at the cost of the violator) remedial cleanup actions pursuant to the New Jersey Water Pollution Control Act of 1981. The State is currently handling nearly 500 private contamination cases and is supervising more than 100 on-going private cleanup projects (William Althoff, New Jersey Department of Environmental Protection, written commun., 1986). As efforts on these private cases continue, millions of dollars of private funds have already been spent, thereby saving millions of public dollars for private parties not able to address their contamination cleanup. Other State cleanup funding and authority is provided by the New Jersey Spill Commission and Control Act of 1977 and the New Jersey Hazardous Discharge Bond Act of 1981.

New Jersey's Environmental Cleanup Responsibility Act (ECRA) of 1983 imposes preconditions on the sale, transfer, or closure of industrial establishments or property involved in the generation, manufacture, refining, transportation, treatment, storage, or disposal of either hazardous substances or wastes. Analagous to home buyer protection programs, this environmental audit determines potential and existing contamination problems, and establishes where and to what extent cleanup is required "before" sale, transfer, or closure can be legally completed. ECRA provides preventative legislation that will benefit New Jersey's environment and economy. From January 1984 through September 1986, a total of 1,990 ECRA cases had been received and 928 cases are closed (Lance Miller, New Jersey Department of Environmental Protection, written commun., 1986).

In 1984, amendments to the New Jersey Safe Drinking Water Act, commonly called "A-280", were signed into law establishing New Jersey as a national leader in assessing drinking-water quality. The law requires all public community water supplies to report to the State the test results on their finished water for 22 hazardous organic contaminants twice a year. Metals and other inorganic constituents are required on a less frequent basis as mandated by the national interim primary drinking-water standards. The law also requires that a 15-member Drinking Water Quality Institute be established to determine additions to the water-quality-constituents list, to develop maximum contaminant levels, and to determine appropriate sampling and analytical protocol. The NJDEP administers the "A-280" program and is extending considerable effort in quality assurance of the data collected, in planning financial aid programs for systems with problems, and in bringing problem systems within compliance quickly.

New Jersey has more than 900,000 acres of wetlands (Tiner, 1985), which serve as important components of ground-water surface-water systems. The New Jersey Pinelands Protection Act of 1979 substantially protects the integrity of some 278,000 acres of freshwater wetlands in the Coastal Plain. Another 243,000 acres of coastal area salt and freshwater (mostly saltwater) wetlands are afforded protection under the New Jersey Wetlands Act of 1970. The remaining freshwater wetlands, more than 380,000 acres, are only partly protected through five State and one U.S. Army Corps of Engineers permit programs (Robinson, 1986).

To emphasize the importance of New Jersey's ground water to its citizens and industries, the NJDEP petitioned the U.S. Environmental Protection Agency in 1985 to declare practically the entire State as a sole-source aquifer. The added protection provided by this unprecendented sole-source aquifer petition for the entire State goes hand in hand with the active ground-water discharge permit program and aggressive implementation of Federal and State ground-water-quality legislation.

Despite the fact that ground-water contamination, especially from organic compounds, is locally a very serious problem, New Jersey continues to have a sufficient supply of good quality ground water for most users throughout the State. Furthermore, in-place management practices of the State indicate a comprehensive approach to ground-water protection, whereby all known and potential sources of contamination are subject to controls. Clearly, the future of New Jersey's ground-water resources lies in the continued ability to implement and strengthen these controls as new and unforeseen water-quality problems arise.

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Water well drilling offshore of Atlantic City, New Jersey, summer 1985. The U.S. Geological Survey, in cooperation with the New Jersey Department of Environmental Protection, drilled two deep observation wells 1.9 and 5.3 miles offshore to evaluate the likelihood of saltwater intrusion toward onshore freshwater supplies. At these respective sites, the wells were drilled to depths of 933 and 1,025 feet below the sea floor. Dissolved solids increased seaward, but freshwater was found in both wells.

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NEW MEXICO
Ground-Water Quality

New Mexico, a State with an arid to semiarid climate, relies on fresh ground-water supplies for almost one-half of its water needs. About 1.9 million acre-feet of fresh ground water was withdrawn during 1980, of which 86 percent of this supply was used for the irrigation of 861,000 (U.S. Geological Survey, 1985, p. 317) acres of farmland and 12 percent was used in urban and rural areas for public or domestic supplies to serve about 1.2 million people (or 89 percent of the State's population). The remaining 2 percent was used for industries, electric powerplants, or livestock watering (Solley and others, 1983). The State's major population centers and population distribution are shown in figure 1.

The total volume of water in aquifers in New Mexico is estimated to be 20 billion acre-feet. Although ground water is abundant, the total volume cannot be extracted. It is not available everywhere in the State, and 75 percent of it is too saline for most uses. The remaining 25 percent contains dissolved-solids concentrations of smaller than 2,000 mg/L (milligrams per liter), and is suitable for most uses; however, these more suitable supplies commonly are found in unconfined shallow aquifers where water quality is easily affected by human activities and by the water quality of nearby rivers (Hale and others, 1965). This situation exists along the principal rivers in the State, especially in the Rio Grande basin where most of the State's commercial, industrial, and agricultural enterprises are located (Sorenson, 1982).

New Mexico's 1980 population of about 1.3 million was about 28 percent greater than the 1970 population (U.S. Bureau of the Census, 1982), and the State's population is projected to reach 2.0 million by the year 2000. Most of this growth has been and is anticipated to continue in the State's few large urban centers. Metropolitan Albuquerque, located on the Rio Grande near the center of the State, is New Mexico's largest city. During 1980, metropolitan Albuquerque's population was 454,000, or 34 percent of the State's total. The State's next two largest urban centers, Santa Fe to the north and Las Cruces to the south of Albuquerque, are both located in the Rio Grande basin. Each had a population of about 45,000 in 1980. Albuquerque and Las Cruces rely totally on ground water for their public supply. Santa Fe, which relies mostly on surface water for its public supply, is becoming more dependent on ground-water supplies as its population grows.

New Mexico's aquifers generally have not been affected by the many water-quality problems associated with the more densely populated regions of the Nation. Still, significant ground-water-quality problems have been identified and reported in New Mexico's biannual water-quality report to Congress (New Mexico Water Quality Control Commission, 1984). The ground-water-quality problems occur along the major river valleys and in other areas with shallow aquifers where numerous sewage-disposal systems and leaking underground storage tanks are located; in oil-and-gas producing and refining areas in the southeastern and northwestern parts of the State; at uranium mining and milling sites in McKinley and Cibola Counties; at copper mines and mills in Grant County; at coal mines and coal-fired electric power-generation plants in San Juan County; at molybdenum mining and milling sites in Taos County; at potash mining and processing sites in Eddy and Lea Counties; within industrialized areas of Bernalillo County; near dairy farms in Dona Ana and Sierra Counties; and at a few Federal civilian and military installations throughout the State (New Mexico Water Quality Control Commission, 1984). In most places, the severity and extent of the ground-water-quality problem are only partially known.

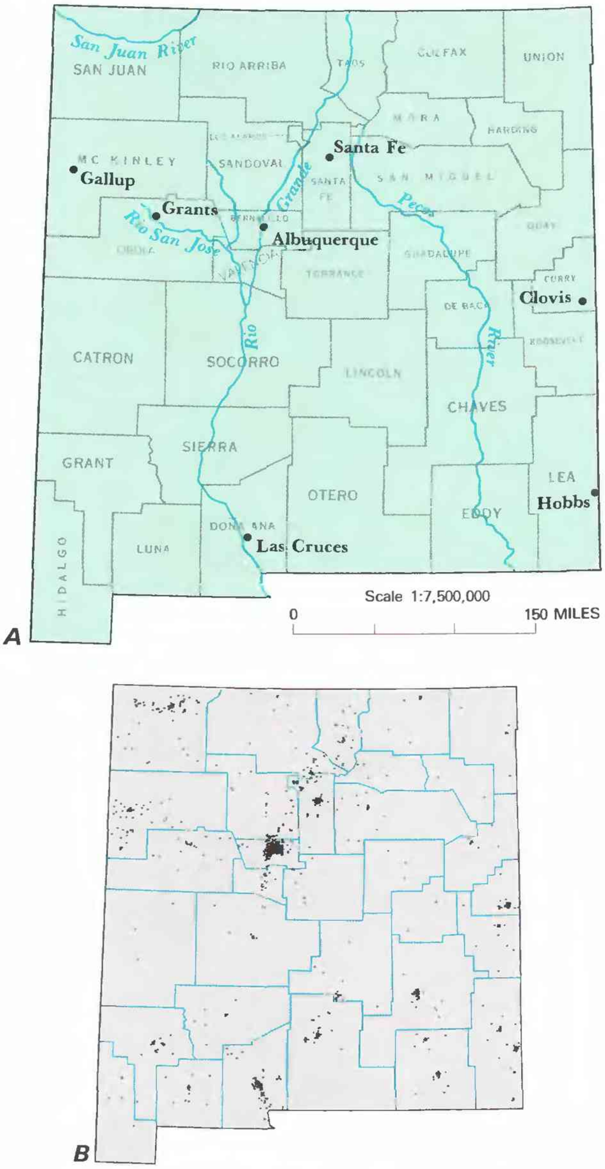

Figure 1. Selected geographic features and 1985 population distribution in New Mexico. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

WATER QUALITY IN PRINCIPAL AQUIFERS

New Mexico's fresh ground water is withdrawn from parts of the principal aquifers described in the 1984 edition of the National Water Summary (U.S. Geological Survey, 1985, p. 317–322). Those aquifers which are outlined in figures 2*A* and 2*B* are grouped into four types: (1) Valley-fill aquifers along New Mexico's major rivers; (2) basin-fill aquifers in eastern, central, southern and southwestern New Mexico; (3) sandstone aquifers in the San Juan River basin in northwestern New Mexico; and (4) limestone artesian aquifers in the Pecos River basin and in the Rio San Jose basin.

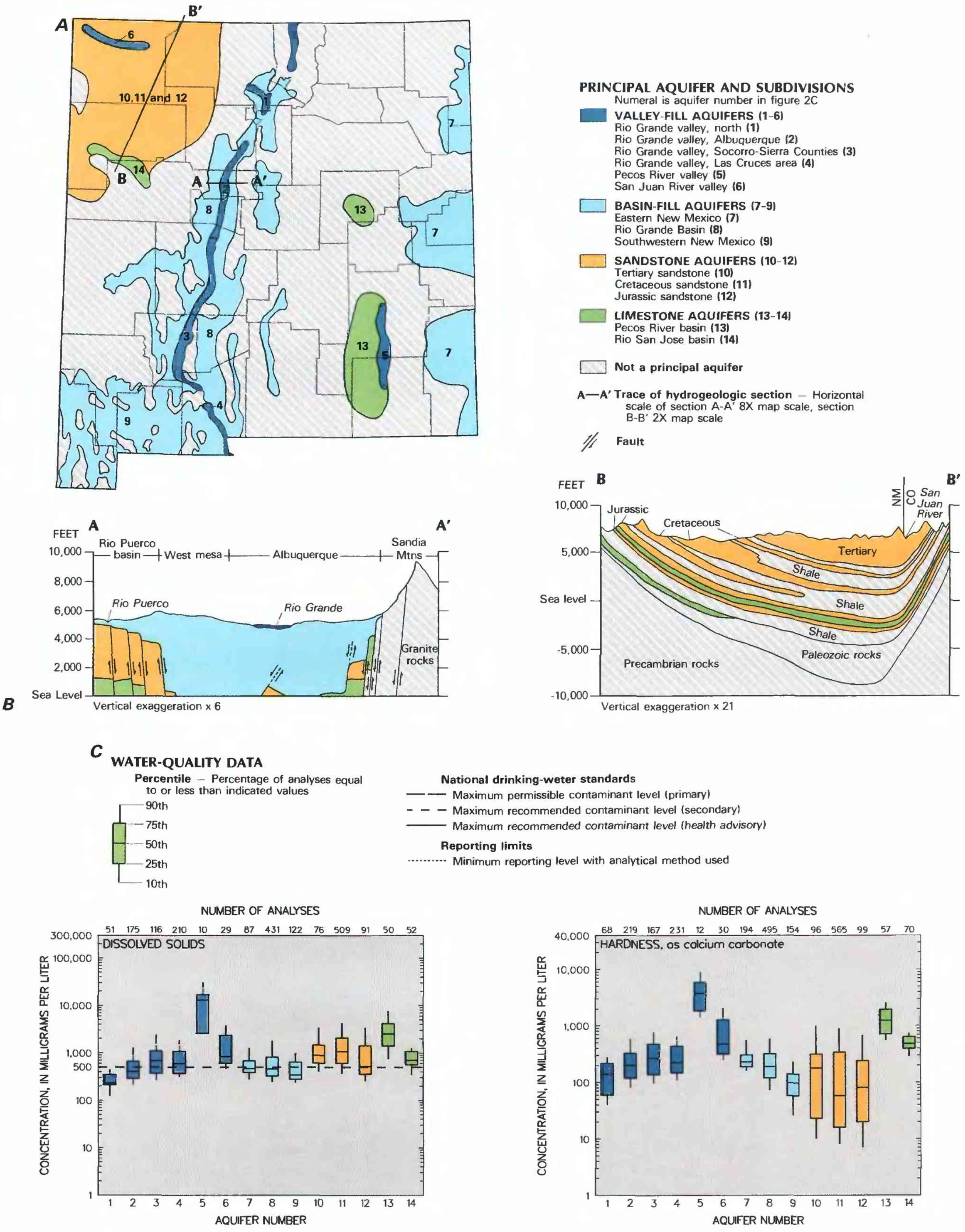

Figure 2. **Principal aquifers and related water-quality data in New Mexico.** *A*, Principal aquifers. *B*, Generalized hydrogeologic sections. *C*, Selected water-quality constituents and properties, as of 1986. (Sources: *A*, Modified from Hale and others, 1965. *B*1, Modified from Bjorklund and Maxwell, 1961. *B*2, Modified from Lyford, 1979. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

Concentrations of chemical constituents differ in these principal aquifers, mostly because of natural causes. However, human activities may be responsible for some of the larger extremes.

BACKGROUND WATER QUALITY

Background water-quality conditions are described in the following paragraphs for each of the four types of aquifers. A graphic statistical summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) (U.S. Geological Survey, 1975) through 1986 is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), sodium, and sulfate analyses of water samples collected from about 2,000 wells. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (EPA) (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 250 mg/L sulfate. The health advisory level of 20 mg/L for sodium is not a primary standard, but it is recommended by EPA for individuals with very restricted sodium-intake diets as prescribed by their physicians.

Valley-Fill Aquifers

Principal valley-fill aquifers (fig. 2*A*, aquifers 1–6) are located along the Rio Grande, Pecos River, and San Juan River. Principal valley-fill aquifers 1 through 4 are along the Rio Grande. Wells located upstream along the Rio Grande produce water with smaller dissolved-solids concentrations than wells downstream. The median dissolved-solids concentration was 230 mg/L for aquifer 1 and 406 mg/L for aquifer 2, whereas the median was 681 mg/L for aquifer 3 and 598 mg/L for aquifer 4. Increased salinity in these aquifers usually is caused by infiltration of more mineralized water from low river flows, tributary inflows, or irrigated fields. Seventy-five percent or more of the wells completed in the Rio Grande's valley-fill aquifers produce water that was classified as hard (120 to 180 mg/L as calcium carbonate) to very hard (more than 180 mg/L). Wells producing soft water (less than 60 mg/L) generally were located in the northern valley-fill aquifers. Wells that produce moderately hard water (60 to 120 mg/L) were located near recharge areas that are underlain by carbonate rocks, such as the mountainous area east of Albuquerque (Bjorklund and Maxwell, 1961). Nitrate concentrations were smaller than 4.0 mg/L for more than 90 percent of the wells sampled (fig. 2*C*). Water in these aquifers is suitable for public supplies and irrigation. The usually small salinity and small sodium concentrations are tolerated by most crops (U.S. Department of Agriculture, 1954).

The Pecos River valley-fill aquifer (aquifer 5) contains water that is much more saline than the water in the valley-fill aquifers

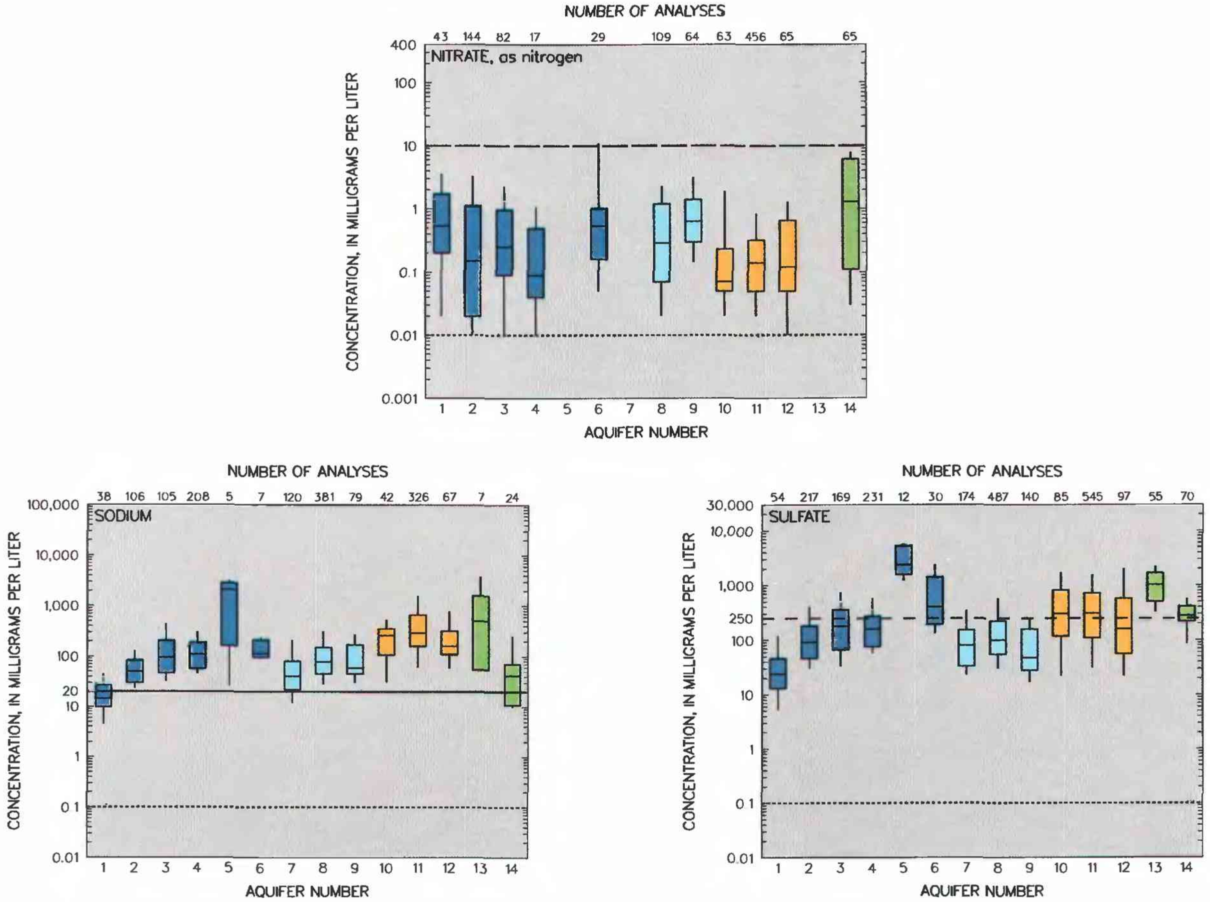

Figure 2. Principal aquifers and related water-quality data in New Mexico—Continued.

along the Rio Grande. The small number of wells in the statistical summary for aquifer 5 may not be representative of the entire aquifer. However, the large salinity values that are characteristic of the water withdrawn from these few wells make the water unsuitable for most uses, which probably explains the small number of wells completed in this aquifer. The increased salinity is caused by contact of the water with soluble evaporite deposits, such as gypsum. Saline water also seeps upward from the underlying limestone aquifer (Welder, 1983), and brine moves into the southern part of the aquifer from deeper and older deposits that contain halite (Hale and others, 1965).

The San Juan River valley-fill aquifer (aquifer 6) is less extensive than the valley-fill aquifers along the Rio Grande and Pecos Rivers. The moderately saline water near the edge of the aquifer is caused by ground water infiltrating from the adjacent or underlying sedimentary formations of the San Juan basin (Lyford, 1979). Water-quality characteristics are similar to those characteristics found in the San Juan River itself, except that the valley-fill aquifer contains water with larger salinity values. Calcium and bicarbonate ions are predominant in the less saline river water, whereas sodium and sulfate ions are predominant in the more saline aquifer water. The source of the aquifer solutes is the shale or clay deposits of the underlying formations (Roybal and others, 1983). Wells completed in the aquifer produce water for rural domestic supplies, livestock watering, and limited irrigation. The San Juan River with its tributaries has the largest streamflow volume in New Mexico and is used for the major public, industrial, and irrigation-water supplies along the valley. The more saline and much smaller water supply available from the valley-fill aquifer is used mostly in isolated rural areas.

Basin-Fill Aquifers

Principal basin-fill aquifers (aquifers 7, 8, and 9) consist of extensive deposits of coarse sediments with differing amounts of clay. Water in these aquifers is suitable for most uses; consequently, these aquifers have been extensively developed. About 70 percent of the ground-water withdrawn in New Mexico during 1980 (Sorenson, 1982) was taken from the basin-fill aquifers.

The Eastern New Mexico basin-fill aquifer (aquifer 7) is part of the High Plains aquifer, mainly the Tertiary Ogallala Formation. The High Plains aquifer is an extensive sandstone aquifer, but it is included in the basin-fill category because many of its lithologic and water-quality characteristics are similar to the basin-fill aquifers in other parts of the State. The water in the aquifer generally contains small concentrations of dissolved solids, hardness, and sodium which make the aquifer suitable for agricultural irrigation. The fluoride concentrations in water from about 5 percent of the wells sampled in this aquifer (U.S. Geological Survey files) were larger than 4.0 mg/L (not shown in fig. 2*C*). The Federal primary drinking-water standard for fluoride is 4.0 mg/L (U.S. Environmental Protection Agency, 1986a).

The Rio Grande basin-fill aquifer (aquifer 8) is composed of Quaternary and Tertiary sediments of the Santa Fe Group. The aquifer flanks the Rio Grande in a very irregular pattern and may be more than 6,000 feet deep (fig. 2*B*, section A-A′). Freshwater is found at depths ranging from 10 to 3,500 feet. Large volumes of saline water usually occur near the edges or in deeper parts of the aquifer (Kelly, 1974). Large sodium concentrations in this aquifer are found in association with the large salinity values. Some very saline water may be moving upward into different parts of the basin-fill aquifer through faults (Anderholm, 1983). Water quality in the shallow part of the aquifer commonly is indistinguishable from that in the overlying valley-fill aquifer because the two are hydraulically connected (fig. 2*B*, section A-A′). Although irrigation is the principal use of the water withdrawn from aquifer 8, about 40 percent of the withdrawals during 1980 based on county data were for nonagricultural use, mostly near Albuquerque (Sorenson, 1982). About 75 percent of the wells completed in aquifer 8 produce freshwater, which usually is hard.

The southwestern New Mexico basin-fill aquifer (aquifer 9) consists of coarse-grained sediments deposited in closed basins. Irrigation accounted for about 85 percent of the 1980 withdrawals from this aquifer based on county data. Copper mining and milling accounted for 9 percent, and the remaining 6 percent was mostly for domestic or public-supply uses (Sorenson, 1982). The water was fresh in 90 percent of the wells sampled and soft to moderately hard in nearly 75 percent of the wells sampled (fig. 2*C*). Nitrate concentrations were smaller than 3.2 mg/L in 90 percent of the wells. Fluoride data from aquifer 9 were not included in figure 2*C*, but concentrations exceeded 4.0 mg/L in 10 percent of the analyses on file with the U.S. Geological Survey.

Two other locally important, but smaller, basin-fill aquifers, the Estancia basin-fill aquifer in Santa Fe and Torrance Counties and the Tularosa basin-fill aquifer in Lincoln and Otero Counties, accounted for about 5 to 6 percent of the State's total ground-water withdrawal during 1980 (Sorenson, 1982). Both of these aquifers contain saline water that is the result of the concentration of salts by evaporation in the topographically lower parts of these closed-basin aquifers (Smith, 1957; McLean, 1970). The Tularosa aquifer contains some relatively soluble calcium-sulfate minerals, which also contribute to the large salinity values.

Sandstone Aquifers

The principal sandstone aquifers in New Mexico are part of the geologic structure called the San Juan basin in the northwestern part of the State. The principal aquifers, differentiated by geologic ages, are composed of Tertiary sandstone (aquifer 10), Cretaceous sandstone (aquifer 11), and Jurassic sandstone (aquifer 12). These aquifers are separated by semipermeable and confining shale layers (fig. 2*B*, section B-B′).

Water withdrawn from the sandstone aquifers is used primarily for rural domestic supplies or livestock watering. These aquifers also supply Gallup and other communities away from the San Juan River with freshwater that contains large concentrations of sulfate and iron (Dinwiddie and others, 1966). Until recently, large quantities of water were pumped from the sandstone aquifers to dewater uranium mines near Gallup and Grants. Nearly all the mines are currently inactive because of depressed uranium markets.

Water in about 50 percent of the wells sampled in these aquifers was fresh. Freshwater generally occurred in outcrop areas where recharge takes place, mostly around the perimeter of the San Juan basin.

Salinity of water in the sandstone aquifers is increased mostly by solution of sodium, carbonate, chloride, and sulfate ions present in the interbedded shale, sandstone cement, or small localized deposits of readily soluble minerals, such as gypsum or halite (Roybal and others, 1983). Water with larger salinity values occurred in the Cretaceous sandstone (aquifer 11). Hardness of the water in all three sandstone aquifers varied considerably, with the greatest range of hardness occuring in the Cretaceous aquifer. Nitrate concentrations for more than 90 percent of the wells in the sandstone aquifers were smaller than 1.0 mg/L, with the larger concentrations occurring in the Jurassic sandstone. Water from about 5 percent of the wells in the principal sandstone aquifers contained more than 4.0 mg/L fluoride, with most of those wells located in the Cretaceous sandstone.

Limestone Aquifers

The two principal limestone aquifers in New Mexico (aquifers 13 and 14) are in the Pecos River basin and the Rio San Jose basin.

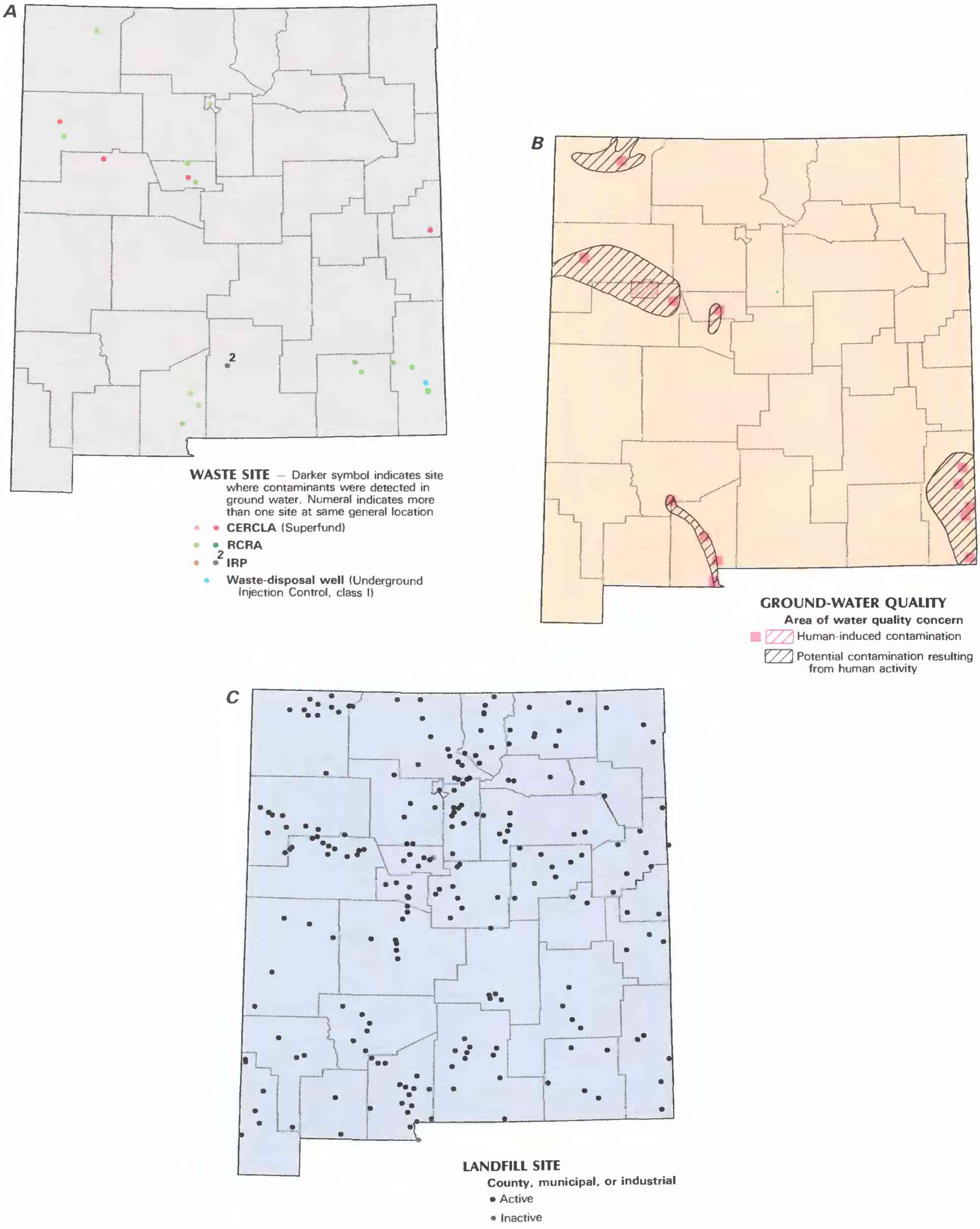

Figure 3. Selected waste sites and ground-water-quality information in New Mexico. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of human-induced and potential contamination, as of 1986. *C*, County, municipal, and industrial landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1984, 1986c; U.S. Department of Defense, 1986; and New Mexico Environmental Improvement Division files. *B*, New Mexico Water Quality Control Commission, 1986. *C*, New Mexico Environmental Improvement Division files.)

These aquifers are segments of the areally extensive, but discontinuous, San Andres Formation of Permian age.

Water in the Pecos River basin limestone aquifer (aquifer 13) flows eastward from its recharge area toward the Pecos River where the water discharges either to the river, to the valley-fill aquifer, or to wells. Increased salinity in aquifer 13 occurs as the water moves toward the Pecos River and dissolves gypsum within the aquifer. The relatively large sulfate concentrations of water from most wells may indicate this process. The water was fresh in less than 25 percent of the wells sampled, most of which were located near the recharge areas. In many wells in the eastern part of the aquifer, salinity has increased because saltier water in adjacent aquifers has been drawn into this aquifer by large irrigation withdrawals (Welder, 1983).

The Rio San Jose basin limestone aquifer (aquifer 14) produced freshwater from about 75 percent of the wells sampled and very hard water from 100 percent of the wells (fig. 2*C*). The sodium concentrations usually were small, whereas the sulfate concentrations usually were large. Water with smaller dissolved-solids concentrations occurred in recharge areas of the San Andres Formation in the Zuni Mountains between Gallup and Grants. Large differences in salinity values between nearby wells indicate complex flow patterns (Gordon, 1961) that are caused by the irregular topography, geologic faults, and complex solution channels in the limestone.

The Rio San Jose basin limestone aquifer (aquifer 14) produces water for domestic, community, livestock-watering, irrigation, and industrial supplies. Large ground-water withdrawals have modified local ground-water flow patterns, including seepage to or from the Rio San Jose (Risser, 1982). Aquifer 14 is located within the Grants Mineral Belt, an area rich in uranium that extends from 20 miles west of Albuquerque to Gallup (Gordon, 1961). The effects on water quality of waste-water from uranium-milling operations are a major concern. Contamination of ground-water by radioactive elements, such as radium and uranium, and by nonradioactive elements, such selenium, sulfate, and molybdenum, have been reported by the U.S. Environmental Protection Agency (Kaufman and others, 1975) and the New Mexico Environmental Improvement Division (New Mexico Water-Quality Control Commission, 1986).

EFFECTS OF LAND USE ON WATER QUALITY

Sewage disposal, leaking underground storage tanks, urbanization, mining, mineral milling, petroleum production and refining, and concentrated dairy-farm activities have caused water-quality changes in the principal aquifers. A summary of known water-quality contamination is presented in the table below, which was modified from information in New Mexico's biannual water-quality report to Congress (New Mexico Water Quality Control Commission, 1984).

Known Water-Quality Contamination in Principal Aquifers

Water-quality contaminant	Number of occurrences	Principal aquifer number (fig. 2*A*)	Primary sources of contamination
Nitrate and ammonia	27	1,2,3,4,5,7, 8, and 9	Sewage-treatment plants, individual septic systems, fertilizer use, dairy waste-disposal systems.
Bacteria	6	1,2, and 7	Septic tanks.
Salinity	50	2,5,6,7, and B	Oil, gas, and mineral production.
Trace inorganic compounds	7	1,9,10,11, 12, and 14	Mining and mineral milling
Natural and synthetic organic compounds	25	2,3,4,5,6,7, 8, and 13	Commercial and industrial sites.
Petroleum products (oils, gases, fuels)	53	1,2,3,5,6,7, 8, 9, 10, and 13	Service stations, petroleum refineries, leaky underground storage tanks, and highway spills.

The table includes the four sites in New Mexico that were placed on the Environmental Protection Agency's (EPA) National Priorities List (NPL) of hazardous waste sites under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (U.S. Environmental Protection Agency, 1986c). The four CERCLA (Superfund) sites are shown in figure 3*A* and the ground-water quality problems associated with these sites follow:

(1) San Jose industrial area in Albuquerque's south valley (Bernalillo County)—Numerous organic compounds including benzene and chlorinated solvents have been found in the valley-fill and basin-fill aquifers.
(2) Uranium-mill-tailings disposal area near Grants (Cibola County)—Radioactive isotopes and trace elements in leachates from tailings ponds are infiltrating the local valley-fill or limestone aquifers.
(3) Uranium-mill-tailings disposal area near Gallup (McKinley County)— Radioactive isotopes, trace elements, nitrate, and ammonia are infiltrating the sandstone aquifers from tailings ponds.
(4) Railway company (Curry County) refueling facility in Clovis—Diesel fuel and organic solvents in waste impoundments are infiltrating the local ground-water supply in the basin-fill aquifer.

Also shown in figure 3*A* are 15 sites that the State is monitoring closely under the Federal Resources Conservation and Recovery Act (RCRA) for hazardous waste (U.S. Environmental Protection Agency, 1985). These sites are the locations of electronic-fabrication companies, petroleum refineries, petrochemical companies, natural-gas plants, governmental research facilities, and military installations. Most of these RCRA sites overlie the principal aquifers, and wastes that are stored or processed at these sites may consist of a mixture of inorganic chemicals, such as acids, bases and trace metals; organic compounds, such as halogenated solvents, polychlorinated biphenyls (PCB's), and spent petroleum products; and explosive materials, both inorganic and organic.

In addition, one New Mexico well is registered by the EPA as a Class-I injection well under the Federal Underground Injection Control Act (UIC) (U.S. Environmental Protection Agency, 1984). The well is used for disposal of industrial effluent and its location in Lea County is shown in figure 3*A*.

As of September 1985, 48 hazardous-waste sites at 5 facilities in New Mexico have been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established during 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. The DOD evaluated the 48 sites in New Mexico and determined that 12 sites contained contaminants but did not present a hazard to the environment. Additionally, two sites at one facility in Dona Ana County (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA (U.S. Department of Defense, 1986). The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

The New Mexico Environmental Improvement Division has designated five areas of potential contamination that have special ground-water concerns (New Mexico Water Quality Control Commission, 1986). These areas (fig. 3*B*) all overlie principal aquifers and are:

(1) Albuquerque's south valley industrial and commercial area.
(2) Lea County's oil-production and sewage-disposal area.
(3) Grants Mineral Belt's uranium-mining and milling area, west of Albuquerque.
(4) San Juan River valley's oil and gas refinery and liquid-landfill area, mostly near Farmington (San Juan County).
(5) Lower Rio Grande's dairy farms and agricultural disposal area.

Within these areas, zones of known or suspected human-induced ground-water contamination are delineated in figure 3*B*.

POTENTIAL FOR WATER-QUALITY CHANGES

New Mexico has experienced a rapid population growth during the past two decades, and that growth is anticipated to continue, mostly in Albuquerque and other established urban centers along the Rio Grande valley (U.S. Bureau of Census, 1982). The use of water by cities, commerce, light industries, and government will increase, but agricultural irrigation will continue to be the State's major water use. Limited freshwater supplies will continue to restrict the development of heavy industries. The depletion of ground-water resources by irrigation in the eastern and southern parts of the State and increases in pumping costs may cause a decrease in agricultural activities in these areas. Unless 1986 marketing conditions improve for New Mexico's petroleum and mineral resources, these industries probably will continue to decrease their production levels or will cease operations completely. However, the large quantities of mining and petroleum wastes that presently exist in tailings piles or holding ponds are sources of contamination for the principal aquifers. The human-induced water-quality contamination that has occurred already in the principal aquifers probably will persist unless cleanup techniques can be implemented. As more inventories are conducted by the New Mexico Environmental Improvement Division and by other agencies, more contaminated sites probably will be discovered.

The potential for water-quality changes will be greater in the valley-fill and basin-fill aquifers along the Rio Grande because of intensive land use and greater susceptibility of the aquifers. These changes probably would be related to urban, commercial, industrial, and governmental activities. The potential exists for large quantities of nitrate, trace elements, synthetic organic compounds, and petroleum products to infiltrate these aquifers. Sources for these compounds are the large number of landfills overlying these aquifers (fig. 3*C*).

Many different types of pesticides have been applied to irrigated fields overlying the Rio Grande valley's principal aquifers and the eastern New Mexico High Plains aquifer during the past several decades, and pesticide usage will continue in these and other irrigated areas. These pesticides have the potential to percolate into the underlying aquifers. When fully implemented the Navajo Indian Irrigation Project in northwestern New Mexico will irrigate 110,000 acres of arid mesas south of the San Juan River. Fertilizers and pesticides may infiltrate the Tertiary sandstone aquifers underlying the project area.

Radioactive wastes, generated by military and national defense projects, are planned for underground storage in salt deposits in Eddy County, southeastern New Mexico. The geohydrology of the waste site has been studied to aid in assessing the potential for radioactive waste to move into adjacent aquifers (Mercer, 1983).

New Mexico's abundant saline ground water has been considered as a potential supply for municipal use. Research on various methods of desalinization was initiated in 1963 at a U.S. Department of the Interior-sponsored test facility near Roswell in Chaves County (U.S. Department of the Interior, 1963). Saline ground water also is being evaluated for use in large-scale, shallow, solar ponds for the commercial cultivation of algae for energy fuels, food, and chemicals (Lansford and others, 1986). Application of successful research findings in either of these activities potentially could affect ground-water quality.

GROUND-WATER-QUALITY MANAGEMENT

New Mexico has taken the primary legal role in the protection of ground-water quality through the New Mexico Water Quality Control Commission (NMWQCC), which was established by the New Mexico Water Quality Act adopted in 1967. The Commission consists of the head (or designee) of each of eight State agencies plus a representative of the public appointed by the Governor (Goad, 1982). The eight agencies are the New Mexico Environmental Improvement Division (NMEID), the State Engineer and the Interstate Streams Commission, the State Department of Game and Fish, the State Oil Conservation Division, the State Park and Recreation Division, the State Department of Agriculture, the State Soil and Water Conservation Division and the State Bureau of Mines and Mineral Resources. This commission has the authority and responsibility for pollution control in both surface and ground water.

During 1977, regulations were adopted to protect all ground water with a dissolved-solids concentration of 10,000 mg/L or less for present and potential future use as domestic and agricultural water supplies, and to protect those segments of surface waters that are gaining because of ground-water inflow for use designated in the New Mexico (surface) Water-Quality Standards (Goad, 1982). For ground water containing 10,000 mg/L dissolved solids or less, water-quality standards have been set for 24 inorganic constituents, 2 radiochemicals, and 21 natural or synthetic organic compounds in order to protect the ground-water supply for human health, domestic-water supply, and irrigation use. These standards do not apply to effluent discharged at the land surface, but rather, to the ground water itself. If the concentration of any contaminant in ground water already exceeds the standard, the existing concentration becomes the standard.

The primary administrative and enforcement authority and responsibility for these regulations are delegated to the NMEID, with other NMWQCC agencies having coordinating roles for activities related to their respective agency mission. For example, the State's Oil and Conservation Division administers and enforces the regulations as they apply to the production and refinement of oil and gas; the State Engineer may, under other laws, regulate the withdrawal of ground water to prevent the impairment of water rights caused by the movement of saline water into pumped zones.

The NMWQCC's regulations apply to underground injection, seepage from surface impoundments or leach fields, land application of wastes, and any other discharges of effluent or leachate that may affect ground water. Discharges from certain oil, natural gas, carbon-dioxide or geothermal facilities, from coal mines, or from small home septic systems are covered by other statutes and regulations that were enacted before the NMWQCC's regulations (Goad, 1982).

Effluent dischargers are required to submit discharge plans that must be approved by NMEID. The plan must demonstrate that the water-quality standards will not be violated in ground water at any place of present or foreseeable future use. The plan must provide for adequate monitoring and reporting of water-quality conditions. The public has opportunities to hear and to review those plans for conformance with the regulations. Approved discharge plans essentially become discharge permits (New Mexico Water Quality Control Commission, 1984).

The EPA is the lead agency for the CERCLA programs, but the NMEID has an active role in coordinating these projects among the various industrial, commercial, and governmental entities (New Mexico Water Quality Control Commission, 1986). The EPA has delegated to the NMEID the primary enforcement authority for the hazardous-waste program under RCRA, for underground waste injection under UIC, and for the drinking-water-supply programs under the Federal Safe Drinking Water Act (New Mexico Water Quality Control Commission, 1986). The State recently returned authority to the U.S. Nuclear Regulatory Commission for issuing and regulating uranium milling and in-situ leaching licenses. This authority includes assessing and monitoring the effects of uranium milling and leaching on ground-water supplies.

The agencies that manage ground-water quality in New Mexico may require additional hydrologic information to help remedy existing contamination or to help prevent potential contamination in the principal aquifers. Ground-water studies that include completely the areas of human-induced and potential contamination (fig. 3*B*) may help document the extent and severity of known contamination. The establishment of a network of monitoring wells and periodic sampling in these areas would help detect any water-quality changes in the principal aquifers.

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NEW YORK
Ground-Water Quality

Ground water is the source of supply for approximately 6.2 million of New York State's 17.5 million residents. More than one-half of those relying on ground water live on Long Island, one of the most densely populated areas of the State (fig. 1). The chemical quality of water in the State's major aquifers is generally good for most uses and does not exceed the drinking-water-quality standards established by the New York State Department of Health (NYSDOH). Naturally large concentrations of dissolved solids, iron, and manganese restrict use in some localized areas. In some parts of the State, primarily on Long Island, concentrations of nitrate, as nitrogen, exceed the State recommended drinking-water standard of 10 mg/L (milligrams per liter). These exceed naturally occurring concentrations and are attributed primarily to urbanization and, to a lesser extent, agriculture.

The New York State Department of Environmental Conservation (NYSDEC) has identified contamination by synthetic organic chemicals (SOC) as the most serious ground-water-quality problem in the State. Since 1978, SOC in ground water have caused the closing of more than 120 public water-supply wells, about 75 percent of which are on Long Island. Most of the well closings have been due to chemicals used as solvents and degreasers, but some have been due to petroleum products and pesticides. The SOC contaminants are associated mainly with accidental leaks and spills and poor industrial housekeeping, all of which accompany urbanization, but also are derived from domestic sewage systems and agriculture. Other widespread potential sources of SOC contaminants are the State's approximately 300 confirmed hazardous-waste-disposal sites and 420 municipal landfills.

Many of New York's most important aquifers lie beneath areas of substantial to intensive urban, industrial, and agricultural development. Development over these aquifers will continue in the future, and although contaminant sources associated with future development will be controlled, the potential for contamination by accidental spills and leaks will remain. Contamination by SOC is expected to remain the State's greatest ground-water-quality problem.

WATER QUALITY IN PRINCIPAL AQUIFERS

The principal aquifers in New York consist of (1) unconsolidated glacial stratified-drift deposits that are composed chiefly of sand and gravel, (2) unconsolidated coastal-plain aquifers, and (3) sandstone and carbonate bedrock aquifers (U.S. Geological Survey, 1985, p. 323). For convenience of discussion, these aquifers are grouped into two regions—upstate New York and Long Island. Upstate New York, as used here, includes all counties north of New York City (fig. 1). Ground water under New York City, except for parts of the Boroughs of Queens and Brooklyn on western Long Island, is not considered in this summary, as it is a minor source of supply. The geographic distribution of principal aquifers is shown in figure 2*A*. "Principal aquifer", as used in this summary, does not have the same meaning as, and should not be confused with, the term used by the New York State Department of Environ-

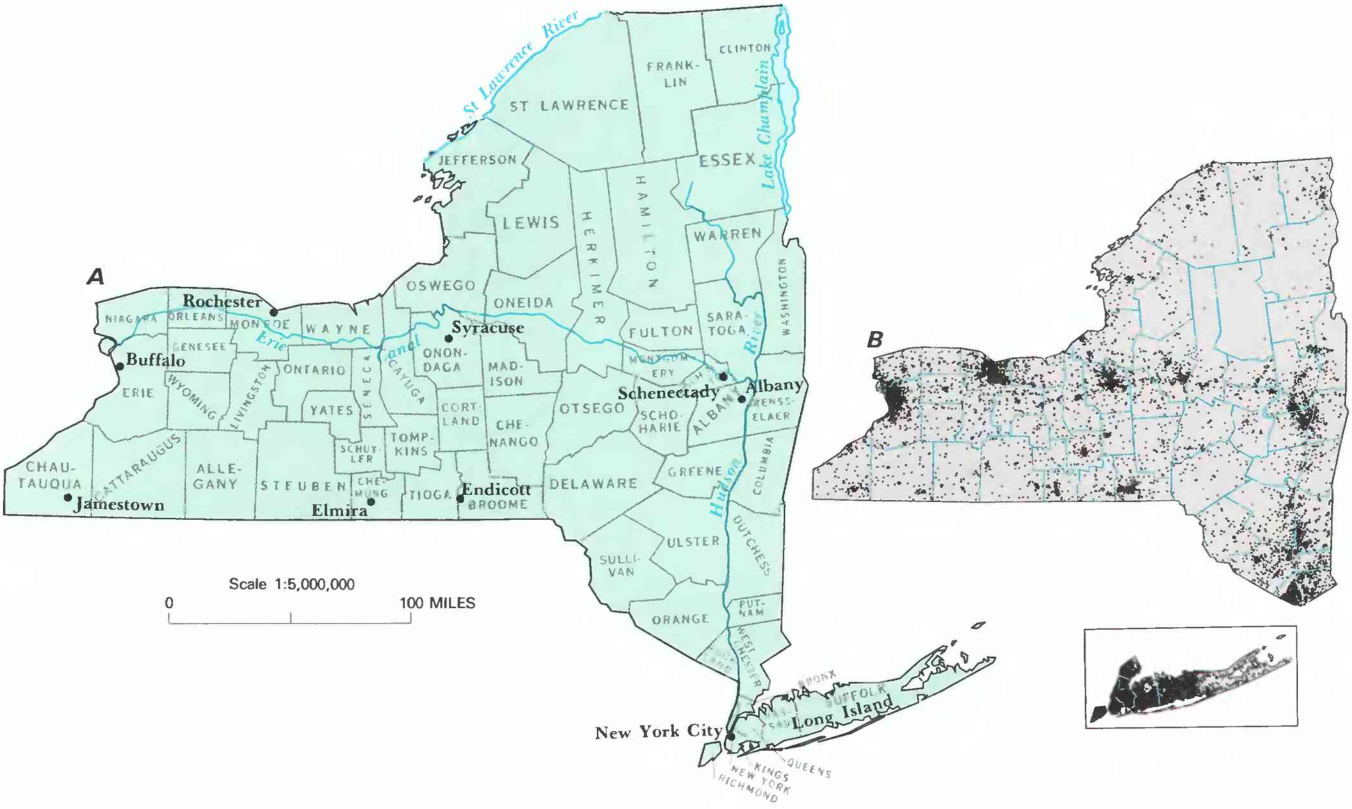

Figure 1. Selected geographic features and 1985 population distribution in New York. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

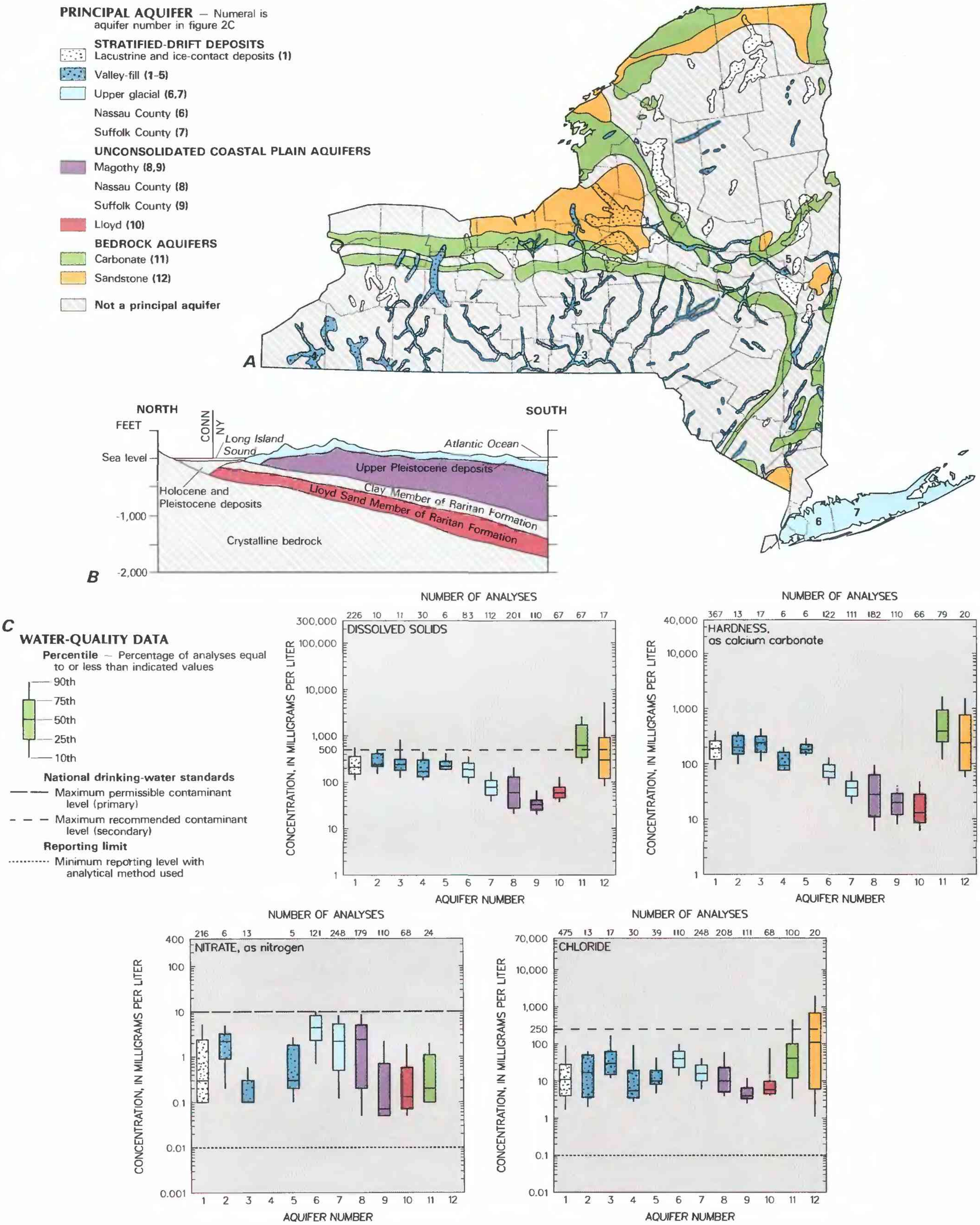

Figure 2. Principal aquifers and related water-quality data in New York. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1985. (Sources: *A* and *B*, U.S. Geological Survey, 1985, fig. 1. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b).

mental Conservation (1987; 1987) in the State's ground-water-management programs.

Upstate New York.—Stratified-drift deposits that underlie flood plains and terraces along larger valleys generally form the most important aquifers. In upstate New York, glacial-lake and beach sand in upland areas also may contain significant aquifers. Bedrock is a significant aquifer only in the sandstone formations of Rockland, St. Lawrence, Franklin, and Clinton Counties and in areas of carbonate rock across the State.

The major use of ground water in upstate New York is for public and domestic drinking-water supplies (U.S. Geological Survey, 1985, p. 323). About 1 million people in upstate New York rely on public water supplies that use ground water, primarily from valley-fill aquifers. Virtually all rural residents of upstate New York, about 2 million people, obtain their drinking water from private domestic wells, some of which have significant yields from stratified-drift deposits and bedrock aquifers, but most from low-yielding aquifers that underlie most of upstate New York.

Long Island.—Long Island is underlain by the largest aquifer system in New York State. The system consists of three aquifers of unconsolidated clastic sediments—the upper glacial, the Magothy, and the Lloyd aquifers (fig. 2*B*). These three aquifers are continuous throughout most of Long Island except along the north shore and parts of the western end of the Island where the Magothy and Lloyd aquifers are absent.

Long Island's aquifer system supplies more than 3.2 million people, including the entire population of Nassau and Suffolk Counties and about 500,000 New York City residents in Queens (New York State Department of Environmental Conservation, 1986, p. I-4). About 300,000 Long Island residents, mostly in Suffolk County, rely on private domestic wells; the remainder are served by community systems that withdraw water primarily from the Magothy aquifer.

BACKGROUND WATER QUALITY

Ground water in most areas of New York is of good quality and suitable for most uses, including human consumption. Locally, however, water in areas of stratified-drift deposits in upstate New York and in the upper glacial and Magothy aquifers of Long Island contains iron and manganese from natural sources that exceed drinking-water standards. Some stratified-drift deposits and shallow bedrock aquifers between Buffalo and Syracuse (fig. 1) yield slightly to moderately saline water as the result of solution of evaporite minerals in the bedrock (U.S. Geological Survey, 1985, p. 324). Some wells in nearshore areas of Long Island, especially in eastern Suffolk County, yield saline water as a consequence of saltwater intrusion caused by excessive pumping (U.S. Geological Survey, 1985, p. 326).

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The range in concentration of four indicators of background water-quality—dissolved solids, hardness (as calcium carbonate), nitrate (as nitrogen), and chloride—in 12 selected aquifers is shown. The data from upstate New York represent (1) the stratified-drift deposits, (2) four important valley-fill aquifers near the cities of Jamestown, Elmira, Endicott, and Schenectady, (3) the carbonate bedrock aquifer, and (4) the sandstone bedrock aquifer (fig. 2*A*). The data for the upstate New York aquifers were collected between the late 1940's and early 1980's, although most were gathered between the late 1950's and early 1970's. Data representing the upper glacial and Magothy aquifers of Long Island, collected during 1984–85, are presented separately for Nassau and Suffolk Counties. Data on the Lloyd aquifer represent both Nassau and Suffolk Counties and were collected during 1960–85. Where more than one analysis from a given well was available, the mean concentration was used.

Percentiles of the selected water-quality variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 250 mg/L chloride. State standards are the same as the national standards.

All principal aquifers in New York except the carbonate bedrock aquifer have median dissolved-solids concentrations that do not exceed the 500-mg/L standard for public-water supplies (fig. 2*C*). The large dissolved-solids concentrations in the carbonate aquifer are due to the solubility of carbonate minerals. Dissolved-solids concentrations exceeding 1,000 mg/L in upstate New York aquifers in the western one-half of the State generally can be attributed to areas of naturally saline ground water.

Water in principal upstate New York aquifers generally ranges from hard to very hard. The hardest water occurs in the carbonate bedrock aquifer. On Long Island, ground water is soft. The slightly harder water in Nassau County than in Suffolk County reflects the effects of urbanization.

All principal aquifers in New York have median nitrate concentrations (as nitrogen) that are less than the 10-mg/L standard for water supplies. The nitrate plot in figure 2*C* reflects local nitrate contamination, which is widespread in the upper glacial aquifer on Long Island, especially in Nassau County (New York State Department of Environmental Conservation, 1986, p. II-15).

The median chloride concentrations of water in all principal aquifers are appreciably less than the 250-mg/L standard for drinking-water supplies. The occurrence of saline ground water in some upstate areas and saltwater intrusion in parts of Long Island are responsible for the increased chloride concentrations indicated for some aquifers.

EFFECTS OF LAND USE ON WATER QUALITY

Although ground-water quality in most of New York is good, quality problems exist in some areas. The problems are considered to be significant, and their extent has not been identified fully in all areas, especially in upstate New York where data are limited (New York State Department of Environmental Conservation, 1987). Many urban areas in upstate New York overlie important valley-fill aquifers; agricultural land also occupies such valleys. On Long Island, all development lies directly above the principal aquifers. Consequently, many of the State's major aquifers are exposed to actual or potential sources of contaminants. Some are nonpoint sources, such as agricultural and urban runoff; others are point sources, such as waste-disposal sites.

The NYSDEC has identified approximately 300 sites that have received hazardous waste or have been contaminated by hazardous material (fig. 3*A*), and more than 600 additional sites are suspected to have received or been contaminated by hazardous material and are undergoing additional investigation (New York State Department of Environmental Conservation, 1985). The U.S. Environmental Protection Agency (EPA) has included 54 hazardous-waste sites (fig. 3*A*) on the National Priorities List (NPL) of hazardous-waste Superfund sites, under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Another 41 waste-disposal sites (fig. 3*A*) require monitoring under the Federal Resource Conservation and Recovery Act (RCRA). Approximately 420 municipal solid-waste landfills (fig. 3*C*) in the State are active

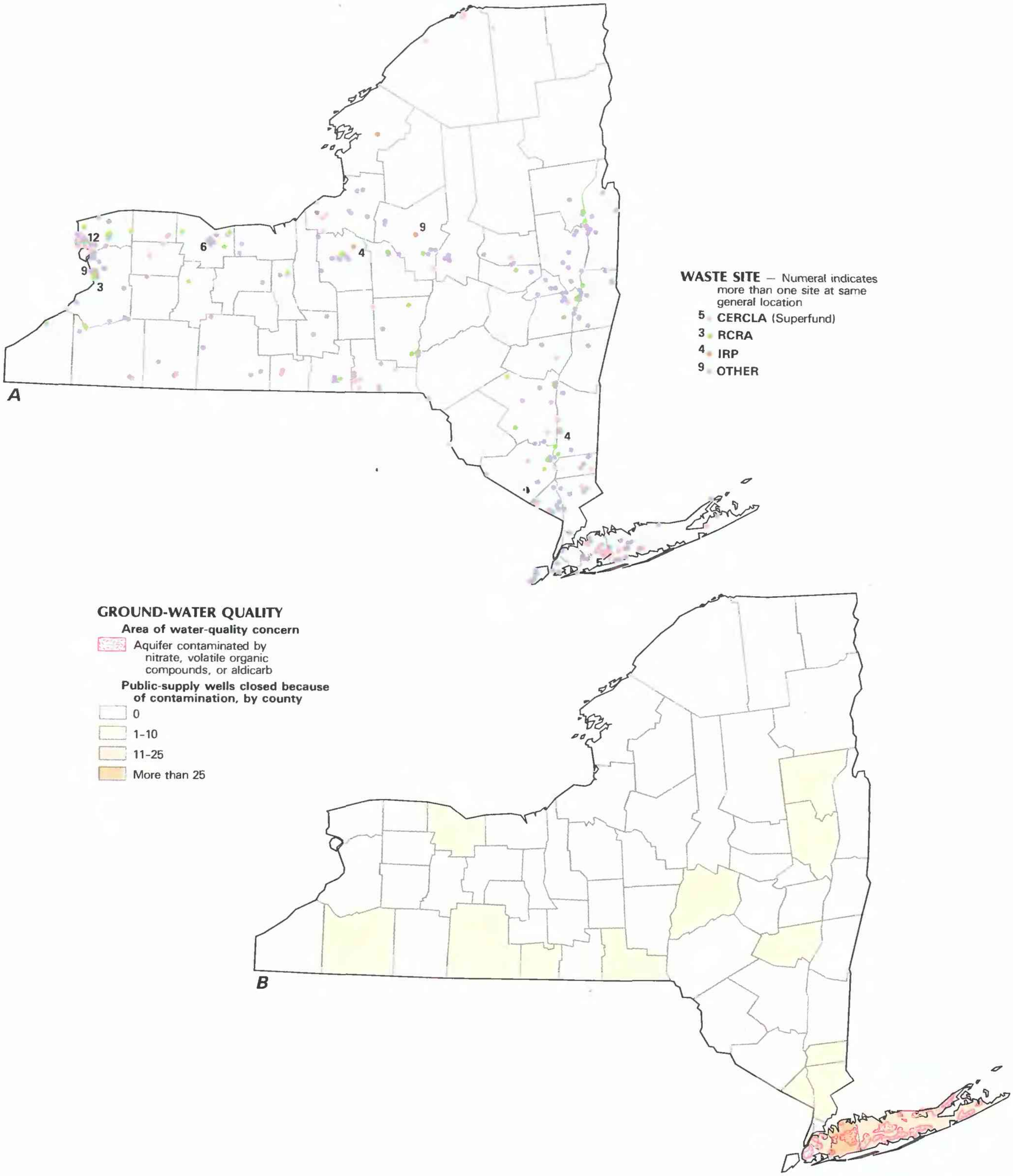

Figure 3. Selected waste sites and ground-water-quality information in New York. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resources Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1986; and other selected waste sites, as of 1986. *B*, Areas of human-induced contamination, and distribution of public-supply wells closed because of contamination, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; Michell Taylor and Edward Miles, New York State Department of Environmental Conservation, oral commun., 1986; U.S. Department of Defense, 1986; New York State Department of Environmental Conservation, 1985b. *B*, New York State Department of Environmental Conservation, 1986; R. A. Entringer, New York State Department of Health, written commun., 1986. *C*, J. A. Sacco, New York State Department of Environmental Conservation, written commun., 1986.)

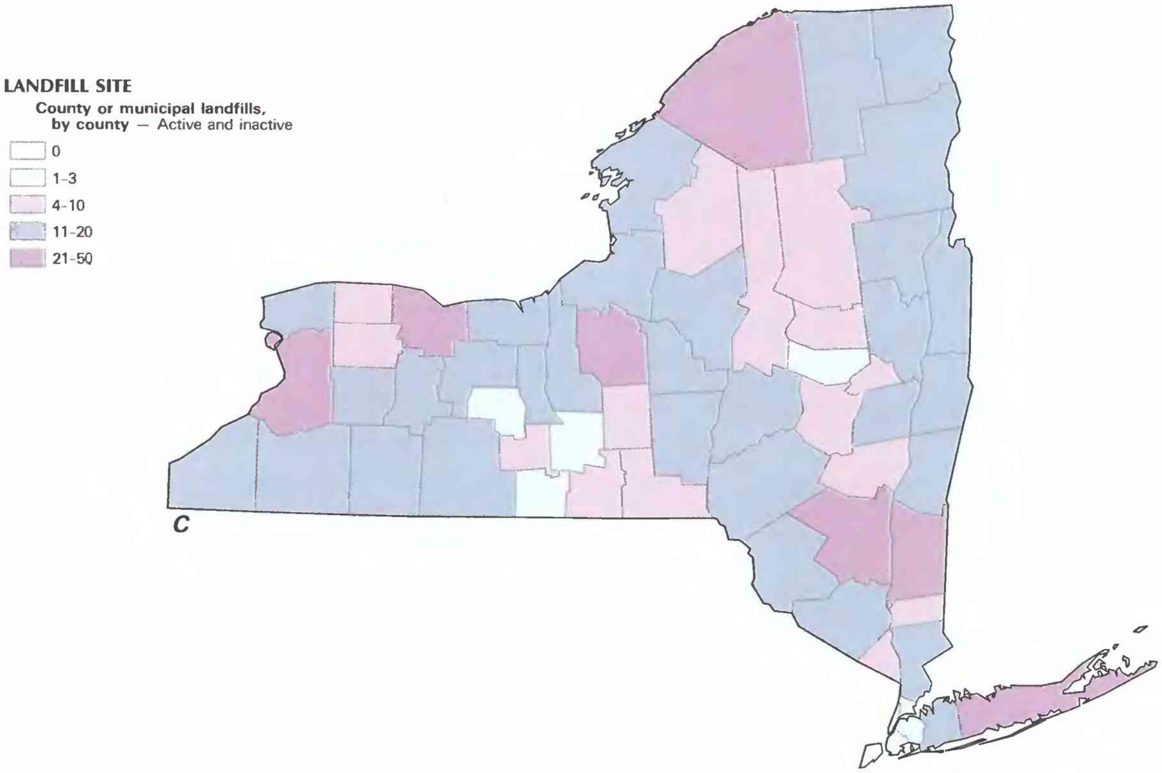

Figure 3. Selected waste sites and ground-water-quality information in New York—Continued.

(New York State Department of Environmental Conservation, 1987, p. II–24). Most waste-disposal sites are located outside areas overlying the principal aquifers, but more than 100 active municipal landfills lie over or adjacent to important aquifers (New York State Department of Environmental Conservation, 1987, p. II–24). Ground-water contamination has been documented at many waste-disposal sites, and the sites continue to be a significant threat to ground-water quality.

As of September 1985, 42 hazardous-waste sites at 8 facilities in New York had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 42 sites in the program, 8 sites contained contaminants but did not present a hazard to the environment. Fourteen sites at 3 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Contamination by SOC particularly industrial and commerical solvents and degreasers, gasoline and petroleum products, and pesticides, is the greatest threat to the State's ground-water resources (New York State Department of Environmental Conservation, 1987; 1986). Inorganic chemicals also contaminate ground water, but only nitrate, chloride, and metals are of statewide concern. The source and extent of each of these contaminants are discussed below.

Solvents and Degreasers

Solvents and degreasers contain a variety of toxic organic compounds. The most common ones detected in public-supply wells are the halogenated compounds trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane. The State drinking-water standard for these organic solvents is 50 μg/L (micrograms per liter). The threat to ground water by solvents and degreasers increases with development and population density, as has been documented on Long Island by Eckhardt and others (1987). The most significant sources of these contaminants include: (1) leaks and spills at storage, industrial, and commercial facilities; (2) improper industrial disposal; (3) improper consumer-product use and disposal; (4) landfills; and (5) septic tanks. New York contains many active and inactive hazardous-waste sites and landfills (fig. 3*A*,*C*) that may be sources of solvents, degreasers, and other contaminants. The activities that most commonly release solvents and degreasers to ground water, however, are leaks and spills, poor industrial housekeeping, and domestic use and disposal.

The three aforementioned compounds—trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane—alone had caused the closing of about 95 public-supply wells in the State by June 1986 (Ronald A. Entringer, New York State Department of Health, written commun., 1986). Most of these closings were on Long Island (fig. 3*B*), where general areas of ground-water contamination by organic chemicals have been delineated by the New York State Department of Environmental Conservation (1986, p. II–7). In Suffolk County, Long Island, more than 440 water samples from private wells, or 3 percent of those tested, contained 1,1,1-trichloroethane in concentrations exceeding the State guideline for drinking water (Suffolk County Department of Health Service, 1984).

Gasoline and Petroleum Products

Potential sources of gasoline and other contaminants derived from petroleum products are numerous and widespread. Leaking underground storage tanks, especially at gasoline service stations, are primary sources of petroleum-product contamination. Petroleum contamination also occurs through accidental spills and mishandling at the land surface.

The New York State Department of Environmental Conservation (1987, p. II–23) has estimated that New York State has approximately 100,000 underground petroleum-storage tanks with more than 1,100-gallon capacity and that approximately 25 percent of these are leaking. From 1978 to 1983, approximately 2,300 spills and leaks of gasoline and petroleum products were reported in upstate New York; almost 500 of these affected wells or otherwise violated ground-water standards (New York State Department of Environmental Conservation, 1987, p. II-23). Records of the New York State Department of Transportation show that from April 1978 to March 1980 more than 700 petroleum spills occurred in Nassau and Suffolk Counties, Long Island (New York State Department of Environmental Conservation, 1986, p. II-10).

State ground-water or water-supply standards do not exist for gasoline or other petroleum products. However, guidelines require water supplies to be free of oil and grease and tastes and odors associated with petroleum products. Standards exist, however, for three compounds found in petroleum products—benzene, xylene, and toluene.

Contamination by gasoline or other petroleum products has caused less public water-supply well closings than organic solvents, but more than one-half of the reported contamination problems with individual household wells in the State are related to petroleum products (New York State Department of Environmental Conservation, 1987, p. II-12). Many violations of ground-water-quality standards by petroleum products that have not affected drinking-water wells also have been reported.

Pesticides

Contamination of New York State's ground water by pesticides has become a serious concern during the past 10 years. The greatest cause of such contamination is agricultural usage, especially potato farming, but use and disposal of pesticides by homeowners also can create localized problems.

In the potato-farming areas of eastern Suffolk County, Long Island, pesticide contamination has adversely affected both public and private water supplies (fig. 3*B*). Aldicarb is the pesticide most widely detected in ground water; others detected include carbofuran, Dacthal, 1,2-dichloropropane, and paraquat. By June 1986, four public-supply wells had been closed in Suffolk County because of pesticide contamination (Ronald A. Entringer, New York State Department of Health, written commun., 1986). The Suffolk County Department of Health Services (1984) is conducting an extensive ground-water monitoring program for aldicarb and other pesticides. By April 1984, aldicarb had been detected in approximately 2,000 private wells in concentrations exceeding the State drinking-water standard for aldicarb of 7 μg/L. Aldicarb is no longer in use on Long Island.

Ground-water contamination by pesticides is expected to be less severe and less widespread in upstate New York than on Long Island (New York State Department of Environmental Conservation, 1987, p. II-30), although the extent of ground-water contamination in upstate New York has not been fully assessed. The first significant documentation of pesticide contamination in upstate New York came in 1983 when analyses by Cornell University and other researchers detected aldicarb in ground water at levels exceeding 1 μg/L at approximately 30 percent of 76 sites in areas considered to be at risk of aldicarb contamination (New York State Department of Environmental Conservation, 1987, p. II-13).

Nitrate

Ground-water contamination by nitrate (as nitrogen) is a less severe problem than contamination by SOC because its health effects are less. Ground-water contamination by nitrate is widespread in the upper glacial aquifer on Long Island (fig. 3*B*) and, although not widespread in upstate New York, it presents a problem in some areas. Sources of nitrate contamination include: (1) agricultural and turf fertilizers, (2) onsite sewage-disposal systems, (3) animal wastes, and (4) landfills. When large numbers of onsite sewage-disposal systems are concentrated over an aquifer, they constitute a significant source of nitrate contamination.

The effect of urbanization on the concentrations of dissolved solids and nitrate in ground water in the upper glacial and Magothy aquifers of Nassau and Suffolk Counties, Long Island, is illustrated in figure 4. Concentrations of both water-quality constituents are greater in Nassau County, the more densely populated, and in the upper glacial aquifer, the uppermost aquifer. Median concentrations have increased with time as development has increased.

Nitrate concentrations of about 10 mg/L, the primary standard for drinking-water supplies, were found in ground water under many unsewered or recently sewered areas of Nassau County. At the end of 1982, the use of 19 public water-supply wells in Nassau County was restricted because nitrate concentrations exceeded the standard (New York State Department of Environmental Conservation, 1986, p. II-15). The nitrate problem also affects private household wells. Since 1972, almost 19,000 ground-water samples from Suffolk County have been analyzed for nitrate, 7.7 percent of which exceeded the 10-mg/L standard (Suffolk County Department of Health Services, 1984, p. 11). Statewide, perhaps as many as 5,000 private wells are contaminated by nitrate (Association of State and Interstate Water Pollution Control Administrators, 1985).

Chloride

Chloride contamination of household wells is not uncommon, but few public water-supply wells in the State have been affected in recent years. Chloride can make water supplies unsuitable for drinking, but it is not a major public-health risk at concentrations found in most ground water. Sources of chloride include: (1) onsite domestic sewage-disposal systems, (2) storage and use of road-deicing salts, (3) landfills, (4) saltwater intrusion on Long Island, and (5) natural salt deposits underlying western and central New York.

Chloride contamination due to excess pumpage was responsible for the closing of many public-supply wells on western Long Island from the early 1900's through 1974. The aquifer under this area is no longer excessively pumped for drinking-water supply. Several public-supply wells in Nassau and Suffolk Counties operate under pumpage restrictions because of the potential for saltwater intrusion.

Other Organic Chemicals and Toxic Metals

Ground-water contamination by organic compounds other than those discussed earlier has not been widespread. Among the other organic compounds that have been detected in public-supply wells are polychlorinated biphenyls (PCB's), chloroform, vinyl chloride, and carbon tetrachloride. Concentrations are generally less than State drinking-water standards, with few exceptions (New York Department of Environmental Conservation, 1987, p. II-15).

Toxic-metal contamination of ground water is not widespread, but significant local instances of such contamination have been documented. Plumes of toxic-metal contamination have been identified around landfills and industrial-waste disposal sites.

POTENTIAL FOR WATER-QUALITY CHANGES

Ground-water-quality problems will continue as a consequence of past, present, and future development. In New York, the areas of most intense ground-water use generally have permeable soils that allow contaminants to move readily from the surface downward to the aquifer without significant attenuation. These areas also are characterized generally by substantial or intense urban, industrial, and agricultural development. On Long Island in particular, all development and, therefore, all potential sources of contamination are directly above the principal aquifers. Because the aquifers

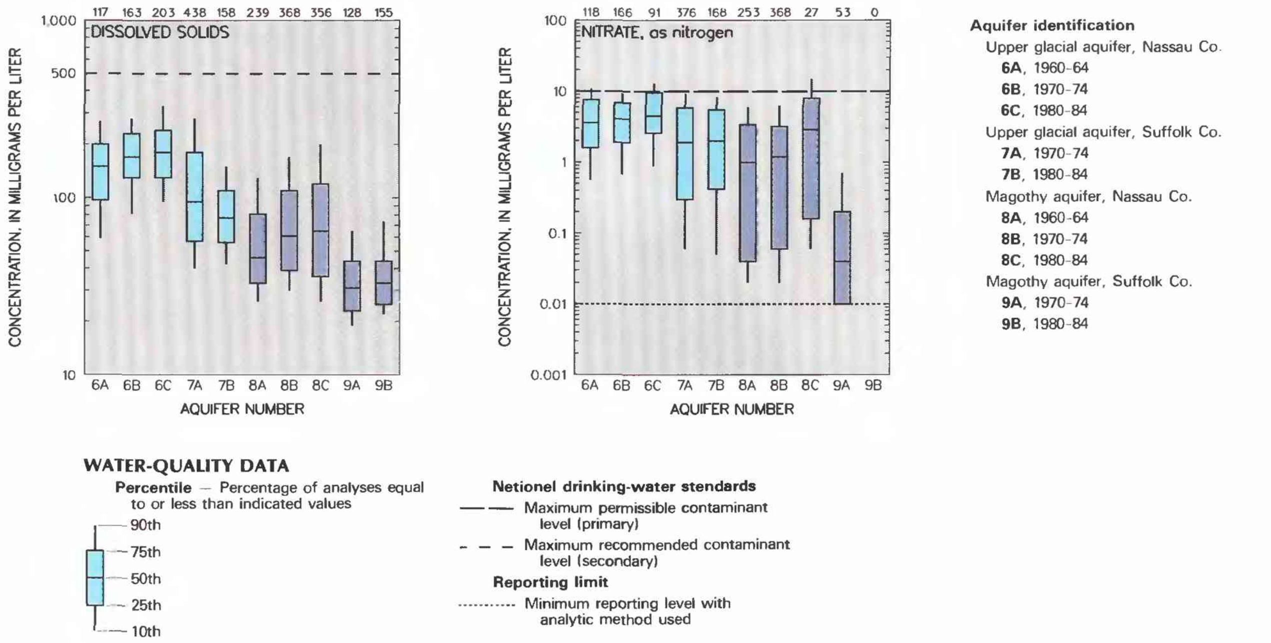

Figure 4. Dissolved-solids and nitrate in the upper glacial and Magothy aquifers of Nassau and Suffolk Counties, Long Island, 1960–84. Aquifer locations as given in fig. 2. (Source: U.S. Geological Survey files.)

are the sole source of drinking water for about 3.2 million people, their protection is vital. The greatest concern today (1986) is directed toward Long Island's deeper aquifers, which are the major source of public water supply (New York State Department of Environmental Conservation, 1986, p. II-3). In short, where ground water is most readily available and most intensely used in New York, it also is most vulnerable to contamination.

Thousands of potential sources of contaminants, including toxic substances, currently overlie the State's important aquifers, and the number of potential sources probably will increase, even though development will be increasingly regulated. Many potential sources of contaminants that accompany development are not readily controlled; for example, railroad and truck accidents will continue to cause chemical and petroleum spills.

Petroleum products and SOC are expected to remain the cause of New York's most serious ground-water-quality problems. The storage and handling of those materials, even though regulated, create a constant potential for spills and leaks. Steel petroleum-storage tanks, for example, are being replaced by fiberglass tanks, which do not corrode, yet they are subject to leaks from accidental fracturing.

Active and inactive hazardous-waste-disposal sites will continue to be sources of toxic organic contaminants. Pesticide contamination of ground water will remain a concern. Changing agricultural practices, such as the increase in tilled acreage, may increase the potential for pesticide migration to ground water.

Nitrate contamination of Long Island's major public-supply aquifers also is expected to remain a concern. The continued increased concentrations of nitrate in aquifers underlying sewered areas indicate that uncontrolled sources of nitrate, such as lawn fertilizers, are persisting, and they will continue to be a concern (New York State Department of Environmental Conservation, 1986, p. II–A).

The major areas of ground-water contamination in New York probably have been identified; therefore, as more complete data are gathered in the future, a large number of unexpected well closings is unlikely. Yet, ground-water contamination threatens to expand if strong actions are not taken. Consequently, New York State has conducted a review of its ground-water resources and developed a thorough ground-water-management program.

GROUND-WATER-QUALITY MANAGEMENT

Two State agencies, NYSDEC and NYSDOH, have responsibility for most aspects of the State's ground-water-management program. These agencies also have been delegated responsibility for implementing many Federal programs related to ground water.

The NYSDEC, the State's environmental agency, is responsible for administering a full array of environmental-quality and natural-resource programs such as ground-water resource management, program development, and interagency coordination. Specifically, NYSDEC is charged with the "coordinated management of water resources" (Environmental Conservation Law, Section 3–0301) and the control of water pollution and maintenance of reasonable standards of purity of the State's ground and surface water (Environmental Conservation Law, Article 17).

The NYSDOH works closely with the NYSDEC in ground-water policy development and oversight. Under the New York State Public Health Law, NYSDOH is responsible for the protection of public health and for ensuring a safe supply of drinking water for the State's citizens. This responsibility pertains to water that is pumped by water suppliers for distribution to the consumer. Under the Public Health Law and Part 5 of the State Sanitary Code, NYSDOH administers a major program to ensure that all water-supply systems in the State are operated and maintained properly and that all consumers are assured delivery of a safe and adequate supply of water.

New York State's government has long recognized the value of ground-water resources. Since the 1930's, the State has had the authority and has administered programs to regulate most ground-water withdrawals on Long Island. During the 1950's and 1960's it provided substantial funds for county and basinwide water-resource studies for most of the State in cooperation with the U.S. Geological Survey. These efforts resulted in many ground-water maps and interpretive reports.

New York State has had a system of ground-water-quality classifications and standards since 1967. The most recent revision, in 1978, included effluent standards and limitations that provide the basis for State Pollutant Discharge Elimination Systems (SPDES) permits. New York State requires SPDES permits for all municipal, industrial, and commercial wastewater discharges to ground water.

In addition to those initiatives that specifically address ground water, the NYSDEC currently administers a range of programs in areas such as solid- and hazardous-waste disposal, pesticide use, mined-land reclamation, oil and gas regulation, and others that have helped to protect ground water in the past and are being adjusted to continue this protection in the future.

Despite the current programs to protect ground water, evidence indicates that past efforts have been inadequate to meet the task. For several years, the State has undertaken significant measures toward development of a new ground-water program, partly funded by grants from EPA under Section 208 of the Clean Water Act.

The State's overall management strategy is set forth in two major reports. The Long Island Groundwater Management Program report (New York State Department of Environmental Conservation, 1986) was certified to EPA in mid-1986. The Upstate New York Groundwater Management Program (New York State Department of Environmental Conservation, 1987) was certified to EPA in May 1987.

The primary emphases of New York State's ground-water-protection strategy, as defined in these documents, are: (1) to strengthen its current programs that regulate contamination sources so ground-water problems may be better anticipated and prevented; (2) to geographically target special regulatory policies to provide a more intensive management focus on the largest yielding and most intensively utilized aquifers; (3) to develop new regulatory programs for important contamination sources that are not addressed adequately at the present time, particularly petroleum and chemical bulk storage; and (4) to work closely with local government agencies to foster protection of critical aquifers.

The State currently is implementing some of the key recommendations contained in these reports. It is (1) supporting a program with the U.S. Geological Survey to update and expand the available aquifer maps; (2) implementing policies to restrict the location of landfills over principal aquifers; (3) improving management of the SPDES program to control toxic discharges to both ground water and surface water; (4) developing regulations to implement the State's Petroleum Bulk Storage Law (passed in 1983); and (5) continuing efforts to improve water-quantity management on Long Island.

The State's ground-water-management strategy incorporates Federal programs delegated to the State under legislation, such as the Safe Drinking Water Act, CERCLA, and RCRA. In general, authorities in these acts are paralleled by State legislation, which in some instances goes beyond the Federal counterpart. For example, the State's SPDES program regulates wastewater discharges to surface water and ground water, whereas the Federal National Pollutant and Discharge Elimination System regulates only surface-water discharges. Also, a State Superfund has been established to renovate hazardous-waste sites not under the Federal Superfund (CERCLA).

County health agencies in New York State have long assisted in conducting the State's pollution-control and water-supply-regulation programs through delegation and local assistance. Some counties administer additional programs of their own, especially on Long Island. Historically, local health agencies have conducted most of the day-to-day activities within the Long Island Groundwater Management Program. Suffolk County's Article 12 program is one of the best examples of a strong preventive regulatory program for petroleum and chemical bulk storage. The Long Island Groundwater Management Program (New York State Department of Environmental Conservation, 1986) is neither a purely State nor a purely local program, but rather, a comprehensive framework for the activities of several independent State and local agencies.

Towns, cities, and villages in New York State are responsible for regulating land use, a key factor in protecting ground water. Few municipalities in New York State have made full use of local zoning, subdivision approval, and other land-use control powers to protect ground water, although some local governments, particularly on Long Island, have begun to do so. An important element of the State's long-term strategy is to improve guidance to local governments to assist the development of effective local protection efforts.

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NORTH CAROLINA
Ground-Water Quality

In North Carolina (fig. 1*A*), about 3.2 million (55 percent) of the 5.9 million people (fig. 1*B*) rely on ground water for their water supply. The overall quality of North Carolina's ground-water resources is good; most water supplies meet drinking-water standards established by the North Carolina Administrative Code (North Carolina Department of Human Resources, 1984) with little treatment. However, treatment is required in some places to meet State drinking-water standards because of naturally occurring or human-induced water-quality problems.

Naturally occurring problems usually result from large concentrations of inorganic constituents in water. The most widespread, naturally occurring water-quality problem is the presence of saltwater at depth in all aquifers in the eastern part of the State (fig. 3*B*). Removal of salt from the water generally is impractical. The lack of large freshwater supplies has been a limiting factor in economic development of some areas of the State, particularly in parts of northeastern North Carolina and the Outer Banks.

Human-induced water-quality problems in North Carolina's aquifers (fig. 2*A*1) most commonly result from contamination of ground water by leachate from landfills and seepage from waste lagoons, underground storage tanks, septic tanks, and accidental spills of chemicals. Also, where pumping occurs near naturally occurring saltwater, the saltwater may move upward (upcone) and laterally toward pumped wells and result in increased salinity of water from the wells. Human-induced water-quality problems, though serious where they occur, are usually local in extent.

A total of 715 sites have been identified by the North Carolina Department of Human Resources (DHR) as possible sources of human-induced ground-water contamination. Included are 35 sites that require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976; contamination has been confirmed at 33 of these RCRA sites. Another 6 of the 715 sites are included on the U.S. Environmental Protection Agency's (EPA) National Priorities List (NPL) of hazardous-waste sites under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and 2 others were under consideration for that list as of June 1986 (U.S. Environmental Protection Agency, 1986c). As of September 1985, the U.S. Department of Defense (DOD) has identified 51 potential hazardous-waste sites at 4 facilities in North Carolina; nine sites at one facility were considered to present a hazard significant enough to warrant remedial action.

Potential for future contamination of ground water near hazardous-waste sites is significant. Ground water typically moves slowly, so that the effects of contamination may go undetected for several decades. Generally, aquifer recharge areas are most vulnerable to ground-water contamination; ground-water discharge areas, usually along streams, are least vulnerable to contamination.

WATER QUALITY IN PRINCIPAL AQUIFERS

North Carolina lies in parts of three physiographic provinces—the Atlantic Coastal Plain, Piedmont, and Blue Ridge (fig. 2*A*2). Four of the five principal aquifers (fig. 2*A*1) used for water supply in North Carolina are in unconsolidated to partly consolidated sedimentary deposits in the Coastal Plain (U.S. Geological Survey, 1985, p. 329). These four aquifers are the surficial, the Yorktown, the Castle Hayne, and the Cretaceous aquifers. The other principal aquifer is the crystalline-rock aquifer, which consists of crystalline igneous, metasedimentary, and metavolcanic rocks in the Piedmont and Blue Ridge provinces.

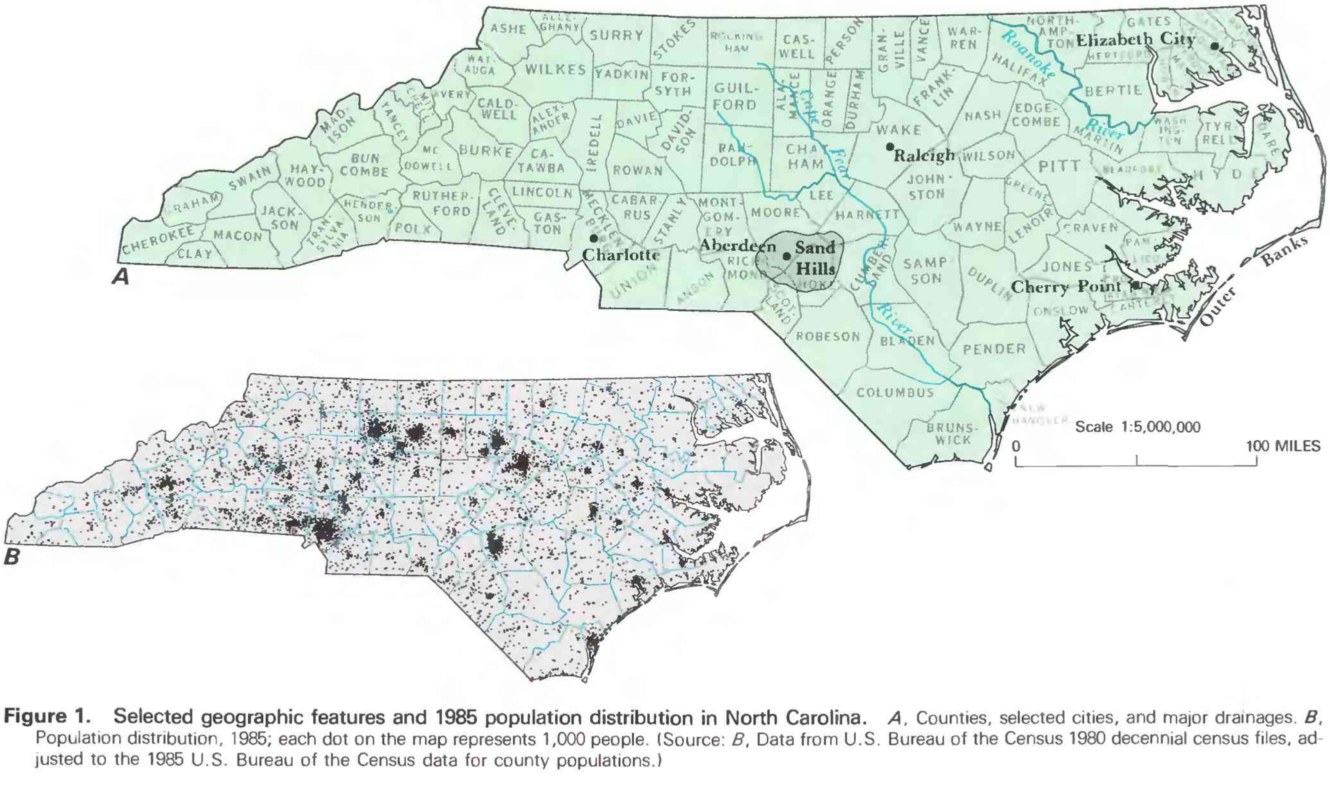

Figure 1. **Selected geographic features and 1985 population distribution in North Carolina.** *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

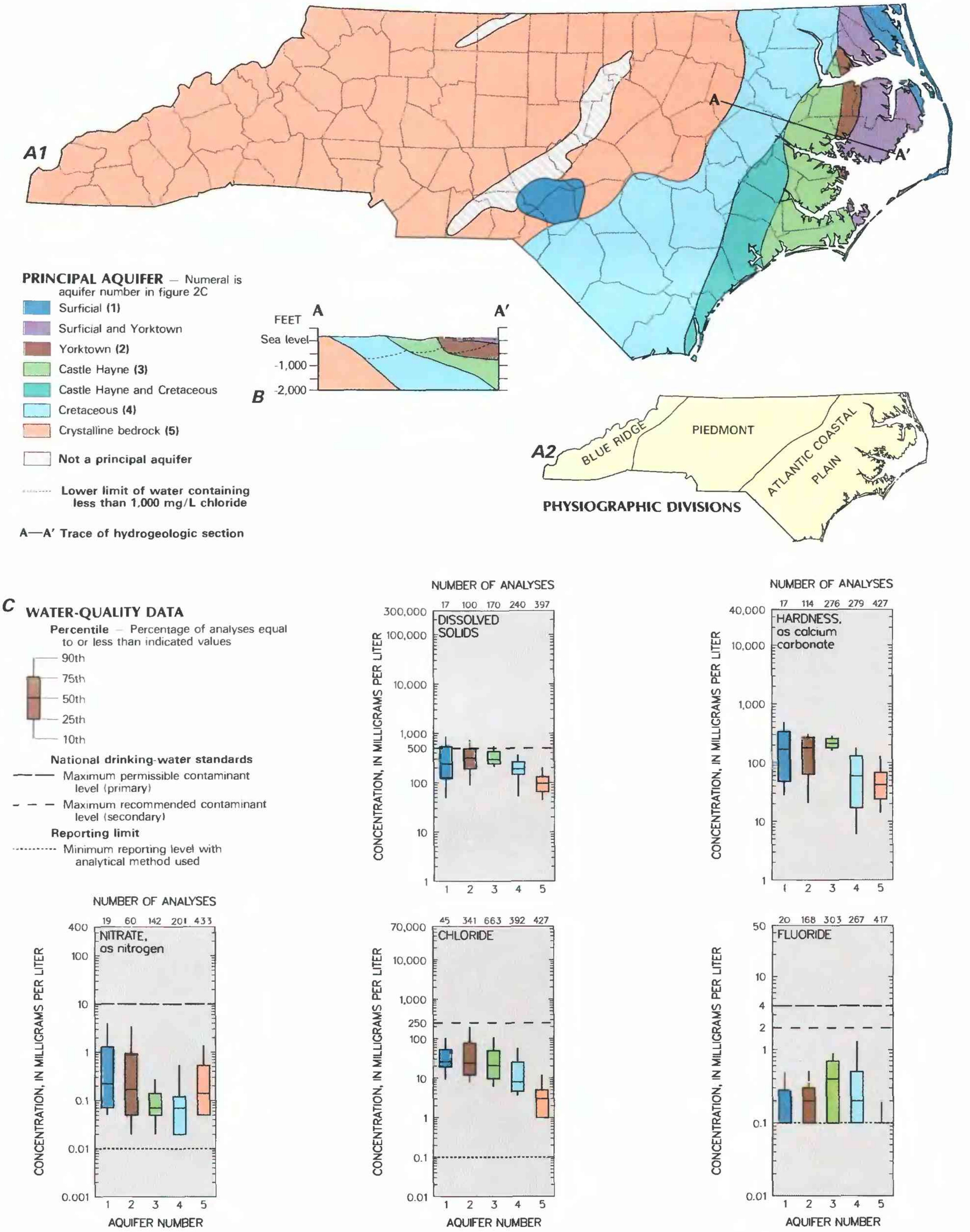

Figure 2. Principal aquifers and related water-quality data in North Carolina. *A1*, Principal aquifers; *A2*, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1932–86. (Sources: *A1*, Compiled by R.W. Coble from U.S. Geological Survey and North Carolina Department of Natural Resources and Community Development files. *A2*, Fenneman, 1938; Raisz, 1954. *B*, Compiled by R.W. Coble from U.S. Geological Survey and North Carolina Department of Natural Resources and Community Development files. *C*, Analyses compiled from U.S. Geological Survey files; analyses for crystalline rock are from North Carolina Department of Natural Resources and Community Development, Division of Environmental Management; national drinking-water standards from U.S. Environmental Protection Agency, 1986b,c.)

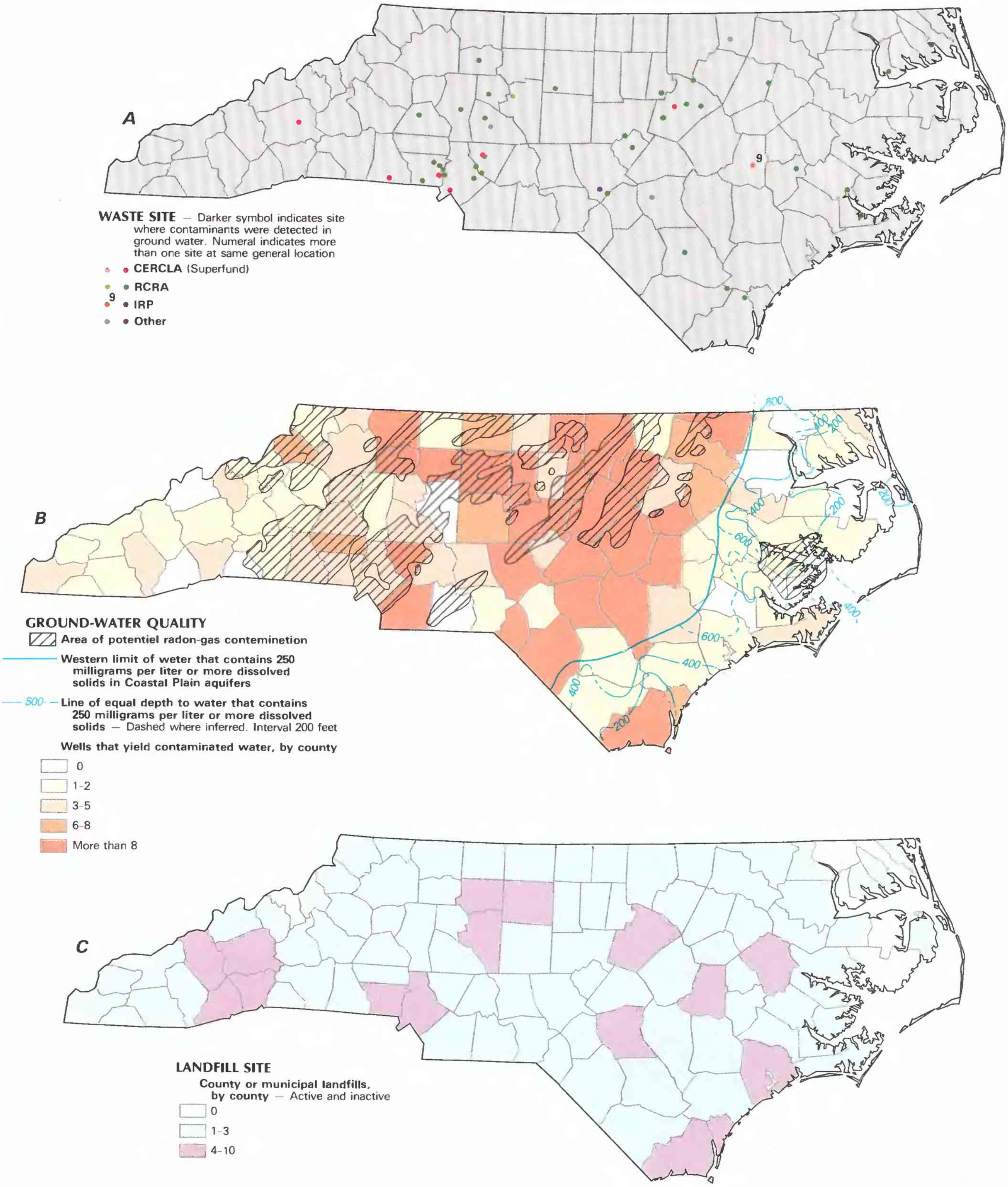

Figure 3. **Selected waste sites and ground-water-quality information in North Carolina.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of September 1986; Resource Conservation and Recovery Act (RCRA) sites, as of September 1986; Department of Defense Installation Restoration Program (IRP) sites, as of September 1985; and other selected waste sites, as of September 1986. *B*, Areas of naturally impaired water quality and potential contamination, and distribution of wells that yield contaminated water, as of September 1986. *C*, County and municipal landfills, as of September 1986. (Sources: *A*, Gary Babb, Lee Crosby, and Robert Glaser, North Carolina Department of Human Resources; U.S. Department of Defense, 1986. *B*, Radon areas by A.G. Strickland from State geologic map by Brown and Parker, 1985; saltwater areas from Meisler, 1987; wells that yield contaminated water from Ted Taylor, Bill Williams, and Leon Pryor, North Carolina Department of Human Resources. *C*, Michael Babuin and Lois Walker, North Carolina Department of Human Resources.)

Generally, the background quality of freshwater in North Carolina's principal aquifers is suitable for most domestic and industrial purposes. Among the naturally occurring water-quality characteristics that may require treatment or may render ground water unsuitable for some purposes are excessive hardness, high and low pH, and large concentrations of dissolved solids, chloride, fluoride, iron, manganese, and sodium.

Radioactive radon gas dissolved in ground water and the resulting possibility of increased risk of cancer, have come to public attention recently. Results of preliminary studies indicate that the gas may accumulate to undesirable concentrations in poorly ventilated homes in areas underlain by rocks of larger-than-average uranium concentrations and low permeability. North Carolina contains abundant rocks of this type, including shale, clay, granite, and phosphate ore. Areas underlain by rocks with larger-than-average uranium content are shown in figure *3B*. More definitive research is needed before the health risks of radon gas in ground water can be assessed accurately.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure *2C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), chloride, and fluoride analyses of water samples collected from 1932 through 1986 from the principal aquifers in North Carolina. Percentiles of these variables (except for hardness) are compared to national standards that specify the maximum concentration or level of a contaminant in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen) and 4 mg/L fluoride. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 2 mg/L fluoride. For these variables, the State drinking-water standards are the same as the national standards. As shown on figure *2C*, 90 percent of the ground-water analyses from each of the principal aquifers in North Carolina did not exceed the primary and secondary drinking-water standards for nitrate (as nitrogen), chloride, and fluoride.

Surficial Aquifer

The surficial aquifer (fig. *2A1*) is a principal aquifer in three relatively small areas of the State—the Sand Hills, the Outer Banks (fig. *1A*), and parts of northeastern North Carolina. Yields to individual wells in the surficial aquifer commonly range from 25 to 200 gal/min (gallons per minute) but may exceed 500 gal/min (U.S. Geological Survey, 1985, p. 330).

The 90th-percentile concentrations of nitrate (4.0 mg/L) and fluoride (0.5 mg/L) for surficial-aquifer samples did not exceed the drinking-water standards (fig. *2C*). Median concentrations were 240 mg/L dissolved solids, 170 mg/L hardness, 0.22 mg/L nitrate, 26 mg/L chloride, and 0.1 mg/L fluoride.

In the Sand Hills area, the surficial aquifer is used for public and individual water supplies and for irrigation of numerous golf courses. Water from the surficial aquifer in the Sand Hills area typically contained less than 25 mg/L dissolved solids and 10 mg/L hardness. However, the water tended to be acidic and, therefore, corrosive.

For much of the Outer Banks, the surficial aquifer is the only source of freshwater other than precipitation. However, freshwater is seldom found below 100 feet on the Outer Banks. To avoid saltwater contamination, supplies commonly are obtained from a large number of shallow vertical wells or from shallow horizontal wells. Because of the presence of saltwater, either naturally occurring or as a result of pumping, the dissolved-solids concentration of water obtained from the surficial aquifer in this area can exceed the 500-mg/L national secondary drinking-water standard. Also, ground water from the surficial aquifer on the Outer Banks and elsewhere in northeastern North Carolina ranged from soft to very hard, with hardness exceeding 180 mg/L in many places. Concentrations of iron larger than the 300-μg/L (micrograms per liter) national secondary drinking-water standard were common.

Yorktown Aquifer

The Yorktown aquifer (fig. *2A1*) is shallow in the northern part of the Atlantic Coastal Plain (fig. *2A2*). In places, such as Elizabeth City where it supplies 1.4 Mgal/d (million gallons per day) to a well field, the Yorktown is the only aquifer capable of yielding large supplies of freshwater to wells. Yields of individual wells in the Yorktown aquifer may exceed 500 gal/min, but yields of 15–90 gal/min are more common (U.S. Geological Survey, 1985, p. 330).

The 90th-percentile concentrations of nitrate (3.4 mg/L) and fluoride (0.5 mg/L) for Yorktown-aquifer samples did not exceed the drinking-water standards (fig. *2C*). Median concentrations were 319 mg/L dissolved solids, 180 mg/L hardness, 0.17 mg/L nitrate, 24 mg/L chloride, and 0.2 mg/L fluoride. Water from the Yorktown aquifer at some places contains excessive iron.

Background concentrations of sodium are generally larger in water from the Yorktown aquifer than from any other principal aquifer; the median sodium concentration in samples from the aquifer was 38 mg/L; 25 percent of the sodium concentrations exceeded 130 mg/L. No State (North Carolina) or national standards have been established for sodium in drinking water; however, the U.S. Environmental Protection Agency (1985b, p. 46980) has proposed a health advisory guidance level maximum of 20 mg/L for sodium in drinking water. Although relatively large sodium concentrations in the Yorktown aquifer in part reflect the presence of saltwater, the ratio of sodium to other constituents is larger than would be expected just from the presence of diluted sea water. Probably, ion exchange is taking place (Wilder and others, 1978), wherein calcium in the ground water exchanges for sodium in the aquifer materials; this process increases the concentrations of sodium and decreases the concentrations of calcium in the ground water. This process would account for the larger than expected ratios of sodium to other constituents in diluted seawater. The same process may occur to varying degrees in all the Coastal Plain aquifers but appears to be pronounced in the Yorktown aquifer.

Castle Hayne Aquifer

The Castle Hayne aquifer (fig. *2A1*), the most productive in North Carolina, is capable of yielding more than 2,000 gal/min to individual wells. The Castle Hayne aquifer is the source of water for public supply for several Coastal Plain communities and, in places near the coast, may contain freshwater even where aquifers above and below it contain saltwater. A phosphate mine in Beaufort County pumps nearly 60 Mgal/d from the Castle Hayne aquifer to decrease the artesian pressure and dewater the overlying phosphate ore beds.

The 90th-percentile concentrations of nitrate (0.28 mg/L) and fluoride (0.9 mg/L) for water from the Castle-Hayne aquifer did not exceed the drinking-water standards (fig. *2C*). Median concentrations were 298 mg/L dissolved solids, 215 mg/L hardness, 0.07 mg/L nitrate, 21 mg/L chloride, and 0.4 mg/L fluoride. Based on the data, water from the Castle Hayne aquifer generally is hard (121 to 180 mg/L as calcium carbonate) or very hard (greater than 180 mg/L). Hardness is less near recharge areas but increases with residence time in the limestone rocks of the aquifer.

Iron concentrations, in contrast to hardness, are more likely to exceed the State drinking-water standard of 300 µg/L in recharge areas, but the iron precipitates as the water moves into the limestone (Wilder and others, 1978). Water from the Castle Hayne aquifer also may contain silica in concentrations larger than 50 mg/L. Deeper parts of the Castle Hayne aquifer contain saltwater in many places, but the depth to water with dissolved solids of 250 mg/L or more may exceed 600 feet (fig. 3*B*).

Cretaceous Aquifer

The Cretaceous aquifer (fig. 2*A*1) is the most extensively used aquifer in the Coastal Plain and contains the best quality of water in much of the area. Yields to individual wells generally range from 200 to 400 gal/min and may exceed 1,400 gal/min (U.S. Geological Survey, 1985, p. 330).

The 90th-percentile concentrations of nitrate (0.55 mg/L) and fluoride (1.3 mg/L) for Cretaceous-aquifer samples did not exceed the drinking-water standards (fig. 2*C*). Median concentrations were 190 mg/L dissolved solids, 59 mg/L hardness, 0.07 mg/L nitrate, 8.0 mg/L chloride, and 0.2 mg/L fluoride. Based on the data, water from the Cretaceous aquifer is soft, except where it leaks downward from the overlying Castle Hayne aquifer. Once in the Cretaceous aquifer, the hardness of water from the overlying limestone aquifer is decreased by natural ion exchange of calcium and magnesium for sodium (in the clay), resulting in a soft, alkaline water that requires little or no treatment for most uses (Wilder and others, 1978).

Water from the Cretaceous aquifer, particularly in the part of the aquifer identified as the Black Creek Formation, may contain fluoride in concentrations larger than 4 mg/L, the maximum permissible concentration under national drinking-water standards (U.S. Environmental Protection Agency, 1986a). Thus, fluoride may limit the use of water for drinking from some wells in the Cretaceous aquifer. In many places, the Cretaceous aquifer also contains salty water in its deeper parts.

Crystalline Rock Aquifer

The crystalline rock aquifer (fig. 2*A*1) underlies the entire State and is the principal aquifer in the Piedmont and Blue Ridge provinces (fig. 2*A*2). In contrast to the unconsolidated to partly consolidated sediments of the four aquifers of the Atlantic Coastal Plain (fig. 2*A*1), the crystalline rocks have little storage capacity and well yields commonly range from only about 5 to 35 gal/min. However, where efforts have been made to design the wells to maximize yields and to construct wells in optimum locations, such as in valleys and draws where the chances of intercepting interconnected fractures are greatest (U.S. Geological Survey, 1985), it is common to obtain 200 gal/min or more from this aquifer (Heath and Giese, 1980). More than 50 percent of the 4 million people in the Piedmont and Blue Ridge provinces rely on water from the crystalline rock aquifer for water supply, mostly from individually owned wells in rural areas.

The quality of water from the crystalline rock aquifer generally is acceptable for human consumption and most other uses. The 90th percentile concentrations of nitrate (1.4 mg/L) and fluoride (0.2 mg/L) for water from the crystalline rock aquifer did not exceed the drinking-water standards (fig. 2*C*). Median concentrations were 96 mg/L dissolved solids, 42 mg/L hardness, 0.14 mg/L nitrate, 3.0 mg/L chloride, and 0.1 mg/L fluoride. Thus, most ground-water samples at most places did not exceed drinking-water standards; however, treatment of some supplies from the crystalline rock aquifer may be necessary. Variables and the respective drinking-water standards that were exceeded in some water samples were iron (300 µg/L), manganese (50 µg/L), and pH (6.5–8.5 units). Based on the data, the water generally was soft (hardness less than 60 mg/L as calcium carbonate) in most areas. Chemical analyses available from WATSTORE showed that background iron concentrations ranged from 100 µg/L at the 10th percentile to 1,000 µg/L at the 90th percentile; manganese concentrations ranged from 50 to 110 µg/L, and pH ranged from 6.0 to 7.4 for the same percentiles.

EFFECTS OF LAND USE ON WATER QUALITY

Most observed changes in ground-water quality in North Carolina are related to patterns and trends in land-use and waste-disposal practices. Underground storage tanks, waste lagoons, and disposal landfills commonly are responsible for the point-source contamination that has been identified in North Carolina (fig. 4). The detection of petroleum, pesticide, and biological contamination in public and private wells is increasing; however, these sources of contamination commonly represent more dispersed, nonpoint sources of contamination (H.E. Mew, North Carolina Department of Natural Resources and Community Development, written commun., 1985). An estimated 68 public and 690 private wells are known to have been contaminated (fig. 3*B*) (Leon Pryor, North Carolina Department of Human Resources, written commun., September 1986; Bill Williams and Ted Taylor, Department of Human Resources, written commun., September 1986).

Hazardous-Waste Disposal

Hazardous wastes are treated and stored at 81 of 3,030 RCRA sites. As shown in figure 3*A* contamination of shallow aquifers has been detected at 33 of these 81 sites (fig. 3*A*); two other sites have suspected contamination. No permitted commercial hazardous-waste-disposal sites are presently being operated in the State (Gary Babb, North Carolina Department of Human Resources, written commun., October 1986).

As of June 1986, ground-water contamination has been confirmed at six CERCLA sites (fig. 3*A*) in North Carolina and at two proposed NPL sites (not shown in fig. 3*A*). One former NPL site, an extensive polychlorinated biphenyl spill along 210 miles of rural roadside in Cumberland, Johnston, Harnett, Lee, Chatham, Nash, Franklin, Halifax, Hoke, Moore, and Warren Counties, was removed to a secured, monitored land fill in Warren County (fig. 3*A*).

The CERCLA Unit of DHR has evaluated 580 of 715 potential hazardous-waste sites identified by DHR for public health and environmental impact. Ground-water contamination has been confirmed at 25 of these sites and is suspected at about 405 other sites. The most common contaminants found include cadmium, chromium, arsenic, lead, pentachlorophenol (PCP), perchloroethylene (PCE), creosote, and common pesticides such as chlordane, aldrin, and heptachlor. No contamination was indicated at approximately 150 sites. The need for remedial action will be evaluated further at many of the sites. The remaining 135 sites that were identified by DHR are being investigated by other agencies.

As of September 1985, 51 hazardous-waste sites at 4 facilities in North Carolina had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Nine IRP sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

The vertical and lateral extent of contamination is specific to each hazardous-waste site. At one site near the town of Aberdeen in Moore County (an "Other" site in fig. 3*A*), concentrations of as much as 250 µg/L of the pesticide lindane were found at depths of 25 feet at a distance of more than 1 mile from the source of contamination (Ned Jessup, U.S. Environmental Protection Agency, Emergency Response Unit, Atlanta, Ga., oral commun., October 1986). At the same site, 1.5 miles from the source, lindane

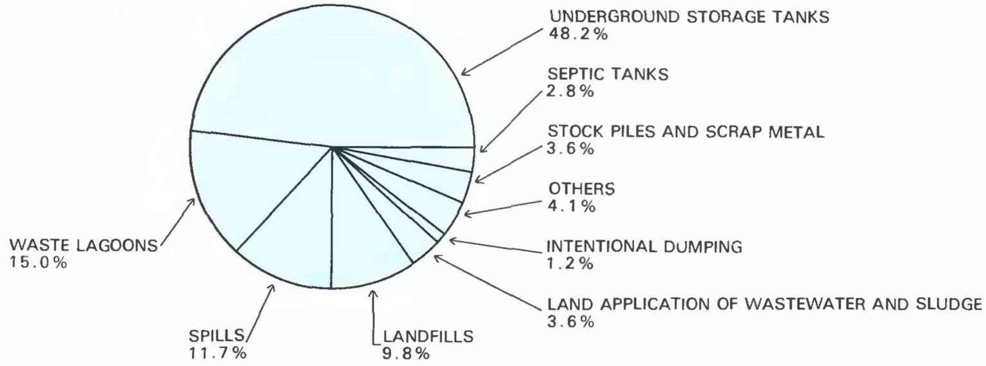

Figure 4. Percentage of total number of confirmed ground-water contamination sources by type of source for 247 selected sites. (Source: Modified from H.B. Mew, North Carolina Department of Natural Resources and Community Deveopment, written commun. 1985.)

concentrations of 12 $\mu g/L$ reportedly were detected 150 feet below land surface.

Industrial Facilities

H.B. Mew (North Carolina Department of Natural Resources and Community Development, written commun. 1985) characterized the operational types of sites where ground-water contamination was confirmed (fig. 4). Landfills, waste lagoons, and leaking underground storage tanks were the most common sources of contamination from industrial sources. In a survey (Huisingh and Hatley, 1983) of sites owned by chemical companies and paint manufacturers, solvents and metal-finishing and agricultural chemicals were suggested as probable sources of ground-water contamination. Sites associated with companies that produced or distributed fiber, wood, paper, and petroleum products also were mentioned in that survey.

The sources of contamination at about one-half of the confirmed contamination sites studied by Mew were underground storage tanks (fig. 4). Since 1983, the DHR has detected petroleum products in 516 wells. An estimated 1,500 to 2,000 people are reported to have been affected (Ted Taylor, North Carolina Department of Human Resources, written commun., September 1986). In one instance, a petroleum-products operation in Scotland County contaminated the wells of 60 families who were forced to use bottled water for more than a year, while public water-supply lines were extended to their homes (Dennis Harrington, Scotland County Health Department, oral commun., September 1986). Well drillers report petroleum-products contamination as the most common reason for well replacement (Miller and others, 1977).

Many of the sites where ground-water contamination has been detected were designed or originally constructed according to acceptable or state-of-the-art procedures. In the past, lagoons and trenches commonly were constructed without liners or containment structures. Commonly, the only treatment of water consisted of solidifying waste materials by allowing the liquids to evaporate or seep into the soil. At the Aberdeen site in Moore County (fig. 3*A*), for example, the waste pesticide (lindane) was disposed of in an unlined trench 750 feet long, 35 feet wide, and 15 feet deep. When the site was closed, it was covered with 6 feet of clayey soil. Afterward, ground water as far as 5 miles from the trench reportedly became contaminated to some degree (Ned Jessup, U.S. Environmental Protection Agency, Emergency Response Unit, Atlanta, Ga., oral commun., October 1986).

Agricultural Practices

The use of farm fertilizers, pesticides, and animal-waste lagoons has caused some local contamination of shallow aquifers. Pesticides have been detected in water from 202 private wells and 1 public-supply well (Bill Williams, North Carolina Department of Human Resources, written commun., September 1986; Leon Pryor, Department of Human Resources, written commun., September 1986). The public-supply well was abandoned; some of the private wells still may be in use. Contamination by pesticides is found most commonly in water from springs and shallow wells. Although many of the wells that yield contaminated water are near agricultural lands where pesticides have been applied, some of the wells seem to have been contaminated by spills that occurred during the preparation, mixing, or handling of the chemicals before application, or from infiltration of rinse water used to clean application equipment or tanks.

Although pesticide contamination occurs throughout the State, the counties of Durham, Wake, and Johnston account for 24 percent of the reported incidents (Bill Williams, North Carolina Department of Human Resources, written commun., September 1986). Chlordane, aldrin, and heptachlor were the most commonly detected pesticides in ground water; many of the occurrences of contamination appear to be associated with termite treatment.

Fertilizers caused the contamination of four public-supply wells, all of which were abandoned (Leon Pryor, North Carolina Department of Human Resources, written commun., September 1986). Data are not available to document contamination of private wells by either fertilizers or other sources of nutrients, such as nitrate (fig. 2*C*) or phosphate.

Public Facilities

Ground-water contamination at public facilities usually is associated with landfills and underground storage tanks and generally is limited in areal extent. H.E. Mew (North Carolina Department of Natural Resources and Community Development, written commun., 1985) indicated that one-third of the contaminated sites were publicly owned; of these, 23 percent were municipal or county landfills, which were also the second most common source of probable contamination in the survey described by Huisingh and Hatley (1983). Landfill leachate commonly is rich in organics and metals from chemicals in pesticide, paint, fuel containers, waste oils, and solvents.

For many years, landfills were not regulated in North Carolina; no laws prevented disposal of liquid waste in landfills, and few landfills were secured or fenced. Some landfills were located either in areas where ground-water levels were near land surface or in fractured rock that provided little filtration of leachate. Leachate from some landfills has migrated into ground and surface water, but the extent of contamination and the number of people affected generally are unknown. The State has required ground-water-quality monitoring of all new landfills since 1981 and has mandated that existing sanitary landfills be monitored beginning in 1987 (Michael Babuin, North Carolina Department of Human Resources, oral commun., September 1986). There are 208 operating landfills in North Carolina (fig. 3*C*); these include all permitted landfill sites and unpermitted RCRA sites that are landfills.

Domestic Land Use

Contamination that results from domestic land use is commonly associated with septic disposal systems or improper storage, use, or disposal of household and lawn chemicals. Berkowitz (1981) determined that 30 percent of the homes in Graham, Haywood, Jackson, and Macon Counties had drinking-water supplies that were bacteriologically contaminated (though not necessarily unfit for use). The contamination was partly caused by onsite sewage-treatment problems. Berkowitz (1981) reported that septic-system drainfields constructed where the water table is shallow did not provide effective treatment. In a separate study, Carlile and others (1981) reported that satisfactory locations for septic-tank systems are difficult to find in the Atlantic Coastal Plain, primarily because of the shallow water table. According to Carlile and others (1981), many septic-disposal systems near public- or private-supply wells are a problem of unknown magnitude. This may be related to reports that biological contamination is the leading cause of closures of public wells (Leon Pryor, North Carolina Department of Human Resources, written commun., September 1986).

Saltwater Encroachment

Saltwater encroachment is a serious problem in some coastal areas (R.C. Heath and H.B. Wilder, U.S. Geological Survey, written commun., 1979). Saltwater occurs in the sediments underlying the eastern part of the Atlantic Coastal Plain at depths controlled by both the freshwater pressure heads and the stratification of sediments. Depths to water that contain 250 mg/L or more dissolved solids generally range from 200 to 600 feet (fig. 3*B*). Saltwater encroachment induced by withdrawals from wells is an increasingly serious problem in some areas of the Coastal Plain and Outer Banks, particularly in the northeastern parts. Two public-supply wells in Hyde County have been closed because of saltwater contamination.

POTENTIAL FOR WATER-QUALITY CHANGES

The greatest potential for future changes in ground-water quality is in recharge areas in and near aquifer outcrops. Contaminants that originate in recharge areas can move into deeper parts of the aquifers and contaminate them for great distances. The farther upgradient from a discharge area that a contaminant enters the ground-water system, the deeper it penetrates into the ground-water system and the larger the area ultimately affected (Heath, 1983).

Aging underground storage tanks will continue to be a major hazard to ground water and a source for future adverse water-quality changes. Underground storage tanks are in use throughout the State. One area of major concern is the Sand Hills (fig. 2*A*1) where acidic ground water hastens the deterioration of underground metal tanks and the release of contaminants. Once in the ground, contaminants will be relatively unrestricted in movement, because of the large permeability and small clay content of the sediments that underlie the Sand Hills. In addition, acidic ground water inhibits soil absorption or adsorption of many contaminants.

The cumulative effects of some agricultural practices also may cause adverse water-quality changes. Pesticides and fertilizers are being used more frequently and in larger amounts, particularly in the Atlantic Coastal Plain. Improper use, storage, or disposal of these chemicals also could result in severe contamination of ground water. The trend toward minimum-tillage farming and a resulting reliance on herbicides may present an additional source of ground-water contamination. Chemirrigation also is increasing. Application of these agricultural chemicals with excessive amounts of irrigation water can increase the chances that the chemicals will enter the ground-water system. The State is formulating regulations to control the increased use of chemirrigation and to license users.

GROUND-WATER-QUALITY MANAGEMENT

The North Carolina Department of Natural Resources and Community Development (NRCD) maintains a statewide ground-water-quality network to monitor background water quality and implements an incident-management program to investigate reported ground-water contamination. The DHR monitors all permitted solid-waste landfills in the State for ground-water contamination. Operators of wastewater-treatment plants, lagoons, and land-application systems are required to submit results of self-monitoring to the NRCD. The U.S. Geological Survey maintains cooperative agreements with NRCD and DHR, but no ground-water-quality studies are being conducted (1986) under these agreements. However, the U.S. Geological Survey currently is conducting several interpretive studies of ground-water quality with other cooperating agencies, including a study of the effects of urbanization on ground-water quality in the City of Charlotte and throughout Mecklenburg County, and a study of the ground-water supply and potential for contamination at the Cherry Point Marine Corps Air Station in Craven County.

The NRCD implements most of the regulatory and planning procedures related to ground-water resources in North Carolina. The Division of Environmental Management (DEM) within NRCD has the major responsibility for ground-water management and regulatory programs. The North Carolina Environmental Management Commission (EMC) has broad authority over the permitting process for land development that may affect ground water. In 1983, the Commission adopted standards and classified the State's ground waters according to best-usage criteria. All applicable EMC permit applications are reviewed by the Groundwater Section, DEM, for compliance with established standards.

The National Pollution Discharge Elimination System (NPDES), or point-source permit program, is administered by the DEM Water Quality Section under authority of North Carolina General Statute (NCGS) 143–215.1. This is a Federal permitting program over which the State has primacy. Although these permits primarily regulate facilities that discharge to surface water, they also include unlined basins and holding ponds that have the potential to contaminate ground water.

The nondischarge-permit program, which regulates waste-disposal activities that do not include discharges to surface water, is a State program also administered by the DEM Water Quality Section under authority of NCGS 143–215.1. The program is, in essence, a ground-water-permit program that regulates activities, such as sewer-line extensions, sludge disposal and other land-application systems, and waste lagoons that do not discharge to surface water.

Monitoring to assure compliance with permit conditions is an important element of the ground-water permitting program to control ground-water pollution. The DEM Groundwater Section has developed an extensive compliance-monitoring program. An estimated 750 wells are being monitored by the owners in accordance with conditions of the permits, most of which are nondischarge permits.

The DEM Groundwater Section also has implemented a program for Underground Injection Control (UIC) (U.S. Environmental Protection Agency, 1984). A UIC permit is required for wells that are to be used for injection, recharge, or disposal. Injection wells for waste disposal, other than class-V wells (for injection of heated water into the ground), are prohibited by State statute. Presently, the DEM is developing rules for the regulation of underground storage tanks.

Landfills in North Carolina are regulated by the Solid and Hazardous Waste Management Branch in the DHR, Division of Health Services, under authority of the North Carolina General

Statutes. Under a formal Memorandum of Agreement between the DHR and the NRCD, "DHR will provide NRCD with a copy of each permit application for a landfill or for a hazardous-waste facility that requires ground-water monitoring and (or) ground-water protection standards, and a copy of each application for a modification of such facilities." Hazardous-waste-facility permits are reviewed to assure compliance with State ground-water regulations.

The DHR, through its Division of Health Services, is responsible for monitoring solid-waste and hazardous-waste-disposal sites. Data collected in this monitoring program are shared with the DEM Groundwater Section under the Memorandum of Agreement.

Mining in North Carolina is regulated under the Mining Act of 1971, NCGS 74–50, which requires a permit for any mining activity. This permit program is administered by the Land Quality Section of the NRCD, Division of Land Resources; those mining permit applications involving areas where ground water may be affected are reviewed by the DEM Groundwater Section.

Under the North Carolina Coastal Area Management Act of 1974, permits are required (under NCGS 113A–118) for any development in coastal "areas of environmental concern" designated by the State. This Act is administered by the NRCD Division of Coastal Management, and any projects requiring a permit that may affect ground water are reviewed by the DEM.

The Division of Health Services of DHR is responsible for the human-health aspects of public water-supply systems, including review of plans and specifications for water-treatment and distribution facilities, approval of sources of raw water, establishment of drinking-water standards, and requirements for monitoring the quality of drinking water delivered by public systems.

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NORTH DAKOTA
Ground-Water Quality

Ground water is an important resource in North Dakota. About 62 percent of the population (fig. 1) of the State rely on ground water, and nearly all of the rural population depend on ground water for domestic supply. Ground water provides about sixty percent of the water used for public and private drinking-water systems and nearly fifty percent of the water used for agricultural purposes (Rick Nelson, North Dakota State Department of Health, written commun., 1986.)

Unconsolidated aquifers tend to provide less-mineralized water than sedimentary bedrock aquifers; however, water quality from both types of aquifers is marginal for some uses (fig. 2). Excessive dissolved-solids concentrations can limit the usability of water for drinking, irrigation, and manufacturing processes. Although dissolved-solids concentrations generally are less than 1,000 mg/L (milligrams per liter), the median concentrations in some areas exceed 1,000 mg/L. Water in unconsolidated aquifers tends to be hard to very hard. Locally, concentrations of nitrate (as nitrogen) greater than 10 mg/L have been detected. There is no current (1986) evidence to indicate that these nitrate concentrations are due to the use of agricultural chemicals.

North Dakota has 37 documented cases of ground-water quality degradation. Of those cases, about two-thirds are gasoline, diesel-fuel, fuel-oil, or lubricating oil contamination resulting from leakage or spills. Most of the degradation has been corrected by simple means, such as excavating contaminated earth materials. However, at one site about 1 million gallons of diesel fuel is floating on the water surface of an unconsolidated aquifer.

North Dakota has one site that has been evaluated under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (fig. 3). The CERCLA site, in the southeastern part of the State, has reported concentrations of arsenic in ground water greater than 50 μg/L (micrograms per liter), the primary drinking-water standard established by the U.S. Environmental Protection Agency (EPA) (1986a). The U.S. Department of Defense (DOD) has identified seven hazardous-waste sites at three facilities as having potential for ground-water contamination.

WATER QUALITY IN PRINCIPAL AQUIFERS

North Dakota has two principal types of aquifers (fig. 2*A*)—unconsolidated (glaciofluvial and glaciolacustrine deposits) and sedimentary bedrock (consolidated sedimentary rocks) (U.S. Geological Survey, 1985, p. 335). The unconsolidated aquifers generally are more productive and yield less-mineralized water than bedrock aquifers; however, the bedrock aquifers are more widespread and areally continuous. Most of the unconsolidated aquifers are located in the eastern one-half of the State. Dissolved-solids concentrations of the unconsolidated aquifers commonly are less than 1,000 mg/L. The sedimentary bedrock aquifers provide a source of water in the western one-half of the State. Although these aquifers generally are used as sources for domestic water supply and livestock watering, excessive dissolved-solids concentrations and increased salinity limit their use as a source of water for irrigation.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), sodium, and fluoride analyses of water samples collected from 1946 to 1985 from the principal aquifers in North Dakota. Percentiles of these variables, are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen). The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 250 mg/L sulfate.

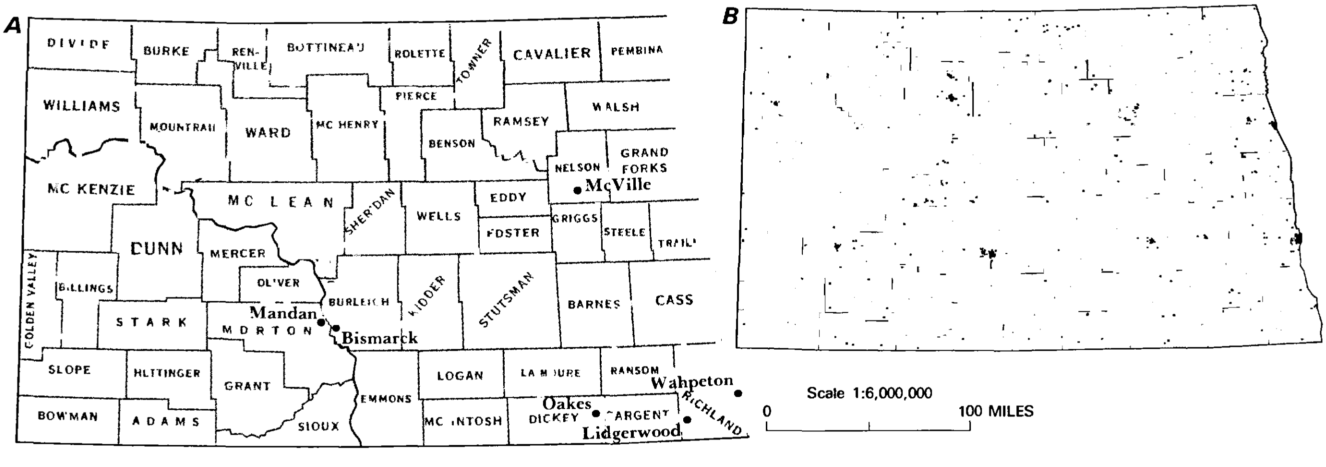

Figure 1. Selected geographic features and 1985 population distribution in North Dakota. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

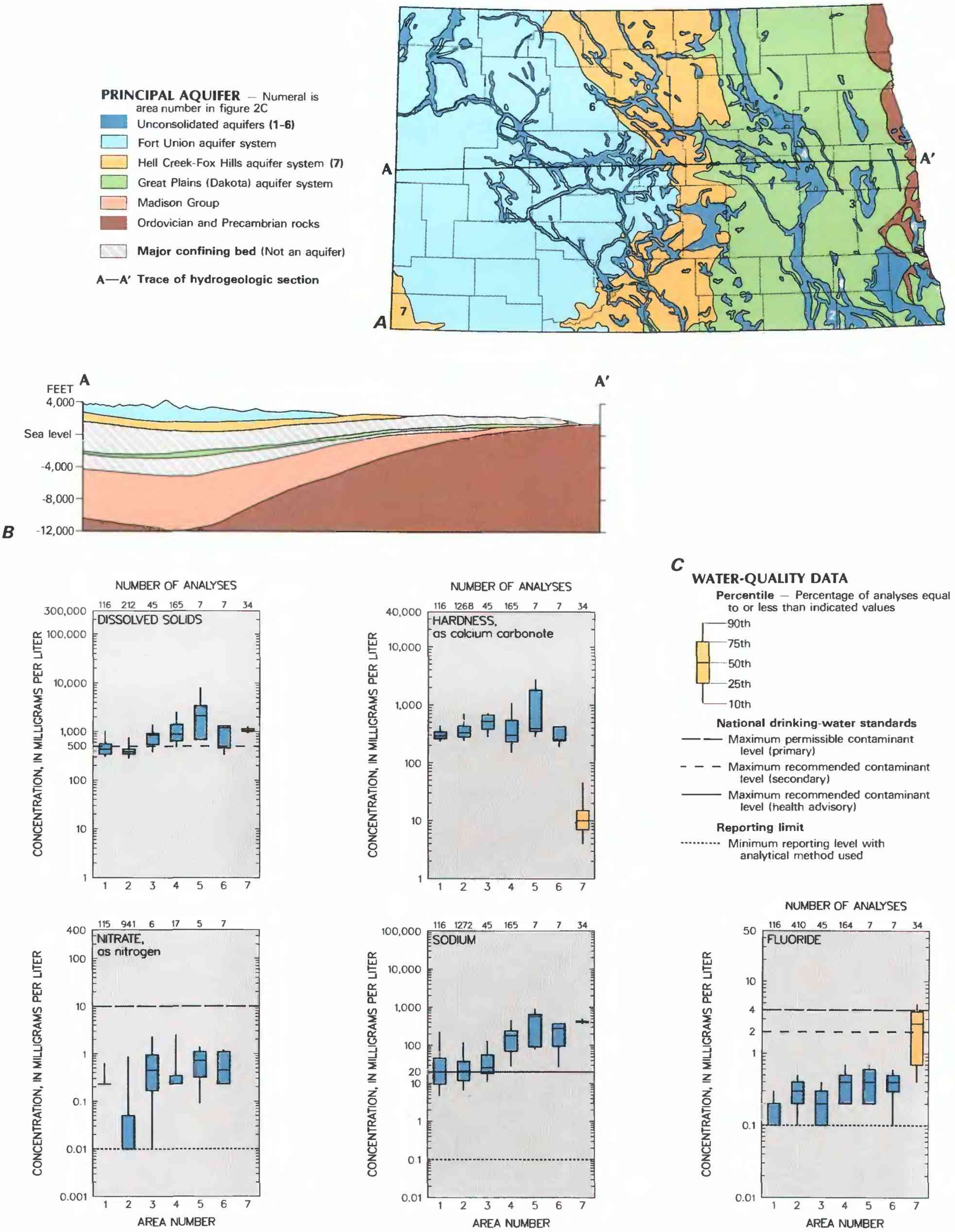

Figure 2. Principal aquifers and related water-quality data in North Dakota. *A*, Principal aquifers, *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, 1946-85. (Sources: *A*, North Dakota State Water Commission, 1982, *B*, Paulson, 1983. *C*, Analyses complied from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

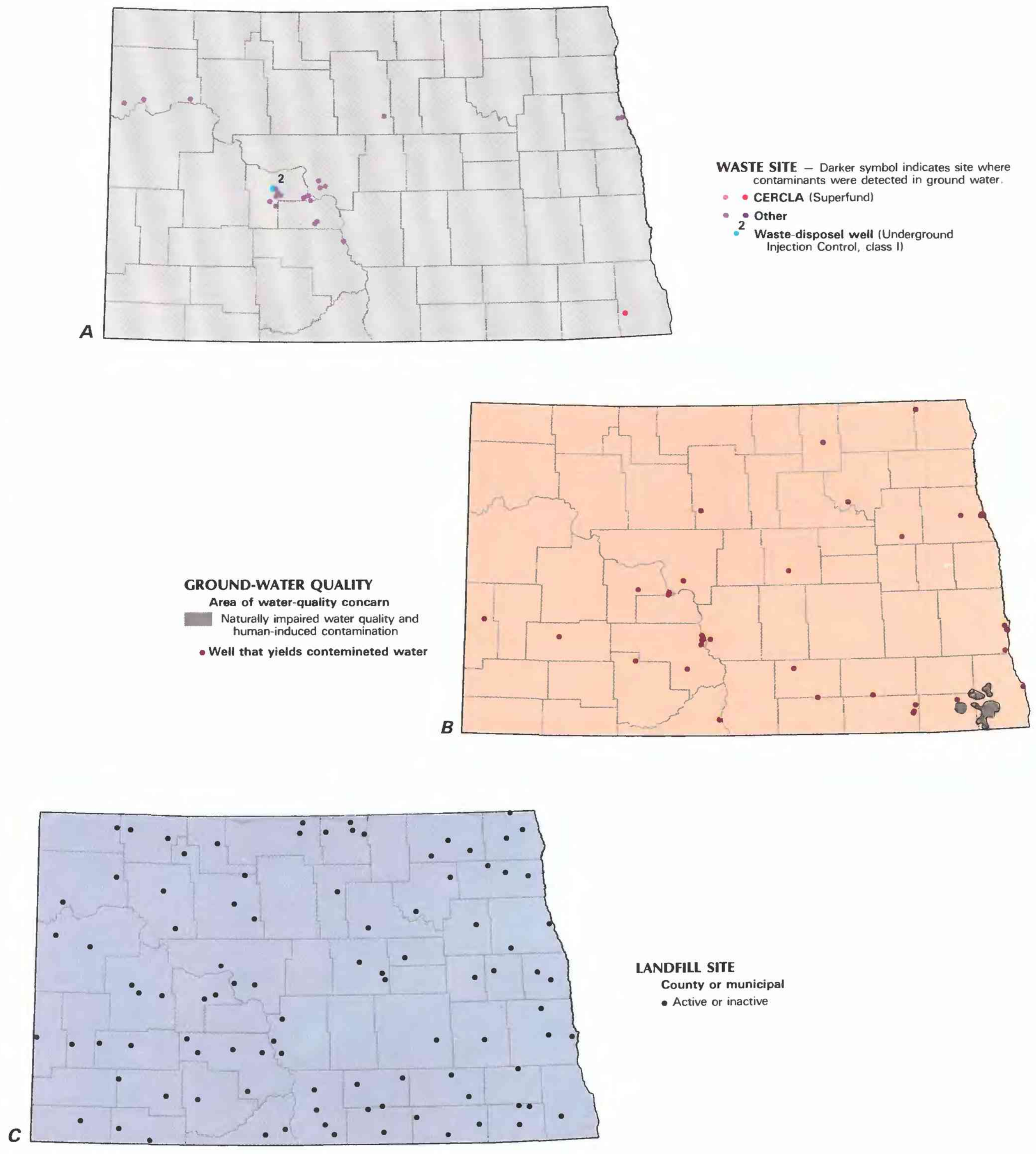

Figure 3. Selected waste sites and ground-water-quality information in North Dakota. *A* Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, *B*, and *C*, North Dakota State Department of Health, written commun., 1986.

The graphic summary is limited to six unconsolidated aquifers (fig. 2*C*, areas 1-6), and one sedimentary bedrock aquifer (fig. 2*C*, area 7). The data were interpreted without regard to sample depth. The principal uses of ground water in these areas are: areas 1-4, irrigation; area 5, public supply; area 6, public supply and industrial; and area 7, public supply.

Unconsolidated Aquifers

The degree of mineralization of water in the unconsolidated aquifers depends on the hydraulic properties of and the geochemical processes occurring in the aquifer. In general, the longer the residence time of the water in an aquifer, the greater the degree of mineralization. In many areas of North Dakota, mineralized water in confined bedrock aquifers is under sufficient hydraulic pressure to cause upward flow into unconsolidated aquifers, where it mixes with the less mineralized water.

In unconsolidated aquifers that occupy buried valleys, water at the bottom of the aquifer tends to be more mineralized than water at shallow depths. This is due to both increased residence time of the water in the aquifer and mixing.

The median dissolved-solids concentrations in areas 1 and 2 are less than 500 mg/L; in areas 3, 4, 5 and 6, the median concentrations exceed 500 mg/L. At greater than 500-mg/L concentrations, ground water is marginally acceptable for irrigation.

In general, water in the unconsolidated aquifers is very hard, with median hardness concentrations (as calcium carbonate) ranging from about 300 to 500 mg/L.

Median concentrations of nitrate (as nitrogen) in ground water from areas 1-6 are less than 1 mg/L; much less than the primary drinking-water standard of 10 mg/L. Concentrations of nitrate greater than 10 mg/L have been detected in private wells throughout the State. In most instances, the source of nitrate is not known, but septic-tank drainfields, nitrogen fertilizers, and feedlot operations are suspected.

Median concentrations of sodium in areas 1-6 range from 20 to 570 mg/L. As a component of dissolved solids, increased sodium concentrations decrease the usability of water for irrigation. Concentrations of sodium and potassium in excess of 50 mg/L, in combination with suspended matter, cause foaming, which accelerates scale formation and corrosion in boilers.

Ninetieth-percentile fluoride concentrations in water from unconsolidated aquifers, areas 1-6, are all less than 1 mg/L. Median percentiles for areas 1-6 range from 0.1 to 0.4 mg/L. At optimum concentrations, fluoride has a beneficial effect on the resistance to decay of teeth, but concentrations in excess of optimum can cause mottling of teeth.

Median sulfate concentrations (sulfate percentiles not shown in fig. 2*C*) in areas 3 and 5 exceed the secondary drinking-water standard of 250 mg/L. In areas 1, 2, 4, and 6, median sulfate concentrations range from 58 to 221 mg/L. Sulfate concentrations greater than 500 mg/L may impart a bitter taste to water and can have a laxative effect. Sulfate combines with calcium and magnesium to form scale in heating equipment.

Sedimentary Bedrock Aquifers

FORT UNION AQUIFER SYSTEM

The Fort Union aquifer system is the uppermost bedrock aquifer system. In general, these aquifers differ in horizontal extent and thickness, and therefore, are less reliable sources of water than deeper aquifers. Water in the Fort Union aquifer system is used by farms, ranches, and small communities for most purposes except irrigation (U.S. Geological Survey, 1985, p. 336).

The quality of water in this aquifer system is variable. The water generally is soft (hardness, as calcium carbonate, generally is less than 60 mg/L) and contains large concentrations of sodium and dissolved solids. Locally, water from aquifers near the top of the Fort Union aquifer system may yield hard water with smaller concentrations of sodium and dissolved solids. Naturally occurring selenium, in concentrations ranging from 50 to 600 μg/L, has been detected in water from this aquifer system. The EPA primary drinking-water standard for selenium is 10 μg/L.

Hell Creek-Fox Hills Aquifer System

The Hell Creek-Fox Hills aquifer system (fig. 2*A*, area 7) is a relatively dependable source of water, supplying many farms, ranches, and small cities in central and western North Dakota. Water in this system is generally soft; median hardness (as calcium carbonate) is 10 mg/L (fig. 2*C*, area 7). Because the median dissolved-solids concentration is 1,060 mg/L, the water generally is not used for irrigation. Sodium is the principal dissolved-solids constituent. The median sulfate concentration, 220 mg/L, does not exceed the secondary drinking-water standard of 250 mg/L; however, at least 25 percent of the water from this aquifer system exceeds this standard (not shown in fig. 2*C*). At least 50 percent of the water from this aquifer system exceeds the secondary drinking-water standards of 2 mg/L fluoride, and at least 10 percent exceeds the primary drinking-water standard of 4 mg/L. Data were insufficient to compile a statistical summary for nitrate concentrations.

Great Plains (Dakota) Aquifer System

Although the Great Plains (Dakota) aquifer system underlies most of the State, most of the wells completed in this aquifer system are in the southeastern part of the State. The primary use of the water in this area is for watering livestock. In the western part of the State, the water is moderately saline, with an average dissolved-solids concentration of 7,300 mg/L. Because of the salinity of the water in this area, the only use is in oil-field operations (U.S. Geological Survey, 1985, p. 338).

Madison Group Aquifer

Water in the Madison Group aquifer generally is the most mineralized ground water in the State. Dissolved-solids concentrations generally are greater than 10,000 mg/L. In deeper parts of the aquifer, in western North Dakota, dissolved-solids concentrations are greater than 200,000 mg/L. The Madison Group aquifer is not developed in North Dakota.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water contamination in North Dakota is relatively minor. North Dakota is primarily an agricultural State and has not experienced the degradation of ground-water quality usually associated with industrial development. Most of the problems with ground-water quality in the State are due to naturally occurring, excessive concentrations of dissolved solids and hardness. Although ground water in North Dakota generally is of marginal quality for many uses, it is used because there are no other available sources of water.

Waste Disposal

As of September 1985, seven hazardous-waste sites at three facilities in North Dakota had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under the CERCLA of 1980. The U.S. Environmental Protection Agency (1986c) presently ranks these sites under a hazard-ranking system and may include them in the National Priorities List (NPL). There are no Resource Conservation and Recovery Act (RCRA) sites, one CERCLA site, and two Underground Injection Control (UIC) Program sites (U.S. Environmental Protection Agency, 1984) in the State (fig. 3*A*).

Landfills are the most commonly used disposal method for nonhazardous waste in North Dakota. Nonhazardous-waste-disposal sites are classified as either sanitary landfills (fig. 3*C*) or special-use disposal sites (identified as "other" in fig. 3*A*). Special-use disposal sites are used for containment of fly-ash residue, flue-gas desulfurization wastes, oil-field drilling muds, industrial wastes, lime sludge, and construction/demolition wastes.

Fly-ash residue and flue-gas desulfurization wastes from lignite-fired electricity generating plants generally contain large concentrations of dissolved solids, arsenic, molybdenum and, selenium. An increase in dissolved-solids concentration in ground-water has been detected at five special-use disposal sites containing these wastes. Water at these sites is being monitored to determine the effect on local ground-water quality and to define a course of remedial action.

Although no sanitary landfills have been identified as sources of contamination of ground water, 24 have been identified as geologically unacceptable by the North Dakota State Department of Health, Division of Hazardous Waste Management and Special Studies (written commun., 1986). Criteria defined as unacceptable includes construction of landfills in very permeable material, or the presence of shallow ground-water levels close to the base of the landfill.

The 37 sites where ground-water contamination has been detected are shown in figure 3*B*. Dissolved-solids concentrations in ground water have increased at seven additional sites. The increases have been attributed to disposal of fly-ash residue and seepage from storage lagoons. Arsenic and saltwater have contaminated ground water at two other sites. Most of the sites where ground water has been contaminated have been identified in the last five years.

Agriculture

North Dakota has about 40 million acres of land that are used for farming and ranching; therefore, the effects of agricultural chemicals on ground-water quality is a major concern. The North Dakota State Department of Health (NDSDH), Division of Water Supply and Pollution Control, recently analyzed 218 samples of water from private and municipal wells for a suite of synthetic organic chemicals. At 14 sites, ground water was found to contain trace concentrations of pesticides, however, none of the concentrations were large enough to pose a health hazard. The most commonly detected chemical was picloram.

Nitrate (as nitrogen) concentrations in excess of 10 mg/L were detected in water from 22 private, irrigation, and observation wells south of the town of Oakes. Nitrate contamination of ground water has been detected at many feedlots, corrals, and farmsteads.

Arsenic was detected in ground water in excess of 50 μg/L in four areas in Ransom, Sargent, and Richland Counties, in the southeastern part of the State (fig. 3*B*). These areas, near the town of Lidgerwood, total about 170 square miles. The sources of arsenic are considered to be from natural leaching from earth materials and from the application of arsenic-laced grasshopper bait used in the area through 1947. The arsenic contamination was examined during a CERCLA ("Superfund") remedial investigation (Roberts and others, 1985).

Hydrocarbon Contamination

Most incidents of ground-water contamination in North Dakota are from hydrocarbon leaks and spills. Gasoline, diesel fuel, fuel oil, or lubricating oil are the most common hydrocarbons detected in contaminated areas. Most spills and leaks are minor and require minimal remedial action. There are, however, five restoration projects to remove hydrocarbons from ground water in North Dakota. The largest of these is at the city of Mandan, where about 1 million gallons of diesel fuel is floating on the surface of the shallow aquifer (North Dakota State Department of Health, written commun., 1986).

Wastewater Impoundments

Wastewater impoundments are the most widely used method for wastewater treatment and storage in North Dakota because of inexpensive operating costs and availability of land. Water from a public-supply well at the city of Wahpeton had an increase in dissolved-solids concentrations due to seepage from a wastewater lagoon, but the ground-water quality was restored by installing and operating two contaminant recovery wells (North Dakota State Department of Health, written commun., 1986). Seepage from a city lagoon at the town of McVille has increased concentrations of dissolved solids, chloride, and ammonium in the underlying shallow aquifer. A ground-water investigation is being conducted at McVille to determine the extent of effects on the ground-water quality of the shallow aquifer. Permitting, monitoring, and research by State agencies at several wastewater-impoundment sites has minimized the effects of seepage from municipal, industrial, agricultural, and mining impoundments on ground-water quality.

POTENTIAL FOR WATER-QUALITY CHANGES

Areas of contaminated ground water in North Dakota are limited in extent and degree of degradation. In large part, this is due to the limited industrialization within the State. Because North Dakota is primarily an agricultural state, the potential effect of agricultural chemicals on ground-water quality is a major concern. Large concentrations of nitrate in ground water in the State may be caused by both natural sources and the use of fertilizers. Other agricultural chemicals have not been determined to have degraded ground-water quality, but further monitoring within the State will better define their effects on ground-water quality.

Oil-and-gas development and mining are other activities that may degrade ground-water quality. Potential effects of oil-and-gas development on ground-water quality come from possible blowouts of wells, leaching and seepage from reserve pits, and contamination from underground injection wells. Evaporation ponds are not used for the disposal of brines associated with oil and gas development in North Dakota. Current mining operations are under evaluation to determine the extent to which they have affected local ground-water quality. Existing mining operations are in sparsely populated areas of the State and changes in ground-water quality that may occur probably will be localized.

Subsurface disposal of domestic waste in septic-tank and other onsite-treatment systems has not been identified as a problem in North Dakota. However, the increased abundance and use of household chemicals may cause degradation of ground water near improperly designed or installed systems.

GROUND-WATER-QUALITY MANAGEMENT

North Dakota ground-water-quality protection programs are primarily source oriented. Their implementation is designed to prevent ground-water contamination by controlling potential sources of contamination. This control is accomplished by maintaining contaminant-source permit programs, defining effluent limitations, setting minimum performance and design standards, and encouraging use of best-management practices. Implementing ground-water protection programs in North Dakota is a task shared by several State agencies with their own legislative authority and rules governing various aspects of ground-water protection and use. These agencies and their respective activities are:

North Dakota State Department of Health (NDSDH)—Overall ground-water protection responsibilities.

North Dakota State Water Commission (NDSWC)—Water allocation and ground-water monitoring and mapping.

North Dakota State Industrial Commission, Oil and Gas Division (OG)—Ground-water protection associated with oil and gas development.

North Dakota Geological Survey (NDGS)—Ground-water protection from mineral and geothermal exploration and development.

North Dakota State Public Service Commission (NDPSC)—Ground-water protection and monitoring associated with coal-mine development and reclamation.

Chapter 61–28 of the North Dakota Century Code establishes the NDSDH as the primary State agency responsible for the protection of water in the State. This chapter directs the NDSDH to develop comprehensive programs for the prevention, control, and decrease of polluted water and establishes the State policy to protect, maintain, and improve the quality of water for continued use as public and private water supplies for domestic, agricultural, industrial, recreational, and other legitimate beneficial uses.

The NDSDH administers most of the Federal water-quality legislation, including the Safe Drinking Water Act (SDWA), RCRA, CERCLA, and the Clean Water Act.

The SDWA includes the Drinking Water Program and the UIC program, for which the State has complete primacy, and the Sole Source Aquifer Program, which is administered on the Federal level by the EPA. The NDSDH, Division of Water Supply and Pollution Control (WSPC) administers the Drinking Water Program. This includes monitoring water quality and inspecting 333 community and 373 noncommunity water-supply systems throughout the State. The UIC program is a multiagency program. The WSPC administers the Federal grant and regulates municipal and industrial injection wells. The OG controls oil- and gas-injection wells, and the NDGS controls solution-mining injection wells. An application for a sole-source designation of the New Rockford unconsolidated aquifer in southwestern Eddy County has been submitted to the EPA. The WSPC and SWC currently are involved in a vulnerability study of the aquifer to assist the EPA in making a decision on the application.

The RCRA program is administered through the NDSDH, Division of Hazardous Waste Management and Special Studies (HWMSS). The RCRA program includes the Hazardous Waste Management Program, the PCB Inspection Program, and the Underground Storage Tank Program. The HWMSS also is responsible for issuing permits for all nonhazardous-solid-waste facilities. There are no permitted hazardous-waste facilities in North Dakota.

The CERCLA is administered by the EPA, through agreements with both the WSPC and HWMSS, to conduct and assist in preliminary site assessments, site inspections, remedial investigations, and feasibility studies. A remedial investigation and feasibility study has been completed on a large site where arsenic-contaminated ground water has been detected near Lidgerwood.

The NDSDH currently has a nondegradation policy and uses an aquifer-classification process based on the UIC program. Aquifers with water having dissolved-solids concentrations less than 10,000 mg/L are identified as Class-I aquifers and are fully protected. Aquifers with water having dissolved-solids concentrations greater than 10,000 mg/L are identified as Class-II aquifers and are given limited protection. In administering the nondegradation policy, the NDSDH has the discretion to consider certain social and economic factors in the decision-making process. Therefore, many ground-water-quality issues are considered on a case-by-case basis.

The NDSDH, NDSWC, NDPSC, and the U.S. Geological Survey all collect and compile ground-water-quality data in North Dakota. Examination of these data has identified sites that may need remedial action and ground-water cleanup. Through monitoring of organic substances in about 200 wells in North Dakota, the NDSDH has detected trace concentrations of several pesticides. The NDSDH plans to concentrate this monitoring program on the most vulnerable areas of the State during the next year.

An initial inventory of ground-water resources of the State has recently been accomplished by a long-standing cooperative program between the NDSWC and the U.S. Geological Survey. During a 25-year period, the geology and ground-water resources of all 53 counties in the State were evaluated. The information resulting from this program is the data base for the State ground-water protection programs.

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OHIO
Ground-Water Quality

In 1980, about 42 percent of Ohio's population of 11 million people (fig. 1) depended on ground water. About 740 Mgal/d (million gallons per day) of ground water for domestic, industrial, and agricultural use (Eberle and McClure, 1984) is withdrawn from more than 550 public supplies and nearly 1 million individual wells. About 2.8 million persons in Ohio are supplied by public ground-water systems, and 1.7 million persons are supplied by private ground-water systems (Joyce A. McClure, U.S. Geological Survey, oral commun., 1986). Ground water is the only practical source of water for many people in Ohio (Palmstrom, 1984).

Most ground water in Ohio has not been significantly contaminated and meets U.S. Environmental Protection Agency (EPA) primary and secondary drinking-water standards without treatment. Median concentrations of dissolved solids, hardness, nitrate (as nitrogen), chloride, and sulfate in water from 146 public-supply well fields and 20 individual wells indicate that ground water is generally suitable for human consumption and most other uses (fig. 2*C*). According to Palmstrom (1984), "ground-water contamination problems are generally of limited extent and involve no more than one or two wells close to a pollution source." The leading sources of ground-water contamination are onsite sewage systems (primarily septic tanks). From 1974 through 1985, the Ohio Department of Health (ODH) analyzed 217,185 samples from public wells and 177,366 samples from private wells to determine if water was contaminated by bacteria. Some of the wells were sampled more than once during that period. About 8 percent of the water samples from public wells and about 28 percent of the water samples from private wells were contaminated with coliform bacteria. In addition to septic-tank leach fields, other leading sources of contamination are hydrocarbon leaks and spills, pesticide application around the home, and oil and gas drilling (Palmstrom, 1984). Abandoned and active waste-disposal sites are potential sources for contamination and are most numerous in urban areas.

Changes in ground-water quality have not been well documented in Ohio. Although a large number of chemical analyses exist, consistent, long-term water-quality data at any given site are not available. Many analyses before the mid-1970's lack the quality control and quality assurance required for accurate appraisals. Many of the analyses are stored in paper-copy files in 88 county health department offices.

A study of glacial-outwash (sand and gravel) aquifers along the Great Miami River in southwestern Ohio (fig. 2*A*) indicates that some degradation may have occurred in parts of these aquifers (Evans, 1977). Analyses of water samples from a few of the wells in this area indicated significant increased concentrations of common constituents, such as calcium, magnesium, sulfate, and chloride. The increases occurred between the late 1950's and 1976 and probably are related to the effects of urbanization and industrial activities.

Surface mining of coal causes localized degradation of ground water in parts of eastern Ohio. For example, a study by Hren (1986) indicates that surface mining of coal caused significantly increased concentrations of dissolved solids, manganese, sulfate, and chloride in ground water in a mining area in Jefferson County. The increases occurred between 1980 (before mining started) and 1984 (about 3 years after mining stopped).

There are 771 known sites in Ohio where municipal and (or) industrial waste is being or has been disposed of (fig. 3). Ground-water contamination has been confirmed at 27 of the sites.

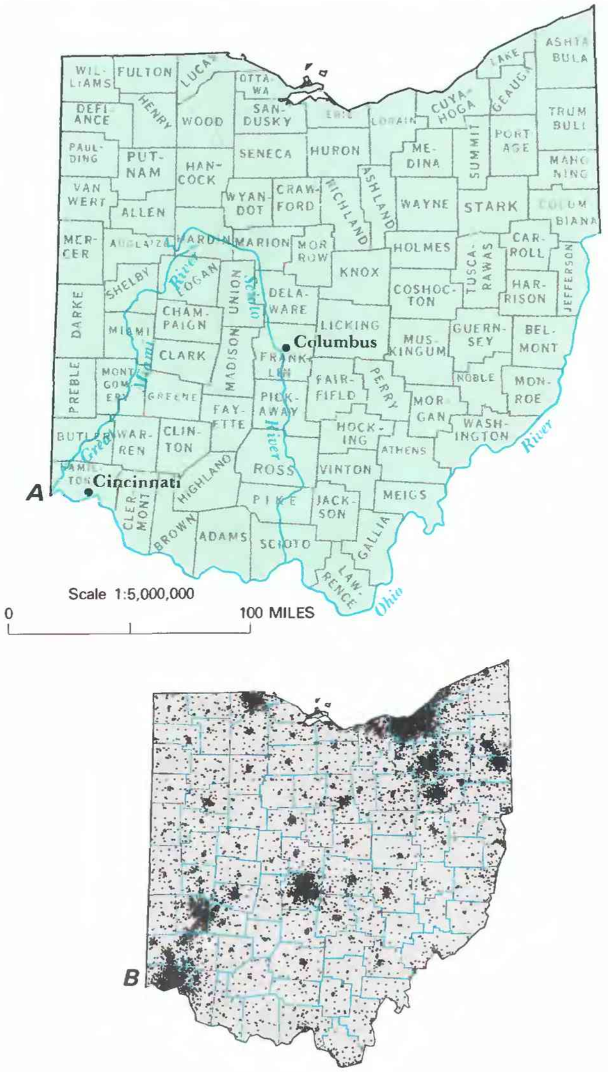

Figure 1. Selected geographic features and 1985 population distribution in Ohio. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Ohio has seven principal aquifers (fig. 2*A*). The two types of unconsolidated aquifers (coarse-grained and fine-grained) are considered together as sand-and-gravel aquifers in this report. The four most productive aquifers are the unconsolidated sand and gravel aquifers, and the consolidated shaly sandstone and shale aquifers, sandstone, and carbonate. The consolidated shale and shaly carbonate aquifers, although very important for domestic supplies, are not productive enough for commercial or public supplies. Ohio has no ground-water-quality sampling network for the shale and shaly carbonate aquifers, and their water quality is not discussed in this report.

BACKGROUND WATER QUALITY

The primary sources of background ground-water-quality data in Ohio are public-water-supply analyses by the Ohio Environmental Protection Agency (OEPA). Most of the OEPA analyses used for this report were from samples collected during the late 1960's through the late 1970's. Public ground-water supplies typically are derived from a well field rather than a single well. Commonly samples were collected from a manifold containing untreated water from several pumped wells, particularly for larger public supplies. Each set of water-quality analyses from a municipal well field consisted of analytical results from 2 to 10 water samples taken at different times. About 20 of the 166 sets of water-quality analyses used to describe background water quality were taken from a report of ground-water quality in southeastern Ohio (Razem and Sedam, 1985). Those analyses were based on single samples collected during 1983 commonly from individual domestic wells.

A graphic summary of selected water-quality variables is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), chloride, and sulfate analyses of water samples collected from 1965 to 1983 from four of the principal aquifers in Ohio. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supplies as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a max-

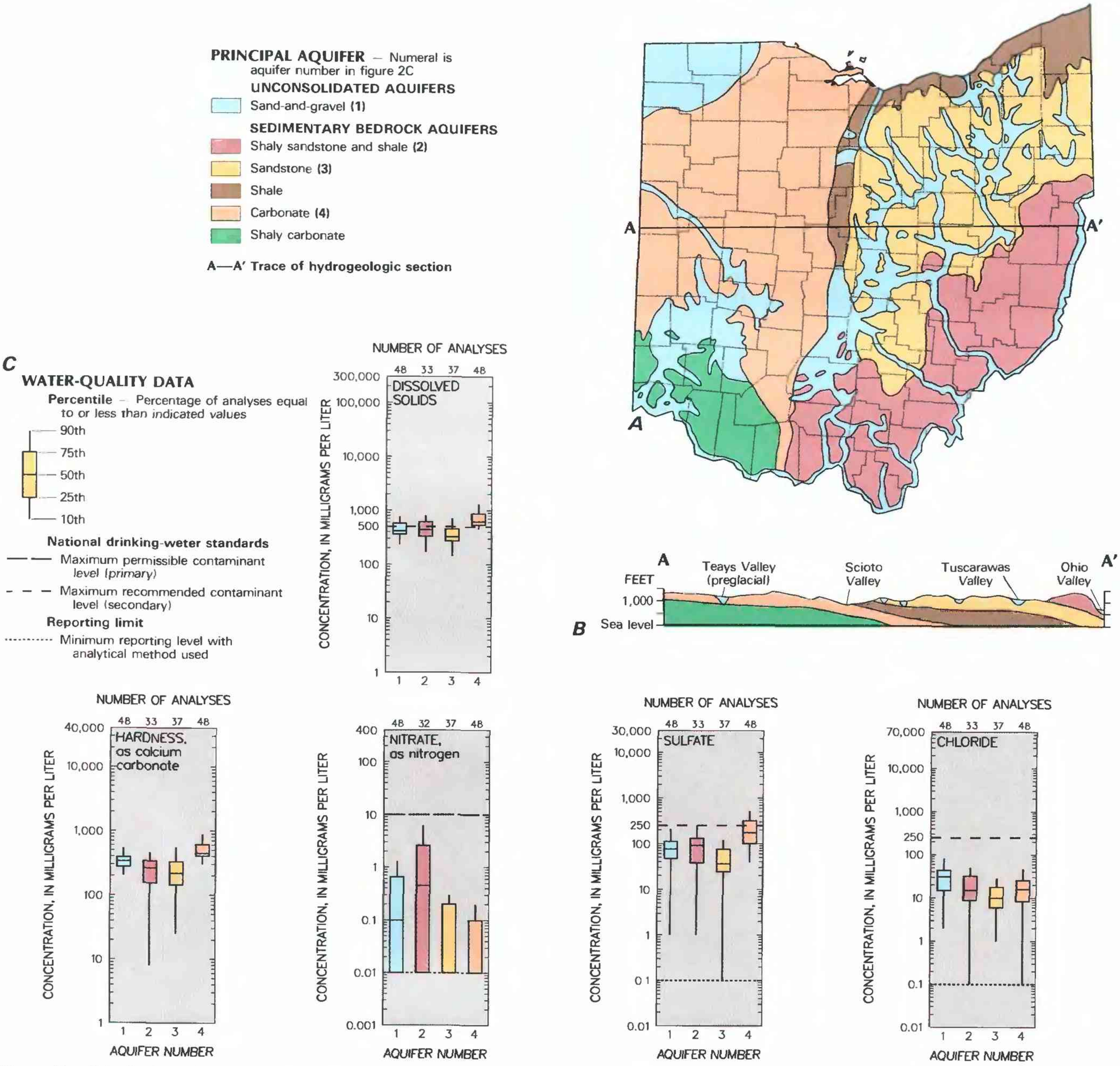

Figure 2. Principal aquifers and related water-quality data in Ohio. *A*, Principal aquifers; *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituent and properties, as of 1983. (Sources: *A*, Ohio Department of Natural Resources, Division of Water files. *B*, Ohio Department of Natural Resources, Division of Geological Survey files. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

imum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 250 mg/L sulfate.

In much of Ohio, ground water is a calcium-bicarbonate type (Stein, 1974). In southeastern Ohio, many aquifers are shallow and are associated with coal deposits. The water from those aquifers is a calcium-magnesium-bicarbonate type. Most ground water in Ohio is very hard. Median hardness (as calcium carbonate) ranges from 216 mg/L in the sandstone aquifers to 447 mg/L in the carbonate aquifers.

Sand and Gravel Aquifers

The sand and gravel aquifers (aquifer 1, fig. 2*C*) are located along many of the major streams of the State (fig. 2*A*). Median concentrations of selected constituents in water from the sand and gravel aquifers are: 413 mg/L dissolved solids; 337 mg/L hardness (as calcium carbonate); 0.10 mg/L nitrate (as nitrogen); 31 mg/L chloride; and 76 mg/L sulfate (fig. 2*C*). Iron concentrations are as large as 560 µg/L (micrograms per liter) in a few locations within the Great Miami River valley (Evans, 1977) and the Scioto River valley (de Roche and Razem, 1981).

Most major ground-water withdrawals in Ohio are from sand and gravel aquifers (U.S. Geological Survey, 1985, p. 341). The sand and gravel aquifers have the largest yields, 25 to 500 gal/min (gallons per minute) and many of Ohio's urban areas are located close to major streams, which are associated with the large sand and gravel aquifers. None of the sand and gravel aquifers from which major withdrawals are made are known to be contaminated to any significant extent.

The most extensively developed sand and gravel aquifers in Ohio are in the Great Miami River valley. The largest concentrations of population (fig. 1*B*) and industry in the Great Miami River valley are in Montgomery, Butler, and Hamilton Counties, where approximately 16 percent of Ohio's population resides. Although part of Cincinnati's public water supply comes from the Ohio River, most of the people and industry of the three-county area obtain their water from sand and gravel aquifers.

Other extensively developed sand and gravel aquifers are present in the State. Sand and gravel aquifers in Stark County are used in conjunction with the sandstone aquifers for public and industrial supplies (U.S. Geological Survey, 1985, p. 345).

Shaly Sandstone Shale Aquifers

The shaly sandstone and shale aquifers (aquifer 2, fig. 2*C*) are located in southeastern Ohio (fig. 2*A*). Median concentrations of selected constituents in water from the shaly sandstone and shale aquifers are: 435 mg/L dissolved solids; 263 mg/L hardness (as calcium carbonate); 0.45 mg/L nitrate (as nitrogen); 15 mg/L chloride; and 91 mg/L sulfate .

Most of the ground water from the shaly sandstone and shale aquifers is a calcium-magnesium-bicarbonate type, but a sodium-bicarbonate type is also common (Razem and Sedam, 1985). The water quality of the shaly sandstone and shale aquifers is similar to the water quality of the sandstone aquifers except that the shaly sandstone and shale aquifers have larger nitrate and sodium concentrations.

Concentrations of nitrate from the shaly sandstone and shale aquifers are significantly larger than those from the other major productive aquifers in Ohio. The median concentration of nitrate

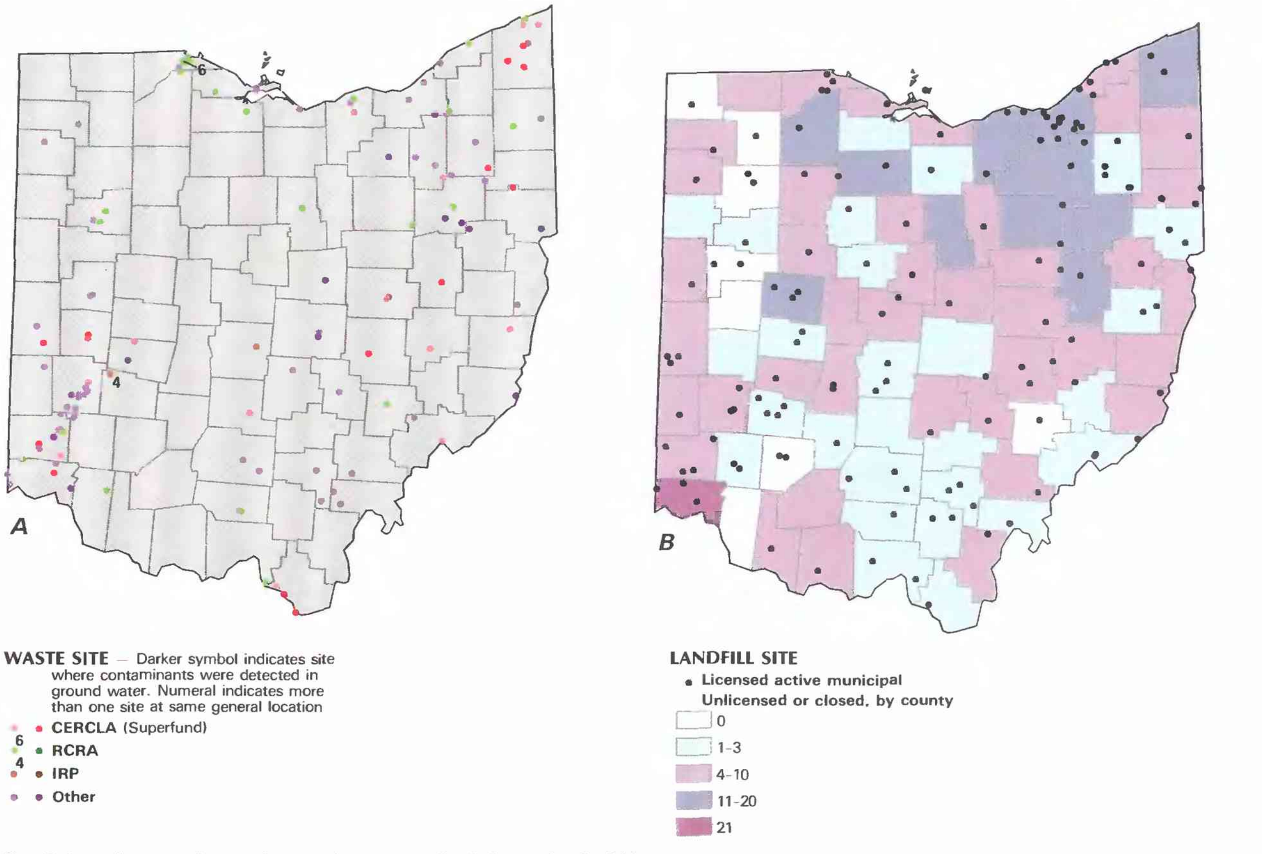

Figure 3. Selected waste sites and ground-water-quality information in Ohio. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Licensed, unlicensed, and closed municipal landfills, as of 1986. (Sources: *A*, Ohio Environmental Protection Agency files; U.S. Department of Defense, 1986. *B*, Ohio Environmental Protection Agency files.)

(as nitrogen) is 0.45 mg/L for the shaly sandstone and shale aquifers, 0 1 mg/L for the sand and gravel aquifers, and less than or equal to the detection limit for the sandstone and the carbonate aquifers. Twenty of the 32 analyses for the shaly sandstone and shale aquifers were from rural domestic wells sampled in a study of ground-water quality in southeastern Ohio (Razem and Sedam, 1985); most rural landowners in this area have onsite sewage disposal, are engaged in livestock production, and use agricultural fertilizers.

The shaly sandstone and shale aquifers have the smallest yield (1 to 5 gal/min) of the productive aquifers in Ohio (U.S. Geological Survey, 1985, p. 342). Well yields are so small in some areas that domestic ground-water supplies are supplemented with cisterns. Even though the aquifer yields are small, the shaly sandstone and shale aquifers are very important to southeastern Ohio because they offer the only practical water supply to many people of that area.

Sandstone Aquifers

The sandstone aquifers (aquifer 3, fig. 2*C*) are located in east-central and northeastern Ohio (fig. 2*A*). Median concentrations of selected constituents in water from the sandstone aquifers are: 322 mg/L dissolved solids; 216 mg/L hardness (as calcium carbonate); 10 mg/L chloride; and 36 mg/L sulfate. The median concentration of nitrate (as nitrogen) was less than the detection limit. The median concentrations of dissolved solids, hardness, chloride, and sulfate are smaller for the sandstone aquifers than for the other three major productive aquifers in Ohio. The sandstone aquifers of northeastern Ohio generally contain saline water below 300 feet. Many of the major ground-water withdrawals in northeastern Ohio involve both sandstone and sand and gravel aquifers (U.S. Geological Survey, 1985, p. 345).

The population and industry of northeastern Ohio, except for those close to Lake Erie, are very dependent on the sandstone aquifers for water supplies. Suburban and rural populations also depend on the sandstone aquifers for their domestic and agricultural supplies. In many rural areas, the sandstone aquifers are the only practical source of supply.

Carbonate Aquifers

The carbonate aquifers (aquifer 4, fig. 2*C*) are located in west-central and northwestern Ohio except for extreme northwestern Ohio, where sand and gravel aquifers are present (fig. 2*A*). Median concentrations of selected constituents in water from the carbonate aquifers are: 617 mg/L dissolved solids; 447 mg/L hardness (as calcium carbonate); 16 mg/L chloride; and sulfate, 176 mg/L. The median concentration of nitrate (as nitrogen) was less than or equal to the detection limit. The median concentrations of dissolved solids, hardness, and sulfate are larger for the carbonate aquifers than for the other three major aquifers.

The quality of water from carbonate aquifers is more variable than that of the other three major aquifers (Norris, 1974). Norris found that ground water becomes progressively more mineralized as it moves down the potentiometric gradient. Concentrations of all major ions except bicarbonate increase in the direction of ground-water flow. The water is a calcium bicarbonate type in the areas of regional recharge and a calcium sulfate type in principal discharge areas. Bicarbonate exceeds 80 percent of the total anions in the recharge areas but decreased to less than 40 percent of the total anions in the discharge areas. Data collected during an earlier study (Norris and Fidler, 1973) show that calcium concentrations in the carbonate aquifers averaged 88 mg/L for five wells in regional recharge areas and 323 mg/L for five wells in regional discharge areas; dissolved-solids concentrations averaged 435 mg/L in the recharge area and 1,826 mg/L in the discharge area; chloride concentrations averaged 5 mg/L in the recharge area and 28 mg/L in the discharge area; and sulfate concentrations averaged 69 mg/L in the recharge area and 981 mg/L in the discharge area.

Several population centers and a large rural area depend on the carbonate aquifers for their water supply. Most industrial, agricultural, and domestic supplies in west-central and northwestern Ohio come from the carbonate aquifers, and they are the only practical source of water for many persons in the area.

EFFECTS OF LAND USE ON WATER QUALITY

Ohio has an economy supported predominantly by service industries, manufacturing, and agriculture. Throughout eastern and northwestern Ohio, oil and gas are produced, and coal is mined in eastern Ohio. All of these land uses can lead to contamination of ground water.

Waste-Disposal Sites

There are 27 Resource Conservation and Recovery Act (RCRA) sites 27 Comprehensive Environmental Response Compensation and Liability Act (CERCLA) sites, sites, and 5 Installation Restoration Program (IRP) sites in Ohio (fig. 3*A*). Ground-water quality is being monitored systematically at the CERCLA and RCRA sites. In addition, Ohio has 69 licensed landfills that accept industrial as well as municipal waste; these landfills are referred to as "other" sites in figure 3*A*. Ground-water contamination has been confirmed at 13 of the CERCLA sites and at 14 of the "other" sites (fig. 3*A*). There is no known ground-water contamination at 14 CERCLA sites, at any of the 27 RCRA sites, and at 55 of the "other" sites.

As of September 1985, 28 hazardous-waste sites at 5 facilities in Ohio had been identified by the DOD as part of their IRP as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under the CERCLA of 1980. The EPA presently ranks these sites under a hazard ranking system and may include them in the National Priorities List (NPL). Five sites at two facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Ohio also has 140 licensed landfills that receive only municipal waste (fig. 3*B*). Some of the predominantly rural counties have no licensed landfills, whereas some of the densely populated or industrialized counties have several. None of the landfills is known to have contaminated local ground water; however, the quality of ground water near licensed landfills is not monitored routinely.

The concentration of urban areas and industry along the sand and gravel aquifers has resulted in an increased number of waste-disposal sites near those aquifers, particularly in southwestern Ohio (figs. 2*A*, 3*A*, and 3*B*). Most of the CERCLA and RCRA sites in Ohio are within or close to major urban areas. Chloride concentrations are elevated (25 percent are more than 43 mg/L) in some urban areas. There are numerous waste-disposal sites in the area of the sandstone aquifers in northeastern Ohio (figs. 2*A*), some of which may have caused ground-water contamination of limited extent. Many of the waste-disposal sites are near population centers (fig. 1*B*). The area of the carbonate aquifers in west-central and northwestern Ohio is primarily rural and tends to have fewer waste-disposal sites than the other productive aquifer areas of the State (fig. 3*A*). The area of the shaly sandstone and shale aquifer has fewer CERCLA and RCRA sites, but a similar number of licensed landfills, compared with the areas of the other major productive aquifers. There are 503 unlicensed or closed landfills in Ohio that have not been classified as CERCLA and RCRA, or "other" sites; the distribution of these landfill sites in each county is also shown in figure 3*B*. None of these sites is known to have caused contamination of ground water

In summary, there are 771 known sites in Ohio where municipal and (or) industrial waste is being or has been disposed of. About 500 of those sites are unlicensed or closed. Ground-water contamination has been confirmed at 27 of the sites.

Oil and Gas Production

Brines associated with oil and gas production can contaminate ground water during drilling operations or by improper handling or disposal of the brines. The ODNR Division of Oil and Gas has records of 62 private wells that yielded water with concentrations of chloride greater than 250 mg/L from March 1984 through July 1986.

Domestic Sources

Bacterial contamination affects the water from more wells for which records are available than any other form of contamination in Ohio. Most bacterial contamination of ground water is from onsite sewage systems (Palmstrom, 1984). The Ohio Department of Health (ODH) has compiled a list of water samples that were analyzed for bacterial contamination (total coliform). About 8 percent of the samples from public-supply wells and about 28 percent of the samples from private wells were contaminated by bacteria. The ODH compilation shows that 18,123 ground-water samples collected from 1974 through 1985 from public water supplies were bacterially contaminated, 1 colony per 100 mL (milliliters) (Ohio Environmental Protection Agency, 1980), and that 49,970 samples from private wells were bacterially contaminated (3 colonies per 100 mL; Ohio Environmental Protection Agency, 1981). A summary of the ODH bacterial sample analyses is shown in figure 4 for each of the five districts that ODH and the Ohio Environmental Protection Agency (OEPA) have established to administer their programs.

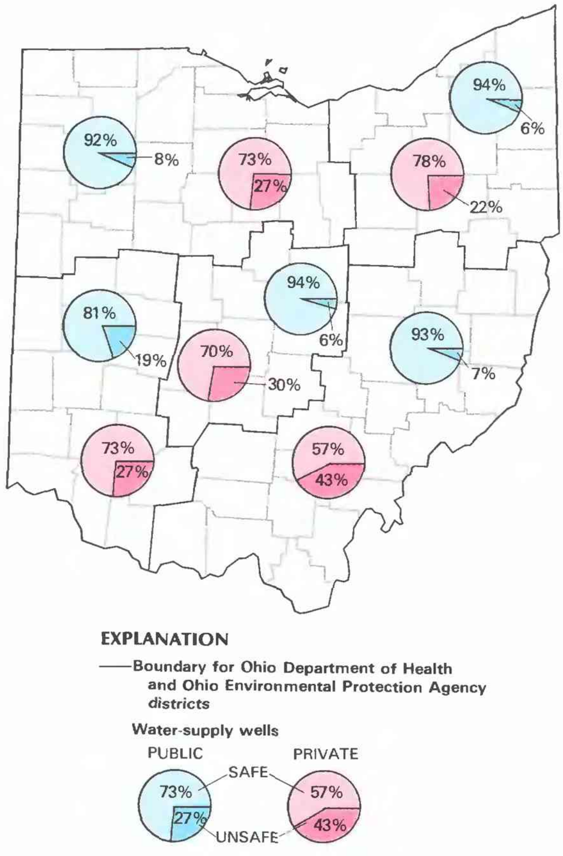

Figure 4. Categories of water-supply wells, based on total coliform bacteria analyses from 1974 to 1985. (Source: Compiled by R.I. Lane from Ohio Department of Health annual reports.)

Onsite sewage systems are the source of bacterial contamination in some areas of Ohio. In a residential division in Wood County, for example, the carbonate aquifers are generally less than 40 inches below the land surface, and each home is served by a domestic well and its own sewage system (Ohio Department of Health, 1982). Each of 10 wells sampled in this subdivision showed contamination from domestic sewage. Three of the 10 wells had coliform or nitrate (as nitrogen) concentrations that exceeded primary drinking-water standards (1 colony per 100 milliliters and 10 mg/L, respectively).

Mining

Coal has been mined extensively throughout most of eastern and southeastern Ohio during this century, but it is difficult to determine how many freshwater aquifers may have been contaminated from the mining of coal and how many persons may have been affected because ground-water quality has not been monitored regionally in Ohio except at some waste-disposal sites and for public water supplies. Water from some observation wells sampled by the U.S. Geological Survey in coal mining areas of southeastern Ohio was contaminated (Hren, 1986; Razem, 1983). However, no water-supply wells have been sampled, so that no public or private water supplies are known to be directly affected.

POTENTIAL FOR WATER-QUALITY CHANGES

Most of the sand and gravel aquifers in Ohio are along the major streams and near major urban areas where the probability of toxic spills and mismanagement of waste materials is greater than in sparsely populated areas. These aquifers are very susceptible to contamination because they are recharged close to or at land surface, with only limited travel distance and limited adsorption of any contaminants in soils through which the recharge water percolates. Thus, the proximity of the sand and gravel aquifers to the land surface in areas where population densities are greatest affords the greatest chance of contamination. Some instances of increased specific conductance and concentrations of calcium, magnesium, chlorides, and sulfates in urbanized parts of the Great Miami River valley have been reported (Evans, 1977).

The mining of coal could affect additional areas of the shaly sandstone and shale aquifers and the southern part of the sandstone-aquifer area. Many of the domestic wells in eastern Ohio where coal is mined, particularly those in the shaly sandstone and shale aquifers, are somewhat shallow (50- to 100-foot depth) and yield less than 5 gal/min (Razem and Sedam, 1985). Many of these aquifers also have limited geographic extent. The surface mining of coal has been shown to affect the quality of ground water, but its effects have not been well documented in Ohio.

Oil and gas production could affect the sandstone aquifers of northeastern Ohio. Enforcement of brine-disposal regulations is difficult. As an example, a brine-disposal well in Geauga County accidentally discharged brine at land surface when the injection pressure within the well exceeded the recharge capacity of the formation (Jeffrey T. de Roche, U.S. Geological Survey, oral commun., 1986). This accident caused contamination of nearby wells.

A few suburban communities are mandating residential use of public sewage systems rather than private septic tanks while continuing to use private residential wells for water supply. The ground water affected by bacterial contamination in those communities may decrease in the future.

GROUND-WATER-QUALITY MANAGEMENT

The protection of Ohio's ground water has emerged as one of the important environmental concerns of this decade. Increased public awareness regarding the safety of drinking water has resulted in increased efforts by all levels of government to develop and implement new programs for comprehensive resource protection.

The State's efforts to study, evaluate, and protect its ground-water resources are performed in conjunction with a number of Federal, State, and local agencies. The U.S. Geological Survey, has conducted numerous hydrologic studies of ground-water flow and ground-water quality. The studies have ranged in scope from regional (southeastern Ohio) to small areas consisting of one or two townships. Many of the studies cover single counties. Most of the studies were conducted in cooperation with State and local agencies. The most prominent ground-water program functions at the State level are within the Department of Natural Resources, the Department of Health, and the Environmental Protection Agency.

The Ohio Department of Natural Resources (ODNR), Division of Water, has conducted a ground-water program for nearly 40 years and is responsible for the quantitative evaluation of the resource. Specific functions include ground-water mapping; administering Ohio's well-log and drilling-report law; special hydrogeologic investigations; and technical assistance to municipalities, industries, and the general public regarding local geology, well drilling and development, and quantitative problem assessment. The Division has completed county ground-water availability maps for nearly three-fourths of Ohio and has recently initiated a new mapping program to show ground-water pollution potential. Approximately 9,000 new well logs and more than 5,000 technical-assistance requests are received and responded to each year.

The ODNR Division of Oil and Gas administers rules and regulations to insure optimum management of oil and gas reserves and the control of pollution from activities associated with production. Major functions that directly relate to ground-water protection include controls over well drilling, well casing, and well-abandonment techniques; and the regulation of storage and disposal practices for associated waste fluids. The Division also administers the State's underground injection control program for more than 4,000 Class-II and Class-III injection wells (U.S. Environmental Protection Agency, 1984).

The Ohio Department of Health (ODH) is responsible for programs to regulate the siting, design, operation, and maintenance of private residential water-supply systems and sewage-disposal systems, both of which may have direct impacts on local ground-water quality and drinking-water safety. ODH has developed rules governing specific well-construction practices and a well-permit system that are administered in cooperation with local health departments. Other ground-water-related activities include a registration program for private water-system contractors and a local inspection and sampling program for noncommunity public water supplies.

The activities of the Ohio Environmental Protection Agency (OEPA) are directed toward ground-water-quality monitoring and assessment and evaluation and control of ground-water pollution from existing and proposed waste-disposal sites. Technical assistance is provided to government officials, industries, and the general public on the identification, prevention, control, and abatement of ground-water pollution from a wide range of land-use activities.

The OEPA's Division of Ground Water functions as a technical-support unit for all other programs of OEPA to provide technical expertise on local hydrogeology and ground-water quality. Among the specific activities of the ground-water staff are responses to formal complaints about ground-water problems and the review of plans and site-feasibility reports to insure that adequate and sufficient ground-water protection and surveillance measures are incorporated into land-disposal sites and facilities. The staff currently is redesigning the State's ground-water-monitoring network, which will include more than 500 individual wells sampled semiannually to measure ambient water quality in major aquifers and the effects of pollution near selected waste-disposal sites and facilities. Each year, the ground-water staff investigates and assesses ground-water conditions at approximately 350 sites and responds to more than 1,000 requests for technical assistance.

Ground-water-related functions within other Divisions of OEPA include the public-water-supply supervision program (as authorized by the Federal Safe Drinking Water Act); administration of the federally mandated underground injection program for Class-I, IV, and V injection wells (U.S. Environmental Protection Agency, 1984); and management of the required programs of the RCRA for preventing and abating ground-water pollution from regulated and unregulated hazardous-waste facilities. The OEPA also maintains an office of Emergency Response, which responds to and assists in the clean-up of about 300 spills, accidents, and other sudden releases annually that might affect ground water. The OEPA's Planning Coordinator reviews and administers Federal grant awards to local planning agencies for water-quality-management plans and studies.

Other State and local agencies with ground-water-protection responsibilities include the State Fire Marshall, who administers the underground storage tank program; the ODNR, Division of Reclamation, which issues surface coal-mining permits with requirements that insure adequate ground-water protection; and county health departments, which inspect new private water and sewage systems for compliance with State rules. The Hazardous Waste Facility Board, consisting of representatives from several agencies and the governor's office, issues hazardous-waste permits. Those permits contain terms and conditions designed to protect ground water. These terms and conditions are enforced by OEPA.

The OEPA, in cooperation with other State agencies, currently is engaged in the final stages of developing a comprehensive ground-water-strategy framework and action plan that will emphasize the prevention of ground-water pollution from all future sources, and the identification and control of pollution from existing sources. Five major initiatives have been identified in the strategy to be addressed for Ohio to protect its water resources efficiently and effectively:

1. Strengthen controls over all existing and potential sources of pollution through increased regulatory, institutional, and enforcement capabilities;
2. Improve ground-water-information systems and data bases to define more clearly the resource, define resource problems, and provide easier access to reliable information;
3. Improve interagency and intra-agency coordination among the numerous State offices, which often share jurisdiction over various ground-water-related activities;
4. Provide stronger safeguards for public water supplies and critical aquifer areas that comprise essential sources of drinking water; and
5. Encourage greater participation by local governments to undertake additional responsibilities in providing more effective ground-water protection and management.

Throughout 1987, government agencies and a public-advisory group will be developing a ground-water strategy-implementation plan and schedule. Among the specific program initiatives under consideration will be exploration of options for developing an aquifer-classification system and ground-water-quality standards. These particular management techniques are not currently in effect in Ohio, but soon will be seriously considered for development.

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U.S. Geological Survey hydrologist sampling water from a spring in a quarry in the Bass Islands Dolomite, near Lime City, in northwestern Ohio, to provide baseline water-quality information on regional ground-water flow systems. (Photograph by Alan C. Sedam, U.S. Geological Survey.)

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OKLAHOMA
Ground-Water Quality

In Oklahoma, ground water is the major source of water for irrigation, the largest single use of water. The major population centers (fig. 1) rely primarily on surface water for public supply, but many of the smaller towns and rural water systems depend on ground water. Ground water accounts for about 28 percent of the total public water supply in Oklahoma (Solley and others, 1983, p. 10). Except for the Dog Creek-Blaine and the Arbuckle-Timbered Hills aquifers (fig. 2*A*), the principal aquifers provide water supplies that generally meet all Federal and State standards for drinking-water quality. Large sulfate concentrations, with a median value of 1,750 mg/L (milligrams per liter) in the Dog Creek-Blaine, and large fluoride concentrations, with a median value of 9.1 mg/L in the Arbuckle-Timbered Hills, preclude the general use of these two aquifers for public water supply. In all principal aquifers except the Arbuckle-Timbered Hills, the water is hard to very hard, with median hardness values ranging from 135 to 2,000 mg/L as calcium carbonate. All principal aquifers supply water of acceptable quality for irrigation of some types of crops.

Large nitrate (as nitrogen) concentrations are present in many of the State's aquifers, particularly in the shallow alluvium and terrace aquifers, but specific causes have not been identified. Evidence exists that ground water is contaminated in some areas by large sodium chloride concentrations resulting from oil and gas operations. Fifty hazardous-waste sites have been identified under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 (fig. 3*A*). Of these 50 sites, ground-water-quality monitoring is required at 30. Four sites in Oklahoma have been included on the National Priorities List (NPL) of hazardous waste sites (U.S. Environmental Protection Agency, 1986c) for action or further evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Remedial action is almost completed at the CERCLA (Superfund) site in northeastern Oklahoma (fig. 3*A*). There are 11 underground injection control (UIC) Class I wells (U.S. Environmental Protection Agency, 1984) in Oklahoma (fig. 3*A*). The U.S. Department of Defense (DOD) has identified 29 hazardous-waste sites at 4 facilities in Oklahoma as having potential for contamination.

Although the urban population has continued to increase, Oklahoma has had a net loss in population since 1983 (Oklahoma Employment Security Commission, 1986, p. 4) because of the depressed economy. Contamination of shallow ground water may occur in the urban areas as an indirect result of population and industrial growth. Statewide, the potential for ground-water contamination resulting from agriculture and energy production has been decreased by a reduction in these activities.

WATER QUALITY IN PRINCIPAL AQUIFERS

Oklahoma has three principal types of aquifers—alluvial, unconsolidated and semiconsolidated, and bedrock (U.S. Geological

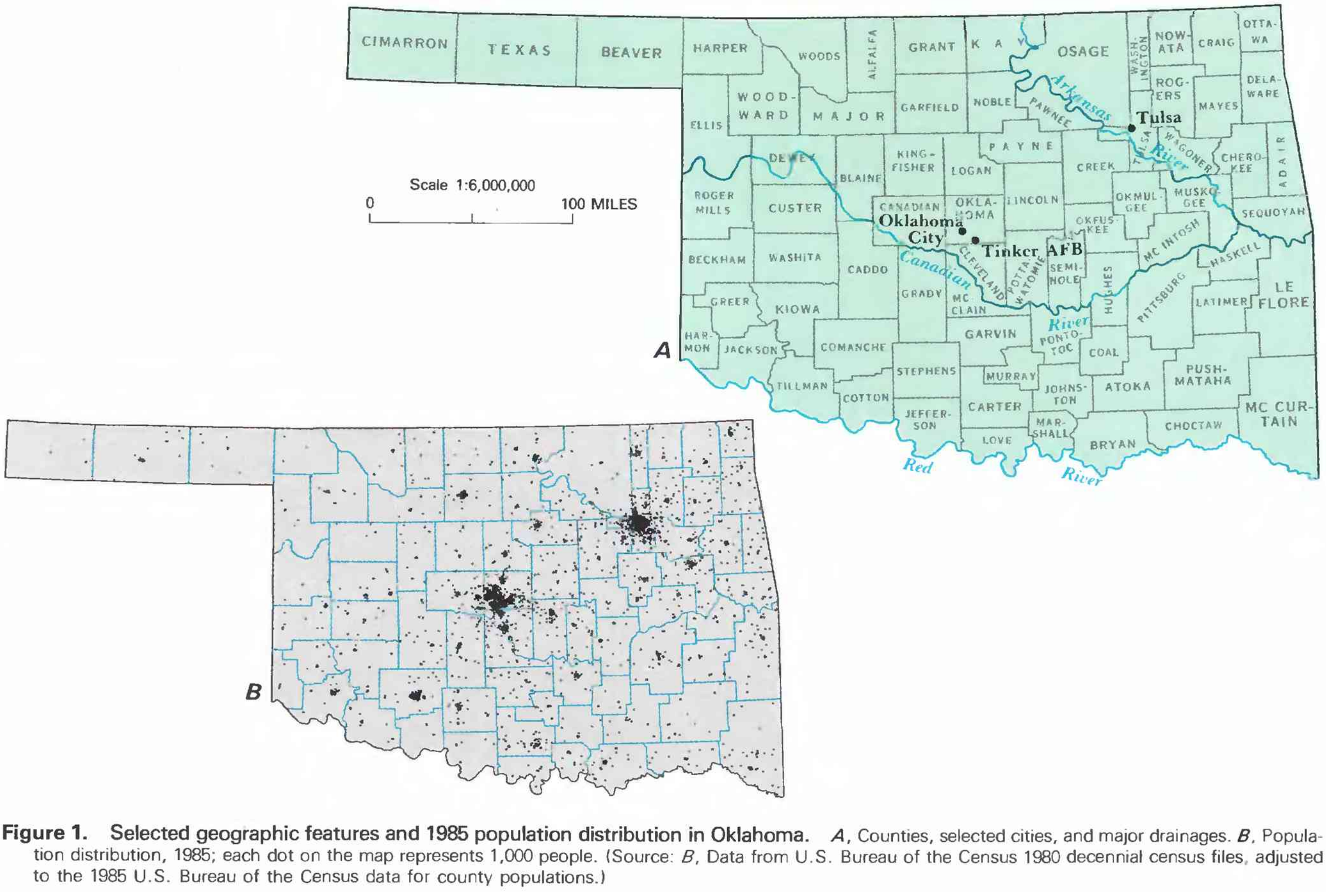

Figure 1. Selected geographic features and 1985 population distribution in Oklahoma. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

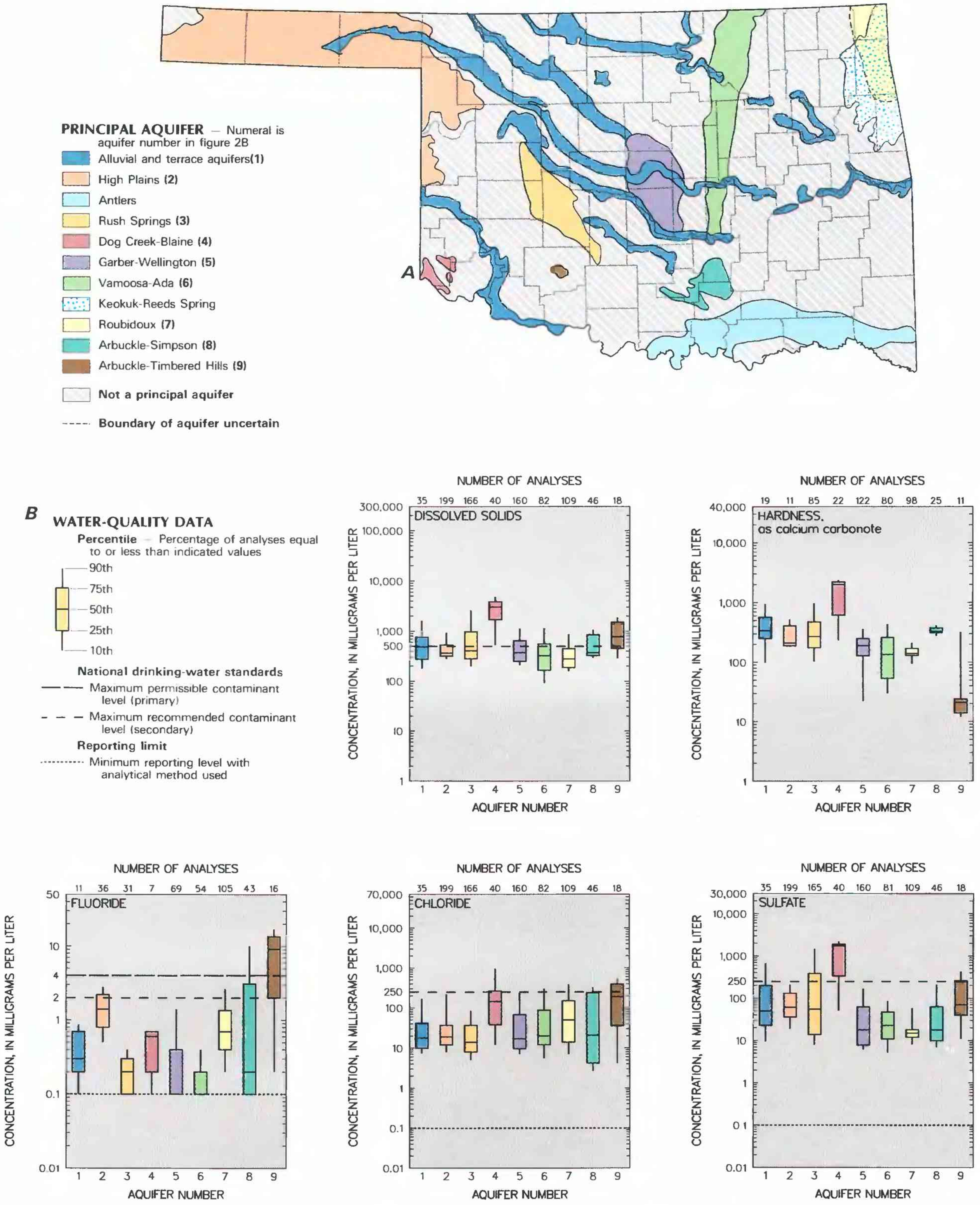

Figure 2. Principal aquifers and related water-quality data in Oklahoma. *A*, Principal aquifers. *B*, Selected water-quality constituents and properties, as of 1946-86. (Sources: *A*, Marcher, 1972. *B*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

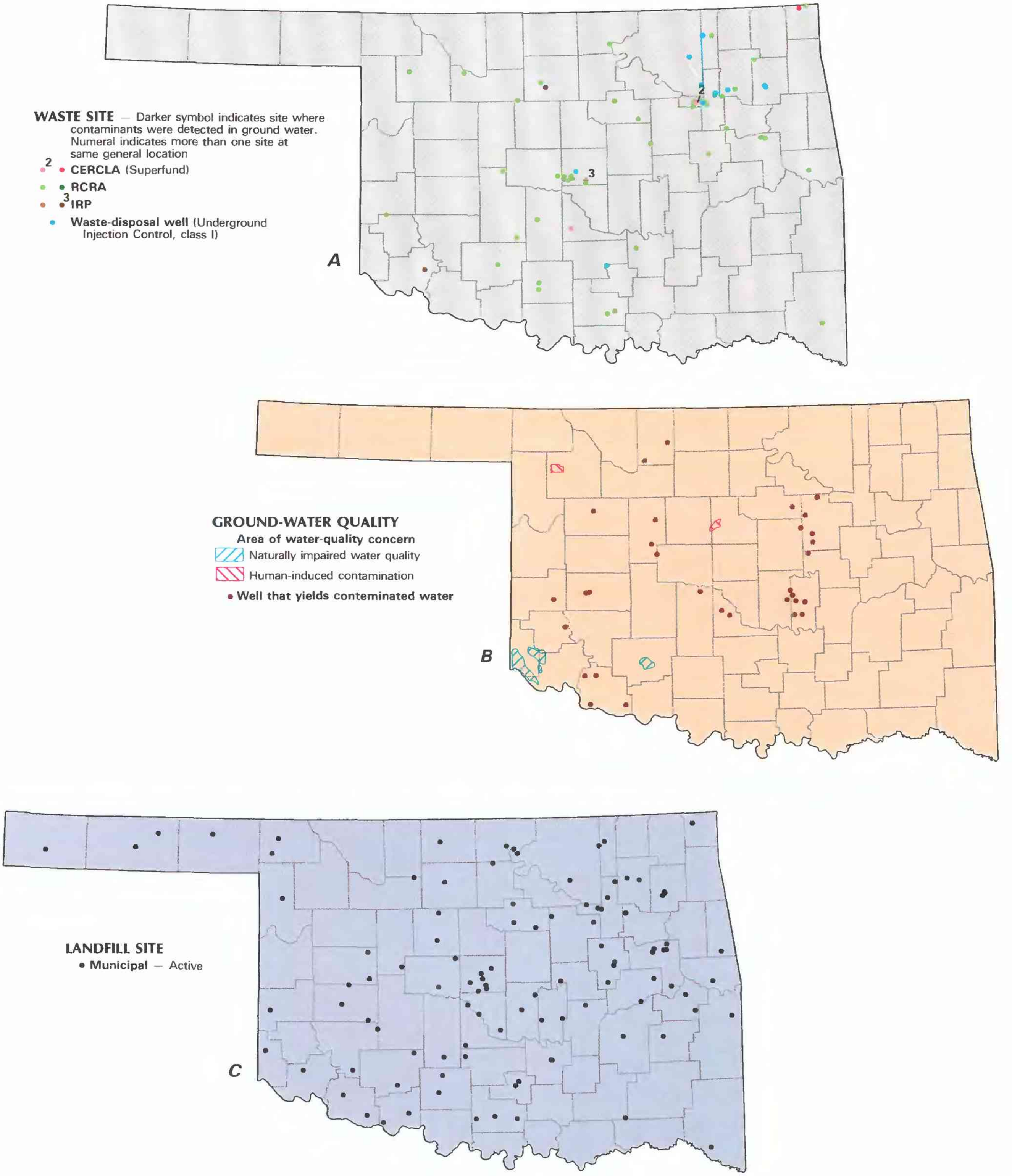

Figure 3. **Selected waste sites and ground-water-quality information in Oklahoma.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of August 1986; Resource Conservation and Recovery Act (RCRA) sites, as of August 1986; and Department of Defense Installation Restoration Program (IRP) sites, as of September 1985; and other selected waste sites, as of August 1986. *B*, Areas of naturally-impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of August 1986. *C*, Municipal landfills, as of August 1986. (Sources: *A*, Oklahoma State Department of Health files; U.S. Department of Defense, 1986. *B*, U.S. Geological Survey, Oklahoma Water Resources Board, and Oklahoma State Department of Health files. *C*, Oklahoma State Department of Health files.)

Survey, 1985, p. 347). Ground water in Oklahoma is withdrawn predominantly for irrigation and public supply, and is the source for most self-supplied domestic users. Irrigation is the primary water use in the western part of the State and public supply is the primary water use in the central and eastern parts. During 1982, ground-water withdrawals accounted for 46 percent of the total water withdrawals (Stoner, 1985, p. 18). Irrigation withdrawals from the High Plains, Rush Springs, and Dog Creek-Blaine aquifers in the west (fig. 2*A*) accounted for about 60 percent of the total State ground-water withdrawals.

Dissolved-solids concentrations in Oklahoma ground water generally increase with depth. Except for the Dog Creek-Blaine and the Arbuckle-Timbered Hills aquifers, water suitable for public supply can be found in all the State's principal aquifers. However, not all areas or depths within these aquifers produce water suitable for public supply.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*B*. The summary is based on dissolved-solids, hardness, fluoride, chloride, and sulfate analyses of water samples collected from 1946 to 1986 from the principal aquifers in Oklahoma. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986 a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 4.0 mg/L fluoride, and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 2.0 mg/L fluoride, 250 mg/L chloride, and 250 mg/L sulfate.

The data presented in figure 2*B* were summarized by principal aquifer and were interpreted for each aquifer without distinction as to areal location or depth. Owing to insufficient data, the Keokuk-Reeds Spring and Antlers aquifers have not been included in this discussion. Nitrate (as nitrogen) data were not sufficient to produce statistical summaries for any of the principal aquifers.

Except for the Dog Creek-Blaine aquifer, the median dissolved-solids concentrations in the State's principal aquifers were smaller than 1,000 mg/L and ranged from 280 to 772 mg/L (fig. 2*B*). Hardness concentrations for most of Oklahoma's ground water generally were larger than 120 mg/L (hard water) and commonly were larger than 180 mg/L (very hard water). Some chloride and sulfate concentrations exceeded the drinking-water standards of 250 mg/L, rendering the water unsuitable for use as a public supply. Fluoride concentrations in water from some aquifers exceeded the 4.0 mg/L primary standard for the range in average annual temperature in Oklahoma of 58 to 64° F (Oklahoma Water Resources Board, 1984).

Alluvial and Terrace Aquifers

Water withdrawn from the alluvial and terrace aquifers is used principally for irrigation and domestic supply. Water from these aquifers ranged from a calcium-magnesium carbonate-bicarbonate type to a calcium-magnesium sulfate type (U.S. Geological Survey, 1985, p. 348). The median dissolved-solids concentration was 485 mg/L (fig. 2*B*), with about 20 percent of the concentrations exceeding 1,000 mg/L. The water was very hard, with a median hardness concentration of 340 mg/L; more than 80 percent of the concentrations were larger than 180 mg/L. Most of the chloride and sulfate concentrations were small; median values were 18 mg/L and 50 mg/L, respectively. Fewer than 10 percent of the chloride concentrations and 20 percent of the sulfate concentrations exceeded 250 mg/L. The median fluoride concentration was 0.3 mg/L, and the maximum was 0.9 mg/L. The water generally is suitable for use as a public supply. However, large chloride and sulfate concentrations found in some areas and at various depths decrease the suitability of the water for public supply.

High Plains Aquifer

The major use of water from this aquifer is for irrigation. Public water suppliers in this area also rely on the High Plains aquifer for potable water. The water is a calcium-magnesium chloride-sulfate type (fig. 4). The median dissolved-solids concentration was 364 mg/L (fig. 2*B*), with about 10 percent of the samples exceeding 1,000 mg/L. The water was very hard, with a median hardness concentration of 210 mg/L; 95 percent of the samples had concentrations larger than 180 mg/L. The chloride and sulfate concentrations were small; median concentrations were 19 mg/L and 61 mg/L, respectively. About 5 percent of the chloride and sulfate concentrations were larger than 250 mg/L. The median fluoride concentration was 1.4 mg/L, and about 25 percent of the concentrations exceeded 2.0 mg/L. Although the water is suitable for use as a public supply, chloride, sulfate, and fluoride concentrations can be large enough to make the water unsuitable in some areas.

Rush Springs Aquifer

The primary use for water withdrawn from the Rush Springs aquifer is irrigation. The water is a calcium-magnesium chloride-sulfate type (fig. 4). The median dissolved-solids concentration was 408 mg/L (fig. 2*B*), with about 25 percent of the concentrations greater than 1,000 mg/L. The water was very hard, with a median hardness concentration of 270 mg/L; 70 percent of the concentrations were larger than 180 mg/L. Chloride and sulfate concentrations were small; median values were 14 mg/L and 55 mg/L, respectively. Fewer than 5 percent of the chloride concentrations and about 30 percent of the sulfate concentrations were larger than 250 mg/L. The maximum fluoride concentration was 0.9 mg/L. The water generally is suitable for public supply, although chloride and sulfate concentrations exceeded the drinking-water standards in some areas.

Dog Creek-Blaine Aquifer

Water from the Dog Creek-Blaine aquifer is used almost exclusively for irrigation. The chemistry of the water, a calcium-magnesium chloride-sulfate type (fig. 4), results from solution of the gypsum and dolomite in the aquifer. Water from this aquifer was slightly to moderately saline, with a median dissolved-solids concentration of 3,040 mg/L (fig. 2*B*). About 80 percent of the dissolved-solids concentrations were larger than 1,000 mg/L. The water was very hard, with a median hardness concentration of 2,000 mg/L; more than 90 percent of the values were larger than 180 mg/L. The median chloride concentration was 145 mg/L, and about 25 percent of the values exceeded 250 mg/L. Sulfate concentrations were large; the median value was 1,750 mg/L and more than 75 percent of the concentrations were larger than 250 mg/L. The maximum fluoride concentration was 0.7 mg/L. The water is unsuitable for use as a public-water supply.

Garber-Wellington Aquifer

The primary use for water withdrawn from the Garber-Wellington aquifer is for public supply and self-supplied domestic use. The water is a calcium-magnesium carbonate-bicarbonate type (fig. 4). The median dissolved-solids concentration was 372 mg/L (fig. 2*B*), with about 10 percent of the concentrations larger than 1,000 mg/L. The water was hard to very hard, with a median hardness concentration of 190 mg/L; more than 75 percent of the values were larger than 120 mg/L. Chloride and sulfate concentrations normally were small; median concentrations were 17 and 18 mg/L, respectively. About 10 percent of the chloride and 10 percent of the sulfate concentrations were larger than 250 mg/L. The median fluoride concentration was 0.1 mg/L, and fewer than 10 percent of the values were larger than 2.0 mg/L. The water in the aquifer normally is suitable for use as a potable water supply, but chloride, sulfate, and fluoride concentrations may exceed the drinking-water standards.

Vamoosa-Ada Aquifer

Water withdrawn from the relatively undeveloped Vamoosa-Ada aquifer is used primarily for drinking. The water is a sodium-potassium chloride-sulfate type (fig. 4), with a tendency toward a sodium-potassium mixed type. The median dissolved-solids concentration was 325 mg/L (fig. 2*B*), with 10 percent of the concentrations greater than 1,000 mg/L. The water ranged from soft to very hard, with a median hardness concentration of 135 mg/L; about 45 percent of the values were larger than 180 mg/L. Chloride and sulfate concentrations generally were small; median concentrations were 20 and 23 mg/L, respectively. About 10 percent of the chloride and 1 percent of the sulfate concentrations were larger than 250 mg/L. The maximum fluoride concentration was 1.3 mg/L. Except for areas of local contamination resulting from past oil and gas activities, the water is suitable for use as a public supply.

Roubidoux Aquifer

Water from the Roubidoux aquifer is withdrawn primarily for public-supply use, and the aquifer is the principal source of potable water for Ottawa County. The water is a mixed type with a tendency toward a sodium-potassium chloride-sulfate type (fig. 4). The median dissolved-solids concentration was 280 mg/L (fig. 2*B*), with about 5 percent of the concentrations larger than 1,000 mg/L. The water was hard, with a median hardness concentration of 140 mg/L; about 80 percent of the values were larger than 120 mg/L. Chloride and sulfate concentrations generally were small; median concentrations were 50 and 15 mg/L, respectively. About 15 percent of the chloride concentrations and 1 percent of the sulfate concentrations were larger than 250 mg/L. The median fluoride concentration was 0.7 mg/L; about 15 percent of the values were larger than 2.0 mg/L. The water normally is suitable for use as a public supply, although chloride, sulfate, and flouride concentrations exceeded the drinking-water standards in some areas.

Arbuckle-Simpson Aquifer

The Arbuckle-Simpson aquifer is used primarily for drinking water, but the aquifer is largely undeveloped. The water is a calcium-magnesium carbonate-bicarbonate type (fig. 4). The median dissolved-solids concentration was 369 mg/L (fig. 2*B*), with about 10 percent of the concentrations greater than 1,000 mg/L. The water was very hard, with a median hardness concentration of 330 mg/L; all hardness concentrations were larger than 180 mg/L. Chloride and sulfate concentrations were small; median concentrations were 21 and 18 mg/L, respectively. About 25 percent of the chloride and 10 percent of the sulfate concentrations were larger than 250 mg/L. The median fluoride concentration was 0.2 mg/L, with about 30 percent of the values larger than 2.0 mg/L. Much of the water in the aquifer is potable, but large concentrations of chloride and fluoride in some areas may make the water unsuitable for public supply.

Arbuckle-Timbered Hills Aquifer

The Arbuckle-Timbered Hills aquifer is largely undeveloped, but some water is withdrawn for domestic and irrigation use. The water is a sodium-potassium mixed type (fig. 4). The median dissolved-solids concentration was 772 mg/L (fig. 2*B*), with about 35 percent of the concentrations larger than 1,000 mg/L. The water was soft, with a median hardness concentration of 21 mg/L. Chloride concentrations generally were large, with a median concentration of 190 mg/L; about 40 percent of the chloride concentrations exceeded 250 mg/L. The median sulfate concentration was 70 mg/L, and about 25 percent of the values exceeded 250 mg/L. Fluoride concentrations were very large, with a median concentration of 9.1 mg/L; about 75 percent of the concentrations were larger than 2.0 mg/L. The water normally is unsuitable for public supply because of the widespread occurrence of large chloride and fluoride concentrations.

EFFECTS OF LAND USE ON WATER QUALITY

Changes in the quality of Oklahoma's ground water generally have not been documented by repeated sampling of specific wells. Poor ground-water quality may represent human-induced degradation or, more commonly in Oklahoma, impairment may be natural. With the limited information available, it is usually difficult to distinguish whether water-quality impairment is natural or human induced. Analyses for the class of contaminants that nearly always are attributable to human activities, such as organic compounds, are almost totally lacking for Oklahoma ground water.

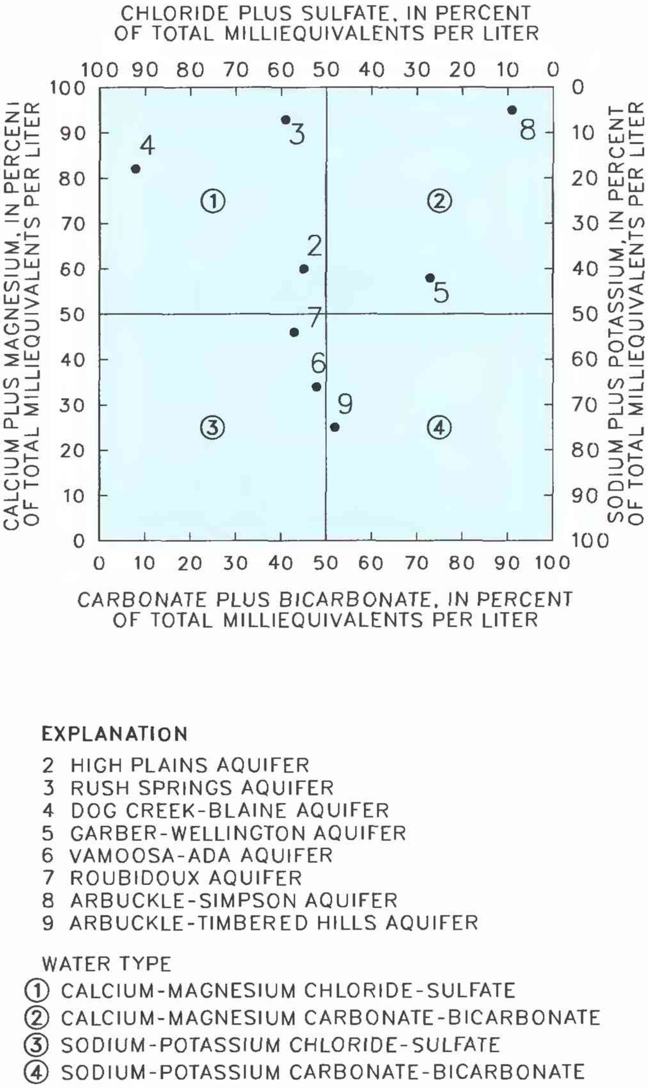

Figure 4. Water types of the principal aquifers in Oklahoma. Percentages are based on the average concentration of constituents. (Source: U.S. Geological Survey files.)

Of the 11 major Oklahoma aquifers (fig. 2*A*), the Roubidoux is the only aquifer for which appreciable trace-metals data are available. Of the trace metals, cadmium exceeded the maximum contaminant level of 10 μg/L (micrograms per liter) (U.S. Environmental Protection Agency, 1986a) in 4 of 91 samples taken from the Roubidoux. Eleven of the 26 samples from the Roubidoux that were analyzed for gross alpha activity exceeded the maximum contaminant level of 15 picocuries per liter. Of the constituents covered by the drinking-water standards, chloride and sulfate most commonly exceeded the 250-mg/L limits. Sulfate concentrations in more than 75 percent of the samples from the Dog Creek-Blaine aquifer exceeded 250 mg/L,; for this reason the aquifer is represented as naturally impaired in figure 3*B*. The Arbuckle-Timbered Hills aquifer also is shown in figure 3*B* as naturally impaired, owing to the persistence of fluoride concentrations in excess of the drinking-water standard.

Many occurrences of substandard ground-water quality may not be attributed with confidence to specific causes or factors. Although available nitrate data were insufficient to produce statistics (fig. 2*B*), nitrate contamination commonly is measured in Oklahoma's ground water. Most of the nitrate data are stored in the files of various State agencies. Samples from one or more wells in virtually every major aquifer in the State have nitrate concentrations that exceed the 10-mg/L maximum contaminant level. The alluvial and terrace aquifers, because they tend to have shallow water tables and overlying soils with large permeability values, are particularly susceptible to nitrate contamination resulting from fertilizer application, septic-tank effluent, and industrial-process wastes. In addition, the outcrop areas of bedrock aquifers are susceptible to the same contaminants. Seventeen of the wells that yield contaminated water shown in figure 3*B* are public-supply wells with nitrate problems. The actual number of affected wells, both public and private, is larger, but accurate locations for the wells were not available. Gopal (1984) reported on an area in western Woodward County (fig. 3*B*) where nitrate concentrations exceeded 10 mg/L in at least one of several repetitive samples in 40 percent of the shallow wells tested. The contamination was attributed to various sources at specific sites.

Urbanization

The effects of urbanization on ground-water quality in Oklahoma are not well documented. The State's largest city, Oklahoma City, overlies the Garber-Wellington aquifer, which is a principal water-supply source for parts of the metropolitan area. Most of the available chemical data for the Garber-Wellington are from municipal wells completed in the deeper parts of the aquifer. Nitrate contamination is a common problem in the shallow areas of the aquifer. Data are lacking to determine if trace metals and organic compounds are present in the shallow zones of the aquifer that would be affected first by human activities. Arsenic, chromium, and selenium in excess of the drinking-water standards are common, but the source of these dissolved metals is presumed to be minerals that occur naturally in the aquifer.

Agricultural Practices

The major known effect of agriculture on ground-water quality in Oklahoma is nitrate contamination. Chemigation is practiced in several areas of Oklahoma, but ground-water contamination resulting from a system malfunction, accident, or misuse of the practice has not been documented. Also, there is no evidence that pesticides are present in Oklahoma's ground water. However, very few analyses for pesticides have been made as of March 1986. The Oklahoma State Department of Agriculture began a project in 1986 to sample for pesticides in shallow aquifers throughout Oklahoma. This project is the first systematic effort to look statewide for evidence of pesticides in ground water.

Oil and Gas Industry

One of the ground-water-quality issues of great concern in Oklahoma is the contamination potential of oil and gas exploration and production. Nearly 400,000 oil and gas wells have been drilled in Oklahoma since oil was first produced in 1891 (Northcutt, 1985). Until several years ago, the requirements for plugging abandoned wells were not stringent regarding the protection of freshwater aquifers. Many of the older unplugged or partly plugged wells may serve as conduits for saltwater movement from deep reservoirs into shallower freshwater aquifers. Leaking casings in old producing wells or saltwater-injection wells could have a similar effect. Imperfectly sealed drilling-fluid disposal pits and brine-evaporation pits also may contribute contaminants to ground water. The contaminants typically associated with oil and gas activity are chloride, chromium, and sodium. Other trace metals that are a part of the natural composition of the brines produced with the oil and gas, and metals that are used in drilling-fluid additives also may be introduced to freshwater zones.

Two published reports are known to relate activities of the oil and gas industry directly to demonstrated ground-water contamination. An investigation into the cause of apparent saltwater contamination of the Vamoosa-Ada aquifer and overlying streams in central Oklahoma indicated that the quality of ground water in the vicinity of 15 wells (fig. 3*B*) had been degraded by oilfield brines (Morton, 1984). Leakage from evaporation pits was the presumed cause of large chloride concentrations, as much as 9,000 mg/L, discovered in an area of several square miles in the southern part of the Cimarron Terrace aquifer in Logan County (fig. 3*B*) (Oklahoma Water Resources Board, 1975).

Waste Disposal

Early in 1986, State records showed that Oklahoma had 106 active municipal landfills (fig. 3*C*), and 50 RCRA sites for storage or disposal of hazardous waste, 4 CERCLA sites, and 11 UIC wells (fig. 3*A*). About 30 of the RCRA sites have permits for land disposal and must have ground-water monitoring networks in place. Ground-water contamination has not been detected at any of the RCRA sites; however, many do not yet (1986) have monitoring networks fully in place. Contamination has been documented at one of the CERCLA sites. There are two commercial waste-disposal facilities in Oklahoma. One, a land-disposal facility, is in Major County. The other facility (two disposal wells) is in Tulsa County. Both facilities also are RCRA sites.

As of September 1985, 29 hazardous-waste sites at 4 facilities in Oklahoma had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 29 sites in the program, 3 sites contained contaminants but did not present a hazard to the environment. Three other sites, all at one facility (fig. 3*A*), were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites are scheduled for confirmation studies to determine if remedial action is required.

One of Oklahoma's CERCLA sites, the Tar Creek site in Ottawa County (fig. 3*A*), has posed a threat to ground-water quality in the Roudidoux aquifer, a major source of water for public supply in northeastern Oklahoma. Abandoned underground lead-zinc mines have filled with water and large concentrations of iron, zinc, and sulfate now are evident in the mine water. Other constituents present in lesser, but significant, concentrations include aluminum, arsenic, cadmium, cobalt, lead, manganese, and nickel. The mines are located in the Boone Formation. Hydraulic gradients in the area indicate that mine water will migrate laterally within the formation and may migrate downward into other formations, including the Roubidoux aquifer. Many abandoned wells, which once supplied water for mining and milling operations, penetrate the Roubidoux aquifer and now provide a conduit for the mine water to reach the Roubidoux aquifer. A major goal of a CERCLA remedial project that will conclude in 1986 is to plug all abandoned wells in the area that could convey water from the mine workings to the Roubidoux aquifer.

Feasibility studies at the CERCLA site in southern McClain County (fig. 3*A*), the Hardage/Criner site, have been completed, and the proposed cleanup plans were issued for public comment early in 1986. The U.S. Department of Justice filed a civil suit in June 1986 against 36 companies to arrange for and to pay for cleanup of the 60-acre site. From 1972 through 1980 the site was operated as an industrial waste-disposal facility, and more than 18 million gallons of liquid waste were accepted. The wastes include polychlorinated biphenyls, cyanides, solvents, acids, caustics, oil, paints, plating and etching solutions, waste ink, carbon black, pesticides, and sludges containing trace metals (U.S. Environmental Protection Agency, 1986d). Additional investigation at this site is planned to determine the extent, if any, of ground-water contamination.

As of June 1986, cleanup of the Sand Springs Petrochemical Complex near Tulsa (fig. 3*A*) was underway. Federal and State response actions were underway at the Compass Industries site, also near Tulsa, but cleanup activities had not begun (U.S. Environmental Protection Agency, 1986c).

A hydrogeologic investigation was begun in 1985 to determine if ground-water contamination had occurred near several former waste-disposal sites on Tinker Air Force Base in the Oklahoma City metropolitan area. A preliminary investigation indicates that trichloroethylene (TCE) is present in the Garber-Wellington aquifer in a localized area beneath one of the disposal sites (U.S. Army Corps of Engineers, Tulsa District, oral commun., 1986).

POTENTIAL FOR WATER-QUALITY CHANGES

The two major land-use activities in Oklahoma, agriculture and energy production, are likely to decrease. To improve its economy, Oklahoma is seeking to diversify its economic base and lessen its dependence on agriculture and energy production. The potential for change in ground-water quality by this diversification will depend to a great extent on the types of industry that are attracted.

Reduction in agricultural activity, particularly in crop production, could decrease potential ground-water contamination. A decrease in crop production would reduce the application of fertilizer and pesticides, as well as reduce the amount of irrigation water applied to the land surface. The potential for increased nitrate contamination of ground water from agricultural activities probably will not increase soon. However, if crop production in Oklahoma increases, it could increase the potential for change in water quality.

Oil and gas exploration and production presently (1986) are curtailed in Oklahoma because of unfavorable market conditions. Pumping from many marginal production wells has ceased because of the economic unfeasibility of continued operation. The potential for acceleration of changes in ground-water quality due to energy production or exploration will be minimal while the current market conditions exist. The potential for water-quality changes from past oil and gas operations probably will not change appreciably.

GROUND-WATER-QUALITY MANAGEMENT

Seven Oklahoma State agencies share statutory authority for the management and protection of ground-water quality. The Oklahoma Department of Pollution Control, one of the seven agencies, has the primary duty of coordinating the activities of other State agencies relating to environmental pollution when duplication of effort is possible. The Department functions as a clearing house for pollution complaints, particularly if there is a jurisdictional question. The Department is administered by a board composed of the heads of seven other agencies (one of which has no ground-water management authority) with responsibilities relating to the prevention and control of water pollution.

The Oklahoma Water Resources Board is responsible for the allocation of water rights that are based on hydrologic investigations of the State's aquifers, including considerations of possible ground-water pollution. The board is authorized to classify the State's water according to beneficial uses and to promulgate water-quality standards to protect those uses. The board also establishes well-construction standards, primarily to protect ground-water quality.

The Oklahoma State Department of Health has broad authority stemming from its mandate to safeguard the health of the State's people. It has jurisdiction in any situation that could contaminate or has contaminated a drinking-water source. The Department has approval and regulatory authority for all public water supplies, solid waste-management facilities, and septic systems. It also regulates hazardous waste, including the RCRA sites, and all classes of UIC wells except Class II.

The Oklahoma Corporation Commission has sole jurisdiction over any production activities of the oil and gas industry that may affect ground water. It has the authority to issue rules and regulations to prevent pollution of ground water that may result from those activities. The Commission administers that part of the UIC program that deals with saltwater-disposal wells and enhanced-recovery injection wells (Class II wells). It also is responsible for inventories in Oklahoma that are required by the Underground Storage Tank program of the EPA (RCRA of 1976).

The Oklahoma State Department of Agriculture has jurisdiction over the labeling, sale, handling, and use of pesticides and herbicides. Statutory authority gives the Department some control over the eventual distribution of applied pesticides in the environment. The Department also regulates feedlots and may promulgate rules to prevent contamination of natural waters.

The Oklahoma Conservation Commission has jurisdiction over nonpoint-source pollution programs that are not specifically delegated to other authorities, but its enforcement role is limited. The Oklahoma Department of Mines is responsible for approval of mine permits and regulation of mining operations to assure minimal disturbance to the quantity and quality of water resources.

The Oklahoma Department of Pollution Control coordinates the efforts of several agencies to develop an integrated strategy for the protection of Oklahoma's ground water. An important interim result of that work has been the recognition that many of the water-quality data that are needed to implement an effective protection strategy—one that includes enforceable water-quality standards—currently are not available. A ground-water-quality monitoring program begun in 1983 by the Oklahoma Water Resources Board has provided trace-metals data for areas where previously there were none, but analyses for organic compounds are few.

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OREGON
Ground-Water Quality

Ground water is a precious resource, and in some areas of Oregon (fig. 1) it is the only source of potable water. However, localized ground-water-quality problems exist at several locations in the State. These quality problems are of major concern because ground water is the source of drinking water for about 40 percent of the State's population (Winslow Ladue and Dave Leland, Oregon State Health Division, written commun., 1987). Ground water also is used for agricultural irrigation and industrial processes. Water quality in all the principal aquifer groups (fig. 2) generally does not exceed national drinking-water standards for hardness, dissolved solids, and nitrate plus nitrite—some of the properties used to evaluate the suitability of water for drinking as set forth by the U.S. Environmental Protection Agency (1986a,b) and the Health Division of the Oregon Department of Human Resources. The chemical quality of ground water, however, can be altered by human activities. Miller and Gonthier (1984) noted several areas in Oregon that showed evidence of ground-water-quality degradation as a result of urbanization and industrial activities.

Nine hazardous-waste sites in Oregon require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. In addition to these nine RCRA sites, six sites have been included in the National Priorities List of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c). These six Superfund sites (fig. 3) require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Contamination of ground water has been documented at seven of the RCRA and all CERCLA sites in Oregon; contamination is suspected, but has not been documented, at the two remaining RCRA sites. Many additional industrial and agricultural sites, where contamination has been documented or is suspected, are of concern to the U.S. Environmental Protection Agency (EPA) and the Oregon Department of Environmental Quality (DEQ).

In addition to ground-water monitoring conducted by the DEQ to detect migrating leachates near landfills, there are several ground-water-quality monitoring networks for specific sites in Oregon. The DEQ is the State agency responsible for the protection of ground-water quality and, as such, actively conducts or directs sampling designed to monitor the movement of known or suspected contaminants, while also requiring numerous source industries to conduct onsite monitoring. A small set of ambient ground-water-quality data has been collected by the U.S. Geological Survey as part of various projects through the years. This data set is stored and maintained in the Water Data Storage and Retrieval System (WATSTORE) data base, which is updated periodically by the U.S. Geological Survey.

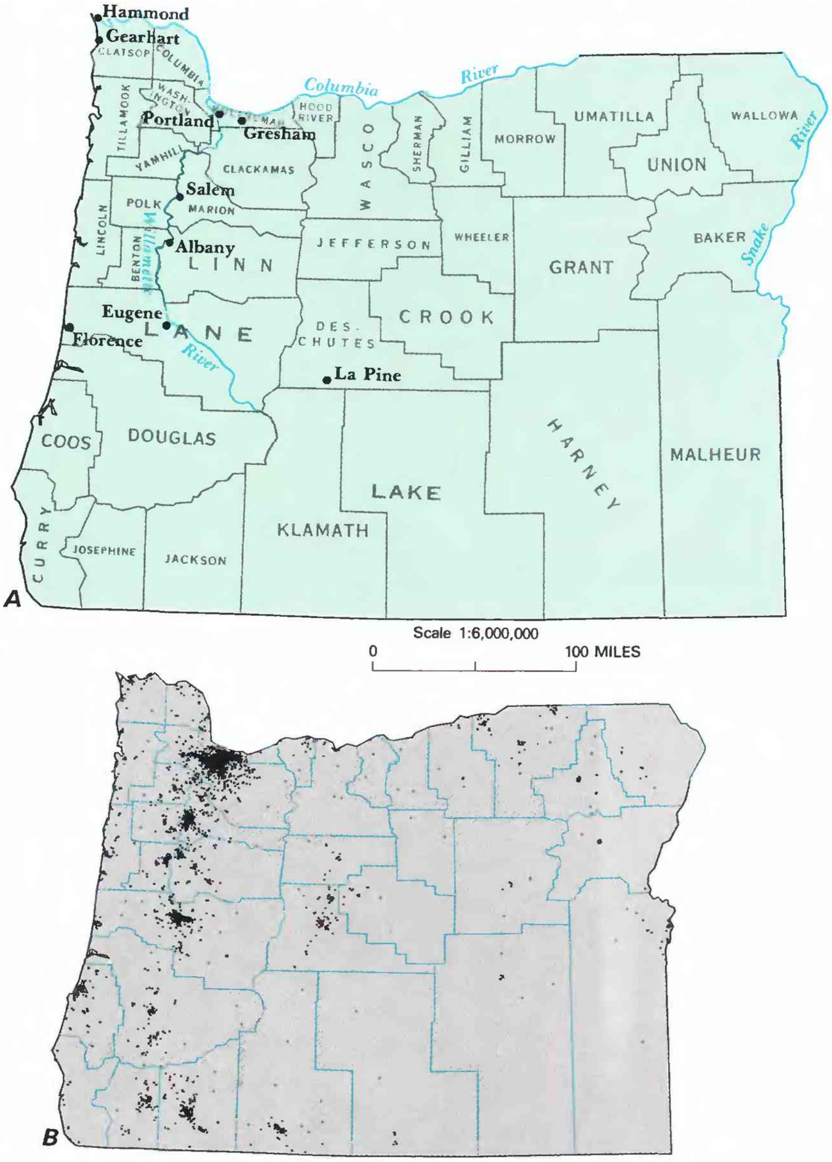

Figure 1. Selected geographic features and 1985 population distribution in Oregon. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Oregon has three principal aquifer groups, which consist of unconsolidated to consolidated sediments and several types of volcanic and pyroclastic rocks. These aquifer groups (fig. 2*A*, 2*B*) are basin-fill and alluvial deposits, volcanic and sedimentary rocks, and the Columbia River Basalt (U.S. Geological Survey, 1985, p. 357).

The basin-fill and alluvial aquifer group occurs in all parts of the State and consists of unconsolidated to consolidated sediments, alluvium, and coastal dune and beach deposits (U.S. Geological Survey, 1985). The thickness of this aquifer group differs markedly from basin to basin throughout the State. Water from this aquifer group has a median dissolved-solids concentration of 170 mg/L (milligrams per liter), and generally is suitable for most uses.

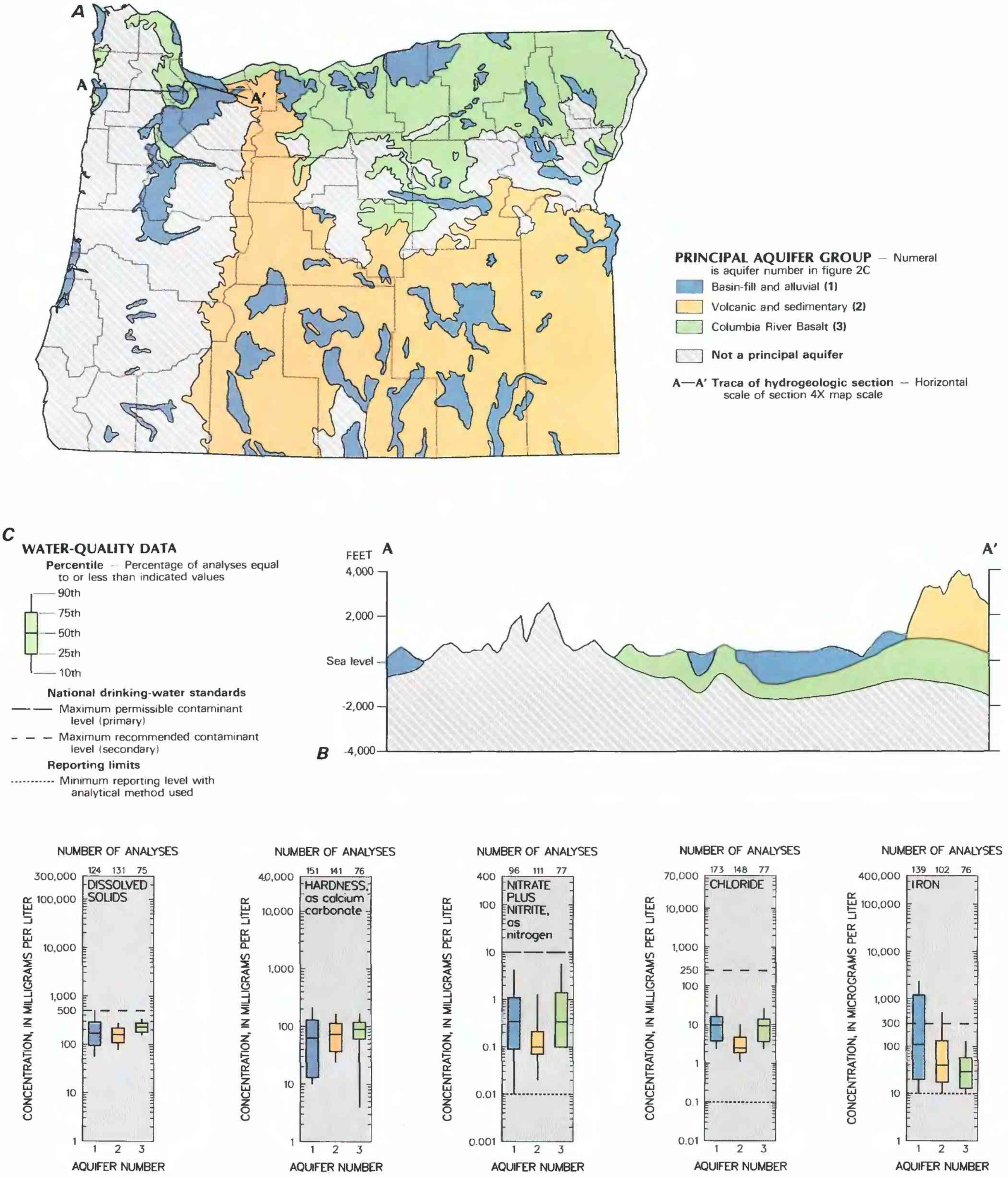

Figure 2. Principal aquifers and related water-quality data in Oregon. *A* Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1958-86. (Sources: *A*, U.S. Geological Survey, 1985. *B*, McFarland, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a, b.)

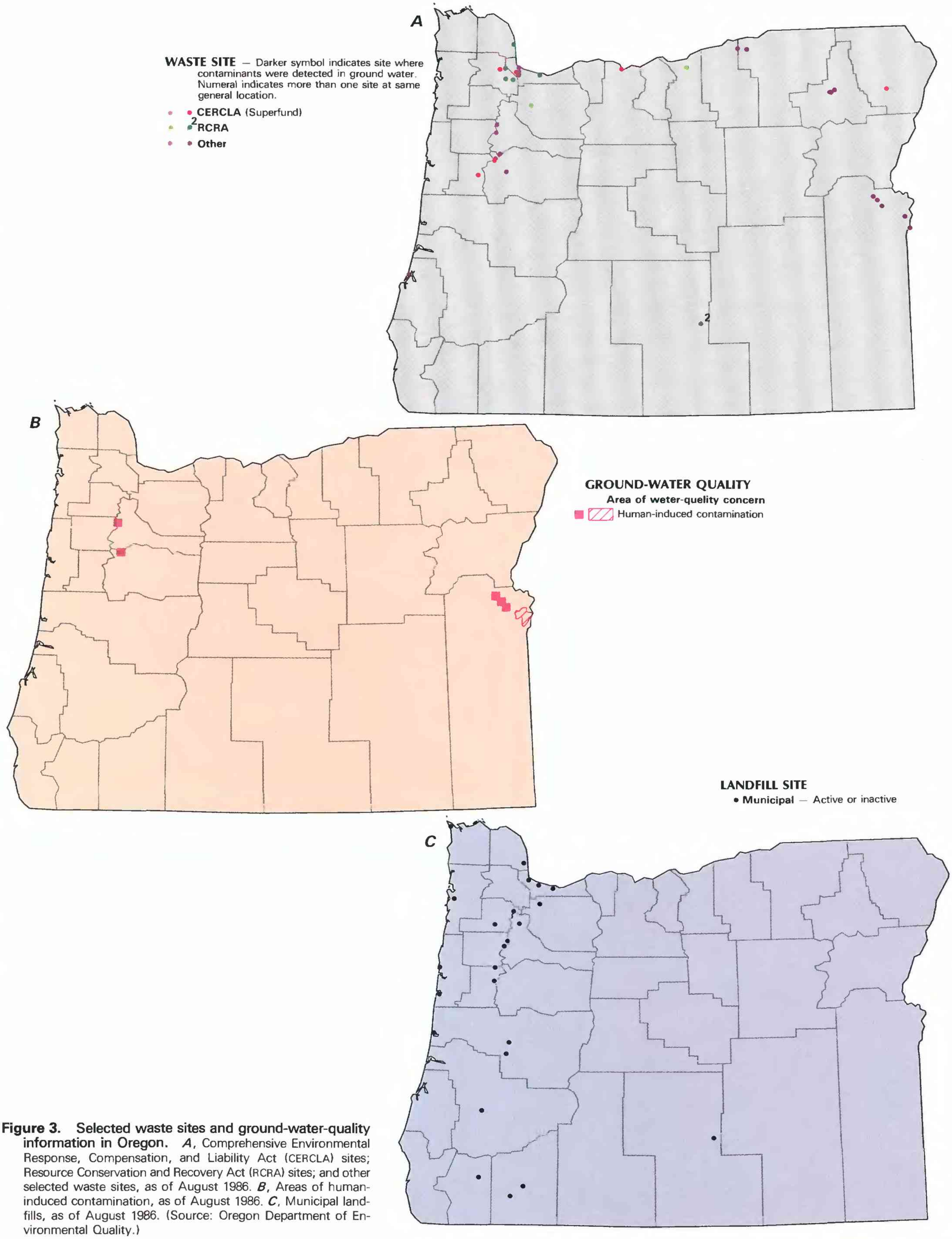

Figure 3. **Selected waste sites and ground-water-quality information in Oregon.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of August 1986. *B*, Areas of human-induced contamination, as of August 1986. *C*, Municipal landfills, as of August 1986. (Source: Oregon Department of Environmental Quality.)

The volcanic and sedimentary aquifer group consists of a complex assemblage of basalts and andesites, interbedded with clastic sediments. The thickness of this aquifer group probably exceeds several thousand feet (U.S. Geological Survey, 1985). Aquifers of this group are generally developed only in small basins; therefore, little is known about the hydrology of this aquifer group outside the developed basins. Water from this aquifer group has a median dissolved-solids concentration of 160 mg/L and is suitable for most uses.

The Columbia River Basalt aquifer group underlies the north-central and northeastern parts of Oregon. This aquifer group consists of basalt flows interbedded with tuffaceous sediments, together comprising five separate formations. This group may be more than 5,000 feet thick and has been developed as much as 600 feet below land surface, primarily for irrigation (Gonthier, 1985). Water from this aquifer group has a median dissolved-solids concentration of 230 mg/L and generally is suitable for most uses.

Potential sources of contamination to these aquifer groups include elements dissolved from natural sources and human activities. The latter includes intrusion or upwelling of more mineralized waters as a result of overpumping, seepage from landfills and hazardous waste-disposal sites, infiltration of agricultural chemical products including fertilizers, pesticides and herbicides, and subsurface sewage disposal (Miller and Gonthier, 1984).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's WATSTORE data base is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), chloride, and iron analyses of water samples collected from 1958 to 1986 from the principal aquifers in Oregon. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L (micrograms per liter) iron.

The summary (fig. 2*C*) illustrates the variability of the chemical quality of water from the three principal aquifer groups. Analytical data for a given aquifer were differentiated from the other aquifers by well location and the aquifer identification provided by Miller and Gonthier (1984) without regard to the possibility of interaquifer mixing of the sampled ground water. The data were further interpreted without distinction as to sampling depth or geographic location within an individual aquifer.

Generally, in the principal aquifer groups of Oregon, larger concentrations of dissolved solids correspond to increases in the water hardness. The median concentrations of hardness for the basin-fill and alluvial, volcanic and sedimentary, and Columbia River Basalt aquifer groups are 63 mg/L, 73 mg/L, and 90 mg/L, respectively; water of these concentrations is soft to moderately hard (U.S. Environmental Protection Agency, 1976, p. 75).

Figure 2*C* shows larger nitrate-plus-nitrite concentrations and wider ranges in the basin-fill and alluvial and the Columbia River Basalt aquifer groups than in the volcanic and sedimentary aquifer group. Median nitrate-plus-nitrite concentrations in the basin-fill and alluvial and the Columbia River Basalt aquifer groups are 0.34 mg/L, and in the volcanic and sedimentary aquifer group is 0.1 mg/L. The basin-fill and alluvial aquifer group occurs primarily in densely populated areas of the Willamette River valley, and the Columbia River Basalt aquifer group occurs in the agricultural area of the northeast part of the State. Specific areas of large nitrate concentrations occur in western Clatsop County near Hammond, in eastern Multnomah County near Gresham, in southern Deschutes County near La Pine, in Lane County north of Eugene, in west Lane County along the coast near Florence, in Malheur County near Ontario, in Umatilla County near Hermiston, in Morrow County near Boardman, and in Marion County near Salem (Oregon Department of Environmental Quality, 1980).

Chloride concentrations throughout the three principal aquifer groups do not exceed the national standard for drinking water (250 mg/L), with median concentrations of 9.7 mg/L, 2.5 mg/L, and 9.4 mg/L in the basin-fill and alluvial, volcanic and sedimentary, and Columbia River Basalt aquifer groups, respectively. Exceptions to the small concentrations are the 3,100 and 990 mg/L maximums measured in the basin-fill and alluvial and the volcanic and sedimentary aquifer groups, respectively. These large concentrations may indicate the intrusion of more saline waters from sources such as seawater or from underlying aquifers during periods of maximum withdrawals from the affected aquifer groups.

The median iron concentrations in the basin-fill and alluvial, volcanic and sedimentary, and Columbia River Basalt aquifer groups are 109, 40, and 29 μg/L, respectively. These median concentrations do not exceed the national drinking-water standard (300 μg/L). The 75th and 90th percentiles for the basin-fill and alluvial aquifer group are, however, 1,200 and 2,400 μg/L, respectively, indicating large iron concentrations within this aquifer. In particular, some iron concentrations are as large as 16,000 μg/L in the basin-fill and alluvial aquifer group near Coos Bay in western Coos County.

EFFECTS OF LAND USE ON WATER QUALITY

The chemical quality of ground water has been altered by human activities and land-use practices in localized areas in Oregon. These activities and practices include silviculture, various types of construction, mining, industrialization, urbanization, disposal of various types of wastes, irrigation, and application of agricultural chemicals (Miller and Gonthier, 1984).

Industry

Twenty-eight industrial sites have been identified where localized ground-water contamination is suspected or has been detected (fig. 3*A*). Industrial activities that contribute to this contamination include chemical manufacturing, metals plating, wood treatment, oil and gas storage and refueling, electronics, food processing, aluminum plants, and pulp and paper plants. Fifteen of these industrial sites are included in the RCRA and CERCLA classifications. Potential contaminants resulting from some of these industrial activities include organic chemicals, dissolved metals, nitrates, cyanide, and excessive dissolved solids.

Specific examples of industrial contamination problems in Oregon are increased turbidity in wells near a sand and gravel operation in the vicinity of Milton-Freewater in Umatilla County; oil in domestic wells near a railroad refueling facility in La Grande, Union County; and contamination of domestic wells by leachates seeping from a wood-products disposal pit in Turner, Marion County (Miller and Gonthier, 1984). Additionally, the DEQ has identified nitrate contamination near several potato and sugar-beet processing operations, increased levels of trichloroethylene and other volatile solvents in eastern Multnomah County and Washington County, chromium contamination at Corvallis in Benton County, and pentachlorophenol contamination at Hillsboro in Washington County.

Agriculture and Irrigation

The economy of Oregon depends largely on agriculture; the possibility exists, therefore, that additional ground-water contamination will occur, either directly or indirectly, from agricultural practices. Some examples of these agricultural practices include excessive application of chemicals to croplands, poor irrigation practices, and overpumping of irrigation wells.

Figure 3*B* identifies the locations of sites in Oregon where ground water has become contaminated as a result of agricultural practices. In general, contamination at these sites has resulted from the leaching of chemicals and other dissolved substances into the ground water and the decrease of natural dilution and attenuation. Specific examples of agricultural-related ground-water contamination problems in Oregon include (1) large nitrate concentrations in localized areas of the Willamette River valley west of the Cascade Mountains and the Ontario area of Malheur County; and (2) contamination by pesticides such as ethylene dibromide in the Willamette River Valley, and dachthal and telone in the Ontario area of Malheur County.

Waste Disposal

Disposal of manufactured wastes is a major problem for all industrialized nations. In addition to industrial wastes, other waste categories of importance in Oregon are solid waste, onsite sewage, and municipal sewage.

The DEQ has identified 24 landfill sites (fig. 3*C*) where seepage through buried refuse has resulted in ground-water contamination. Typically the contaminating leachate contains large concentrations of ammonia, nitrate, chloride, sulfate, iron, manganese, and organic matter.

Onsite disposal of domestic sewage through septic tanks and cesspools takes advantage of the natural ability of the soils to cleanse the sewage by filtration and microbial activity. The DEQ has conducted studies at various locations in the State where the septic system density has rendered the soils inadequate to clean the sewage or where the ground water has become contaminated from effluents. Contaminants from onsite sewage disposal consist primarily of nitrate, chloride, organic solvents (such as trichloroethylene or TCE), and bacteria. These contaminants have been detected in the following areas of Oregon: Clatsop Plains along the north coast from Gearhart to Hammond, near La Pine, in mid-east Multnomah County between Gresham and Portland, near Florence, in the Santa Clara River Road area west of Eugene, and in North Albany.

Municipal sewage-treatment facilities are another potential source of ground-water contamination. These facilities typically incorporate sewage lagoons, sludge drying beds, and sludge disposal as part of the treatment process. Monitoring of municipal sewage-treatment facilities and disposal practices by the DEQ has been limited. However, where ground-water quality has been monitored, nitrate and bacterial contamination has been detected in the ground water near lagoons and sludge disposal areas.

POTENTIAL FOR WATER-QUALITY CHANGES

Presently (1986), ground water in Oregon generally is unpolluted and is suitable for most uses; however, contamination may exist and yet be undetected in many areas. If existing areas of contamination are allowed to remain unchecked, the indiscriminate use of chemical contaminants and the uncontrolled disposal of waste products could pose the greatest threat to Oregon's ground-water resources.

The quality of ground water in Oregon can be protected for the future by assessing the resource, preventing contamination, and planning necessary strategies, as outlined here by the DEQ:

> "Assessment–The characteristics and extent of the resource must be known to adequately evaluate the effects of contamination. That is, the ground-water flow characteristics, the types and characteristics of the contaminants present, and the distribution of the contaminant within the aquifer must be known.
>
> Prevention–Because of the difficult nature of aquifer cleanup and the present state-of-the-art ability to detect pollution problems, the initial contamination of the ground water must be prevented if at all possible.
>
> Planning–All Federal, State, and local governmental agencies responsible for the regulation of ground-water quality must work in a coordinated effort to ensure the protection of the resource."

GROUND WATER-QUALITY MANAGEMENT

Ground-water quality in Oregon is the responsibility of the DEQ, whereas ground-water quantity is the responsibility of the Oregon Water Resources Department. Local governments also have participated in developing ground-water-quality protection plans, chiefly for certain aquifers. The EPA, with the cooperation of the DEQ, implements several ground-water-quality programs in Oregon.

The Federal Safe Drinking Water Act contains three programs concerning ground-water quality. In Oregon, primary responsibility for these three programs is divided among three different agencies.

(1) The Health Division of the Oregon Department of Human Services has primary responsibility for the Public Water System Supervision Program. Under this program the Health Division provides technical assistance and regulatory oversight of public water supplies. Included are the assessment and review of required water-quality analyses. When ground-water contamination is detected, the Health Division works cooperatively with the DEQ in risk assessment and public notification.

(2) The DEQ has primary responsibility of the Underground Injection Control (UIC) program. Oregon UIC rules prohibit the use of injection wells for hazardous-waste disposal and for in-situ mining.

(3) The EPA implements the Sole Source Aquifer Program. The Florence Dunal Aquifer, within the basin-fill and alluvial aquifer (1) group, has been proposed for designation as a Sole Source Aquifer under this program.

Both CERCLA and the Toxic Substances Control Act are non-delegated Federal programs. Those two Federal programs are administered by the DEQ under a cooperative agreement with the EPA.

On behalf of the EPA, the DEQ implements both Hazardous and Solid Waste Programs of RCRA. Extensive site investigations required under these programs include: hydrologic investigations, ground-water-quality monitoring, risk assessments, geologic studies and, where necessary, remedial action. In 1985, the department received enabling legislation for the development of a State underground storage tank (UST) regulatory program. More recently, the department received a grant from the EPA to assist in the development of a UST program.

Water-quality programs included in the Federal Clean Water Act are implemented by the EPA through the DEQ. Federal support for the development of State ground-water-quality protection programs comes from Sections 106 and 205J of the Clean Water Act.

The DEQ is responsible for establishing and enforcing rules designed to prevent contamination of Oregon's ground-water resources. The department's ground-water protection practices are guided by the Oregon Ground-Water Protection Policy (Administrative Rule 340-41-029). This policy, which was adopted by the Oregon Environmental Quality Commission in August 1981, provides an overall strategy for protecting ground-water quality. Since its adoption, the policy has been the foundation of the State's ground-water-quality protection efforts.

The Ground-Water Protection Policy establishes antidegradation as the prime objective; this policy protects the natural quality from impairment that could affect the present and future beneficial use of ground water. The policy does not discriminate—

that is, protection applies equally to all ground waters of the State. However, sensitive aquifers are identified so that priorities can be assigned to ground-water quality protection efforts. The policy contains three sections: (1) general policies, (2) source control policies, and (3) problem abatement policies. The best practical treatment and control are required to minimize potential pollutant loading to ground water. The policy is implemented through permit programs for facilities responsible for hazardous waste, solid waste, underground injection control, onsite sewage disposal, and water-pollution control. Waste discharges to ground water are not allowed. Nonpoint-source pollution is minimized through the use of best management practices.

Under the statewide land-use planning law, cities and counties in Oregon must develop and adopt comprehensive land-use plans to comply with State land-use planning goals. The DEQ has a statutorily mandated memorandum of understanding with the Oregon Land Conservation and Development Commission, which requires that all land-use plans comply with agency water-quality management plans, rules, and laws before approval.

The DEQ conducts ground-water-quality monitoring, which focuses on the identification and quantification of known or suspected ground-water-quality problems. Additionally, industrial-waste disposers are regulated by permit and audited by the Department.

During 1986, the DEQ formed a citizen advisory committee to review the need for changes in the Ground-Water Quality Protection Policy. Changes considered by the committee include additional ground-water-quality standards, and aquifer-classification system, more specific policy-implementation instructions, and more stringent nonpoint-source pollution control. The Department also publishes ground-water-quality information for public distribution and presents information to groups interested in various ground-water-quality protection programs.

Recent ground-water-quality monitoring by the DEQ has identified numerous occurrences of contamination in Oregon, including the presence of organic and toxic substances in ground water. These discoveries have led to demands for sampling and analyses that exceed current fiscal resources. General information is available for many of the aquifers of the State, but detailed information is lacking, particularly with regard to natural background and variability of ground-water quality. The Department has entered into a long-term project with the Oregon Water Resources Department to characterize the natural water quality of the aquifers of the State. This study will include analyses for organic and toxic substances. Because of limited fiscal resources, this study will focus on only a few selected aquifers. However, a more comprehensive, statewide, monitoring network for ambient ground-water quality is needed.

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PENNSYLVANIA
Ground-Water Quality

Since Colonial times, ground water in Pennsylvania has become increasingly important for domestic, commercial, and industrial use. The largest withdrawals have always been concentrated in the industrial areas of Pittsburgh and Philadelphia (fig. 1). Whereas ground-water withdrawals today comprise only about six percent of the total water use in Pennsylvania, more than one-third of the population depends on nearly one billion gallons of high quality uncontaminated ground water for its daily needs (Solley and others, 1983). Twenty one of the 67 counties obtain more than one-half their total supply from ground water, and two rural counties obtain as much as 98 percent (Becher, 1970). Although there has been only minimal population growth during the past two decades, the sustained migration of people and industry from the cities to a more rural setting has been responsible for the development of ground-water resources at a rate three times that of surface water (fig. 1).

Ground water in the principal aquifers is generally acceptable for drinking with little or no treatment. Excess iron, sulfate, and dissolved-solids concentrations near mining and oil and gas production activities in western Pennsylvania contribute to quality problems. Hardness and nitrate problems are generally limited to the carbonate aquifers in the central and southeastern part of the State.

Ground-water contamination is a serious problem in some urban and agricultural areas. Important coastal-plain aquifers in the extreme southeastern part of Pennsylvania have been severely contaminated by industrial waste including such persistent organic compounds as trichloroethylene (TCE) and tetrachloroethylene [Perchloroethylene (PCE)]. Leaking underground gasoline storage tanks have contributed to local ground-water problems statewide. Major water-quality concerns are related to contamination from malfunctioning septic systems, landfills, illegal dumping of waste, overfertilization with nutrients, organic chemicals, and road salts.

Approximately 70 land-disposal facilities require monitoring under the Federal Resource Conservation and Recovery Act (RCRA) of 1976, and 47 sites have been included in the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c). The 47 Superfund sites require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Contamination has been detected at 26 of the CERCLA sites.

WATER QUALITY IN PRINCIPAL AQUIFERS

Natural ground-water quality in Pennsylvania is extremely diverse due to the large number of rock formations and their lithologic and chemical differences. Because of Pennsylvania's complex geologic history, ground-water basins are limited in areal extent and bedrock aquifers are regionally less significant. Four principal types of aquifers exist in Pennsylvania (fig. 2): (1) Unconsolidated sand-and-gravel aquifers; (2) sandstone and shale aquifers; (3) carbonate aquifers; and (4) crystalline aquifers. Physical descriptions of the aquifer groups along with water-well characteristics are discussed in the U.S. Geological Survey (1985) and in Barker (1984).

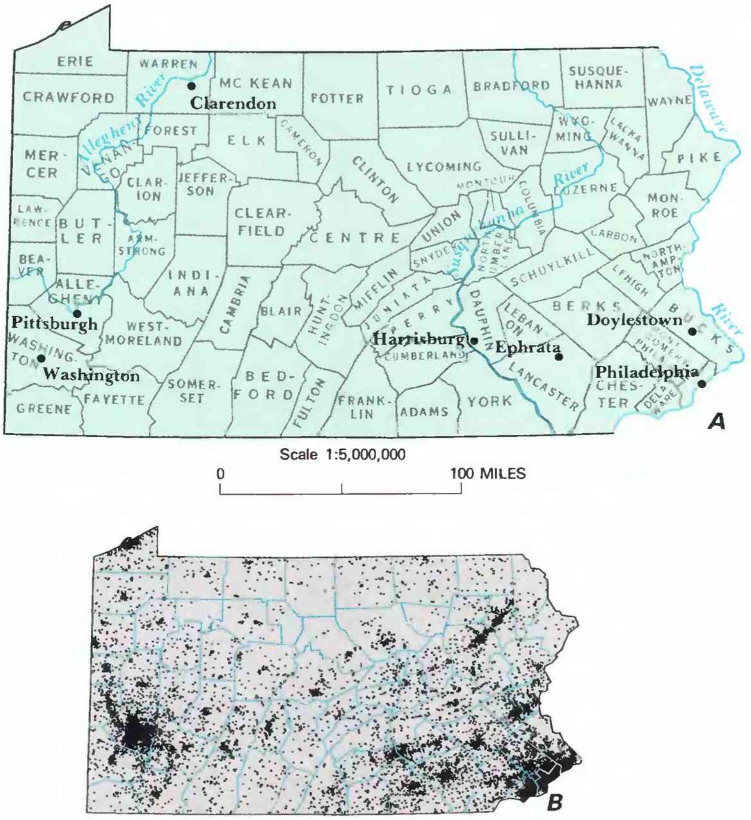

Figure 1. Selected geographic features and 1985 population distribution in Pennsylvania. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

The constituents of water that generally determine its suitability for most purposes are dissolved solids, calcium carbonate, and iron. Concentrations of chloride and nitrate may also restrict the use of water. A water supply with a dissolved-solids content of less than 500 mg/L (milligrams per liter), a hardness (as calcium carbonate) of less than 150 mg/L, and an iron content of less than 300 μg/L (micrograms per liter) is satisfactory for domestic purposes. For industrial purposes, acceptable concentrations depend on the intended use.

A recent statewide analysis of ground-water-quality data (Barker, 1984) indicates that about 93 percent of the nearly 4,700 water samples examined contained less than 500 mg/L of dissolved solids. In general, natural ground-water quality in Pennsylvania is within the U.S. Environmental Protection Agency (EPA) national primary and secondary drinking-water standards. Except in isolated cases, such as excess iron and sulfate in some sedimentary rocks, the major aquifers do not contain significant amounts of poor-quality ground water. Areas of naturally impaired ground water are not well defined nor cause apparent serious problems.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure

2*C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), chloride, and iron analyses of water samples collected from 1925 to 1985 from the principal aquifers in Pennsylvania. The summary is limited to selected representative geologic units where the data base for chemical quality is adequate for statistical summaries. Water-quality analyses with obvious natural or man-made contamination were not included. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are legally enforceable. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 300 μg/L iron.

Unconsolidated Sand-and-Gravel Aquifers

The unconsolidated sand-and-gravel aquifers consist of the coastal-plain sediments and glacial fluvial and alluvial deposits. The coastal-plain sediments are along the Delaware River estuary from north of Philadelphia to the Delaware state line. The sediments consist of a wedge of sand, silt, clay, and gravel deposited in a marine and non-marine environment that thickens from a few feet at the Fall Line to more than 6,000 ft at the shore of the Atlantic Ocean. The glacial outwash and alluvial deposits occupy most major stream

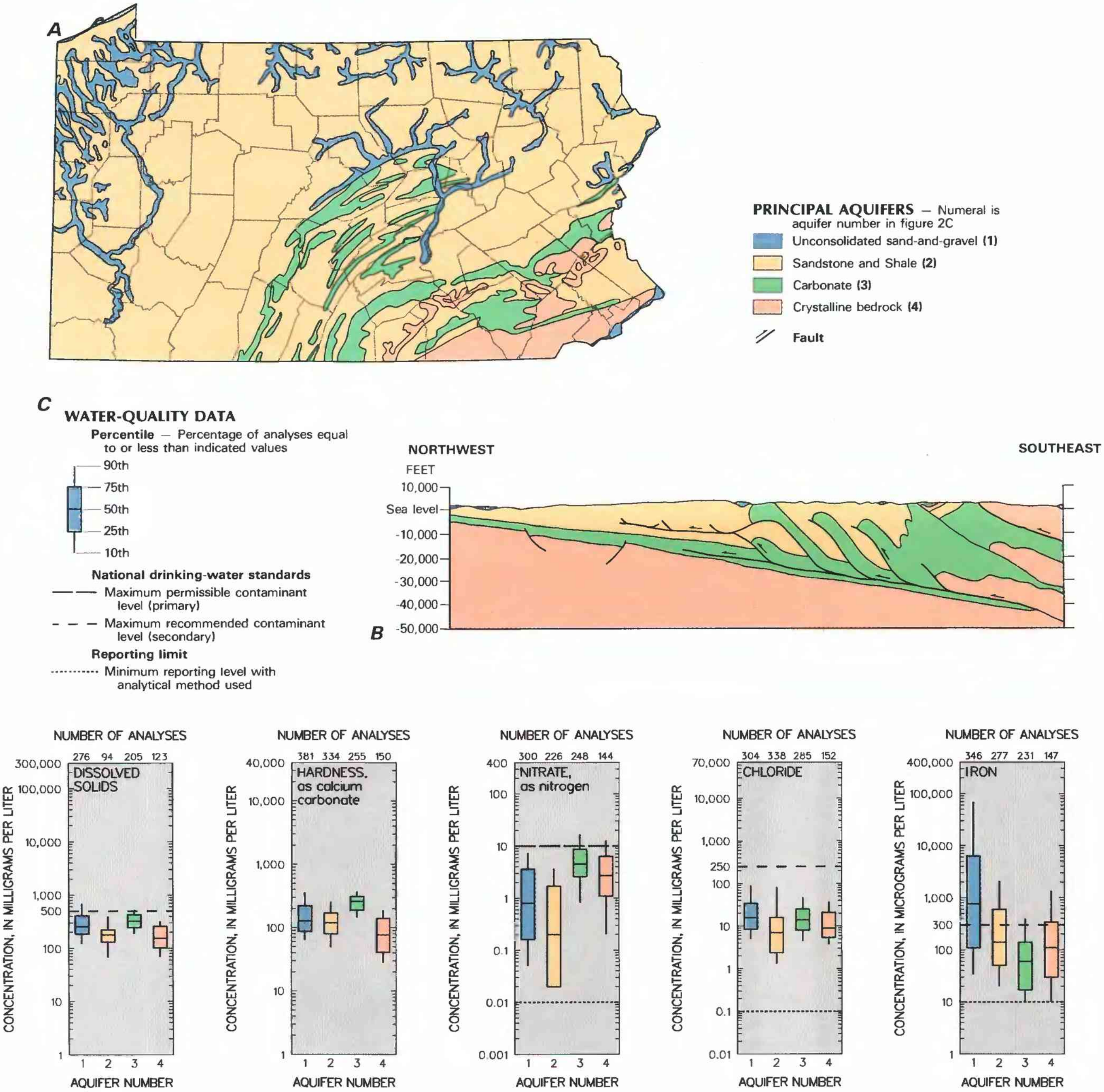

Figure 2. Principal aquifers and related water-quality data in Pennsylvania. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, 1925 to 1985. (Sources: *A*, *B*, Pennsylvania Topographic and Geologic Survey. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

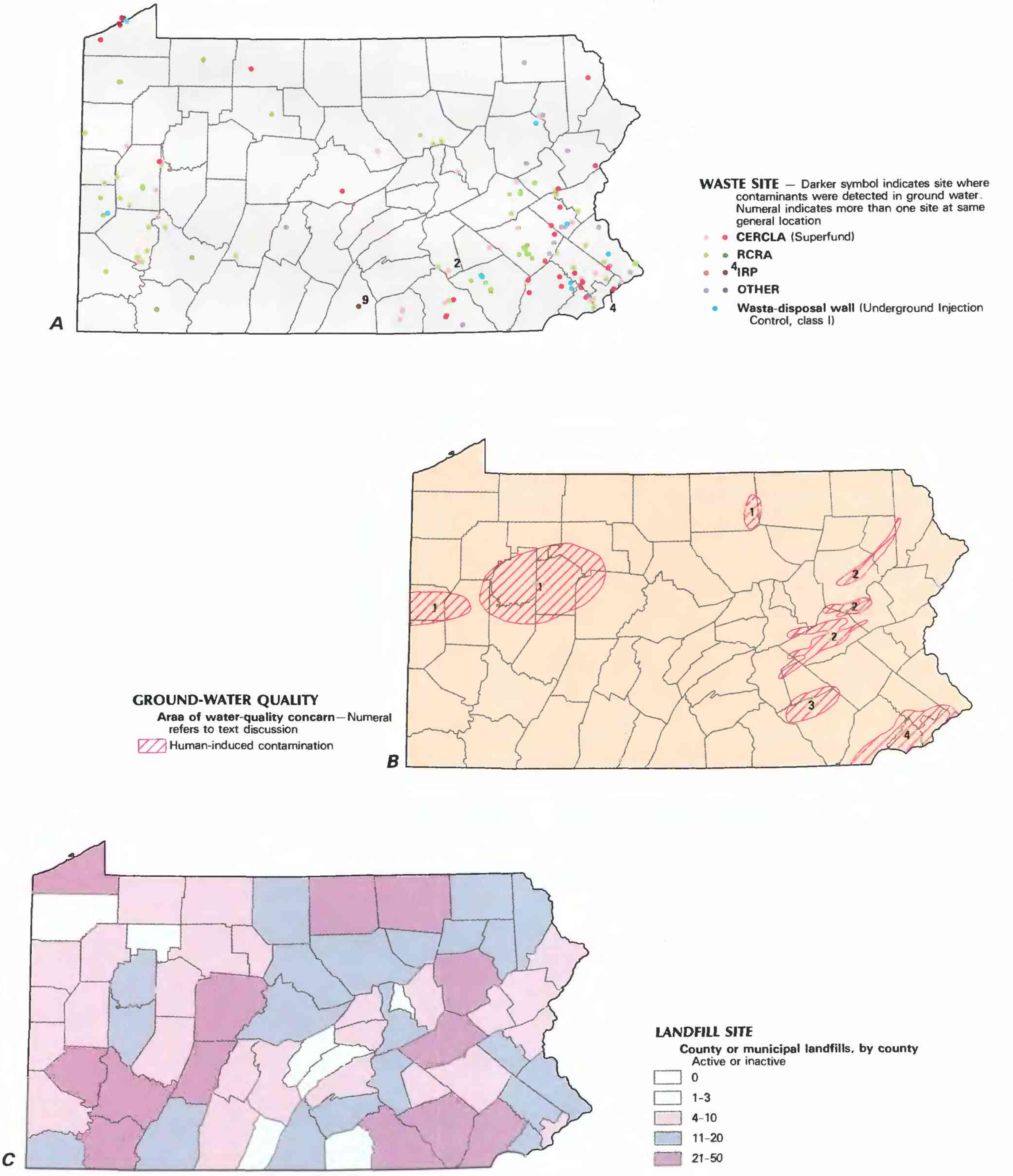

Figure 3. Selected waste sites and ground-water-quality information in Pennsylvania. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of human-induced contamination, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A*, Commonwealth of Pennsylvania 1986; U.S. Department of Defense 1986; U.S. Environmental Protection Agency, 1986c. *B*, Delaware River Basin Commission, 1982; Durfor and Anderson, 1963; Fishel and Lietman, 1986. *C*, Commonwealth of Pennsylvania 1986.)

valleys affected by glaciers that covered the northern part of the State. These deposits range from a few feet to more than 200 ft thick.

The unconsolidated sand-and-gravel aquifers contain the Commonwealth's most important and productive water-bearing formations. Yields of 1,000 gal/min (gallons per minute) or more are common and occasionally 2,000 gal/min or more are obtained from a single well. The ground water in most areas is of good to excellent quality. However, ground-water contamination is a serious problem near Philadelphia where overdevelopment has resulted in saltwater intrusion and down-dip migration of contaminants. Contamination by trace metals and synthetic organic compounds from industrial waste and landfill leachate is also a threat to water supplies.

Water from the aquifers in the unconsolidated sand-and-gravel are chemically highly diverse but dominated by ions of calcium and bicarbonate. The dissolved-solids concentrations range from 20 to more than 4,000 mg/L. About 20 percent of the well water tested exceeded the national secondary drinking-water standard of 500 mg/L.

Hardness, mainly as calcium and magnesium, ranges from about 60 to 1,900 mg/L. The median value of 128 mg/L indicates that almost half of the water tested exceeded the suggested State criteria of 150 mg/L for domestic use.

Nitrate (as nitrogen) is an end product of the bacterial oxidation of organic material. Problems with nitrate pollution are present in many local areas due to the ease with which wastes from leaky sewers, septic tank drain-field systems, and barnyards infiltrate the unconsolidated aquifers. Concentrations are as large as 39 mg/L. The median value for the aquifer group is 0.8 mg/L, and less than 10 percent of the water supplies exceed the national primary drinking-water standards of 10 mg/L as nitrogen.

Chloride is present in all natural waters but is rarely the dominant ion. The median value of 16 mg/L (fig. 2*C*) for the unconsolidated sand-and-gravel aquifers is considerably above the State median of 10 mg/L due to the large number of wells in the coastal-plain sediments that are affected by saltwater intrusion caused by over-development. The national secondary drinking-water standard of 250 mg/L was exceeded in only four percent of the more than 300 samples tested. Salt used for deicing highways and industrial waste may be a factor in chloride concentrations.

Iron is an abundant and widespread constituent of water in the coastal-plain aquifers. Concentrations of iron range upward to more than 400,000 μg/L. The median value is 765 μg/L (fig. 2*C*), exceeding the EPA national secondary drinking-water standard of 300 μg/L.

Sandstone and Shale Aquifers

The sandstone and shale aquifers are an extremely diverse group of interbedded sandstones, siltstones, and shales that dominate the lithology of much of Pennsylvania's bedrock. Their combined thickness can be from 16,000 to 20,000 ft. Most water-bearing units are confined. The water is contained in fractures that may permit vertical flow, and yields are commonly from 5 to 60 gal/min; yields of 500 gal/min are possible. The State's complex geology has resulted in ground-water supplies that commonly obtain water from more than one water-bearing zone and, therefore, have a chemical character that is the product of diverse lithology. Where sandstones predominate, the water is soft; where shales predominate, the water is usually hard.

Ground water in the sandstones and shales in southeastern, central, and northern Pennsylvania predominantly contains calcium and bicarbonate ions where the dissolved-solids concentration is less than 300 mg/L and contains calcium and sulfate ions where the dissolved-solids concentration is greater than 300 mg/L (Durfor and Anderson, 1963).

Less than 10 percent of the water samples tested exceeded the national drinking-water standard of 500 mg/L for dissolved solids, whereas nearly half the samples tested contained water that exceeded 150 mg/L hardness (fig. 2*C*). Nitrate (as nitrogen) contamination is rarely a problem and chloride is only a problem in a few deep wells that intercept saline water. Iron is a common problem in some units, particularly those associated with Pennsylvanian Age coal-bearing formations.

Carbonate Aquifers

The carbonate aquifers containing limestone and dolomite, chiefly of Cambrian and Ordovician Age, are in the valleys in the central and southeastern parts of the State. Carbonate aquifers are among the most important water-bearing formations in Pennsylvania. Solution channels, fractures, and partings between rock layers yield moderate to large supplies of water to wells. These characteristics also make the shallow carbonate aquifers susceptible to contamination from agricultural chemicals, landfills, and spills.

Water quality in the carbonate aquifers is also highly diverse. The major ions are calcium and bicarbonate, which account for the group's median hardness of 260 mg/L and dissolved-solids concentration of 325 mg/L. About 10 percent of the samples tested exceeded the secondary drinking-water standard of 500 mg/L for dissolved solids.

Nitrate contamination, primarily from agricultural waste, exceeds the national primary drinking-water standard of 10 mg/L as nitrogen in almost 25 percent of the samples tested. Most of this water is within the drinking water criteria for chloride and iron.

Crystalline Bedrock Aquifers

Crystalline bedrock aquifers, consisting of Precambrian, Cambrian, and Silurian Age igneous and metamorphic rocks, occupy a large part of southeastern Pennsylvania (fig. 2). Because of their crystalline nature, these rocks store only small to moderate amounts of water, and commonly yield about 5 to 25 gal/min—sufficient for domestic needs. Water-bearing zones that yield significant quantities of water are found only near the surface in fractures and crevices of weathered rock. The median well depth is only about 100 feet.

The quality of water from the crystalline bedrock aquifers is suitable for most uses, and is among the freshest in the state; the median dissolved-solids concentration is less than 200 mg/L. The water is soft, with a median hardness of less than 80 mg/L (fig. 2*C*). The predominant ions are calcium, sulfate, and bicarbonate, and the water is generally slightly acidic. Nitrate (as nitrogen) exceeds the 10 mg/L national primary drinking-water standard in about 12 percent of the samples tested. Chloride is not a common contaminant but iron and manganese exceed the recommended standard in about 35 percent of the samples tested. Iron and manganese generally increase with depth. Contamination with metals and volatile organics from storage tank leakage, industrial waste discharge, and landfill leachate is a local problem.

EFFECTS OF LAND USE ON WATER QUALITY

As the fourth most populated state and the second-ranking industrial state, Pennsylvania's cultural activities are severely affecting the ground-water resources in many areas. Ground-water quality is particularly susceptible to the effects of urbanization, effluent from mining, gas and oil wells, agriculture, and industrial wastes. In 1985, for example, the Pennsylvania Department of Environmental Resources (PADER) investigated more than 400 ground-water pollution incidents. The most commonly investigated incidents were related to underground storage tanks, oil and gas brine pits, road salting, septic tanks, and agricultural activities in that order (Commonwealth of Pennsylvania, 1986). Sewage-treatment facilities that apply sludge directly to the land, waste-disposal sites, liquid-storage lagoons, and landfills that use natural or artificial depressions over highly permeable formations are high risks.

Waste Disposal

Human activities are a primary cause of ground-water-quality problems in all aquifer groups. A recent study by R.E. Wright Associates, Inc. (1982), concluded that 84 percent of documented ground-water contamination cases in the Middle Delaware River Basin were related to contamination by hydrocarbons or organic chemicals. They also found that the volatile organic chemicals (VOC), TCE and PCE accounted for nearly one-third of the reported cases. The losses to public water supplies in the region due to TCE and PCE contamination range between 3.0 and 3.5 million gallons per day.

The PADER has identified approximately 70 hazardous-waste land-disposal facilities or RCRA sites in the Commonwealth. Forty-seven hazardous waste CERCLA sites have met the requirements of the EPA (U.S. Environmental Protection Agency, 1986c) for remedial action under Superfund because it has been determined that a "hazardous substance" was released into the environment or that there is a substantial threat of such release. Many of the sites (fig. 3*A*) are in the densely populated areas of southeastern Pennsylvania and are a potential health threat.

As of September 1985, 80 hazardous-waste sites at facilities in Pennsylvania had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 80 sites in the program, 9 sites contained contaminants but did not present a hazard to the environment. Fifteen sites at three facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at four of these sites has been completed under the program. The remaining sites were scheduled for contamination studies to determine if remedial action is required.

Mining

Deep and surface mining of coal in northeastern and western Pennsylvania, and oil and gas drilling activities in the northwestern part of the Commonwealth have caused some ground-water supplies to have increased acidity and elevated concentrations of sulfate, hardness, dissolved solids, and methane gas (fig. 3*B*, area 1). Some aquifers in the northeastern anthracite fields (fig. 3*B*, area 2) can no longer be used as potable water supplies as the result of contaminated mine water.

State and U.S. Geological Survey studies have documented such impacts throughout much of the coal, oil, and gas region. Authorities and citizens in Washington County are concerned about the effects large-scale mining of coal will have on water resources including the reduction of ground-water storage in shallow aquifers and municipal reservoirs which serve about 69 percent of the county residents. A recently completed U.S. Geological Survey study (D.R. Williams, U.S. Geological Survey, written commun., 1986) indicates that underground mining resulted in lowered water levels in wells, and increased concentrations of iron, manganese, sulfate, and dissolved solids. Well owners reported an objectionable sulfur odor and an iron taste in their water during and after mining.

In Warren County, near Clarendon, and in Erie County, several private wells were investigated for the presence of natural gas following complaints by residents. An investigation by PADER showed concentrations of methane, as much as 70 parts per million, to be a safety hazard. The methane gas was traced to local gas wells that had a build-up of pressure causing migration into the private water wells (Robert H. Gleason, Pennsylvania Department of Environmental Resources, written common., 1986).

Agricultural Practices

Contamination of ground water from excessive application of manure and agricultural chemicals has led to the deterioration of ground-water quality in many intensively farmed areas, particularly those underlain by carbonate bedrock (fig. 3*B*, area 3). A study by Fishel and Lietman (1986) has shown that in an area near Ephrata, Lancaster County, nitrate (as nitrogen) concentrations reached 40 mg/L and the median concentration was about 10 mg/L. Following spring fertilizer applications, the ground water from one 55-acre field contained nitrate (as nitrogen) concentrations that ranged from 7.4 to 130 mg/L. This is about three times that which is required by corn crop.

Median concentrations of nitrate were generally three times higher in water from carbonate aquifers than noncarbonate aquifers. Forty percent of the ground-water supplies that were both in a carbonate aquifer and an agricultural area had nitrate (as nitrogen) concentrations that exceeded the 10-mg/L criterion established by the EPA as excessive for drinking water. Atrazine, simazine, alachlor, and metolachlor are commonly used herbicides that were found almost exclusively in the ground water of the agricultural carbonate areas. Concentrations in ground water often reached 3 to 4 μg/L following application.

Urbanization

Human activity has a cumulative effect on ground-water resources during the progressive stages of urbanization. The effects may include diversion of recharge, aquifer overdevelopment, and contamination from industry, sewage-treatment plants, and municipal landfill sites. The largest number of municipal landfill sites are in counties adjacent to areas of high population densities (fig. 3*C*).

Overdevelopment of the aquifers in the urbanized and industrial areas of the coastal plain has resulted in large cones of depression that have created a number of water-quantity and quality problems as a result of induced infiltration of contaminants and saltwater intrusion (fig. 3*B*, area 4). Identified problems include increased concentrations of iron, manganese, sulfate, chloride, and nitrate. The effects of induced infiltration and aquifer contamination are illustrated with the fifteen-year documentation of changing water quality in a well in the Coastal Plain (fig. 4). Possibly as much as 43 percent of the total flow to the Potomac-Raritan-Magothy aquifer, in 1973, was induced from the Delaware River (Delaware River Basin Commission, 1982). VOC have been detected in 39 percent of the samples from wells in the industrial and commercial areas of the coastal plain, and in 28 percent of the ground-water supplies from the Potomac-Raritan-Magothy aquifer (Delaware River Basin Commission, 1982).

A 65-mi^2 area in southeastern Pennsylvania just south of Doylestown (fig. 1) that sustained rapid suburban development and industrial growth following World War II, increased in population by more than 1,700 percent between 1940 and 1970. Ground-water pumpage in 1980 of 2.7 billion gallons has resulted in significant aquifer drawdown as far as 2,500 feet away, thereby reducing the quantity of streamflow. Reduced streamflow has resulted in degradation of surface-water quality due to higher concentrations of sewage-plant effluent. Seven wells, sampled in the mid-1950's and again in 1979, had an average of 22 percent increase in the median concentration of most dissolved constituents. Contamination by VOCs has made water from some wells unsuitable for public supply. Reported concentrations of two of the most common VOCs, Trichloroethylene (TCE) and Tetrachloroethylene (PCE), were as high as 87,000 μg/L, and 26,000 μg/L, respectively (Sloto and Davis, 1983).

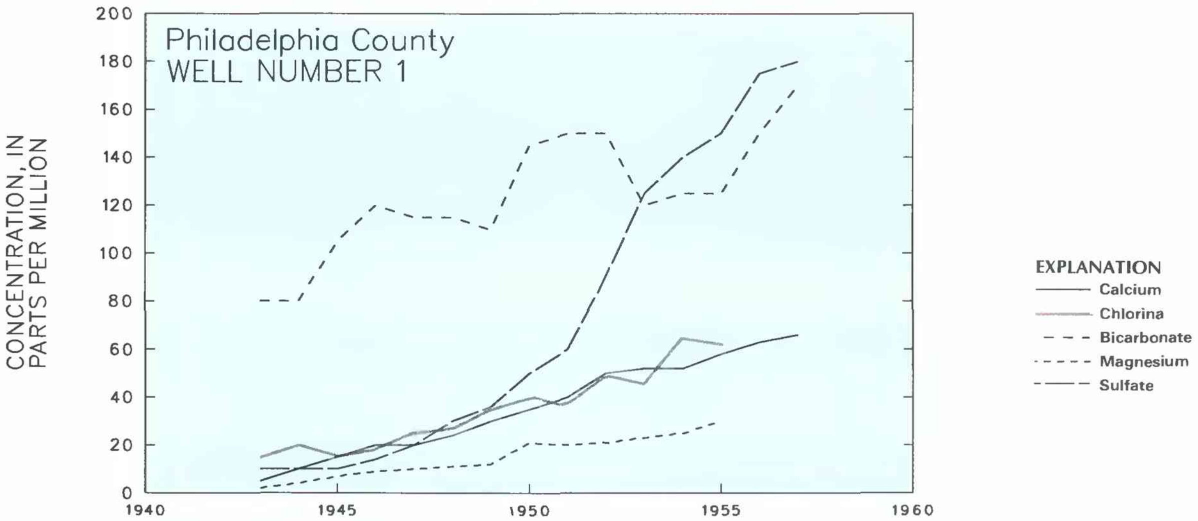

Figure 4. Changes in selected chemical constituent concentrations in well PH-1 from 1943 to 1957. (Sources: Greenman and others, 1961.)

POTENTIAL FOR WATER-QUALITY CHANGES

Future demands upon available ground-water resources may require planned development as the needs reach the maximum sustained yield of a region or aquifer. Development of the ground-water resources will likely follow patterns similar to those of the past. Industry and suburban expansion near to existing population centers will continue to require ground water to supply its growth needs. The agricultural industry and the domestic needs of a growing number of rural dwellers will also need to be satisfied. According to the 1980 census, the Commonwealth's population has nearly stabilized at just under 12 million with a growth of only 0.5 percent since 1970. It is significant that between 1950 and 1970, the urban population decreased by 2.6 percent while the rural population increased by 8.4 percent. This trend toward to a more rural environment has been at least partly responsible for a 35-percent increase in ground-water use between 1960 and 1966, a rate three times that of surface water (Becher, 1970).

Known sources of ground-water contamination in Pennsylvania are many and varied. A recent (1986) tally by PADER shows there are approximately 4,000 surface mines, 300 deep mines, 420 coal-refuse disposal sites, 1,000 community on-lot disposal systems greater than 10,000 gal/d, 7,250 industrial and mining waste impoundments, 159 hazardous-waste-management facilities, 1,700 municipal and residual waste-management facilities, 60 open dumps, 11 hazardous-injection wells and industrial disposal wells, and 85 spray irrigation sites. In addition, there have been at least 560 hydrocarbon spills since 1968.

Whereas Pennsylvania has relatively large ground-water supplies in the developed and undeveloped areas of both the unconsolidated sand-and-gravel aquifers and the carbonate aquifers, these aquifer groups also are the most susceptible to contamination. Projected industrial expansion, population trends, and agricultural trends are expected to stimulate ground-water development in these areas. Primary future concerns will be related to ground-water depletion due to overdevelopment, contamination from malfunctioning on-lot septic systems, landfills, illegal dumping of toxic substances, the excessive use of nutrients, organic chemicals, and road salts (U.S. Department of Commerce, 1984).

GROUND-WATER QUALITY MANAGEMENT

The PADER is the State agency primarily responsible for the protection and management of Pennsylvania's ground-water resources. Several bureaus within the PADER Offices of Environmental Protection and Resources Management implement ground-water programs within the Commonwealth. The majority of these ground-water management programs rely upon the development and implementation of regulations, siting criteria, and permits to prevent and abate pollution from all major sources. As examples, PADER is developing siting criteria and regulations governing the development and operation of solid-waste and hazardous-waste facilities. State mining regulations require evaluation of mine impacts on the hydrologic balance and water quality of affected aquifers and watersheds before permitting, and mandate reclamation of disturbed lands concurrent with mining. Proposed oil and gas regulations adopted in 1985 address significant potential pollution problems through standards for casing, brine disposal, and closure of abandoned wells.

In addition to State regulatory control, certain activities are also governed by federal agencies and basin commissions. A dual program exists with the Federal Government in regard to the Underground Injection Control (UIC) Program. Both the Susquehanna and Delaware River Basin Commissions have adopted programs regulating significant withdrawals of ground water throughout their respective basins. In addition, an intensive program instituted by the Delaware River Basin Commission (DRBC) in the five county Southeastern Pennsylvania Ground Water Protected Area (near Philadelphia) is aimed at protecting stressed ground-water resources within the predominantly Triassic aquifers. This DRBC program requires permits for withdrawals of ground water that exceed 10,000 gal/d within the Protected Area, and imposes strict pump-test, environmental-review, and conservation criteria.

IMPLEMENTATION OF FEDERAL WATER-QUALITY LEGISLATION

Current program areas under federal legislation include primacy under the Safe Drinking Water Act, RCRA, CERCLA, Clean Water Act, Toxic Substance Control Act, and the Surface Mining Control and Reclamation Act.

The Bureau of Community Environmental Control has the prime responsibility for the implementation of the Pennsylvania Safe Drinking Water Act and the development of State maximum contaminant levels (MCLS) for drinking-water supplies, on a case by case basis, where MCLS have not been established by the EPA. In addition to drinking-water supplies, the Safe Drinking Water Act has various other programs associated with it—the UIC Program, Well Head Protection Program, and the Sole Source Aquifer Designation Program.

The Bureau of Waste Management is responsible for the program areas of RCRA and CERCLA. The RCRA regulations govern the control, usage, and disposal of hazardous wastes requiring cradle to grave manifests for regulatory purposes. The CERCLA or Superfund investigation and clean-up activities are also carried out in the State at many sites. To date, two sites have been cleaned up to levels acceptable to EPA.

Several activities were carried out recently under Section 208 of the Clean Water Act. One of the projects was titled "The Evaluation of Soil Dependent Treatment Systems." This project examined sites with marginal soil cover to determine the sites' renovative capabilities for treating sewage effluent. Other section 208 activities included the development of a proposed ground-water management protection strategy and a proposed ground-water monitoring strategy. These strategies are currently being revised internally within PaDER.

STATE POLICIES AND STRATEGIES

As stated, the development of a ground-water-management program was initiated under Section 208. It is being continued under Section 106 grants. The proposed ground-water-management program consists of two strategies: 1) a proposed ground-water-quality protection strategy; and 2) a proposed ground-water-quality monitoring strategy. The ground-water quality-protection strategy is designed to protect ground water for two designated statewide uses: 1) potable-water supply; and 2) surface-water-quality maintenance. In addition, the protection strategy also proposed the delineation of special protection in areas where no ground-water degradation would be permitted by waste sources regulated by the Department. The protection strategy also provides for delineation of mixing and buffer zones for all major land treatment/disposal systems.

The proposed ground-water-quality monitoring strategy will provide for a greater utilization of the ground-water data currently collected by the compliance monitoring activities of the bureaus in the Department. To supplement this effort, a fixed-station monitoring network has been proposed for high-priority ground-water basins. In addition, special in-house surveys would be used in areas where ground-water data gathering efforts are limited or more detailed data are needed because of a suspected pollution problem.

ADEQUACY OF GROUND-WATER INFORMATION

An assessment of existing data indicates that data are available, but they are not readily accessible. Collection is accomplished as part of the compliance and monitoring activities routinely carried out by the various bureaus and through specific activities such as the pilot project monitoring ground-water quality in ground-water basins. Most of the data are stored in paper form or on various computer systems with limited compatibility and accessibility. Adequate information exists on maps and geological documentation to provide support for any type of ground-water protection program. The proposed monitoring strategy recommends that most ground-water monitoring data be placed in a computer data base which is accessible by both State and federal agencies.

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Mommoth Spring flowing from Alexander Cavern near Reedsville, Pennsylvania. Inflow of surface water draining nearby agricultural lands to the shallow limestone aquifer results in water flowing from the spring with bacterial indicators of recent warm-blooded animal fecal contamination. (Photograph by James L. Barker, U.S. Geological Survey.)

Prepared by James L. Barker, U.S. Geological Survey; "Ground-Water-Quality Management" section by Nicholas Molina, Pennsylvania Department of Environmental Resources.

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Puerto Rico
Ground-Water Quality

Aquifers in Puerto Rico (fig. 1) provide 170 Mgal/d (million gallons per day) of freshwater for domestic, industrial, and agricultural uses. Ground water is the source of drinking water for about 900,000 people and for most of the irrigation requirements and the expanding pharmaceutical and electronics industries.

The quality of Puerto Rico's ground water is suitable for most purposes and generally meets the drinking-water standards established by the Puerto Rico Department of Health (PRDOH). However, large water withdrawals from aquifers along the coast have caused seawater encroachment, resulting in well abandonment. Large concentrations of iron and manganese are local problems for users of ground water on the east and west coasts.

The most important aquifers in Puerto Rico (U.S. Geological Survey, 1985, p. 367) occur along the south and north coasts (figs. 2*A*, 2*B*). The South Coastal Plain alluvial aquifer provides about 50 percent of the total public water supply of the south coast. The North Coast limestone water-table and artesian aquifers provide about 20 percent of the public water supply to north-coast communities. Other aquifers occur in alluvial valleys along the east and west coasts, within the alluvial and volcanic rocks of the interior of the island, and in the Esperanza and Resolucion Valley on the island of Vieques. About 50 percent of the total ground-water withdrawals in Puerto Rico are from the South Coastal Plain alluvial aquifer, 35 percent from the North Coast limestone aquifers, 10 percent from the East and West Coast alluvial valley aquifers, and 5 percent from the alluvial and volcanic rock aquifer of the island interior.

Degradation of water quality from accidental spills of organic chemicals and waste disposal is an increasing problem. Recent investigations by the U.S. Geological Survey have shown that ground-water contamination with volatile, synthetic organic chemicals is widespread (Guzman-Rios and Quinones-Marquez, 1985). The contamination has affected the suitability of ground water for public water supply in areas of the north, south, and east coasts.

At present (1986), the U.S. Environmental Protection Agency (EPA) has permitted a total of 362 generators of hazardous waste to operate under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Eight sites (fig. 3) have been included in the National Priorities List (NPL) of hazardous waste sites and designated as Superfund sites (U.S. Environmental Protection Agency, 1986c). These sites are currently monitored as part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Although no ground-water contamination has been detected at any of the RCRA sites, contamination has been confirmed at four of the eight CERCLA (Superfund) sites. However, the chemicals contaminating the aquifers have not been linked in all instances to surface releases or specific site contaminants.

Since 1955, the U.S. Geological Survey has monitored ground-water quality in cooperation with several agencies of the Commonwealth of Puerto Rico. One of the programs included analyses of various organic and inorganic constituents at 243 public water-supply wells. In addition, where ground-water-quality problems are suspected or identified, the Geological Survey has provided technical support to various Commonwealth and Federal agencies in conducting interpretive hydrologic investigations to determine the extent and severity of contamination and to maintain appropriate monitoring networks. The Geological Survey assisted the EPA in defining the hydrology of the Vega Alta CERCLA site (fig. 3*A*, site H) in north-central Puerto Rico. Test wells were drilled and soil and water samples were collected and analyzed to define the horizontal and vertical distribution of contaminants and to determine hydraulic properties of the shallow aquifer and confining beds. Assistance in collecting and interpreting ground-water-quality and geologic data was also provided to the EPA and local agencies at the Barceloneta CERCLA site (fig. 3*A*, site G).

WATER QUALITY IN PRINCIPAL AQUIFERS

Ground water throughout Puerto Rico is generally suitable for most uses except near the coast where the aquifer contains saltwater. Puerto Rico has several geochemically distinct aquifer environments. The North Coast limestone artesian aquifer, consisting of the Cibao Formation and Lares Limestone, contains water geochemically similar to the overlying North Coast limestone water-table aquifer, which consists of the Aymamon and Aguada limestones and the incised alluvial valleys (fig. 2*C*). Distinct chemical characteristics have been observed in water from alluvial aquifers in the South Coastal Plain, the West Coast, and the East Coast systems. These regional distinctions in chemical composi-

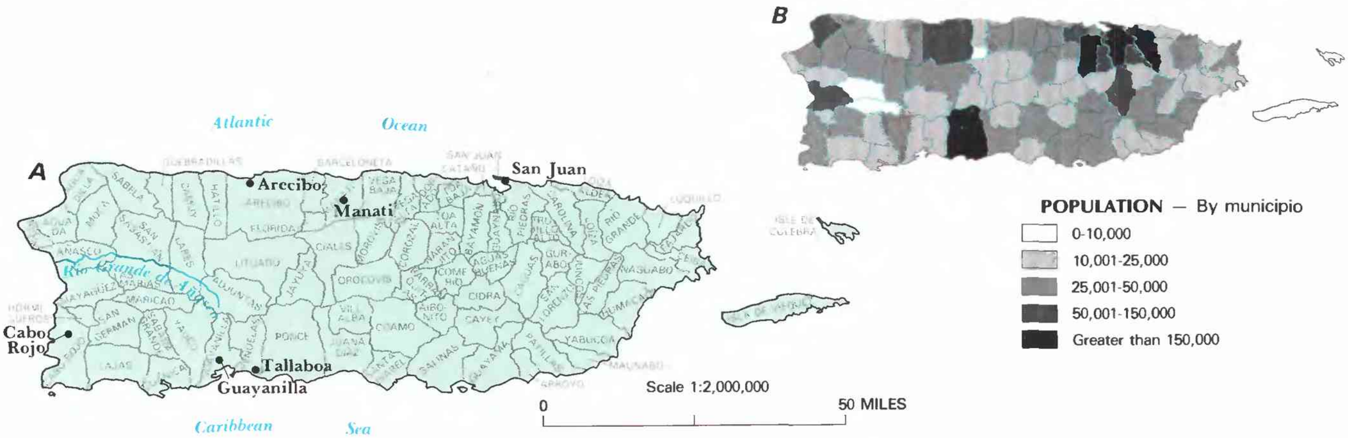

Figure 1. Selected geographic features and 1980 population distribution in Puerto Rico. *A*, Municipios and selected cities. *B*, Population distribution, as of 1980. (Sources: *B*, Data from U.S. Bureau of the Census data for municipio populations.)

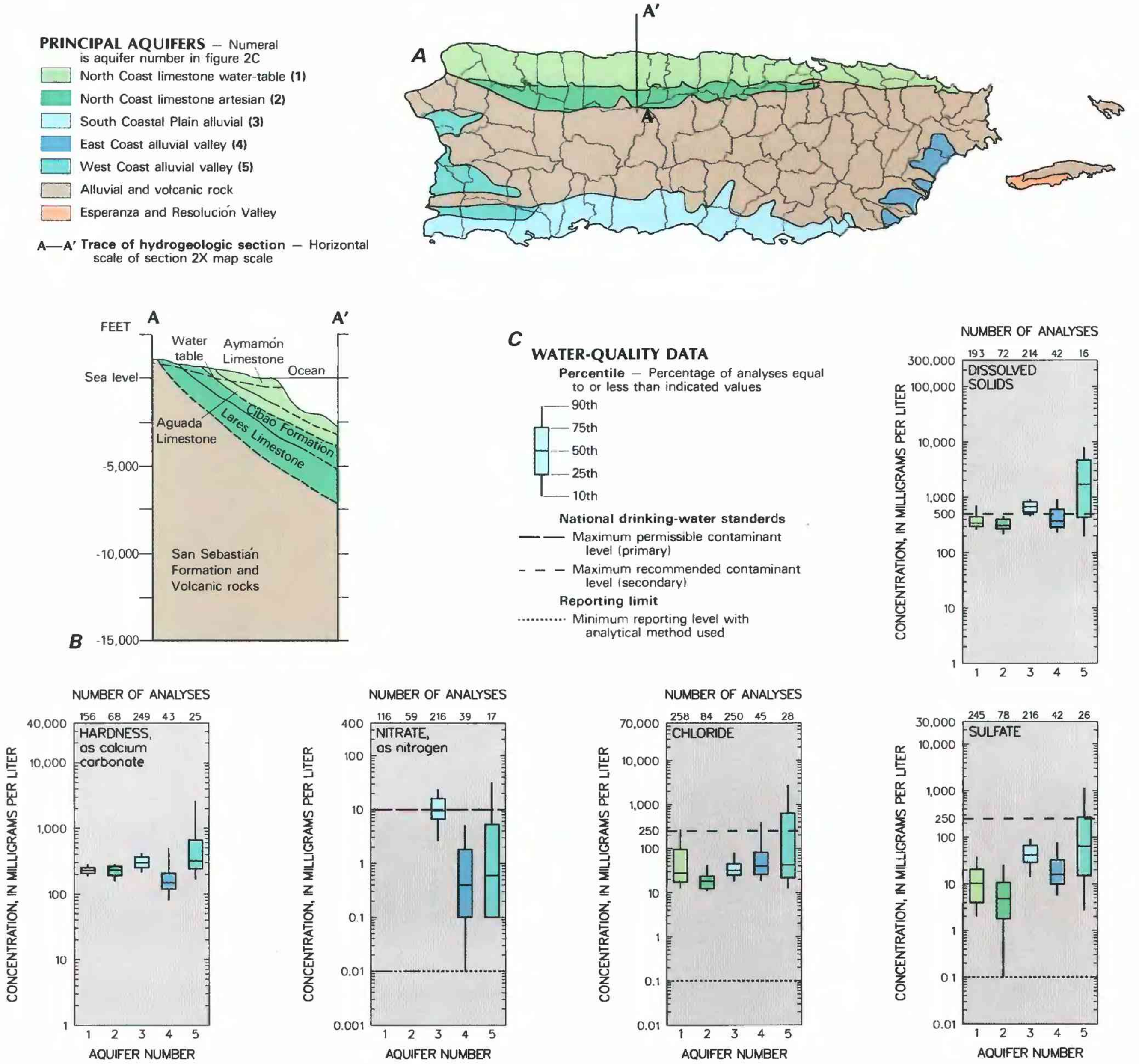

Figure 2. Principal aquifers and related water-quality data in Puerto Rico. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1955–85. (Sources: *A*, Adapted from Gomez-Gomez and Heisel, 1980. *B*, Adapted from Giusti, 1978. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

tion of the ground water are related in part to areal differences in aquifer composition and texture.

Saltwater occurs in all aquifers in Puerto Rico except within the interior alluvial and volcanic rock aquifer and the North Coast limestone artesian aquifer. The saltwater commonly underlies freshwater or is kept in hydrodynamic equilibrium laterally by inland freshwater moving outward from the island.

BACKGROUND WATER QUALITY

Reliable ground-water-chemistry data have been collected since 1955 in Puerto Rico. The largest number of samples was collected from aquifers most intensively developed—the South Coastal Plain alluvial aquifer and the North Coast limestone water-table aquifer. Fewer data are available for the North Coast limestone artesian aquifer, and the East and West Coasts alluvial valley aquifers. Water-quality data are scarce for the alluvial and volcanic rock aquifer and the Esperanza and Resolucion Valley aquifer.

The quality of water from all aquifers in Puerto Rico is generally similar. A statistical summary of data from 1955 to 1985 for dissolved solids, hardness (as calcium carbonate), nitrate (as nitrogen), chloride, and sulfate (fig. 2*C*) characterizes the small variability in chemical composition of the water. The summary has been compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). Percentiles of the variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include

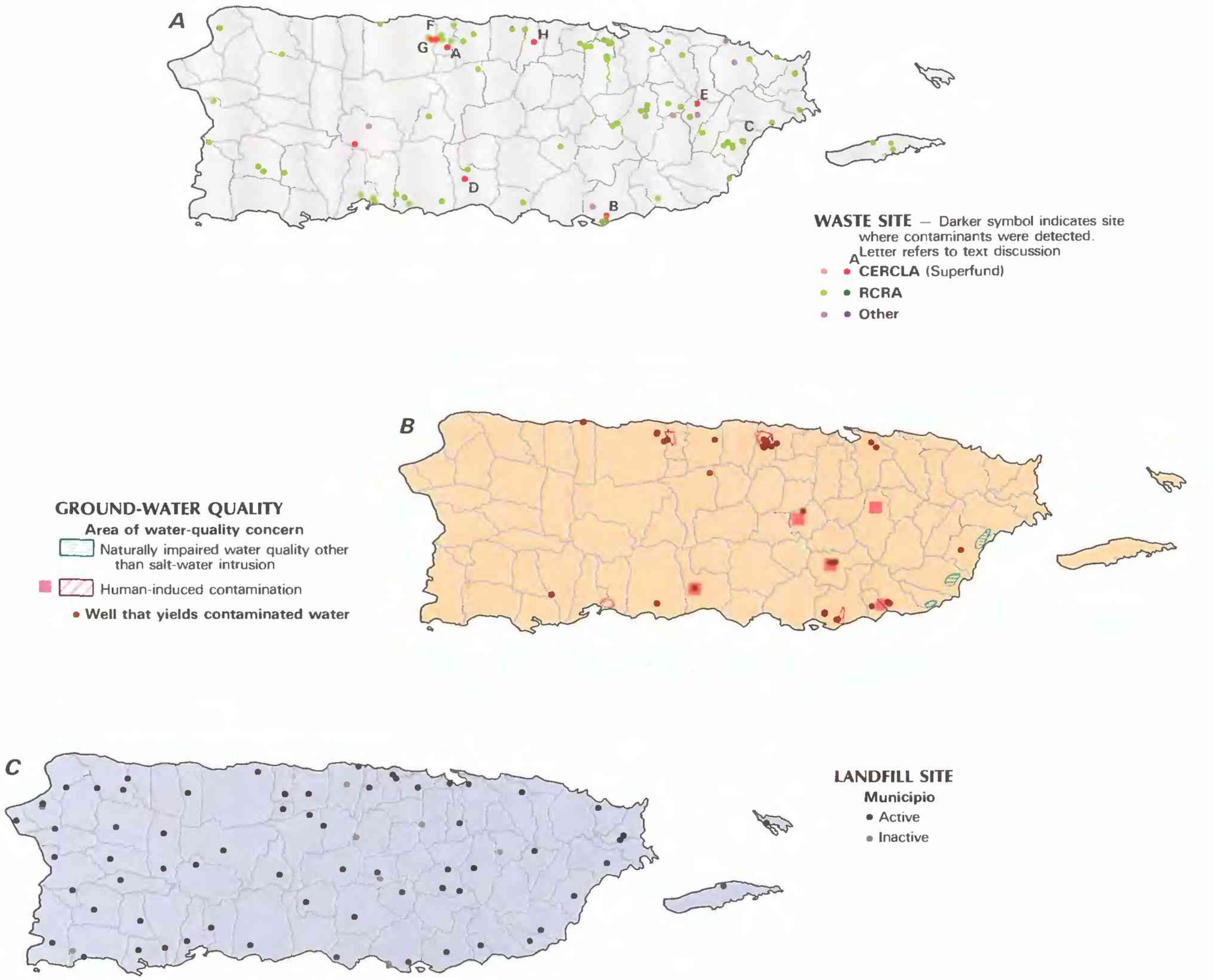

Figure 3. Selected waste sites and ground-water-quality information in Puerto Rico. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A*, Laura J. Livingston, U.S. Environmental Protection Agency, Region II, written commun., 1986; Victor Mata, Puerto Rico Environmental Quality Board, written commun., 1986. *B*, Guzman-Rios and others, 1986; Guzman-Rios and Quinones-Marquez, 1984; 1985. *C*, Victor Mata, Puerto Rico Environmental Quality Board files.)

a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 250 mg/L sulfate.

The water is generally very hard (fig. 2*C*), as calcium and bicarbonate are the dominant ions. The calcium and bicarbonate facies is replaced by a sodium chloride facies near the coast in a zone of freshwater-saltwater mixing.

North Coast Limestone Aquifers

Dissolved-solids concentrations for the North Coast limestone aquifers—water table and artesian—increase along the hydraulic gradient. Dissolved-solids concentrations can be larger than 500 mg/L in areas of saltwater intrusion or encroachment near the coast. Suitability of water for irrigation and public water supply is affected within these areas. The North Coast limestone artesian aquifer has dissolved-solids concentrations smaller than 500 mg/L throughout the aquifer. The freshwater-saltwater interface of the North Coast limestone artesian aquifer probably is seaward and freshwater discharges directly at the seabed.

Calcium and bicarbonate are the dominant ions within the artesian aquifer and the freshwater parts of the water-table aquifer, because they are derived from the aquifer matrix (Roman-Mas and Lee, 1985). The calcium bicarbonate facies is replaced by a sodium chloride facies in areas of the water-table aquifer where saltwater intrusion occurs. Chloride concentrations can be as large as 1,900 mg/L.

Background concentrations of nitrate for the water-table and artesian aquifers are smaller than the detection limit. Sulfate concentrations are usually small as the sulfate source within these aquifers is gypsum, a relatively uncommon mineral.

South Coastal Plain Alluvial Aquifer

Dissolved-solids concentrations throughout the South Coastal Plain alluvial aquifer are relatively large (fig. 2*C*), ranging from 130 to 1,750 mg/L. Calcium and bicarbonate are the predominant ions; these ions originate from beach and reef deposits that were buried by sediments eroded from the interior igneous rocks during the last rise in sea level (Fernando Gomez-Gomez, U.S. Geological Survey, written commun., 1986). Near the coast, where large dissolved-solids concentrations are derived from saltwater intrusion or encroachment, and sodium and chloride become the predominant ions.

Relatively large nitrate concentrations are observed within the South Coastal Plain alluvial aquifer; nevertheless, observed concentrations generally do not exceed the primary drinking-water standard. Because of the presence of relatively soluble and finely disseminated pyrite within the South Coastal Plain alluvial aquifer, sulfate concentrations are generally larger than in the North Coast limestone aquifers.

East and West Coastal Alluvial Valley Aquifers

Chemical composition and evolution of water within the East and West Coast alluvial aquifers are similar to those in the North and South Coast aquifers. However, dissolved-solids concentrations are larger: as much as 4,270 and 10,000 mg/L within the East and West Coast alluvial aquifers, respectively. Chloride concentrations also are relatively large, reaching 1,700 and 5,800 mg/L in the East and West Coast alluvial aquifers, respectively. These large dissolved-solids and chloride concentrations indicate significant saltwater encroachment within these aquifers, particularly the West Coast alluvial aquifer, in comparison to the North and South Coast aquifers.

Nitrate concentrations are generally small, with median concentrations of 0.4 mg/L (aquifer 4) and 0.6 mg/L (aquifer 5). However, in some areas of the West Coast alluvial aquifer, nitrate concentrations may exceed drinking-water standards.

Sulfate concentrations within the West Coast alluvial aquifer are considerably larger than for the other aquifers. The median sulfate concentration is 64 mg/L; however, about 25 percent of the compiled analyses exceeded the secondary drinking-water standard.

Areas of naturally impaired water quality have been found within the East Coast alluvial aquifer (fig. 3*B*). Large concentrations of iron and manganese, derived from plutonic rocks and ancient swamp deposits, have been reported for many wells in the area (Anders, 1971; Adolphson and others, 1977; Robert Graves, U.S. Geological Survey, written commun., 1986). Concentrations of iron and manganese can be as large as 2.4 and 6.2 mg/L, respectively, but do not affect the suitability of ground water for irrigation and livestock—the primary uses of ground water in these areas. However, the large concentrations are objectionable because they can clog pipes, produce unpleasant taste, and stain plumbing fixtures as well as clothes during laundering.

The Puerto Rico Aqueduct and Sewer Authority (PRASA) has recently reported concentrations of selenium larger than EPA recommended maximum level of 0.01 mg/L in four wells drilled in the volcanic rock of the south and west coasts of the island (Nicolino Liberatore, Puerto Rico Aqueduct and Sewer Authority, written commun., 1986). Two of the wells located at Guayanilla and one at Cabo Rojo were intended for public water supply, but were not used after selenium concentrations as large as 0.10 mg/L were reported.

Until 1978, the Esperanza and Resolucion Valley aquifer was the only source of freshwater for the population of the island of Vieques. Most wells completed in this aquifer in the Esperanza Valley were affected by sea-water encroachment when ground-water withdrawals exceeded 400,000 gallons per day (Sigfredo Torres, U.S. Geological Survey, oral commun., 1986). Chloride concentration in water withdrawn from several public-supply wells became as large as 500 mg/L. Ground-water withdrawals from the Esperanza Valley well field were discontinued in 1978 when a pipeline for public water supply was installed from the east coast of Puerto Rico. By 1981, the seawater drawn into the aquifer by intensive pumping was pushed seaward by rainfall recharge. The aquifer currently (1986) has reverted to its original pre-pumping condition, with chloride concentrations of 90 mg/L or less.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has been degraded in parts of several principal aquifers in Puerto Rico. Investigations by the U.S. Geological Survey and interpretation of data collected as part of the cooperative monitoring program have documented widespread aquifer contamination in Puerto Rico (Guzman-Rios and Quinones-Marquez, 1985; Guzman-Rios and others, 1986). Contamination has been caused by industrial-waste disposal and accidental spills, municipal landfills, agricultural-pesticide application, large ground-water withdrawals for urban centers and irrigation, and barnyard waste or septic drainage.

Industrial-Waste Disposal and Accidental Spills

The most serious threat to the continued use of aquifers as a source of drinking water in Puerto Rico is the contamination of ground water by various synthetic volatile organic chemicals (VOC). These chemicals are used as industrial solvents, degreasers, and cleaning agents, or are generated as toxic byproducts from metal, electronic, and pharmaceutical industries. Trichloroethylene (TCE) and tetrachloroethylene (PCE) have been identified as the principal organic contaminants. Concentrations of TCE and PCE as large as 480 and 776 μg/L (micrograms per liter), respectively, were measured during a study in which 243 public water-supply wells were sampled throughout the island (Guzman-Rios and Quinones-Marquez, 1984; 1985). The PRDOH has established an enforceable limit of 50 μg/L for TCE or PCE, and 100 μg/L for total VOC. The PRASA has discontinued use of 13 public water-supply wells with a combined production of 5.5 Mgal/d because of increased concentrations of VOC (fig. 3*B*).

Waste-disposal wells have contributed to ground-water contamination. In 1969, about 40 waste-disposal wells were operating in Puerto Rico. Wastes injected through wells included sewage, oil, neutralized acid, organic compounds, dyes, pickling liquors, pineapple cannery wastes, and brewery wastes (Donald Jordan, U.S. Geological Survey, written commun., 1969). In all known instances, the wastes were injected into North Coast limestone aquifers, both the water table and the artesian. At present (1986), the injection of any waste, except cooling waters, is prohibited.

Five waste-disposal sites in Puerto Rico have been designated as CERCLA (Superfund) sites (fig. 3*A*; Sites A, C, D, E, and F). Hazardous wastes disposed at these sites include pharmaceutical wastes, mercury pesticides, mercury from thermometer and light-switch manufacturing, chromium, iron, and selenium.

There are 362 generators of hazardous wastes in Puerto Rico operating under RCRA, of which about 73 (fig. 3*A*) are facilities for treatment, storage, and disposal (L.J. Livingston, U.S. Environmental Protection Agency, Region II, written commun., 1986). The remaining 289 sites temporarily store the waste at their industrial facilities for later removal to a permanent storage site or for transport to the United States. At present (1986), only one operating commercial industrial landfill in Puerto Rico is used for storing hazardous waste and toxic byproducts. It is near Tallaboa on the south coast and reportedly accounts for 10 percent of all industrial hazardous waste produced in the island (Carl-Axel Soderberg, Puerto Rico Environmental Quality Board, oral commun., 1986). The Puerto Rico Environmental Quality Board (PREQB) estimates that more than 500,000 tons per year of hazardous wastes are produced in Puerto Rico, of which 40 percent is shipped to the United States (Carl-Axel Soderberg, Puerto Rico Environmental Quality Board, oral commun., 1986).

As of September 1985, 18 hazardous-waste sites at 2 facilities in Puerto Rico had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund

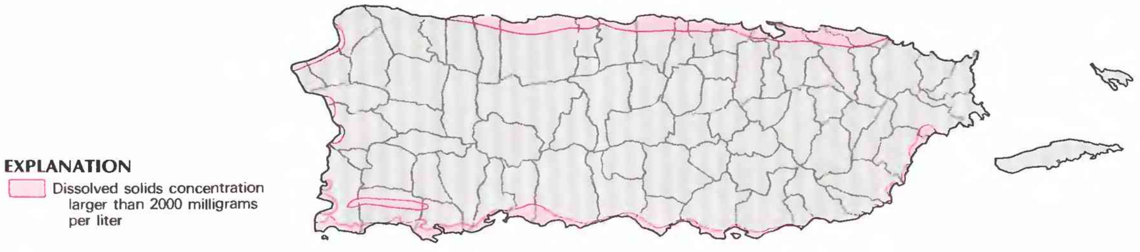

Figure 4. Areas of ground water containing a dissolved-solids concentration larger than 2,000 milligrams per liter. (Source: Modified from Romas-Mas and Lee, 1985; Gomez-Gomez and Heizel, 1980; Robert Graves, U.S. Geological Survey, written commun., 1986.)

program under CERCLA. EPA presently ranks these sites under the hazard ranking system and may include them in the NPL.

During September 1982, 15,000 gallons of carbon tetrachloride was accidentally spilled in the Barceloneta area. Laboratory analyses of water samples collected after the spill indicated concentrations of carbon tetrachloride as large as 5 mg/L. The spill resulted in the closing of two industrial, one domestic, and three public water-supply wells. About 10,000 persons, who obtained their drinking water from those wells, were affected. The area was designated as a CERCLA site by the EPA (fig. 3*A*, Site G).

Municipal Landfills

Seventy-four municipal landfills throughout Puerto Rico (fig. 3*C*) are used for the disposal of non-hazardous wastes. In 1977, the U.S. Geological Survey conducted a reconnaissance study of 50 selected solid-waste disposal sites in Puerto Rico (Torres-Gonzalez and Gomez-Gomez, 1982, p. 7) to determine the potential for ground-water contamination by the percolation of leachate. In many of the locations, the cover material was relatively permeable and offered insignificant resistance to infiltration of the leachate. Although aquifer contamination has not been the subject of any studies, 25 sites showed potential for leachate percolation. Further investigation is needed to determine contamination potential at other waste-disposal sites. Open-burning dumps are no longer allowed in Puerto Rico. Six known former open-burning dump sites are shown in fig. 3*A* as "other."

Agricultural-Pesticide Application

Preliminary tests have detected pesticides and pesticide residues in several wells in aquifers, both on the north and on the south coasts of Puerto Rico (Quinones-Marquez and Alicea-Ortiz, 1985). Large quantities of pesticides, including dieldrin and dichlorodiphenyl trichloroethane (DDT), were used in Puerto Rico for many years, primarily on sugarcane plantations. These synthetic organic pollutants can affect ground-water quality at any time in unpredictable ways, because the migration rate of these contaminants through the soil and into the water table in Puerto Rico is unknown.

Large Ground-Water Withdrawals

Large withdrawals for urban centers and irrigation along coastal areas of Puerto Rico have indirectly affected the quality of ground water on a local scale. Between 1960 and 1980, the population increased by 36 percent, with the largest increases being within the principal coastal urban areas. Large ground-water withdrawals have induced saltwater encroachment and upconing to pumping centers. In addition, expanding urbanization has covered large parts of aquifer-recharge areas with relatively impermeable structures, thereby decreasing aquifer recharge from rainfall infiltration. As a result, the freshwater-saltwater interface has moved inland. Several large irrigation wells located between Arecibo and Manati on the north coast of Puerto Rico have experienced upconing of saltwater after periods of intensive pumping. Rice crops have been damaged on occasion by the applied water.

Information is being collected continuously by the U.S. Geological Survey to determine the islandwide extent of saltwater encroachment. Areas of dissolved concentrations greater than 2,000 mg/L are shown in figure 4.

Barnyard Waste or Septic Drainage

Increased levels of nitrate (as large as 72 mg/L as nitrogen) have been documented in water samples withdrawn principally from the South Coastal Plain alluvial aquifer. Large nitrate concentrations are generally associated with shallow water-table conditions, where wastes from animal feedlots, septic drainage, or surface contamination have percolated to an aquifer. Fertilizer application in areas of the south coast where the water table is near the land surface may be the source of large nitrate concentrations in the ground water (Carl-Axel Soderberg, Puerto Rico Environmental Quality Board, written commun., 1986).

POTENTIAL FOR WATER-QUALITY CHANGES

Recent estimates by the Puerto Rico Planning Board (PRPB) indicate that the population of Puerto Rico will reach about 4 million in the year 2010 (Quinones-Marquez and Alicea-Ortiz, 1985). The population increase and the associated demand for employment will undoubtedly cause further industrial development, which will place additional demands on the ground-water resources. The Puerto Rico Aqueduct and Sewer Authority will continue to develop ground-water resources to provide drinking-water supplies for rural areas. Further development of the alluvial aquifers near the coast will require careful planning to avoid saltwater encroachment.

Agricultural development is declining in Puerto Rico. However, use of large volumes of fertilizers and pesticides provides a potential source of contamination of the water-table aquifer.

To date (1986), the North Coast limestone artesian aquifer has been free of contamination except where wastes were directly injected by disposal wells into the aquifer. Although subsurface injection has been discontinued, some residual contamination probably remains.

GROUND-WATER-QUALITY MANAGEMENT

The management of ground-water quality in Puerto Rico is shared by several local agencies and the EPA. The Puerto Rico Department of Natural Resources (PRDNR) is responsible for planning and regulating the use, improvement, conservation, and development of the water resources of Puerto Rico (Water Law, No. 136 of June 3, 1976). In September 1984, the Department published regulations that included the management of ground water. The most important sections of the regulations include: (1) a system of permits for drilling wells and a franchise to use the ground water, (2) authorization to designate "critical" areas where the ground-water resources could be affected by excessive demand or contamination, and (3) a system of permits to regulate the quantity of fluids recharged into the aquifers.

At the Federal level, the EPA is the principal agency responsible for the use and management of ground water. The EPA delegates to local agencies the implementation of some of its programs and regulations such as the Safe Drinking Water Act of 1974 and the Pesticide Control Act. The PREQB is responsible for the regulation of industrial, domestic, and agricultural discharges under the Clean Water Act of 1977. The Board similarily manages the Underground Injection Control Program defined by the Safe Drinking Water Act of 1974. In 1985, the Board published extensive regulations for the control of fluids injected into aquifers. This agency has developed regulations to control discharges into sinkholes and the construction and operation of underground storage tanks.

The EPA has delegated the regulation of pesticides that may contaminate ground water (Pesticide Control Act) to the Puerto Rico Department of Agriculture (PRDOA). The PRDOH has been granted primacy by the EPA to oversee the drinking-water program in Puerto Rico. The PRDOH is responsible for the Safe Drinking Water Act of 1974 as regards the quality of drinking water. This agency has implemented a set of regulations that establishes maximum concentrations of ions and chemical compounds permissible in drinking water. The Department relies on the Puerto Rico Aqueduct and Sewer Authority to conduct quality-assurance monitoring for their public-supply wells.

Other Federal laws related to the conservation of ground water have not been delegated by the EPA to Commonwealth agencies. The EPA administers the Resource Conservation and Recovery Act (RCRA), which regulates the management of solid and liquid waste materials; it also manages the Toxic Materials Act of 1976, which controls the production and disposal of toxic materials, as well as CERCLA or Superfund law of 1980. The CERCLA legislation authorizes the Federal government to respond directly to releases (or threatened releases) of hazardous substances and contaminants that may endanger public health or welfare.

Although the EPA has delegated most of the responsibility for the administration of the ground-water-quality management laws to Commonwealth agencies, it still is actively involved in environmental programs that affect ground water. The EPA, through the PREQB, directs its efforts toward programs that regulate the design, construction, and operation of municipal landfills, underground storage tanks, and discharge pools.

Landfills and underground storage tanks constitute potential sources of contamination to aquifers. In Puerto Rico, nearly 50 landfills are located over aquifers that provide drinking water to municipalities. The new regulations will require continuous monitoring and cleaning of those landfills that contain dangerous contaminants. Since 1985, the PREQB has issued orders against 11 service stations for gasoline spills from underground storage tanks.

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RHODE ISLAND
Ground-Water Quality

In 1985, 24 percent of Rhode Island's nearly 1 million people (fig. 1) obtained their drinking supplies from ground water. Most of this water was pumped from public-supply wells completed in principal stratified-drift aquifers (fig. 2). The quality of ground water in most parts of the State is suitable for human consumption and other uses with little or no treatment. Typically, ground water in the State has dissolved-solids concentrations smaller than 200 mg/L (milligrams per liter) and is soft (hardness less than 60 mg/L as calcium carbonate), slightly acidic (pH 5.5 to 7.0), and cold (10 to 12° Celsius). However, Rhode Island's ground water is very vulnerable to contamination because it occurs nearly everywhere under unconfined conditions and because the water table commonly is less than 20 feet beneath the land surface. Locally, the quality of ground water has been moderately to severely degraded (fig. 3).

Infiltration of water from streams is induced near many excessively pumped public-supply and industrial wells, so that the quality of ground water pumped from such wells may be affected by the quality of streamflow. Fortunately, the quality of water in most streams is sufficiently good that few problems of well-water quality have resulted from stream infiltration.

The quality of ground water has been degraded severely at several locations by landfill leachate, spills of hazardous and nonhazardous chemicals, seepage from wastewater lagoons, leaks from buried fuel tanks, leaching of deicing salts from highway runoff and salt-storage facilities, leaching of applied fertilizers and pesticides, and seepage of septic-system effluent. Since 1975, the water from 9 public-supply wells and more than 250 domestic wells has become unsuitable for human consumption as a result of contamination by hazardous chemicals.

The percentage of the State's land area, beneath which the quality of ground water has been made unsuitable for drinking and other uses, is relatively small. Ground-water contamination from most sources, such as lagoons, landfills, and buried tanks, typically is confined to cigar-shaped plumes only a few hundred feet wide and a few thousand feet long. Thicknesses and depths of these plumes differ considerably. Most contaminant plumes discharge to streams, ponds, springs, swamps, and other areas of natural ground-water discharge.

Maintaining the quality of the State's ground-water resources for use as a source of drinking water requires careful management. The Rhode Island Department of Environmental Management (RIDEM) presently (1986) is developing a strategy to manage and protect this resource under the authority of the 1985 State Ground-Water Protection Act.

WATER QUALITY IN PRINCIPAL AQUIFERS

Ground water in Rhode Island is present in two types of aquifers—unconsolidated Pleistocene glacial deposits and consolidated Paleozoic bedrock (figs. 2*A*, 2*B*). The glacial deposits, which overlie and largely conceal bedrock, are divided into stratified drift and till. Stratified drift consists of interbedded lenses of stratified and sorted gravel, sand, and silt. Till consists of a poorly sorted mixture of boulders, gravel, sand, silt, and some clay. Stratified drift constitutes the principal aquifer. Till and bedrock constitute minor, but important, aquifers that provide small supplies to homes. Most domestic wells in Rhode Island obtain water from bedrock aquifers.

Although both consolidated and unconsolidated rocks have been subdivided into a large number of rock types, most of them are composed of relatively insoluble minerals—chiefly quartz and feldspar. As a consequence, ground water in Rhode Island typically has small concentrations of dissolved solids, generally less than 200 mg/L, and its chemical character does not differ greatly among rock units.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), iron, and manganese analyses of water samples collected from about 1950 to 1983 from selected parts of stratified-drift aquifers in Rhode Island. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supplies as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter) iron, and 50 μg/L manganese.

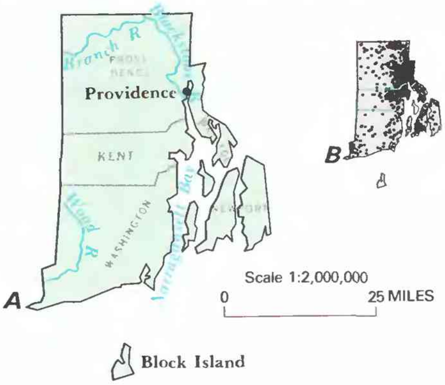

Figure 1. Selected geographic features and 1985 population distribution in Rhode Island. *A*, Counties, selected cities, and major rivers. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Stratified-Drift Aquifers

Stratified drift mantles the bedrock surface in about one-third of the State, chiefly in valleys. These deposits are commonly 75 to 125 feet thick. The thickest and most transmissive parts of the stratified-drift aquifers can yield as much as 700 gal/min (gallons per minute) to wells. Aquifers in 21 areas have been designated by the State as ground-water reservoirs (Rhode Island Statewide Planning Program, 1979) in recognition of their importance as existing and potential sources of public water supply.

The quality of water from stratified-drift aquifers in seven river basins is shown in figure 2*C*. The locations of these aquifers are shown in figure 2*A*. Also shown is the quality of ground water on Block Island, where till and stratified drift overlie unconsolidated sand and clay of Cretaceous age. Most of the analyses for Block Island are believed to be for water from glacial sediments. However, because of the complex lithology at Block Island, the source rock for several samples is not known.

The quality of ground water in the upper Wood River basin (fig. 2*A*, 2*C*; aquifer 6), much of which is undeveloped land managed by the State, probably is most representative of the quality of predevelopment ground water in Rhode Island. The quality of ground water in the other river basins and on Block Island has been affected to a greater degree by human activities.

Dissolved-solids concentrations in ground water generally were less than 100 mg/L, which is significantly smaller than the drinking-water standard of 500 mg/L. The largest median (50th-percentile) concentrations of dissolved solids shown in figure 2*C* were for ground water from wells in the Branch-Blackstone River basin (aquifer 1) and on Block Island (aquifer 8). In the Branch-Blackstone basin, the large median concentration of dissolved solids in ground water results from infiltration of water from the Blackstone River, which is affected by municipal- and industrial-waste discharges (Johnston and Dickerman, 1974b, pl. 2). On Block Island, increased concentrations of dissolved solids result from movement of saline water, which surrounds and underlies the island, toward intakes of the wells. In the Providence area, where stratified drift overlies and is partly derived from sedimentary rocks, a few analyses of water from wells indicated that dissolved-solids concentrations in ground water may be larger there than in most other areas of Rhode Island.

Water from the stratified-drift aquifers that are underlain by granitic bedrock is soft in most parts of Rhode Island. Exceptions occur in the Branch-Blackstone basin, where infiltration from the Blackstone River has increased water hardness from some municipal and industrial wells. Ground water also is hard at many locations in the Providence area.

Concentrations of nitrate (as nitrogen) in ground water in areas that are relatively unaffected by human activities, such as the upper Wood River basin (figs. 2*A*,*C*), are likely to be smaller than 0.2 mg/L. Concentrations of nitrate in ground water in developed areas, where ground water is affected by wastes discharged from individual sewage-disposal systems and by fertilizers, are likely to be somewhat larger. Locally, concentrations exceed the primary

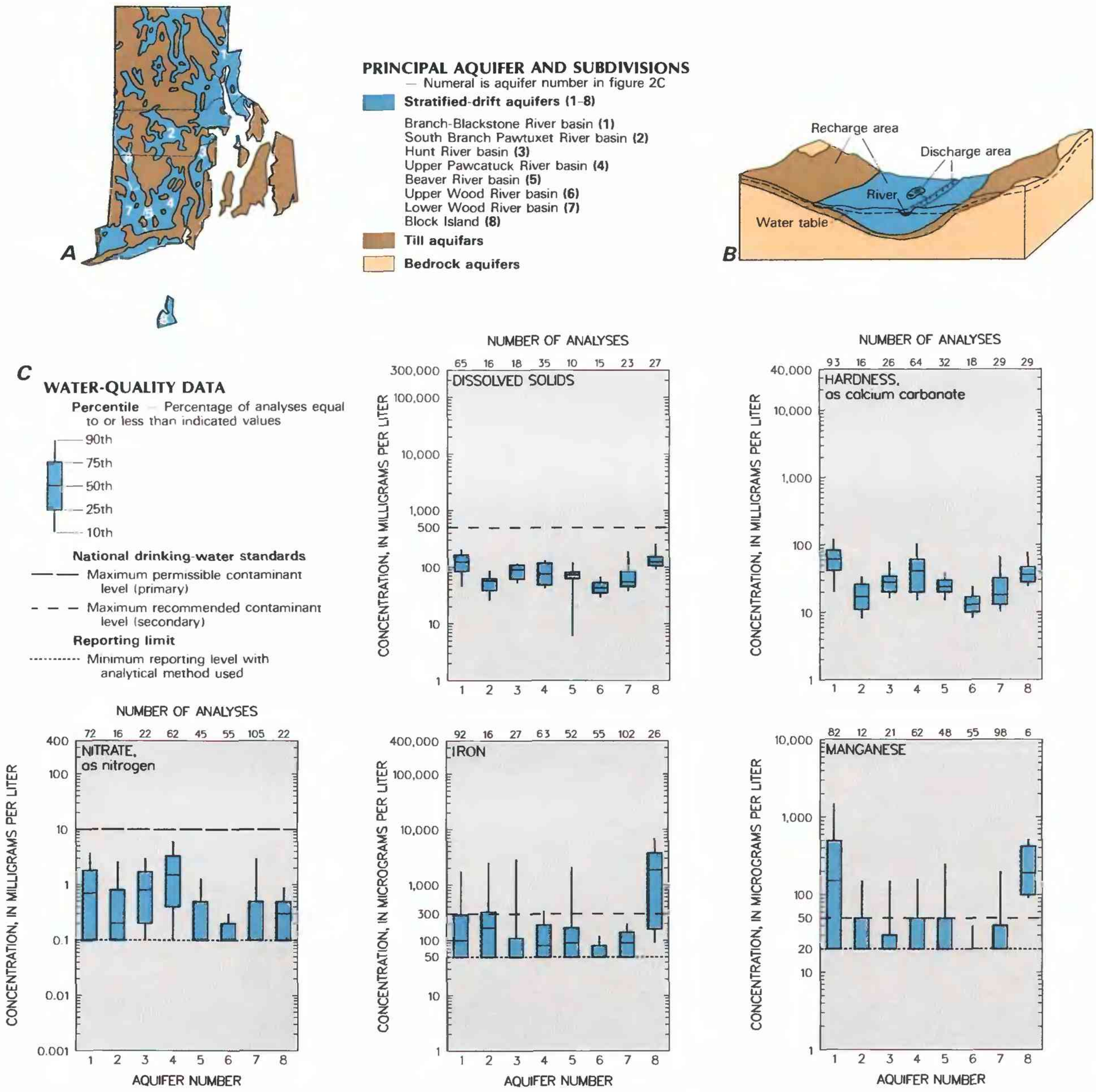

Figure 2. Principal aquifers and related water-quality data in Rhode Island. *A*, Principal aquifers. *B*, Generalized block diagram. *C*, Selected water-quality constituents and properties as of 1950-83. (Sources: *A*, U.S. Geological Survey, 1985. *B*, Modified from U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files and reports; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b).

drinking-water standard of 10 mg/L. Available data suggest, however, that in most areas concentrations of nitrate probably do not exceed 2 mg/L.

Concentrations of iron generally do not exceed the standard of 300 μg/L recommended for public drinking-water supplies (fig. 2*C*). Exceptions are ground water from the mixed deposits on Block Island, where concentrations of iron commonly exceed 300 μg/L), and from stratified drift in the Providence area where concentrations locally exceed 300 μg/L.

Concentrations of manganese in water pumped from newly developed wells are generally less than 50 μg/L, which is the secondary drinking-water standard. However, in several areas where prolonged pumping from public and industrial-supply wells has caused substantial infiltration of surface water from nearby rivers and ponds, concentrations of manganese commonly exceed 50 μg/L. Ten percent of these wells have yielded water containing manganese concentrations greater than 1,500 μg/L. The cause of manganese enrichment with time in well water is attributed mainly to infiltration of water with small amounts of dissolved oxygen (Johnston and Dickerman, 1974b; Silvey and Johnston, 1977).

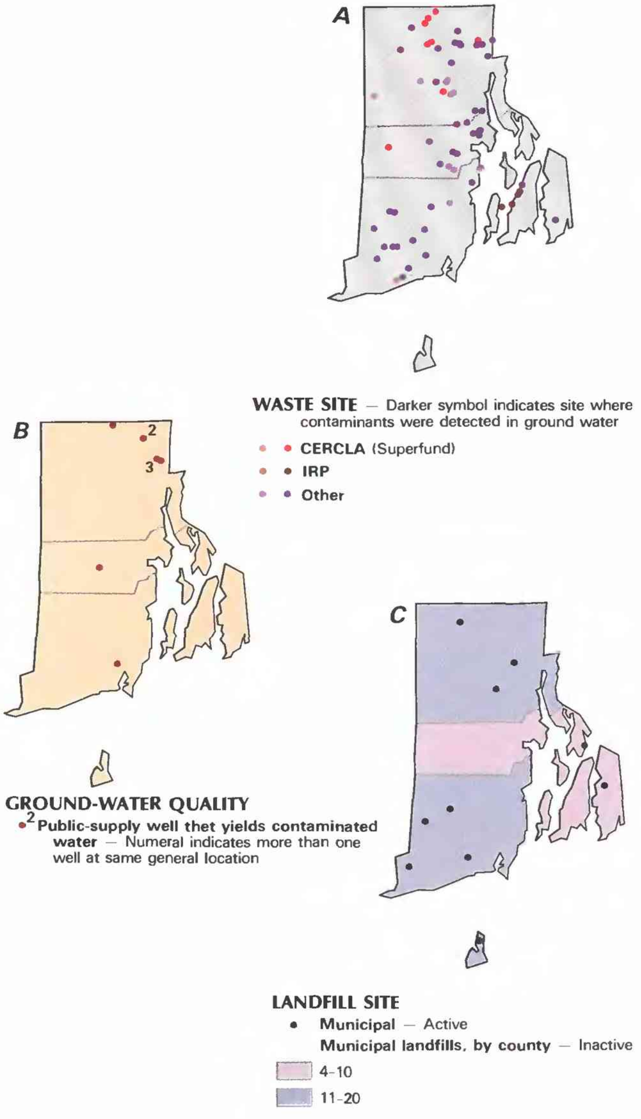

Figure 3. Selected waste sites and ground-water-quality information in Rhode Island. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of April 1986; Department of Defense Installation Restoration Program (IRP) sites, as of September 1985; and other selected waste sites, as of April 1986. *B*, Distribution of wells that yield contaminated water, as of February 1986. *C*, Active and inactive publicly owned landfills, as of April 1986. (Sources: *A*, Rhode Island Department of Environmental Management, 1986a; U.S. Department of Defense, 1986. *B*, Rhode Island Department of Environmental Management, 1986a. *C*, Rhode Island Department of Environmental Management, 1986a.)

Till Aquifers

Glacial till covers bedrock in about two-thirds of the State, chiefly in the upland areas. Average thickness of the till is about 20 feet. Till aquifers once were tapped by many large-diameter dug wells that provided small, commonly unreliable, yields to much of the State's population. Many older homes still obtain water from the till aquifers. However, because wells in till may become dry during droughts and because these wells are more susceptible to contamination from individual sewage-disposal systems, most have been abandoned in favor of deeper wells drilled into bedrock.

In a statewide reconnaissance completed in the early 1950's, data were summarized for 15 wells in till aquifers (Allen, 1953, table 10). Median concentrations for dissolved solids, hardness, and nitrate were 68, 32, and 1.3 mg/L, respectively. The median concentration for iron was 40 μg/L.

Bedrock Aquifers

Bedrock aquifers in Rhode Island are composed of igneous, metamorphic, and consolidated sedimentary rocks that store and transmit water through a network of narrow, widely spaced fractures. Significantly indurated to largely metamorphosed sedimentary rocks (conglomerate, sandstone, shale, and some coal) of Pennsylvanian age underlie Narragansett Bay and adjacent land areas. Crystalline igneous and metamorphic rocks that are mostly of granitic composition underlie the southeasternmost part of the State and most of the area west of Narragansett Bay. These bedrock units generally yield less than 20 gal/min to wells usually 100 to 300 feet deep. Most of the 9 percent of the State's population not served by public-supply systems obtain their water from wells that penetrate bedrock aquifers.

Water quality in bedrock aquifers was determined for 26 wells in crystalline bedrock and 19 wells in sedimentary bedrock in the statewide reconnaissance by Allen (1953, table 10). Some samples were analyzed by the Rhode Island Department of Health (RIDH) and, in some instances, may have been submitted for analysis because contamination was suspected. The median concentrations of dissolved solids, hardness, and nitrate were 125, 66, and 2 mg/L, respectively, in samples from crystalline bedrock and 156, 95, and 0.3 mg/L, respectively, in samples from sedimentary bedrock. The slightly larger concentrations of dissolved solids and hardness in water from sedimentary rocks reflect the slightly greater solubility of minerals composing these rocks. The median concentration of iron was 70 μg/L in samples from crystalline bedrock and 200 μg/L in samples from sedimentary bedrock.

EFFECTS OF LAND USE ON WATER QUALITY

The quality of ground water in many areas of Rhode Island has been degraded to varying degrees by land-use activities. In most areas degradation of ground-water quality, although measurable, has not impaired its suitability for drinking and most other uses. Locally, however, the effects of waste disposal, agriculture, and urbanization have made ground water unsuitable for drinking and most other uses.

The principal sources of ground-water contaminants are waste-disposal sites, underground fuel-storage tanks, surface impoundments of liquid wastes, solid-waste landfills, septic systems and cesspools, storage areas for highway deicing salt, and oil and chemical spills (Rhode Island Department of Environmental Management, 1986a, p. D-1). The principal ground-water contaminants derived from these sources are volatile organic chemicals, pesticides, metals, nitrate, sodium, and chloride (Rhode Island Department of Environmental Management, 1986a, p. D-3, table 14). In addition, manganese concentrations have increased to the level that they exceed the standard for drinking water (50 μg/L) in some excessively pumped industrial- and public-supply wells that induce infiltration of surface water.

Waste-Disposal Sites

Hazardous chemicals have been found in ground water at or near 27 sites in Rhode Island (Rhode Island Department of Environmental Management, 1986a, table 12) and are suspected of being present at many others. There is a potential for ground-water contamination by hazardous wastes at more than 200 sites (A.M. Good, Rhode Island Department of Environmental Management, oral commun., 1986). Eight hazardous-waste sites on the U.S. Environmental Protection Agency's (EPA) National Priorities List (NPL) are being studied under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Hazardous substances deposited at the CERCLA sites (fig. 3*A*) include motor oils, plating wastes, industrial oils and emulsions, solvents, and lacquers. Hazardous organic-chemical contaminants most commonly found in ground water at these sites include benzene, chloroform, methylene chloride, tetrachloroethylene, 1,1,1-trichloroethane, trichloroethylene, and toluene. Hazardous metals commonly found include arsenic, cadmium, chromium, and lead. There are no disposal sites in Rhode Island licensed under the Resource Conservation and Recovery Act (RCRA) of 1976.

As of September 1985, 12 hazardous-waste sites at 2 facilities in Rhode Island had been identified by the U.S. Department of Defense (1986) as part of their Installation Restoration Program (IRP) as having potential for contamination. The IRP, established in 1976, parallels the EPA CERCLA (Superfund) program. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 12 sites in the program, 3 sites contained contaminants but did not present a hazard to people or the environment. Three sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. No remedial actions at any of these sites have been completed under the program.

Nine public-supply wells have been contaminated by hazardous chemicals (fig. 3*B*)—eight by organic solvents and one by the pesticide aldicarb—and have been removed from service (Rhode Island Department of Environmental Management, 1986a, table 11). Water samples from 437 of 1,092 private wells tested within one-half mile of 27 known hazardous-waste sites have been contaminated by hazardous chemicals (Rhode Island Department of Environmental Management, 1986a, table 12). Seventy-one of these wells have yielded water with concentrations of hazardous chemicals, mainly organic solvents, that exceeded EPA advisory limits for drinking water. However, the hazardous-waste sites have not been determined to be the source of the contaminants in all instances. Septic-system effluent could be the source of some of the hazardous chemicals found in water from some private wells because several common household products that may enter septic systems contain the same chemicals.

Of the approximately 70 solid-waste landfills in Rhode Island, 52 are publicly owned. Only 10 of the publicly owned landfills were active in 1986 (fig. 3*C*). Contamination of ground water by landfill leachate has been documented at 30 landfills (Rhode Island Department of Environmental Management, 1986a, table 10). Ground water beneath and downgradient from landfills typically contains increased concentrations of dissolved solids, iron, manganese, and chloride. Mercury and phenols also have been detected at many sites. The areal extent of ground water contaminated by leachate from landfills is only a small percentage of the State's total land area. Nevertheless, their potential for degrading the quality of drinking-water supplies is substantial. Sixteen landfills overlie major ground-water reservoirs, and 11 lie within the drainage areas of these reservoirs (Rhode Island Statewide Planning Program, 1978, p. 9).

A statewide survey has identified 145 surface impoundments into which wastes were being discharged (Rhode Island Department of Environmental Management, 1979, p. 18). Most of the 107 industrial, 21 municipal, and 17 agricultural impoundments were unlined lagoons that allowed contaminated water to seep into ground water. Three-quarters of these impoundments were located in permeable stratified drift. Wastes discharged to industrial impoundments included alkaline tumbling waste, light oily waste, degreasing agents, acid or alkaline rinse waters, and dye waste mixed with sanitary waste. Wastes discharged to municipal impoundments were either water-purification sludge or septic-tank sludge. Animal wastes were discharged to agricultural impoundments.

Leakage from a lined lagoon at a now-closed uranium recovery plant in Washington County resulted in development of a plume of radioactively contaminated ground water between the plant and the nearby Pawcatuck River, into which the ground water discharges. Contamination from the plume has not been detected in the river. The contaminant plume, which is about 300 feet wide, 2,300 feet long, and 80 feet thick, is within a stratified-drift aquifer (fig. 2*A*, aquifer 7) and constitutes a potential source of contamination of public water supply for southern Rhode Island. Principal radioactive contaminants in the plume are strontium-90 and technetium-99; other major contaminants are nitrate, boron, and potassium (Ryan and Kipp, 1985, p. 21). It will require an estimated 6 to 18 years before the concentration of strontium-90 decreases to levels that are acceptable in public-drinking water supplies (Kipp and others, 1986, p. 528).

Disposal of commercial and industrial wastewater to leach fields and dry wells also is a source of ground-water contamination, but its extent and severity have not been documented (E. Panciera, Rhode Island Department of Environmental Management, oral commun., 1987).

Agricultural Practices

Leaching of chemicals applied to commercially cultivated land has caused local contamination of ground water in southern Rhode Island by the pesticide aldicarb and by nitrate. Since 1984, the RIDH has tested water from 980 drinking-water wells near potato fields where aldicarb was applied; aldicarb was detected in 169 of the wells (J. Boghosian, Rhode Island Department of Health, oral commun., 1986). Sixty-nine of the wells that yield contaminated water are in Washington County; 100 are in Newport County. One of the wells that yields contaminated water was part of a public-supply system that supplies water to about 20,000 people in Washington County. In water samples from 42 of the wells that yield contaminated water, concentrations of aldicarb have exceeded a proposed recommended EPA maximum contaminant level for drinking water of 9 μg/L (U.S. Environmental Protection Agency, 1985).

Leaching of inorganic nitrogen fertilizers applied to fields in Washington County has increased nitrate (as nitrogen) concentrations in nearby ground water substantially above background levels. Locally, concentrations exceed 10 mg/L (Johnston and Dickerman, 1984). Although cultivated land accounts for only 5 percent (31,000 acres) of the State's land area (Volpe, 1986, p. 8), much cultivated land is in Washington County where it overlies major stratified-drift aquifers.

Urbanization

Contamination of ground water by petroleum products that have leaked from buried storage tanks has been confirmed or is suspected at 25 sites in Rhode Island (D. Sheldon, Rhode Island Department of Environmental Management, oral commun., 1986). The potential for additional contamination of ground water by these products is considerable because aging petroleum-storage tanks are scattered throughout the State. Damage to water supplies resulting from contamination by petroleum products, as with many other hazardous materials, can be difficult and expensive to remedy. For example, leakage for several years from one or more buried fuel-storage tanks at gasoline stations in a Washington County community contaminated 29 nearby private drinking-water wells. The contamination necessitated development, in 1984–85, of a new public water-supply system to serve the people affected (Rhode Island Department of Environmental Management, 1986a, table 12).

In 1984, the RIDEM identified 32 salt-storage sites that were uncovered or had a permeable base. Contamination of ground water by sodium chloride has been documented at 10 of these sites (Rhode Island Department of Environmental Management, 1986a, p. D-3). Sodium-chloride contamination of water from private wells located near highways has been reported, but the extent and severity of such contamination are not known.

Effluent from individual sewage-disposal systems, which serve about one-third of the State's population, contributes significant quantities of nitrate and other contaminants to ground water. Summaries of water-quality tests by the RIDH for 1975 to 1985 indicate that nitrate (as nitrogen) exceeded 10 mg/L in water samples from about 2 percent of about 1,000 private wells tested annually. Nitrate in some samples may have been derived from lawn fertilizers. Of the 1,700 tons of nitrogen added to Rhode Island soils annually as fertilizer, more than one-half is estimated to have been applied to home lawns (S.M. Volpe, Rhode Island Department of Environmental Management, oral commun., 1986).

Bacteriological contamination of well supplies has been caused also by effluent from individual sewage-disposal systems. In water from private wells tested by the RIDH between 1975 and 1985, concentrations of bacteria in excess of State drinking-water standards were detected, on the average, in nearly 40 percent of the samples from shallow dug wells, and in about 8 percent of the samples from deeper driven and drilled wells. The percentage of wells yielding bacterially contaminated water might be smaller if samples had been collected from wells selected at random. Some water samples tested by RIDH are submitted for analysis because contamination is suspected, either because of taste and odor problems or because bacterial contamination was detected previously.

POTENTIAL FOR WATER-QUALITY CHANGES

Because of the enactment and anticipated vigorous enforcement of a variety of State laws regarding ground-water quality, that quality is expected to remain about the same or improve in the future.

The Ground-Water Protection Act (Rhode Island General Laws (R.I.G.L.) 46-13.1) passed in 1985 establishes a policy of maintaining and restoring ground-water quality in Rhode Island. Implementation of this policy and enforcement of Federal, State and local laws, regulations, and zoning ordinances are expected to maintain or improve the future quality of ground water in Rhode Island.

Enforcement of State laws relating to siting of hazardous-waste and refuse-disposal sites (R.I.G.L. 23–19.1-32 and R.I.G.L. 23–18.9) will decrease potential contamination of ground water from these sources by effectively decreasing the number of new facilities. In 1986, Rhode Island had no active hazardous-waste disposal sites and 10 active solid-waste disposal sites (fig. 3*C*).

Introduction of State regulations in 1985 that provide for registration of underground tanks used to store petroleum products and hazardous materials also should be effective in decreasing ground-water contamination from leaking underground tanks. The regulations include stringent requirements for design and construction of tanks, leak detection, and closure procedures.

State regulation of waste discharges to streams already has improved water quality in many streams and may prevent further degradation of the quality in most others. As a result, the quality of water pumped from many wells that induce infiltration from streams may be expected to remain about the same or to improve.

GROUND-WATER-QUALITY MANAGEMENT

In 1983, the State's Water Pollution Control Act (R.I.G.L. 46–12–28) was amended to include ground water as "waters of the State" and to give the RIDEM authority to regulate and control pollution of ground water. In 1984, the RIDEM became lead agency for developing a comprehensive strategy to protect the quality of the State's ground-water resources. Authority to undertake specific tasks leading to development of this strategy was provided in the 1985 Ground Water Protection Act. The tasks include conducting studies of the availability and use of the State's ground-water resources, classifying ground water, establishing standards for ground-water protection, and recommending land-use controls that will provide for protection of ground-water quality. The RIDEM currently (1986) is undertaking these tasks.

Through its authority to regulate the direct discharge of industrial and commercial wastewater to ground water, the siting and construction of landfills and individual sewage-disposal systems, the commercial use of pesticides, and the construction, maintenance, and closure of underground storage tanks, the RIDEM indirectly controls several land-use activities that contaminate ground water. The authority of RIDEM to control stream pollution also is important in controlling the quality of water in wells that induce infiltration from streams.

The State Underground Injection Control Program is the principal mechanism for controlling the direct discharge of industrial and commercial wastewater to ground water by way of pits, ponds, lagoons, leach fields, wells, and other means. The rules and regulations for this program became effective in May 1984. These regulations prohibit discharge to ground water of any water containing hazardous waste and are being used to control discharge of water containing nonhazardous wastes at more than 60 locations (D. Sheldon, Rhode Island Department of Environmental Management, oral commun., 1987).

Primary control of land-use activities that may adversely affect the quality of ground water resides with the State's 39 cities and towns which have authority to establish land-use restrictions under the State's zoning enabling act (R.I.G.L. 45-24). Six towns already have amended their zoning ordinances to include overlay districts that prohibit land uses considered potentially harmful to the quality of ground water where underlying aquifers are actual or potential sources of public-water supply (E. Panicera, Rhode Island Department of Environmental Management, written commun., 1986). Several municipalities also have increased minimum lot-size requirements for new residential construction, in part, to limit ground-water contamination by septic-system effluent. New minimum lot sizes range from 2 to 5 acres.

The ground-water protection program being developed under provisions of the 1985 legislation calls for the RIDEM to classify ground-water sources into four categories (GAA, GA, GB and GC). These, like the somewhat similar categories into which Rhode Island stream segments have been classified, are intended as standards of ground-water quality to be maintained for selected uses. Ground-water class GAA is suitable for public drinking-water supply without treatment. Class GA is possibly suitable for public or private drinking-water supply without treatment. Class GB is possibly unsuitable for public or private drinking-water supply without treatment, owing to known or presumed degradation. Class GC is suitable for certain waste-disposal practices because past or present land use, or hydrogeologic conditions, render the ground water more suitable for receiving permitted discharges than for development as public or private water supplies.

To assist in the implementation and management of its ground-water protection program, the RIDEM is developing a computerized Geographic Information System (GIS). When operational, the GIS will be used to integrate and manipulate environmental data geographically and to display them in graphs and on maps. The GIS is expected to provide rapid updating of a variety of environmental maps, such as those showing actual or potential sources of ground-water contamination. These maps can be overlain on computerized ground-water-classification maps to assess where measures need to be taken to protect ground water.

One goal of the State ground-water protection program will be to provide the greatest degree of protection for stratified-drift aquifers that constitute actual or potential sources of public water supply. In addition to State protection efforts, cities and towns will be encouraged to enact protective zoning ordinances covering these aquifers and their recharge areas.

Data on ground-water quality needed to support a ground-water protection program in Rhode Island are available, but many are not in computerized data bases. The RIDH periodically monitors the quality of water from more than 400 public-supply wells scattered throughout the State. These wells constitute a network for monitoring trends in the ambient quality of ground water. The RIDH also periodically tests for aldicarb in water from almost 1,000 private wells located near commercially cultivated land, and for organic and other hazardous chemicals in water from more than 1,000 private wells near hazardous-waste sites. Sampling frequency for private wells under RIDH monitoring programs ranges from semiannual to annual.

A certain amount of ground-water contamination is unavoidable and will occur as a consequence of selected land uses. Nevertheless, if the laws, regulations, and management practices described here continue to be implemented effectively by State and local governments, the quality of ground water in most areas of Rhode Island can remain suitable for drinking with little or no treatment.

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SOUTH CAROLINA
Ground-Water Quality

Ground water is the source of supply for 42 percent of the population of South Carolina (fig. 1). Twenty-two percent of the public water supplies and almost 100 percent of the domestic water supplies rely on ground-water sources (Lonon and others, 1983). Withdrawal for these supplies accounts for 68 percent of the total ground-water withdrawals in the State. Almost all ground water used for public supply is withdrawn from Coastal Plain aquifers because they have greater water-storing and transmitting characteristics than the Piedmont and Blue Ridge aquifers (U.S. Geological Survey, 1985, p. 382).

Ground-water quality throughout much of the State is good for most uses. Water-quality impairment or limitations on the use of ground water for public supply are caused primarily by natural geochemical processes rather than by widespread degradation of water quality by human activities (fig. 3). Ground-water contamination induced by human activities generally is localized and associated with chemical spills, waste disposal, or saltwater intrusion.

South Carolina lies within three physiographic provinces: Coastal Plain, Piedmont, and Blue Ridge (fig. 2). The principal aquifers used for water supply consist of unconsolidated to semiconsolidated sedimentary rocks in the Coastal Plain province and fractured igneous and metamorphic rocks and the overlying saprolite in the Piedmont and Blue Ridge provinces (U.S. Geological Survey, 1985, p. 379). The Coastal Plain is divided, based on the ground-water hydrology into the upper Coastal Plain toward the Fall Line (inland margin of Coastal Plain sediments) and the lower Coastal Plain toward the Atlantic Ocean (fig. 2).

The Coastal Plain aquifers consist of either limestone or clastic sediments. The Floridan aquifer system (fig. 2) is the only major limestone aquifer. The clastic aquifers include the shallow aquifers, the Tertiary sand aquifer, the Black Creek aquifer, and the Middendorf aquifer. Calcareous material in many of the clastic aquifers increases in abundance toward the coast. The Tertiary sand aquifer is equivalent in geologic age to the limestone units that compose the Floridan aquifer system. The water-table aquifers consist of the shallow aquifers in the lower Coastal Plain; the upper parts of the Tertiary sand, Black Creek, and Middendorf aquifers where they crop out in the upper Coastal Plain; and the saprolite and parts of the fractured rocks of the Piedmont and Blue Ridge aquifers.

The background quality of ground water meets most national drinking-water standards (U.S. Environmental Protection Agency, 1986a,b). Naturally impaired water quality (fig. 3) has concentrations that exceed the drinking-water standards of one or more of the following variables in much of the State: pH, dissolved solids, chloride, iron, manganese, and fluoride. Although the standards establish no primary concentration limits for sodium, concentrations of several hundred milligrams per liter are present in water from aquifers in part of the lower Coastal Plain. Concentrations of these constituents result from natural geochemical and hydrologic processes.

Human-induced ground-water contamination has been identified at 28 of 33 sites monitored under the Federal Resource Conservation and Recovery Act (RCRA) of 1976; at 17 of the 19 sites listed or proposed for evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980; and at numerous other sites (fig. 3). In addition, the U.S. Department of Defense (DOD) has identified 17 sites at 4 facilities where contamination has warranted remedial action.

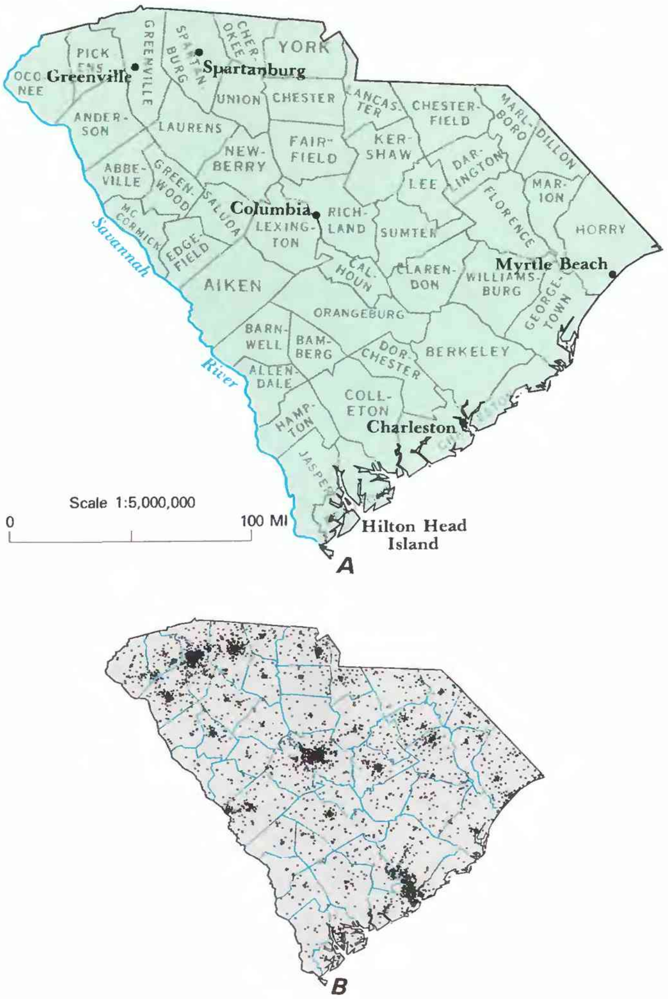

Figure 1. Selected geographic features and 1985 population distribution in South Carolina. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Human-induced contamination generally extends over limited areas. Leaking underground tanks storing gasoline or other liquids have major potential for contamination in the State, but investigations of this potential have begun only recently. Although the potential for saltwater intrusion exists along the coast where potentiometric gradients have been reversed due to pumping, intrusion has been documented only locally. Widespread contamination from regional land-use practices such as agriculture and urbanization has not been documented.

Ground-water quality has been evaluated in several programs conducted by the U.S. Geological Survey and its cooperators and by State agencies. Numerous wells throughout the State have been sampled only once but others are sampled periodically. Public-supply wells are sampled every 3 years. Monitoring wells near sites

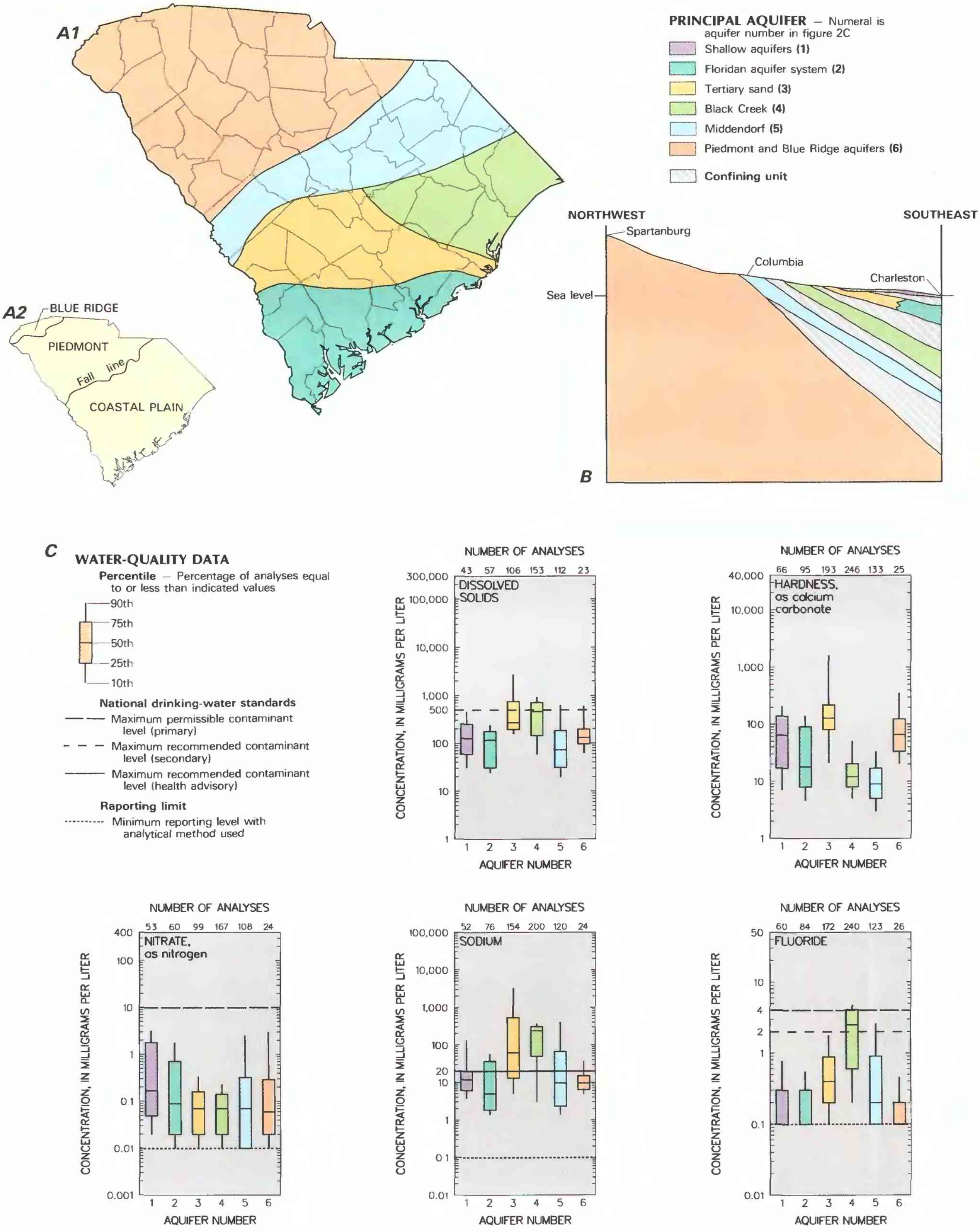

Figure 2. **Principal aquifers and related water-quality data in South Carolina.** *A1*, Principal aquifers; *A2*, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1946-85. (Sources: *A1*, *A2*, *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986b,c.)

of potential contamination are sampled quarterly or biannually. Along the coast, samples are collected semiannually to monitor saltwater intrusion.

WATER QUALITY IN PRINCIPAL AQUIFERS

The quality of water differs considerably within individual Coastal Plain aquifers, reflecting the effects of flow patterns and differences in the mineralogy of the sediments (figs. 2*C* and 4). Concentrations of most constituents are small near recharge areas close to the Fall Line (fig. 2*A*2) where sediments consist primarily of silicate minerals that react slowly with ground water. Concentrations increase downgradient toward the coast (fig. 4), where water has been in contact with the sediments for a longer time and where sediments contain more calcite and marine clays that react more rapidly with the ground water. In the Piedmont and Blue Ridge aquifers, concentrations of several constituents are related to geologic belts, whereas concentrations of other constituents are not (Patterson and Padgett, 1984).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium

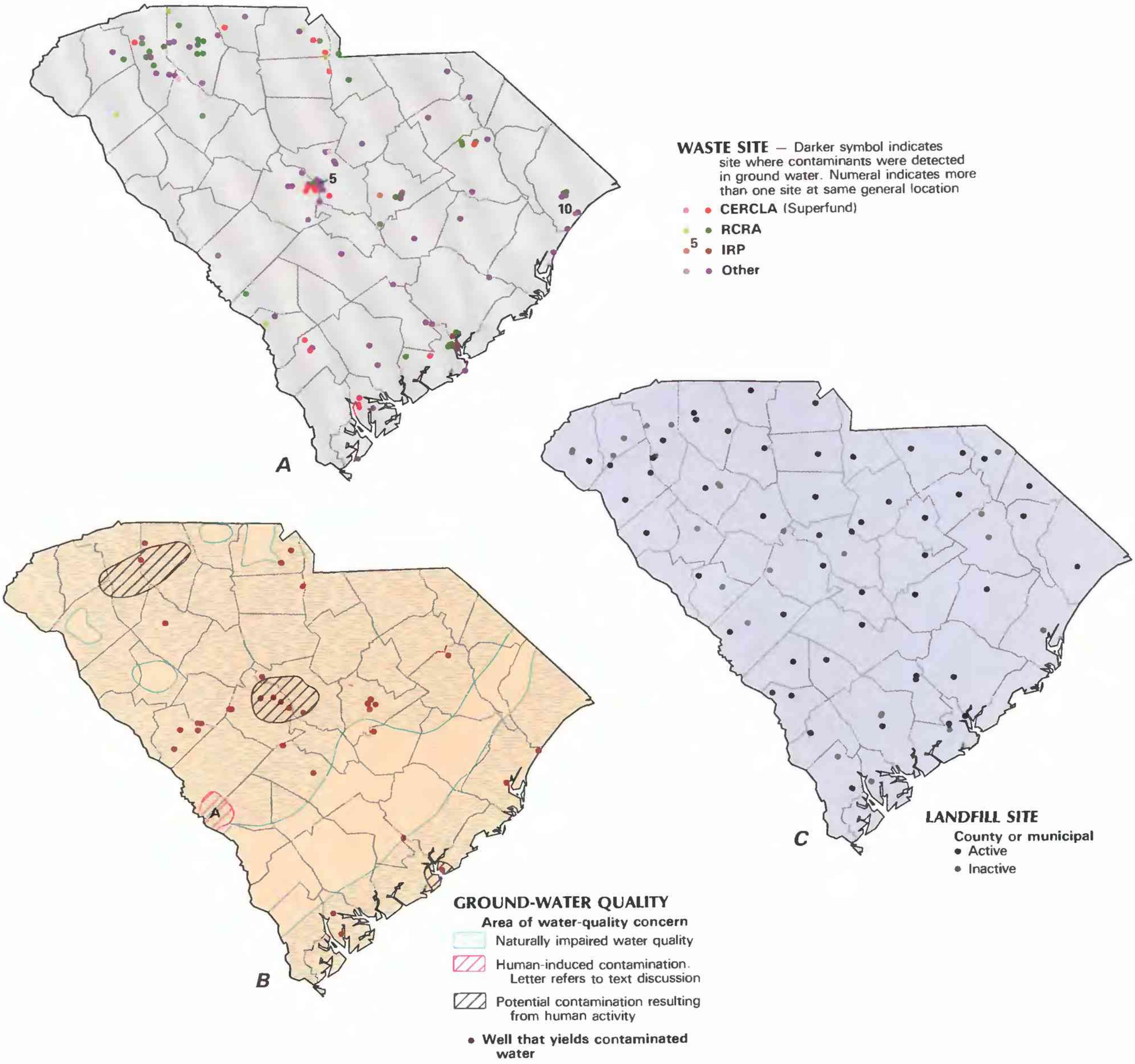

Figure 3. Selected waste sites and ground-water-quality information in South Carolina. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of June 1986; Resource Conservation and Recovery Act (RCRA) sites, as of June 1986; Department of Defense Installation Restoration Program (IRP) sites, as of September 1985; and other selected waste sites, as of June 1986. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of June 1986. *C*, County and municipal landfills, as of June 1986. (Sources: *A*, South Carolina Department of Health and Environmental Control files. *B*, Human-induced contamination and wells from South Carolina Department of Health and Environmental Control files; Naturally impaired water quality from U.S. Geological Survey files, and Patterson and Padgett, 1984. *C*, South Carolina Department of Health and Environmental Control files.)

carbonate), nitrate (as nitrogen), sodium, and fluoride analyses of water samples collected from 1946 to 1985 from the principal aquifers in South Carolina. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986 a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen) and 4 mg/L fluoride. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 2 mg/L fluoride.

As a result of naturally impaired water quality, several primary and secondary drinking-water standards are exceeded in one or more aquifers (fig. 2*C*). The only primary or health-related standard that is exceeded in major areas is the 4.0 mg/L limit for fluoride; all other standards that are exceeded are secondary or esthetic, including the secondary standard of 2.0 mg/L for fluoride. Additional secondary drinking-water standards established by the U.S. Environmental Protection Agency (1986b) are 6.5–8.5 units of pH, 300 μg/L (micrograms per liter) iron, 50 μg/L manganese, and 250 mg/L chloride. The secondary standards for pH, iron, and manganese, although exceeded in raw water, can be attained by treatment using relatively inexpensive processes. The only major area in which standards are exceeded in one or more aquifers and cannot be attained by relatively inexpensive treatment is along the coast where dissolved solids, chloride, and fluoride exceed the standards. Even though the pH of water supplies can be adjusted after withdrawal, low pH before adjustment corrodes well screens and casings, decreasing the usable life of wells. Well casings and screens made of polyvinyl chloride (PVC) are used in many domestic and small public-supply wells to alleviate the effects of low pH on wells. Stainless-steel screens (usually used in large-capacity wells) decrease, but do not eliminate, the effects.

Shallow Aquifers

Water quality in shallow aquifers is locally more variable than in other aquifers and is more likely to be affected by land use than the deeper, confined aquifers. Water in the shallow aquifers near the coast may contain concentrations of chloride that exceed the 250-mg/L secondary drinking-water standard as a result of the mixing of freshwater with saltwater, but the problem is not extensive. Although water from the shallow aquifers exceeds the standards for nitrate and fluoride in some areas, these areas appear to be limited in areal extent. The drinking-water standard most commonly exceeded in water from the shallow aquifers is for dissolved iron, 300 μg/L.

Floridan Aquifer System and Tertiary Sand Aquifer

The Floridan aquifer system and the Tertiary sand aquifer are discussed collectively to illustrate their hydraulic connection and the water-quality changes caused by a facies change from limestone to sand. (figs. 2*B* and 4). Concentrations of dissolved solids are less than 50 mg/L (fig. 4) and pH is less than 6.0 near recharge areas, but both increase sharply downgradient with the increase of calcareous material in the aquifer. Dissolved-solids concentrations increase to several hundred milligrams per liter, and the water quality is dominated by calcium and bicarbonate ions. Hardness of the ground water changes from soft to very hard (fig. 2*C*). Concentrations of iron exceed the 300-μg/L secondary drinking-water standard in some upgradient areas.

Mixing of freshwater with saltwater results in a dominance of chloride and sodium ions in parts of both aquifers along the coast. Natural concentrations of chloride exceed the 250-mg/L secondary drinking-water standard in many of these areas.

Black Creek and Middendorf Aquifers

The water quality of the Black Creek and Middendorf aquifers is similar. Water quality within these units changes significantly from the upper Coastal Plain near recharge areas to the lower Coastal Plain near the coast (fig. 4).

In the upper Coastal Plain, concentrations of dissolved solids are less than 50 mg/L, pH generally range from 4.5 to 6.0, and bicarbonate is 10 mg/L or less. Thus, pH is less than the 6.5 minimum secondary drinking-water standard throughout most of the upper Coastal Plain. Iron concentrations exceed the 300-μg/L drinking-water standard in a band in the northern part of the upper Coastal Plain where concentrations are as much as several thousand micrograms per liter. The major ions that dominate the water quality are variable in this part of the upper Coastal Plain, and silica comprises as much as one-half of the dissolved solids (Aucott and Speiran, 1986, p. 42). Water-quality characteristics in the Black Creek and Middendorf aquifers in the upper Coastal Plain reflect the quality of recharge water and the slow reaction rates between the ground water and the silicate minerals that compose the aquifers.

In the lower Coastal Plain ground water is predominantly a sodium bicarbonate type that results from dissolution of carbonate material and subsequent calcium-for-sodium exchange. The pH ranges from 8.0 to 9.2, exceeding the 8.5 maximum drinking-water standard in much of the area. Concentrations of dissolved solids and fluoride exceed the secondary drinking-water standards (500 mg/L and 2.0 mg/L, respectively) in a band along the entire coast (fig. 3*B*). Concentrations of fluoride also exceed the 4.0-mg/L primary drinking-water standard in this area. Along the extreme northern coast, concentrations of chloride exceed the 250-mg/L secondary drinking-water standard in both aquifers (Aucott and Speiran, 1986). Along the southern coast, the chloride standard is exceeded in the Black Creek aquifer. There, concentrations of chloride were about 900 mg/L in the Black Creek aquifer but generally range from 10 to 200 mg/L in the Middendorf aquifer. In much of the lower Coastal Plain, concentrations of dissolved sodium are several hundred milligrams per liter (fig. 4).

Piedmont and Blue Ridge Aquifers

Concentrations of alkalinity, hardness, sodium, magnesium, and chloride in water of the Piedmont and Blue Ridge aquifers are generally larger in geologic belts that were formed by low-grade metamorphism. However, other water-quality constituents do not appear to correlate with these belts (Patterson and Padgett, 1984). The quality of water from the Piedmont and Blue Ridge aquifers is generally within national drinking-water standards for most constituents. Concentrations of dissolved solids range from 22 to 1,100 mg/L but exceed the 500-mg/L secondary drinking-water standard only in limited areas (Patterson and Padgett, 1984). The standard most often exceeded is the 50-μg/L limit for manganese, which is exceeded in almost all the Piedmont and Blue Ridge aquifers (Patterson and Padgett, 1984, p. 22). Hardness is another water-quality property affecting water use in large areas. Water is soft in most of the Piedmont and Blue Ridge aquifers but ranges from moderately hard to very hard in many areas. Drinking-water standards for several other water-quality constituents are exceeded in much more limited areas. These include pH, chloride, fluoride, and nitrate.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has deteriorated in some limited areas because of contamination from industrial, county and municipal, agricultural, and domestic sources. The South Carolina Department of Health and Environmental Control has documented human-induced ground-water contamination from data derived by various permitting processes, from site investigations, and from compilation of a statewide inventory (Glowacz and others, 1980; McFadden, 1981; Hardee and McFadden, 1982; Ferguson and Workman, 1983). Many of the sites and wells that yield contaminated water are near Charleston, Columbia, Greenville, and Spartanburg. Problems with current or potential saltwater contamination have been identified in coastal areas.

Industrial Sources

Many instances of localized ground-water contamination from industrial sources have resulted from past waste-disposal practices that once were commonly accepted. Treatment, storage, and disposal of hazardous wastes occur at 33 RCRA facilities (fig. 3*A*). Ground-water contamination has been detected at 28 of these sites. Contaminants have not been detected or evaluation is incomplete at the five other sites. Ground-water contamination has been detected at 10 CERCLA sites, which are currently on the National Priorities List (NPL), and at 7 sites which are proposed additions (fig. 3*A*). Ground-water quality is threatened by soil contamination at two other sites.

As of September 1985, 63 hazardous-waste sites at 8 facilities in South Carolina had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 63 sites in the program, 7 sites contain contaminants but do not present a hazard to the environment. Seventeen sites at 4 facilities (fig. 3*A*) are considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites are scheduled for confirmation studies to determine if remedial action is required.

Contamination also has been identified at many other sites that may require remedial actions based on State regulations. Most of the contaminated sites in South Carolina are at chemical companies, manufacturing companies, gasoline stations, and U.S. Department of Energy facilities. The Savannah River Plant is a U.S. Department of Energy nuclear materials facility with about 164 waste-management sites. Hazardous waste at the plant is treated, stored, or disposed in trenches, in settling and seepage basins, and in underground storage tanks. Ground-water contamination has been detected at seven RCRA sites over a large area at the Savannah River Plant (fig. 3*B*, area A). Trichloroethylene, tetrachloroethylene, trichloroethane, other organic compounds, trace metals, and radionuclides (primarily tritium) have been detected in ground water at this facility.

In March 1986, trichlorethylene and other volatile organic compounds were detected in water of the Black Creek aquifer near

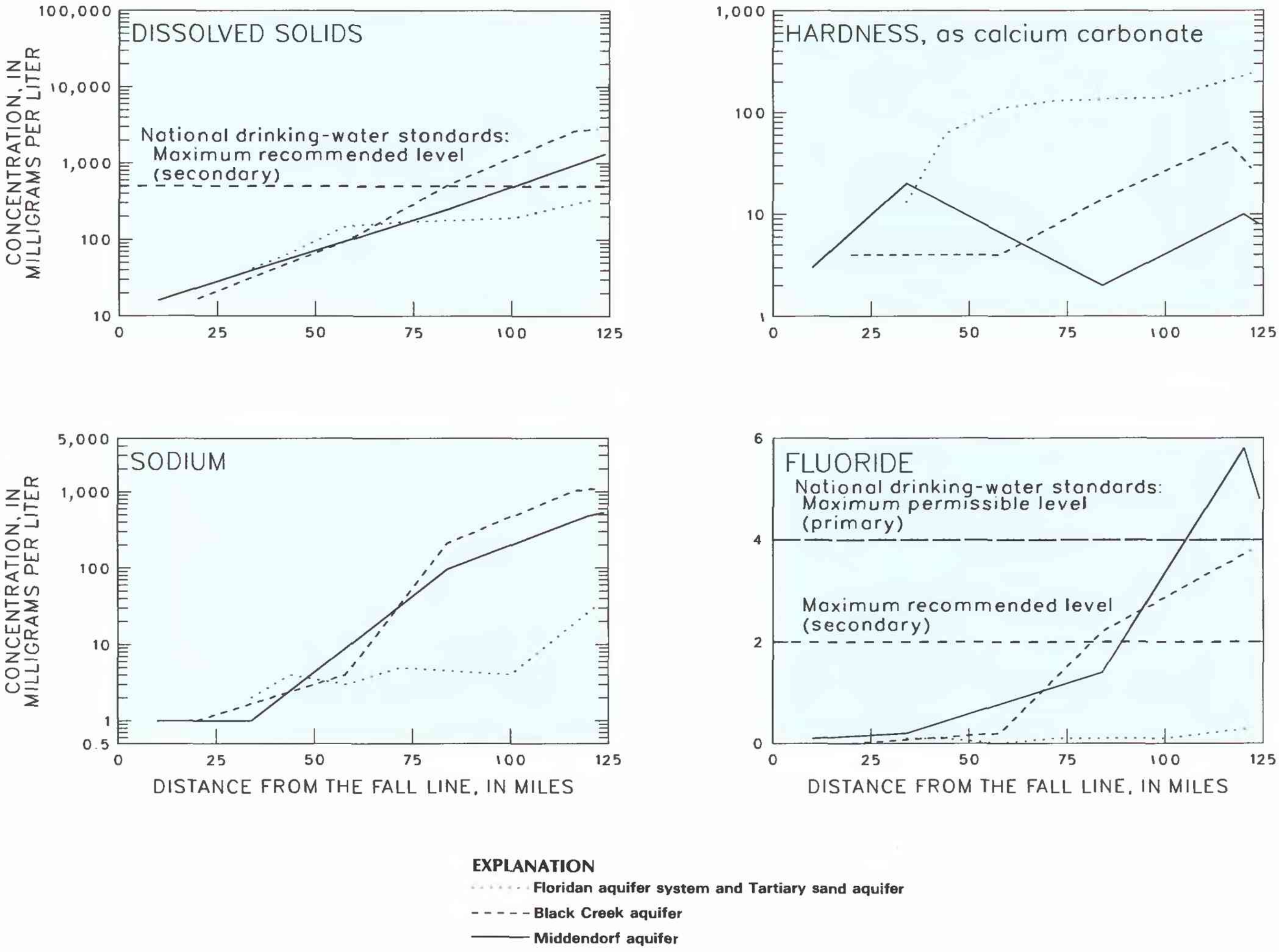

Figure 4. Water quality along flow paths from the recharge area toward the coast in the Floridan aquifer system and the Tertiary sand aquifer the Black Creek aquifer, and the Middendorf aquifer in South Carolina. (Source: U.S. Geological Survey files.)

an active hazardous-waste landfill in southern Sumter County. The source of contamination has been investigated by the site operator but the inquiry has not been completed.

Many small chemical companies and manufacturing facilities have caused localized ground-water contamination at sites that are neither RCRA nor CERCLA sites (fig. 3*A*). Landfills, underground storage tanks, drums stored at land surface, unlined lagoons, and spray irrigation sites are common sources of ground-water contamination. Nitrate, sulfate, metals, and organic chemicals have been detected in ground water near these facilities.

Treatment and disposal of metals by spray irrigation and discharge into a seepage basin resulted in local ground-water contamination at a printing company in Lexington County. Concentrations of lead (5,600 μg/L), chromium (620 μg/L), and cadmium (780 μg/L) were detected in shallow ground water. The company subsequently altered waste-handling practices, and no longer discharges waste into the ground water.

Spills and pipeline leaks also have contributed to ground-water contamination. In 1979, about 800,000 gallons of fuel oil escaped from ruptures in a pipeline in Greenville County, resulting in localized contamination of the shallow saprolite part of the Piedmont and Blue Ridge aquifers. Although an attempt was made to clean the contamination, 162,000 gallons could not be recovered.

Leaking underground storage tanks at gasoline service stations also cause contamination of shallow ground water. Leaks usually are identified after hydrocarbons are detected in nearby domestic water wells or storm sewers. An extreme case occurred in Florence County where a contaminated site was investigated only after a city storm drain caught fire. Several sources of gasoline and fuel oil were discovered nearby, and recovery actions were implemented.

County and Municipal Sources

Ground-water contamination from county and municipal sources is usually associated with landfills (fig. 3*C*) or facilities for treating and disposing of waste water. Typical contaminants include metals, nutrients, insecticides, herbicides, waste oils, and other organic compounds. Typically, contamination at landfills is localized and affects shallow ground water underneath a limited area. However, landfills located in recharge areas for deeper aquifer systems are a greater threat to ground-water quality. One such landfill in a coastal county is located in a recharge area for the Floridan aquifer system. The contaminant plume, which contains nutrients and organic compounds, is at least 33 feet deep, with the top of the Floridan aquifer system about 100 feet deep.

Waste water from an unlined municipal sewage lagoon in Lexington County contaminated shallow ground water with chromium (1,100 μg/L), lead (1,380 μg/L), iron (200,000 μg/L), and nickel (400 μg/L). The contaminant plume is 10 feet deep but appears to discharge into a nearby stream. No public water-supply wells have been closed as a result of contamination from municipal and county sources.

Agricultural Sources

The use of fertilizer, insecticides, and herbicides in irrigated agricultural fields has caused local contamination of shallow ground water with nitrate, phosphate, and organic chemicals (DDT, DBCP, and endosulfan). The accumulation of large quantities of nitrogen-rich animal wastes has caused nitrate contamination of ground water near two feedlots. Six private and five public water-supply wells have been affected.

Contamination of the water-table aquifer in an area of about 5 mi^2 (square miles) north of the city of Sumter has been attributed to agricultural sources. Concentrations of nitrate as nitrogen ranged from 33 to 250 mg/L in the area. Another site with similar contamination was identified where monitoring wells were installed in a proposed subdivision that was to be supplied by shallow water wells. Concentrations of nitrate of as much as 12 mg/L were traced to a combination of fertilizer application, septic tanks, and animal feedlots.

Domestic Sources

Contamination resulting from domestic sources is associated most commonly with septic tank drain fields, improper storage of chemicals, spills, and fuel oil leaking from tanks. Bacterial contamination of shallow ground water at a subdivision in Lexington County was caused by a dense accumulation of septic-tank systems and resulted in the temporary closure of one public water-supply well.

Improper storage of organic chemicals contaminated ground water near a domestic well in Horry County. Alachlor (1,730 μg/L), carbofuran (4,000 μg/L), and carbaryl (360 μg/L) were detected in the domestic well water. Spills related to termite treatment at a residence in York County contaminated a private well with chlordane (0.42 μg/L). Fuel oil from above-ground and underground storage tanks has contaminated domestic wells in Laurens and Lexington Counties. An abandoned domestic well, which had been completed in the Floridan aquifer system in Beaufort County, was mistaken for an access port to a fuel-oil tank, and a large amount of fuel oil was pumped into the well. Five hundred gallons of fuel oil were recovered.

Saltwater Contamination

Saltwater contamination has occurred along the coast of South Carolina through two processes: excessive ground-water withdrawals and hydraulic connection of freshwater and saltwater aquifers. Ground-water withdrawals, particularly near Savannah, Georgia, and Hilton Head Island, South Carolina, have resulted in water-level declines and reversal in the water-level gradient that have increased the potential for saltwater intrusion into the Floridan aquifer system. The potential for intrusion is increasing because ground-water withdrawals are increasing as the population of the area increases. There is also a potential for saltwater intrusion into the Black Creek aquifer in the Myrtle Beach area where water levels have declined more than 100 feet since major pumping began and are continuing to decline as much as 9.5 feet per year. Saltwater contamination also has occurred in open-hole wells that hydraulically connect freshwater and saltwater aquifers in coastal areas of South Carolina.

POTENTIAL FOR WATER-QUALITY CHANGES

The greatest potential for change is in ground-water quality near aquifer recharge areas, particularly near aquifer outcrops. These areas are most subject to change because downward potentiometric gradients will allow contaminants to move into deeper aquifers. One area of major concern is along the Fall Line where the Tertiary sand and Middendorf aquifers crop out (fig. 2*A*1). Because of the significant permeability and small clay content of most sediments, recharge rates are rapid and retardation of contaminant movement is usually negligible. The limited buffering capacity of the ground water in this area makes the water quality susceptible to changes in pH caused by introduction of chemicals from outside sources. A major part of the Columbia metropolitan area (fig. 1*A*) is located on the Tertiary sand and Middendorf aquifer outcrop. The numerous contamination sites in the area (fig. 3*A*) further indicate the concern for future contamination of deeper parts of the aquifers.

Ground-water contamination in areas near the Fall Line also may have a significant effect on surface-water quality where streams deeply incise the land surface. The deep incisement combined with significant rates of ground-water recharge result in rapid rates of ground-water discharge to the streams, producing some of the highest base flows in streams in the State. Thus, contaminated ground water may ultimately contaminate rivers and streams.

The potential for water-quality changes is increasing near expanding industrial and urban centers. Specifically, the growth of industry along the corridors of interstate highways near Columbia, Greenville, and Spartanburg (fig. 1*A*) has the potential to change the quality of the ground water in these areas. General land use in urban areas also may change ground-water quality by affecting the quality of recharge water. Development of coastal areas and the accompanying increase in ground-water withdrawals will increase the potential for saltwater intrusion.

Trends in agricultural and residential practices also increase the potential for changes in ground-water quality. Application of fertilizers, herbicides, and insecticides is increasing. Such application is often made by irrigation systems, which are being used more extensively. If chemicals are applied improperly to croplands and residential areas or are handled carelessly, severe ground-water contamination can occur over extensive areas.

Contaminants that have been identified at several sites across the State in the shallow parts of the aquifer are being removed by treatment. These operations will decrease contamination and are intended to prevent contamination from migrating into deeper aquifers.

GROUND-WATER-QUALITY MANAGEMENT

The South Carolina Department of Health and Environmental Control (DHEC) has the primary responsibility for managing ground-water quality throughout South Carolina. The South Carolina Water Resoures Commission (WRC) has limited responsibility for managing ground-water quality in designated-capacity use areas.

Federal ground-water-quality legislation has been implemented by the DHEC through various State and Federal funding programs. Program management and work-plan objectives are in accordance with the Safe Drinking Water Act of 1974 and its amendments. The State Primary Drinking Water Regulations were adopted in 1981 by the DHEC and have been implemented.

The State's ground-water-protection policy provides for nondegradation of ground-water resources. All aquifers in the State have been classified GB (underground sources of drinking water) by regulations under the State's Water Classifications and Standards of 1985. Ground water that is extremely vulnerable to contamination may be classified as GA if it meets certain criteria. This classification provides for greater protection of the ground water. Ground water also may be classified GC if it cannot be used for public supply because of its quality. Currently (1986), no ground water is classified as GA or GC.

CERCLA and RCRA programs are administered by the Bureau of Solid and Hazardous Wastes Management with technical assistance on ground-water issues provided by the Bureau of Water Supply and Special Programs (BWSSP). Many spills of hazardous substances have been reported as a result of the CERCLA comprehensive notification program. Hazardous materials in the RCRA program are handled persuant to the State's Hazardous Waste Management Act of 1978 and the Hazardous Waste Management Regulations. Evaluation of 33 RCRA sites is in progress.

The State's discharge-permitting process facilitates the identification of existing contamination and decreases the potential for future contamination. Within the BWSSP, the Ground Water Protection Division manages and implements programs for Underground Injection Control and for Underground Storage Tanks, adopted in 1983 and 1985, respectively. Well drillers are required to be certified, and wells must be constructed according to South Carolina Well Standards and Regulations. A network for sampling the background quality of ground water is being developed, and a public education program has been implemented through the Speakers Bureau of the Department of Health and Environmental Control.

Under the Ground-Water Use Act of 1969, the WRC has the authority to regulate ground-water withdrawals within designated capacity-use areas. The purpose of this Act is to minimize the adverse effects of excessive pumping on the availability and quality of ground water where the resource is threatened. All users withdrawing 100,000 gal/d (gallons per day) or more within these areas must obtain a permit from WRC and report monthly usage quarterly.

State ground-water protection programs have been supported by regional, multicounty, and local geohydrologic and water-quality investigations. Background data on ground-water quality have been collected by the WRC, the DHEC, and the U.S. Geological Survey. Geohydrologic knowledge of the Piedmont and Blue Ridge provinces generally is not as complete as for the Coastal Plain province.

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SOUTH DAKOTA
Ground-Water Quality

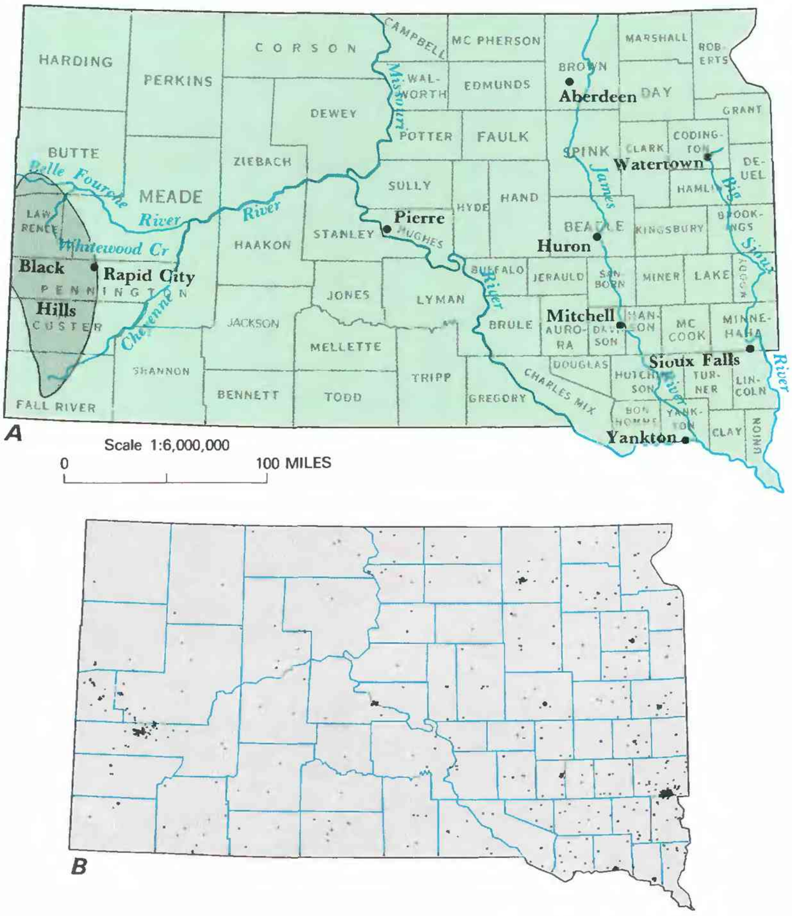

Figure 1. Selected geographic features and 1985 population distribution in South Dakota. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Ground water provides 77 Mgal/d (million gallons per day) for about 77 percent of South Dakota's population of 690,000 people (fig. 1). The majority of the State's 934 community wells, 301 noncommunity wells, and 60,350 private wells are located near the more populated areas of South Dakota. There is no evidence of widespread human-induced contamination in the glacial-drift and alluvial aquifers, and the sedimentary bedrock aquifers (fig. 2). The principal water-quality concern in South Dakota is that the quality of water from large areas of the State commonly exceeds the U.S. Environmental Protection Agency's (EPA) (1986a,b) primary or secondary standards for drinking-water supplies. Dissolved solids, chloride, fluoride, nitrate, sulfate, iron, manganese, selenium, and radionuclides are constituents that most commonly exceed the standards. Although the concentrations of most of these constituents are due to the mineralogy of the aquifers within the State, elevated concentrations of dissolved solids and nitrate are known to result from human activities.

Although areas of ground-water contamination do exist within the State, most cases are isolated (fig. 3). Inorganic and organic nutrients resulting from feedlots, septic tanks, and improper handling and storage of fertilizers have contaminated several community and private water-supply wells. Additional inorganic contaminants affecting wells include dissolved solids resulting from leaking artesian aquifers, saltwater intrusion from saline lakes, brine spills, and leaking brine pits. Arsenic contamination of groundwater supplies in the Black Hills in western South Dakota is known to occur from mine tailings.

Organic contamination of ground water, primarily from pesticides and petroleum products, has been documented in South Dakota (South Dakota Department of Water and Natural Resources, 1984). However, areas of known contamination are limited to those downgradient of spills, leaky storage tanks, and landfills. A hazardous-waste site is present within the Whitewood Creek drainage in western South Dakota as a result of the movement of trace metals from mine tailings to the Whitewood Creek alluvium. Also, the Whitewood Creek site was identified as part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and is part of EPA's Superfund program. U.S. Department of Defense has identified 16 sites at one facility as having potential for ground-water contamination.

Data assessing organic contaminants in ground water in South Dakota are limited because no statewide ground-water-monitoring network exists and because analyses of organic chemicals are not part of routine water-quality analyses of samples from water-supply and observation wells. The potential for organic contamination is particularly great in shallow glacial-drift and alluvial aquifers. For example, the Big Sioux aquifer, a glacial-drift and alluvial aquifer, in eastern South Dakota, provides drinking water for more than 80 percent of the population in the Big Sioux River basin (about 26 percent of the State's population) and is especially vulnerable to contamination because of the shallow depth to water, the extension of permeable material to the land surface, and urban areas where organic materials are produced and stored overlying substantial parts of the aquifer.

WATER QUALITY IN PRINCIPAL AQUIFERS

South Dakota has two principal types of aquifers (fig. 2*A*)—glacial-drift and alluvial aquifers, and sedimentary bedrock aquifers (U.S. Geological Survey, 1985, p. 385). Glacial-drift aquifers underlie most of the State east of the Missouri River and alluvium occurs along major streams throughout the State. Glacial-drift aquifers and alluvial aquifers consist of unconsolidated sand and gravel. Water from the glacial-drift and alluvial aquifers is fresh to slightly saline and is suitable for domestic, livestock, and irrigation uses. Water from shallow glacial-drift and alluvial aquifers contains predominately calcium, bicarbonate, and sulfate ions. Water from deeper glacial-drift aquifers contains predominately calcium, sodium, and sulfate ions. The Big Sioux aquifer, a glacial-drift and alluvial aquifer within the Big Sioux River basin, is the most im-

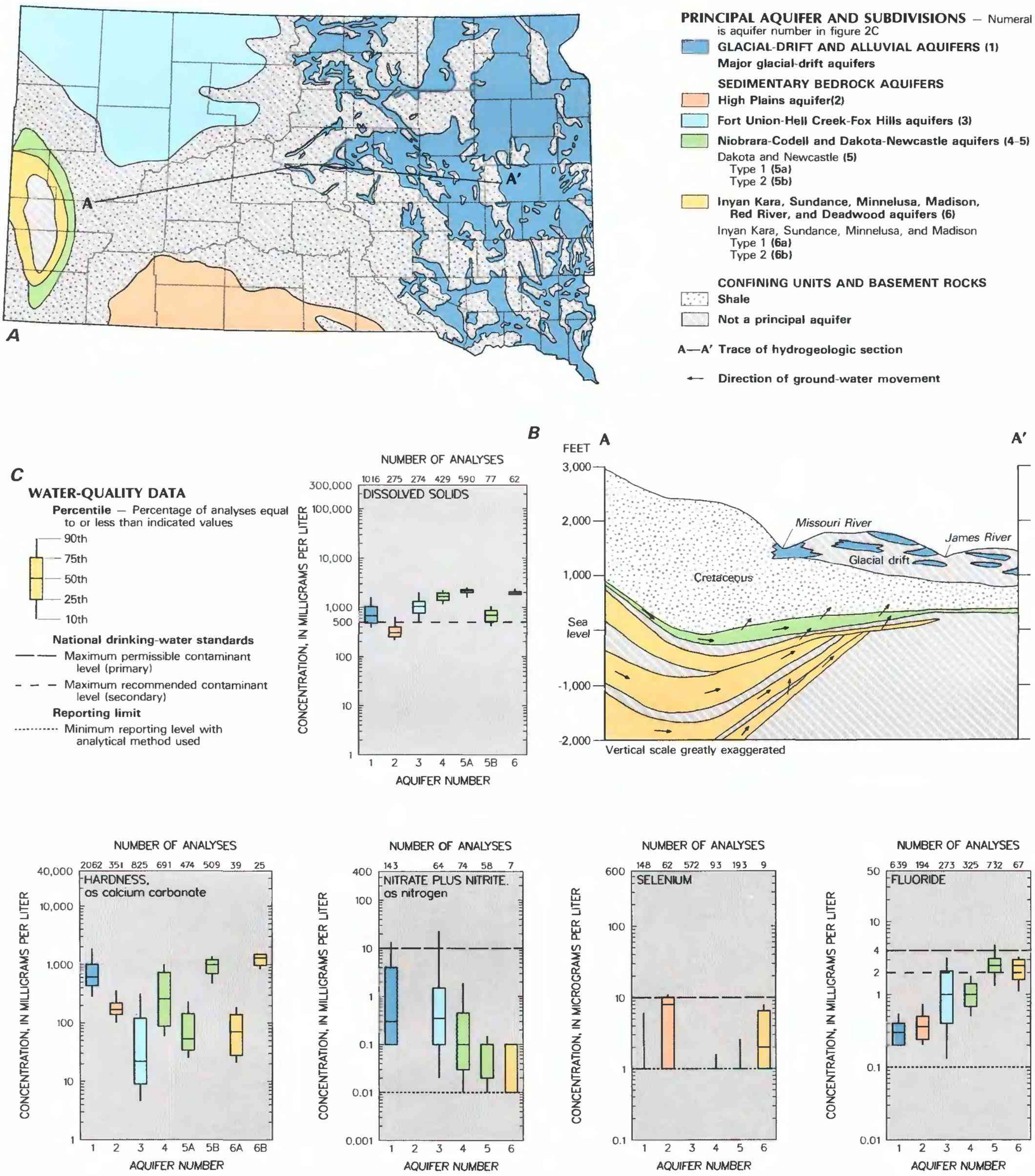

Figure 2. Principal aquifers and related water-quality data in South Dakota. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1930-85. (Sources: *A*, U.S. Geological Survey; 1985; Bardwell, 1984. *B*, Modified from Swenson, 1968. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 b,c.)

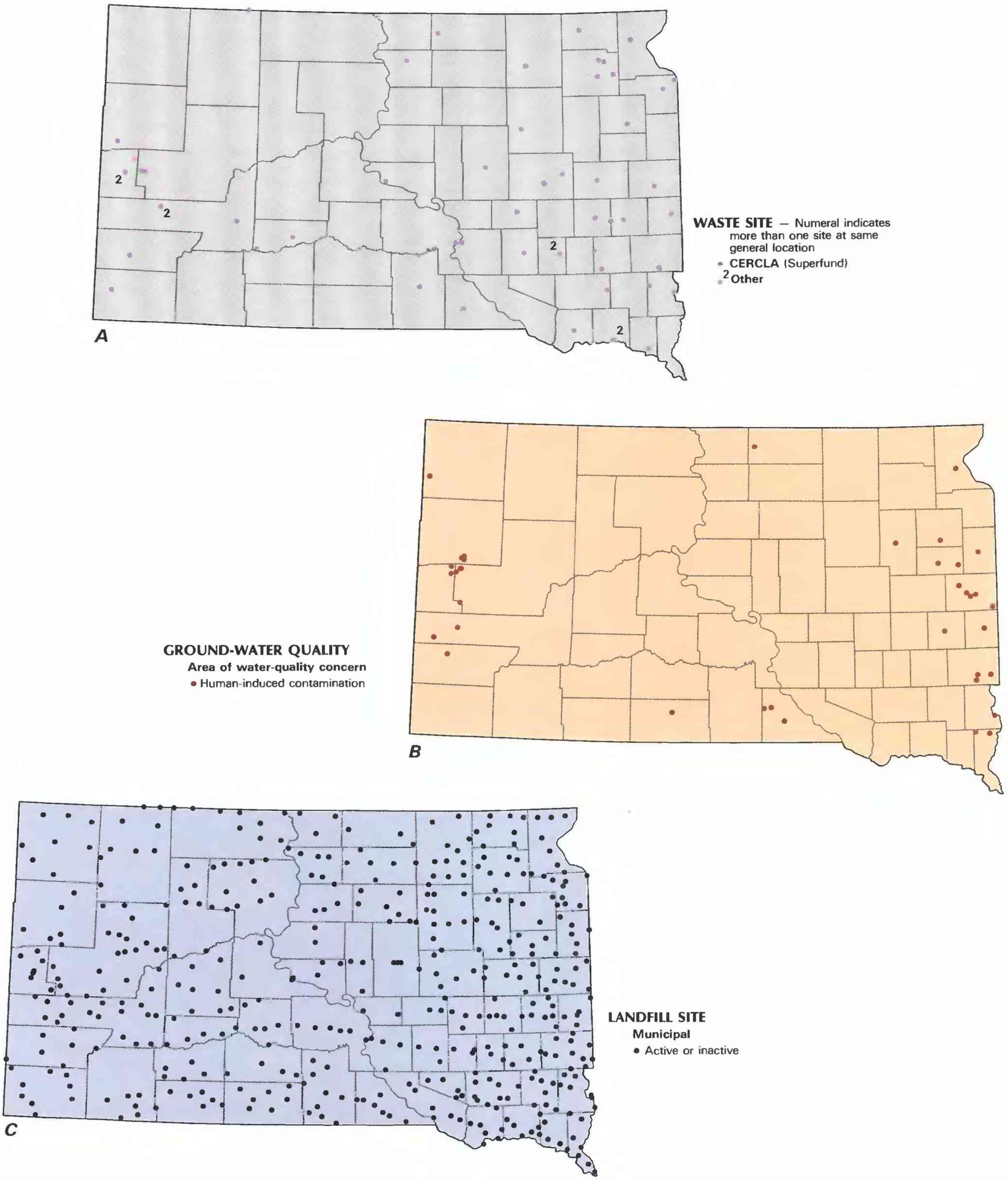

Figure 3. Selected waste sites and ground-water-quality information in South Dakota. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; and other selected waste sites, as of 1986. *B*, Areas of human-induced contamination, as of 1985. *C*, Municipal landfills, as of 1986. (Sources: *A*, Jeanne Goodman, South Dakota Department of Water and Natural Resources, written commun., 1986. *B*, William Markley, South Dakota Department of Water and Natural Resources, written commun., 1985. *C*, Jeanne Goodman, South Dakota Department of Water and Natural Resources, written commun., 1986.)

portant surficial aquifer in the State. There are 14 sedimentary bedrock aquifers in South Dakota (fig. 2*A*). These aquifers are the only source of ground water west of the Missouri River, except for a few small ares of alluvium along major streams. Although commonly very mineralized, except for the High Plains aquifer, and found at relatively great depth away from the Black Hills, water from these aquifers is used extensively for rural-domestic and stock supply. Several of the bedrock aquifers extend into eastern South Dakota beneath the glacial drift (fig. 2*A*).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) data base is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate-plus-nitrite (as nitrogen), selenium, and fluoride analyses of water samples collected from 1930 to 1985 from the principal aquifers in South Dakota. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986b,c). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), 10 μg/L (micrograms per liter) selenium, and 4 mg/L fluoride. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 2 mg/L fluoride.

Glacial-Drift and Alluvial Aquifers

Glacial-drift aquifers consist of unconsolidated sand and gravel deposited by meltwaters from glaciers. Alluvial aquifers consist of unconsolidated sand and gravel deposited by streams.

The water within the shallow glacial-drift and alluvial aquifers had a median dissolved-solids concentration of 670 mg/L; dissolved solids in about 75 percent of the samples exceeded the national drinking-water standard of 500 mg/L. Water from deeper glacial-drift aquifers had a median dissolved-solids concentration of 1,250 mg/L. Whereas dissolved solids provide an indication of the total mineral content of the water, hardness (as calcium carbonate) provides a general indication of the calcium and magnesium content. The median hardness of water from the glacial-drift and alluvial aquifers was 605 mg/L; hardness in 75 percent of the samples was less than 1,000 mg/L (fig. 2*C*). Although uncommon, maximum dissolved-solids and hardness concentrations were as much as 8,300 and 5,000 mg/L, respectively. Calcium and magnesium are the major components of the dissolved-solids concentration in water from the glacial-drift and alluvial aquifers.

Concentrations of nitrate plus nitrite (as nitrogen) in water from the glacial-drift and alluvial aquifers tended to differ somewhat, with a median concentration of 0.3 mg/L. Nitrate plus nitrite in about 10 percent of the samples exceeded the national drinking-water standard of 10 mg/L, with concentrations ranging between 13 and 143 mg/L. Water from many domestic water-supply wells contained large concentrations of nitrate plus nitrite primarily because such wells are downgradient from septic drainage fields, feedlots, or barnyards. In addition, excessive nitrate-plus-nitrite concentrations have been detected downgradient from fertilizer storage areas.

Seventy-five percent of the samples analyzed for selenium contained concentrations less than the detection limit of 1.0 μg/L. Although uncommon, selenium concentrations have exceeded the national drinking-water standard of 10 μg/L. Fluoride concentrations in water from the glacial-drift and alluvial aquifers were less than 0.60 mg/L in 90 percent of the samples. The maximum national drinking-water standard for fluoride concentration is 4.0 mg/L.

High Plains Aquifer

The High Plains aquifer in south-central South Dakota primarily is composed of unconsolidated and slightly consolidated sandstone of the Ogallala and Arikaree Formations. The High Plains aquifer generally is a water-table aquifer in South Dakota, but may be confined in places within the Arikaree Formation. Water in the High Plains aquifer predominately is a calcium-bicarbonate type, and is suitable for domestic, livestock, and irrigation uses; about 90 percent is used for irrigation.

The High Plains aquifer generally contains the least mineralized water of any aquifer in the State although water from the Arikaree Formation tends to contain relatively large concentrations of sodium. Dissolved-solids concentrations generally are less than 400 mg/L (fig. 2*C*) but have been as much as about 1,400 mg/L. The hardness concentration also is smaller than other aquifers in the State with a median value of 170 mg/L and a range of 100 to 770 mg/L. The water generally is hard to very hard. No water samples from the High Plains aquifer have been analyzed for nitrate in South Dakota.

About 25 percent of the selenium concentrations exceeded the national drinking-water standard of 10 μg/L. The median selenium concentration was 8 μg/L. Ground-water samples from some areas have contained selenium concentrations as large as 5,600 μg/L. Selenium concentrations tend to be largest where the Ogallala Formation overlies the Pierre Shale, and the smallest where the Ogallala overlies the Arikaree.

Fort Union, Hell Creek, and Fox Hills Aquifers

The Fort Union, Hell Creek, and Fox Hills aquifers in northwestern South Dakota mostly are confined aquifers but may be unconfined in certain areas. These aquifers are composed of very fine unconsolidated sandstone (U.S. Geological Survey and U.S. Bureau of Reclamation, 1975). Water from these aquifers generally is fresh to slightly saline. Major ions in the water are predominately sodium, sulfate, and bicarbonate. The water is used for public water supplies and agricultural and domestic purposes. Molybdenum is known to be associated with uranium in lignite deposits in the Fort Union and Hell Creek aquifers at concentrations large enough to cause molybdenosis in cattle (Meyer, 1984a). Methane or hydrogen sulfide or both occur in water from some wells completed in the Hell Creek aquifer (Thorstensen and others, 1979).

Water quality within the Fort Union, Hell Creek, and Fox Hills aquifers tends to be significantly different than that in either the glacial-drift and alluvial or the High Plains aquifers. Dissolved-solids concentrations were mostly less than 2,000 mg/L with a median of about 1,050 mg/L (fig. 2*C*), but have been as much as about 8,500 mg/L. The hardness of water from Fort Union, Hell Creek, and Fox Hills aquifers differs. The hardness of most samples was less than 120 mg/L (moderately hard), with a median of 22 mg/L (soft). Although not common, hardness concentrations of 2,000 mg/L have been recorded. The water contains a large amount of sodium, with less calcium and magnesium.

Nitrate plus nitrite (as nitrogen) concentrations differed in these aquifers. Although 75 percent of the samples contained less than 1.5 mg/L, the maximum nitrate plus nitrite concentration was 180 mg/L. The median concentration was 0.35 mg/L The source of the larger nitrate plus nitrite concentrations is not known.

Selenium concentrations were mostly less than the detection limit of 1.0 μg/L, although the maximum concentration was 15 μg/L. Fluoride concentrations in about 75 percent of the samples were less than 2.0 mg/L. The median fluoride concentration was 1.0 mg/L. Concentrations in about 18 percent of the samples were more than 2.4 mg/L.

Niobrara and Codell Aquifers

The Niobrara and Codell aquifers in eastern South Dakota primarily are confined, and composed of shale, chalk, and fine-grained quartz sandstone (U.S. Geological Survey and U.S. Bureau of Reclamation, 1975). The water is slightly saline and contains predominately sodium and sulfate ions. The water is used for domestic and livestock purposes but generally is too mineralized for irrigation use.

The median dissolved-solids concentration in water from the Niobrara and Codell aquifers was 1,670 mg/L (fig. 2*C*). Eighty percent of the samples from these aquifers contained dissolved solids concentrations between 1,150 and 2,250 mg/L. The maximum dissolved-solids concentration was 9,140 mg/L. The hardness of water from these aquifers generally ranged between about 90 mg/L (moderately hard) and 730 mg/L (very hard) with a median value of 260 mg/L (very hard). However, the maximum hardness concentration was 2,900 mg/L.

The concentrations of nitrate plus nitrite generally were less than 1.0 mg/L, but the maximum concentration was 35 mg/L. The median concentration was 0.1 mg/L. The cause of nitrate plus nitrite concentrations greater than 10 mg/L in ground water is not known.

Selenium concentrations generally were less than the detection limit (fig. 2*C*), although water from several wells contained concentrations of about 10 μg/L. Fluoride concentrations were less than the national drinking-water standard in water from most wells. The median concentration was 1.0 mg/L; concentrations in 90 percent of the samples were less than 1.8 mg/L. Fluoride concentrations were as much as 3.2 mg/L.

Dakota and Newcastle Aquifers

The Dakota and Newcastle aquifers, which underlie most of South Dakota (fig. 2*C*), are confined and composed of sandstone interbedded with shale and siltstone (U.S. Geological Survey and U.S. Bureau of Reclamation, 1975). The water is slightly to moderately saline and contains predominately sodium, chloride, and sulfate ions. The water is used primarily for livestock, but is too mineralized for irrigation use and commonly is not used for human consumption.

Two water types were identified within the Dakota and Newcastle aquifers. Type 2 water occurs in southeastern South Dakota, and type 1 water occurs elsewhere in the State. Type 1 had a median dissolved-solids concentration of 2,170 mg/L, which is larger than water from the previously described aquifers (fig. 2*C*). Ninety percent of the dissolved-solids concentrations were less than 2,550 mg/L. Type 2 water had a median dissolved-solids concentration of 690 mg/L. Ninety percent of the dissolved-solids concentrations in the type 2 water were less than 1,060 mg/L. In some areas in Brown County, the Dakota aquifer is being recharged by underlying aquifers that contain freshwater under greater pressure; this recharge has resulted in a decrease in chloride concentration from 200 to 160 mg/L from 1938 to 1963 (Koch and Bradford, 1976).

Hardness concentrations were the major difference between the two water types. Type 1 water is soft to moderately hard, whereas type 2 is classified as very hard. The median hardness concentration of type 1 is 53 mg/L, with 90 percent of the concentrations less than 230 mg/L. Type 2 water had a median hardness concentration of 990 mg/L, with 90 percent of the concentrations less than 1,400 mg/L. Type 1 water has a large proportion of sodium to calcium and magnesium. Type 2 water has a large proportion of calcium and magnesium to sodium.

A differentiation between water types was not made for nitrate plus nitrite, selenium, or fluoride concentrations because their differences were minimal. Seventy-five percent of the nitrate plus nitrite concentrations were less than 0.1 mg/L. The median concentration was also 0.1 mg/L. The maximum nitrate plus nitrite concentration was 1.1 mg/L. Seventy-five percent of the selenium concentrations were less than the detection limit of 1 μg/L. The maximum selenium concentration was 35 μg/L, which exceeded the national drinking-water standard of 10 μg/L. Fluoride concentrations in water from the Dakota and Newcastle aquifers tend to be more than 2.4 mg/L. The median fluoride concentration in water from these aquifers was 2.5 mg/L, with 90 percent of the concentrations less than 4.8 mg/L. The maximum fluoride concentration in water from this aquifer was 26 mg/L. These large fluoride concentrations were caused by naturally occurring minerals in the aquifers.

Inyan Kara, Sundance, Minnelusa, Madison, Red River, and Deadwood Aquifers

The Inyan Kara is a confined aquifer composed of sandstone interbedded with shale and siltstone; the Sundance aquifer also is confined but composed of shale interbedded with limestone, sandstone, and shale. The Minnelusa aquifer is confined and is composed of sandstone interbedded with limestone, dolomite, and shale; the Madison aquifer also is a confined aquifer but composed of limestone and dolomite interbedded with shale, anhydrite, and halite (U.S. Geological Survey and U.S. Bureau of Reclamation, 1975).

Water in the Inyan Kara, Sundance, Minnelusa, and Madison aquifers is a sodium-sulfate type in western South Dakota and a calcium-sulfate type in eastern parts of the State. The least mineralized water occurs where these aquifers are exposed at land surface in the western part of the State. In some areas, water from the Inyan Kara and Madison aquifers have concentrations of radium-226 and gross alpha that exceed national primary drinking-water standards [5 and 15 pCi/L (picocuries per liter), respectively]. Uranium concentrations also are greater than background concentrations but do not exceed national standards (South Dakota Department of Water and Natural Resources, 1984). Water is used for public supply, domestic, and livestock purposes and is suitable for irrigation use in some areas, particularly within the Black Hills.

Water from the Red River and Deadwood aquifers appears to be markedly different from water in other sedimentary bedrock aquifers within the State. Water from the Red River aquifer is predominately a sodium-chloride type. Water from the Deadwood aquifer is fresh within the Black Hills. These aquifers generally are undeveloped, and their potential for development is unknown.

The differences of dissolved-solids concentration for this group of aquifers appear to be very small except for the Red River and Deadwood aquifers. The median dissolved-solids concentration for the group was 1,996 mg/L and 90 percent of the concentrations were less than 2,400 mg/L (fig. 2*C*). The maximum dissolved-solids concentration was 4,300 mg/L. Nearly all water samples from these aquifers had dissolved-solids concentrations greater than the national drinking-water standard of 500 mg/L. Water from the Red River aquifer had a maximum dissolved-solids concentration of 25,000 mg/L. Water from the Deadwood aquifer had a minimum dissolved-solids concentration of 400 mg/L.

The hardness concentrations for the Inyan Kara, Sundance, Minnelusa, and Madison aquifers can be grouped into two water types. Type 1 water is soft to moderately hard. The median hardness concentration was 71 mg/L, and 90 percent of the concentrations were less than 190 mg/L. The maximum hardness concentration for type 1 water was 219 mg/L. Type 2 water is hard to very hard. The median hardness concentration was 1,300 mg/L. Eighty percent of the concentrations were between 840 and 1,600 mg/L. Type 1 water has a large proportion of sodium to calcium and magnesium; whereas type 2 water has a large proportion of calcium and magnesium to sodium.

Water types were not differentiated for nitrate plus nitrite, selenium, and fluoride concentrations because their differences were minimal. Seventy-five percent of the nitrate plus nitrite concentrations were less than 0.1 mg/L. The median concentration was 0.01 mg/L as nitrogen.

All total selenium concentrations were less than the National drinking-water regulation of 10 μg/L; the median concentration was 2 μg/L. Fluoride concentrations in water from these aquifers tended to be greater than the national drinking-water standard of 2 mg/L. The median fluoride concentration was 2.5 mg/L, and 80 percent of the concentrations were between 1.1 and 3.3 mg/L. The maximum fluoride concentration was 7.2 mg/L.

EFFECTS OF LAND USE ON WATER QUALITY

As of 1986, there was no evidence of widespread contamination of ground water in South Dakota. However, ground water has been contaminated in local areas due to the effects of flowing wells, releases of petroleum products and agricultural chemicals, wastewater-disposal systems, feedlots, mining activities, and oil and gas activities (South Dakota Department of Water and Natural Resources, 1984). The contamination of ground-water supplies for about 15,000 people, about 2.6 percent of the 586,000 people served by ground water, has been documented (fig. 3*B*). Contamination of most water wells in the State is associated with chemical spills, feedlots, and septic systems. Commonly, the wells are contaminated with one or more of the following: nitrate, bacteria, hydrocarbons, or pesticides.

There are 58 permitted solid-waste facilities (fig. 3*A*) and about 350 municipal landfills (fig. 3*C*) in South Dakota. Contamination of potable water supplies at or near these facilities and landfills has not been documented. As of September 1985, 16 hazardous waste-sites at 1 facility in South Dakota had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. EPA presently ranks these sites under the hazard ranking system and may include them in the National Priorities List (NPL).

Flowing Wells

Shallow glacial-drift aquifers in the James River basin have been contaminated by saline water from flowing wells completed in bedrock aquifers. Flowing wells completed in bedrock aquifers have discharged billions of gallons of saline water onto the land surface during the last 70 years (Koch and Bradford, 1976). Today (1986), the casing in many of these wells has corroded, and saline water is leaking directly into the glacial-drift aquifers. Saline water from about 15,000 wells completed in bedrock aquifers is contaminating overlying aquifers (South Dakota Department of Water and Natural Resources, 1984).

Petroleum Products and Agricultural Chemicals

Releases of petroleum products and agricultural chemicals can occur as leaks from storage tanks, as improper disposal of rinse water, or as spills during transport. Petroleum products are the most common material involved in releases and are responsible for the contamination of 16 water-supply wells and about 6.1 mi^2 (square miles) of land (Jeanne Goodman, South Dakota Department of Water and Natural Resources, written commun., 1986).

Agricultural chemicals account for the remainder of the contamination problems. Leaking tanks, improper disposal of rinse water, and improper storage of the chemicals and associated equipment have resulted in the contamination of 22 water-supply wells and about 4.23 mi^2 of land (Jeanne Goodman, South Dakota Department of Water and Natural Resources, written commun., 1986)

Wastewater Disposal Systems

According to the 1980 census (U.S. Bureau of the Census, 1982), there were 72,000 individual wastewater-disposal systems serving 185,600 people in South Dakota. More than 443,000 people are served by about 350 centralized wastewater-disposal systems. Individual systems, mostly septic tanks, have caused nitrate and bacterial contamination in domestic water wells because the systems commonly are near domestic wells. However, contamination caused by septic tanks usually is localized.

The majority of the municipal wastewater-disposal systems are stabilization ponds. Localized ground-water degradation has occurred near some of the ponds as a result of leakage. No known water-supply wells have been affected.

Feedlots

Nitrate-plus-nitrite concentrations in excess of 10 mg/L as nitrogen are common in water from wells in or near feedlots. An undetermined number of domestic water wells have been contaminated by feedlot wastes. The extent of ground water contaminated by feedlots is not defined because of the numerous feedlots throughout the State, the diffused movement of nitrogen compounds from feedlots, and the effects of septic systems and improper storage of fertilizers on the nitrate concentrations in ground water. Shallow glacial-drift and alluvial aquifers are particularly susceptible to contamination by feedlots.

Mining Activities

Gold-mining in the Black Hills for about 100 years has produced large quantities of tailings that were discharged directly into Whitewood Creek. This resulted in arsenic and mercury contamination of the alluvial sediments along the creek and identification of the site as part of the EPA's Superfund program (CERCLA, fig. 3*A*). Arsenic concentrations have exceeded the national drinking-water standard of 50 μg/L in water from 10 water-supply wells. At least 5 mi^2 of land have been contaminated (Jeanne Goodman, South Dakota Department of Water and Natural Resources, written commun., 1986). The construction of new water wells in the alluvial aquifer along Whitewood Creek is prohibited in some areas.

Oil and Gas Activities

Oil and gas production in South Dakota is limited to two areas in the western part of the State. These activities have caused increases in dissolved-solids concentrations in ground water, mostly as a result of increases in chloride and sodium concentrations. These increases commonly are associated with leakage from unlined mud pits and from brine-disposal pits. Contamination has been documented (Meyer, 1984a), but no potable water supplies are known to be affected.

POTENTIAL FOR WATER-QUALITY CHANGES

Shallow, near-surface aquifers are susceptible to contamination by human activities because of the thin, permeable soils overlying the aquifers and shallow depth to water. An example is the Big Sioux aquifer (a glacial drift and alluvial aquifer) in eastern South Dakota, which supplies water to about 26 percent of the State's population. Numerous gasoline, fertilizer, and agricultural-chemical spills have occurred in recent years. Such spills, coupled with a shallow water table, create a situation that increases the likelihood of ground-water contamination. Deeper aquifers usually are protected by upward pressure gradients under predevelopment or moderate development conditions and by overlying confining units of clay or shale.

The major land use in the State is agriculture. Although ground-water contamination from nonpoint sources has not been documented as a problem, the current trend toward the increased use of fertilizers and pesticides may degrade or contaminate ground water in some areas. The Oakwood Lake-Poinsett Rural Clean Water Program is a current (1986) ground-water-monitoring project designed to determine the effects of fertilizers and pesticides on receiving ground water as a result of land-use management practices. Contamination of ground water by point sources, such as accidental spills and feedlots, is expected to continue. However, only local areas are expected to be affected by such contamination.

It is estimated that South Dakota has more than 10,000 buried tanks containing petroleum products (Jeanne Goodman, South Dakota Department of Water and Natural Resources, 1980). Because many of the tanks have been buried for a long time, it is expected that isolated instances of ground-water contamination will occur because of petroleum products leaking from the tanks.

The potential for ground-water contamination will probably increase in the Black Hills along with the recent increase in gold-mining activities. Cyanide heap leaching (the leaching of gold from crushed ore using a cyanide solution) is being used at one mining operation and has been proposed for use at two other mining operations. These renewed activities will increase the potential for cyanide and arsenic contamination of local aquifers. However, ground-water-monitoring systems required by the State should detect any aquifer contamination caused by the leaching process.

GROUND-WATER-QUALITY MANAGEMENT

Ground-water management and implementation of the ground-water-quality strategy for prevention, control, and abatement of ground-water contamination are functions of the South Dakota Department of Water and Natural Resources (DWNR). The various aspects of ground-water policies are the responsibility of divisions within that department.

The Division of Water Quality (DWQ) has the primary responsibility in dealing with ground-water contamination and is responsible for development of ground-water-quality strategy. Through this office, Federal Construction Grants, National Pollution Discharge Elimination Systems, and Underground Injection Control permits are reviewed, although U.S. Environmental Protection Agency maintains primacy in some cases. The RCRA Subtitle I-Underground Storage Tanks and remedial action also are administered by this office.

The Division of Drinking Water (DDW) monitors public drinking-water supplies under the Federal Safe Drinking Water Act. Suspected domestic-well contamination may be investigated by this division.

The Division of Environmental Quality (DEQ) coordinates activities to protect ground-water quality. The Division's Office of Air Quality and Solid Waste is responsible for the management of solid and hazardous wastes in the State. This includes administering the majority of the Federal RCRA regulations within the State in addition to issuing disposal-permit applications and conducting some ground-water monitoring. State hazardous-waste regulations are based on RCRA requirements.

The State Division of Water Rights (DWR) regulates water use, well construction, and well-driller licensing. Approval of water-use permits is the responsibility of a seven-member Water Management Board appointed by the Governor. The Board's duties include establishment of general well-construction standards and water-quality functions, which were revised in 1985.

The Division of the Geological Survey (DGS) conducts ground-water investigations involving quality, quantity, and contamination of ground water. Some investigations are conducted in cooperation with the U.S. Geological Survey.

Various divisions within DWNR are taking remedial actions to abate or eliminate reported ground-water contamination. Information on ground-water quality collected through the existing programs does not indicate widespread ground-water contamination; however, background water-quality data are needed for some areas.

The initiation of elements necessary for establishing a State ground-water quality strategy date back to 1979 when the Big Sioux Aquifer Water Quality Study began. A network of monitoring wells was established by the U.S. Geological Survey in cooperation with DGS (Leibbrand, 1985). Monitoring wells were installed in areas of large nitrate concentrations around landfills, in areas of petroleum spills, and around a municipal wastewater-treatment lagoon. Water samples from a group of municipal wells and numerous domestic wells were analyzed for contaminants on the EPA's priority pollutant list (U.S. Environmental Protection Agency, 1986a). A nitrogen-isotope study also was conducted in an attempt to identify sources of nitrate contamination.

DWNR, in cooperation with the U.S. Army Corps of Engineers, is evaluating selected aspects of ground-water resources in eastern and western South Dakota. Among the information compiled under this effort are: (1) A comprehensive bibliography of ground-water-related references; (2) characterization of water-quality suitability by aquifer for specific uses; (3) estimates of recharge rates; (4) compilation and computerization of available water-quality, well-construction, and aquifer data; (5) preparation of ground-water-quality maps and charts; and (6) determination of water use by aquifer.

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TENNESSEE
Ground-Water Quality

Ground water, suitable for most uses, is potentially available in nearly all communities in Tennessee (fig. 1). About 51 percent of the State's population depends on ground water for household use. Industrial consumption averages 190 Mgal/d (million gallons per day) (U.S. Geological Survey, 1985, p. 391). Most ground water is withdrawn in the western one-quarter of the State, where confined sand aquifers yield ample supplies of water satisfactory for most uses. Interest is increasing in additional development of ground-water resources in middle and eastern Tennessee. These areas are underlain primarily by carbonate aquifers that differ in yield and water quality.

Where adequate supply exists, water quality is seldom a limiting factor on use. However, concentrations of dissolved solids and iron are large in some ground water. As in most areas of the country, the major focus of water quality is contamination induced by waste disposal and other human activities. These problems are localized at hazardous-waste sites, landfills, and spill areas. Tennessee has seven hazardous-waste sites on the National Priorities List (NPL) (U.S. Environmental Protection Agency, 1986c), six of which pose some threat to local ground-water use. At several of these sites, organic chemicals, including industrial solvents and residues from pesticide manufacturing, are of concern. The problems at these sites are being addressed under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Of the State's 13 non-federal disposal sites regulated under the Resource Conservation and Recovery Act (RCRA), 12 show evidence of ground-water contamination (Dwight Hinch, Tennessee Department of Health and Environment, written commun., 1988). In addition to these sites, the State is the site of developmental efforts in atomic energy at Oak Ridge Reservation, Tennessee, where radioactive and chemically hazardous wastes have contaminated local ground water (Geraghty and Miller, Inc., 1985). In addition, six sites at three facilities were identified by the U.S. Department of Defense (DOD) as requiring response action in accordance with CERCLA. Other sources of contamination in urban communities include leaking underground storage tanks and domestic septic tank systems.

Water-quality problems will remain a major concern in Tennessee as urbanization and industrialization increase (see population distribution in fig. 1*B*). This concern is manifest within the State government, where new legislation and administrative structures have been designed to address problems of ground-water quality.

WATER QUALITY IN PRINCIPAL AQUIFERS

Tennessee's ground-water resources occur in nine regional aquifers: the alluvial, the Tertiary sand, the Cretaceous sand, the Pennsylvanian sandstone, the Mississippian carbonate, the Ordovician carbonate, the Knox, the Cambrian-Ordovician carbonate, and the crystalline rock aquifers (figs. 2*A*,*B*). The physical characteristics of these aquifers have been described previously (U.S. Geological Survey, 1985, p. 391-396).

Chemical constituents and physical properties of ground water in Tennessee generally do not exceed the national drinking-water standards (U.S. Environmental Protection Agency, 1986a,b). Water in sand aquifers is commonly soft and slightly acidic, with small concentrations of dissolved solids. In several regions, increased iron and sulfate concentrations result from the dissolution of pyrite and other iron- and sulfur-bearing minerals. In carbonate aquifers, geochemical interactions cause increases in hardness and alkalinity along most flow paths. Saline water occurs in deep aquifers or within poorly developed solution openings in flat-lying carbonate rocks. Nitrate is seldom a problem in Tennessee's ground waters.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness, nitrate

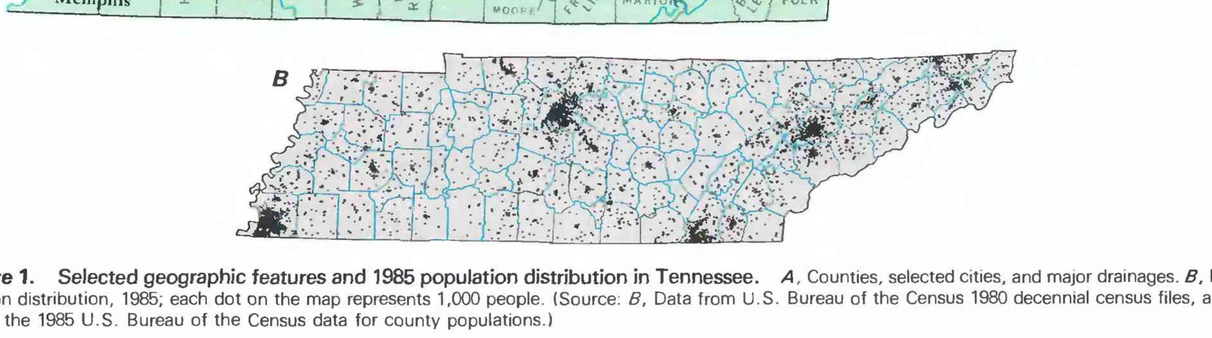

Figure 1. Selected geographic features and 1985 population distribution in Tennessee. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

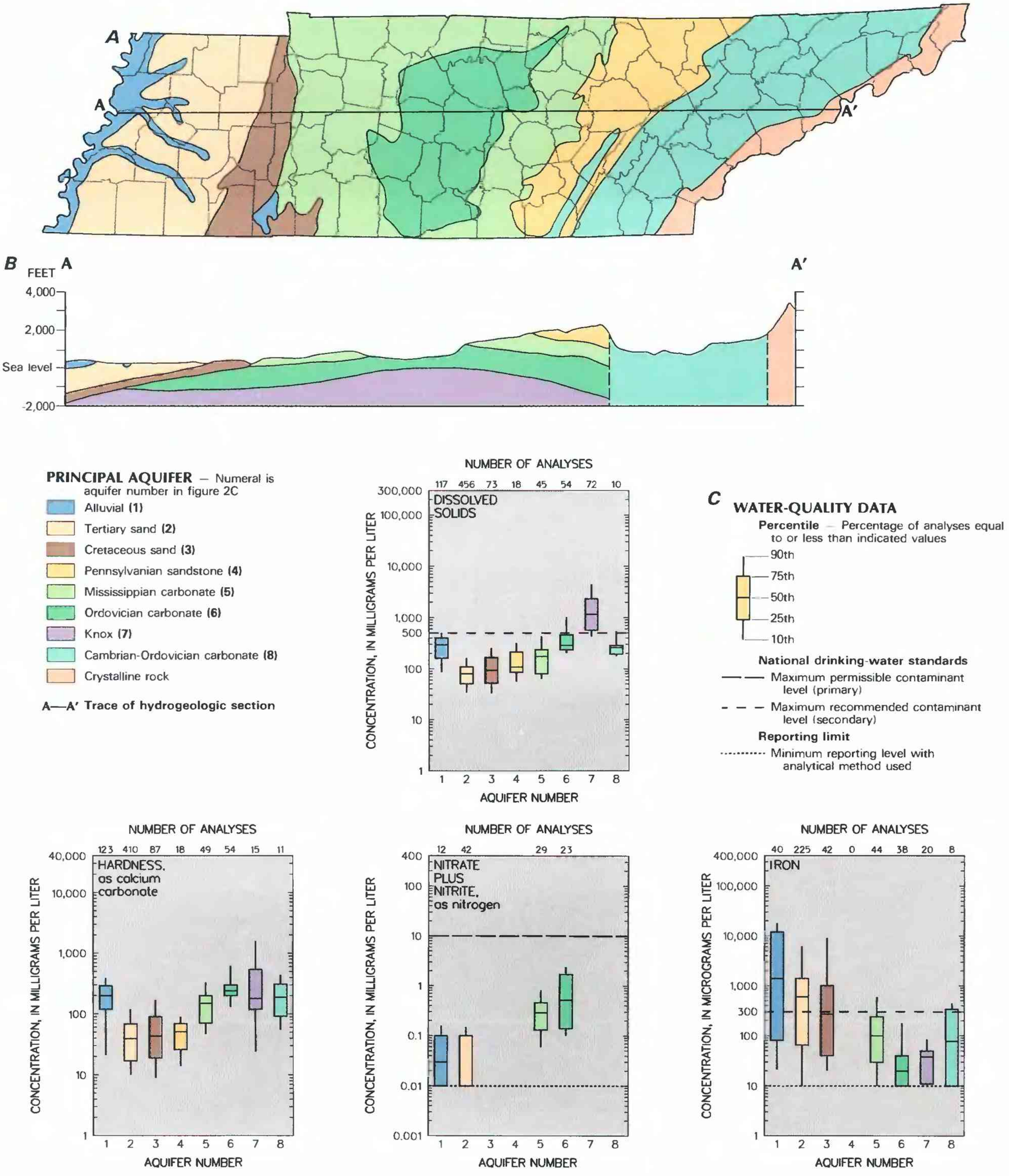

Figure 2. Principal aquifers and related water-quality data in Tennessee. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1965-85. (Sources: *A*, Miller, 1974; *B*, Compiled by M.W. Bradley from U.S. Geological Survey files; *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

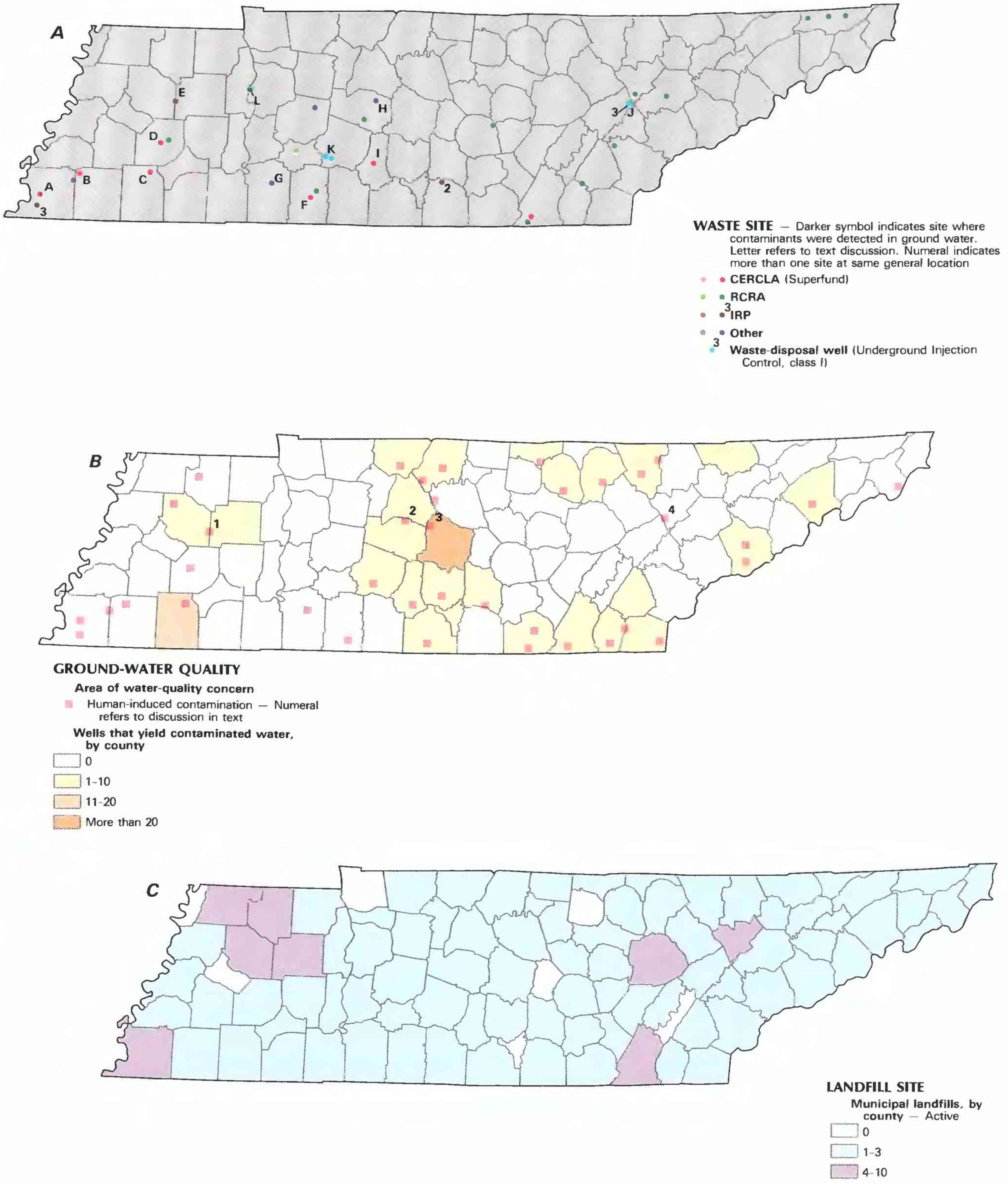

Figure 3. Selected waste sites and ground-water-quality information in Tennessee. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1986. *B*, Areas of human-induced contamination and distribution of wells that yield contaminated water, as of 1985. *C*, Municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c and Tennessee Department of Health and Environment, unpublished data; U.S. Department of Defense, 1986; *B*, Association of State and Interstate Water Pollution Control Administrators, 1985; *C*, Tennessee Department of Health and Environment, unpublished data.)

plus nitrite (as nitrogen), and iron analyses of water samples collected from 1965 to 1985 from the principal aquifers in Tennessee. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 300 μg/L (micrograms per liter) iron.

Alluvial Aquifer

The alluvial aquifer underlies the flood plain of the Mississippi River and its tributaries in extreme western Tennessee (fig. 2*A*). Use of the alluvial aquifer is limited primarily to rural-domestic supplies, because in most areas of western Tennessee water of better quality is available from a deeper aquifer. Although concentrations of dissolved solids are not excessive (90 percent of the analyses are less than 500 mg/L), the calcium bicarbonate type water is very hard. Median hardness is 200 mg/L. Iron concentrations generally exceed 1,000 μg/L, and some industrial users have been forced to abandon wells in the alluvial aquifer because of iron accumulation in pipes. The alluvial aquifer is unconfined, and, therefore, susceptible to contamination from all waste sites.

Tertiary Sand Aquifer

The most extensive and productive aquifer in Tennessee is the Tertiary sand, which supplies about 190 Mgal/d to the City of Memphis. Calcium bicarbonate type water from this confined aquifer has small concentrations of dissolved solids (90 percent of analyses are less than 163 mg/L), and is generally soft (median hardness is 39 mg/L). The only major water-quality problem is a large iron concentration, which requires that the water be treated before use. The median iron concentration is 600 μg/L. There is concern, however, that leakage of contaminated water from the overlying alluvial aquifer may degrade water quality in the Tertiary sand. In addition, several hazardous-waste sites are located in recharge areas of this important aquifer (fig. 3*A*).

Cretaceous Sand Aquifer

The Cretaceous sand aquifer is an important water source in its outcrop area. The concentration of dissolved solids is smaller than 256 mg/L for 90 percent of the analyses. In general, the concentration of dissolved solids increases along the flow paths. In the downgradient confined part of the aquifer, the concentration of dissolved solids may exceed 500 mg/L; the water type changes from calcium bicarbonate to sodium bicarbonate; and iron concentrations may be excessive. In 25 percent of all analyses, the iron concentrations exceed 1,000 μg/L. In the McNairy Sand, a Cretaceous formation underlying the Memphis area, the sodium bicarbonate type water is soft, but the fluoride concentration may exceed the primary drinking-water standard of 4 mg/L (U.S. Environmental Protection Agency, 1986a).

Pennsylvanian Sandstone Aquifer

Seventeen public utilities on the Cumberland Plateau withdraw water from the Pennsylvanian sandstone aquifer, where shallow flow paths occur in interconnected fractures. Seventy-five percent of the dissolved-solids concentrations are smaller than 210 mg/L, and the median hardness is 51 mg/L. Where flow paths intercept sandstone or shale containing pyrite or other minerals rich in ferrous and sulfurous compounds, ground water may develop large concentrations of iron, sulfate, or hydrogen sulfide. No hazardous-waste sites are documented in areas served by this aquifer, but because of mining and oil and gas operations, degradation of ground-water quality has been observed.

Mississippian Carbonate Aquifer

The Mississippian carbonate aquifer, which underlies the Highland Rim of middle Tennessee, is used extensively for public drinking-water supplies. Most ground-water movement is through the relatively thick regolith and the secondary openings in the underlying rock. Concentrations of dissolved solids increase along the flow paths; the median concentration of dissolved solids is 174 mg/L. Water is generally hard (median hardness is 150 mg/L), and iron, manganese, and sulfate concentrations are large in some areas. The Mississippian carbonate aquifer has some protection from potential contamination because it is overlain by a clay-rich regolith that is 80 feet thick in some areas. In certain regions, however, the land overlying the aquifer is characterized by sinkholes. Industrial wastes, including sulfuric acid, heavy metals, and petroleum products, have been dumped into these sinkholes, and a few localized flow systems have become contaminated.

Ordovician Carbonate Aquifer

Water in the Ordovician carbonate aquifer travels primarily through fractures and solution channels, and flow systems are commonly localized. Water-quality characteristics differ and reflect local flow dynamics and geochemical conditions. Where ground-water velocities are rapid and flow paths are relatively short, the concentration of dissolved solids is generally smaller than 500 mg/L. In contrast, concentrations exceeding 1,000 mg/L are not uncommon in isolated flow cells. Calcium bicarbonate type water is common in this aquifer, where 90 percent of the analyses for hardness exceed 130 mg/L. Hydrogen sulfide gas is present in about one-fifth of all wells, indicating reducing geochemical environments. Caves and sinkholes occur in some recharge areas, rendering this aquifer locally vulnerable to infiltration by surface contaminants. Also, the Ordovician carbonate aquifer underlies the Nashville metropolitan area, where numerous septic tanks have caused widespread degradation of shallow ground water.

Knox Aquifer

The Knox aquifer of middle Tennessee is a deep-lying limestone and dolomite aquifer. Currently, public supplies are not obtained from the Knox, but small yielding private wells have been drilled in areas where no alternative water source is available. Where the Knox aquifer is shallow, concentrations of dissolved solids are smaller than 600 mg/L. However, most of the Knox is deeper than 700 feet, and the water is very mineralized (the median dissolved-solids concentration is 1,160 mg/L). Where concentrations of dissolved solids exceed 1,000 mg/L, the water type is sodium chloride or sodium sulfate. Fluoride concentration exceeds 2.0 mg/L in many areas. Owing to its relative isolation and poor water quality, the Knox, at depths greater than 3,000 feet, has been used for deep-well injection of industrial wastes. However, confining layers between the lower and upper Knox are not well defined, and the potential may exist for contamination of drinking-water supplies.

Cambrian-Ordovician Carbonate Aquifer

Within the Cambrian-Ordovician carbonate aquifer, water occurs in solution openings in carbonate rocks and in fractures and bedding planes in sandstone and shale. More than 75 communities use this aquifer for their public water supply. Most withdrawals are from springs or wells less than 300 feet deep. In these shallow systems, concentrations of dissolved solids seldom exceed 500 mg/L, although the water is commonly very hard (median hardness is 190 mg/L). The combination of complex rock structure and rapid ground-water movement renders this aquifer particularly vulnerable to contamination.

Crystalline Rock Aquifer

Little information is available on water quality in the crystalline rock aquifer. Flow is localized in the thick regolith and in the bedrock fractures beneath mountainous terrain (Zurawski, 1979). The few water-quality data available indicate that the ground water is very soft and has small concentrations of dissolved solids.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has been degraded in some areas of Tennessee because of waste disposal. The State's CERCLA and RCRA sites, areas of contaminated ground water, and the distribution of wells that yield contaminated water and municipal landfills are shown in figure 3. The U.S. Geological Survey has conducted hydrogeologic and geochemical investigations at several of these sites and continues to be active in research on the transport and fate of hazardous constituents in the subsurface environment.

Hazardous-Waste Sites

Several dump sites in the Memphis area contain hazardous wastes (Parks and others, 1982; Graham, 1985). One of these landfills, the North Hollywood Dump in Shelby County (fig. 3*A*, site A), is the State's top-ranked CERCLA site. It is also the study area for a U.S. Geological Survey project investigating the mobility of hazardous organic compounds in an alluvial aquifer. The contaminants of major concern at the North Hollywood Dump are organochlorine pesticides, including lindane, heptachlor, and chlordane. Hazardous-waste sites in the Memphis area contribute toxic leachates to the unconfined alluvial aquifer. In most places, a clay confining layer separates this aquifer from the Memphis Sand, a Tertiary sand unit that provides the drinking water for the city. The potential for contaminated water from the alluvial aquifer to enter the Memphis Sand is a primary concern.

Two other pesticide-laden waste sites that are also on the NPL are located in outcrop areas of the Tertiary sand aquifer. At Gallaway Pits in Fayette County (fig. 3*A*, site B), chlordane, endrin, and lindane have been detected in shallow ground water. In Hardeman County, localized contamination of the aquifer has forced the abandonment of 13 private drinking-water wells (fig. 3*A*, site C). At this site, low-molecular-weight organic solvents are migrating faster than a plume of organochlorine pesticides. Apparently, the transport of pesticides is being retarded because of sorptive interactions with the aquifer matrix. This site was the study area for two investigations by the U.S. Geological Survey (Rima and others, 1967; Sprinkle, 1978). Creosote, pentachlorophenol, and other phenolic wastes have contaminated local ground water at a CERCLA site near Jackson (Madison County), Tennessee (fig. 3*A*, site D). In Gibson County (fig. 3*A*, site E; fig. 3*B*, site 1), lagoons and landfills serving an Army munitions plant have leaked, resulting in ground-water contamination by trinitrotoluene and several heavy metals.

Two hazardous-waste sites are located in the recharge area of the Mississippian carbonate aquifer. In Lawrence County (fig. 3*A*, site F), a metal-plating company has contaminated local ground water with chromium and nickel, and in Wayne County (fig. 3*A*, site G), polychlorinated biphenyls have been detected in monitoring wells near a waste-disposal site.

Hazardous-waste sites that may affect the Ordovician carbonate aquifer include a disposal area for organic solvents in Williamson County (fig. 3*A*, site H) and a municipal dump in Marshall County (fig. 3*A*, site I). The U.S. Geological Survey is conducting an investigation at the Williamson County site, where several domestic wells may be threatened. The site in Marshall County has been placed on the NPL. Situated in an abandoned limestone quarry, this dump accepted industrial wastes, including paint, pickling liquor, and wood-product residues.

In northwest Rutherford County (fig. 3*B*, site 3), waste oils and solvents dumped into sinkholes have contaminated water in the Ordovician carbonate aquifer supplying domestic wells. Organic constituents, including trichloroethylene and other chlorinated hydrocarbons, were detected in 29 of 44 samples from local wells and springs. Twenty-seven private wells were closed, and a public water system was extended to the affected households.

At Oak Ridge Reservation (fig. 3*A*, site J; fig. 3*B*, site 4), radionuclides, heavy metals, nitric acid, and various organic compounds were discharged into waste ponds or buried underground (Geraghty and Miller, Inc., 1985). The distribution of these constituents in local ground water is being investigated by several public and private agencies, including the U.S. Geological Survey (Pulliam, 1985).

Deep-well injection of industrial wastes continues in Maury County (fig. 3*A*, site K) and Humphreys County (fig. 3*A*, site L). These wastes, which include inorganic acids and some organic compounds, are injected into the lower part of the Knox aquifer. Although carbonate rocks in this formation have the capacity to neutralize acidic wastes, uncertainties concerning flow paths within the Knox and the integrity of well casings have caused some concern about potential contamination of drinking-water sources at shallower depths in the area.

As of September 1985, 83 hazardous-waste sites at 6 facilities in Tennessee had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under CERCLA of 1980. EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 83 sites in the program, 30 sites contained contaminants but did not present a hazard to the environment. Six IRP sites at three facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at three of these sites has been completed under the program. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Other Sources of Contamination

Other sources of ground-water contamination include leaking underground storage tanks and domestic septic systems. An average of two reports per week are being filed with the Tennessee Division of Groundwater Protection, the office that responds to suspected leaks from underground storage tanks (Robert Hall, Tennessee Division of Ground Water Protection, oral commun., 1986). Widespread use of septic fields for domestic sewage disposal in several middle Tennessee communities has led to ground-water degradation. Ground water in the cities of Nashville, Hendersonville (Sumner County), La Vergne (Rutherford County), and Mt. Juliet (Wilson County) has been particularly affected (D. Elmo Lunn, Tennessee Division of Water Quality Control, written commun., 1981), as has ground water in Hamilton County (Tennessee Department of Health and Environment, 1986a).

Acid mine drainage in certain areas of the Cumberland Plateau has degraded local ground water. In well water near mines, lower pH values and increased concentrations of heavy metals have been detected (D. Elmo Lunn, Tennessee Division of Water Quality Control, written commun., 1981). Large sulfate concentrations and iron precipitation at springs are also common. Elsewhere, unplugged boreholes, drilled for zinc exploration, in the Central Basin may provide pathways for migration of water from the very mineralized Knox aquifer to the Ordovician carbonate aquifer.

POTENTIAL FOR WATER-QUALITY CHANGES

Tennessee faces continuing challenges to its ground-water resources. These challenges result from increasing urbanization, industrialization, and demand for larger quantities of clean water.

Ground-water use throughout the State has increased steadily during the past century. In the Memphis area, the potentiometric surface has declined 100 feet in the Memphis Sand, the upper unit of the Tertiary sand aquifer. Intensive pumping from this aquifer has increased the hydraulic gradient and has accelerated recharge from the overlying alluvial aquifer by leakage through localized confining beds. Water quality in the alluvial aquifer is inferior, and toxic constituents are present near several hazardous-waste sites. As the demand for water increases, it is important that water quality within these two aquifers be monitored carefully, and that the hydraulic relations between the two units be better defined. A report addressing the potential for leakage among the principal aquifers in the Memphis area was published by the U.S. Geological Survey (Graham and Parks, 1986).

In middle and eastern Tennessee, continuing development and decreasing availability of Federal funds for surface-water treatment plants will increase the demand for ground-water supplies. Throughout areas of Tennessee where carbonate aquifers are the predominant water-supply source, sinkholes and caves provide rapid flow paths for the transport of contaminants into these aquifers. Moreover, such features create complex flow paths that are difficult to predict. Disposal of domestic wastes by septic systems is widespread and will continue to threaten the quality of shallow ground water in many areas. Wells may be drilled deeper in attempts to find cleaner water; however, deeper aquifers may produce water of inferior quality because of larger concentrations of dissolved solids. Also, deeper aquifers are more costly to develop as principal water supplies. Finally, if deep-well injection continues as a method of industrial waste disposal, questions of potential contamination of both shallow and deep aquifers will remain.

GROUND-WATER-QUALITY MANAGEMENT

The State of Tennessee recognizes the importance of ground water and has provided for the protection of this resource through the Tennessee Department of Health and Environment. Within this Department, the Division of Ground Water Protection provides general oversight and technical assistance for the State's efforts in areas related to ground-water quality. Drillers have been licensed since 1963 and are required to file reports for each well constructed. As needed, the Division of Ground Water Protection inspects new wells and performs limited water-quality analyses. The Division administers the State's program for control of leaking underground storage tanks and regulates the use of underground injection wells. Subsurface sewage disposal systems are also regulated by this agency.

The Division of Solid Waste Management administers the State's RCRA program and regulates all forms of solid-waste disposal. The Division of Superfund oversees the State's CERCLA-related activities. In addition to the seven sites on the NPL, the Division of Superfund has nominated three sites for the Federal program. These sites are located in Wayne, Shelby, and Hickman Counties, and are shown as "other" sites in figure 3*A*. It also has cataloged 253 sites that "pose or may reasonably be anticipated to pose a danger to public health, safety, and environment" (Tennessee Department of Health and Environment, 1986b). These sites, which were selected from an original list of 862 nominees, compose the "State Superfund Eligible Sites List". Hydrogeologic investigations and remedial activities are being conducted at many of these sites.

The Division of Construction Grants and Loans is responsible for programs addressing the impact of nonpoint sources of pollution on ground-water quality. In 1987 this Division began a series of cooperative studies with the U.S. Geological Survey to assess the effects of septic tank systems, urban runoff, and agricultural chemicals on ground-water quality.

The Tennessee Department of Health and Environment has defined two major priorities for its ground-water protection programs. The first priority is to establish an aquifer classification system. This system will define the need for water-quality protection as a function of an aquifer's potential use. Currently, aquifers may be classified as "underground sources of drinking water" if the dissolved-solids concentration is smaller than 10,000 mg/L. The second priority is to establish a statewide ground-water monitoring network. Recently, the State's Safe Growth Team received a report recommending such a network from researchers at the Center for the Management, Utilization, and Protection of Water Resources at Tennessee Technological University (Wilson and others, 1986). Specific recommendations included an initial sampling of about 200 representative wells to define water-quality profiles for each major aquifer. The samples would be analyzed for common and trace inorganic constituents and composite organic characteristics, such as total organic carbon and organic halides. Spatial and temporal variation in background water-quality patterns would be described and would be used to determine the optimal density of monitoring wells and sampling frequency. Finally, localized problems of ground-water quality would be addressed by synoptic studies featuring more intensive sampling for constituents of major local concern.

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Drilling operations at a hazardous-waste site in west Tennessee. The U.S. Geological Survey in cooperation with the City of Memphis installed monitor wells at the Hollywood Dump in Memphis, Tennessee to evaluate the extent of ground-water contamination in the shallow unconfined alluvial aquifer beneath the site. All of the water being used for municipal and industrial supplies in Memphis is derived from deeper confined aquifers. (Photograph by David D. Graham, U.S. Geological Survey.)

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TEXAS
Ground-Water Quality

In Texas, aquifers provide about 60 percent of the freshwater used. More than 80 percent of this water is used for irrigation, and about 9 percent is used for public supply. About 46 percent of all water used for public supply (see population distribution in fig. 1) comes from ground water (Bill Moltz, Texas Water Development Board, written commun., 1986). Ground-water supplies occur primarily in 7 principal (fig. 2*A*) and 17 minor aquifers that underlie more than 75 percent of the State.

Most ground water in all the principal withdrawal areas of each principal and minor aquifer does not exceed the drinking-water standards established by the Texas Department of Health (1985) for dissolved solids, nitrate, and fluoride, which are important for evaluating the suitability of water for public use. The freshwater that is present in the outcrop and shallow subcrop areas of these aquifers progressively changes to saline water in the deeper, downdip areas of most of the aquifers.

Most of the principal and minor aquifers, however, have had water-quality problems affecting limited areas. The problems generally have resulted from natural excessive salinity or salinity that has been induced by excessive withdrawals of ground water. The excessive withdrawals can cause an intrusion of more mineralized water from nearby locations in the same producing strata or from adjacent strata. These problems have been associated mostly with agricultural and public ground-water withdrawals in parts of the alluvium and bolson deposits, the Gulf Coast aquifer system, the High Plains (Ogallala) aquifer, and the Trinity Group aquifer.

Twenty-one hazardous-waste sites in Texas (fig. 3*A*) have been listed in the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c). These Superfund sites require additional evaluation as established by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Six of the CERCLA sites have been documented to have shallow ground-water contamination (Texas Water Commission, 1986), but none have caused widespread contamination of drinking-water supplies in the deeper aquifers. Additionally, about 180 other hazardous-waste sites (fig. 3*A*) require monitoring of ground-water quality as established by the Federal Resource Conservation and Recovery Act (RCRA) of 1976. At most of the RCRA sites, ground-water contamination has been minimal and at shallow depths. Many of the waste-disposal sites are located in a part of the Gulf Coast area where clay of the Beaumont Formation occurs at the land surface; this clay is relative impermeable (Gabrysch, 1977) and probably has helped to prevent contaminants from entering deeper aquifers used for public supply. In addition, the U.S. Department of Defense (DOD) has identified 31 sites at 7 facilities where contamination has warranted remedial action.

There are 118 Class-I underground injection control (UIC) wells (U.S. Environmental Protection Agency, 1984) in the State that are operated under permits issued by the Texas Water Commission (fig. 3*A*). These wells are used to inject industrial waste into aquifers containing moderately saline to briny water; the aquifers are located at great depths below the base of slightly saline ground water containing dissolved-solids concentrations of more than 3,000 mg/L (milligrams per liter) (Winslow and Kister, 1956, p. 5). Thus far, ground-water contamination has not been associated with the underground injection wells (Knape, 1984, p. 3-12).

Projections for the next 20 years indicate that about 4,500 new wells will be needed to supply water for public supply needs. Many of these projected wells will be located in areas where extensive ground-water use has yet to occur (Texas Department of Water Resources, 1984a, p. 37). The greatest number of these wells will be located in the High Plains and along the Gulf Coast. Past experience indicates that salinity increases induced by ground-water withdrawals can be one of the primary ground-water-quality problems in some parts of these areas.

WATER QUALITY IN PRINCIPAL AQUIFERS

Most of the ground water used in Texas comes from seven principal aquifers (fig. 2*A*). These aquifers are: alluvium and bolson deposits, the Gulf Coast aquifer system, High Plains (Ogallala), Carrizo-Wilcox, Edwards (Balcones fault zone), Edwards-Trinity (Plateau), and Trinity Group (U.S. Geological Survey, 1985, p. 398). Except for the alluvium and bolson deposits and the High Plains (Ogallala), the aquifers dip to the south and east towards the Gulf of Mexico (fig. 2*B*). All these aquifers supply water for public, industrial, and irrigation uses. The High Plains (Ogallala) aquifer, the most intensively developed, is used primarily for supplying water for irrigation. The Gulf Coast aquifer system, Carrizo-Wilcox, Edwards (Balcones fault zone), and Trinity Group aquifers are the next most intensively developed; most of the water is used for public supply in areas of dense population (fig. 1*B*), although each aquifer also supplies a substantial volume of water for irrigation. There are 17 minor aquifers delineated in Texas (Muller and Price, 1979, p. 49). Each minor aquifer is important locally and, in some places, constitutes the only source of freshwater supply in the area.

BACKGROUND WATER QUALITY

Ranges in concentrations of five water-quality variables from each of the principal aquifers were complied from about 30,000 water analyses available from the Texas Water Development Board, based on samples collected from 1900 to 1986 (fig. 2*C*). The data include analyses of many samples collected to investigate problem areas and thus may indicate larger concentrations than would be expected from a uniform distribution of samples. The data are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and 4 mg/L fluoride. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 2 mg/L flouride.

Comparison of the analyses to drinking-water standards established by the Texas Department of Health (1985) indicated that water from 32 percent of the wells sampled contained one or more of the following constituents in excess of the State drinking-water standard (indicated in parentheses): dissolved solids (1,000 mg/L), chloride (300 mg/L), nitrate (10 mg/L as nitrogen), or fluoride (2.4 mg/L). Records from the Texas Department of Health were used to estimate that between 1 and 2 percent of the total population had used at some time drinking water that contained one or more of these constituents in excess of Texas drinking-water standards.

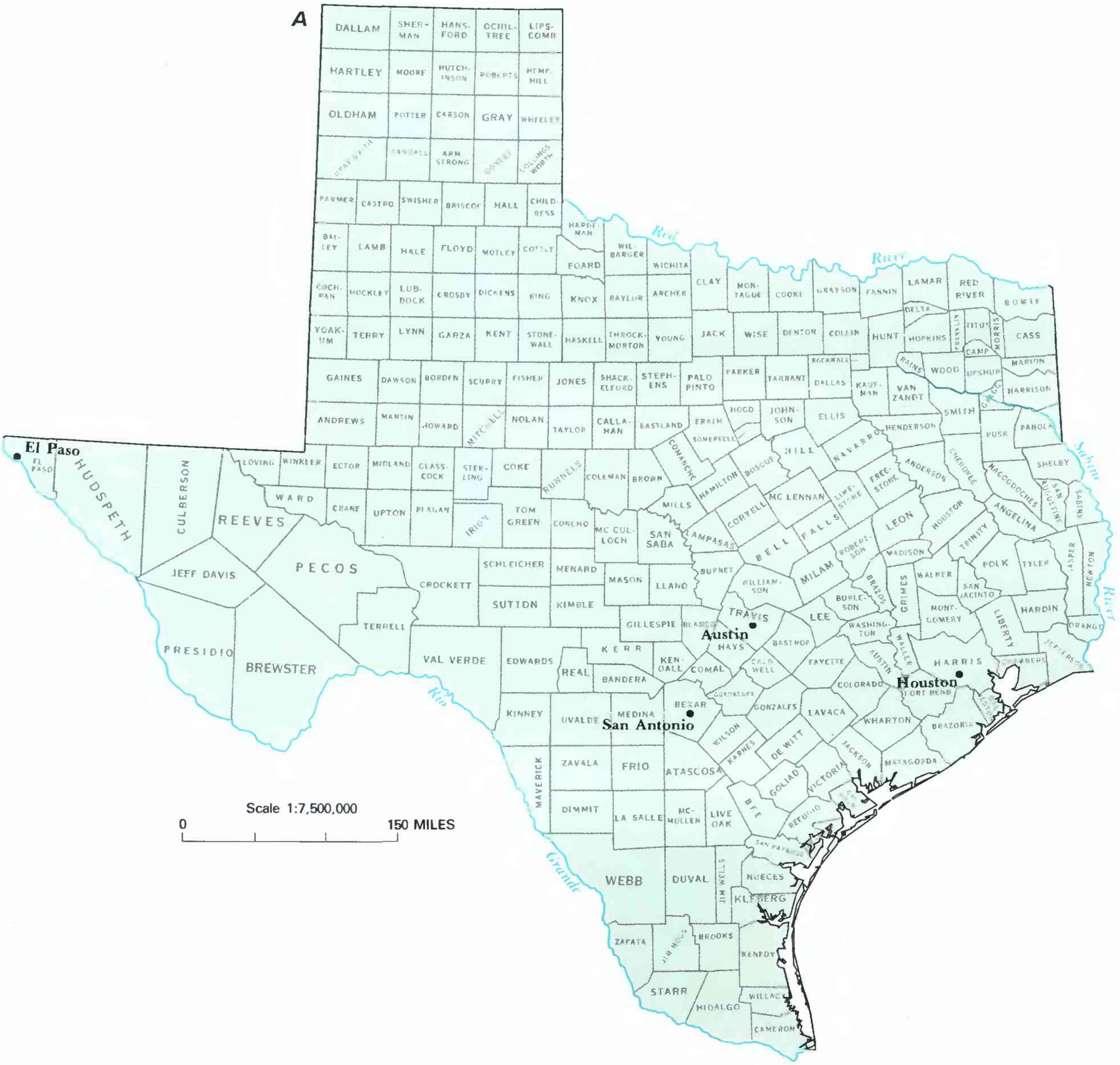

Figure 1. Selected geographic features and 1985 population distribution in Texas. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Alluvium and Bolson Deposits

Water from the alluvium and bolson deposits is used mainly for irrigation and public supply. Alluvial deposits (fig. 2*A*) are found locally in extensive areas in far western and north-central Texas (Alvarez and Buckner, 1980; Muller and Price, 1979). The chemical quality of the water ranges considerably. Dissolved-solids concentrations ranged from 100 to about 35,000 mg/L in the far west (Gates and others, 1980) and from 500 to 2,500 mg/L in north-central Texas. The median concentration was 771 mg/L (fig. 2*C*), and nearly 45 percent of the samples had dissolved-solids concentrations exceeding 1,000 mg/L. The water had a median hardness (as calcium carbonate) concentration of 378 mg/L; more than 75 percent of the samples were classified as very hard. About 40 percent of the samples had nitrate concentrations that exceeded 10 mg/L.

Gulf Coast Aquifer System

Ground water in the Gulf Coast area is used mainly for public supply in densely populated areas and for irrigation and public supply elsewhere. The Gulf Coast aquifer system generally yields water containing from 500 to 1,000 mg/L dissolved solids. In much of the eastern part of the aquifer, the water contains about 300 to 500 mg/L dissolved solids. In the southern part of the aquifer, water generally is more saline. Along the Rio Grande valley in southern Texas, ground water generally contains between 1,000 and 1,500 mg/L dissolved solids. The median concentration of dissolved solids for the Gulf Coast aquifer system was 420 mg/L (fig. 2*C*). About 19 percent of the samples analyzed had dissolved-solids concentrations that exceeded 1,000 mg/L. The water was moderately hard, with a median hardness of 80 mg/L. At shallow depths, the water

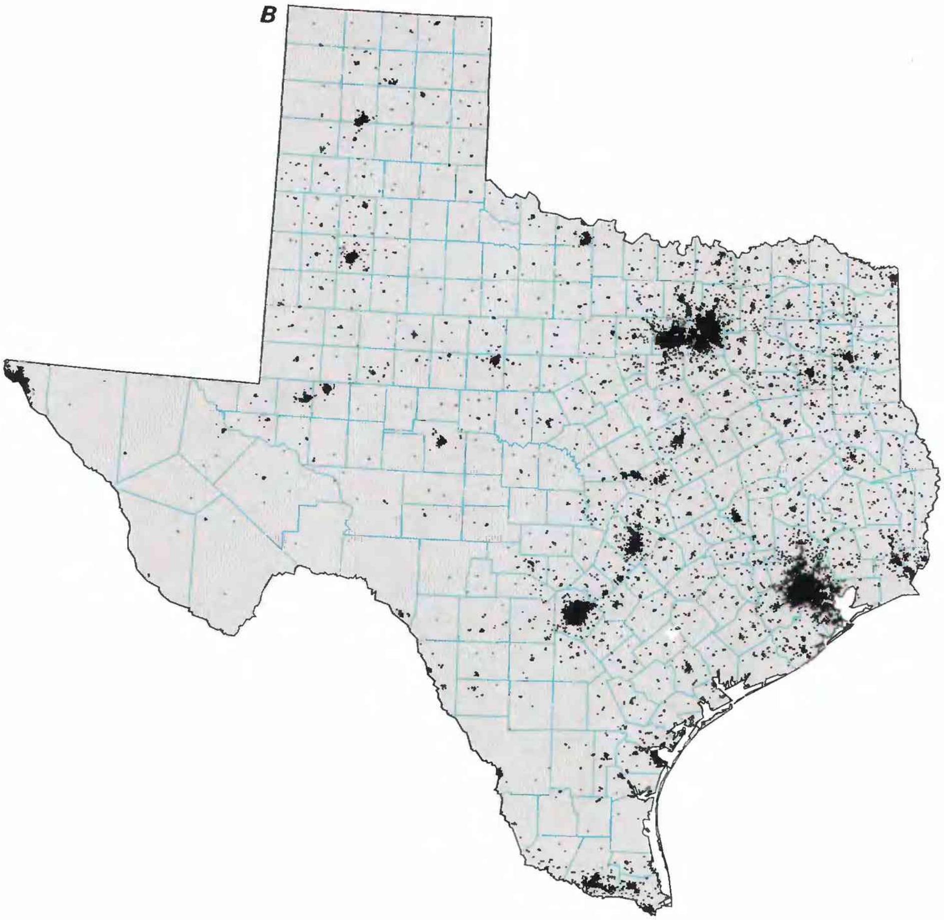

Figure 1. Selected geographic features and 1985 population distribution in Texas—Continued.

was hard; but below about 500 feet it softened, with sodium replacing calcium. Slightly more than 10 percent of the samples had nitrate concentrations that exceeded 10 mg/L. In 1985, about 40 water samples from the Gulf Coast aquifer system near Houston were analyzed for 15 trace-elements (J. L. Strause, U.S. Geological Survey, written commun., 1986). With the exception of barium and strontium, trace-element concentrations in most samples were less than 10 μg/L (micrograms per liter) for each of 15 elements. Barium had a median concentration of 220 μg/L, and strontium had a median concentration of 110 μg/L. Additionally, large concentrations of radionuclides have been detected in samples from several locations in this aquifer. Samples from several wells had gross alpha concentrations of more than 100 picocuries per liter (Texas Department of Health, written commun., 1985). The source of these radionuclides has not been defined, and no changes in ambient concentrations due to human activities have been identified.

High Plains (Ogallala) Aquifer

Although most of the water withdrawn from the High Plains (Ogallala) aquifer is used for irrigation, the water withdrawn for public supply provides the only source of drinking water for many towns and cities. Excessive ground-water withdrawals coupled with natural and human-induced salinity, natural fluoride concentrations, or increased nitrate concentrations due to human activities have threatened or decreased ground-water use in local areas. Dissolved-solids concentrations ranged from about 200 to 9,000 mg/L (Knowles and others, 1984), with a median concentration of 419 mg/L (fig. 2*C*). About 18 percent of the samples analyzed had dissolved-solids concentrations that exceeded 1,000 mg/L. The water was very hard, with a median hardness of 254 mg/L. Small and randomly distributed areas of saline water occur in the southeastern part of the aquifer in association with saline playa lakes. There, the water table is shallow, and salt deposits and evaporation cause an increase in ground-water salinity. In 25 percent of the analyses, the nitrate (as nitrogen) concentration exceeded 10 mg/L. Fluoride also can limit the aquifer as a source of public supply; almost 20 percent of the analyses had fluoride concentrations that exceeded 4.0 mg/L (fig. 2*C*).

Carrizo-Wilcox Aquifer

This aquifer provides irrigation and public supplies throughout much of east-central and southern Texas. The Carrizo-Wilcox yields fresh to slightly saline water that had dissolved-solids concentrations ranging from about 100 to 3,100 mg/L, with a median concentration of 369 mg/L (fig. 2*C*). Dissolved-solids concentrations in a farming area southwest of San Antonio ranged from about 100 to 3,100 mg/L (Klemt and others, 1976). About 10 percent of the samples had dissolved-solids concentrations that exceeded 1,000 mg/L. The water was moderately hard, with a median hardness of 72 mg/L. The exchange of calcium for sodium occurs with depth, and results in a decreasing hardness as in the Gulf Coast aquifer system (Foster, 1950). Nitrate and fluoride concentrations did not exceed State standards in any of the samples, but iron concentrations limit the use of water from the Carrizo-Wilcox aquifer in parts of eastern Texas (Texas Department of Water Resources, 1984b). Intensive withdrawals for irrigation in the farming area southwest of San Antonio have caused some leakage of saline water

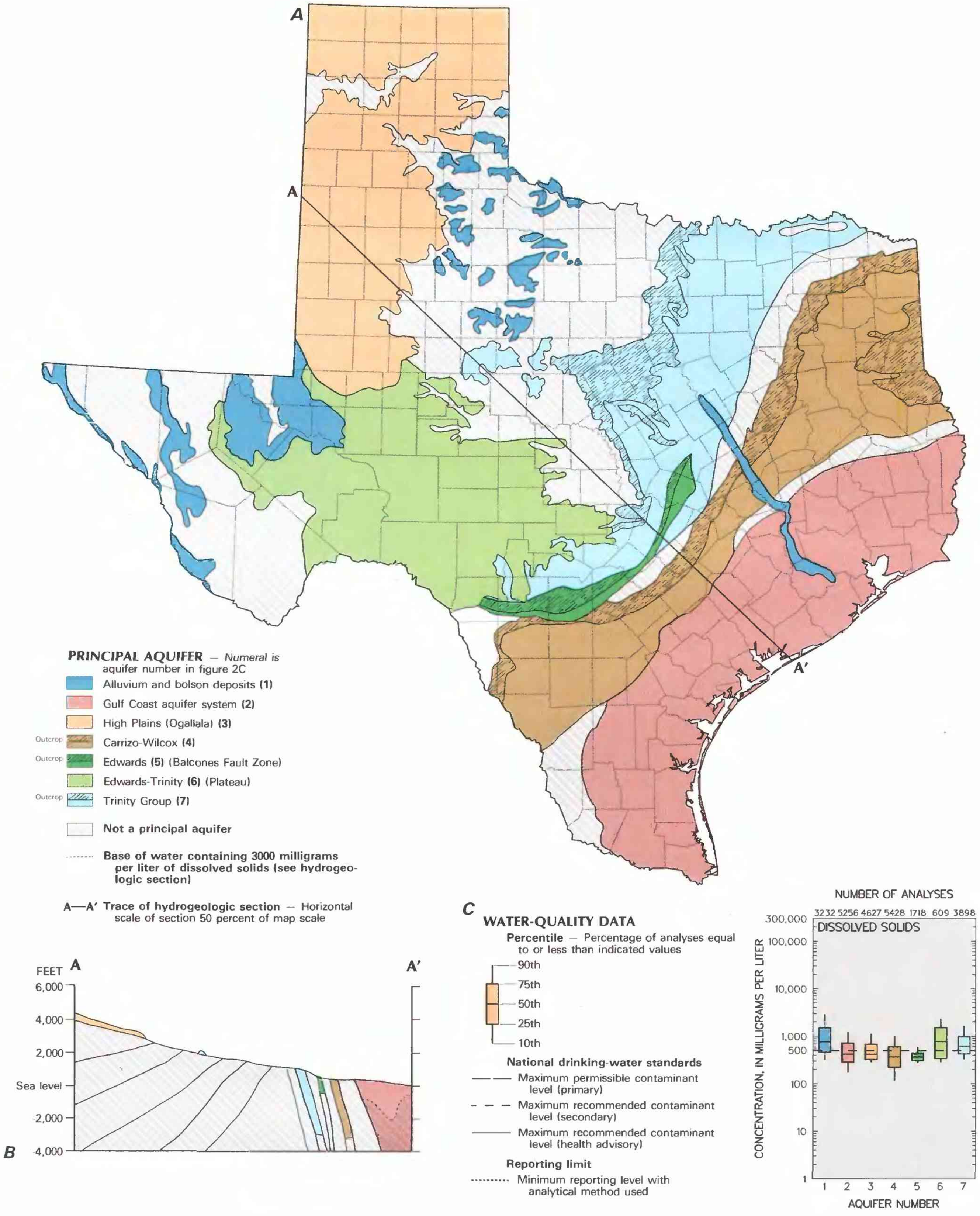

Figure 2. Principal aquifers and related water-quality data in Texas. *A*, Principal aquifers; *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1900-86. (Sources: *A*, Modified from Texas Department of Water Resources, 1984b. *B*, Compiled by E.T. Baker, Jr., from U.S. Geological Survey files. *C*, Analyses compiled from Texas Water Board files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

into the aquifer from overlying formations (Texas Department of Water Resources, 1984b, p. II–12).

Edwards (Balcones Fault Zone) Aquifer

The Edwards aquifer in the area of the Balcones fault zone provides water primarily for public supply, although some water is used for irrigation. The aquifer yields water through springflow that sustains not only a viable tourist economy but also downstream water rights. The dissolved-solids concentrations in the water ranged from about 200 to 3,000 mg/L (Baker and others, 1986), with a median concentration of 371 mg/L (fig. 2*C*). The water was very hard, with a median hardness of 270 mg/L. About 15 percent of the samples had nitrate concentrations that exceeded 10 mg/L. Between 1976 and 1985, about 50 water samples were analyzed for 14 trace elements (P.M. Buszka, U.S. Geological Survey, written commun., 1986). With the exception of barium and strontium, trace-element concentrations in most of the samples were smaller than 10 μg/L. Barium had a median concentration ranging from 110 to 140 μg/L in four classes of samples based on the depth of the water-yielding strata. Strontium had a median concentration ranging from 370 to 545 μg/L in three of the classes and 17,000 μg/L in the fourth class defined as the deeper confined zone.

Edwards-Trinity (Plateau) Aquifer

The Edwards-Trinity (Plateau) aquifer in the area of the Edwards Plateau yields water that is used primarily for irrigation but also for public supply. Dissolved-solids concentrations in the water ranged from about 200 to 3,500 mg/L (Walker, 1979), with a median concentration of 773 mg/L (fig. 2*C*) ; about 45 percent of the samples contained dissolved solids in excess of 1,000 mg/L. The water generally becomes more mineralized towards the western part of the area (Texas Department of Water Resources, 1984b; Walker, 1979). The water was very hard, with a median hardness of 407 mg/L. About 35 percent of the samples had nitrate concentrations that exceeded 10 mg/L.

Trinity Group Aquifer

The Trinity Group aquifer provides public supplies in densely populated parts of northern Texas and irrigation supply throughout much of northern and central Texas. However, its use is becoming limited in some areas because of major declines in water levels. The dissolved-solids concentration of water ranged from about 70 to 3,500 mg/L (Nordstrom, 1982), with a median concentration of 619 mg/L (fig. 2*C*). About 25 percent of the samples had dissolved-solids concentrations that exceeded 1,000 mg/L. The water was very hard, with a median hardness of 258 mg/L. About 30 percent of the samples had nitrate concentrations that exceeded 10 mg/L.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality in the principal aquifers has been degraded in localized areas by the effects of ground-water withdrawals, urbanization, agricultural practices, industrial activity, and waste disposal.

Ground-Water Withdrawals

The most commonly documented type of ground-water degradation has been the increase in salinity caused by intensive ground-water withdrawal and migration of saline water toward centers of pumping. This degradation is a result of public, irrigation, and industrial ground-water withdrawals. Fewer instances of ground-water degradation involving nitrate, trace elements, and organic substances have been documented. Very few analyses are available for trace elements and organic substances in deep ground water. Records of individual well contamination are maintained by State agencies, but the records are not sufficiently consolidated to allow a statewide appraisal or general description of contamination (Association of State and Interstate Water Pollution Control Administrators, 1985, p. 29).

Urbanization

Increases in ground-water salinity due to public and industrial pumpage have occurred near several population centers in the Gulf Coast area, in northern Texas, and near El Paso. Isolated incidents of the introduction of synthetic organic substances into the ground water have been documented in San Antonio and Austin where the permeable Edwards (Balcones fault zone) aquifer is at land surface (Andrews and others, 1984; P.M. Buszka, U.S. Geological Survey, written commun., 1986).

Agricultural Practices

Nitrate in ground water occurs in several parts of Texas, predominantly within the Edwards-Trinity (Plateau) and the High Plains (Ogallala) aquifers and the alluvial and bolson deposits. The relative differences between human-induced contamination and naturally large concentrations of nitrate in water from these aquifers

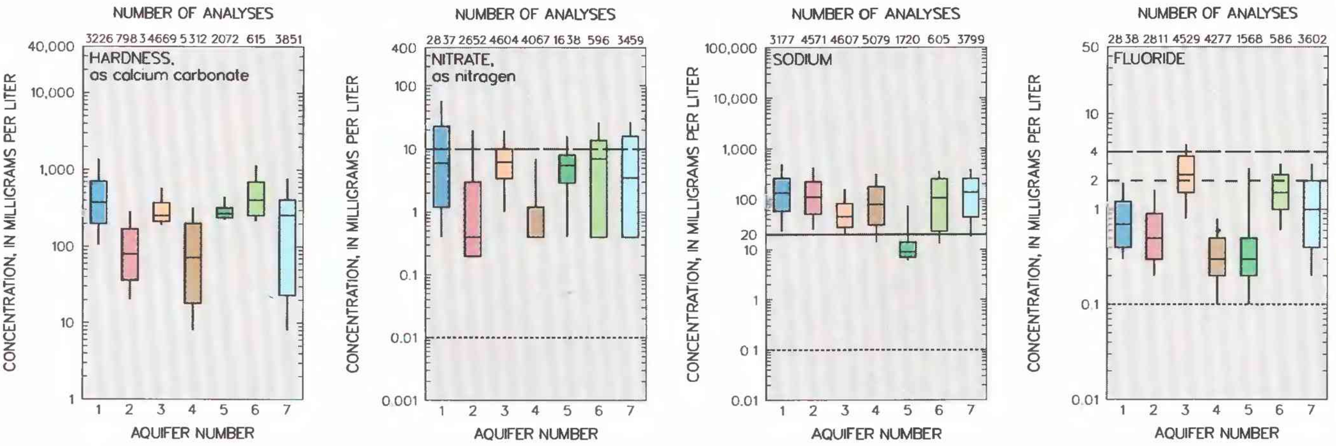

Figure 2. Principal aquifers and related water-quality data in Texas—Continued.

have not been well defined. Arsenic from cotton-gin waste has contaminated a limited part of the High Plains (Ogallala) aquifer (C. E. Nemir, Texas Department of Water Resources, written commun., 1984). The effects of widespread pesticide and fertilizer use throughout much of the State have not been determined.

The percentage of samples, by county, that contained nitrate concentrations in excess of Federal drinking-water standards (U.S. Environmental Protection Agency, 1986a) are shown in figure 4*A*; similar data for fluoride are shown in figure 4*B*. The greatest percentage of samples containing excessive nitrate are from counties in western Texas where the Edwards-Trinity (Plateau) and the High Plains (Ogallala) aquifers are the predominant water sources. The specific causes of these excessive concentrations have not been identified but probably result from a combination of naturally excessive concentrations and agricultural practices. The greatest percentage of samples containing excessive fluoride also is from counties in western Texas (High Plains aquifer) and probably are natural in origin (Gutentag and others, 1984).

Industrial Activity

The primary effects of industrial ground-water use have been the salinity increase resulting from excessive withdrawals, commonly occurring in combination with public-supply use. Most of the Class-I injection wells shown in figure 3*A* are used for the disposal of industrial waste. A majority of the industrial waste-disposal wells in Texas are located along the Gulf Coast and are used to inject chemical-petrochemical industrial effluent (fig. 3*A*). Only two of the Class-I injection wells have had to be plugged and abandoned as a result of leakage; aquifers containing freshwater were not endangered because of the leaks (W. B. Klemt, Texas Water Commission, oral commun., 1986). Nearly all the CERCLA sites are located within major urban centers and about 6 of the 21

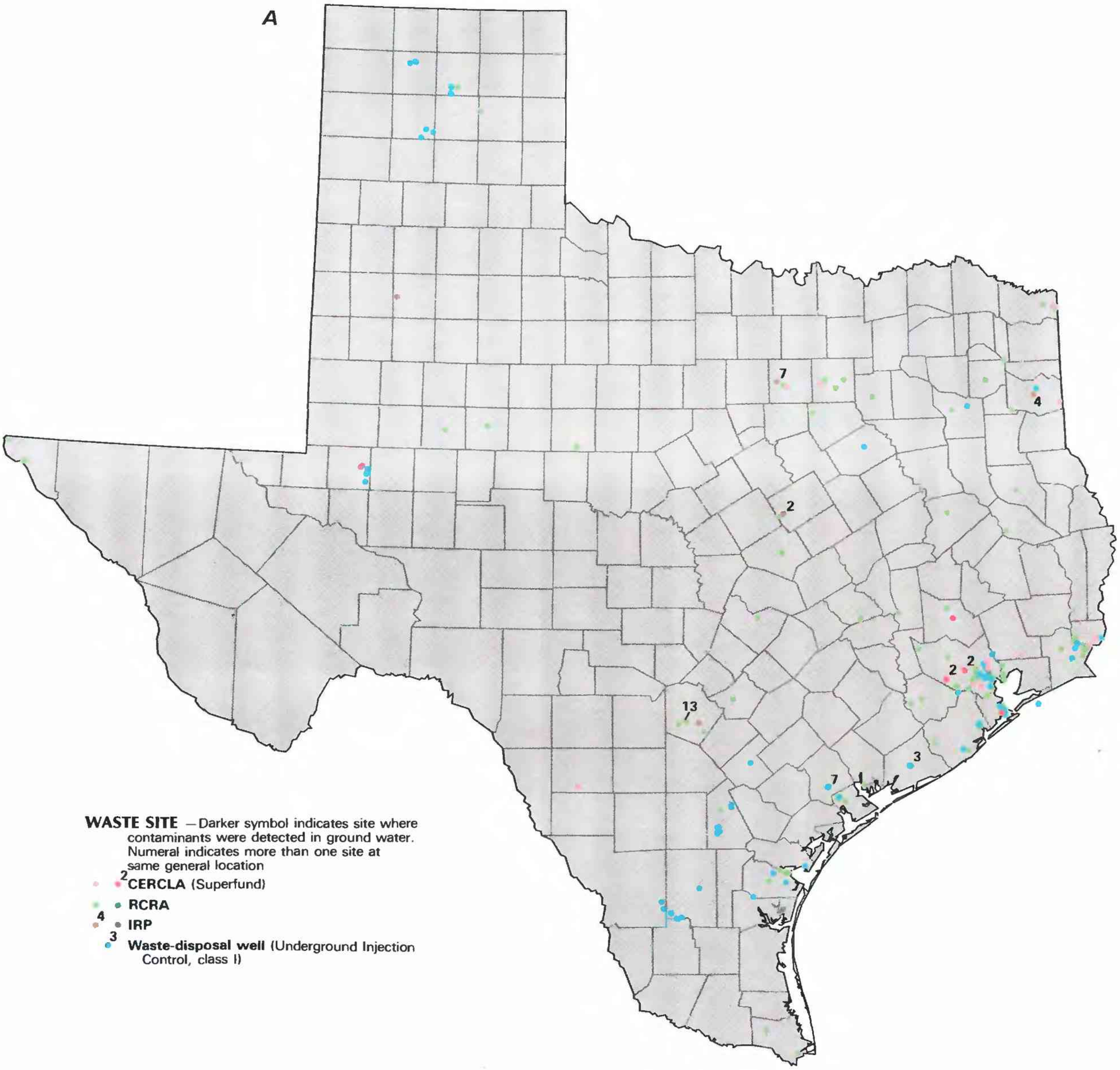

Figure 3. Selected waste sites and ground-water-quality information in Texas. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Municipal landfills, as of 1986. (Sources: *A*, CERCLA, RCRA, and other waste-disposal sites, Texas Water Commission files; IRP sites, U.S. Department of Defense, 1986. *B*, Texas Department of Health files.)

have some type of shallow ground-water contamination involving minor elements or organic substances or both (Texas Water Commission, 1986). There are about 180 RCRA sites, and some type of shallow ground water contamination has occurred at more than one-half of them. Widespread degradation of drinking-water supplies has not been detected. However, the Texas Water Commission is in the midst of a multiyear effort to evaluate ground-water quality at these sites (P.S. Lewis, Texas Water Commission, oral commun., 1986).

In addition to the Class-I injection wells shown in figure 3*A*, the Railroad Commission of Texas has authorized, by permit, slightly more than 15,000 saltwater disposal wells and slightly more than 33,000 secondary-recovery injection wells used throughout the State for oil and gas production (Knape, 1984). Both types of wells range in depth from a few hundred feet to about 10,000 feet and have a basic requirement that the injection zone be below the base of moderately saline ground water (dissolved-solids concentration more than 10,000 mg/L). About 40,000 solution-mining wells also exist in the State (Texas Water Resources Institute, 1986). Most of these wells are used for mining sulfur in southeastern Texas and uranium in southern Texas. Extensive State regulations cover the operations of these wells.

Prior to the last 20 years, when unlined surface pits were used for disposing brines produced with oil, ground-water contamination by salts near oil- and gas-well operations was common. Although numerous instances of ground-water contamination from oil and gas activities have been reported (Shamburger, 1959; R.W. Harden and Associates, 1978; Sandeen, 1985;), their overall effects have not been evaluated thoroughly on a statewide basis.

Waste Disposal

Locations of waste-disposal sites regulated under RCRA, CERCLA, and UIC regulations are shown in figure 3*A*, and sites

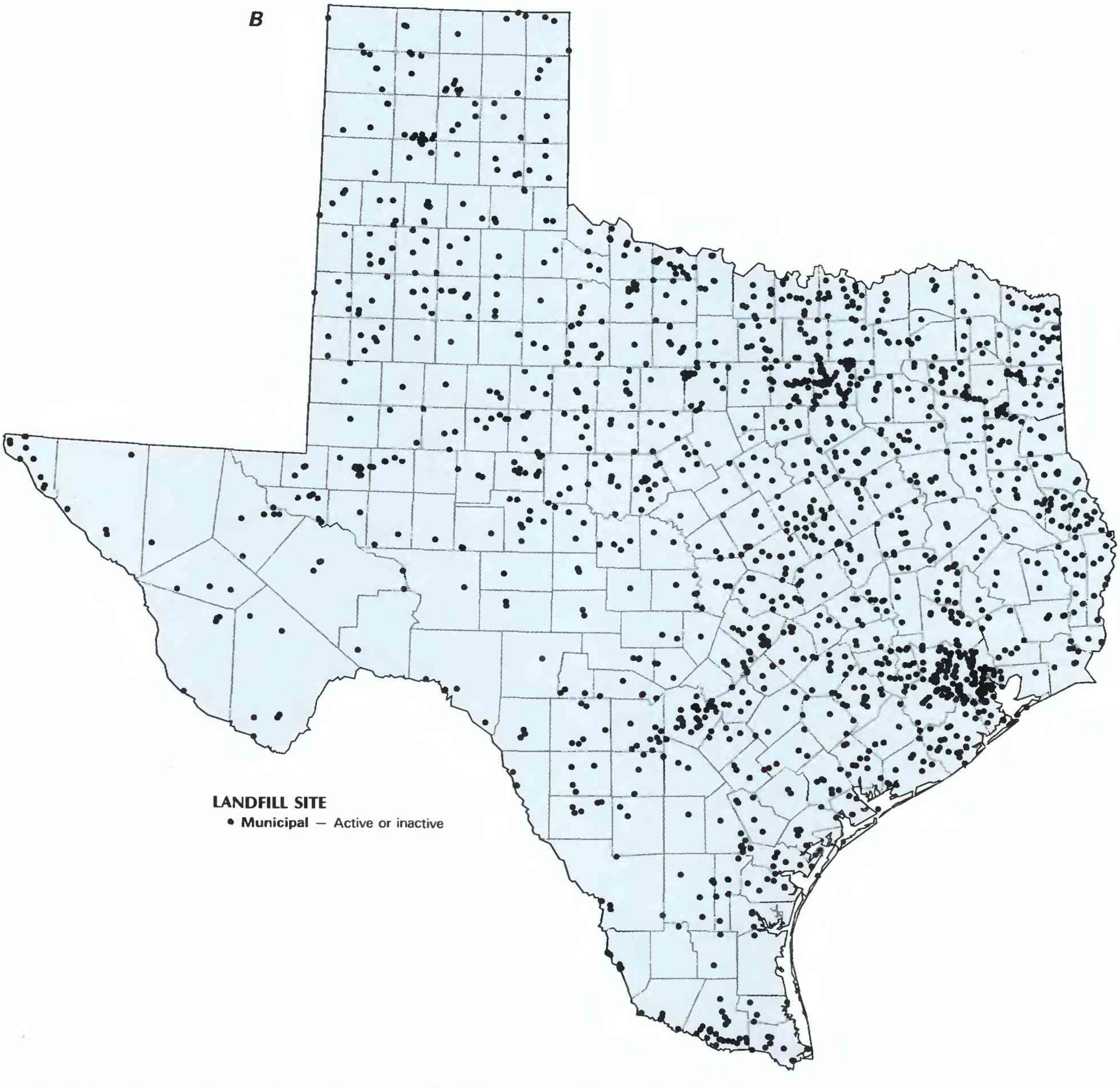

Figure 3. Selected waste sites and ground-water-quality information in Texas—Continued.

regulated as municipal landfills are shown in figure 3*B*. As of September 1985, 168 hazardous-waste sites at 19 facilities in Texas had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency (EPA) Superfund program under the CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 168 sites in the program, 52 sites contained contaminants but did not present a hazard to the environment. Thirty-one sites at 7 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at three of these sites has been completed under the program. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

POTENTIAL FOR WATER-QUALITY CHANGES

Several major aquifers in Texas are susceptible to ground-water contamination because of hydrogeologic setting, projected ground-water withdrawals, or current and projected land use. The following is a brief list of some activities and their possible effects:

(1) Continued and accelerated intrusion of saline water is possible in most of the major aquifers in Texas but most likely will occur—under current ground-water withdrawal patterns—along the Gulf Coast, in the Trinity Group aquifer in northern Texas, and in the alluvium and bolson deposits near El Paso. Introduction of synthetic organic compounds and trace elements is a primary concern in the San Antonio and Austin areas where the Edwards (Balcones fault zone) aquifer allows rapid recharge of surface water into the ground-water system. In parts of the Gulf Coast aquifer

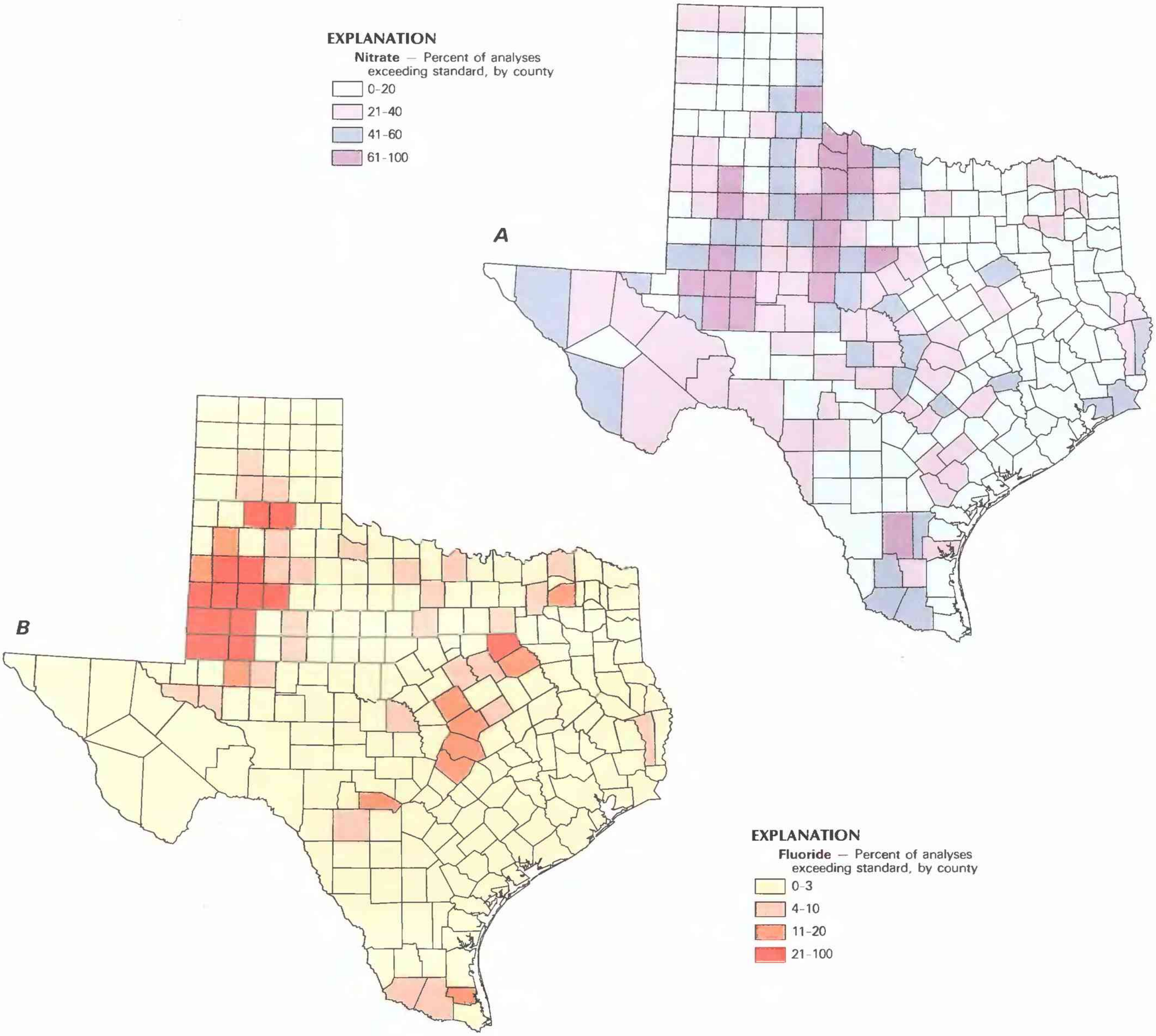

Figure 4. Percentage of water-quality analyses that exceed U.S. Environmental Protection Agency national drinking-water standards for (*A*) nitrate and (*B*) fluoride, by county. (Source: Texas Water Commission files).

system, radioactive ions from deposits containing radium are present in water wells. Continued development of ground-water supplies near Houston could result in individual wells producing water with radionuclide concentrations at or near the limits established by national drinking-water standards.

(2) Degradation from the return flow of irrigation is possible in the High Plains (Ogallala) and Edwards-Trinity (Plateau) aquifers. The introduction of irrigation return flow containing excessive nitrate (as nitrogen) and pesticide concentrations to shallow, unconfined aquifers is most likely where the water table is shallow and where water-application rates are large.

(3) The potential effects of industry parallel those of urbanization, being greatest in the San Antonio and Austin areas where the permeable Edwards (Balcones fault zone) aquifer is at the surface. Degradation from the largest concentration of industrial waste-disposal sites in the Gulf Coast probably will continue to be ameliorated by the poorly permeable Beaumont clay at the surface. However, the danger of intrusion of contaminants through vertical avenues, such as abandoned well casings, will continue. Many of these industrial waste-disposal sites also are near the major population centers along the Gulf Coast. Similar types of degradation from oil and gas activities, past and present, are a continuing possibility throughout the State in all the major aquifers.

GROUND-WATER-QUALITY MANAGEMENT

State legislation to regulate ground-water quality is contained primarily in the Texas Water Code, Chapters 16, 26, 27, 28, 29, and 52. Ground-water-protection programs in Texas are administered by six agencies: the Texas Water Commission, the Texas Water Development Board, the Texas Water Well Drillers Board, the Railroad Commission of Texas, the Texas Department of Health, and the Texas Department of Agriculture.

The Water Commission, as the lead agency for water resources, has the responsibility to coordinate the State's efforts to develop a comprehensive ground-water-protection strategy. The Water Commission's ground-water policy is to help ensure maintenance of the State's ground-water quality through planning and education, and cooperation with other State agencies and the public and private sectors. Four Federal laws administered in some degree by the Commission include: the Safe Drinking Water Act; the Resource Conservation and Recovery Act; the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund); and the Clean Water Act. State legislation administered by the Commission includes the Texas Water Code, the Texas Solid Waste Disposal Act, and the Texas Water Well Drillers Act. The Commission, in response to State and Federal mandates, has promulgated rules that establish waste-disposal regulatory programs and that outline technical and administrative requirements for meeting goals of the individual programs. A State-funded Superfund program recently has identified 14 sites for consideration from a list of more than 100 sites judged to be potential threats but which did not meet criteria for the Federal program (Kidd, 1986). Deep-well waste injection has been regulated since the passage of the Texas Disposal Well Act in 1962, and the current program contains technical elements more restrictive than Federal requirements. A feature of this program in Texas is a mandatory "area of review" requirement of a 2.5-mile radius from the well for Class-I injection wells.

The purposes and policies of the Texas Water Development Board are to collect and analyze ground-water data and to assist users of this information. The Board's activities include investigations of the occurrence, quantity, quality, and availability of ground-water resources; operation of ground-water level and quality-monitoring networks; estimation of future water supplies; determination of current water use and projections of future water demands; and development of plans to meet future water demands. A ground-water-quality monitoring program operated by the Board includes the collection of about 700 samples per year from a network of 5,700 wells for analysis of several inorganic constituents.

The Texas Water Well Drillers Board was created and charged by the Legislature to help ensure the quality of the State's ground water through the licensing of water-well drillers. Staff and assistance are provided to the Board by the Texas Water Commission.

The Oil and Gas Division of the Railroad Commission protects ground water from pollution from activities associated with the exploration, development, and production of oil, gas, and geothermal resources through several provisions of the Texas Natural Resources Code and the Texas Water Code. The EPA delegated authority to the Railroad Commission to administer an underground-injection control program through the Safe Drinking Water Act to regulate injection wells associated with oil and gas operations (Class-II wells). The Surface Mining and Reclamation Division of the Railroad Commission protects ground water from pollution by surface-mining activities through the Texas Surface Mining and Reclamation Act.

The Texas Department of Health is involved in ground-water protection through activities and functions administered by three separate sections—Division of Water Hygiene, Bureau of Solid Waste Management, and Bureau of Radiation Control. Federal (Safe Drinking Water Act, Resource Conservation and Recovery Act, Atomic Energy Act, Uranium Mill Tailings Radiation Control Act) and State (Texas Sanitation and Health Protection Law, Texas Solid Waste Disposal Act, and Texas Radiation Control Act) legislation establishes authority and specifies functions to be administered by these three sections.

The Texas Department of Agriculture's role in the protection of ground water is to ensure compliance with Federal and State laws and with regulations relating to pesticide distribution and use. Under the Federal Insecticide, Fungicide, and Rodenticide Act, the Department has primary enforcement responsibility for pesticide-use violations.

Additionally, 17 underground water conservation districts have been created in Texas through specific administrative and electoral procedures (Chapter 52 of the Texas Water Code) or by the Legislature to monitor, protect, and conserve ground water in particular geographic areas. Special regulations are imposed on certain activities in the recharge zone of the Edwards (Balcones fault zone) aquifer in the San Antonio area. Some of the regulations are enforced locally and others are enforced by State and Federal agencies.

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TRUST TERRITORY OF THE PACIFIC ISLANDS, SAIPAN, GUAM, AND AMERICAN SAMOA
Ground-Water Quality

The Trust Territory of the Pacific Islands (TTPI) has more than 2,100 tropical islands, which include the principal island (Saipan) of the Commonwealth of Northern Mariana Islands; Guam, Moen (Truk), and American Samoa (Tutuila), (fig. 1).

Ground water (fig. 2) is developed for public supply on the islands of Saipan, Guam, Tutuila (American Samoa), Moen (Truk), and Yap. Nearly all of Saipan's population of 20,000 depends on ground water. About 80 percent of Guam's 120,000 residents rely on water pumped from limestone aquifers in the northern part of the island. About 10,000 on Moen and 36,000 people on Tutuila rely on ground water for public and industrial supplies, (U.S. Geological Survey, 1985, p. 403). Population distribution in Saipan, Guam, Moen, and Tutuila is shown in figure 1*B*.

Except in Saipan, the quality of all ground water developed for public supplies is within the drinking-water standards recommended by the World Health Organization (WHO) (1984) for dissolved solids, 1,000 mg/L (milligrams per liter); chloride, 250 mg/L; and nitrate, 10 mg/L, as nitrogen. In major areas of ground-water withdrawal, the median concentration of dissolved solids is less than 1,000 mg/L, and in all areas, the median nitrate concentration, as nitrogen, is less than 10 mg/L (fig. 2*B*). Excessive pumping of the aquifers can cause reduction of hydraulic head that results in seawater intrusion into the freshwater zones. Degradation of the chemical quality of water is associated mainly with excessive pumping of ground water, which can result in increases of chloride concentrations to more than the 250 mg/L standard recommended by WHO for drinking-water supply. Degradation of water quality by seawater intrusion has occurred mainly in limestone aquifers of the southern and west-central parts of Saipan. Except for Guam, few data are available to evaluate organic constituents in ground-water resources. Guam's extensive monitoring efforts under the Safe Drinking Water Act reveal no organic contamination in its drinking-water supplies.

No hazardous-materials disposal sites are located in TTPI, Saipan, and American Samoa; and no ground water is being monitored under Federal Resources Conservation and Recovery Act of 1979 (RCRA) guidelines. On Guam, the landfill at Andersen Air Force Base is being monitored for closure purposes under RCRA procedures (fig. 3, site A) . The Ordot Landfill, also on Guam (fig. 3), has been included in the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (EPA) (1986a). This Superfund site requires additional evaluation and monitoring under Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). Currently, (1986) contamination of ground water at the CERCLA site has not been detected. The U.S. Department of Defense (DOD) has identified 27 sites at three facil-

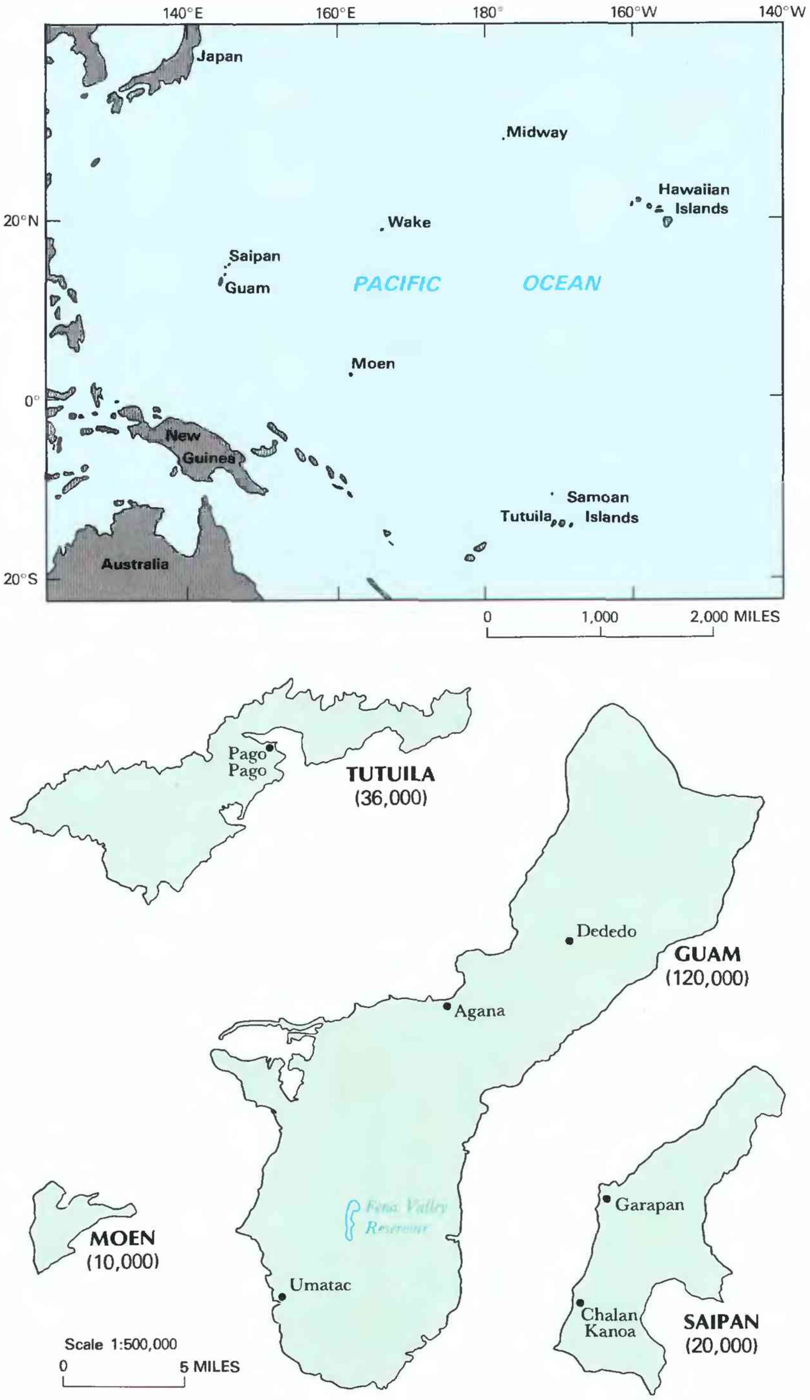

Figure 1. Selected geographic features and 1985 population distribution in Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. *A*, Islands, selected cities, and major drainages. *B*, Population distribution, 1985; number in parenthesis is total by island. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, 1987 Pacific World Directory, and published reports.)

ities as having potential for contamination. The sites are scheduled for confirmation studies to determine if remedial action is required.

Beginning in 1979, the U.S. Geological Survey in cooperation with the governments of Saipan, Guam, American Samoa, and TTPI, initiated a ground-water-quality observation program to monitor chloride concentrations in wells to determine the extent of seawater intrusion into the freshwater lenses beneath the islands. By 1986, the program included chloride measurements at more than 64 wells. Few data on other inorganic constituents and none on organic constituents were collected as part of the program. Regulatory agencies on Guam, American Samoa, Saipan, and TTPI also collect water-quality data identified under the Safe Drinking Water Act.

WATER QUALITY IN PRINCIPAL AQUIFERS

Principal aquifers (fig. 2*A*) in the islands are: (1) the Tagpochau limestone and (2) the Mariana limestone on Saipan, (3) the Barrigada limestone, and (4) the Mariana limestone on Guam, (5) the Truk volcanic rock on Moen, and (6) the Leone volcanic rock on Tutuila. Water in these aquifers occurs as a basal freshwater lens that floats in equilibrium on the denser saline water. This lens is recharged by rainfall; if the recharge is reduced, thinning of the

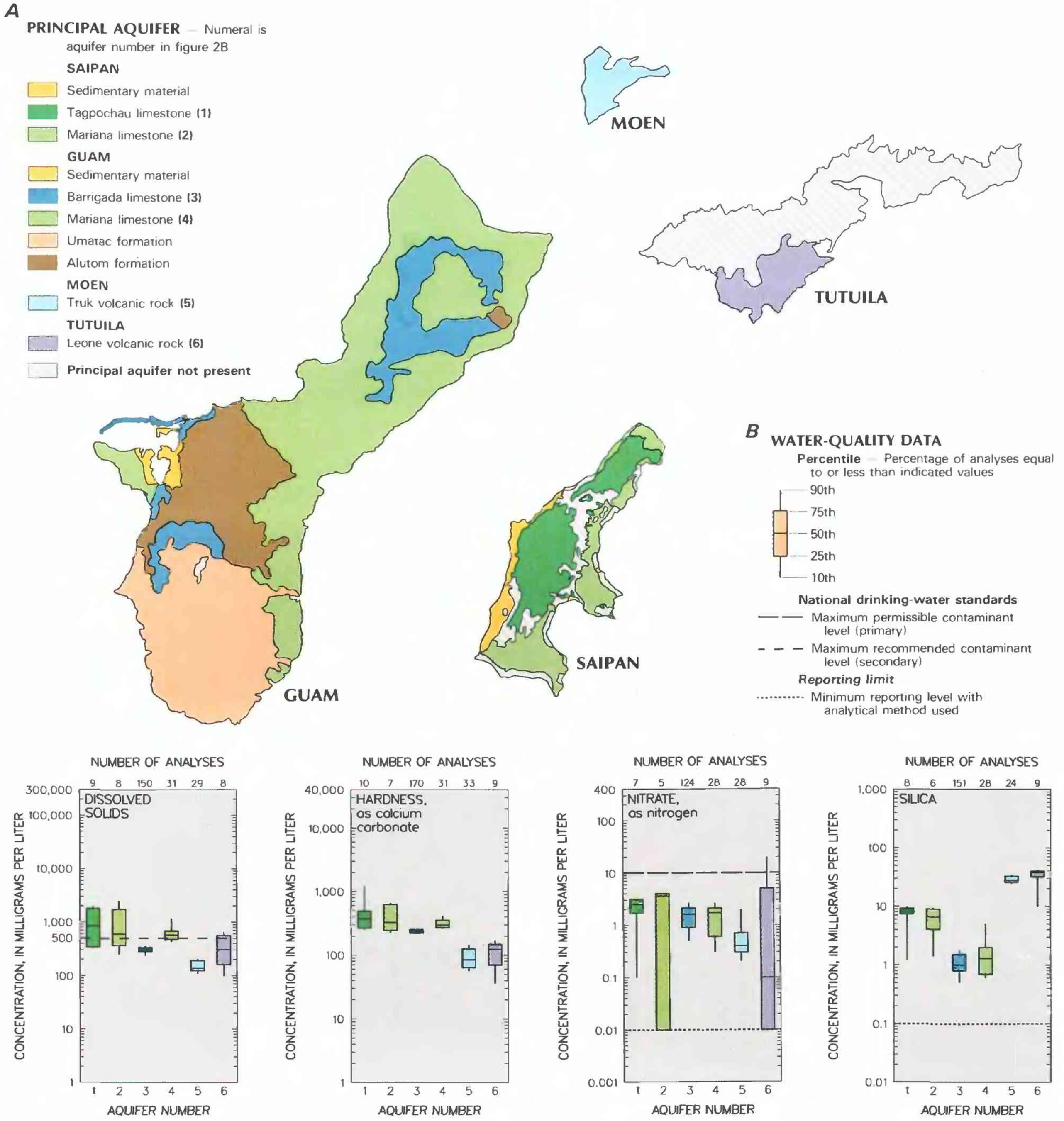

Figure 2. Principal aquifers and related water-quality data in Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. *A*, Principal aquifers; *B*, Selected water-quality constituents and properties, as of 1985. (Sources: *A*, U.S. Geological Survey, 1985. *B*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

lens and subsequent encroachment by seawater can occur. Seawater encroachment, primarily upconing induced by excessive pumping, is the biggest threat to the islands' basal freshwater lens. In Guam, there also exists parabasal water, which is defined as basal water that rests on an impervious formation instead of floating on saltwater (Mink, 1976). Other ground-water bodies, small in comparison to the principal aquifers, are perched or isolated from the major basal-water aquifers.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*B*. The summary is based on dissolved-solids, hardness, nitrate (as nitrogen), and silica analyses of water samples collected from 1965 to 1985 from the principal aquifers on the Islands of Saipan, Guam, Moen, and Tutuila. The data base is not adequate to make statistical inferences for other aquifers. The data were interpreted without consideration of sample depth within the aquifer; where more than one chemical analysis was available, the median concentration for a site was used in the statistical analysis. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in a drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to the esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids.

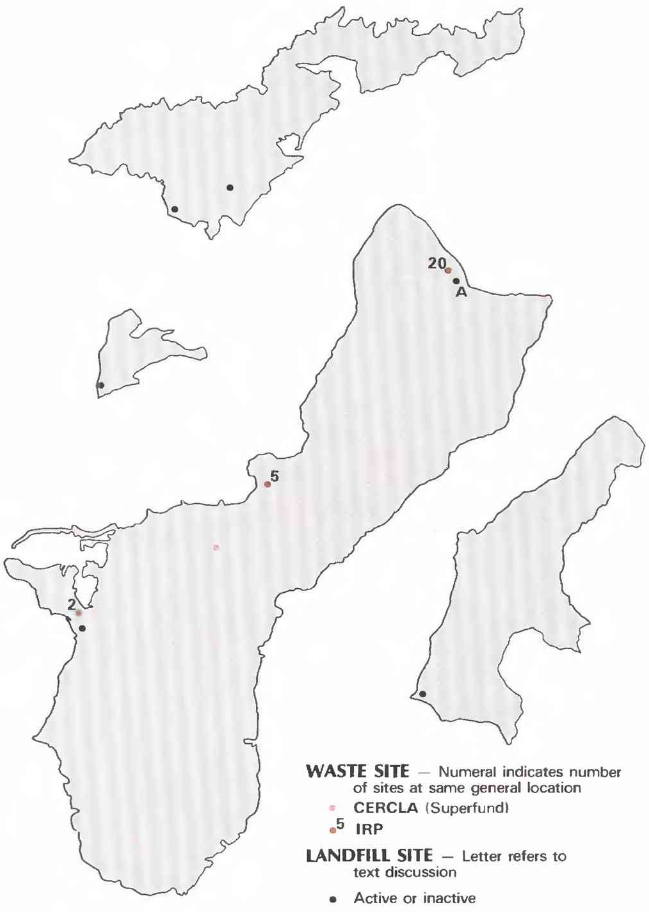

Figure 3. Selected waste sites and ground-water-quality information in Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; and Department of Defense Installation Restoration Program (IRP) sites, as of 1986; private and government landfills, as of 1985. (Sources: U.S. Environmental Protection Agency, 1986c; U.S. Department of Defense, 1986; and, U.S. Geological Survey records.)

Limestone Aquifers

ISLAND OF SAIPAN

The Tagpochau and Mariana limestone aquifers are the most extensive aquifers in Saipan from which most of the withdrawal for public supply is made. Dissolved-solids concentrations in the Tagpochau aquifer ranged from about 325 to 2000 mg/L, and the median was about 850 mg/L. Dissolved solids in the Mariana aquifer ranged from about 250 to 2500 mg/L, and the median was about 600 mg/L. Median concentration of dissolved solids in water from other aquifers is more than 1,000 mg/L in some parts of southern and western Saipan. This concentration exceeds the EPA's national secondary drinking-water recommendation of 500 mg/L. Although these limits do not apply to water used for irrigation, the higher the concentration of dissolved solids, the less desirable the water is for irrigation or other beneficial uses.

Calcium and magnesium, which contribute to the hardness of water, are among the more soluble minerals in the limestone aquifers. Generally, within these aquifers, the higher the concentration of dissolved solids, the higher the hardness (fig. 2*B*). Water from the Tagpochau and Mariana limestone aquifers is classified as very hard, with median hardness concentrations (as calcium carbonate) of 372 mg/L and 330 mg/L, respectively.

Nitrate concentration, as nitrogen, is less than the recommended limit of 10 mg/L. No wells in Saipan produce water that exceeds this limit. Median concentration for nitrate, as nitrogen, is 2.5 mg/L in Tagpochau limestones, and 3.6 mg/L in Mariana limestones. These concentrations are higher than the median nitrate concentrations in water from volcanic-rock aquifers in Moen and Tutuila (fig. 2*B*, aquifers 5 and 6).

The median concentration for silica is less than 9.0 mg/L in water from the limestone aquifers (fig. 2*B*). In general, silica does not affect the beneficial use of water.

ISLAND OF GUAM

The Barrigada and Mariana limestone aquifers (fig. 2*B*, aquifers 3 and 4) are the two primary aquifers in northern Guam. About 70 percent of the water for Guam's public supplies is withdrawn from about 100 production wells completed in these aquifers (U.S. Geological Survey, 1985). In 1978 these aquifers, commonly called the Northern Guam Lens aquifer, were designated by the EPA as a "principal source aquifer", and special management of the aquifers to protect the quality of water from degradation has been stated by the Guam Environmental Protection Agency (GEPA). Substantial efforts have been made by the GEPA to manage and monitor this important ground-water resource.

In the Barrigada limestone aquifer, the median concentration of dissolved solids is 308 mg/L; and in the Mariana limestones aquifer, the median is 574 mg/L. The water in the aquifers is classified as very hard with hardness concentrations (as calcium carbonate) exceeding 200 mg/L (fig. 2*B*, aquifers 3 and 4). Median nitrate concentration, as nitrogen, is about 2 mg/L in the limestone aquifers. This is less than the EPA primary drinking-water standard of 10 mg/L. No wells produce water with nitrate concentrations that exceeds this limit. The median silica concentration is about 1 mg/L for all waters in the limestone aquifers.

Volcanic-Rock Aquifers

In water from the volcanic-rock aquifers in Moen and Tutuila, the median concentrations for dissolved solids are less than 500 mg/L; hardness is less than 125 mg/L; nitrate, as nitrogen, is less than 0.5 mg/L; and silica less than 38 mg/L. All concentrations are within the recommended limit for safe drinking water set by the WHO. One occurrence of nitrate exceeding 10 mg/L was reported for Tutuila (Paul Eyre, U.S. Geological Survey, written commun., 1986). Repeated sampling of the well showed a nitrate concentration of 0.7 mg/L.

EFFECTS OF LAND USE ON WATER QUALITY

Water quality has deteriorated in some areas as a result of seawater encroachment induced by excessive pumping or by dense placement of wells. Investigations by the U.S. Geological Survey and interpretation of data collected by local government agencies have documented increased chloride concentrations in well waters withdrawn from aquifers in Saipan, Guam, and American Samoa. Examples of the fluctuation of pumpage and increase of chloride concentration in selected wells in Guam are shown in figure 4. Although no precipitation data are available for the period of record shown in figure 4, it is likely that some of the fluctuations in chloride concentrations are caused by decreases in precipitation. This is indicated in Well 18-2546-04, June 1982 through July 1983. During this period, constant rates of water withdrawal were accompanied by steadily increasing chloride concentrations; this probably indicates a dry year, reduced recharge to the freshwater basal lens, thinning of the freshwater lens, and subsequent seawater encroachment induced by heavy pumping.

Though waste-disposal practices have not been thoroughly investigated, these practices can affect the sanitary quality of the ground water in some of the Pacific Islands. Incidences of coliform densities in ground water that exceed drinking-water standards have been reported from Moen and Tutuila.

Urbanization

Population in the Trust Territory of the Pacific Islands is growing at an annual rate of 3.5 percent and is expected to double every 10 years if the current trend continues (Trust Territory Environmental Protection Board, 1985). The demands for water to meet this growth have resulted in intensive ground-water development on Moen island.

Saipan's population is expected to grow at an annual rate of 3 to 4 percent. To meet the demands for water, extensive pumping of existing wells and the drilling of new wells has taken place in the limestone aquifers. The effect of this development on the aquifers has been a reduction in the hydraulic head, which has induced seawater intrusion and caused an increase in dissolved solids in ground water. The dissolved-solids concentration in Saipan's limestone aquifer exceeds the EPA national secondary drinking-water standard of 500 mg/L. It is, however, within the maximum limit of 1,000 mg/L set by the WHO.

In Tutuila, American Samoa, contamination of wells by seawater has been induced by pumping, especially during dry periods, which has caused upconing of the underlying saltwater in the Leone volcanic-rock aquifer. Water from wells that tap this aquifer had chloride concentrations ranging from 7 to 1,200 mg/L during 1975 to 1983 (U.S. Geological Survey, 1985).

In addition to increased pumping, which induces saltwater intrusion and results in increased dissolved chloride, urbanization can cause a decrease of recharge to the aquifer. Because of the increase of impervious areas associated with urban development, much of the recharge from rainfall that normally would percolate down to the water table in recharge areas is lost by evaporation or runs off into storm drains.

Agriculture

Because of the limited availability of land in the western Pacific islands, agriculture is practical only on a small scale, and irrigation has little effect on the quality of ground water. However, the potential exists for fertilizers and pesticides, which are used to increase crop yield and to control insects, to contaminate the aquifers on Saipan, Guam, Moen, and Tutuila.

Waste-Disposal

Presently, no RCRA waste-disposal sites are operating on Saipan, Moen, or Tutuila. RCRA guidelines are being implemented at Andersen Air Force Base on Guam to monitor its landfill (fig. 3*B*, site A) as a part of the procedure to close the landfill. Also on Guam, one site is on the NPL for evaluation under CERCLA (fig. 3*A*). This is the major solid-waste disposal site for civilian activities on Guam. The GEPA has monitored the site since 1983 to determine the effect of the landfill on ground-water quality in the area. Results, thus far, have shown no ground-water contamination by leachate from the disposal site (Guam Environmental Protection Agency, 1986).

Military installations on Guam have a wide variety of waste-disposal areas, including active and inactive landfills, sludge and chemical disposal pits, and petroleum disposal areas.

As of September 1985, 27 hazardous-waste sites at 3 facilities in Guam (shown as "other" sites on fig. 3*A*) had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. The EPA presently ranks these sites under the hazard ranking system and may include them in the NPL. These sites are scheduled for confirmation studies to determine if remedial action is required.

Other waste-disposal sites on Saipan, Moen, and Tutuila are associated with landfills (fig. 3*B*) that are used to dispose of solid wastes from domestic and industrial activities. Except for Guam, few data are being collected to evaluate the effects of landfill sites on ground-water quality. Most landfills are located away from ground-water recharge areas. Trace metals and other organic chemicals commonly associated with landfills have not been detected in potable water supplies. The islands lack dense urban and industrial activities that produce the type of pollutant loads found in industrialized areas.

POTENTIAL FOR WATER-QUALITY CHANGES

Seawater intrusion of the freshwater aquifers has the largest potential for future ground-water quality changes in Saipan, Guam, Tutuila, and the TTPI. Heavy pumping of the basal freshwater aquifers to meet increasing water demands has caused an increase in dissolved-solids concentrations in many wells. As little as 2 percent contamination of the freshwater by seawater will result in the water that exceeds the chloride standards recommended by the EPA's secondary drinking-water regulations. Although unused at present, treatment may be needed in the future to reduce dissolved solids or salinity in areas where drinking-water standards are exceeded.

Use of pesticides associated with urbanization and agricultural activities can introduce organic contaminants into the ground water. Current monitoring under the Safe Drinking Water Act (SDWA) guidelines indicates that concentrations of all constituents are less than the maximum contaminant levels established by the EPA. The SDWA constituents being monitored, however, do not include many of the pesticides being used on the islands.

The median nitrate, as nitrogen, concentration on Saipan, 3.6 mg/L, is the highest reported value from any of the limestone aquifers (fig. 2*B*). Guam's nitrate concentration which averages

2 to 2.5 mg/L, is reported to be twice the national average (Guam Environmental Protection Agency, 1982). GEPA data collected during 1986 not only confirmed these levels, but also showed some wells with greater than 5 mg/L nitrate, as nitrogen. The cause of these relatively high nitrate concentrations in ground water has not been fully determined. Indications are that leachates from surface waste-disposal activities such as cesspools, open-toilet facilities, and unregulated animal wastes may be the major causes of high nitrate concentrations in ground water. Nitrogen fixation by plants and buried bird guano may also contribute to nitrate concentrations in ground water.

Bacterial contamination in ground water has been reported in Moen and Tutuila, especially in shallow wells and spring areas where the rural population obtains most of its water supplies. The unsanitary quality of ground water in Moen probably is the cause of high incidences of amoebiasis, infectious hepatitis, and other bacterial and viral gastrointestinal problems among the population (Trust Territory Environmental Protection Board, 1985). Improving the sanitary quality of the water will require improving the sewer and waste-disposal systems on this island.

GROUND-WATER-QUALITY MANAGEMENT

The Trust Territory Environmental Protection Board monitors the quality of water resources in the TTPI. Each island group has its own Public Works Department that operates its central water-supply system. Saipan's water quality is monitored by the Commonwealth of Northern Mariana Islands, Division of Environmental Quality. Guam's water resources are monitored by GEPA, created by the 1973 Guam Environmental Protection Agency Act (Title LXI, Chapter 1). The GEPA is responsible for planning activities and the development of regulations to insure the protection and conservation of Guam's water resources. GEPA has established a comprehensive program to manage and monitor ground-water-quality on Guam. The program includes the extensive study and management of the Northern Guam Lens Aquifer (aquifers 3 and 4) implementing water-quality monitoring efforts, and creating a specific section within GEPA's Water Division to implement ground-water management policies. Tutuila's ground-water quality is monitored by the American Samoa Government (ASG), Office of Environmental Protection Agency. Chloride in ground water on Tutuila is monitored by the Department of Public Works, in cooperation with the U.S. Geological Survey as part of a program to measure saltwater intrusion into the basal aquifers.

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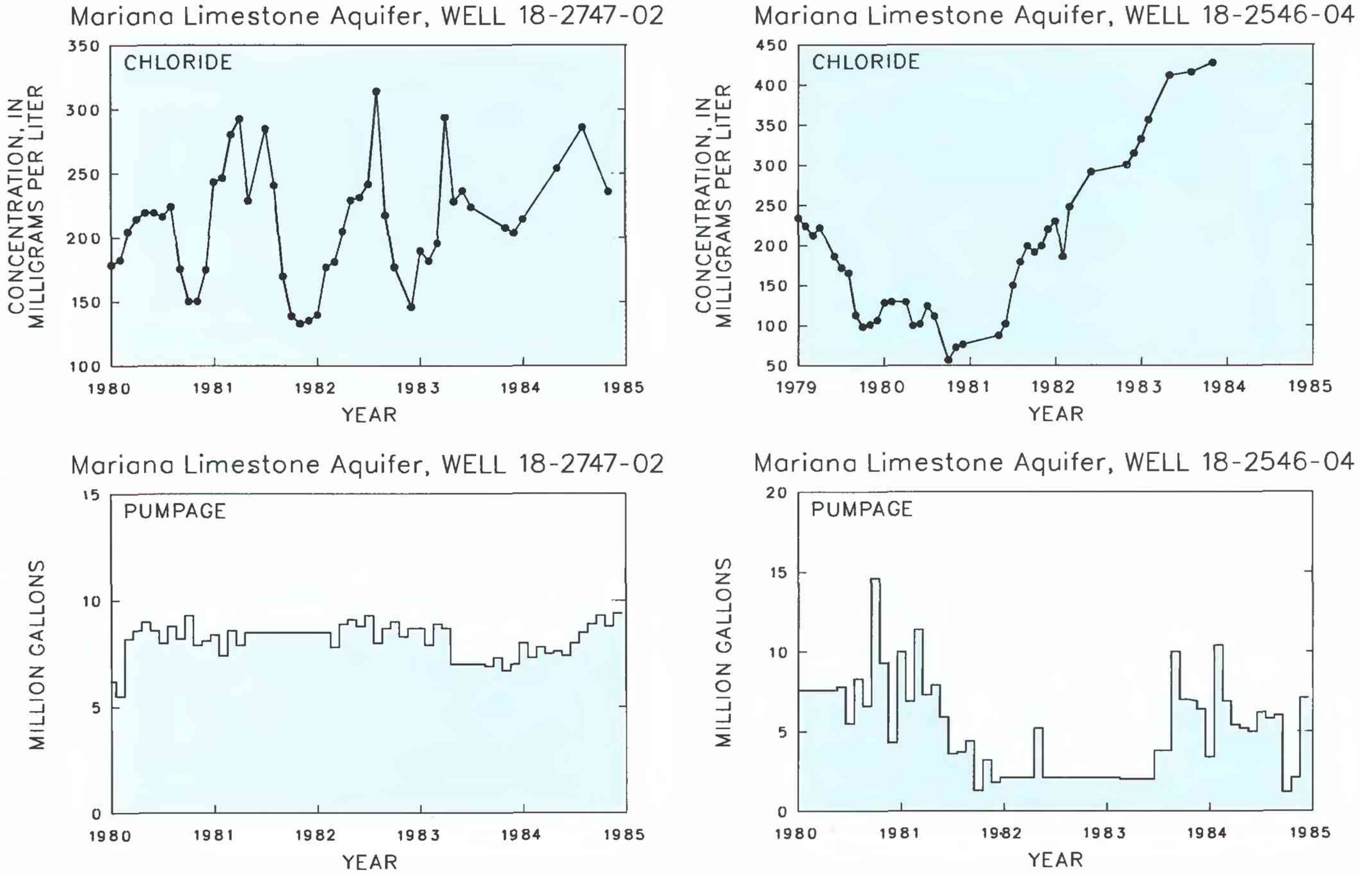

Figure 4. Long-term fluctuation pumpage and chloride concentration in selected wells in Guam, 1980-84. (Sources: U.S. Geological Survey files and Guam water-data-management system.)

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U.S. Virgin Islands
Ground-Water Quality

The ground-water resources of the U.S. Virgin Islands are inadequate to meet the needs of the 100,000 inhabitants (fig. 1*B*) of the three major islands of St. Thomas, St. Croix, and St. John. Perennial streams are nonexistent; aquifers are limited in areal size and provide small yields to wells. Ground water, generally, does not meet the primary and secondary drinking-water standards established by the U.S. Environmental Protection Agency (1986a,b).

Ground water with a dissolved-solids concentration of less than 1,000 mg/L (milligrams per liter) is scarce throughout the U.S. Virgin Islands, and water with chloride concentrations as large as 500 mg/L is generally considered potable (Gomez-Gomez and Heisel, 1980, p. U14). In addition, large concentrations of nitrogen and widespread contamination by fecal coliform and fecal streptococci bacteria threaten the already limited ground-water resources (Garcia and Canoy, 1985).

The principal aquifers of the Islands supply about 17 percent of the Islands' water supply. Rooftop-rainfall catchments and desalination of seawater supply the remaining 83 percent. Ground-water withdrawals from aquifers in the U.S. Virgin Islands (fig. 2*A*) average 1.7 Mgal/d (million gallons per day) (Torres-Sierra and Dacosta, 1984; Torres-Sierra, 1986, p. 11); however, less than 10 percent of these withdrawals can be classified as freshwater (dissolved-solids concentration less than 1,000 mg/L). The remaining saline ground-water withdrawals are either treated with reverse-osmosis desalination units or used for toilets, swimming pools, laundry, or wash water.

In spite of a steadily increasing demand for water, the geohydrology of the islands generally remains unstudied, and plans for further ground-water development are uncertain. Ground-water-quality data are scarce, and there are no active ground-water-quality monitoring networks on any of the three islands.

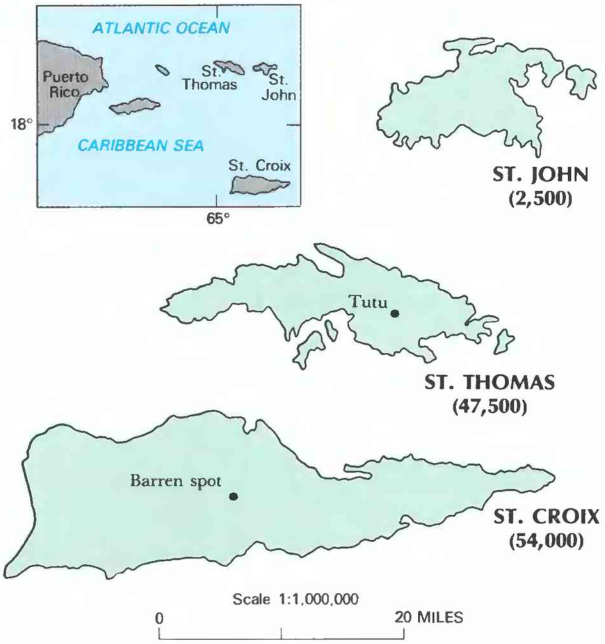

Figure 1. Selected geographic features and 1985 population distribution in the U.S. Virgin Islands. Selected cities and population distribution, 1985; number in parentheses is total by island. (Source: Virgin Islands Office of Policy Planning Research, 1987.)

WATER QUALITY IN PRINCIPAL AQUIFERS

The U.S. Virgin Islands has three principal aquifers—the Kingshill aquifer, the volcanic rock aquifer, and the coastal embayment aquifer (fig. 2*A*). The Kingshill aquifer on St. Croix provides 67 percent of the total ground-water withdrawals in the U.S. Virgin Islands. The volcanic rock and coastal embayment aquifers, which occur on all three of the islands, represent 25 and 8 percent of the total ground-water withdrawals, respectively.

Ground-water quality is affected by precipitation which contains large concentrations of salt derived from sea-spray-laden air (Jordan and Cosner, 1973). The salt concentration in ground water is increased further by the rapid rate of evapotranspiration (U.S. Geological Survey, 1985, p. 409). Near coastal areas, saltwater occurs in all of the aquifers.

Background Water Quality

In 1984, the U.S. Geological Survey conducted a reconnaissance of selected wells throughout the U.S. Virgin Islands to determine the ground-water quality in the three principal aquifers. Water samples from wells located in the principal aquifers were analyzed to determine the physical, chemical, and bacteriological characteristics. Selected water samples also were analyzed for priority pollutants, as designated by the U.S. Environmental Protection Agency (EPA).

A graphic summary of selected water-quality variables compiled by the U.S. Geological Survey is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), chloride, and sulfate analyses of water samples collected from 1965 to 1985 from the principal aquifers in the U.S. Virgin Islands. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 250 mg/L chloride, and 250 mg/L sulfate.

Kingshill Aquifer

The Kingshill aquifer is the most productive and extensively developed aquifer in the U.S. Virgin Islands. The aquifer, which underlies approximately 25 square miles of central Saint Croix (U.S. Geological Survey, 1985, p. 410) is composed primarily of calcareous sediments. Along the coast and within the drainage basins, the aquifer is overlain with alluvium. The Kingshill aquifer is unconfined and contains a lens of relatively freshwater that overlies saline water (Robison, 1972).

Water from the Kingshill aquifer exceeds the secondary drinking-water standards for dissolved solids and chloride (fig. 2*C*), with median concentrations of 1,440 mg/L and 560 mg/L, respectively. A maximum chloride concentration of 2,200 mg/L has been reported for connate water within the Kingshill marl. The median nitrate (as nitrogen) concentration, 8.3 mg/L, does not exceed the primary drinking-water standard; however, nitrate (as nitrogen) concentrations as large as 16 mg/L have been reported.

Volcanic Rock Aquifer

The volcanic rock aquifer, which is present on each of the islands (fig. 2*A*), is used almost exclusively for domestic supply, except on St. John, where the aquifer is used to supplement the public supply of desalinated water that is barged from Saint Thomas (U.S. Geological Survey, 1985, p. 410). The aquifer, which is composed of lava flows, fluvial tuffs, and breccias, is under confined to semiconfined conditions in fractures or in the weathered-rock mantle.

Although water from the volcanic rock aquifer is very hard (more than 180 mg/L as calcium carbonate), the water contains considerably smaller concentrations of dissolved solids, chloride, and sulfate than water from either the Kingshill or coastal embayment aquifers (fig. 2*C*). The median concentration of 2.7 mg/L nitrate (as nitrogen) is less than the primary drinking-water standard.

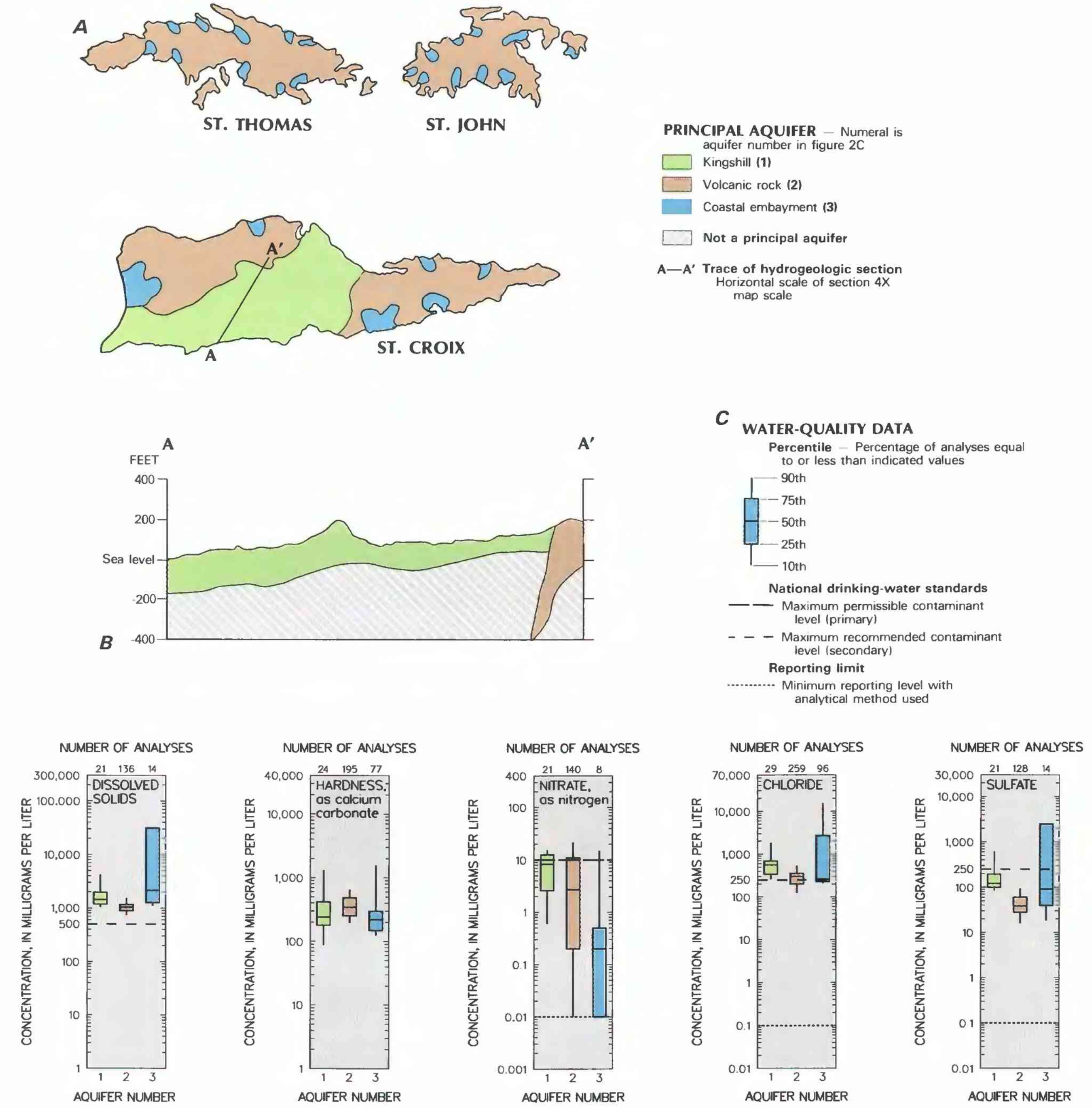

Figure 2. **Principal aquifers and related water-quality data in U.S. Virgin Islands.** *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, 1965 to 1985. (Sources: *A*, Modified from Donnelly, 1960; Cederstrom, 1950. *B*, Robison, 1972. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

Coastal Embayment Aquifer

The coastal embayment aquifer, which is present on each of the islands (fig. 2*A*), consists of relatively thick deposits of unconsolidated sediments overlying weathered and fractured volcanic rocks (U.S. Geological Survey, 1985, p. 410). Although wells drilled in the unconsolidated sediments can yield more than 50 gallons per minute, the water is generally saline.

Median concentrations of dissolved solids and chloride are 2,150 mg/L and 261 mg/L, respectively. The median concentration of nitrate (as nitrogen) is 0.2 mg/L. This is the smallest median nitrate concentration for the three aquifers.

Recent investigations by the U.S. Geological Survey in two of the coastal embayment aquifers on St. Thomas indicate that development of freshwater supplies may be possible (Fernando Gomez-Gomez, U.S. Geological Survey, written commun., 1986).

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has deteriorated in all three principal aquifers of the U.S. Virgin Islands, principally from excessive ground-water withdrawals, septic-tank drainage, and infiltration from stream courses conveying sewage-treatment-plant discharges or septic-tank overflows.

During the ground-water-quality reconnaissance in the islands in July 1984, water samples from several wells were analyzed to determine the presence of contamination by volatile organic chemicals and pesticides (Garcia and Canoy, 1985). In all the samples, concentrations of these constituents were less than minimum detection levels.

A report on 1983 ground-water conditions in the U.S. Virgin Islands (Geraghty and Miller, Inc., 1983) discusses degradation of ground-water quality, principally for the Kingshill aquifer on St. Croix and the volcanic rock aquifer on St. Thomas. The report indicates that many wells in the Kingshill aquifer contained an accumulation of lubricating oil from malfunctioning lubricating systems on well pumps. In several wells, as much as 8 feet of oil, floating on top of the water, was measured. The report also indicated that pentane was detected in water samples withdrawn from public water-supply wells in the Barren Spot well field in southern St. Croix (fig. 2*A*). Barium concentrations as large as 1.83 mg/L were also detected in some of the wells; the primary drinking-water standard for barium is 1 mg/L. It is not known if the contaminating source of the barium and the pentane is the same.

Figure 3. Selected waste sites and ground-water-quality information in the U.S. Virgin Islands. Resource Conservation and Recovery Act (RCRA) sites as of 1986; distribution of wells that yield contaminated water, as of 1986; municipal landfills, as of 1986. (Sources: Waste sites, L.J. Livingston, U.S. Environmental Protection Agency, written commun., 1986. Ground-water quality sites, Fernando Gomez-Gomez, U.S. Geological Survey, written commun., 1986. Landfill sites, Fernando Gomez-Gomez, 1980.)

Volatile organic chemicals were reported at a water-supply well at a Tutu housing project on St. Thomas (Geraghty and Miller, Inc., 1983). In addition, dichloroethylene, trichloroethylene, and tetrachloroethylene were detected by a private laboratory in three other wells on St. Thomas in concentrations of 12, 10, and 5.5 μg/L (micrograms per liter), respectively.

Ground-water contamination has not been detected at the one Resource Conservation and Recovery Act (RCRA) site on St. Croix (fig. 3), nor at any of the municipal landfills on the three islands (fig. 3). There are no Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) sites on any of the three islands (U.S. Environmental Protection Agency, 1986c).

Ground-Water Withdrawals

Excessive ground-water withdrawals from the Kingshill aquifer on St. Croix have caused saltwater upconing and encroachment. Several investigations of the Kingskill aquifer (Cederstrom, 1950; Buros, 1976; Geraghty and Miller, Inc., 1983) have shown a correlation between pumping rate and chloride concentrations; however, such a correlation for wells in the coastal embayment aquifer or volcanic rock aquifer has not been documented. It is possible that the saltwater-yielding wells in the volcanic rock and coastal embayment aquifers are screened on the saltwater side of the freshwater-saltwater interface and, therefore, have not actually experienced saltwater encroachment.

Septic-Tank Drainage and Sewage Effluent

Wells throughout the U.S. Virgin Islands have been contaminated by septic-tank drain fields, leaky sewer lines, and sewage infiltration from sewage-treatment plant discharges to stream courses (fig. 3). Nitrate (as nitrogen) concentrations commonly exceed 5 mg/L, and fecal coliform and fecal streptococci bacteria have been detected in most wells (Garcia and Canoy, 1985). Fecal streptococci bacteria concentrations were as large as 5,800 colonies/100 mL (milliliters) in a raw water from a well in the volcanic rock aquifer on St. Croix. In comparison, the Kingshill aquifer in St. Croix had the smallest concentrations of fecal coliform and fecal streptococci bacteria.

Contamination of wells and aquifers frequently occurs through the annular space between the well casing and the soil and rock materials of operating or abandoned wells. Substandard well-construction practices and deterioration of casings have apparently exposed some wells and the associated aquifers to contamination. In addition, the soil zone, usually less than 2 feet thick, is incapable of adequately filtering septic wastes and surface contamination and thus provides easy access to the aquifer through open joints or fractures.

POTENTIAL FOR WATER-QUALITY CHANGES

The continued use of aquifers as a water supply in the U.S. Virgin Islands is in jeopardy. The aquifers are being contaminated by sewage wastes, and saltwater encroachment is threatening the already limited, fresh ground-water resources.

Population increases have spurred housing developments in the headwaters of streams and in areas of ground-water recharge. In 1977, the Virgin Islands Planning Office estimated a population of 156,000 by the year 2000 (Peebles, and others, 1979, p. 17). Approximately one-half of the population of the U.S. Virgin Islands uses septic tanks, the effluent of which is often inadequately filtered because of a thin soil cover. In areas where soil and surface conditions are effective in filtering the sewage wastes, the density of septic systems often results in overloading the filtration capacity of the subsoil (Jordan and Cosner, 1973, p. 53). In the volcanic rock aquifer, open joints and fractures can promote widespread contamination of the aquifer.

Frequent breakdowns and overloads of sewage-treatment plants at many of the larger housing developments increase the chances of bacterial pollution in the aquifers. The treatment plants (and polishing ponds), which are intended to decrease the density of the septic-tank systems, are designed to eliminate most of the bacteria from the effluent. However, inadequate sewage treatment or plant overload generally is relieved by discharging effluent to dry stream channels. Discharging effluent into the stream channels, which are major ground-water-recharge areas, increases the potential for sewage effluent to contaminate the aquifers.

Saltwater contamination will also continue to threaten fresh ground-water supplies as long as wells continue to be improperly constructed. Continued overpumping of the aquifers will cause the freshwater-saltwater interface to move landward, thereby increasing the chances for further saltwater intrusion into the aquifers. Wells can be drilled in areas and at depths to take full advantage of the available freshwater, while not initiating saltwater migration. Controlled pumping, scavenger-wells, and barrier systems might be the most efficient freshwater-development strategy for the islands.

GROUND-WATER-QUALITY MANAGEMENT

The Department of Conservation and Cultural Affairs (DCCA) is charged with administering and enforcing most laws related to water resources and water pollution in the U.S. Virgin Islands. The DCCA develops standards for public water-supply systems; plans for emergency water supplies; controls well-construction permits; issues water-appropriation permits for all ground-water withdrawals greater than 500 gallons per day; and designs and constructs wastewater-treatment facilities. Also, the EPA has delegated to the DCCA the responsibility of implementing and enforcing the Safe Drinking Water Act of 1974, the Pesticide Control Act, and the Clean Water Act of 1977.

Other U.S. Virgin Islands agencies involved in the management of the water resources are the Public Works Department, the Water and Power Authority, the Virgin Islands Planning Office, and the Health Department. Under Title 30, Section 51, of the Virgin Islands Code, the Commissioner of Public Works is designated to supervise and control the construction, repair, maintenance, operation, and administration of the public-water system. The Virgin Islands Water and Power Authority is responsible for the production and distribution of electrical energy and for the production of potable water from seawater desalination systems. Water-management planning is within the charter of the U.S. Virgin Islands Planning Office, but the DCCA is active in planning as well. The Department of Health analyzes the bacteriological and chemical content of private cisterns and wells.

The EPA has not delegated to the U.S.Virgin Islands government the management and implementation of several laws concerning ground-water quality. The EPA is responsible for enforcing the RCRA, which regulates the management of solid and liquid hazardous wastes. There is at present only one RCRA site in the Virgin Islands on St. Croix (fig. 3). Presently, little has been done in water programs in the Virgin Islands regarding toxics identification under the Toxic Materials Act. There are no known problems with respect to industrial discharges to public sewage-treatment plants, and there are very few sources that would be expected to pose problems with respect to toxic-substances discharge (U.S. Environmental Protection Agency, 1979, p. 59).

The continued use of ground water as a drinking-water supply in the U.S. Virgin Islands will require a concerted effort to: (1) develop freshwater while minimizing disturbance to the freshwater-saltwater interface, and (2) reduce the potential for sewage infiltration to aquifers from septic tanks and sewage-treatment plant discharges.

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UTAH
Ground-Water Quality

In Utah (fig. 1), ground water is the major source for public supply—about 63 percent of the population depends on ground water. Ground-water-quality in the principal withdrawal areas (fig. 2) generally does not exceed the drinking-water standards established by the Utah Department of Health (1979) for dissolved solids and nitrate, which are important properties for evaluating the suitability of water for public use. The median concentration of dissolved-solids does not exceed the national drinking-water standard of 500 mg/L (milligrams per liter) in 7 of the 13 areas of ground-water withdrawals and does not exceed the State drinking-water standard of 1,000 mg/L in 11 of the 13 areas. In all 13 areas, the median concentration of nitrate plus nitrite does not exceed the national and State standard of 10 mg/L as nitrogen. However, there is some degradation of ground-water quality in several areas associated with urbanization (fig. 1*B*), irrigation, and leachates from mine and mill tailings and surface impoundments, including impoundments of brine produced with petroleum. Contamination from many organic compounds has been detected in the shallow zones of some of the basin-fill aquifers but has not been detected in the deeper zones.

Twenty-one hazardous-waste sites require monitoring of ground-water quality under the Federal Resource Conservation and Recovery Act (RCRA) of 1976 (fig. 3*A*). In addition to these sites, three sites have been included on the National Priorities List (NPL) (also known as Superfund) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c), and three "other" sites are under consideration for inclusion in the NPL. The three Superfund sites require additional evaluation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (U.S. Environmental Protection Agency, 1980). Contamination of shallow ground water has been detected at six of the RCRA sites, two of the CERCLA sites, and two "other" sites (proposed CERCLA sites). At the remaining 17 sites, either no contamination has been detected or monitoring data have not been evaluated. In addition, the U.S. Department of Defense (DOD) has identified six sites at one facility where contamination has warranted remedial actions.

In 1957, the U.S. Geological Survey, in cooperation with the State of Utah, formally began a ground-water-quality observation program. By 1985, the program included annual measurements at more than 250 wells. The program has included only a limited number of inorganic constituents and no organic constituents. Organic constituents, however, have been measured at specific sites where the presence of hazardous wastes has prompted investigations by State and county agencies and by private industry.

WATER QUALITY IN PRINCIPAL AQUIFERS

Utah has four principal types of aquifers (fig. 2*A*)—basin-fill, valley-fill, sandstone, and carbonate-rock (U.S. Geological Survey, 1985, p. 415). More than 85 percent of the State's total ground-water withdrawals by wells are from the unconsolidated basin-fill aquifers and about 10 percent of the withdrawals are from the unconsolidated valley-fill aquifers (estimated from data in Seiler and others, 1985). Less than 1 percent of the withdrawals are from the sandstone aquifers, which are not developed extensively; the remaining withdrawals are from the carbonate-rock aquifers and from miscellaneous aquifers that are not classified as "principal".

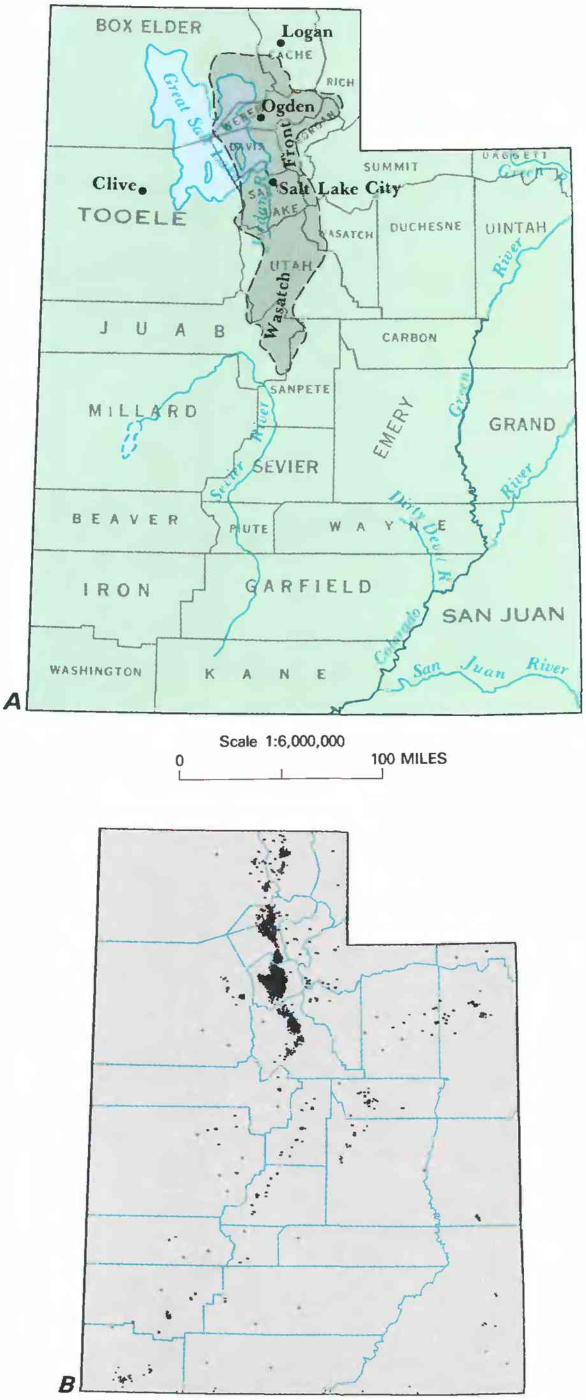

Figure 1. Selected geographic features and 1985 population distribution in Utah. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

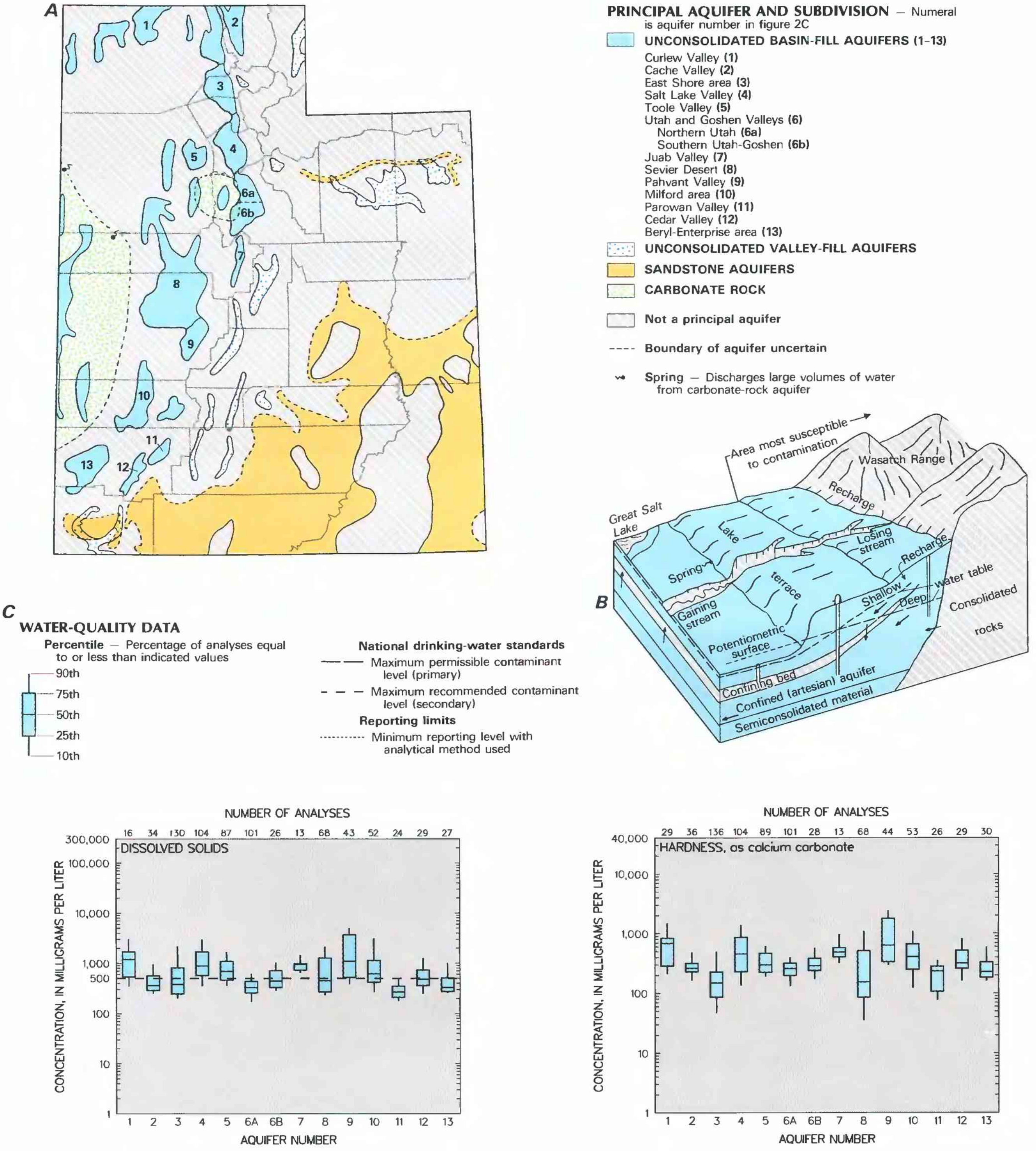

Figure 2. Principal aquifers and related water-quality data in Utah. *A*, Principal aquifers. *B*, Block diagram showing typical characteristics of a basin-fill aquifer. *C*, Selected water-quality constituents and properties, as of 1985. (Sources: *A*, Compiled by J.S. Gates and G.W. Freethey from U.S. Geological Survey files. *B*, Hely and others, 1971, figure 3. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), fluoride, and boron analyses of water samples collected from 1969 to 1985 in Utah. The summary is limited to the basin-fill aquifers, because of their importance as a water supply and because the data base for chemical quality was considered to be adequate for making statistical inferences. The data were interpreted without distinction as to the depth from which the samples were collected within the aquifers; where more than one analysis was available, the median concentration was used. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen) and 4 mg/L fluoride. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 2 mg/L fluoride. The State standards (Utah Division of Environmental Health, 1979) for dissolved-solids is 1,000 mg/L. The State standard for fluoride in drinking-water is based on the average air temperature of the area and may range from 1.4 to 2.4 mg/L.

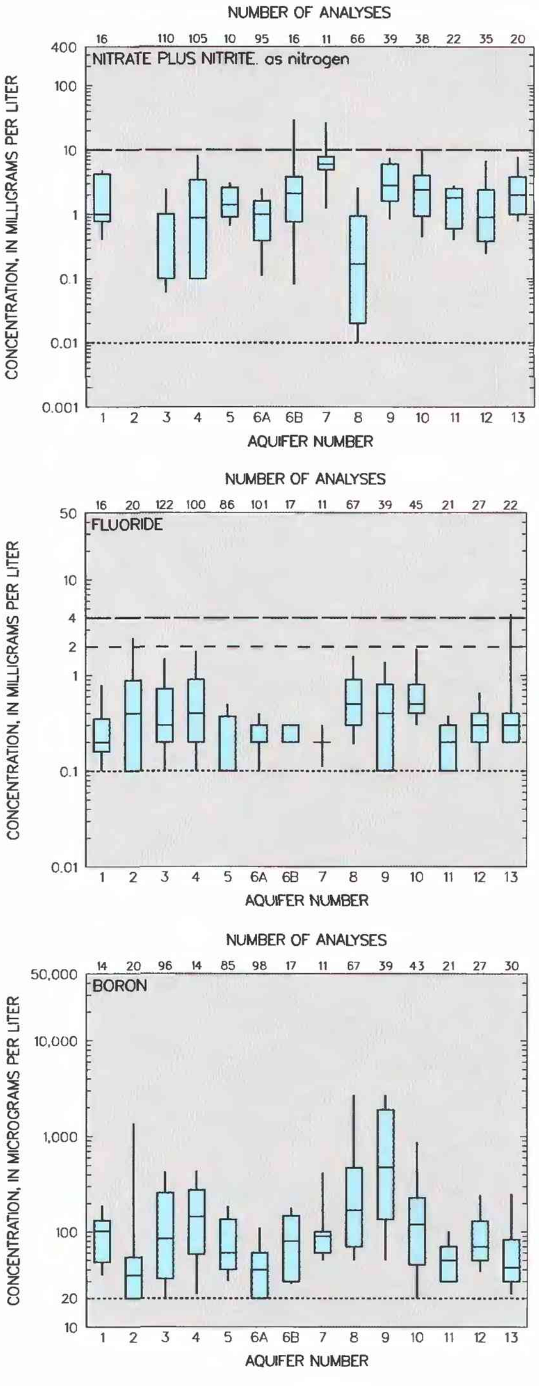

Figure 2. Principal aquifers and related water-quality data in Utah—Continued.

Basin-Fill and Valley-Fill Aquifers

Water from the basin-fill and valley-fill aquifers generally has less than 1,000 mg/L dissolved solids, is fresh, and is suitable for most uses, including public supply. The basin-fill aquifers provide supplemental water supplies to most major cities and to much of the irrigated land.

Ground water containing less than 250 mg/L dissolved solids occurs in the recharge zones of the basin-fill and valley-fill aquifers adjacent to the Wasatch Range and other high mountain areas. Slightly saline ground water generally underlies the lowest parts of valleys, where ground water discharges to the Great Salt Lake and playa areas of western and northwestern Utah; in the Uinta Basin in Duchesne and Uintah Counties; in northwest Emery County; and along the base of the Book Cliffs in Carbon, Emery, and Grand Counties (Price and Arnow, 1985, p. 31). Locally, very saline to briny ground water occurs in areas of natural ground-water discharge from the basin-fill and valley-fill aquifers.

Along the Wasatch Front, which includes areas 3, 4, 6A, 6B, and in figure 2*A*, where most ground water used for public supply is withdrawn, the median concentration of dissolved solids (fig. 2*C*) was smaller than the 1,000 mg/L State drinking-water standard. Although the standard does not apply to water used for irrigation, a large concentration of dissolved solids or salinity is not desirable for irrigation. In north-central Boxelder County and in the Pahvant Valley (fig. 2*A*, areas 1 and 9), where irrigation is the principal use of water, the median concentration of dissolved solids was slightly larger than 1,000 mg/L (fig. 2*C*).

Calcium and magnesium, which contribute to the hardness of water, are among the more soluble ions in most rocks and sediments in the recharge areas of the basin-fill aquifers. Generally, in the basin-fill aquifers of Utah, the larger the concentration of dissolved solids, the greater is the hardness (fig. 2*C*). The median concentration of hardness generally was larger than 250 mg/L, which is considered very hard.

For all areas of major withdrawals from the basin-fill aquifers (fig. 2*A*, areas 1–13), the median concentration of nitrate plus nitrite was less than 10 mg/L as nitrogen (fig. 2*C*). Only a few wells produced water that contained nitrate plus nitrite in excess of this concentration. A large concentration of nitrate plus nitrite in ground water indicates possible contamination from human or animal wastes or fertilizers.

The concentration of fluoride in drinking water can prevent dental cavities if the concentration is small, or it can cause mottling of teeth if the concentration is large. For all basin-fill aquifers

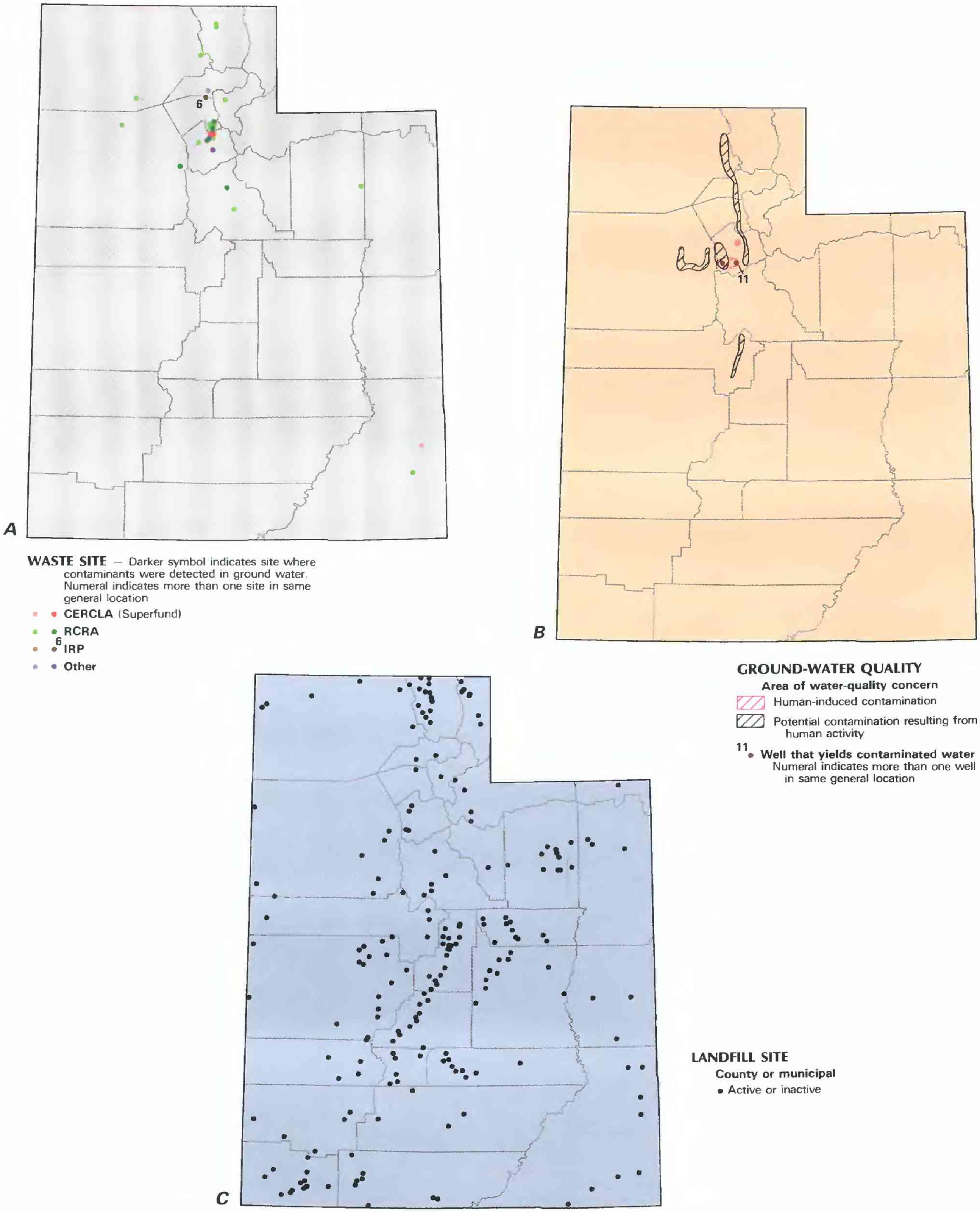

Figure 3. **Selected waste sites and ground-water-quality information in Utah.** *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of human-induced contamination, areas of potential contamination, and distribution of wells that yield contaminated water, as of 1985. *C*, County and municipal landfills, as of 1986. (Sources: *A*, Data from Utah Department of Health. *B*, Compiled from U.S. Geological Survey files. *C*, Modified from Utah Department of Health unpublished map.)

in Utah, the median concentration of fluoride was smaller than the State standard for drinking water.

Some boron is necessary for normal growth of all plants, but in larger concentrations it is toxic. According to the water-quality classification of Eaton (1935), water containing less than 330 μg/L (micrograms per liter) boron is excellent for irrigation of even the most sensitive crops. In Pahvant Valley (fig. 2*A*, area 9) the median concentration is 480 μg/L, but for all other major basin-fill aquifers, the median concentration is smaller than 180 μg/L (fig. 2*C*).

A public-supply well in the Sevier Desert (fig. 2*A*, area 8) was closed in January 1982, because of excessive concentrations of arsenic. Arsenic is naturally abundant in the rocks in the general vicinity of this well (Larry Scanlon, Utah Division of Environmental Health, oral commun., 1985).

Sandstone and Carbonate-Rock Aquifers

The sandstone aquifers provide water supplies for public use and irrigation in southern Utah. In recharge areas, water from the sandstone generally contains less than 1,000 mg/L dissolved solids, but locally where the sandstone is deeply buried and ground-water movement is slow, the concentrations may be larger than 35,000 mg/L. Uncharacteristically large dissolved-solids concentrations are present in the sandstone aquifers at shallow depths in the Dirty Devil River basin (eastern part of Wayne and Garfield counties), and near the southeastern corner of the State in the San Juan River basin. The large concentrations are presumed to be caused by vertical movement of more saline water from older and younger formations into the sandstone aquifers (Hood and Danielson, 1981; Kimball, 1987). The carbonate-rock aquifer is not extensively used, and little is known about it.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has changed in some areas because of the effects of urbanization, mining, irrigation, and waste disposal. Reports from investigations conducted by the U.S. Geological Survey, State and local agencies, private companies, and consultants have documented some of these changes. In addition to these investigations, interpretation of data collected by the U.S. Geological Survey as part of cooperative programs with State and local agencies (Price and Arnow, 1986) has aided in documenting the changes. Examples of the effects of urbanization or irrigation on the dissolved-solids concentration in ground water are shown in figure 4.

Urbanization

Between 1970 and 1980, population in Utah increased by about 38 percent and most of the increase was in the Wasatch Front area (fig. 1*A*, 1*B*). The population in Salt Lake County, which is the most densely populated area in Utah, increased from 458,607 in 1970 to 619,066 in 1980, an increase of about 35 percent.

Thirty-five wells in the Salt Lake Valley (fig. 2*A*, area 4), which were sampled from 1962 to 1967, were resampled from 1979 to 1985. During this period, the dissolved-solids concentration in water from 13 of the wells increased more than 10 percent (Waddell and others, 1986, p. 8). This increase in dissolved solids was partly attributed to the effects of urbanization.

Since 1965, urban development in the eastern part of the Salt Lake Valley (area 4) has increased the impervious area. Much of the precipitation that formerly infiltrated the land surface and percolated to the ground-water system now flows into storm drains that empty into the Jordan River. Most of the water that now percolates to the water table in the recharge areas is water that has been applied to lawns and gardens; consequently, the water may contain fertilizers and other chemicals that could cause chemical changes in the quality of ground water. The extensive use of salt (primarily sodium chloride) for deicing roads began in the 1960's and its use has increased as equipment for dispensing the salts has become more available. As a result, some of the increase in dissolved solids also may be due to storage and use of salt in the recharge areas and canyons of the Wasatch Range east of Salt Lake City.

In water from one well (fig. 4, area 4), the concentration of dissolved solids began to increase gradually during the late 1950's, and by 1985 the concentration had increased by about 100 mg/L. This increased dissolved-solids concentration was accompanied by an increase in the concentrations of calcium, sodium, and chloride. Waddell and others (1986, p. 8) also determined that between 1962–67 and 1979–84 water from three other wells in the Salt Lake Valley (area 4) had increases of dissolved solids ranging from 24 to 46 percent.

Numerous stormwater-drainage wells are located in the urban areas along the Wasatch Front. These dry wells serve as a direct pathway for storm water and runoff from urban areas to reach the ground-water reservoir. Counties require that facilities such as parking lots and shopping centers provide for disposal of stormwater and runoff in the site plan. The Utah Bureau of Water Pollution Control currently (1986) is developing an inventory of these dry wells as part of the State's Underground Injection Control Program (R.R. Long, U.S. Environmental Protection Agency, written commun., 1986).

Mining

Acidic water from mining operations and leaching of tailings is stored in ponds and reservoirs in recharge areas in Salt Lake Valley (fig. 2*A*, area 4). The dissolved-solids concentration in water from some wells downgradient from the ponds and reservoirs has increased by 200 to 1,400 mg/L (Waddell and others, 1986, fig. 6). Waddell and others (1986, p. 21) indicated that the increased concentrations of dissolved solids were due to increased concentrations of calcium, magnesium, sulfate, and chloride. Except for chloride, the changes were consistent with the effects expected from passage of acidic waters containing large concentrations of magnesium and sulfate through an aquifer containing carbonate minerals. Eleven privately owned wells and 1 public-supply well were closed during 1985–86 in this area, because of ground-water contamination (Joel Hebdon, Utah Division of Environmental Health, oral commun., 1986). The wells were closed because the concentration of dissolved solids and sulfate exceeded the State standards (1,000 and 250 mg/L respectively) for drinking water. About 80 people were affected by the closing of these wells.

Leachates from radioactive tailings resulting from uranium and vanadium ore-processing operations in the Salt Lake Valley (fig. 2*A*, area 4) during the 1950's and 1960's resulted in increases of dissolved solids, trace metals, and radioactivity in water beneath and downgradient from the disposal area. About 7,800 acre-feet of water in the shallow, unconfined part of the aquifer and 12,000 acre-feet of water in the deeper, confined part of the aquifer were contaminated by leachate from the tailings (Waddell and others, 1986, p. 31–33). Removal of the tailings to a remote area west of the Great Salt Lake began in 1985.

Irrigation

The use of ground water for irrigation has contributed to the deterioration of ground-water quality in the Sevier Desert (fig. 2*A*, area 8), Pahvant Valley (area 9), and the Beryl-Enterprise area (area 13) (Handy and others, 1969). In the Sevier Desert, part of the recharge consists of diverted river water that is used for irrigation. This water contains more dissolved solids than other recharge sources. Use of river water for irrigation, as well as recirculated ground water pumped for irrigation, increased the concentration of dissolved solids in water from a well from about 550 mg/L in

1958 to about 950 mg/L in 1979 (fig. 4, area 8). In Pahvant Valley, withdrawals for irrigation have caused a cone of depression in the water table. As the cone of depression expanded, saline ground water from the north and west may have moved into it, causing the concentration of dissolved solids in one well to increase from about 1,700 mg/L in 1957–58 to about 6,500 mg/L in 1984 (fig. 4, area 9). In addition, before and since formation of the cone of depression, part of the water recharging or flowing into this area is recirculated ground water, which is the excess irrigation water not used by crops that percolates to the water table and is withdrawn again by wells for irrigation.

Similar conditions resulted in deterioration of ground-water quality in the Beryl-Enterprise area (fig. 2*A*, area 13). Recirculated ground water used for irrigation intensified the accumulation of salts in this area. For example, the concentration of dissolved solids in water from a well in this area increased by about 900 mg/L between 1960 and 1983 (fig. 4, area 13).

Waste Disposal

Hazardous waste is treated, stored, or disposed of at 21 RCRA sites in Utah (fig. 3*A*). Some of this waste, which may leak from containers or otherwise enter the ground-water system, constitutes hazard to the quality of ground water (fig. 3*B*). The Utah Division of Environmental Health has determined that shallow ground water has been contaminated at six of these sites (fig. 3*A*). At the other 15 sites, either contamination has not been detected or monitoring data have not been fully evaluated. An additional three sites are included on the NPL (U.S. Environmental Protection Agency, 1986a) and contaminants have been detected in shallow ground water at two of these sites. Another three sites (''other'' sites in fig. 3*A*) are under consideration for inclusion in the NPL and contaminants have been detected at two of these sites. Many of the hazardous-waste sites are located in the densely populated Wasatch Front area, which includes areas 3, 4, 6A, 6B, and 7 in figure 2*A*).

Because of the similarities in the types of waste disposed and the chemical characteristics of the waste, the wastes were categorized for this report into four major groups: (1) wastes from the petroleum industry; (2) wastes from the mining, metal-recovery, and steel smelter/mill industries; (3) wastes from other industries; and (4) wastes from military installations.

Waste sites commonly associated with the petroleum industry are landfills, lined and unlined surface impoundments, and land farms where wastes are treated, stored, or disposed. The wastes usually are acidic, and contain trace metals such as chromium, lead, and organic compounds such as toluene, benzene, and ethyl benzene. At sites in the Wasatch Front area where contamination has been detected in ground water, trace metals such as arsenic, chromium, and lead, and organic compounds such as xylene, dichlorobenzene, pyrene, and phenanthrene have been reported. Some of the brines produced with petroleum also are disposed of in surface impoundments.

For the mining, metal-recovery, and steel smelter/mill industries, surface impoundments of wastes and mill tailings typically contain or produce acidic leachates and contain metals such as arsenic, cadmium, chromium, copper, lead, and zinc as well as some organic compounds. At the sites where ground-water contamination has been detected (fig. 3*A*), most of the same metals present in the waste were detected in the ground water. Generally, the acidic waters from these wastes are neutralized within a short distance from the waste site, as most basin-fill aquifers contain considerable amounts of carbonate minerals. Dissolution of additional minerals, however, may be associated with the neutralization.

Other industries, which include barrel cleaning, coal gasification, aerospace, cement, explosives, and clothing manufacture dispose of waste in lined and unlined surface impoundments, sumps, trenches, burning pits, and active and buried landfills and tanks. The wastes include chlorinated solvents, toluene, benzene, methanol, pesticides, herbicides, arsenic, chromium, lead, other metals, and organic compounds as well as ignitable and reactive waste.

Military installations have a variety of waste-disposal areas including surface impoundments, evaporation ponds, chemical-disposal pits, landfills, and unlined beds for drying sludge from wastewater-treatment plants. The types of waste are many and include oils, solvents, paint, photographic chemicals, degreasing agents such as trichloroethylene, warfare agents such as mustard gas, drums of solid and liquid chemicals, metal-plating waste, sulfuric acid, and methylethyl ketone. Organic compounds including trichloroethylene have been detected in ground water at two of the three military installations in areas 3 and 5 (fig. 2*A*).

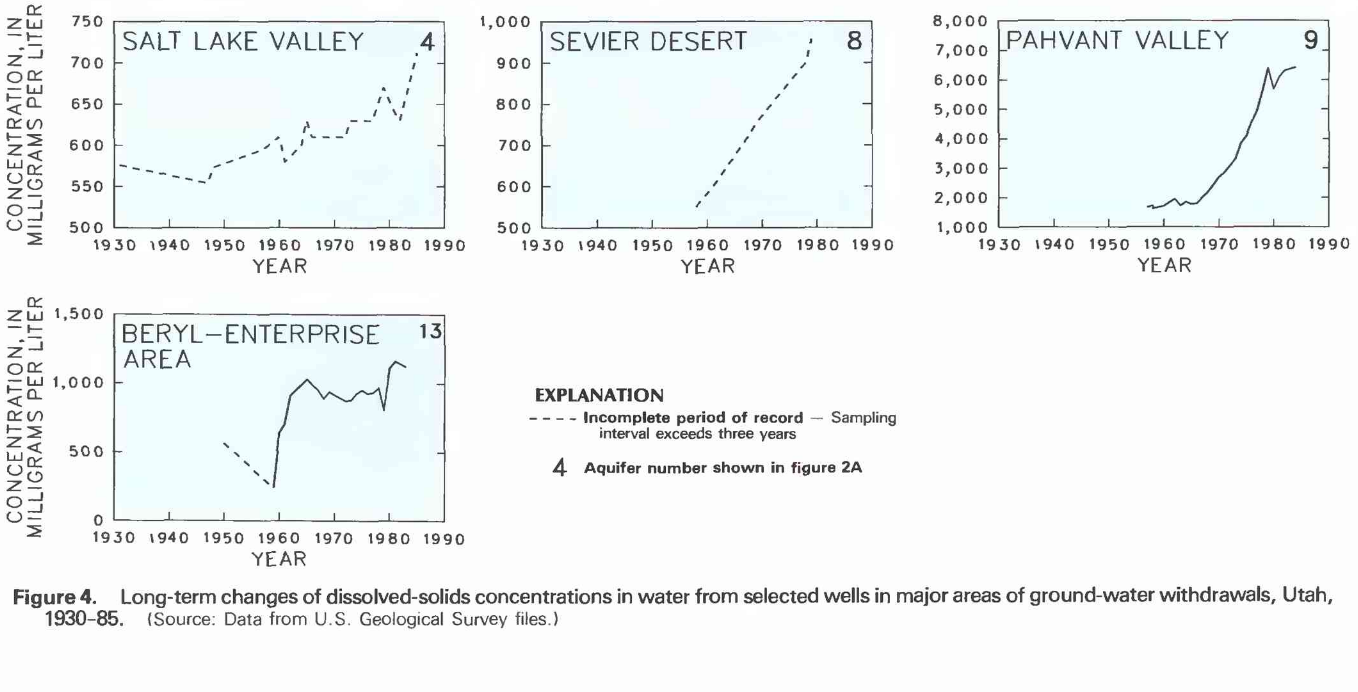

Figure 4. Long-term changes of dissolved-solids concentrations in water from selected wells in major areas of ground-water withdrawals, Utah, 1930–85. (Source: Data from U.S. Geological Survey files.)

As of September 1985, 108 hazardous-waste sites at 5 facilities in Utah had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The U.S. Environmental Protection Agency (EPA) presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 108 sites in the program, 80 sites contained contaminants but did not present a hazard to the environment. Six sites at one facility (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at two of these sites has been completed under the program. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

In addition to the disposal sites described above, Utah has more than 200 municipal and county landfills (fig. 3*C*). Except for the sites in the Salt Lake Valley (fig. 2*A*, area 4), few data have been collected to evaluate the effect of leachates from landfills on the quality of ground water. In the Salt Lake Valley, Seiler and Waddell (1984, p. 1) reported that organic chemicals were detected in water from several wells completed in the shallow, unconfined part of the aquifer; the largest concentrations were in water from wells near landfills or tailings areas. They reported concentrations of benzene, phenol, dichloroethane, and trichloroethylene that exceeded U.S. Environmental Protection Agency (1980) standards. The largest concentrations of trace metals, such as arsenic, cadmium, iron, and manganese, also were detected in water from wells near landfills and tailings areas.

One of the few commercial hazardous-waste disposal facilities in the western United States is located about 80 miles west of Salt Lake City; therefore, it is used by many hazardous-waste generators throughout the region. Virtually all the waste is transported by truck or railroad and is deposited in land-fill disposal units at the facility operated by U.S. Pollution Control, Inc.

POTENTIAL FOR WATER-QUALITY CHANGES

Changes in land-use practices in the major recharge areas for the deep, confined, basin-fill aquifers can cause changes in the quality of ground water downgradient. Although numerous organic chemicals have been reported in the shallow, unconfined part of the aquifer in Salt Lake Valley, none have been detected in the deeper part of the basin-fill aquifers. This probably is because many of the organic compounds were detected in the part of the valley where a confining or semiconfining layer separates the shallow, unconfined part of the aquifer from the deep, confined part of the aquifer (fig. 2*B*). In this area, an upward pressure gradient and the presence of clay materials probably retard the downward migration of the organic chemicals.

Like many aquifers, the deep, confined basin-fill aquifers are most susceptible to contamination in the recharge areas (fig. 2*B*). Much of the recharge to the basin-fill aquifers is by underflow from consolidated rock of the bordering mountains and by seepage from streams and irrigation near the mountains. For example, in the Salt Lake Valley (fig. 2*A*, area 4), about 50 percent of the recharge to the ground-water reservoir is seepage from the consolidated rocks of the bordering mountains and from streams where they emerge from the mountains. Thus, contamination of the water in the bordering mountains along the Wasatch Front could result in contamination of water in the deep, confined basin-fill aquifer.

Another area of large susceptibility is near the mountains where much of the recharge from seepage from streams occurs and where ground water typically occurs under unconfined conditions. In these areas, contaminants can percolate directly to the water table without appreciable impediment by fine-grained deposits. Also, the rate of ground-water movement generally is relatively faster in these areas and contributes to the potential for spread of contaminants.

Areas of substantial potential for contamination of several of the basin-fill aquifers are delineated in figure 3*B*. These areas correspond to the major recharge areas along the Wasatch Front and were delineated mostly where previous studies have defined the extent of recharge areas.

GROUND-WATER-QUALITY MANAGEMENT

On October 4, 1984, then Governor Scott M. Matheson issued an Executive Order entitled "Utah Ground-Water Policy", which stated "The quality of ground water will be protected to a degree commensurate with current and probable future uses." The policy mandated the Utah Department of Health to develop ". . . a ground-water quality strategy for the protection of present and future public and private uses." The Division of Environmental Health of the Utah Department of Health is responsible for the protection of ground-water quality and the prevention, control, and abatement of ground-water pollution. In 1986, the strategy was being developed. The strategy is planned to be anti-degradational, which means that the State will make every effort to protect the existing (1984) water quality. Three statutory committees within the Department of Health have responsibility for ground-water-quality management.

- The Water Pollution Control Committee [Utah Code Annotated, Title 26, Chapter 11 (UCA, 26–11)] is supported by the Bureau of Water Pollution Control, which has assumed delegation for the Federal Construction Grants, Underground Injection Control (in conjunction with the Utah Division of Oil, Gas, and Mining) and National Pollution Discharge Elimination System Programs. This Committee has authority to classify the waters of the State and establish quality standards to protect beneficial uses.
- The Safe Drinking Water Committee (UCA, 26–12) is supported by the Bureau of Public Water Supplies, which has assumed primacy under the Federal Safe Drinking Water Act, and has authority to adopt rules to protect watersheds and water sources used for public water systems.
- The Solid and Hazardous Waste Committee (UCA, 26–14) is supported by the Bureau of Solid and Hazardous Waste, which has assumed primacy under RCRA. In addition to administering RCRA, the Bureau of Solid and Hazardous Waste has a multisite agreement under CERCLA from EPA to conduct the following activities at various Superfund sites in Utah: preliminary assessment, site inspection, hazard-ranking scoring system, forward planning, and a remedial investigation and feasibility study.

Several remedial actions are underway or contemplated. In 1985, the State began directing relocation of 3,500,000 tons of uranium-mill tailings from the tailings site in Salt Lake Valley to two sites (fig. 1*A*) in western Utah, after successfully negotiating the $45 million project with the U.S. Department of Energy under the Uranium Mill Tailings Radiation Control Act of 1978.

The 12 local health departments in the State have authority to ". . .enforce state and local laws, regulations, and standards relating to public health and sanitation. . ." [UCA, 26–24–14(2)]. In addition, the Utah Division of Water Rights, Department of Natural Resources, ". . .has general administrative supervision of the waters of the State, . . ." (UCA, 73–2–1) and has broad authority to ". . .prevent pollution. . ." of ". . . both surface and underground water."

Information pertaining to organic contamination is needed to provide for future management of Utah's water resources, especially in the Wasatch Front area where many hazardous-waste sites are located. Plans to establish a monitoring program for sampling of organic chemicals in ground water are now being evaluated by the U.S. Geological Survey and State agencies.

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VERMONT
Ground-Water Quality

Vermont is a water-rich State, and the quality of ground water is generally suitable for human consumption and most other uses. In 1980, Vermont had a resident population of about 511,000 people in 14 counties, with populations ranging from 4,613 in Grand Isle County to 115,534 in Chittenden County (fig. 1). Ground water is the primary water supply for about 54 percent of the population. In addition, ground water is the major source of water for thousands of visitors from outside of the State. There are 527 public community wells, about 1,500 non-community public wells, and about 50,000 private water wells. Ground-water quality generally does not exceed drinking-water standards established by the Vermont Department of Health and the U.S. Environmental Protection Agency (EPA). Although all the aquifers in the State are extremely susceptible to contamination from the surface, only three public-supply wells have been removed from service since 1980.

Ground-water contamination has occurred at scattered locations throughout the State. The distribution of contamination coincides with population density. Of the 123 documented wells that yield contaminated water (11 public and 112 private), about 40 percent were contaminated with chloride or sodium; 34 percent were contaminated with synthetic organic compounds, petroleum products, or other industrial chemicals; 14 percent were contaminated with agricultural fertilizers from storage leaks, spills, or field application; and 12 percent were contaminated with bacteria. More than 6,000 people have been affected by contamination of aquifers tapped by public-supply wells and more than 300 people have been affected by contaminated private wells.

Two hazardous-waste sites in Burlington and Springfield are included on the National Priorities List (NPL) established by the U.S. Environmental Protection Agency (1986c). These Superfund sites are being evaluated and cleaned under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (U.S. Environmental Protection Agency, 1986c). The U.S. Department of Defense (DOD) has identified two hazardous-waste sites at one facility that are scheduled for confirmation studies to determine if remedial action is required (U.S. Department of Defense, 1986).

Future instances of contamination may follow the pattern of the past, but less contamination is expected because of improved techniques of solid-waste disposal, hazardous-waste storage, and increased surveillance and replacement of underground storage tanks for petroleum products. State agencies with water-related interests are aware of the importance of the ground-water resource, and several regulatory programs respond to instances of ground-water contamination. Other programs help maintain natural water quality. Aquifer protection areas have been established around more than one-half of the community public-supply wells. A recent law requires classification of ground water into one of four quality categories, with State control over certain land uses within each category. The State has not found it necessary to regulate the withdrawal, diversion, or use of ground water, and probably will not develop a program to regulate use unless the number and severity of quantity problems increase greatly.

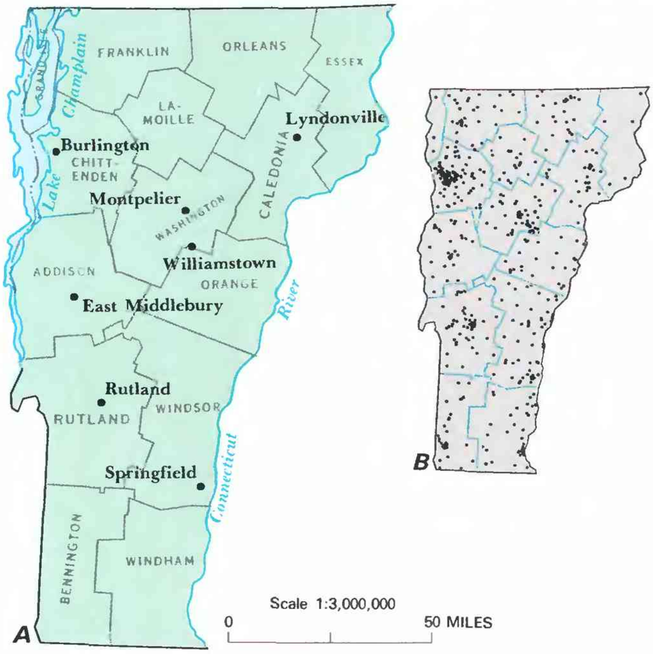

Figure 1. Selected geographic features and 1985 population distribution in Vermont. *A*, Counties, selected communities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Two types of principal aquifers are present in Vermont (fig. 2*A*1) —unconsolidated deposits and bedrock. Stratified drift forms the most productive unconsolidated aquifer; however, many rural private wells are completed in till aquifers. Although dug wells in till can yield enough water for single-family domestic needs, these aquifers may be unreliable during dry periods. Metamorphic and igneous crystalline rock and carbonate rock, which has been metamorphosed to varying degrees, form the bedrock aquifers of the State (U.S. Geological Survey, 1985, p. 421–426).

The quality of ground water in Vermont aquifers generally is suitable for most purposes, and contamination generally does not exceed the EPA primary and secondary national drinking-water standards (U.S. Environmental Protection Agency, 1986a,b). A summary of water-quality analyses from public-supply systems in the State indicated that the median pH of water from 342 public-supply systems was 7.4 (David Manning, Vermont Department of Health, written commun., 1986). The median pH of water was 7.4 in 54 wells in stratified drift, 7.5 in 229 wells in bedrock, and 6.9 in 69 springs.

Radon levels in 689 ground-water samples from 366 public-supply wells range from 0 to 14,400 pCi/L (picocuries per liter). Water samples from four bedrock wells serving one system had the only radon levels larger than 10,000 pCi/L; the next largest level was 6,200 pCi/L. The mean radon level is 1,054 pCi/L (Manning and Ladue, 1986). Presently, there are no drinking-water standards for radon levels.

Concentration of trace elements in ground-water samples from 342 public-supply systems had small values for the following constituents: arsenic, barium, cadmium, chromium, copper, fluoride, lead, mercury, selenium, and zinc (David Manning, Vermont Department of Health, written commun., 1986).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the files of the Vermont Department of Health and from the Vermont Depatment of Environmental Conservation (DEC), formerly theDepartment of Water Resources and Environmental Engineering (Stedman and others, 1980), is presented in figure 2*C*. The summary is based on hardness (as calcium carbonate), nitrate (as nitrogen), chloride, manganese, and sodium analyses of water samples collected from 1979 to 1986 from the principal aquifers in Vermont. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supplies as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable for public water supplies. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 250 mg/L chloride, and 50 μg/L (micrograms per liter) manganese.

The minimum reporting level, as used in this report, is a unique value assigned by the Vermont Department of Health. The level may be equal to or larger than the minimum detection limit, depending on the constituent.

Stratified-Drift Aquifers

Stratified-drift deposits consist of unconsolidated sand or sand and gravel. These deposits are primarily in valley lowlands throughout the State and in some interstream areas along the western side of the Green Mountains. Most of these deposits are isolated from one another.

The water was soft (hardness 0–60 mg/L as calcium carbonate) in 10 percent of the 58 analyses reviewed (fig. 2*C*, aquifer 1). Almost 40 percent of the water was moderately hard (61–120

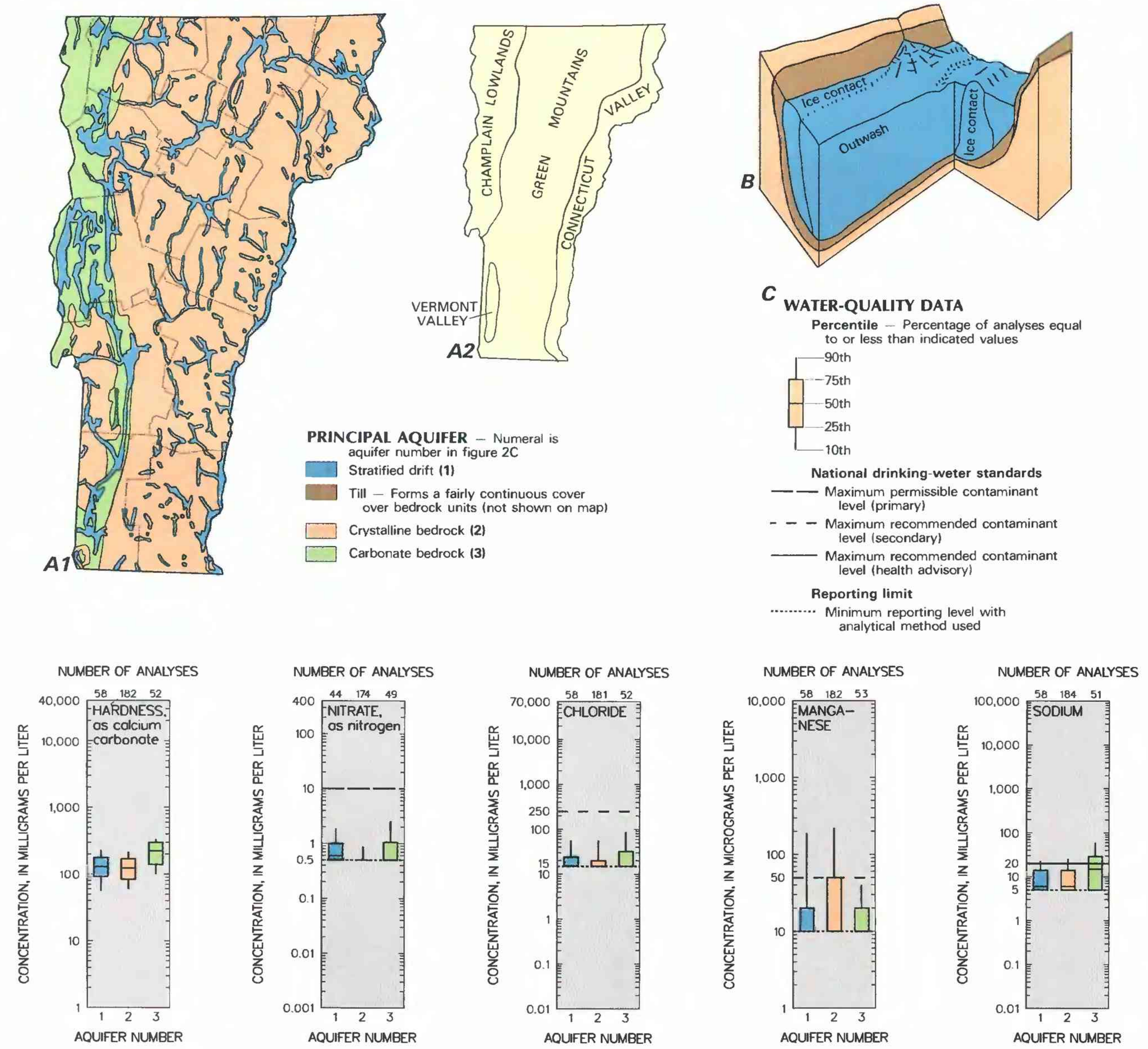

Figure 2. **Principal aquifers and related water-quality data in Vermont.** *A1*, Principal aquifers; *A2*, Physiographic diagram. *B*, Typical stratigraphic sequences of aquifer materials. *C*, Selected water-quality constituents and properties, as of 1979-86. (Sources: *A*, *B*, Compiled by R.E. Hammond and J.E. Cotton from U.S. Geological Survey files; Fenneman, 1938. *C*, Analyses compiled from the files of the Vermont Department of Health and from the Vermont Department of Environmental Conservation (Stedman and others, 1980); national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

mg/L), about 25 percent was hard (121–180 mg/L), and 25 percent was very hard (greater than 180 mg/L). Although dissolved-solids concentrations were larger than 100 mg/L in about 80 percent of the water samples, none of the samples exceeded the secondary drinking-water standard of 500 mg/L for dissolved solids.

At least 75 percent of the 58 samples had iron values at or smaller than the minimum reporting level of 100 μg/L. Iron concentrations exceeded the secondary drinking-water standard of 300 μg/L in less than 5 percent of the water samples. However, ground-water studies in some areas in Vermont indicated that elevated iron concentrations are common (Hodges and others, 1976a,b, 1977; Willey and Butterfield, 1983). At least 50 percent of the 58 water samples had manganese values smaller than the minimum reporting level of 10 μg/L (fig. 2*C*). Manganese concentrations exceeded the secondary drinking-water standard of 50 μg/L in about 15 percent of the water samples.

Combined sodium and potassium concentrations are generally smaller than 10 mg/L, except in the southwestern part of the State

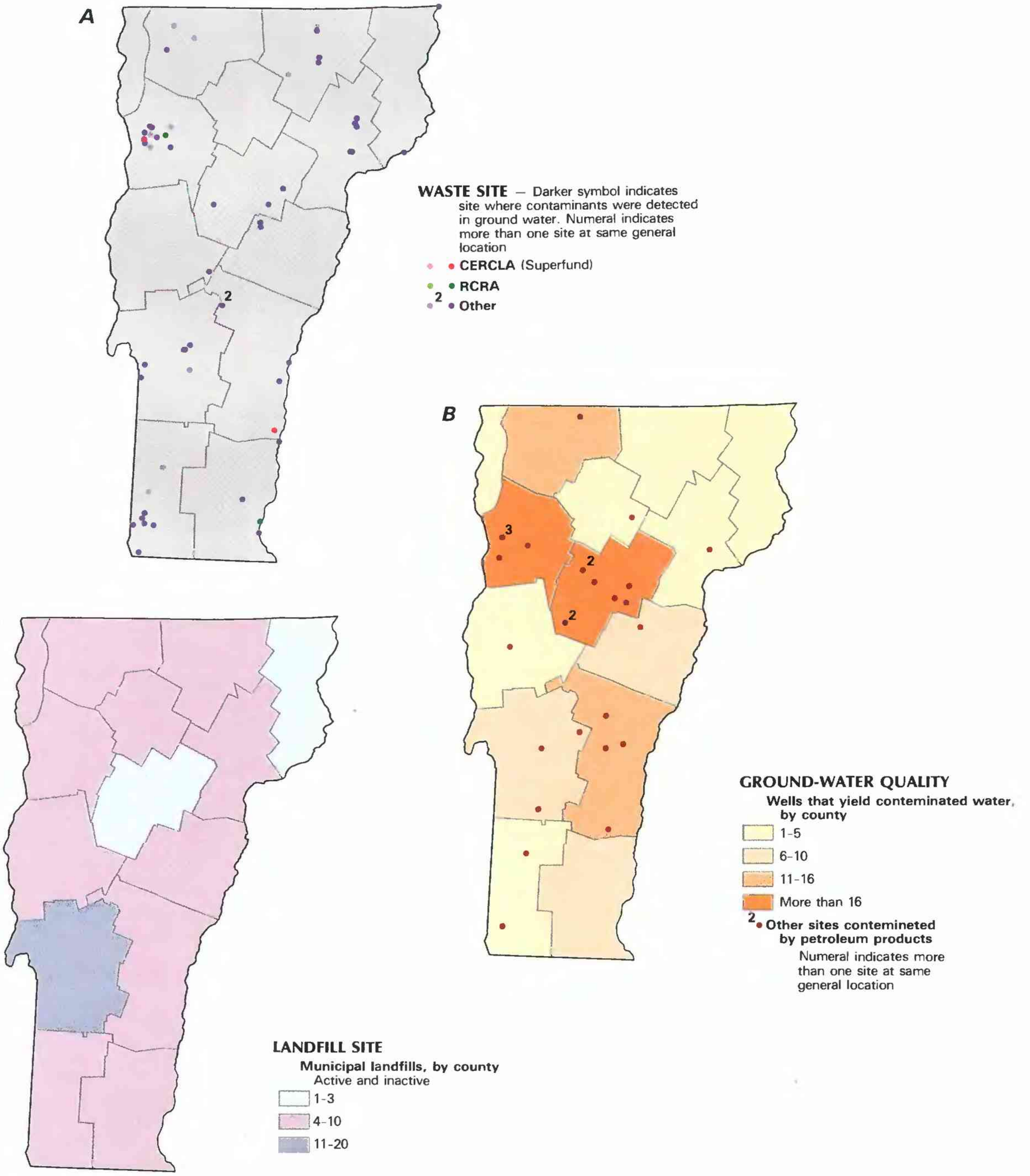

Figure 3. Selected waste sites and ground-water-quality information in Vermont. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of 1986. *B*, Wells that yield contaminated water, by county, and location of ground-water contamination resulting from spills and leaks of petroleum products, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A*, compiled from the files of Vermont Department of Environmental Conservation, Waste Management Division and Water Quality Division. *B*, compiled from the files of Vermont Department of Health and Vermont Department of Environmental Conservation; Marshfield Engineering Services, 1982. *C*, compiled from the files of Vermont Department of Environmental Conservation, Waste Management Division.)

where they range from 10 to 50 mg/L. Chloride and sulfate concentrations each were generally smaller than 25 mg/L (Pettyjohn and others, 1979). Seventy-five percent of the 58 water samples have sodium and chloride concentrations smaller than 14 and 24 mg/L, respectively (fig. 2*C*). About 50 percent of these samples have sodium and chloride concentrations at or near the Department of Health's minimum reporting levels of 5 and 15 mg/L, respectively.

The water from 44 samples had a median concentration of nitrate, as nitrogen, of 0.60 mg/L (fig. 2*C*). Ninety percent of the samples had concentrations smaller than 2.0 mg/L.

More than 70 public-supply wells are drilled in stratified-drift aquifers. Of the 29 public-supply wells that have average daily withdrawals larger than 50,000 gallons, 28 are in stratified-drift aquifers. These aquifers commonly have a saturated thickness of less than 70 feet and they are generally unconfined. Because the water table is commonly less than 30 feet deep, stratified-drift aquifers are susceptible to contamination.

Crystalline-Bedrock Aquifer

Crystalline rock units consist of metamorphic and igneous rocks that contain recoverable water only in open fractures (Doll and others, 1961). The storage capacity of these units is small and generally decreases with depth. Domestic wells that penetrate the crystalline-bedrock aquifer are commonly less than 600 feet deep and yield less than 10 gal/min (gallons per minute). In the valleys in mountainous areas, where the crystalline bedrock is extensively fractured, bedrock wells commonly yield 25 to 50 gal/min. More than 250 public-supply wells tap the crystalline-bedrock aquifer, but only 7 have been approved by the Department of Health for production greater than 100 gal/min (David Manning, Vermont Department of Health, written commun., 1986).

Water from the crystalline-bedrock aquifer had slightly less hardness than water from the stratified-drift aquifers (fig. 2*C*, aquifer 2); however, the percentages of soft, moderately hard, hard, and very hard water were approximately the same. Dissolved-solids concentrations were also a little smaller in this aquifer than in the stratified-drift aquifers.

Iron and manganese concentrations in at least 50 percent of 184 water samples were smaller than the minimum reporting levels. In 10 percent of the water samples, iron concentrations exceeded the secondary drinking-water standard of 300 μg/L; the largest concentration was 1,500 μg/L. In 25 percent of the water samples, manganese concentrations exceeded the secondary drinking-water standard of 50 μg/L; 10 percent of the water samples had manganese concentrations larger than 220 μg/L.

Sodium and chloride concentrations in water from crystalline-bedrock aquifers were similar to those in water from stratified-drift aquifers (fig. 2*C*). Seventy-five percent of the water samples from public-supply wells had sodium and chloride concentrations smaller than 14 and 20 mg/L, respectively.

Nitrate, as nitrogen, concentrations in 75 percent of the water samples were smaller than the minimum reporting level of 0.50 mg/L. Distribution of nitrate, as nitrogen, determined from analyses of 174 water samples, indicated smaller concentrations in the crystalline-bedrock aquifer than in the stratified-drift aquifers.

Carbonate-Bedrock Aquifer

The carbonate-bedrock aquifer is present in the Champlain Lowlands east of Lake Champlain and in the Vermont Valley (fig. 2*A2*, Doll and others, 1961). Rock units include limestone, dolomite, marble, and interbedded noncarbonate shale and quartzite. Domestic wells that penetrate this aquifer commonly are less than 300 feet deep and yield less than 20 gal/min. More than 60 public-supply wells tap this aquifer. Where carbonate minerals have been subjected to solution weathering along fractures, hydraulic conductivity and storage have been increased. A commercial well at the Pittsford National Fish Hatchery (Rutland County) had the largest yield; this well was pumped for 72 hours at 900 gal/min (Gary Smith, D. L. Maher Co., oral commun., 1985).

The hardness of water from the carbonate-bedrock aquifer was significantly larger than in water from the crystalline-bedrock or stratified-drift aquifers (fig. 2*C*). Nearly all the water was at least moderately hard; from 50 to 75 percent was very hard. Iron and manganese concentrations in water from this aquifer were smaller than those in water from the crystalline-bedrock aquifer, and concentrations of manganese in water from this aquifer were smaller than those in water from stratified-drift aquifers.

Sodium concentrations in water from the carbonate-bedrock aquifer were larger than in water in both the crystalline-bedrock and stratified-drift aquifers (fig. 2*C*). Chloride concentrations were smaller than the minimum reporting level of 15 mg/L in more than 50 percent of the samples, but slightly larger than those in the other two aquifers.

Nitrate, as nitrogen, concentrations were smaller than the minimum reporting level in more than 50 percent of the water samples. None of the 49 samples had concentrations that exceeded the 10-mg/L drinking-water standard.

EFFECTS OF LAND USE ON WATER QUALITY

The quality of ground water has been degraded in some areas by urbanization, waste disposal, and agricultural practices. Although the affected areas are generally small, they are widespread.

Urbanization

Degradation of ground-water quality has occurred in the most populous counties from land uses associated with urbanization. Increased concentrations of sodium and chloride occur mostly as a result of the use of highway deicing salts and sewage discharge. Petroleum contamination has been caused by leaks from underground petroleum storage tanks, and by spillage of petroleum at the surface.

Elevated concentrations of sodium and chloride occur in some areas. The source of these two constituents is usually highway deicing salts, but sewage discharge and salty backwash from water softeners are also sources. More than 10 percent of the public-supply wells yield water with sodium concentrations larger than 20 mg/L, the maximum recommended sodium concentration in drinking water for people on sodium-restricted diets. About 5 percent of the wells yield water with concentrations of chloride larger than the secondary standard of 250 mg/L.

The State and many municipalities use deicing salts, primarily sodium chloride, in the winter maintenance of roads. Although most contamination of ground water with sodium chloride has resulted from this practice, at least six instances were as a result of runoff from salt-storage areas. More than 40 of the 123 wells that tap contaminated aquifers, summarized by county in figure 3*B*, were contaminated by road salts. Eight public wells serving 1,300 people in Chittenden County were among those affected (Vermont Department of Public Health files; Marshfield Engineering Services, 1982). Since 1978 the Construction Division of the Department of Transportation has replaced more than 30 private wells that were degraded by State roadway salting (Roderick Maclay, Vermont Department of Transportation, oral commun., 1987).

By February 1986, there were 27 documented sites of contaminated ground water by petroleum leaks and spills (fig. 3*B*) (Thomas Moye, Department of Environmental Conservation, Waste Management Division, written commun., 1986). By February 1987, an additional 19 sites (not shown in figure 3*B*) had been identified (Thomas Moye, Waste Management Division, oral commun., 1987). The actual number of wells that tap aquifers contaminated

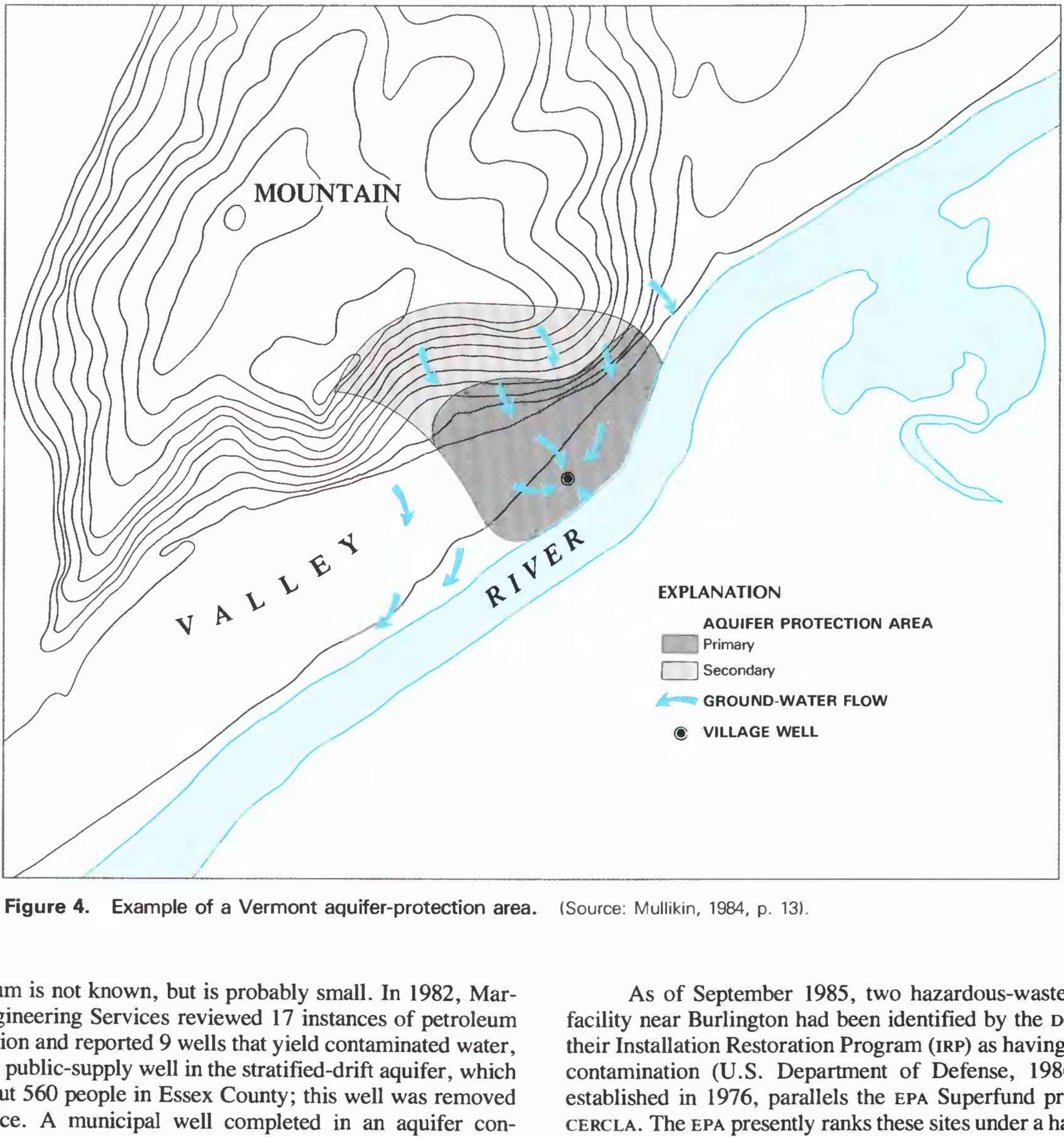

Figure 4. Example of a Vermont aquifer-protection area. (Source: Mullikin, 1984, p. 13).

by petroleum is not known, but is probably small. In 1982, Marshfield Engineering Services reviewed 17 instances of petroleum contamination and reported 9 wells that yield contaminated water, including a public-supply well in the stratified-drift aquifer, which served about 560 people in Essex County; this well was removed from service. A municipal well completed in an aquifer contaminated by petroleum in East Middlebury (Addison County) was removed from service. The Waste Management Division has identified 8,000 to 10,000 underground storage tanks for petroleum products. One-half of these are gasoline tanks with capacities greater than 1,100 gallons. These tanks are now subject to registration and testing for leaks.

Waste Disposal

Disposal of hazardous and municipal wastes has caused serious local problems with ground-water quality. State agencies also receive about 200 reports of spills of hazardous materials annually. Two hazardous-waste sites in Burlington (Chittenden County) and Springfield (Windsor County) are included on the NPL established by the EPA. These Superfund sites will be evaluated and cleaned under CERCLA (U.S. Environmental Protection Agency, 1986c). A public-supply system serves the area around the Burlington site, which was used for the disposal of coal-tar sludge; thus far, no wells have been affected. Houses have been built adjacent to the old Springfield municipal landfill, which contains industrial machine-tool wastes, including oils, solvents, and plating wastes. Several private wells and springs near this site were found to be contaminated by organic compounds and trace metals.

As of September 1985, two hazardous-waste sites at one facility near Burlington had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. These sites were scheduled for confirmation studies to determine if remedial action is required.

Ground-water contamination by hazardous wastes has occurred at 32 sites to an extent that requires assessment and monitoring under Federal guidelines. These sites are included as "other" sites in figure 3*A*. These sites represent locations identified by the Waste Management Division where hazardous materials are being used, created, or temporarily stored. Three additional sites are being monitored under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Two of these sites are shown in figure 3*A*. The third site is not shown but is close to the CERCLA site in Burlington. Organic compounds from industrial waste, mostly solvents, are the major contaminants at most of the 32 sites. Some of the more common compounds are trichloroethylene, methyl chloride, tetrachloroethylene, dichloroethylene, methylethyl ketone, methyl isobutyl ketone, carbon tetrachloride, acetone, benzene, toluene, and phenol.

The Waste Management Division has confirmed ground-water contamination at 9 additional sites and contamination is suspected at 10 other sites. These are also identified as "other" sites in figure 3*A*. Major contaminants are organic compounds and trace metals.

Vermont's most publicized case of ground-water contamination involved the release of tetrachloroethylene from an industrial uniform dry cleaning establishment in the village of Williamstown (Orange County). Cleanup efforts are being conducted and a public well downgradient from the site is being monitored.

Vermont has 69 active and 19 inactive landfills. The CERCLA site in Springfield, two of the RCRA sites, and six of the "other" sites were municipal landfills that were either publicly or privately owned. The number of all municipal landfills in each county identified by the Waste Management Division is shown in figure 3*C*. Some degradation of ground-water quality has probably occurred beneath all landfills. The extent of contamination at all of these sites is still being assessed by the Waste Management Division through a network of about 290 monitoring wells (Julie Hackbarth, Waste Management Division, oral commun., 1986). Leachate from landfills commonly adds iron, dissolved solids, nitrogen as ammonia or nitrate, and a variety of organic compounds to the ground water.

Commercial enterprises, which generate less than 100 kilograms of hazardous wastes per month, are still permitted to dispose of these wastes at certified landfills. Private household wastes, which generally include some hazardous materials, have been disposed of in all landfills.

Effluent from septic systems is known to have contaminated 13 wells and 1 spring (Marshfield Engineering Services, 1982). Large septic systems that service second-home developments and resorts and that are in the shallow soils of mountainous terrain are being monitored by the State. Backflushing of water softeners introduces chloride to septic systems and dry wells; this has resulted in contamination of aquifers, including a bedrock aquifer tapped by two wells serving a college in Orange County and a bedrock aquifer tapped by one well serving a mobile-home park in Windsor County (Marshfield Engineering Services, 1982). Discharge of wastewater to leach fields and dry wells from other facilities, such as restaurant kitchens, laboratory and industrial wastewater, printing and photography facilities, boilers, and floor residues from vehicle-repair shops have degraded ground-water quality at some sites.

Agricultural Practices

Application of chemical fertilizers has increased nitrate concentrations in aquifers in Orleans and Windsor Counties. In Orleans County, increased concentrations of nitrate in water from a well completed in the stratified-drift aquifer were first detected in 1978. By 1984, concentrations were close to the drinking-water standard of 10 mg/L. Since then, restricted use of fertilizer in cornfields during the growing season has stopped the rise in nitrate concentration. Similar, but less severe instances have been documented in Franklin and Washington Counties and in other areas of Windsor County where private wells have been affected (Marshfield Engineering Services, 1982). In addition, ground water was contaminated and the Lyndonville public-supply well in the stratified-drift aquifer was abandoned after vandals ruptured a storage tank for chemical fertilizer. This well served about 3,000 people.

Manure storage can result in ground-water contamination. In Caledonia County, the ground water was contaminated when manure was dumped directly into a gravel pit dug into the stratified-drift aquifer. In another instance, a shallow aquifer was contaminated by a nearby open silage pit (Marshfield Engineering Services, 1982).

POTENTIAL FOR WATER-QUALITY CHANGES

Changes in ground-water quality in response to potential regional human activities and long-term changes in climatic or atmospheric conditions have not been investigated. For example, acid precipitation on areas underlain by thin soils and noncalcareous bedrock with a small buffering capacity is suspected of decreasing the pH of ground water and increasing the iron and aluminum concentrations in the water.

As the population of Vermont increases, the potential for ground-water contamination also will increase. Some ground-water contamination from sources such as septic tanks and road salts will be unavoidable. However, the degree and extent of contamination from these and other sources will depend in large measure on how rigorously State and local agencies manage land-use activities. Control over the storage and disposal of hazardous wastes, such as limiting the number of new disposal sites, will decrease new instances of contamination. Alternative methods for disposing of municipal wastes, such as incineration and recycling, may further decrease contamination caused by leachate from landfills. Hydrostatic testing of and replacement schedules for underground storage tanks for petroleum products can be expected to decrease instances of petroleum leaks.

Although some changes in agricultural practices, such as application rates and times of fertilization, may decrease the amount of nutrients introduced into ground water, the use of pesticides and the level of agricultural activity throughout the State will probably be the major determinants of future effects on ground-water quality.

The designation of aquifer-protection areas by the Water Quality Division (fig. 4; David Butterfield, Vermont Department of Environmental Conservation, Ground Water Management Section, oral commun., 1986; Water Quality Division, 1983) for community public-supply wells is more than one-half complete. These areas and the new classification program should help protect water quality. Aquifer-protection ordinances incorporated into municipal master plans will attempt to assure good water quality in designated stratified-drift and bedrock aquifers (Mullikin, 1984).

GROUND-WATER-QUALITY MANAGEMENT

Vermont's regulatory agencies hope to maintain the good quality of the State's drinking-water sources by limiting those human activities that can degrade ground-water quality. The ability to protect ground-water resources was significantly strengthened in 1985 when the legislature passed Chapter 48 of Title 10 of the Vermont Statues Annotated (10 V.S.A., sections 1390 through 1410). The new law required that ground-water sources be assigned to one of four classes and provided for some State control of land uses within each class.

The Agency of Natural Resources (ANR), formerly the Agency of Environmental Conservation, is responsible for protecting the State's ground-water resources. The Department of Health is responsible for protecting drinking-water supplies. The Department of Agriculture is responsible for controlling the use of pesticides. A ground-water coordinating committee attempts to synchronize agency programs in a comprehensive statewide effort. State and local guidelines for onsite treatment of domestic wastewater are regulated by municipalities. Towns may voluntarily contract with the Vermont Association of Conservation Districts' On-Site Sewage Program (OSSP) to approve the location, review system design, and inspect installation of septic systems.

Regional Planning Commissioners may cooperate with State agencies in establishing local ground-water protection plans and ordinances. The State, assisted by the EPA, supports the New England Interstate Water Pollution Control Commission in activities that pertain to ground water.

Under the provisions of Part b of the Safe Drinking Water Act (SDWA) and Title 18 of the Vermont Statutes Annotated, the Department of Health regulates the quality of water delivered from public water-supply systems and protects ground- and surface-water sources for those systems. The Department of Environmental Conservation under the direction of the ANR, manages the Underground Water Source Protection Program (UWSPP), which is also known as the Underground Injection Control (UIC) Program. The Governor has designated the Department of Health to administer the Well-Head-Protection areas program authorized under Section 1428 of the SDWA.

The ANR, which delineates aquifer-protection areas for public water sources, has State Statutory Authority to designate Classes I, II, and IV ground waters; however, Class I designations involving private land must be approved by the State Legislature. Class III ground water is subject to regulations governing subsurface and surface waste disposal.

Classes I and II ground water are for public water-supply use, Class III is for individual domestic water supplies, and Class IV ground water may be used for some agricultural, commercial, and industrial purposes, and its quality may be less than that for potable water. The draft rules for Class IV assume that safe assimilation of most nonhazardous wastes is possible, and also assume that the best technical methods will be incorporated into specific regulatory programs.

Classes I and II will replace more than 200 aquifer-protection areas that were formerly mapped as protection areas for existing public-supply community sources (fig. 4). About nine Class I ground-water areas have been proposed for legislative approval. Within 3 years, more than 350 Class II designations are anticipated.

The State has a program under the provisions of RCRA that requires permits for the storage, treatment, transportation, and disposal of hazardous wastes. To date, no facilities for disposing of hazardous waste have been authorized within the State.

Vermont uses Sections 106, 205, and formerly used 208 funds to support its ground-water-quality management program. A study is now underway to determine the importance of septic systems as sources of nitrogen in ground water near residential developments. This study is expected to be useful in determining the optimum density of septic systems allowable within Class II ground-water areas.

Until the passage of 10 V.S.A., Chapter 48, the common-law rule of absolute ownership of the land surface (and the ground water beneath it) prevailed. Now, people who cannot use their ground water because of quality problems resulting from acts of others may take the issue to court.

Water-well drillers have been licensed since 1965, and are required to file well reports. These reports now form the largest part of the State's ground-water data base.

The State has not established a network to monitor ground-water quality statewide because existing data are assumed to be adequate to proceed with implementation of a ground-water protection program. As new data about the environment become available, the State will amend its ground-water management decisions. The State will delineate well-protection zones based on its Class I and Class II ground-water boundaries for all new public wells. The Extension Service programs of the University of Vermont and public meetings will help educate the public about the need to protect ground water.

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Vermont Department of Environmental Conservation employee Marsh Thompson obtains a water sample for chemical analysis from a monitoring well in Windsor County, Vermont, as part of an investigation of septic systems as sources of nitrogen in ground water. (Photograph by James W. Ashley, Vermont Department of Environmental Conservation.)

Prepared by John E. Cotton, U.S. Geological Survey; "Ground-Water-Quality Management" section by David Butterfield, Vermont Department of Environmental Conservation, Ground Water Management Section

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VIRGINIA
Ground-Water Quality

The quality of ground water in Virginia (fig. 1*A*) is generally good and suitable for most purposes, and the supply is generally adequate to meet current (1986) needs. Current usage (1986) is about 400 million gallons per day and continues to increase (39 percent increase from 1970 to 1980). In Virginia, 41 percent of the population (fig. 1*B*) partly or entirely depends on ground water for their water supply (T.K. Kull, U.S. Geological Survey, oral commun., 1986); for 1.5 million Virginians, ground water is the only source of water for drinking and domestic purposes (Kull, 1983).

Ground-water-quality problems can originate from natural and human-induced sources. Natural problems include radiation (particularly within the Piedmont province, fig. 2), the presence of saltwater, low pH, and increased concentrations of chemical constituents, such as dissolved solids, iron, manganese, sulfate, fluoride, and hardness. Human-induced sources of contamination, such as landfills and hazardous materials spills, may have a significant effect on the quality of ground water.

According to the Virginia Water Control Board, about 1 percent of Virginia's ground water is contaminated, primarily near intensely populated areas. A 1983 Virginia State Health Department study in 14 south-central counties found chemical or bacterial contamination in 75 percent of 200 randomly sampled wells (Robert Taylor, Virginia State Health Department, oral commun., 1986). Most contamination was caused by improper well design or maintenance. Agricultural fertilizers and pesticides, along with the application of road salts, may constitute a major source of contamination. Leaking surface impoundments, septic tanks, wood preserving operations, inadequately designed landfills, and leaking underground storage tanks also have caused ground-water contamination. The Virginia Surface Impoundment Assessment identified more than 2,000 active or abandoned waste impoundments. Waste-lagoon seepage near Danville, Virginia, may have been responsible for the presence of trichloroethylene and 1,1,1-trichloroethane in the ground water. Selenium, vanadium, and arsenic have contaminated the ground water near Chisman Creek in York County. Sulfide minerals in a waste site in Nelson County contaminated ground water and caused several fishkills. An electroplating facility in Roanoke County caused chromium contamination of the ground-water supplies of 30 families in the area. Tetrachloroethylene was found in ground water that supplied 20,000 Prince William County residents (Howard Freeland, Virginia Department of Waste Management, oral commun., 1986).

Seven facilities in Virginia (fig. 3*A*) have been included by the U.S. Environmental Protection Agency (1986c) on the National Priorities List (NPL) of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980, known as the Superfund act. Six sites are currently proposed for possible inclusion on the NPL. The contents of about 400 active and inactive municipal landfill sites are unknown. In addition, the U.S. Department of Defense (DOD) has identified 23 sites at 7 facilities where contamination has warranted remedial action. All these locations serve as a potential source of additional contamination that might be detected in future ground-water sampling programs.

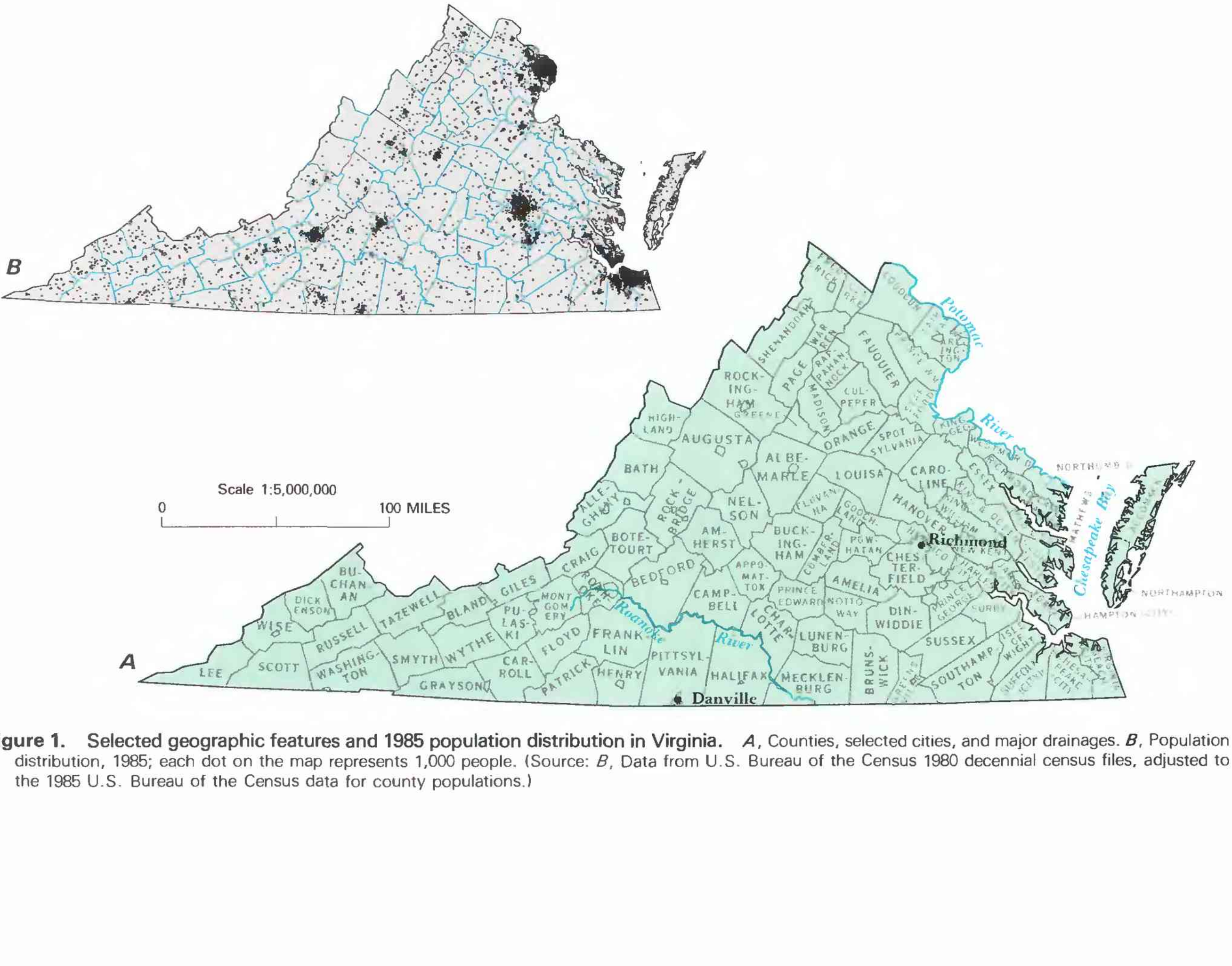

Figure 1. Selected geographic features and 1985 population distribution in Virginia. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

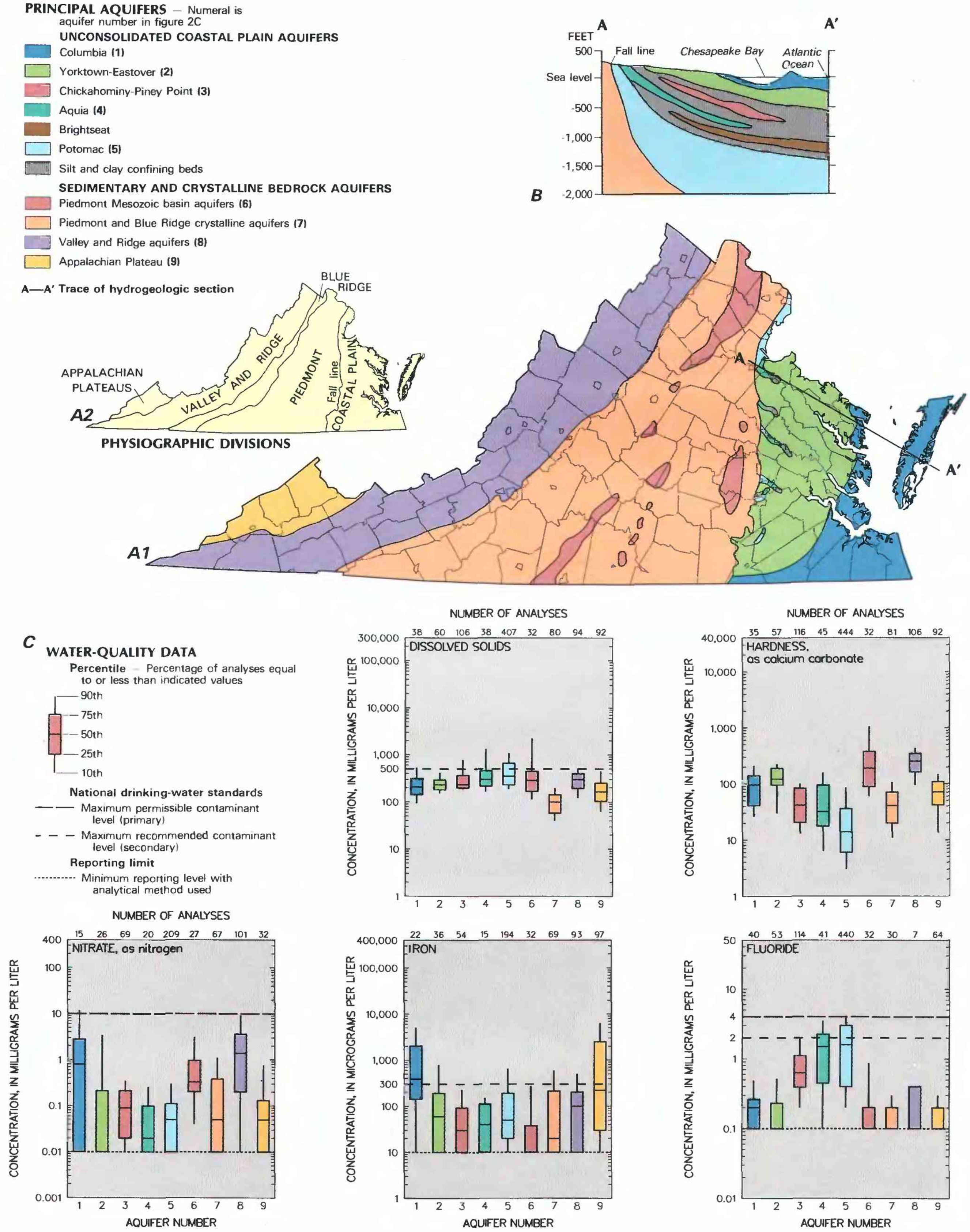

Figure 2. Principal aquifers and related water-quality data in Virginia. *A1*, Principal aquifers; *A2*, Physiographic provinces. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1965-1985. (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Data from Virginia Water Control Board and U.S. Geological Survey files; national drinking water standards from U.S. Environmental Protection Agency, 1986a,b.)

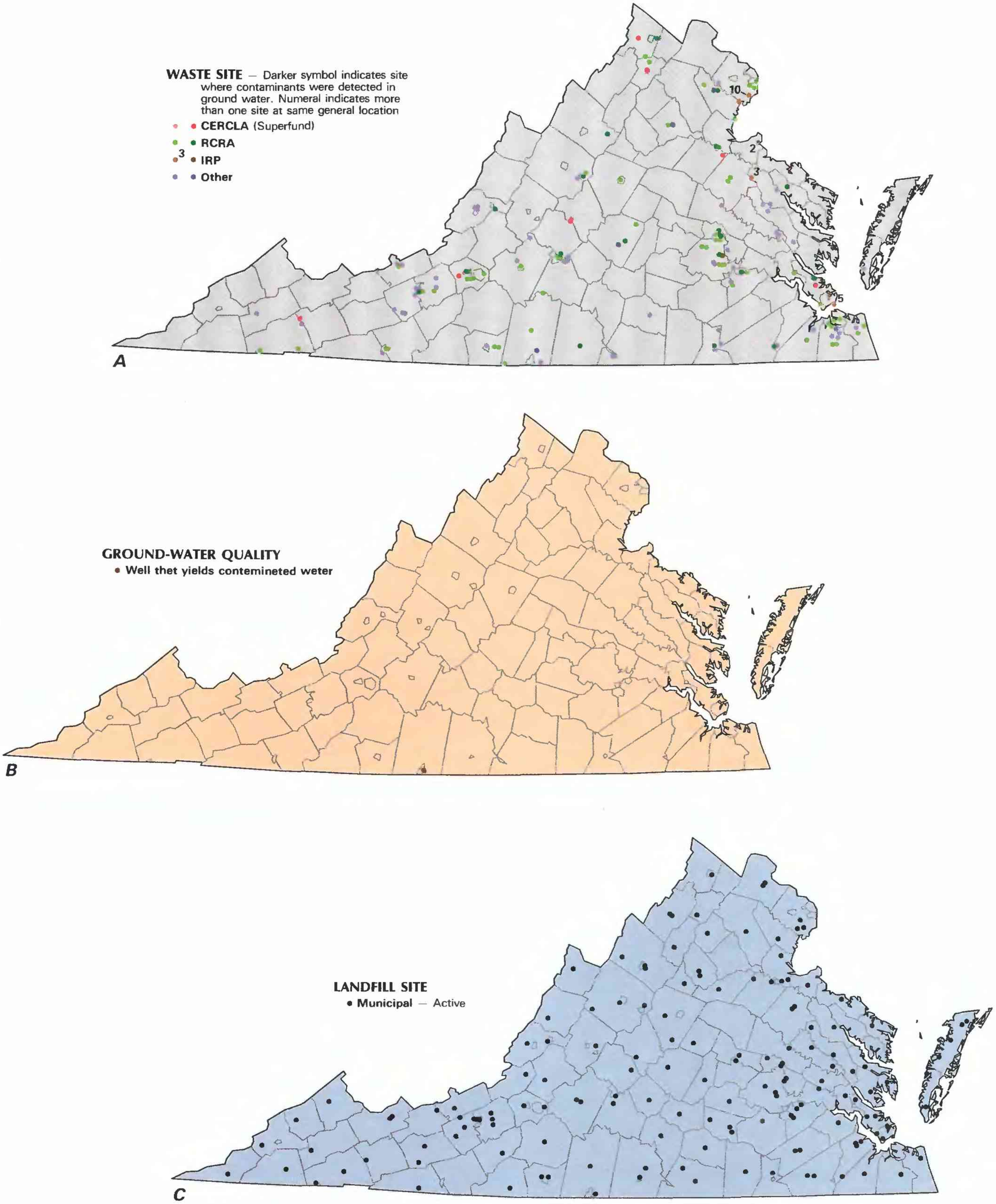

Figure 3. Selected waste sites and ground-water-quality information in Virginia. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; Department of Defense Installation Restoration Program (IRP) sites; and other selected waste sites, as of 1986. *B*, Location of wells that yield contaminated water, as of 1986. *C*, Municipal landfills, as of 1986. (Sources: *A*, Virginia Health Department, Virginia Water Control Board, and U.S. Geological Survey files; U.S. Department of Defense, 1986. *B*, *C*, Virginia Health Department, Virginia Water Control Broard, and U.S. Geological Survey files.)

WATER QUALITY IN PRINCIPAL AQUIFERS

Virginia has two principal aquifer types (fig. 2*A*)—unconsolidated Coastal Plain aquifers, and sedimentary and crystalline bedrock aquifers (U.S. Geological Survey, 1985, p. 429). Each of the principal aquifers has its attendant water-quality problems. The unconsolidated Coastal Plain aquifers include the Columbia aquifer, Yorktown-Eastover aquifer, Chickahominy-Piney Point aquifer, Aquia aquifer, Brightseat aquifer, and the Potomac aquifer (fig. 2*A,B*). The sedimentary and crystalline bedrock aquifers (fig. 2*A*) include the Piedmont Mesozoic basin aquifers, the Piedmont and Blue Ridge crystalline aquifers, the Valley and Ridge aquifers, and the Appalachian Plateau aquifers.

The unconsolidated Coastal Plain aquifers are composed of combinations of clay, silt, sand, and gravel. The uppermost aquifers in the Coastal Plain province are used primarily for domestic supply; the deeper confined aquifers are used for municipal supply.

Naturally occurring chemical constituents in Virginia's aquifers sometimes exceed the drinking-water standards set by the U.S. Environmental Protection Agency (1986a,b). Constituents most commonly with excessive concentrations are dissolved solids, iron, fluoride, chloride, and sulfate.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcuim carbonate), nitrate (as nitrogen), iron, and fluoride analyses of water samples collected from 1965 to 1985 from the principal aquifers in Virginia. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen) and 4 mg/L fluoride. The secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter) iron, and 2 mg/L fluoride.

Unconsolidated Coastal Plain Aquifers

COLUMBIA AQUIFER

The Columbia aquifer, a water-table aquifer, is used primarily for domestic and irrigation supply. It is extremely vulnerable to contamination by bacteria, fertilizers, and pesticides because it is near the surface. The water is moderately hard, with a median concentration of hardness of 96 mg/L (fig. 2*C*). The largest concentrations of nitrate in Virginia are found in this aquifer; at least 10 percent of the wells sampled (fig. 2*C*) exceeded the primary drinking-water standard of 10 mg/L nitrate (as nitrogen). The median iron concentration (390 μg/L) exceeded the secondary drinking-water standard of 300 μg/L).

YORKTOWN-EASTOVER AQUIFER

The Yorktown-Eastover aquifer is a water-table aquifer in the western Coastal Plain where it crops out (fig. 2*A*). The aquifer is confined where it underlies the Columbia aquifer and the intervening confining unit in the eastern Coastal Plain. Yields of water from wells are largest in the east, where the aquifer is used primarily for domestic and light-industrial supply. Water is hard with a median concentration of 122 mg/L. Iron exceeded the secondary drinking water standard of 300 μg/L in at least 10 percent of the wells sampled (fig. 2*C*).

CHICKAHOMINY-PINEY POINT AQUIFER

The Chickahominy-Piney Point aquifer is confined except in the western Coastal Plain where it crops out in very small areas and becomes unconfined. It is an important source of water for domestic, industrial, and public water supplies in the central Coastal Plain. Concentrations of dissolved solids larger than 500 mg/L are present in at least 10 percent of the wells sampled (fig. 2*C*). Water is generally soft, with a median hardness concentration of 42 mg/L. Concentrations of fluoride larger than 2.0 mg/L are present in at least 10 percent of the wells sampled.

AQUIA AQUIFER

The Aquia aquifer is confined except in a small outcrop area in the northwestern Coastal Plain where it is unconfined (fig. 2*B*). It is principal source of water for large industrial and public water supplies. Concentrations of dissolved solids larger than 500 mg/L are present in at least 10 percent of the wells sampled (fig. 2*C*). The water is soft, with a median hardness concentration of 32 mg/L (fig. 2*C*). Concentrations of chloride larger than 250 mg/L are present in at least 10 percent of the wells sampled. Concentrations of fluoride larger than 2.0 mg/L are found throughout the aquifer. Water in at least 25 percent of the wells sampled exceeded the secondary drinking-water standard for fluoride (fig. 2*C*).

BRIGHTSEAT AQUIFER

The Brightseat aquifer is a confined, multiaquifer unit in the north-central part of the Coastal Plain (fig. 2*B*). It is a principal source of water for industries. Available water-quality data are insufficient to characterize the quality of water in this aquifer.

POTOMAC AQUIFER

The Potomac aquifer is a confined, multiaquifer unit. It has a small outcrop area in the northwestern part of the Coastal Plain (fig. 2*B*), and it is the principal source of water for large industrial and public water-supply uses. Concentrations of dissolved solids exceeded the drinking-water standard of 500 mg/L in at least 25 percent of the wells sampled (fig. 2*C*). The water is soft, with a median hardness concentration of 14 mg/L. Concentrations of iron larger than 300 μg/L are present in more than 10 percent of the wells sampled (fig. 2*C*). Concentrations of chloride larger than 250 mg/L are present in more than 10 percent of the wells sampled. The largest concentrations of fluoride in Virginia are present in this aquifer (fig. 2*C*). Fluoride exceeded 2.0 mg/L in at least 25 percent of the wells sampled (fig. 2*C*).

Sedimentary and Crystalline Bedrock Aquifers

PIEDMONT MESOZOIC BASIN AQUIFER

The Piedmont Mesozoic basin aquifers, which are composed of sandstone, siltstone, limestone, and igneous intrusive rocks, are used for industrial, public, and domestic supply. Water from at least 20 percent of the wells sampled exceeded the secondary drinking-water standards of 500 mg/L for dissolved solids and and 250 mg/L sulfate (fig. 2*C*). The water is very hard (median concentration was 190 mg/L), and the largest concentrations of hardness in Virginia are found in these aquifers. Water from deep wells completed in this aquifer contains the largest concentrations of dissolved solids and sulfate of any Virginia aquifers.

PIEDMONT AND BLUE RIDGE CRYSTALLINE AQUIFERS

The Piedmont and Blue Ridge crystalline aquifers, which are composed of intrusive igneous and metamorphic rocks, are used primarily for domestic supply. Although water in the Piedmont and Blue Ridge crystalline aquifers is generally acidic and can leach copper and lead from pipes and plumbing connections, water from this aquifer generally had the smallest concentrations of dissolved solids of the principal aquifers of the State (fig. 2*C*). The water is generally suitable for most purposes, with differing concentrations of hardness and iron depending on the mineral composition of the host rock. The crystalline igneous and metamorphic rocks of the Piedmont and Valley and Ridge provinces have large levels of natural radiation in the ground water.

VALLEY AND RIDGE AQUIFERS

The Valley and Ridge aquifers, which are composed mainly of carbonate rocks (limestone and dolomite), are used for industrial and public water supply as well as for domestic supply. Water in the carbonate aquifers tends to be very hard (median concentration was 254 mg/L; fig. 2*C*) and large concentrations (greater than 10 mg/L) of nitrate (as nitrogen) are a concern in the Valley and Ridge aquifers.

APPALACHIAN PLATEAU AQUIFERS

The Appalachian Plateau aquifers, which are composed mainly of sandstone, siltstone, and coal, are used predominantly for domestic supply. Water in the Appalachian Plateau aquifer was moderately hard (median concentration of 72 mg/L). Appalachian Plateau aquifers tend to have large concentrations of iron (fig. 2*C*). The median iron concentration (220 μg/L) was near the secondary drinking-water standard of 300 μg/L. Concentrations exceeding the secondary drinking-water standard were found in at least 25 percent of the wells sampled.

EFFECTS OF LAND USE ON WATER QUALITY

The most widespread sources of contamination of ground water, in Virginia, are probably septic systems (nitrates and bacteria), agricultural practices (nitrates and pesticides), and improperly designed and maintained wells (bacteria). Contamination of ground water by hydrocarbon compounds and trace metals occurs primarily at wood treatment plants, textile plants, leaking underground storage tanks, and inadequately designed and maintained landfills. Hydrocarbon compounds, because of their carcinogenic nature, are of great concern, although contamination by these compounds is generally local.

In Virginia, 912 sites require permitting according to the Resource Conservation and Recovery Act (RCRA) of 1976, which regulates the generation, transport, storage, treatment, or disposal of hazardous materials. Seventy-eight of these RCRA sites (fig. 3*A*) are locations where hazardous materials are stored, treated, or disposed. These facilities are widely distributed throughout Virginia and have potential to affect ground water. Nineteen of the RCRA sites are undergoing assessment monitoring and are shown as contaminated sites in figure 3*A*.

Seven locations where ground-water contamination has been detected have been included by the U.S. Environmental Protection Agency (EPA) on the NPL of CERCLA known as "Superfund" (fig. 3*A*). Three sites are located in the Valley and Ridge aquifers (Frederick, Roanoke, and Smyth Counties) where wastes have contaminated the ground water with hydrocarbons, dissolved chromium, and mercury, respectively. Two sites are located in the Piedmont and Blue Ridge crystalline aquifers (Nelson and Warren Counties) where sulfide minerals in a waste site have contaminated the ground water and caused several fishkills at the former, and synthetic organic compounds have contaminated the ground water at the latter. Two sites are located in an unconsolidated Coastal Plain aquifer where vanadium, selenium, and arsenic have leaked into the ground water from landfills along Chisman Creek (York County) and organic compounds have contaminated the ground water in Spotsylvania County.

Human-induced sources of potential ground-water contamination exist throughout Virginia; however, only 10 wells to date (1986) have been condemned by the Virginia Health Department (R. Taylor, Virginia Health Department, oral commun., 1986). These wells, which are located in the Piedmont and Blue Ridge crystalline aquifers (fig. 3*B*) near Danville, Virginia, were contaminated by trichloroethylene and 1,1,1 trichloroethane. Many additional wells in Virginia may have been affected by contamination, but wells commonly are abandoned by the owner without notifying the Health Department.

As of September 1985, 112 hazardous-waste sites at 17 facilities in Virginia had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 112 sites in the program, 16 sites contained contaminants but did not present a hazard to the environment. Twenty-three sites at 7 facilities (fig. 3*A*) were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at five of these sites has been completed under the program. The remaining sites were schedule for confirmation studies to determine if remedial action is required.

POTENTIAL FOR WATER-QUALITY CHANGES

Degradation of ground water in Virginia has been associated with leaking underground petroleum storage tanks; surface impoundments used to store, treat, and recycle waste products; septic tanks and associated drainfields; poorly constructed wells; improper use and inadequate design of landfills; and agricultural use of fertilizers and pesticides. According to Virginia Water Control Board data, complaints about ground water related to gasoline or petroleum contamination from leaking underground storage tanks, increased from about 13 in 1979 to more than 120 in 1985. The actual number and locations of all such contamination sites are unknown, and collectively, these may be one of the greatest threats to ground-water quality in Virginia.

Surface impoundments containing hazardous materials also pose a contamination threat to ground water. Surface impoundments have caused ground-water-quality problems near wood-treatment and textile-manufacturing plants. Inadequate design and use of landfills have resulted in the presence of metals and organic compounds in ground water. About 400 active and inactive landfill sites are distributed throughout the State; each site is a potential source of contamination to Virginia's ground water. The approximate locations of active municipal landfills are shown in figure 3*C*.

Effluent from domestic septic systems, along with improperly designed wells, is thought to be a major threat to the local ground-water quality in rural areas. Nitrate contamination, derived from feedlots, fertilization practices, or animal waste disposal, continues to threaten the quality of the shallow ground-water system, particularly in the Coastal Plain and Valley and Ridge provinces. Although there is an effort in Virginia to prevent further contamination of ground water, many instances of contamination resulting from past practices probably remain to be discovered.

The potential for ground-water contamination differs with local geology. Of particular concern are the carbonate aquifers of the Valley and Ridge province, which are very susceptible to contamination. In this area, thin soil coverings are insufficient to filter infiltrating water, and sinkholes facilitate rapid recharge of surface water to ground water. Recharge areas of major aquifers of the Coastal Plain (fig. 2*B*), which occur along the Fall Line near major metropolitan areas, are vulnerable to contamination caused by the handling and disposal of hazardous materials associated with industry.

In some instances, the continued withdrawal of ground water has apparently resulted in lateral and vertical movement of poor-quality water into potable water suplies. There is a large potential for encroachment of salty ground water into the shallow freshwater system near coastal communities in this manner.

GROUND-WATER-QUALITY MANAGEMENT

The Virginia Constitution states that it is the policy of the Commonwealth of Virginia to protect Virginia's water resources from pollution, impairment, or destruction, for the benefit, enjoyment, and general welfare of the people. To accomplish this goal, the General Assembly of Virginia passed the State Water Control Law of 1946, which established the Virginia Water Control Board (VWCB). The VWCB has the responsibility to supervise and control the quality of Virginia's surface water and ground water and to enforce and administer the State Water Control Law. The Groundwater Act of 1973, amended in 1986, authorized the VWCB to establish ground-water management areas to more closely regulate ground-water withdrawal in large areas where ground water is a major water-supply source. Ground-water withdrawals in excess of 300,000 gallons per month require a permit. The two management areas established to date are located in southeastern Virginia and on the eastern shore of Virginia. The 1973 Act also authorized the Virginia Department of Health to protect the State's groundwater resources from contamination by hazardous and solid waste. The responsibility for this mission was moved to the Virginia Department of Waste Management on July 1, 1986. This agency works in close cooperation with the VWCB and the EPA.

Federal statutes involved in protecting Virginia's groundwater resources include the Safe Drinking Water Act of 1974, CERCLA of 1980, the RCRA of 1976, the Toxic Substance Control Act of 1976, the Clean Water Act of 1977, the Federal Insecticide, Fungicide and Rodenticide Act of 1972, the Underground Storage Tank Act of 1984, and Surface Mining Control and Reclamation Act of 1977.

Virginia's ground-water protection policy is based on a philosophy of non-degradation. The VWCB maintains a statewide ground-water-monitoring network of wells sampled each month. In addition, wells along the lower Chesapeake Bay and Atlantic Ocean are monitored for intrusion of saltwater into Coastal Plain aquifers. The U.S. Geological Survey contributes to the water-quality data base through various regional hydrologic studies within Virginia.

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WASHINGTON
Ground-Water Quality

During 1980, about 49 percent (2,014,000 people) of Washington's population used ground water for domestic needs (adjusted for population increase from 1975, after Dion and Lum, 1977). About 21 percent (873,000) of the State's population were rural residents, who depended on ground water from private wells. Nine counties, mostly in eastern Washington (fig. 1), depend solely on ground water to supply all domestic needs.

In general, ground water in Washington is of good quality and suitable for most uses (Barrett, 1986). Median concentrations of dissolved solids and nitrate (as nitrogen) in ground water from nine aquifers (fig. 2) did not exceed national drinking-water standards established by the U.S. Environmental Protection Agency (EPA) (1986a,b). In the Puget Sound area and in southwestern Washington, the suitability of ground water is affected locally by concentrations of naturally occurring iron and manganese (Ebbert and Payne, 1985; Turney, 1986a,), which may exceed national drinking-water standards.

Degradation of water quality due to urbanization, and agriculture, and industrial practices is occurring in densely populated areas (fig. 1*B*) and in some rural areas of the State. In northwestern Washington, the population of San Juan County has nearly doubled since 1974, and that of Island County has increased by 50 percent. Increased ground-water withdrawals associated with coastal development in these and other coastal counties may result in additional occurrences of localized saltwater intrusion. Agricultural effects on ground water include nitrate and pesticide contamination, which is occurring in parts of the Columbia Plateau and western Washington. Within the Hanford nuclear site in Franklin County, south-central Washington, industrial activities have resulted in contamination of the ground water by nitrate in concentrations as much as 226 mg/L (milligrams per liter), and tritium more than 300 pCi/mL (picocuries per milliliter).

Nineteen sites in Washington are on the National Priorities List (NPL) established by the U.S. Environmental Protection Agency (1986c) for hazardous-waste clean-up under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 (fig. 3). Ground-water contamination has been detected at 16 of these CERCLA (Superfund) sites. In addition to the CERCLA sites, 25 hazardous-waste sites (fig. 3) are being monitored or evaluated under the Federal Resource Conservation and Recovery Act (RCRA) of 1976. Contamination of the ground water is known at nine of these RCRA sites. Also, the U.S. Department of Defense has identified 104 sites at 7 facilities as having potential for contamination.

WATER QUALITY IN PRINCIPAL AQUIFERS

Three principal aquifers are found in Washington (fig. 2*A*1); glacial-drift, terrace and valley-fill, and Columbia River basalt. Based on geographic boundaries within the State (fig 2*A*2) and geologic characteristics of the aquifers, the three principal aquifers have been subdivided into nine aquifers (Ebbert and Payne, 1985; Bortleson and Cox, 1987). The glacial-drift aquifer includes the Northeast and Puget Sound glacial-drift aquifers, and the Columbia Plateau unconsolidated aquifer. The Columbia Plateau unconsolidated aquifer includes the chemically similar glacial-drift and terrace and valley-fill aquifers (Turney, 1986b,c). The terrace and valley-fill aquifer includes the Mary's Corner, Vancouver, and Olympic Peninsula terrace and valley-fill aquifers (Molenaar and others, 1980). The Columbia River basalt aquifer includes the Saddle Mountains, Wanapum, and Grande Ronde basalt aquifers (U.S. Geological Survey, 1985, p. 433).

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on sodium-adsorption ratios (SAR), dissolved solids, hardness (as calcium carbonate), nitrate (as nitrogen), and iron analyses of water samples collected from 1960 to 1985 from the nine aquifers in Washington. Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water

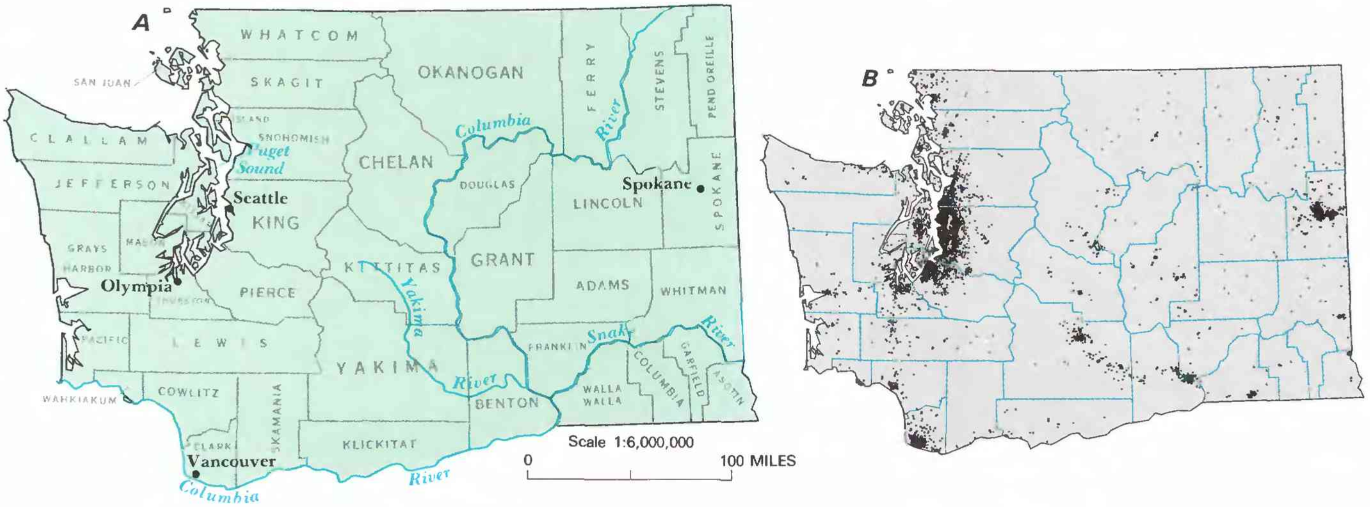

Figure 1. Selected geographic features and 1985 population distribution in Washington. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids and 300 µg/L (micrograms per liter) iron.

Sodium-Adsorption Ratio

The sodium-adsorption ratio (SAR) is one method used to evaluate the suitability of water for irrigation use (U.S. Department of Agriculture, 1954). The SAR is the tendency of a water to replace exchangeable, adsorbed calcium and magnesium ions with sodium ions. If the exchange positions in the soil become saturated with sodium, the soil will tend to become deflocculated, impermeable to water, and difficult to cultivate (Hem, 1985).

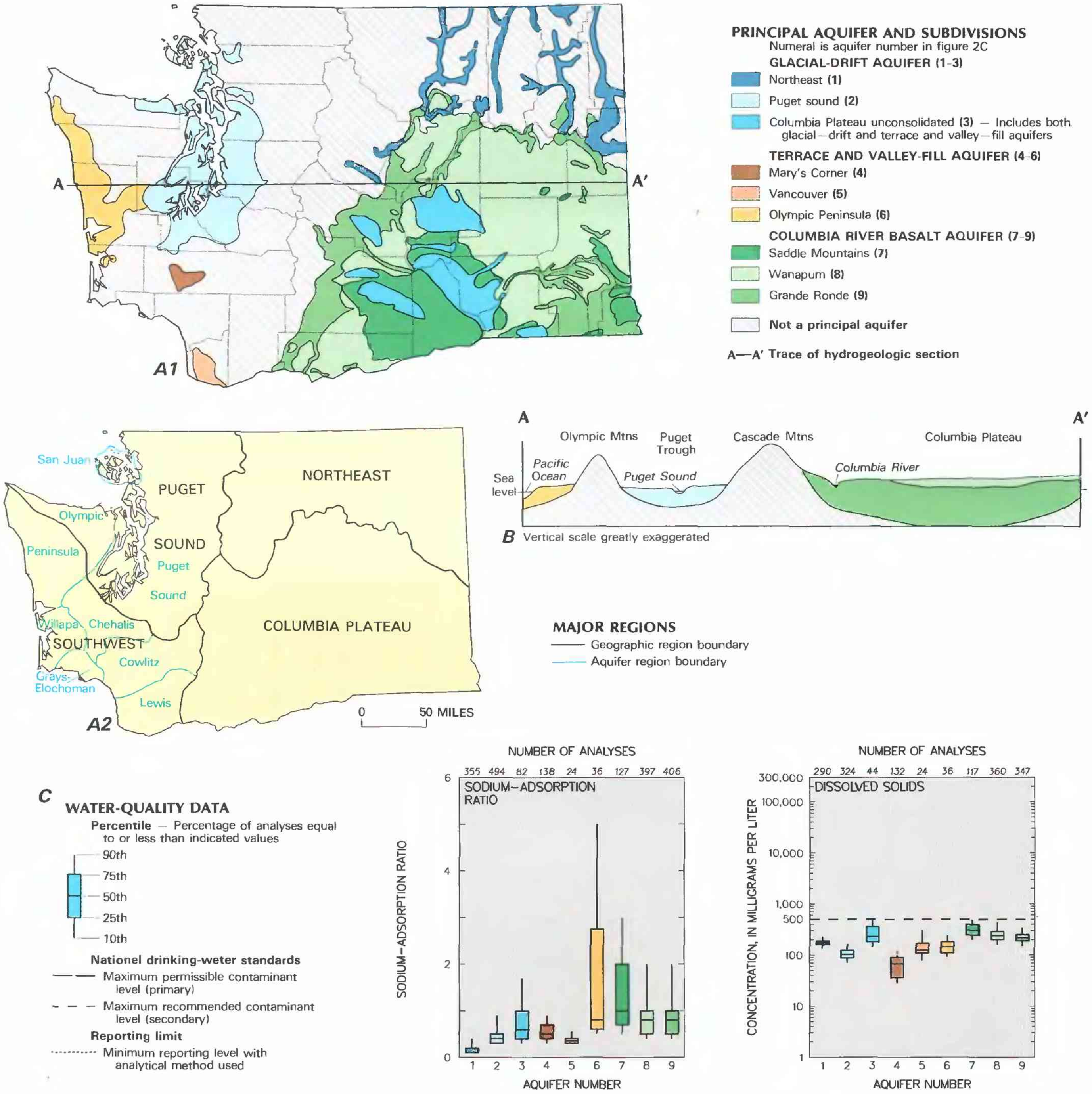

Figure 2. Principal aquifers and related water-quality data in Washington. *A1*, Principal aquifers; *A2*, Major geographic and aquifer-region boundaries; *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1960-85. (Sources: *A1*, U.S. Geological Survey, 1985, p. 433. *A2*, Molenaar and others, 1980. *B*, U.S. Geological Survey, 1985, p. 433; Bortleson and Cox, 1987. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

For waters of medium salinity (where specific conductance ranges from 250 to 750 microsiemens per centimeter at 25° Celsius), SAR values less than about 8 reflect a low sodium hazard; between about 8 and 14, a medium hazard; and more than 14, a high sodium hazard.

The median SAR for the nine aquifers was equal to or less than 1.0 (fig.2*C*), indicating that water from these aquifers most likely is suitable for irrigation. In water from the Northeast glacial-drift aquifer and the Columbia River basalts aquifer, SAR values as large as 23 and 26, respectively, were found. For the basalt aquifers in general, most of the larger SAR values (larger than 8) are located in discharge areas near major streams and in pumping centers within the central part of the Columbia Plateau (Bortleson and Cox, 1987).

Dissolved Solids

Median concentrations of dissolved solids for the nine aquifers were less than 320 mg/L (fig. 2*C*). The smallest median concentration of dissolved solids (68 mg/L) was in the Mary's Corner terrace and valley-fill aquifer; the largest median concentrations (219 to 310 mg/L) were from water in the Columbia Plateau unconsolidated aquifer and in the Saddle Mountains, Wanapum, and Grande Ronde basalt aquifers. Aquifers in the Columbia Plateau area supply all or most of the domestic drinking water and some water for irrigation. The EPA secondary drinking water standard for dissolved solids of 500 mg/L is occasionally exceeded in water from individual wells in the Columbia Plateau area.

Hardness

Hardness is caused primarily by calcium and magnesium in water; however, iron, manganese, and strontium can contribute to hardness. Median concentrations of hardness were less than 60 mg/L (soft) in water from the Puget Sound glacial-drift aquifer, and the Mary's Corner and Olympic Peninsula terrace and valley-fill aquifers; less than 120 mg/L (moderately hard) in water from the Vancouver terrace and valley-fill aquifer and the Grande Ronde basalt aquifer; and less than 180 mg/L (hard) in water from the Northeast glacial-drift aquifer, the Columbia Plateau unconsolidated aquifer, and the Saddle Mountains and Wanapum basalt aquifers.

Nitrate

Median nitrate concentrations were less than 2.0 mg/L for all the unconsolidated aquifers; however, an occasional sample from the Columbia Plateau unconsolidated aquifer and the Mary's Corner terrace and valley-fill aquifer exceeded the EPA primary drinking-water standard of 10 mg/L. Water from the Wanapum basalt aquifer had the largest median nitrate concentration of 2.1 mg/L (fig. 2*C*). Maximum concentrations for the three basalt aquifers ranged from 15 mg/L in the Grande Ronde to 54 mg/L in the Saddle Mountains. Large concentrations of nitrate are probably a result of the agricultural activities (primarily fertilizer application) on the Columbia Plateau (Turney, 1986b).

Iron

Concentrations of dissolved iron and manganese that exceed EPA secondary drinking-water standards are common throughout southwestern Washington and the Puget Sound area (Ebbert and Payne, 1985; Turney, 1986;) and probably reflect natural conditions (Turney, 1986a). Median concentrations of dissolved iron were 40 μg/L in the Puget Sound glacial-drift aquifer and 90 μg/L in the Olympic Peninsula terrace and valley-fill aquifer (fig. 2*C*). A concentration of 31,000 μg/L from a well in the Puget Sound glacial-drift aquifer was the maximum for all nine aquifers; the second largest concentration was 10,000 μg/L from a well finished in the the Grande Ronde basalt aquifer.

EFFECTS OF LAND USE ON WATER QUALITY

Degradation of ground-water quality has occurred from urbanization, agriculture, industry, waste disposal, and from intrusion of saltwater along the coast associated with ground-water withdrawals.

Urbanization

Urbanization in Washington has been accompanied by the use of septic systems for sanitary-waste disposal. For instance, between 1970 and 1980, the population in central Pierce County increased by about 22,000 people, with an additional transient military population of almost 30,000. This growth was accompanied by a deterioration of ground-water quality in the area (Littler and Aden, 1980; Littler and others, 1981). Littler and others (1981) determined that concentrations of nitrate, chloride, and bacteria increased over time, and they identified septic systems as one of the principal causes of ground-water contamination.

The location of wells and areas with known ground-water contamination by one or more constituents—including dissolved solids, nitrate, chloride, trace metals, and pesticides—are shown in figure 3*B*. Nitrate concentrations that exceed the EPA primary drinking-water standard have been reported for several wells in populated areas near the confluence of the Columbia and Snake Rivers (John Aden, Washington State Department of Social and Health Services, written commun., 1986). Nitrate concentrations in water from many of these wells were 20 mg/L or more. Large

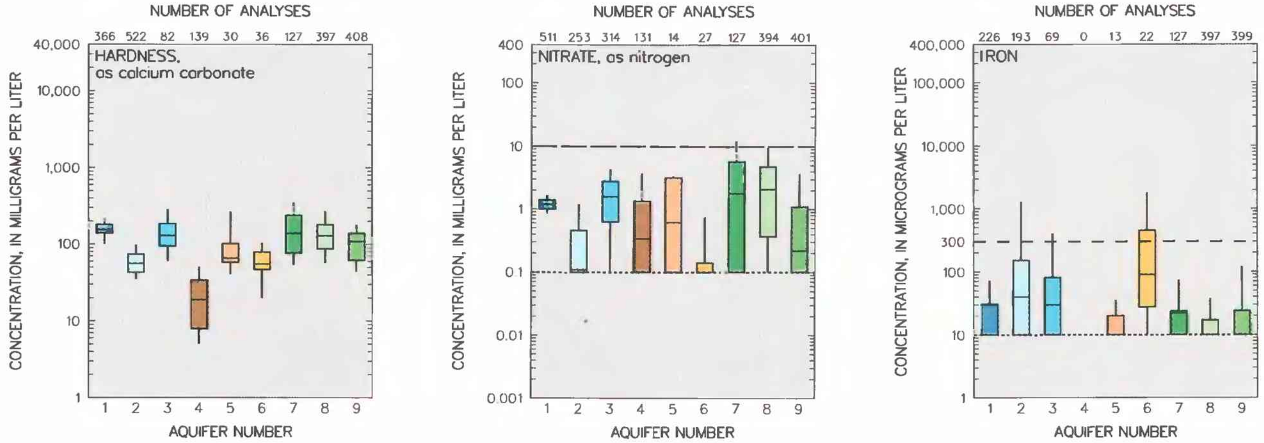

Figure 2. Principal aquifers and related water-quality data in Washington—Continued.

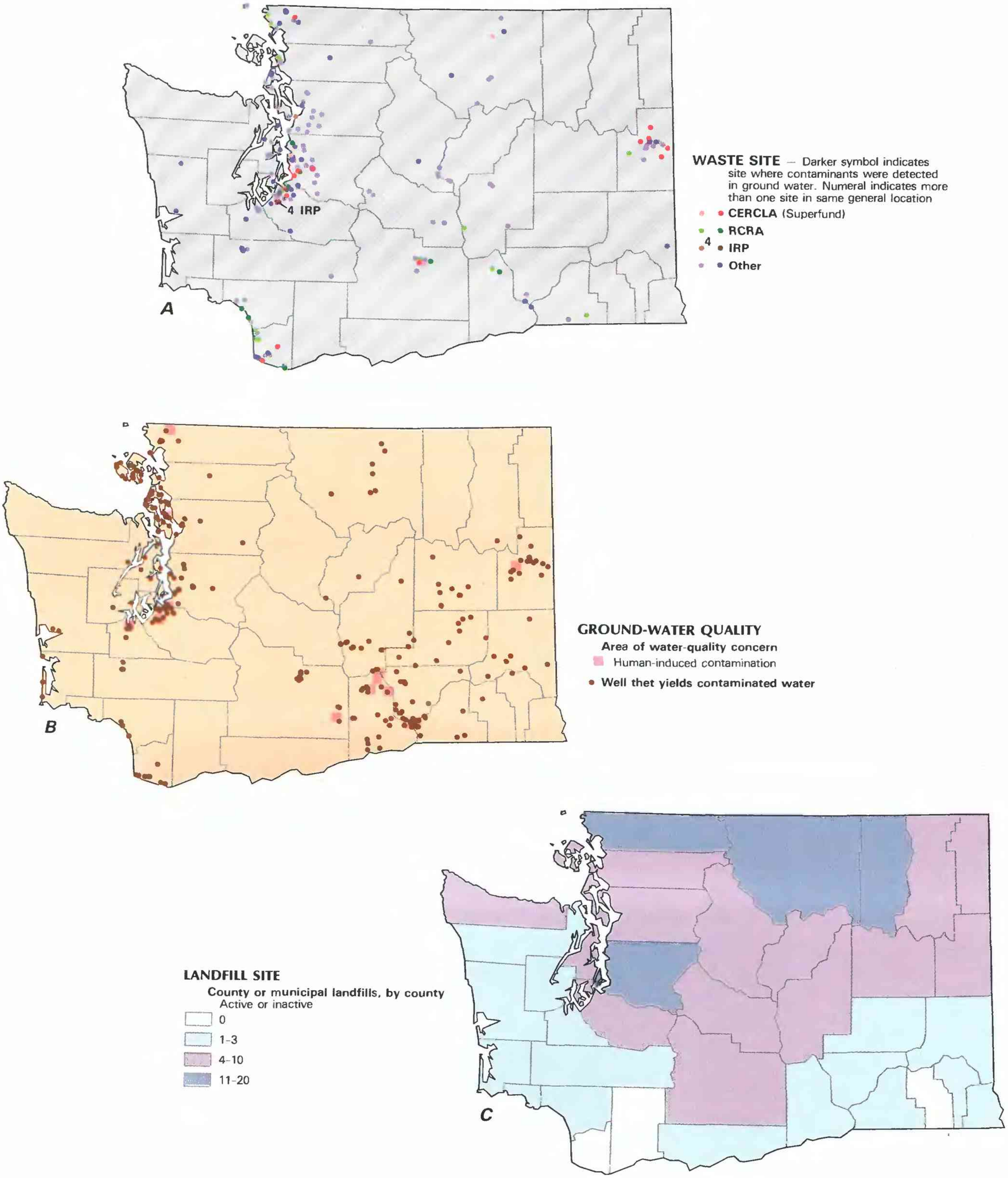

Figure 3. Selected waste sites and ground-water-quality information in Washington. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of human-induced contamination and distribution of wells that yield contaminated water, as of 1975. *C*, County and municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, written commun., 1986; U.S. Department of Defense, 1986. *B*, Prater and others, 1984; Washington State Department of Ecology, written commun., 1986; Washington State Department of Social and Health Services, written commun., 1986; U.S. Environmental Protection Agency, written commun., 1986. *C*, Washington State Department of Ecology, written commun., 1986.)

concentrations of nitrate in these areas are suspected to result from the use of septic systems (Brown, 1979).

Recreational and residential development of the numerous islands in Puget Sound and along Pacific Ocean beaches has resulted in increased populations and corresponding greater demands on ground-water supplies. The population of San Juan County, for instance, increased from 4,500 in 1975 to 8,700 in 1983. Increases in the population of Island County and of coastal Pacific County also were large for the same time period. Dion and Sumioka (1984) described several areas of severe, but localized, saltwater intrusion within several coastal counties. Increased ground-water withdrawals or the installation of additional large-capacity wells in some areas of San Juan and Island Counties could result in additional occurrences of saltwater intrusion (Whiteman and others, 1983; Jones, 1985).

Agricultural Practices

Irrigation of increasingly large areas of the Columbia Plateau (about 1.5 million acres in 1982) using ground water and surface water from the Columbia, Yakima, and Snake Rivers, has occurred since the 1950's. Between 1954 and 1982, the area of irrigated land increased by 819,000 acres; of that amount, 311,000 acres (38 percent) had been added since 1974 (U.S. Department of Commerce, Bureau of the Census, 1982). Irrigated acreage in Adams, Benton, and Franklin Counties increased by more than 43,000 acres each from 1954 to 1982, but the largest addition was 104,000 acres in Grant County, which by 1982 had a total of 397,000 irrigated acres. Ground water pumped from deep basalt aquifers in the central part of the Columbia Plateau has caused soil-dispersion problems due to large SAR values. Large nitrate concentrations in several domestic and public-supply wells in rural areas throughout the Columbia Plateau have been associated with long-term application of fertilizers. Ground-water-quality problems in the Columbia River basalt and Columbia Plateau unconsolidated aquifers are complicated by excessively high water levels. These high water levels are caused by surface-water irrigation recharging the aquifers (Brown, 1979). Ground water in these areas may be subject to contamination where the aquifer is exposed at the land surface or by interception and inundation of septic systems.

Ethylene dibromide (EDB) has been used in Washington as a soil fumigant to protect strawberries, raspberries, and seed potatoes from nematodes. Several wells in berry-producing areas in Whatcom, Skagit, and Thurston Counties tap aquifers contaminated with this pesticide. Ten public water-supply and three private wells had EDB concentrations that exceeded levels considered safe (0.02 μg/L) by the Washington State Department of Social and Health Services (1985) for long-term ingestion.

Industrial Activities

Drost and Seitz (1978) list several instances of documented contamination of ground water in the Northeast glacial-drift aquifer near Spokane. Large chloride concentrations near the Spokane Industrial Park and an aluminum plant near Spokane were noted, and in 1975, a large concentration of phenol (15 mg/L) was reported in a well within the Spokane Industrial Park.

During monitoring efforts in the Spokane area between 1980 and 1982, the organic solvents 1,1,1-trichloroethane, trichloroethylene, tetrachloroethylene, and other organic chemicals, were found individually or together on separate occasions in five public-supply wells, one private well, and one industrial well (John Aden, Washington State Department of Social and Health Services, written commun., 1986). Concentrations as large as 62 μg/L for 1,1,1-trichloroethane, 14 μg/L for trichloroethylene, and 83 μg/L for tetrachloroethylene were measured in water samples collected during 1981.

Operations at the Hanford nuclear site in Franklin County have discharged large volumes of process cooling water and other wastewaters onto the land surface. Areas of large tritium and nitrate concentrations at the site have been detected, and the migration of the constituents has been mapped as part of the Ground-Water Surveillance Program (Prater and others, 1984). The report states that plumes of tritium and nitrate in the unconfined ground water are moving generally eastward from locations within the site and are entering the Columbia River through springs and subsurface flow. Tritium has been detected in concentrations exceeding 300 pCi/mL in wells within two plumes. Areas of large nitrate concentrations (greater than 10 mg/L) generally corresponded to areas where tritium concentrations exceed 30 pCi/mL. Two monitoring wells in the northern part of the site had average nitrate concentrations of 226 and 86 mg/L during the 1983 study (Prater and others, 1984).

Waste Disposal and Hazardous Materials

During 1984, more than 91 percent of all hazardous wastes generated in Washington came from four counties; Spokane County ranked first in tons of waste generated, followed in order by Pierce, King, and Cowlitz Counties. The generated tonnage reported for Spokane County is large because the waste generated primarily is contaminated industrial wastewater, which is relatively heavy. About 66 percent of all hazardous wastes in the State were treated by chemical methods; 11 percent were disposed into surface impoundments for liquid wastes or in landfills; and the remaining 23 percent were stored (Kruger, 1986).

Hazardous waste is stored or treated at 25 RCRA sites that are monitored for their impact on ground-water quality (fig. 3*A*). At nine of these sites, the Washington Department of Ecology has detected onsite ground-water contamination. An additional 19 CERCLA sites in Washington associated with hazardous materials from industrial, waste-disposal, and agricultural activities, are included on the EPA's National Priorities List (NPL) for cleanup of contaminants under the "Superfund" program. Nine sites, including military installations, have been proposed for addition to the NPL. Ground-water contamination has been detected at 16 of the 19 CERCLA sites (fig. 3*A*). The State maintains its own list of priority cleanup sites in addition to the EPA's list, and in July 1986, an additional 132 sites were proposed for the State's list. The nine proposed CERCLA and the 132 State priority sites are shown in figure 3*A* as "other" sites. Ground-water-quality problems evident at these sites include pesticides and petrochemicals, especially near gasoline leaks and spills.

Six municipal landfills are among the 19 CERCLA sites (fig. 3*A*). Five are located in Spokane County, and one is in King County. Contaminants found in landfills include lead, cyanide, and various synthetic organic solvents, such as acetone and methylene chloride. Disposal or storage sites that have received industrial wastes have had synthetic organic chemicals, especially solvents; trace metals, such as lead and chromium; and other chemicals, such as arsenic and cyanide detected in the ground water near them. Six of the nine sites proposed for the CERCLA program are located within military installations. Several types of contaminants, including trace metals, trichloroethylene, and synthetic organic chemicals related to deactivated explosives, have been detected in ground water near five of these installations.

As of September 1985, 104 hazardous-waste sites at seven facilities in Washington had been identified by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under CERCLA. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 104 sites in the program, 2 sites contained contaminants but did not present a hazard to the environment. Six sites at three facilities were considered to present a hazard significant enough to warrant response action in accordance with CERCLA. Remedial action at one of these sites has been completed under the program. The remaining five sites at two facilities (fig. 3*A*) were scheduled for confirmation studies to determine if remedial action is required.

About 160 municipal and county sanitary landfill and waste-disposal sites exist in Washington (fig. 3*C*). Except for the landfills designated as CERCLA sites, little or no monitoring of ground water has been done to provide information on potential or existing contamination. As of May 1986, 55 of these landfills were closed or scheduled to be closed (Washington State Department of Ecology, written commun., 1986).

POTENTIAL WATER-QUALITY CHANGES

Future degradation of ground-water quality may occur as a result of population increase and land-use activities. Urban and industrial development between Spokane and Coeur d'Alene, Idaho, may subject the Northeast glacial-drift aquifer near Spokane to contaminants originating at or near the land surface, (Drost and Seitz, 1978; John Aden, Washington State Department of Social and Health Services, written commun., 1986). Present (1986) development in San Juan, Island, Pacific, and Kitsap Counties and the effect on ground-water resources indicate the vulnerability of coastal aquifers to saltwater intrusion. Contamination of the shallow aquifer, such as has occurred in Kitsap County (Tracy and Dion, 1976) and near a hazardous-waste site in King County, probably will continue under the present methods of waste-management and disposal. The Washington Department of Ecology has compiled a list of 551 sites that are known to contain, or are suspected to contain hazardous wastes. The number of these sites has been increasing by about one to two per month (Barrett, 1986).

In the Columbia Plateau, shallow aquifers are recharged with water containing nutrients, pesticides, and other agricultural chemicals applied to irrigated fields. The extent of pesticide contamination is not yet known. However, because of the incidence of nitrate contamination, it is suspected that significant quantities of these organic chemicals have passed from the land surface into the shallow aquifers (Cohen and others, 1984).

GROUND-WATER-QUALITY MANAGEMENT

In Washington, protection of ground-water resources is the responsibility of the Washington State Department of Ecology (WDOE) and the Washington State Department of Social and Health Services (DSHS). Based on Chapter 90.44 of the Revised Code of Washington, WDOE is responsible for administering all ground water in the State, including water rights, and regulating all well drilling and construction. Chapter 90.48 of the Revised Code designates the WDOE to administer the State's water-pollution-control statutes governing general water-pollution control, including mining and oil and gas activities. The Underground Injection Control provisions of the Federal Safe Drinking Water Act (SDWA) and any ground-water provisions of the Federal Clean Water Act (CWA) are overseen by WDOE. The DSHS is responsible for regulating public-water systems, enforcing all laws for the protection of public health, and for administering the drinking-water protection aspects of the SDWA.

The Hazardous Waste Disposal Act (Chapter 70.105 Revised Code) assigns the WDOE to administer the Federal Resource Conservation and Recovery Act of 1976. This act emphasizes ground-water protection through adequate treatment and disposal of wastes and through issuance of permits, and compliance monitoring. It also provides for remedial actions, including CERCLA sites.

The Northeast glacial-drift aquifer near Spokane and the Puget Sound glacial-drift aquifer on Whidbey and Camano Islands are designated as sole-source aquifers to provide special protection of a drinking-water source. Under Section 208 of the CWA, a management plan was implemented for the Spokane aquifer.

Funding provided under Section 205 of the CWA has allowed studies to address the identification of sites of potential pollution, the development of monitoring programs for the two sole-source aquifer areas, and the establishment of the relation between land-use activities and ground-water quality in a Pierce County basin. The WDOE and the State, under Section 205, are developing a nondegradation ground-water-quality management strategy. The goal of the strategy is "to maintain high quality for all waters of the State, allowing no reduction in water quality, except in overriding consideration of public interest. No reduction would be allowed to affect adversely the ability to use that water for its intended beneficial use." It is the State's goal that implementation of the strategy will provide for the development of statewide standards for ground-water quality, including an aquifer-classification system, and will develop and support protection and management programs, including a comprehensive monitoring program to verify progress toward achieving water-quality goals.

State legislation in 1984 and 1985 permits local governments to deal effectively with ground-water quality and protection, provides means to finance aquifer protection through fees, and directs the WDOE to establish guidance and technical-assistance programs. The State House Bill 865 (1985 session) addition to Title 70 of the Revised Code created a hazardous-substance information and education office at the WDOE.

Historical analytical data for ground-water quality are limited except for conventional inorganic chemicals and bacteria. The expense and difficulty of analyzing for organic chemicals remains a problem. The State is evaluating various approaches to monitoring for and assessing ground-water contamination. Even at sites with a significant contamination potential, there appears to be limited monitoring (Barrett, 1986), and many contamination incidents in Washington were first reported by citizens who suspected that their well water was contaminated.

Implementation of the State's nondegradation policy of the ground-water-quality management strategy presently is limited to determining when, where, and how much degradation is allowable on a case-by-case basis. The policy does not provide guidance to determine what is in the public interest, nor to determine allowable levels of contamination (Barrett, 1986). These limitations and the lack of adequate information on organic contamination of ground water tend to inhibit the development of an effective management strategy for the protection of ground water.

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Part of the Spokane valley in eastern Washington. Commercial, residential, and industrial development has occurred directly over the central part of the sole-source Spokane aquifer where ground-water contamination has been documented (Drost and Seitz, 1978; John Aden, Washington State Department of Social and Health Services, written commun., 1986). (Photograph by S.S. Embrey, U.S. Geological Survey.)

Prepared by S.S. Embrey

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WEST VIRGINIA
Ground-Water Quality

The water supply for about 53 percent of West Virginia's population (fig. 1) is derived from ground-water sources—wells, springs, coal mines, and limestone mines. Although most of the urban areas obtain water for public supply from streams, 90 percent of the rural population depends on ground water for domestic use. Estimated average withdrawal of ground water during 1985 was 58.1 Mgal/d (million gallons per day) for public and self-supplied domestic use, 33.5 Mgal/d for industrial use, and 16.2 Mgal/d for agricultural use (K.E. Suder, West Virginia Geological and Economic Survey, oral commun., 1987). More than one-half of all ground water used for public supply requires treatment to meet the national drinking-water standards established by the U.S. Environmental Protection Agency (1986a,b). Concentrations of iron and manganese in ground water commonly exceed the secondary drinking-water standards of 300 µg/L (micrograms per liter) and 50 µg/L, respectively. Ground water in most of the State does not exceed the primary and secondary drinking-water standards of 10 mg/L (milligrams per liter) for nitrate (as nitrogen) and 500 mg/L for dissolved solids. Nitrate plus nitrate concentrations exceed 10 mg/L, most commonly, in ground water from limestone regions in the eastern part of the State, from alluvial aquifers (fig. 2) in areas of intensive agricultural use, and near reclaimed coal mines.

Ground-water quality has been degraded throughout the State as a result of coal mining, oil and gas drilling, and improper disposal of domestic and industrial wastes (fig. 3*B*). Site investigations, conducted by the West Virginia Department of Natural Resources (WVDNR), are continuing to identify additional areas of ground-water contamination. These areas typically are related to old industrial waste-disposal sites, many of which were never formally designated as disposal sites.

The Federal Resource Conservation and Recovery Act (RCRA) of 1976 requires monitoring of ground-water quality at 24 facilities in West Virginia, where hazardous wastes are disposed or treated. Contamination of ground water has been detected at 19 of the 24 RCRA sites (fig. 3*A*). Five sites, including two RCRA sites, were included on the National Priorities List (NPL) of hazardous-waste sites by the U.S. Environmental Protection Agency (1986c). Evaluation of these Superfund sites is required under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980. Ground-water contamination has been detected at all five of these CERCLA sites.

In 1941, the U.S. Geological Survey, in cooperation with the West Virginia Geological and Economic Survey, established a ground-water observation network. The primary emphasis of this program has been the monitoring of water-level fluctuations; however, in 1984, collection of water-quality data was begun with the intent of sampling at 3-year intervals. Because the incorporation of water-quality data collection into the network is new, information about water-quality trends is not available.

WATER QUALITY IN PRINCIPAL AQUIFERS

There are two major types of aquifers in West Virginia—unconsolidated alluvial deposits and sedimentary bedrock. Major alluvial deposits are located along the Ohio and Kanawha Rivers and in the Teays Valley (fig. 1*A*). The maximum thickness of alluvial deposits is about 100 feet along the Ohio River and 70 feet along the Kanawha River and in the Teays Valley. Other alluvial deposits of limited extent are located along streams throughout the State. Maximum thickness of these minor deposits typically does not exceed 30 feet. About 55 percent of all ground water used for public supply is from alluvial deposits along the Ohio River.

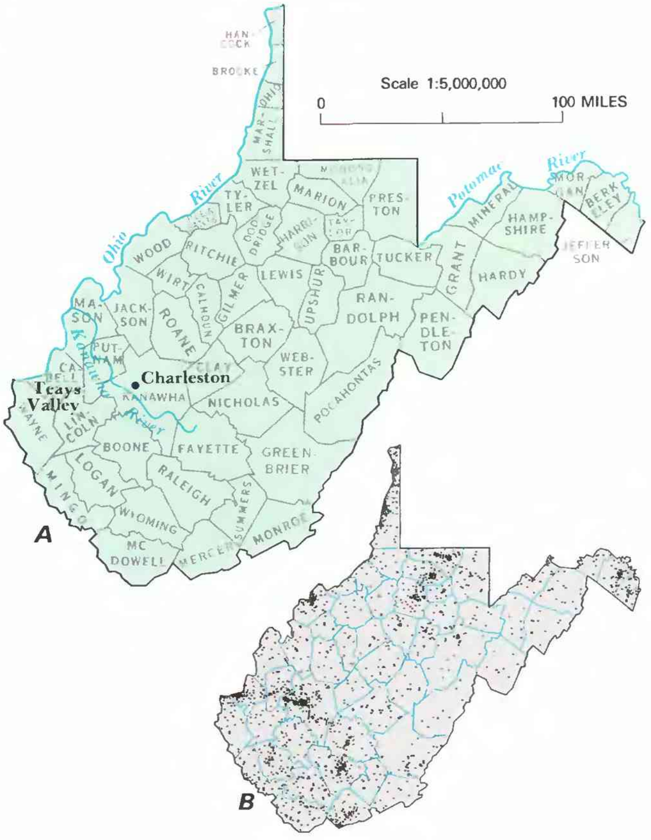

Figure 1. Selected geographic features and 1985 population distribution in West Virginia. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985, each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

The bedrock-aquifer system is typically composed of alternating layers of sedimentary rocks such as sandstone, siltstone, shale, limestone, and, in units of Pennsylvanian age, coal (Puente, 1985). Because of the vertical differences in lithology, aquifer units have been designated by geologic age rather than by lithologic composition. Movement of ground water in these rocks primarily is through fractures, bedding-plane separations, and, in limestone areas, solution openings. Coal mines, both active and abandoned, are an important source of water in the sedimentary bedrock. In 1980, about 70 public-supply systems obtained more than 7 Mgal/d from coal mines to serve about 82,000 individual and commercial users (Lessing and Hobba, 1981). Abandoned mines are commonly used for individual water supplies, particularly in the low-sulfur coal fields located in the southern part of the State. In the eastern part of the State, springs and flooded limestone mines are used for public and individual water supplies.

The topography of West Virginia is primarily mountainous. Little flat land is present except in river valleys and on some

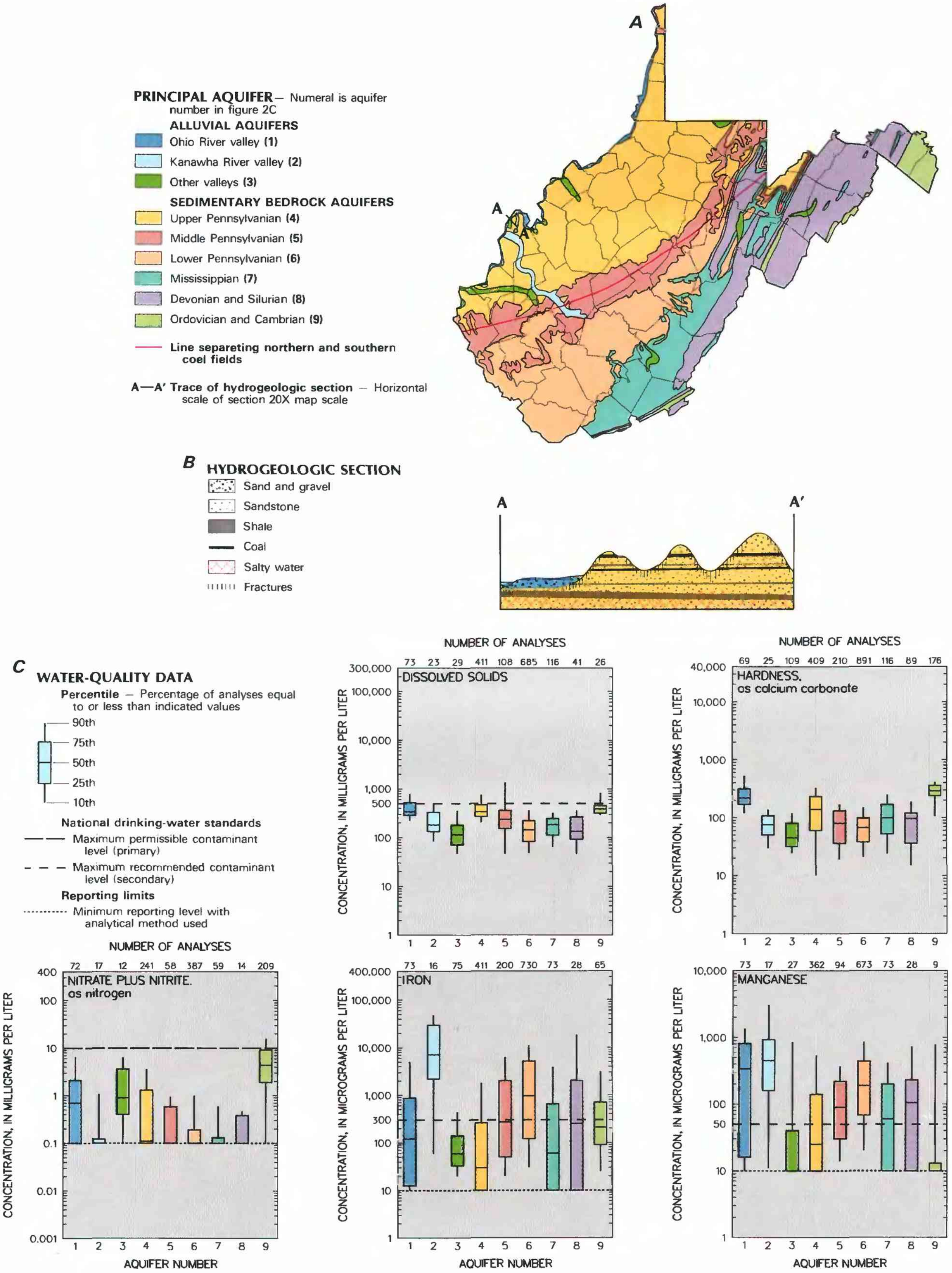

Figure 2. Principal aquifer groups and related water-quality data in West Virginia. *A*, Principal aquifer groups. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1950–85 (Sources: *A*, *B*, Modified from Puente, 1985, and Cardwell and others, 1968. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986a,b.)

ridgetops. In much of the State, topography affects the shallow ground-water flow path. Although recharge occurs at all topographic settings, the flow of ground water typically is toward valleys, resulting in the youngest ground water being from hilltop wells and the oldest ground water being from valley wells. Differences in this pattern occur primarily in steeply folded rocks in the eastern part of the State and in limestone areas where the relationship of recharge and discharge areas is more complex.

Because of chemical changes that occur as ground water percolates downward into valleys or flows laterally to hillside seeps and springs, the chemical composition of ground water tends to differ with respect to topography. These differences are governed by the type and solubility of the rocks the water contacts, the length of time it is in contact with a particular type of rock, and the chemical properties of the water itself. Examples of the differences in ground-water quality that occur with respect to topography are shown in figure 4.

Concentrations of iron and manganese in rocks of Pennsylvanian age generally are larger in ground water from valley settings than in ground water from hilltop settings (fig. 4). Where limestone is common, such as in the Upper Pennsylvanian aquifers, hardness is largest in hilltop settings and smallest in valley settings. In contrast, the sodium concentration of ground water is largest in valley settings and smallest in hilltop settings. The relation between hardness and sodium content primarily is the result of sodium-calcium ion exchange, a softening process that occurs as calcium ions are exchanged for sodium ions in clays as ground water percolates through, or flows along, clay layers. Because of differences

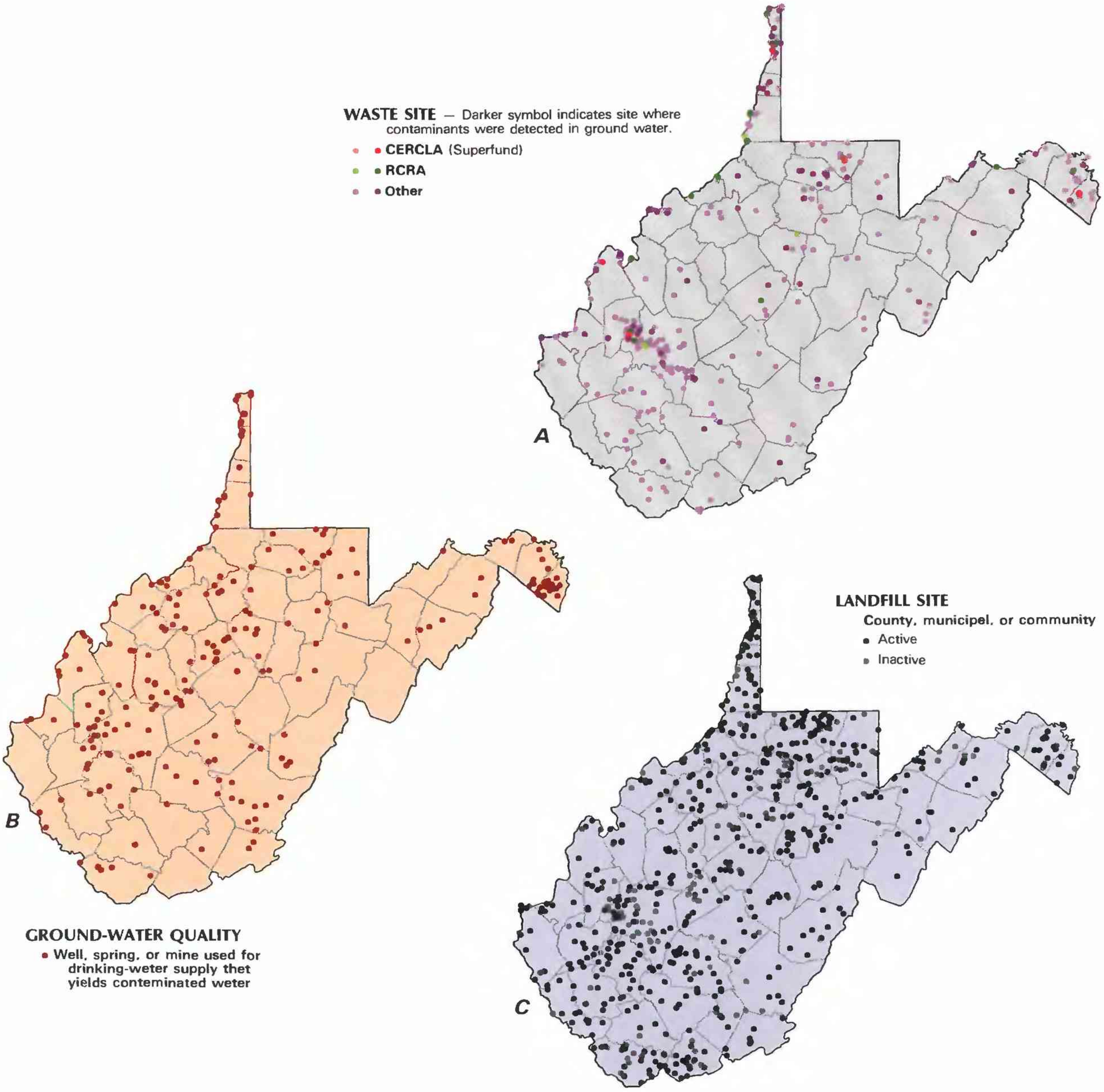

Figure 3. Selected waste sites and ground-water-quality information in West Virginia. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and other selected waste sites, as of December 1986. *B*, Distribution of wells that yield contaminated water, springs, and mine-water supplies, as of October 1986. *C*, County, municipal, and community landfills, as of December 1986. (Sources: U.S. Geological Survey, West Virginia Department of Natural Resources files, West Virginia Department of Agriculture files, and West Virginia Department of Health (1981).)

with respect to topography, the chemical quality of water in the bedrock aquifers cannot be easily mapped on an areal basis. Wells in one topographic setting may yield water of a chemical quality very different from water in nearby wells in another topographic setting.

BACKGROUND WATER QUALITY

A graphic summary of data collected by the U.S. Geological Survey from 1950 to 1985 (fig. 2*C*) for dissolved solids, hardness (as calcium carbonate), nitrate plus nitrite (as nitrogen), iron, and manganese characterizes the variability of the chemical quality of water from alluvial and bedrock wells. Statistical computations of the percentiles were made without regard to the depth at which the sample was obtained within a given aquifer unit. Where more than one analysis was available, median values were used. Most of the data were collected as part of reconnaissance studies to describe general water resources.

Percentiles of these constituents are compared to national standards that specify the maximum acceptable concentration of a contaminant in drinking-water supplies as established by the U.S. Environmental Protection Agency (1986a,b). National drinking-water standards are classified as either primary or secondary. Primary standards are established on the basis of health-related effects and are legally enforceable. Secondary standards apply to esthetic qualities of water and are recommended guidelines. Primary drinking-water standards include maximum concentrations of 10 mg/L nitrate (as nitrogen) and 4 mg/L fluoride. Secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L iron, 50 μg/L manganese, and 2 mg/L fluoride. State drinking-water standards (West Virginia State Board of Health, 1981) are similar to national drinking-water standards.

Alluvial Aquifers

Alluvial aquifers are divided into three categories: deposits found along the Ohio River, deposits found along the Kanawha River, and other alluvial deposits including those along the Teays Valley. Chemical characteristics of water from these three aquifer groups are distinctly different. Water from alluvium along the Ohio River is very hard with a median hardness of 220 mg/L. The median concentration of manganese is 340 μg/L, which exceeds the 50 μg/L secondary drinking-water standard. In water from alluvium along the Kanawha River, median values for iron (7,200 μg/L) and manganese (450 μg/L) exceed the drinking-water standards. Water from alluvial deposits other than along the Ohio and Kanawha Rivers commonly does not exceed the drinking-water standards. Differences in the chemical quality of the water from the three alluvial aquifers appear to be related to ground-water flow patterns as well as to mineral differences in alluvial materials.

Sedimentary Bedrock Aquifers

The median values of manganese in water from the sedimentary bedrock exceed drinking-water standards in all aquifer groups except the Upper Pennsylvanian aquifers and the Cambrian and Ordovician aquifers. The median iron concentration of water from the Lower Pennsylvanian aquifers also exceeds the drinking-water standard. Manganese and iron in concentrations exceeding the drinking-water standards may cause staining of plumbing fixtures and laundry. Calcium and magnesium, which contribute to hardness, are constituents of the more soluble minerals found in the rocks of the State. These elements are particularly common in limestone. As a result, aquifers that contain large amounts of limestone yield water with larger hardness and dissolved solids than the aquifers having less limestone.

The median value for nitrate plus nitrite (as nitrogen) is smaller than 10 mg/L in all aquifers. This limit is exceeded in water from only a few wells—those located primarily in areas underlain by limestone and in agricultural areas. Data from the West Virginia Department of Health (WVDH) indicate that nitrate plus nitrite (as nitrogen) concentrations larger than 10 mg/L are common in water from alluvial deposits in farming areas, particularly along the Ohio River. Nitrate plus nitrite concentrations in excess of 10 mg/L are common in ground water near reclaimed surface mines where nitrogen fertilizers have been used.

Ground water containing concentrations of chloride in excess of the secondary drinking-water standard of 250 mg/L underlies most of the State at depths of about 300 feet below the major streams. However, in several areas saline water is at or near land surface, typically in valleys along the axes of anticlines where intensive vertical fracturing has occurred. Many of these areas have historical significance in that the saline water was used to produce salt during the 1800's.

The WVDH notifies county health departments of all water supplies that contain sodium concentrations larger than 20 mg/L. The county health departments are required to make this information available to physicians and to people on sodium-restricted diets. U.S. Geological Survey data indicate that sodium concentrations exceed 20 mg/L in water from about half of the wells that tap rocks of Pennsylvanian age.

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has been degraded as a result of industrial waste disposal, coal mining, oil and gas drilling, agricultural activities,domestic or municipal waste disposal, transportation, and rural development. Studies by the U.S. Geological Survey, various State and Federal agencies, and academic institutions have documented many such changes.

Industry

Industrial developments are primarily located along the Ohio and Kanawha Rivers. Major industries include the manufacture of chemicals, steel, and aluminum and the production of electric power. Some of the Nation's major chemical-manufacturing complexes are located in the Kanawha River valley near Charleston and along the Ohio River. The location of the State's chemical industry has been linked to the presence of shallow salt brines and natural gas. Brines were used as early as 1900 for the manufacture of chemicals such as bromine, caustic soda, and soda ash.

Based on characteristics such as corrosivity, ignitability, reactivity, and toxicity, waste materials are classified as either hazardous or nonhazardous by the Waste Management Division of the WVDNR. Ground water has been contaminated as a result of improper disposal of both hazardous and nonhazardous industrial wastes. In 1981, West Virginia industries generated more than 8.3 million tons of hazardous wastes, about 35 percent of which was disposed of within the State (Cinquegranna and Ramey, 1982). About 92 percent of this waste was produced in Tyler, Marshall, Brooke, and Kanawha Counties. Most of the hazardous waste disposal in the State is achieved by treatment systems regulated under the National Pollutant Discharge Elimination System (NPDES) Program. Although NPDES methods of waste treatment and disposal primarily affect surface-water resources, impoundments are commonly used during treatment processes and for storage of liquid hazardous wastes. Leakage of wastes from such impoundments, especially unlined impoundments, has been a major cause of ground-water contamination (West Virginia Department of Natural Resources, 1980). Contaminants include chloride, lead, arsenic, chromium, and various organic compounds. Also, improper disposal of solid industrial wastes, both hazardous and nonhazardous, has contaminated ground water.

There are 24 RCRA facilities (fig. 3*A*) for treatment and disposal of hazardous wastes. Most of these sites involve treatment and disposal of wastes generated by the chemical industry. Other RCRA facilities involve waste treatment and disposal for aluminum, steel, and wood-preserving industries. The WVDNR has determined that contamination of ground water has occurred at 19 of the RCRA sites. However, at eight of these sites, contamination is not RCRA related. Most of the RCRA sites are located near densely populated areas along the Ohio and Kanawha Rivers and are underlain by alluvial deposits. Because of the generally permeable nature of alluvial deposits, ground water in these areas is especially susceptible to contamination by leakage of wastes from unlined impoundments. Contaminants detected in ground water at RCRA sites include chloride, mercury, phenol, carbon tetrachloride, chloroform, trichloroethylene, and benzene.

Also of concern are numerous landfill sites (fig. 3*C*) used in the past for disposal of industrial wastes. Little information about the location and types of waste material is available for many such sites. Transportation of chemicals has resulted in accidental spills that have affected ground-water quality. One such incident, involving derailment of a freight train in Mason County, resulted in the closure of the well field for the City of Point Pleasant, because of contamination by epichlorohydrin. Ground-water contamination has been detected at one Department of Defense facility (U.S. Department of Defense, 1986) and at two former ordnance facilities that are CERCLA sites. Contaminants found in ground water at these sites include trinitrotoluene (TNT), dinitrotoluene (DNT), and benzene.

Mining

The effects of coal mining on ground water are largely related to chemical characteristics of the coal and overburden material. The coal fields of West Virginia have been classified based on sulfur content—coal in the northwestern part of the State typically has a larger sulfur content than that of the southern part (fig. 2). Exposure of coal and overburden materials to air during mining increases the rate of oxidation of sulfur-bearing minerals such as pyrite. Oxidation of pyrite results in the formation of acid mine drainage, which is characterized by low pH and large concentrations of iron, manganese, hardness, and sulfate. Acid mine drainage occurs primarily in the high-sulfur coal fields, whereas alkaline mine drainage occurs primarily in the low-sulfur coal fields.

Studies by O'Steen and Rauch (1983) and McCurry and Rauch (1987) describe degradation of the chemical quality of ground water as a result of both surface and subsurface mining of coal. Their results indicate that the effects of mining are most pronounced nearest the mine and diminish with increasing distance from the mine. Acidic mine water is neutralized and diluted as it flows away from the mine and percolates through the ground-water system. Even though the acidity is neutralized in a short distance, water from wells within as much as 1,500 feet of a surface mine have shown increased iron and sulfate concentrations. Increases in iron and sulfate concentrations have been found in water from wells located near streams that receive acid mine drainage. Chemical reactions associated with increased oxidation rates, that occur as a result of mining, can cause mobilization of metals commonly found in coal.

In the low-sulfur coal fields, which are common in the southern part of the State, water from mines is used for public and individual supplies. The chemical quality of water from some of these mines does not exceed drinking-water standards before treatment. However, water from mines commonly requires treatment to decrease iron and manganese content. Most of the mine water used for supplies is derived from abandoned mines, although several communities use water pumped from active mines. Contamination of ground water can occur from chemicals used directly or indirectly in mining processes. Several McDowell County community water supplies were temporarily contaminated by chemicals used to ex-

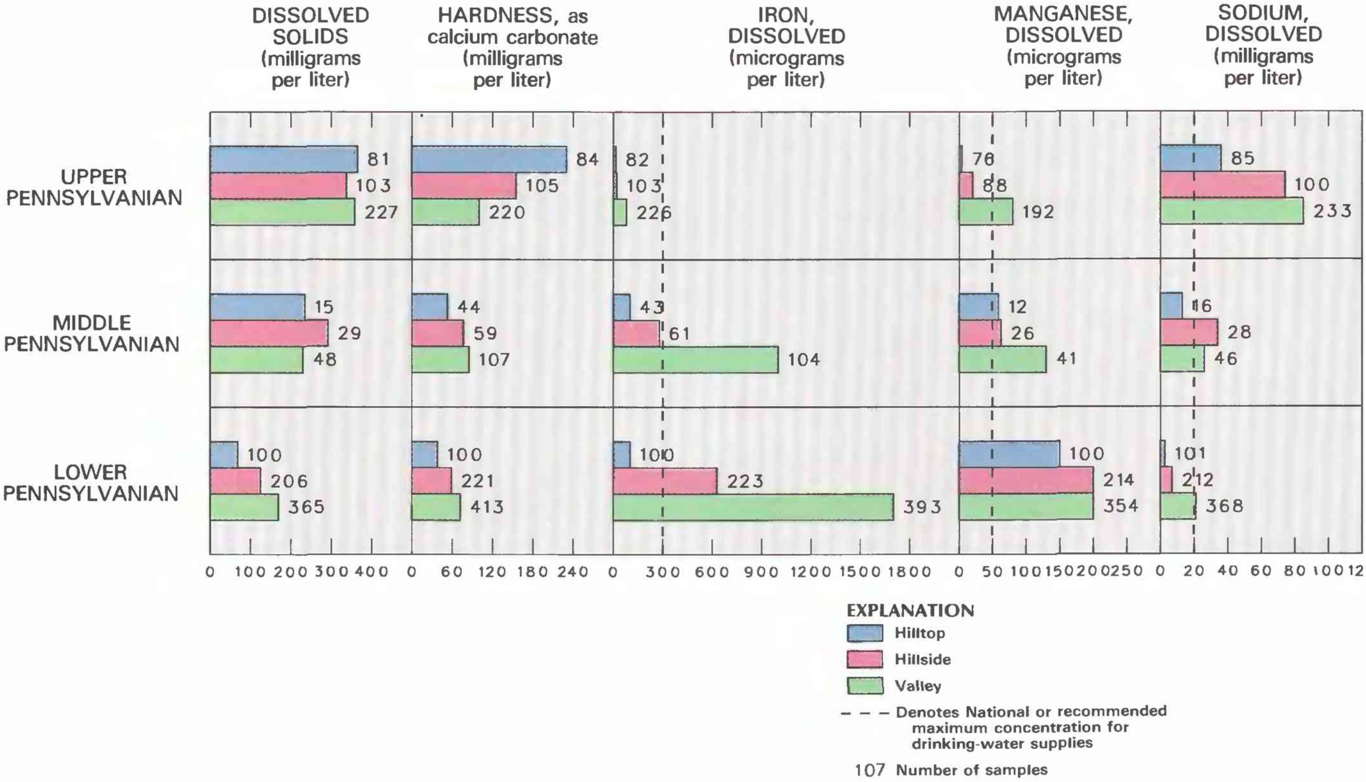

Figure 4. Variation in the chemical quality of ground water by topographic setting. Median values are used for concentrations. (Source: U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986b.)

tinguish a fire in an active underground mine. Other possible contaminants include acrylamide (found in industrial grade polyacrylamide, which is used in coal cleaning processes), oil, grease, and solvents used in association with mine equipment, and polychlorinated biphenyls (PCB's) from transformers which were typically left in the mines upon closure.

Ground water can also be contaminated by leachate from coal refuse. There are about 54,000 acres of coal refuse in West Virginia (Johnson and Miller, 1979). Leachate from a coal-refuse pile on the Ohio River flood plain reportedly contaminated municipal wells in Marshall County. The contamination resulted in closure of four wells because of sulfate concentrations in excess of the secondary drinking-water standard of 250 mg/L.

Oil and Gas

Ground water has been contaminated in conjunction with oil and gas production at many places in the State. Drilling for oil and gas began in the early 1860's. Since then, several major oil and gas fields have been discovered. Saltwater associated with oil and gas in West Virginia commonly is under sufficient pressure to flow upward through oil and gas wells to land surface. Many oil and gas wells, particularly older ones, were not properly constructed or properly abandoned. Where well casings have deteriorated or have been removed during steel shortages such as occurred during World War II, migration of brines has contaminated freshwater aquifers (Bain, 1970). Disposal of brines produced in conjunction with oil and gas also can contaminate aquifers. Several companies reinject brines into oil-and-gas-producing strata for disposal and enhanced recovery processes. Reinjection requires pumping brines under pressure into brine-bearing strata. The reinjection can cause local increases in pressure in the brine-bearing stratum that can facilitate upward migration of brine and associated hydrocarbons through fractures, coreholes, uncased wells, and improperly constructed wells. Improper drilling and brine-disposal methods have resulted in numerous complaints from water-well owners concerning contamination of water supplies with drilling fluids and cuttings, oil, and natural gas.

Agriculture

The estimated total acreage of farm land decreased from 4.2 million acres in 1972 to 3.5 million acres in 1985 (West Virginia Crop Reporting Service, 1982, 1985). There is little irrigated land; most irrigation systems use surface-water sources. Ground-water use for irrigation averages less than 0.4 Mgal/d. Nitrate (as nitrogen) concentrations in excess of 10 mg/L have been detected near feedlots and in agricultural areas where fertilizers have been applied. Most instances of ground-water contamination by pesticides have occurred because they have been applied near improperly constructed or abandoned wells. These wells can provide pesticides with a direct means of entering the ground-water reservoir. Picloram and chlordane are the pesticides most commonly detected in ground water. There is no facility within the State for disposal of unwanted pesticides.

In the eastern panhandle, where valleys are underlain by very permeable limestone, agricultural wastes such as manure have contaminated ground water. Farmers in these areas are encouraged to install lined lagoons for storage of animal wastes. An inventory of 155 rural-domestic water supplies in Preston County indicated that 68 percent exceeded the primary drinking-water standard of 1 coliform colony per 100 milliliters of water (Sworobuk, 1984). Animal wastes appeared to be the major source of the coliform bacteria. Bacterial contamination is most commonly observed in improperly cased or dug wells or in wells located near septic fields.

Timber production is a major agricultural industry. Sawmills and lumber-treatment plants produce waste materials that can contaminate ground water. Leachate from sawmill wastes, analyzed by the WVDNR, contained increased concentrations of phenol, chromium, and arsenic, as well as large chemical and biological oxygen demands. Wood preservatives, such as creosote, have contaminated ground water in several areas of the State.

Domestic Waste Disposal

Mandatory permitting of municipal landfills and monitoring of ground-water quality will be implemented in June 1988 by the WVDNR, Division of Waste Management. About 65 permitted and an estimated 2,000 unpermitted landfills are used for disposal of domestic wastes. Exact locations of many of the unpermitted landfills are unknown; as a result, many sites do not appear in figure 3*C*. Limited data are available concerning the location of sites formerly used for municipal waste disposal. Ground-water contamination has been detected at some municipal landfills that have accepted industrial wastes. Because ground-water quality is monitored at few domestic-waste landfills, relatively little is known about the extent of ground-water degradation at these sites.

Transportation

Degradation of ground-water quality as a result of transportation-related activities has occurred in urban and rural areas. Underground petroleum-storage tank leaks and petroleum product spills have contaminated ground water at several locations. Application and improper storage of salt, used for deicing roads, has degraded water quality in several domestic wells (Hobba, 1985). Concentrations of chloride in ground water exceeded 3,400 mg/L at a Department of Highways salt-storage facility in Braxton County (West Virginia Department of Natural Resources and West Virginia Department of Highways, 1983). Efforts have been made to decrease ground-water contamination from improper storage of road salt by constructing buildings that fully enclose salt-storage areas.

Rural Development

In rural areas, ground-water problems are commonly associated with improper construction, location, and abandonment of water wells. Regulations requiring the certification of well drillers and standards for well construction were implemented in 1984 (West Virginia State Board of Health, 1984a,b). Many wells drilled before that time were not properly sealed or were located near septic fields. Improperly constructed wells can permit percolation of contaminants into underlying aquifers that can contaminate water in nearby wells. Improper abandonment of wells can be a potential problem. For example, many dug wells have been filled with trash that can contaminate surrounding ground water.

POTENTIAL FOR WATER-QUALITY CHANGES

Ground-water contamination has been most extensive in the alluvial aquifers, primarily in the alluvium along the Ohio River. Many major industries and much of the population are located in river valleys, which are typically underlain by alluvial deposits. More than 50 percent of all ground water used for public supply is obtained from alluvial deposits along the Ohio River. The potential exists for migration of known contaminant plumes of benzene, phenol, and mercury into municipal well fields. The permeable nature of alluvial deposits, especially in disturbed areas where surficial clay layers have been removed, makes these deposits susceptible to contamination from surface sources.

Areas underlain by limestone, predominantly in the eastern panhandle and Pocahontas, Greenbrier, and Monroe Counties, are particularly susceptible to ground-water contamination. Many valleys in these areas are located along anticlines where intensive vertical fracturing has occurred. Because of the solubility of limestone, these fractures have been enlarged through solution, and, in some areas, karst topography has developed. Most individuals and communities in these areas obtain water supplies from ground-water sources. Recharge in these limestone areas is rapid and can occur through sinkholes, caves, and streams. These conditions make the safe disposal of wastes difficult. Sinkholes, which are recharge points for underlying aquifers, are commonly used for disposal of domestic wastes, agricultural wastes, and even dead animals. Wells drilled into caves are used as drains for highway runoff, thus permitting direct inflow of contaminants, such as road salt and spilled materials, into the ground-water reservoir.

Pesticide disposal, spills of petroleum products, and leachate from landfills and impoundments have contaminated ground water in areas underlain by limestone. Much of the State's population growth has occurred in the eastern panhandle, particularly in Berkeley and Jefferson Counties. Because of the permeable nature of the carbonate rocks in this area and anticipated population growth, the potential for further contamination of ground water is significant.

Mined-out regions are particularly susceptible to ground-water contamination. There are about 1.6 million acres of abandoned coal mines in the State. Surface mines commonly have been used as landfills. Various industrial and domestic wastes have been dumped into abandoned mine shafts. Underground mine workings are capable of acting as conduits for the movement of ground water and contaminants, and, where underground workings connect with surface mines, direct inflow to ground-water reservoirs can occur. Fracturing associated with subsidence has increased the permeability of strata overlying coal mines, especially in areas of long-wall mining. This increased permeability increases recharge rates and makes the underlying aquifer more susceptible to surface contamination. Open shafts and boreholes into abandoned mines increase the likelihood that surface contaminants will enter the ground-water system.

GROUND-WATER-QUALITY MANAGEMENT

It is the policy of West Virginia to "maintain reasonable standards of purity and quality of the water of the State consistent with (1) public health and public enjoyment thereof; (2) the propagation and protection of animal, bird, fish, aquatic and plant life; and (3) the expansion of employment opportunities, maintenance, and expansion of agriculture and the provision of a permanent foundation for healthy industrial development" [Code of West Virginia, 1931, as amended, chapter 20-5A-1 (WVC, section 20-5A-1)]. The responsibility for protection and management of ground-water resources is shared by the Departments of Natural Resources, Health, Energy, Agriculture, and Highways and the Water Resources Board. On April 3, 1986, these five departments signed a memorandum of agreement to develop a comprehensive ground-water-protection program for the State.

The Department of Natural Resources, Divisions of Waste Management and Water Resources is responsible for implementing most of the regulatory programs related to ground water (WVC, section 20-5A). The Division of Waste Management regulates the disposal of nonhazardous waste and the storage, treatment, and disposal of all hazardous wastes under provisions of the West Virginia Hazardous Waste Management Act (WVC, section 20-5E), which implements RCRA. In addition to RCRA responsibilities, the Division of Waste Management has a cooperative agreement under CERCLA with the U.S. Environmental Protection Agency to conduct preliminary assessments, site inspections, and hazard rankings at various Superfund sites in West Virginia.

The Division of Water Resources includes the Ground Water and Underground Injection Control (UIC) Office, which coordinates ground-water program activities and regulates the subsurface placement of fluids (U.S. Environmental Protection Agency, 1984). In 1986, there were no active injection wells for the disposal of hazardous materials. However, there were about 800 class-II wells for brine disposal and enhanced-recovery processes, 15 class-III wells used in solution mining, and more than 500 class-V wells, including percolation wells receiving highway drainage and wells through which coal wastes are pumped into abandoned mines.

The Permits Branch of the Division of Water Resources is responsible for issuing and enforcing Water Pollution Control permits for municipal and private sewage-treatment works and for industrial facilities, which include landfills, impoundments, and spray irrigation systems that dispose of nonhazardous wastes. Regulation of some industrial waste-disposal activities requires ground-water monitoring. Other ground-water-related responsibilities of the Water Resources Division are the reporting of accidental spills, investigation of ground-water complaints, management of ground-water data, background and compliance monitoring programs, and water-purity analyses.

The Department of Health (WVC, section 16-1) is responsible for the protection of drinking-water supplies, including the regulation of all drinking-water wells, both public and private. The Environmental Engineering Division of the WVDH has primacy for the "Safe Drinking Water Act" to develop laws, design standards, policies, and regulations for public water supplies. This Division also has the authority to enforce drinking-water standards for public-water systems, to issue construction and operating permits for public water systems, and to train and certify well drillers and public water-supply operators. The WVDH laboratories perform chemical, bacteriological, and radiological analyses of drinking water on a routine basis for public water supplies and, at the request of county health departments, for private water supplies. County health departments are responsible for site inspection and issuance of permits for construction of domestic water wells and sampling for contaminants. The county health departments also are responsible for inspection and issuance of permits for the installation and operation of septic-tank systems and other onsite sewage-disposal systems, as well as the regulation of septic disposal.

The Department of Energy, created in 1985, is responsible for the regulation of the coal, petroleum, and natural gas industries (WVC, section 22). The Division of Mining and Minerals requires mine operators to prevent or minimize degradation of the quality and quantity of ground-water resources. The Oil and Gas Division is responsible for preventing the contamination of freshwater by saltwater and by other contaminants associated with the oil and gas industry.

The Department of Agriculture, Plant Pest Control Division, is involved with the usage of pesticides. Responsibilities include training and certification of pesticide applicators, establishment of standards for powerline and right-of-way spraying, and investigation of ground-water complaints involving pesticide contamination. Other activities of the Department of Agriculture related to ground water include dispensing information about proper disposal practices for agricultural wastes, such as fertilizers, manure, and dead animals.

The Department of Highways (DOH) is responsible for the prevention of contamination of ground water by highway deicing materials and highway runoff, the regulation of salvage yards (WVC, section 17-23), and the management of materials stored at DOH maintenance facilities.

The Water Resources Board (WRB) is an independent agency composed of five members appointed by the Governor. It is responsible for the promulgation of regulations needed to protect the waters of the State (WVC, section 20-5, section 20-5A, section 29A-1-1). Regulations written by the WRB include standards of water quality and rules establishing the State's participation in the National Pollutant Discharge Elimination System (NPDES) under the Federal Water Pollution Control Act. The WRB also hears appeals of orders and other actions of the Chief of the Division of Water Resources, Department of Natural Resources.

Development of a ground-water-protection policy and related legislation is needed to provide for the future management of West Virginia's water resources. A computerized data base for qualitative and quantitative ground-water information is being developed to facilitate data management. There also is a need for a statewide ground-water-quality monitoring network that includes sampling for organic compounds.

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WISCONSIN
Ground-Water Quality

About 70 percent of Wisconsin's population depends on ground water for its water supply; about 35 percent are served by public water supplies and 35 percent by private wells (U.S. Geological Survey, 1985). The population dependent on ground water is primarily inland from Lake Michigan (fig. 1*B*). Milwaukee, Green Bay, and many other communities located along the lake obtain their water supplies from Lake Michigan. Water in three major and other minor aquifers is generally suitable for domestic supply and most other uses (see fig. 2). Predominant dissolved constituents in the ground water are calcium, magnesium, and bicarbonate. Naturally occurring constituents and properties that cause local problems include iron, manganese, hardness, radium, hydrogen sulfide, and fluoride.

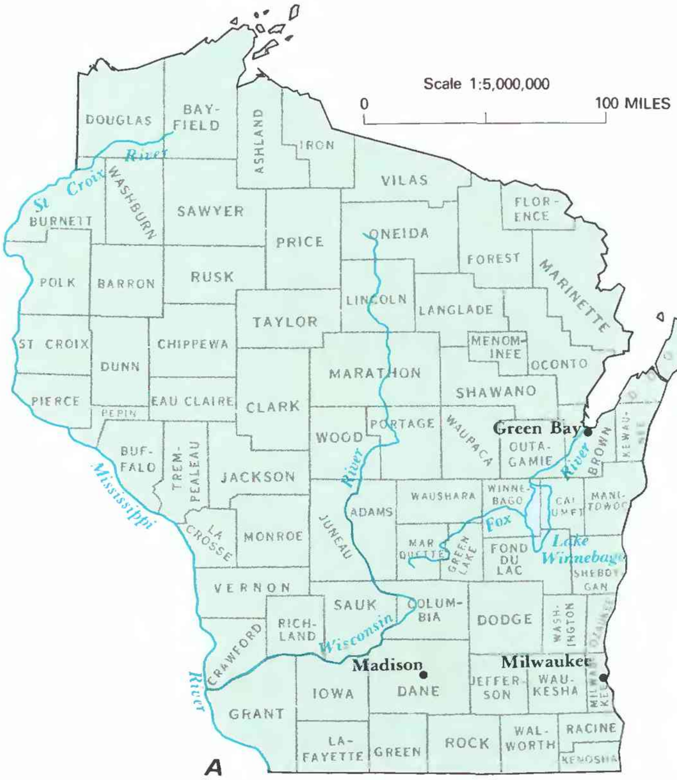
Activities or sources that have been identified as potential or actual contributors to ground-water contamination are land disposal of wastes, some agricultural practices, and underground petroleum storage tanks. Ground-water contamination has been detected at 7 of 12 Federal Resource Conservation and Recovery Act (RCRA) sites and 21 of 26 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites (fig. 3). In addition, the U.S. Department of Defense (DOD) has identified one site at one facility where contamination has warranted remedial action. The potential for contamination is also present at other sites. Contamination has been detected at landfills and wastewater-disposal sites by routine monitoring and incidental to investigation of other water-quality problems. Agricultural practices have caused ground-water contamination by the pesticide aldicarb in the central sand plain (all or parts of Portage, Waushara, Wood, and Adams Counties), and by other pesticides in other areas, and have probably contributed to nitrate contamination in many areas. Underground petroleum storage tanks have been implicated in many instances of ground-water contamination even though there is no regulatory monitoring program to detect this type of contamination. Bacterial contamination has occurred in eastern Wisconsin where fractured dolomite is near the land surface.

Reconnaissance sampling has indicated local instances of ground-water contamination by volatile organic compounds (VOC) and nitrate in scattered areas of the State. These substances can be from several sources. The most frequently detected VOC were trichloroethylene and tetrachloroethylene.

WATER QUALITY IN PRINCIPAL AQUIFERS

Wisconsin has three principal aquifers—the unconsolidated sand and gravel, Silurian dolomite, and sandstone aquifers (fig. 2*A*). More detailed descriptions of these aquifers, well characteristics, and water use are given elsewhere (U.S. Geological Survey, 1985, p. 447–450). Two minor aquifers—the Lake Superior sandstone aquifer and the Precambrian lava flows—also are discussed, because of their local importance. Precambrian igneous and metamorphic rocks that underlie the entire State and the Maquoketa Shale (which is also a confining bed) yield water to wells in some areas, but they are not discussed here because of their limited importance and lack of pertinent data.

Bedrock aquifers are hydraulically connected to each other except for the sandstone and Silurian dolomite aquifers in eastern Wisconsin that are separated by the Maquoketa Shale confining bed. Recharge to bedrock aquifers passes through the unconsolidated sand and gravel aquifer, where it is present, and through soils in most other areas. The dominant recharge area for the confined part of the sandstone aquifer is beyond the western edge of the Silurian dolomite aquifer, but some leakage also occurs through the Maquoketa Shale confining bed.



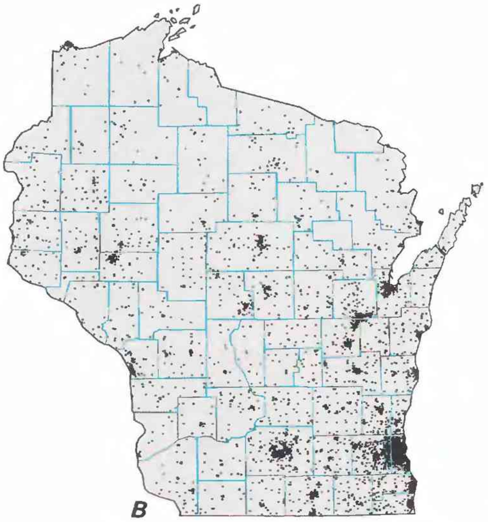


Figure 1. Selected geographic features and 1985 population distribution in Wisconsin. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

Ground-water quality is generally suitable for most uses, but treatment may be necessary for esthetic reasons to decrease naturally occurring hardness and iron or manganese concentrations exceeding drinking-water standards (Wisconsin Department of Natural Resources, 1978). Other naturally caused water-quality problems that affect water uses in local areas of some aquifers are radium, fluoride, and hydrogen-sulfide concentrations exceeding State drinking-water standards.

The predominant dissolved constituents in most of the State's ground water are calcium, magnesium, and bicarbonate. Differences in the concentrations of these constituents generally parallel differences in dissolved-solids concentrations, which are used here as one means of characterizing the background quality of ground water.

BACKGROUND WATER QUALITY

A graphic summary of selected water-quality variables compiled from the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) is presented in figure 2*C*. The summary is based on dissolved-solids, hardness (as calcium carbonate), nitrate (as nitrogen), iron, and manganese analyses of water samples collected from the principal aquifers in Wisconsin. Most of the data used in the summary were collected during the last 30 years. Nitrate plus nitrite concentrations are considered to

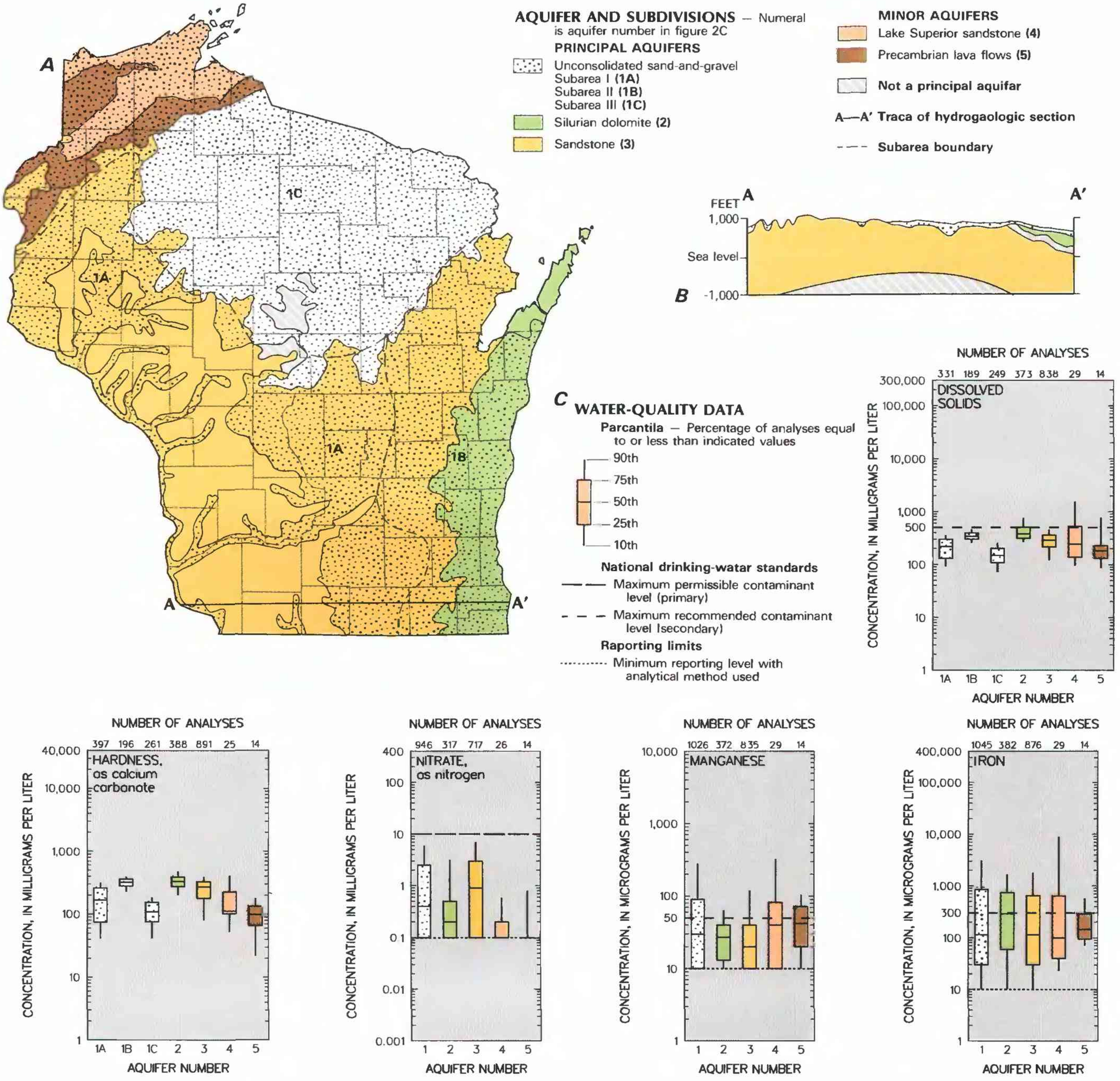


Figure 2. Principal aquifers and related water-quality data in Wisconsin. *A*, Principal aquifers; *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1983. (Sources: *A*, *B*, Modified from U.S. Geological Survey, 1985; Kammerer, 1984. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

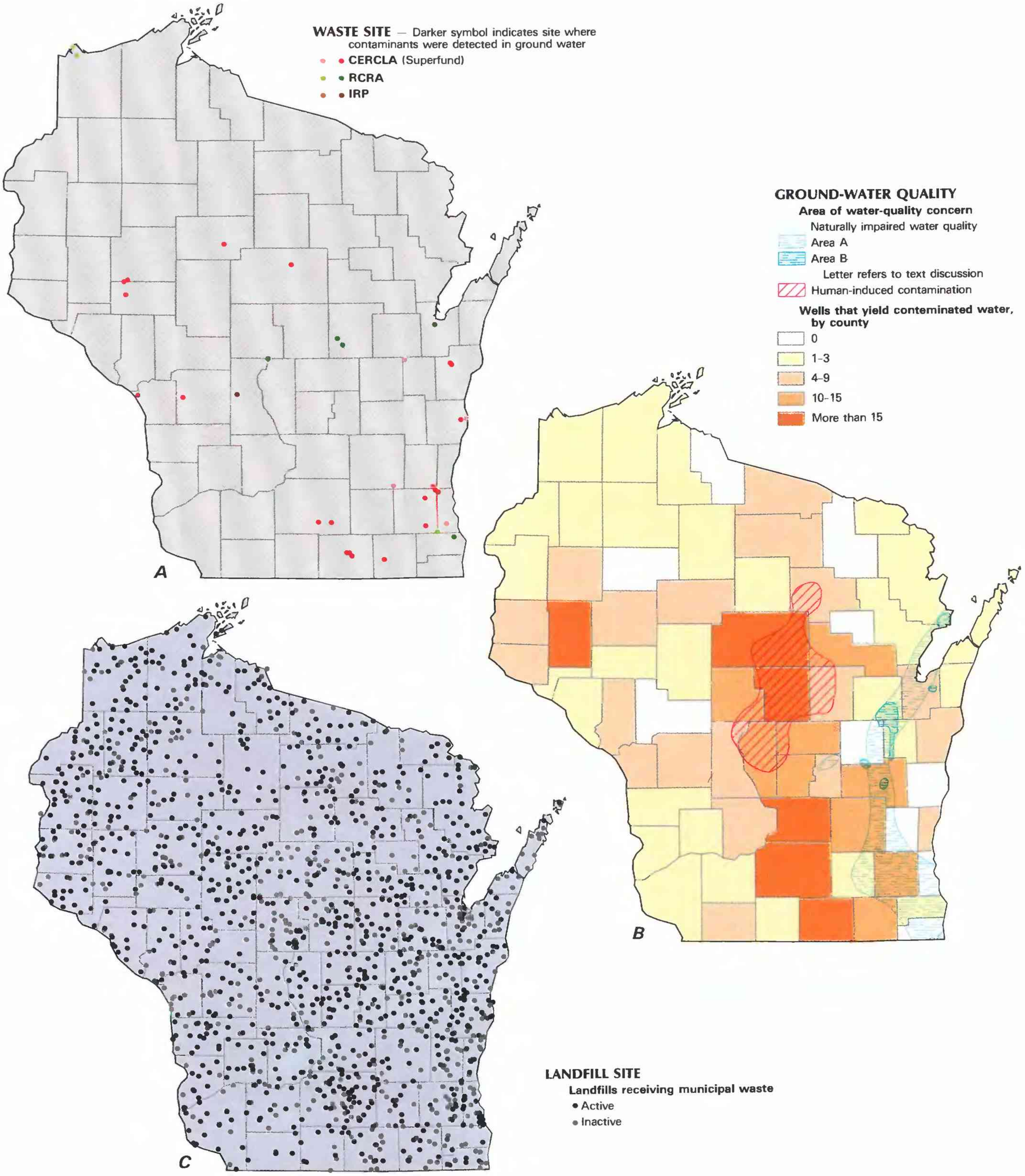


Figure 3. Selected waste sites and ground-water-quality information in Wisconsin. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites; Resource Conservation and Recovery Act (RCRA) sites; and Department of Defense Installation Restoration Program (IRP) sites, as of October 1985. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and distribution of wells that yield contaminated water, as of October 1985. *C*, Landfills receiving municipal waste, as of October 1985. (Sources: *A*, Richard O'Hare, Wisconsin Department of Natural Resources, written commun., 1986; U.S. Department of Defense, 1986. *B*, Modified from Hahn, 1984; Kammerer, 1984; and Koth, 1985. *C*, Jack Connelly, Wisconsin Department of Natural Resources, written commun., 1986.)

be equivalent to nitrate (as nitrogen) concentrations for the purpose of this report. The ratios of these constituents within and among aquifers are discussed in greater detail by Kammerer (1984). Percentiles of these variables are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant level standards are health related and are legally enforceable. The secondary maximum contaminant level standards apply to esthetic qualities and are recommended guidelines. The primary drinking-water standards include a maximum concentration of 10 mg/L (milligrams per liter) nitrate (as nitrogen), and the secondary drinking-water standards include maximum concentrations of 500 mg/L dissolved solids, 300 μg/L (micrograms per liter), iron, and 50 μg/L manganese.

State drinking-water standards are the responsibility of the Wisconsin Department of Natural Resources (DNR). Current State standards (Wisconsin Department of Natural Resources, 1978) are, with minor exceptions, the same as national standards adopted by the U.S. Environmental Protection Agency (1986a,b). Recently enacted ground-water-quality standards (Wisconsin Department of Natural Resources, 1985) are discussed later.

Unconsolidated Sand and Gravel Aquifer

The sand and gravel aquifer is not a continuous aquifer as are most bedrock aquifers, but is present as discontinuous deposits whose origin and lithology differ areally. For the purpose of summarizing hardness and dissolved-solids data, the aquifer is subdivided into three subareas (fig. 2*A*), based on ground-water provinces used by Kammerer (1984, p. 10). The aquifer was subdivided to define the effect of areal differences in aquifer characteristics in the summaries. Dissolved-solids and hardness concentrations are largest in the east (subarea II), where the aquifer overlies the Silurian dolomite aquifer, and in dolomite units of the sandstone aquifer. Concentrations are smallest in the north (subarea III), where the aquifer overlies Precambrian crystalline rocks, sandstones, and lava flows. Hardness of water in these subareas can be classified, in general, as moderately hard to hard (subarea I), very hard (subarea II), or moderately hard (subarea III).

Concentrations of iron, manganese, and nitrate (as nitrogen) do not appear to be affected by areal differences in aquifer characteristics. Therefore, their concentration distributions are summarized for the entire aquifer. Concentrations of iron and manganese exceed the drinking-water standards in water from more than one-third of the wells (fig. 2*C*). Nitrate (as nitrogen) concentrations shown in figure 2*C* represent the range of concentrations expected in uncontaminated ground water.

Silurian Dolomite Aquifer

The Silurian dolomite aquifer is mostly dolomite of Silurian age, but it also includes Devonian dolomite and shale in a small area along Lake Michigan. Water from this aquifer is very hard; hardness values are among the largest in the State. Dissolved-solids concentrations are also large, with concentrations exceeding 500 mg/L in water from about 25 percent of the wells sampled. Iron concentrations exceed drinking-water standards in water from about half of the wells. Manganese concentrations exceeding drinking-water standards occur less commonly, but present problems in many wells. The range of nitrate (as nitrogen) concentrations shown in figure 2*C* is small and probably represents natural conditions. Hydrogen sulfide has been detected locally (Kammerer, 1984, p. 46) in water from wells in the southeastern Kenosha County (the southeastern part of area B in fig. 3*B*).

Sandstone Aquifer

The sandstone aquifer consists of sandstone, dolomitic sandstone, dolomite, and some siltstone. Water-quality data used in the summaries in figure 2*C* are most representative of the unconfined part of the aquifer. The confined part of the aquifer (beneath the Maquoketa Shale) is an important source of ground water, but water-quality data for wells drawing water exclusively from it are scarce and under-represented in the summaries. Water from the aquifer is hard to very hard—hardness is largest in the western, southern, and eastern parts of the State where more wells draw water from dolomite. Dissolved-solids concentrations are generally smaller than 500 mg/L. Iron concentrations exceed drinking-water standards in water from about 33 percent of the wells; manganese concentrations exceed the drinking-water standard less frequently. Hydrogen sulfide has been detected in water from the upper part of the aquifer near Lake Winnebago and in the northeast in area B delineated in figure 3*B* (Kammerer, 1984, p. 46). Radium concentrations near and exceeding the State drinking-water standard of 5 pCi/L (picocuries per liter) have been reported locally, mainly in area A delineated in figure 3*B* (Hahn, 1984). Fluoride concentrations exceeding the State drinking-water standard of 2.2 mg/L are commonly found in water from wells in an area along the Fox River south of Green Bay.

Lake Superior Sandstone Aquifer and Precambrian Lava Flows

The Lake Superior sandstone aquifer and the Precambrian lava flows generally are used for water supplies only where adequate supplies are not obtainable from overlying unconsolidated materials. This situation occurs primarily in Ashland and Bayfield Counties along Lake Superior. Water is moderately hard to hard in the Lake Superior sandstone aquifer and moderately hard in the lava flows. Water from the Lake Superior sandstone aquifer contains a wide range of total dissolved-solids concentrations, and concentrations exceed 500 mg/L in water from more than 25 percent of the wells. Dissolved-solids concentrations in water from the lava flows generally do not exceed 500 mg/L. Iron concentrations exceed drinking-water standards in water from about 25 to 33 percent of the wells in these aquifers; manganese concentrations exceed the standards in water from a larger proportion of the wells in these aquifers than in wells tapping other aquifers. Nitrate (as nitrogen) concentrations are small in both aquifers.

EFFECTS OF LAND USE ON WATER QUALITY

Water-quality changes have been linked to large-scale, easily identified activities (such as waste disposal and agricultural practices) as well as to incidents at specific sites (such as contamination from private septic systems or leaking underground storage tanks), which are more difficult to identify or anticipate. Some contaminants, such as nitrate and VOC, can come from a number of these sources. Some instances of contamination are detected through routine regulatory monitoring programs established in anticipation of water-quality problems (monitoring at waste-disposal sites, for example), but others are unanticipated and undetected until problems are encountered by a water user.

The relative importance of factors contributing to water-quality changes is indicated by records of water-quality problems investigated by the DNR. State ground-water regulations implemented in 1983 provide for compensation to individuals with contaminated domestic water-supply wells. In administering this program, the DNR has attempted to correlate compensation claims with known or suspected sources of contamination. Contaminants or their sources were identified for 706 wells for which contamination advisories were issued between 1983 and January 1, 1986. Principal causes of problems were landfills (36 percent), VOC (33 percent), pesticides (13 percent), underground petroleum storage tanks (8 percent), and other (10 percent) (Schreiber, 1986). Principal sources of contamination identified in an inventory of 197 ground-water contamination cases investigated by DNR between 1929 and 1980 were leakage from pipes and tanks (29 percent), waste lagoons (16 percent), landfills (12 percent), and accidental spills (10 percent). About one-third of all instances were related in some way to storage, treatment, or disposal of wastes (Kammerer, 1984, p. 48).

The perspective of an investigation or source of data is an important consideration in documenting the incidence of a particular water-quality change. This is illustrated by three separate surveys of nitrate contamination. Figure 2*C* indicates a very small incidence of nitrate (as nitrogen) contamination. Figure 2*C* is based on WATSTORE data which, for Wisconsin, are primarily from uncontaminated wells. Results of a 1979–80 sampling by the DNR of 11,396 noncommunity ground-water supplies (systems serving at least 25 people at least 60 days per year) reported by Strous (1986, p. 5) showed that nitrate (as nitrogen) concentrations exceeded the drinking-water standard of 10 mg/L in 2.6 percent of the wells. A considerably larger incidence of nitrate (as nitrogen) contamination is seen in data for private rural water supplies compiled by Delfino (1977). That study showed nitrate (as nitrogen) concentrations exceeding 10 mg/L in 9.2 percent of the 5,950 wells sampled statewide and in more than 20 percent of the wells sampled in some counties.

Figure 3*B* shows a general summary, by county, of the number of wells where contaminants have been detected at concentrations exceeding State ground-water-quality standards. Contaminants considered include only nitrate, VOC, and pesticides. Nitrate contamination data are from community and noncommunity public water supplies only.

The DNR began a VOC sampling program in July 1983. From July 1983 through June 1985, 409 community ground-water systems were tested, and 47 had at least one detectable VOC. The most commonly detected VOC were trichloroethylene (TCE) and tetrachloroethylene (PCE). The DNR is also testing private water-supply wells in "at risk" areas at a rate of about 600 wells per year. Of the 620 wells tested between July 1983 and June 1984, 92 had detectable concentrations of at least one VOC (Koth, 1985, p. 20–23).

Water in the Silurian dolomite aquifer has been contaminated by bacteria where the fractured dolomite of the aquifer is near the land surface. Affected areas include Door County and an area in northeastern Waukesha County (Koth, 1985, p. 8). Contamination potential is large in any area where fractured dolomite is the uppermost bedrock and overlying unconsolidated deposits are thin.

Waste Disposal

Ground-water contamination caused by land disposal of hazardous wastes has been detected at a number of sites. Undetected contamination may have also occurred at other hazardous-waste disposal sites.

Hazardous wastes that pose a threat to ground water have been disposed at 12 RCRA sites in Wisconsin (fig. 3*A*). Ground-water contamination has been detected at 7 of these 12 RCRA sites (Richard O'Hara, Wisconsin Department of Natural Resources, written commun., 1986). Hazardous wastes have been treated or stored at about 58 other sites that are subject to RCRA regulations (these sites are not included in figure 3*A*).

An additional 26 Wisconsin sites (fig. 3*A*) are included on the current National Priorities List (NPL) (U.S. Environmental Protection Agency, 1986c). These sites are eligible for Superfund-assisted remedial action provided for under the CERCLA program. Ground-water contamination has been detected at 21 of these sites (Richard O'Hara, Wisconsin Department of Natural Resources, written commun., 1986).

As of September 1985, 27 hazardous-waste sites at 3 facilities in Wisconsin had been identified by the DOD as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the U.S. Environmental Protection Agency Superfund program under CERCLA of 1980. The EPA presently ranks these sites under a hazard ranking system and may include them in the NPL. Of the 27 sites in the program, 14 sites contained contaminants but did not present a hazard to the environment. One site at one facility (fig. 3*A*) was considered to present a hazard significant enough to warrant response action in accordance with CERCLA. The remaining sites were scheduled for confirmation studies to determine if remedial action is required.

Wisconsin's Environmental Repair Fund (ERF) is used to pay for cleanup of hazardous substances that threaten ground-water resources. As of August 1986, ERF-funded remedial actions have been completed at 13 sites and are in progress at 9 additional sites (James Bakken, Wisconsin Department of Natural Resources, oral commun., 1986).

Landfills are potential sources of ground-water contamination. The DNR regulations requiring licensing of landfills and ground-water-quality monitoring in and around them took effect in 1976. Collection of background water-quality information and continued ground-water quality monitoring are now required as a condition of licensing at all new landfills. A "lookback" provision in the regulations allows the DNR to require monitoring at sites that were operated before these monitoring requirements. As of August 1986, there were about 1,050 active landfills; monitoring was required at 265 landfill sites, including both active and inactive sites (Jack Connelly, Wisconsin Department of Natural Resources, oral commun., 1986). Monitored sites presently receive about 95 percent of the waste disposed in landfills in Wisconsin (Richard Schuff, Wisconsin Department of Natural Resources, written commun., 1986).

Locations of the 1,050 active landfill sites and 562 inactive landfill sites are shown in figure 3*C*. The sites are predominantly municipal landfills, or private landfills that contract with municipalities, but some sites also receive nonmunicipal wastes. Inactive sites shown in figure 3*C* include only those that once had an operating license and represent only a small part of known inactive or abandoned waste-disposal sites. A recent inventory by the DNR (Bakken and Giesfeldt, 1985) identified 2,717 abandoned waste sites; these sites are mostly landfills but also include some industrial wastewater sites and sites of spills. A screening of 2,682 of these sites has resulted in the designation of 303 high-priority sites for followup investigation based on their known or potential threat to ground water. Most of the inactive sites shown in figure 3*C* are included in this inventory.

Land disposal of municipal and industrial wastewater has contributed to ground-water contamination. Most land-disposal systems are surface impoundments (seepage lagoons), but some ridge and furrow and spray systems also are in operation. As of October 1979, the DNR was aware of 1,802 surface impoundments at 1,071 facilities that were used for storage or disposal of liquid or semiliquid waste; about 95 percent of the sites were in active use. Principal waste types at these sites were agricultural (36 percent), industrial (35 percent), and municipal (28 percent) (Kammerer, 1984, p. 50). Ground-water-quality monitoring has been required by the DNR since 1976 at sites with large discharge volumes, but these sites are only a small part of the total known sites. As of August 1986, monitoring was required at about 135 facilities (David Sauer and Charles Ledin, Wisconsin Department of Natural Resources, oral commun., 1986).

Agriculture

Agriculture affects ground-water quality most commonly through contamination by nitrate and pesticides. Nitrate contamination has been linked to leaching of fertilizers resulting from intensive sprinkler irrigation of potatoes and other vegetables in Wisconsin's central sand plain (Hindall, 1978). Contamination is also likely in other areas where light sandy soils, shallow depths to water, and intensive irrigated agriculture occur. Results of a survey by Schuknecht and others (1975) of 793 private wells in Columbia County implicate agricultural practices as causes of nitrate contamination. Overall, water from 38 percent of the wells sampled had nitrate (as nitrogen) concentrations exceeding the drinking-water standard of 10 mg/L. If only wells less than 50 feet from a barnyard or on farms that had feedlots or liquid manure storage facilities were considered, this figure was 50 to 63 percent.

Pesticides have been detected in ground water in two sampling programs conducted by the DNR. Aldicarb, used primarily for pest control on potato plants, has been detected in the central sand plain and, to a lesser extent, in other potato-growing areas. The principal area where aldicarb has been detected in ground water is shown as human-induced contamination in figure 3*B*. Aldicarb contamination is a problem at specific sites, and delineation of this area does not imply uniform or widespread contamination. Samples were collected from 1,008 wells in susceptible areas in 21 counties during 1981–85; aldicarb was detected in water from 227 of these wells (Koth, 1985, p. 23). A more general sampling program is being conducted in areas susceptible to contamination Statewide to test for a broader range of pesticides. Pesticides included in the analyses were selected to represent local use. Samples from 57 of 524 private wells sampled between July 1983 and June 1985 had detectable concentrations of at least one pesticide (Koth, 1985, p. 23). A summary of the results of this sampling program through the end of 1985 by Schreiber (1986) indicates that the most commonly detected organic pesticides were the herbicides atrazine, alachlor, metolachlor, and cyanazine; these compounds were each detected in samples from more than 10 wells. Twelve other pesticides were each detected in less than 10 samples.

Underground Storage Tanks

Leakage from underground storage tanks has been implicated in a relatively large number of instances of local ground-water contamination. This condition is especially noteworthy considering that no regulatory water-quality monitoring is required to detect problems of this sort. Regulation of underground tanks is now being given high priority in the State. Gathering data to evaluate the extent of ground-water contamination from buried storage tanks is a high priority of problem-assessment monitoring conducted by the DNR. The Wisconsin Department of Industry, Labor, and Human Relations (DILHR) is in the process of conducting an inventory of existing tanks that are either in use or have been improperly abandoned. The information obtained will be used to develop an enforcement program to decrease the potential for ground-water contamination from this source.

POTENTIAL FOR WATER-QUALITY CHANGES

The concern for protection of Wisconsin's ground-water quality is reflected in the activities of State, regional, county, and local agencies. Water-quality monitoring has been greatly increased, waste disposal is more closely regulated, and the public concern is intensified. Legislation has enabled more monitoring and regulation. However, in spite of the resulting improvement in the control of pollutants contaminating our ground water, much work remains to be done.

In evaluating the potential for changes in water quality, it is important to consider changes that have already occurred but have not been documented. Instances of contamination from land disposal of solid and liquid wastes have been documented, and much of the documentation is from monitoring well data. Because monitoring wells are presently installed at only a small number of these disposal sites, contamination that may have occurred at unmonitored sites remains undetected. Increased monitoring and regulatory efforts will continue to locate local contamination from leaking underground storage tanks.

Protecting recharge areas from contamination is important. Contaminants introduced in the recharge area have the potential for irreversible contamination of large areas of the aquifer. For the sand and gravel aquifer and uppermost bedrock aquifers, recharge (and the potential for contamination) occurs over their entire areal extent. For confined aquifers, such as the sandstone aquifer in eastern Wisconsin, the predominant recharge area can be a considerable distance from the point of ground-water withdrawal.

Changes in land use create the potential for water-quality changes. Acreage of irrigated agricultural crops in areas such as the central sand plain is expected to increase, thereby increasing the potential for ground-water contamination by fertilizers and pesticides. Conversion of rural land to suburban and urban uses poses a number of threats to ground water, including discharges from septic systems and increased use of road salt.

GROUND-WATER-QUALITY MANAGEMENT

Ground-water management practices in Wisconsin changed substantially in 1983 with the passage of comprehensive ground-water legislation contained in Wisconsin Act 410. Chapter 160 of the Wisconsin Statutes, created as part of this legislation, defines the responsibilities of State agencies with respect to ground water and provides for establishment of ground-water-quality standards, coordination of nonregulatory ground-water activities, compensation to owners of contaminated water-supply wells, and certification of water-quality laboratories. Existing regulations covering well-construction codes and registration of well drillers remain in place.

The DNR has lead responsibility for ground-water management. Within the DNR, the Bureau of Water Resources Management has responsibility for coordination of DNR programs, planning, data management, and development of ground-water-quality standards. Other programs in the DNR that have responsibilities related to ground water are in the Bureaus of Water Supply, Wastewater Management, and Solid and Hazardous Waste Management, and the Office of Technical Services.

Other State agencies also have responsibilities related to ground-water management. The Department of Health and Social Services (DHSS) advises the DNR on toxicology and has a major role in developing the ground-water-quality standards. The DILHR is responsible for regulation of private sewage-disposal systems (septic systems) and buried petroleum storage tanks. The Department of Agriculture, Trade, and Consumer Protection (DATCP) regulates fertilizer storage, animal-waste management, and pesticides; responsibilities for pesticides include enforcement of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and regulation of the manufacture, sale, and use of pesticides in Wisconsin. The Department of Transportation (DOT) regulates the bulk storage of road salt. The Wisconsin Geological and Natural History Survey (WG&NHS) is responsible for the inventory and mapping of geologic and hydrologic resources of the State; programs include basic-data collection and research. The University of Wisconsin has responsibilities for education, basic and applied research, and technical assistance in ground-water management. Both the WG&NHS and the DNR have cooperative ground-water resources programs with the U.S. Geological Survey.

The 1983 ground-water legislation requires that DNR adopt ground-water-quality standards. Chapter NR 140 of the Wisconsin Administrative Code (Wisconsin Department of Natural Resources, 1985) was enacted to meet this requirement. Chapter NR 140 sets two levels of standards—an enforcement standard set at the maximum allowable concentration, and a preventive action limit (PAL) set at 10 to 20 percent, depending on the constituent, of the enforcement standard. The PALS serve as an early-warning system to trigger an evaluation of the need for possible remedial action. As of June 1986, public health standards have been set for 39 constituents, and esthetic or public welfare standards have been set for 10 constituents and properties. Enforcement standards for constituents and properties covered by State drinking-water standards are set at the maximum allowable level specified in the drinking-water standards. All State agencies that regulate potential sources of ground-water contamination are required to use these standards. The DNR also is required to develop a monitoring program to ensure compliance with the standards.

Chapter 160 of the Wisconsin Statutes establishes the duties of the Wisconsin Groundwater Coordinating Council. Members of the Council include the State Geologist and representatives from the Governor's office, the University of Wisconsin, and each State agency responsible for ground-water management. The Council is required to advise and assist State agencies in coordination of nonregulatory programs and exchange of information related to ground water. The Council must report annually to the Legislature on its progress.

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Drilling a deep test well in southwestern Wisconsin. This well was used to measure hydraulic head and water quality differences between individual units of the sandstone aquifer. (Photograph by James T. Krohelski, U.S. Geological Survey.)

Prepared by Phil A. Kammerer, Jr., U.S. Geological Survey. Assistance of numerous members of the staff of the Wisconsin Department of Natural Resources is gratefully acknowledged

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Wyoming

Ground-Water Quality

Ground water that is suitable for most uses has contributed to the development of Wyoming. Wells and springs provide drinking water for 65 percent of the population (fig. 1) and are the principal source of water for livestock (U.S. Geological Survey, 1985). In many parts of the State, ground water is the only source of water because surface water is absent, unreliable, or already appropriated. Most ground-water withdrawals in Wyoming are used for irrigation (69 percent) and industry (24 percent), which include power generation, secondary and tertiary oil recovery, and uranium mining and processing.

Ground-water quality (fig. 2) differs greatly between and within aquifers throughout Wyoming. Dissolved-solids concentrations commonly are large. Where dissolved-solids concentrations are large, usually the concentrations of sulfate or chloride generally are large also. Naturally occurring, but large concentrations of fluoride, selenium, iron, manganese, radionuclides, and hardness are also common (fig. 3).

Despite the small population density (fig. 1), ground water has been contaminated in localized areas of Wyoming. The most common contaminants are gasoline and diesel fuel leaking from underground storage tanks, and nitrate from septic-tank leach fields, from applied fertilizers, and from corrals and feedlots. The potential for ground-water contamination exists from the 17,000 tons of hazardous wastes reported to be produced annually in Wyoming (Wyoming Department of Environmental Quality, 1987). These wastes include only the hazardous wastes that are regulated by the U.S. Environmental Protection Agency (EPA) under provisions of the Resource Conservation and Recovery Act (RCRA) of 1976. In addition, the U.S. Department of Defense has recommended 17 sites at 1 facility for a comprehensive survey to determine whether contamination exists.

In general, the water-quality data do not indicate widespread contamination. The data generally reflect only samples collected from wells that are not in areas of contamination and analyses that were limited to major inorganic constituents commonly found in ground water. Data for potential organic contaminants in ground water, including pesticides, are not available for most areas in the State.

WATER QUALITY IN PRINCIPAL AQUIFERS

More than 100 different aquifers are used for ground-water supplies in Wyoming (Larson, 1984, p. 12), some of which have been grouped into four principal aquifers (U.S. Geological Survey, 1985, p. 453). From youngest to oldest, these aquifers are the alluvial aquifer, the High Plains and equivalent aquifers, the structural basin aquifer, and the carbonate and sandstone aquifer (figs. 2*A*, 2*B*).

Ground-water quality in Wyoming is affected by both natural conditions and human activities. About 60 percent of ground-water samples collected from principal aquifers in Wyoming contain large dissolved-solids concentrations. Much of the ground water in Wyoming is naturally hard. Large nitrate concentrations are not common but are a concern locally because large concentrations are potentially lethal to infants. Large nitrate concentrations, which are mostly associated with human activities (Larson, 1984, p. 62), are most common in water from the alluvial aquifer and where the other aquifers occur at shallow depths. Large concentrations of fluoride generally are found in water from the structural basin aquifer. Large concentrations of selenium have been measured in about 2 percent of the 225 ground-water analyses in the U.S. Geological Survey's water-quality file, as of 1983 (Larson, 1984, p. 67). In addition to data in the file, Crist (1974) documented concentrations as large as 1,300 μg/L (micrograms per liter) in water samples from wells in a 725-mi² (square mile) area near Casper. However, statewide data are too sparse to define the location and extent of all large concentrations of selenium.

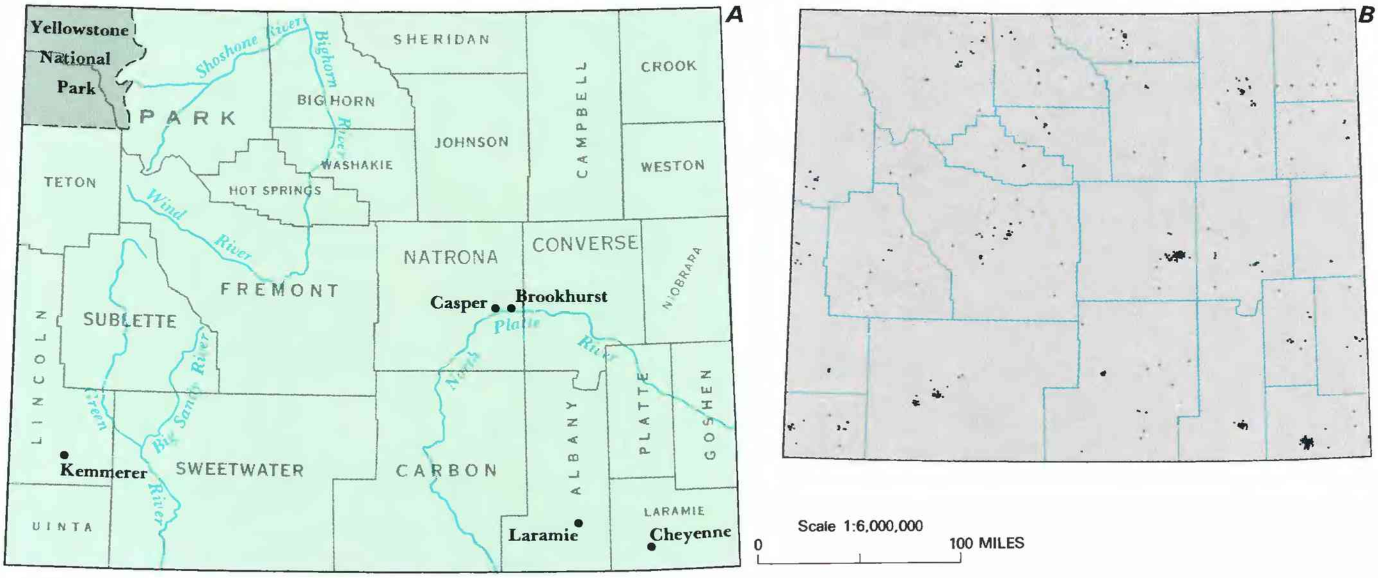

Figure 1. Selected geographic features and 1985 population distribution in Wyoming. *A*, Counties, selected cities, and major drainages. *B*, Population distribution, 1985; each dot on the map represents 1,000 people. (Source: *B*, Data from U.S. Bureau of the Census 1980 decennial census files, adjusted to the 1985 U.S. Bureau of the Census data for county populations.)

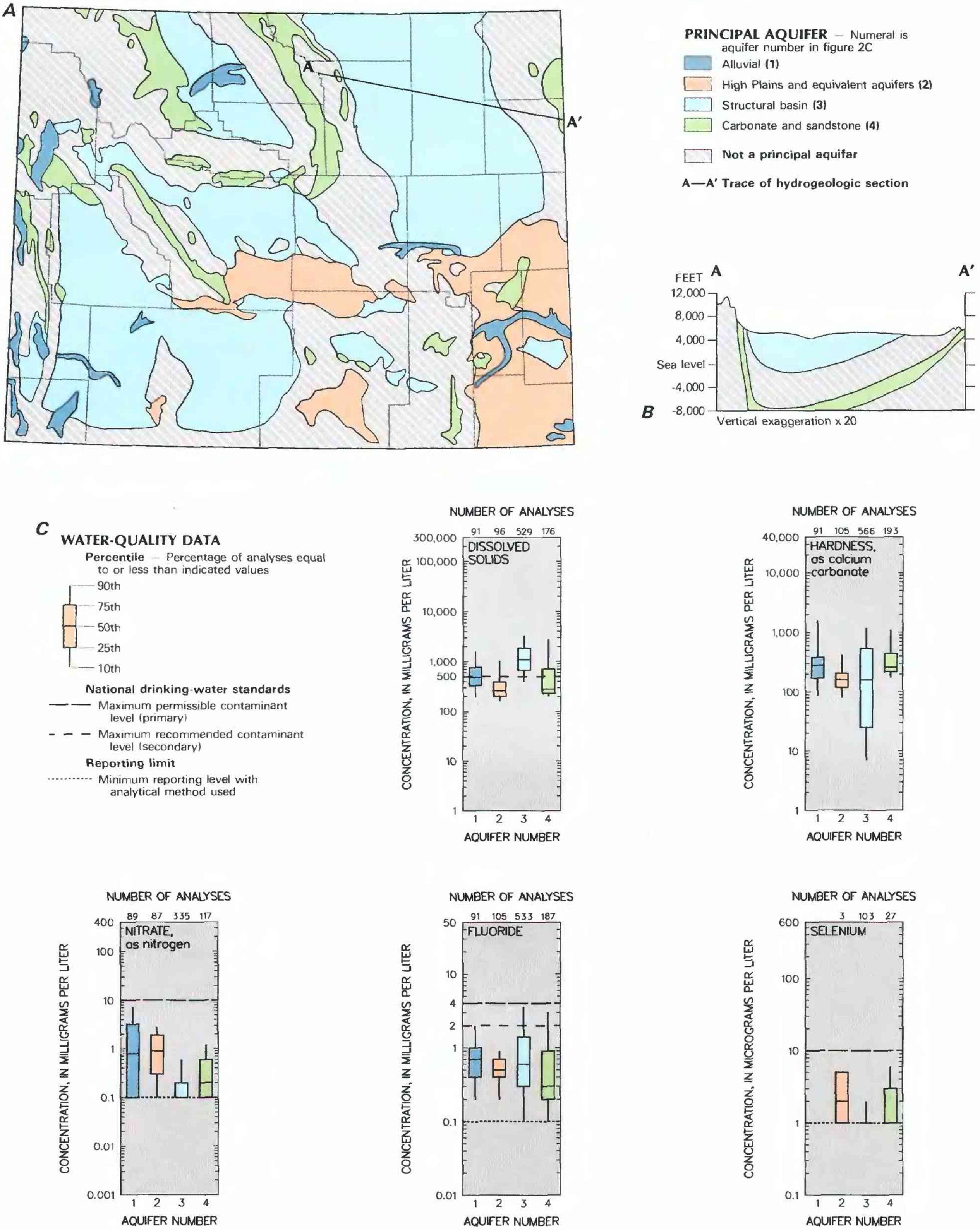

Figure 2. Principal aquifers and related water-quality data in Wyoming. *A*, Principal aquifers. *B*, Generalized hydrogeologic section. *C*, Selected water-quality constituents and properties, as of 1960–85 (Sources: *A*, *B*, U.S. Geological Survey, 1985. *C*, Analyses compiled from U.S. Geological Survey files; national drinking-water standards from U.S. Environmental Protection Agency, 1986 a,b.)

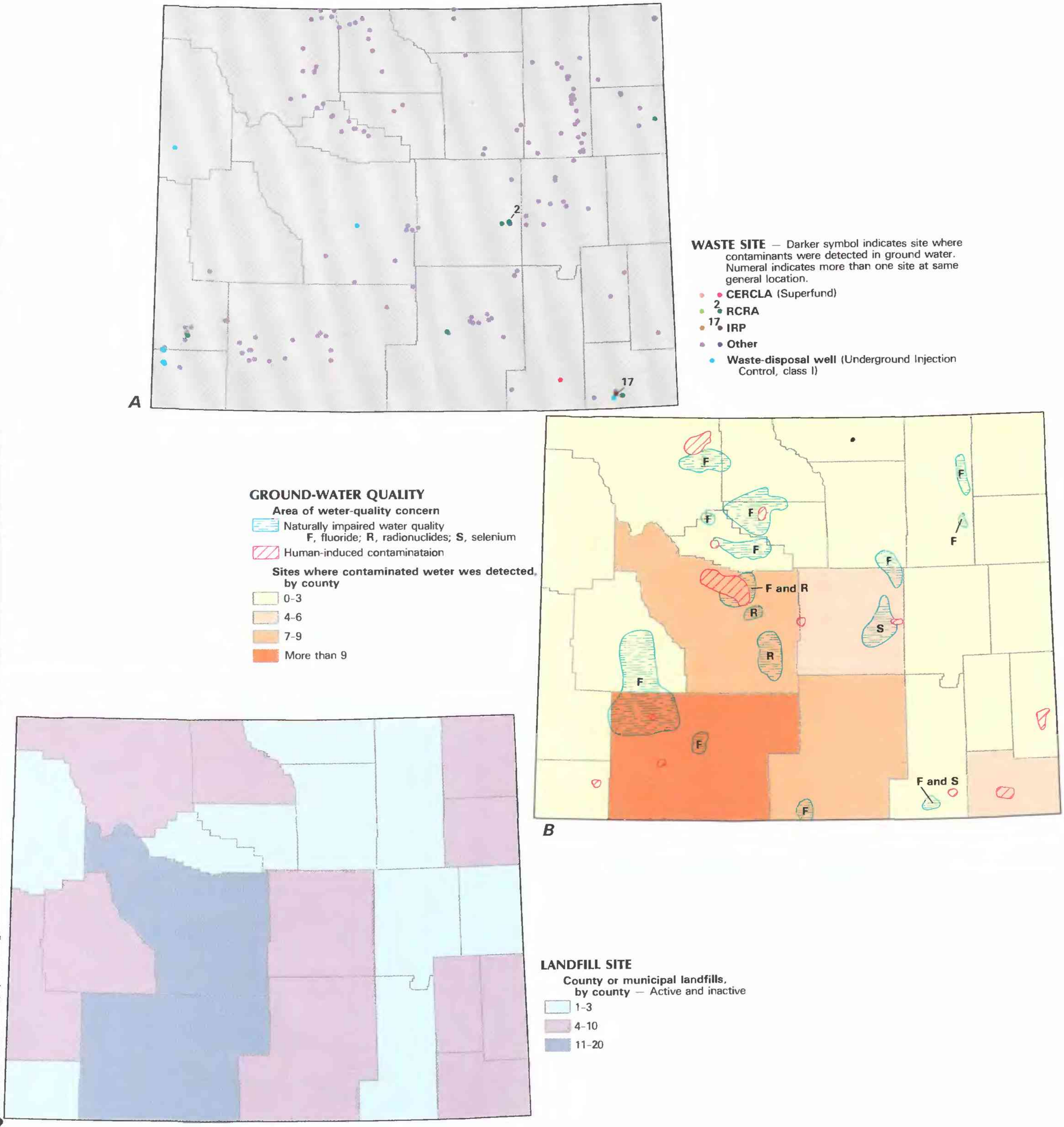

Figure 3. Selected waste sites and ground-water-quality information in Wyoming. *A*, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites, as of 1986; Resource Conservation and Recovery Act (RCRA) sites, as of 1986; Department of Defense Installation Restoration Program (IRP) sites, as of 1985; and other selected waste sites, as of 1986. *B*, Areas of naturally impaired water quality, areas of human-induced contamination, and well sites where contaminated water was detected, as of 1986. *C*, County and municipal landfills, as of 1986. (Sources: *A*, U.S. Environmental Protection Agency, 1986c; U.S. Department of Defense, 1986; Michael Carnevale, Wyoming Department of Environmental Quality, written commun., 1986. *B*, Association of State and Interstate Pollution Control Administrators, 1985; Michael Carnevale, Wyoming Department of Environmental Quality, written commun., 1986. *C*, Michael Carnevale, Wyoming Department of Environmental Quality, written commun., 1986.)

Concentrations of other toxic metals elements, such as dissolved arsenic, barium, cadmium, chromium, lead, and mercury, in ground water from the principal aquifers generally do not limit water use in Wyoming. Large iron and manganese concentrations, which are objectionable for esthetic and economic reasons, are fairly common in water that is used for domestic purposes (Larson, 1984, p. 68).

BACKGROUND WATER QUALITY

The concentrations of dissolved solids, hardness, nitrate, fluoride, and selenium in water from the four principal aquifers are graphically summarized in figure 2*C* from data stored in the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE). The summary is based on analyses of water samples collected from 1960 to 1985 from the principal aquifers in Wyoming. The data reflect the general water quality of the aquifers being used for livestock or domestic supplies.

The percentiles used in figure 2*C* are compared to national standards that specify the maximum concentration or level of a contaminant in drinking-water supply as established by the U.S. Environmental Protection Agency (1986a,b). The primary maximum contaminant standards are health related and are legally enforceable. The secondary maximum contaminant standards apply to esthetic qualities and are recommended guidelines. The maximum concentrations permitted by primary drinking-water standards are as follows: nitrate (as nitrogen), 10 mg/L (milligrams per liter); fluoride, 4 mg/L; and selenium, 10 μg/L. The maximum concentrations recommended by secondary drinking-water standards are as follows: dissolved solids, 500 mg/L; fluoride, 2 mg/L.

In applying these water-quality standards, the assumed use of the aquifers is for drinking. However, an evaluation of water quality for other uses would require that other criteria be applied. Generally, if the water is well suited for drinking, it also is well suited for most other uses.

Areas of naturally impaired water quality have been delineated by the Wyoming Department of Environmental Quality (WDEQ) (fig. 3*B*) using data in their files, files of the Wyoming State Engineer, and a report (Wyoming Water Resources Research Institute, 1981) prepared for the EPA. Naturally occurring constituents that cause the water to be impaired include fluoride, selenium, and radionuclides. Most areas (fig. 3*B*) were delineated on the basis of fluoride concentrations exceeding the secondary drinking-water standard of 2 mg/L. Concentrations of selenium larger than 10 μg/L were measured in two areas. Three areas were delineated on the basis of levels of radionuclides larger than 5 pCi/L (picocuries per liter) for radium 226 plus radium 228, larger than 15 pCi/L for gross alpha activity, larger than 8 pCi/L for strontium 90, or larger than 20,000 pCi/L for tritium. Two areas were delineated on the basis of selenium concentrations or radionuclide levels in addition to fluoride concentrations.

Water may be available from more than a single aquifer in some areas, and the data used for figure 3*B* do not represent any one aquifer. Therefore, water that is suitable for domestic use may be available within an area shown as naturally impaired. The areas of naturally impaired water quality (fig. 3*B*) generally are based on a few scattered wells and also represent several different aquifers.

Alluvial Aquifer

The alluvial aquifer, comprised of gravel, sand, silt, and clay, is located in the valleys and terraces adjacent to most large streams in Wyoming (fig. 2*A*). The alluvial aquifer generally is less than 50 feet thick; however, thicknesses may exceed 200 feet in the Bear River and Snake River drainage basins. Only extensive areas of the alluvial aquifer with potential yields of more than 100 gal/min (gallons per minute) are mapped in figure 2*A*. Many small areas of the alluvial aquifer with lesser potential yields are important locally.

Concentrations of dissolved solids and other variables in water samples from the alluvial aquifer (aquifer 1) are graphically summarized in figure 2*C*. Ten percent of the analyses of water samples collected from the alluvial aquifer had dissolved-solids concentrations of 192 mg/L or less; 25 percent were 330 mg/L or less. The median concentration was 480 mg/L. Seventy-five percent of the concentrations were 760 mg/L or less, and 90 percent were 1,580 mg/L or less. Slightly more than 50 percent of the dissolved-solids concentrations did not exceed the secondary drinking-water standard of 500 mg/L.

Most water from the alluvial aquifer was very hard. The median hardness concentration was 280 mg/L (as calcium carbonate)—the largest median concentration of the four principal aquifers.

Nitrate concentrations in 90 percent of the samples did not exceed the drinking-water standard of 10 mg/L (as nitrogen); most of the remaining samples greatly exceeded the limit. The maximum concentration was 70 mg/L (as nitrogen).

Although concentrations of fluoride in about 90 percent of the water samples from the alluvial aquifer did not exceed the secondary drinking-water standard of 2 mg/L (fig. 2*C*), concentrations in 9 percent of the samples exceeded the primary drinking-water standard of 4 mg/L. Nearly all large fluoride concentrations were measured in water samples collected from alluvial aquifers in Yellowstone National Park. (Large fluoride concentrations commonly are associated with volcanism.) Concentrations of fluoride ranged from 0.1 to 9.1 mg/L, and the median concentration was 0.7 mg/L.

Selenium concentrations exceeded the 10-μg/L standard in 36 of 83 samples collected from the alluvial aquifer in a 725-mi^2 irrigation project near Casper (Crist, 1974); the largest concentration was 1,300 μg/L. These samples were collected from an area where selenium is known to be a problem. They are not representative of selenium concentrations found in ground-water samples collected from the alluvial aquifer in the remainder of the State.

Other than in the area near Casper, only three ground-water samples collected from the alluvial aquifer and analyzed for selenium are contained in the data base; therefore, selenium data for the alluvial aquifer are not included in figure 2*C*. All three concentrations were at or below the 1-μg/L detection limit.

High Plains and Equivalent Aquifers

Large yields of water from wells and excellent water quality make this aquifer a valuable water resource. Wells in the unconsolidated to consolidated gravel, sand, and silt of the High Plains and equivalent aquifers provide water that is well suited and most commonly used for irrigation, public, livestock, and domestic supplies.

Water samples from the High Plains and equivalent aquifers had the smallest median dissolved-solids concentration (260 mg/L) of the four principal aquifers (fig. 2*C*). Concentrations of dissolved solids in about 80 percent of the water samples from the High Plains aquifer in southeastern Wyoming and equivalent aquifers in southern Carbon County were smaller than the recommended drinking-water standard of 500 mg/L. However, dissolved-solids concentrations were smaller than the recommended drinking-water standard in 60 percent of the water samples from an equivalent aquifer in southern Carbon County (Larson, 1984, p. 23).

Most water samples from the High Plains and equivalent aquifers were moderately hard to hard. The median hardness concentration was 160 mg/L (as calcium carbonate).

Nitrate concentrations in 2 of 87 samples of water from the High Plains and equivalent aquifers exceeded the drinking-water standard of 10 mg/L (as nitrogen). The maximum concentration of nitrate was 176 mg/L (as nitrogen)—the largest in water samples from the four principal aquifers. Although nitrate concentrations generally are small in the water samples from the High Plains and equivalent aquifers, concentrations are locally large around communities.

Fluoride concentrations in water samples from the High Plains and equivalent aquifers generally were less than the secondary drinking-water standard of 2 mg/L. One of the 103 samples, with a concentration of 5 mg/L, exceeded the primary drinking-water standard of 4 mg/L.

Three samples from the High Plains and equivalent aquifers were measured for selenium. The concentrations (1, 2, and 5 μg/L) did not exceed the primary drinking-water standard (10 μg/L).

Structural Basin Aquifer

The structural basin aquifer, found in most structural basins in Wyoming, is the most widespread and most extensively used aquifer in terms of number of wells. This aquifer is the only available source of water in many localities and generally is used by municipalities and rural areas for domestic and livestock supplies. Thickness of the lenticular beds of sandstone, coal, and shale of this aquifer may exceed 5,000 feet. Yields of water to wells generally are less than 50 gal/min. Much of the aquifer is confined, and flowing wells are common.

Although the water quality in the structural basin aquifer generally is well suited for livestock watering, the water commonly is less than desirable for a domestic drinking-water supply. Dissolved-solids concentrations commonly exceed the recommended limit of 500 mg/L. The median dissolved-solids concentration for water samples from the structural basin aquifer was 1,100 mg/L—the largest median of the four principal aquifers. Seventeen percent of the 529 samples did not exceed the recommended limit of 500 mg/L. Ninety-five percent of the samples contained 5,000 mg/L or less, which is suitable for watering livestock.

A median hardness concentration of 160 mg/L (as calcium carbonate) for water samples from the structural basin aquifer is the same as the median concentration for water samples from the High Plains and equivalent aquifers. The structural basin aquifer generally yields water that has been naturally softened by the exchange of calcium and magnesium ions for sodium ions; therefore, water in about 30 percent of the water samples was soft.

Nitrate concentrations in most of the water samples from the structural basin aquifer were at or less than the detection limit (0.1 mg/L, nitrate as nitrogen). Nitrate concentrations exceeded the drinking-water standard in 10 of 335 samples; the maximum concentration was 86 mg/L (as nitrogen).

The median concentration of fluoride in 533 water samples from the structural basin aquifer was 0.6 mg/L—the second largest of the four aquifers. The concentration for the 90th percentile (3.6 mg/L) was the largest of the four principal aquifers. Seventeen percent of the samples had concentrations that exceeded the secondary drinking-water standard of 2 mg/L, and 8 percent exceeded the primary drinking-water standard of 4 mg/L. The maximum fluoride concentration was 13 mg/L.

Selenium concentrations in 93 of 103 water samples collected from the structural basin aquifer were at or below the detection limit of 1 μg/L. Concentrations in 5 percent of the samples exceeded the primary drinking-water standard of 10 μg/L; the maximum concentration was 80 μg/L.

Carbonate and Sandstone Aquifer

The carbonate and sandstone aquifer is recharged where exposed at the edges of the basins in largely uninhabited, mountainous terrain. This aquifer becomes progressively more deeply buried toward the center of the basins. The thickness of limestone, dolomite, and sandstone that compose this aquifer may be several thousands of feet. Large secondary permeability (solution cavities, joints, and fractures) characterizes this aquifer; therefore, large yields of water to wells are possible. Yields of 100 to 700 gal/min are common, but one well near Worland (Washakie County) has reportedly flowed at 14,000 gal/min.

Although the water quality is excellent at or near the edges of the basins, fewer wells are completed in this aquifer than in any of the other three aquifers. Because of the great depth to the aquifer except near the edges of the basins, the drilling and completion of a well are too expensive for many potential users. Abundant streamflow and springs in the largely uninhabited recharge areas provide water for livestock and wildlife. Although the dissolved-solids concentrations were small in samples from wells and springs near the recharge areas, concentrations were larger in samples from wells toward the center of the basins. Therefore, location is an important factor in describing the water quality of this aquifer.

The median dissolved-solids concentration in samples collected from wells and springs in the carbonate and sandstone aquifer was 280 mg/L, only slightly larger than the median concentration for water samples from the High Plains and equivalent aquifers. The maximum dissolved-solids concentration in any sample was 9,400 mg/L.

Water from this aquifer tends to be very hard. The median hardness concentration was 260 mg/L (as calcium carbonate).

None of the 117 samples from the carbonate and sandstone aquifer analyzed for nitrate exceeded the drinking-water standard of 10 mg/L (as nitrogen). The maximum concentration was 7.5 mg/L (as nitrogen). Common sources of nitrate contamination generally are absent in the mountainous outcrop area.

The median fluoride concentration (0.3 mg/L) in water from the carbonate and sandstone aquifer is the smallest of the four principal aquifers. Of the 187 water samples from the carbonate and sandstone aquifer, 15 percent exceeded the secondary drinking-water standard (2 mg/L), and 4 percent exceeded the primary drinking-water standard (4 mg/L). The maximum concentration was 6.1 mg/L. All samples that exceeded the primary drinking-water standard for fluoride also had dissolved-solids concentrations that exceeded 2,600 mg/L, which generally is unsuitable for domestic use.

None of the 27 water samples from the carbonate and sandstone aquifer analyzed for selenium had concentrations that exceeded the primary drinking-water standard of 10 μg/L. The median concentration was the detection limit (1 μg/L).

EFFECTS OF LAND USE ON WATER QUALITY

Ground-water quality has changed in some areas of Wyoming because of the effects of waste disposal, agriculture, mineral extraction and processing, and urbanization. Water-quality contaminants at eight sites have been documented under the RCRA of 1980 and one site is on the National Priorities List (NPL) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) of 1980 (fig. 3*A*). Most severe water-quality problems have been local, and the usefulness of principal aquifers has not been impaired (Wyoming Department of Environmental Quality, 1986a). Statewide contamination of aquifers in Wyoming is not a significant problem because of distribution of the industrial development and the sparse population of about 5 persons per mi^2 in 1980 (Wyoming Department of Administration and Fiscal Control, 1983).

Areas of human-induced contamination have been delineated by the WDEQ (fig. 3*B*); contamination sources include waste disposal and leakage from petroleum refineries and industrial facilities, leakage from underground storage tanks, leakage from septic disposal systems, and percolation of fertilizers in irrigated areas. Wells that yield contaminated water shown by county in figure 3*B* may represent one or more wells in a particular area and generally do not represent wells that are used for drinking water.

Waste Disposal

Hazardous wastes currently (1986) are being disposed at sites near Kemmerer in Lincoln County, Casper, Evansville east of Casper, and Sinclair in Carbon County (Wyoming Department of Environmental Quality, 1986b); these are some of the RCRA sites. Six of the RCRA sites are at oil refineries; the soils, water, or both at these sites have been contaminated by chemicals such as benzene, ethylbenzene, toluene, xylene, chloride, sulfate, and phenol. Another RCRA site is a phosphorus-processing plant south of Kemmerer, where large dissolved-solids concentrations are being contributed to the ground water. A railroad tie-treatment facility at Laramie (Albany County) is classified as both a CERCLA or Superfund site and a RCRA site (fig. 3*A*). The site at Laramie is contaminated by the toxic pollutants, creosote and pentachlorophenol.

The WDEQ has applied to the EPA for the classification of the Brookhurst subdivision, which is near the North Platte River east of Casper, as a CERCLA site (identified as "other" in fig. 3*A*). Several domestic wells completed in the alluvial aquifer near an oil refinery and an adjoining industrial area were discovered recently to be contaminated with the suspected carcinogens, benzene and trichloroethylene. Although the extent and source of the contamination have not been defined at this time (1986), the community has been instructed by the WDEQ to obtain an alternative water supply.

Fourteen hazardous-waste sites at Francis E. Warren Air Force Base in Laramie County, Wyoming were identified (September 1985) by the U.S. Department of Defense (DOD) as part of their Installation Restoration Program (IRP) as having potential for contamination (U.S. Department of Defense, 1986). The IRP, established in 1976, parallels the EPA Superfund program under the CERCLA of 1980. The EPA presently ranks these sites under a hazard-ranking system and may include them in the NPL. After an initial assessment completed under the program, 17 sites (fig. 3*A*) were recommended for a comprehensive survey to determine through environmental sampling and analysis whether problems exist (William Metz, U.S. Department of Defense, oral commun., 1987). Remedial action at 1 of these 17 sites is underway.

Although no hazardous wastes are injected into underground wells in Wyoming, eight Class-I Underground Injection Control (UIC) wells (U.S. Environmental Protection Agency, 1984) are permitted by the WDEQ for industrial or municipal wastes (fig. 3*A*). Other injection wells (not shown in fig. 3*A*) in Wyoming include about 4,000 petroleum-related wells, 350 in-situ uranium-related wells, and 400 underground coal-gasification-related wells (Wyoming Department of Environmental Quality, 1987.

Sites identified as "other" in figure 3*A* include 140 industrial landfills and 5 construction and demolition landfills. Each site represents one permit or one proposed permit; each permit may authorize one or more landfills. The number of county and municipal landfills is indicated by county in figure 3*C*. Ground-water quality is not monitored routinely at landfills in Wyoming; therefore, no ground-water-quality data are available for these sites.

Some septic-tank pumpers are contaminating ground water and surface water by improperly disposing of septic-tank wastes (Richards, 1986, p. A-3). The WDEQ reported three such violations and several more suspected incidents that have occurred in the last few years (John Wagner, Wyoming Department of Environmental Quality, oral commun., 1986). The alluvial aquifer and possibly the High Plains and equivalent aquifers would be the most vulnerable to this type of contamination.

Agriculture

Irrigation can increase the concentration of dissolved solids in shallow aquifers. Salts accumulate in the soil after evapotranspiration has consumed the water. Some of the applied irrigation water transports these salts down to the water table. The alluvial aquifer along the Shoshone, Bighorn, and Big Sandy Rivers has been affected by this process (Wyoming Department of Environmental Quality, 1986a). Where soil has small porosity and slow drainage or where the water table locally is high, infiltration from irrigation can cause waterlogging. The fluctuation of the water table combined with evapotranspiration can result in the concentration of salts in the soil and in the ground water, causing an increase in dissolved-solids concentrations. The Wyoming Department of Agriculture (WDA) began a monitoring program in 1986 to determine the possible degradation of ground-water quality resulting from irrigation.

Contamination by nitrate is fairly common in agricultural areas of Wyoming. Nitrates are leached from corrals and feedlots into the ground water. Nitrate fertilizers used on crops also may increase nitrate concentrations in ground water. Large nitrate concentrations have been detected in ground-water samples from wells in agricultural areas in Laramie, Goshen, Fremont, Washakie, Bighorn, and Park Counties (fig. 3*B*).

The WDA has monitored surface water for the presence of pesticides for several years. Although contamination of ground water by pesticides has not been well documented in Wyoming, extensive usage presents a potential problem.

Mineral Extraction and Processing

Large dissolved-solids concentrations in ground water have been associated with spoil material at coal mines and tailings-disposal sites at trona mines. Concentrations of dissolved solids in spoil water at the mine sites generally are larger than concentrations in water from nearby stock and domestic wells, but some of the spoil water is acceptable for use by livestock. Few people are affected by these large dissolved-solids concentrations because of the sparse population near the mines and the slow rate of ground-water movement from mine spoils.

The WDEQ lists 10 sites where seepage from uranium tailings ponds has escaped past the pumpback systems to increase concentrations of dissolved solids, sulfates, chlorides, and radionuclides in the structural basin aquifer (Michael Carnevale, Wyoming Department of Environmental Quality, written commun., 1986). Leachates from five uranium mines have extended beyond the recovery wells. Seepage from a tailings pond at a uranium processing mill in Fremont County is locally contaminating ground and surface water with cyanide, trace metals, and arsenic; the site is being investigated by the WDEQ.

Experimental underground coal-gasification burns have contaminated ground water at three facilities—in Campbell, Carbon, and Converse Counties. These areas have been contaminated locally by suspected carcinogens and constituents included on the EPA's priority list (U.S. Environmental Protection Agency, 1986c).

Urbanization

Sources of ground-water contamination within urbanized areas include leaking underground petroleum-product storage tanks and septic-tank leach fields. Leaking gasoline- and diesel-fuel storage tanks in or near various communities have contaminated local ground water. The WDEQ lists 55 such sites that have been or are being investigated pending additional ground-water-monitoring data (Tom Williams, Wyoming Department of Environmental Quality, written commun., 1987). Eight additional sites where diesel refueling, solvent spills, and illegal waste pits may have contributed hazardous toxic contaminants to the local ground water also are being investigated by WDEQ. This local contamination has occurred most commonly in aquifers underlying Wyoming's communities.

Wells serving several Wyoming communities have concentrations of nitrate exceeding the drinking-water standard. These wells are contaminated generally as the result of too many septic-tank-disposal systems in too small an area. Nitrate is the primary ground-water contaminant in Laramie County (fig. 3*B*).

POTENTIAL FOR WATER-QUALITY CHANGES

Changes in water quality may be expected in the future. These changes include increased nitrate concentrations in agricultural and urban areas, increased dissolved-solids concentrations in irrigated and mined areas, and contamination by petroleum products. Pesticides in ground water have been documented in many agricultural areas outside Wyoming; however, studies in Wyoming are just beginning.

Future contamination by nitrate in areas associated with the application of fertilizers and the use of septic tanks, such as in agricultural and urban areas, may be expected. The aquifers that most commonly occur in agricultural and urbanized areas are the alluvial aquifer and the High Plains and equivalent aquifers. Of these, the alluvial aquifer is very susceptible to nitrate contamination. The water table usually is very shallow, and the sand and gravel typical of this aquifer are very permeable. Nitrate concentrations may be expected to remain relatively small in water from the structural basin aquifer primarily because the areas of occurrence are not significantly agricultural or urbanized. The structural basin aquifer also is much less susceptible to nitrate contamination because the depth to the water table generally is large, and the material between the land surface and the producing saturated zone is relatively impermeable.

Dissolved-solids concentrations generally may be expected to increase in irrigated and mined areas. Irrigation with ground water generally is practiced where either the alluvial aquifer or the High Plains and equivalent aquifers are present. Large dissolved-solids concentrations also are associated with mine spoils and may be expected to increase in mined areas. Mining generally occurs in the structural basin aquifer areas. Most water-quality changes in the structural basin aquifer are considered to be long term because of the slow movement of ground water in these units.

Contamination of ground water by petroleum products is fairly common in Wyoming, and contamination occurrences can be expected to increase as storage tanks and pipelines age, increased leakage occurs. Increased development of petroleum resources also increases the likelihood of accidental spills.

Incomplete data, along with complex geology, hinder any quantitative assessment of future contamination of ground-water supplies in Wyoming. Data are too sparse to permit spatial and vertical assessment of ground-water quality in many aquifers. The U.S. Geological Survey currently (1986) is studying the quality of water in and near several coal-spoil sites and the occurrence of selenium in surface water and ground water. These studies will improve the water-quality data base. Nevertheless, ground-water contamination can be expected to increase, based on the increasing number of sites where contamination or the potential for contamination, already has been identified.

The distribution of the industrial development and the relatively sparse urbanization in Wyoming currently (1986) decreases the potential for any statewide threat of contamination of the principal aquifers. However, continued regulation of activities that may contaminate ground water, as well as the development of a comprehensive statewide ground-water-quality network, would protect the future ground-water quality in Wyoming.

GROUND-WATER-QUALITY MANAGEMENT

The WDEQ—the principal State agency responsible for protecting the quality of ground water in Wyoming—shares and coordinates this responsibility with the EPA. The WDEQ was created in 1973 in response to the Federal Water Pollution Control Act of 1972.

Other State agencies also have regulatory responsibility for activities that potentially affect ground-water quality. The WDA regulates the use of pesticides and has monitored surface water for the presence of pesticides for several years. The Oil and Gas Commission regulates injection wells related to the production of oil and gas. The Wyoming State Engineer is charged by the Wyoming constitution with the administration of all waters within the State. Well permits are issued and water rights are administered by the Wyoming State Engineer's Office.

Three divisions in the WDEQ deal with ground-water quality—the Water Quality Division, the Land Quality Division, and the Solid Waste Management Program. The Water and Land Quality Divisions require monitoring of ground-water pollution through statutory requirements for commercial and research licenses. The Ground Water Operations Section of the Water Quality Division has the responsibility to protect both present and potential uses of ground water in Wyoming; the Section reviews construction plans and issues permits for surface facilities and underground injection control facilities. The Solid Waste Management Program regulates the operation of existing landfills and the design, location, and operation of new sites.

The Water Quality Division is also responsible for administering and enforcing the Wyoming Oil and Hazardous Substance Pollution Contingency Plan (Wyoming Department of Environmental Quality, 1986b). Although all spills must be reported to the Water Quality Division within 24 hours, the degree of Water Quality Division involvement in such situations is dependent upon the severity and complexity of the spill. Any necessary notification of downstream users and other agencies is conducted by the Water Quality Division. The State of Wyoming may recover not only State response expenses and penalties, but also costs for replacement of natural resources and wildlife. The Wyoming Game and Fish Department has a major role in these later efforts.

The EPA has primary responsibility for administering the RCRA and CERCLA sites. The EPA also enforces the national primary drinking-water regulations. Although the State does not have primary responsibility, a State permit is required for any disposal of hazardous waste in Wyoming. During 1985, the Solid Waste Management Program began requiring applications for hazardous-waste disposal.

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SUPPLEMENTAL INFORMATION

GLOSSARY

NATIONAL DRINKING-WATER REGULATIONS

CHEMICAL AND COMMON NAMES OF ORGANIC COMPOUNDS

CONVERSION FACTORS

GEOLOGIC-AGE CHART

Glossary

Absorption—Process by which substances in gaseous, liquid, or solid form are assimilated or taken up by other substances.

Acre-foot—Volume of water required to cover 1 acre of land (43,560 square feet) to a depth of 1 foot; equivalent to 325,851 gallons.

Adsorption—Adherence of gas molecules, ions, or molecules in solution to the surface of solids.

Alluvium—General term for deposits of clay, silt, sand, gravel, or other particulate rock material laid down by a river in a streambed, on a flood plain, on a delta, or at the base of a mountain.

Anion—Ion that has a negative electrical charge; for example, nitrate and chloride ions are anions.

Annular space (annulus)—The space between casing or well screen and the wall of a drilled hole.

Aquaculture—cultivation of organisms that inhabit water; for example, fish farming.

Aquifer—A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquifer system—A heterogeneous layered body of aquifers and confining units that functions regionally as a hydraulic unit; it comprises two or more aquifers separated at least locally by confining unit(s) that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system.

Artesian aquifer—*See* Confined aquifer.

Artesian well—Well tapping a confined aquifer in which the static water level is above the top of the aquifer; a flowing artesian well is a well in which the water level is above the land surface.

Base flow—Sustained low flow of a stream. In most places, base flow is ground-water inflow to the stream channel.

Basement—Assemblage of metamorphic and (or) igneous rocks underlying stratified rocks.

Basal ground water *or* Basal lens—Term that originated in Hawaii and refers to a major body of fresh ground water in contact with underlying saline water in the lowermost part of the flow system.

Bedrock—General term for consolidated (solid) rock that underlies soils or other unconsolidated material.

Biodegradation—Transformation of an organic substance into new compounds through biochemical reactions. Commonly, toxic organic compounds are degraded into smaller, less-toxic organic molecules; in some instances, the new compounds can be more toxic than the original substances.

Bolson—Extensive, flat, saucer-shaped, alluvium-floored basin or depression, almost or completely surrounded by mountains from which drainage has no surface outlet; a term used in the desert regions of Southwestern United States.

Bolson plain—Broad, intermontane plain in the central part of a bolson underlain by thick alluvial deposits washed into the basin from the surrounding mountains.

Brackish—Water that contains between 1,000 and 10,000 milligrams per liter of dissolved solids. *See also* Saline water.

Brine—Water that contains more than 35,000 milligrams per liter of dissolved solids. *See also* Saline water.

Cation—Ion that has a positive electrical charge; for example, sodium and calcium ions are cations.

Chemigation—Application of pesticides or fertilizers to farmlands through irrigation systems.

Chert—Any impure, flintlike rock, essentially of cryptocrystalline quartz or fibrous chalcedony, usually dark in color.

Clastic—Composed of preexisting fragments of rocks or organic structures.

Coliform group—Group of several types of bacteria that are found in the alimentary tract of warm-blooded animals. The bacteria are often used as an indicator of animal and human fecal contamination of water.

Commercial withdrawals—Water for use by motels, hotels, restaurants, office buildings, commercial facilities, and civilian and military institutions. The water may be obtained from a public supply or may be self supplied.

Cone of depression—Depression in the potentiometric surface around a well, or group of wells, from which water is being withdrawn.

Confined aquifer—Aquifer in which ground water is confined under pressure that is significantly greater than atmospheric pressure. Synonym: Artesian aquifer. *See also* Aquifer, Semiconfined aquifer, *and* Unconfined aquifer.

Confined ground water—Water in an aquifer that is bounded by confining beds and is under pressure significantly greater than atmospheric.

Confining bed—Layer of rock having very low hydraulic conductivity that hampers the movement of water into and out of an adjoining aquifer.

Conjunctive use—Combined use of ground and surface waters.

Connate water—Water entrapped in the interstices of sedimentary rock at the time of its deposition.

Consumptive use—Water that has been evaporated, transpired, or incorporated into products, plant tissue, or animal tissue and, therefore, is not available for immediate reuse. Also referred to as water consumption.

Contamination—Degradation of water quality as a result of human activity.

Crop out—To appear exposed and visible at the Earth's surface. *See also* Outcrop.

Crystalline rock—Rocks consisting of minerals in a crystalline state. Usually refers to rocks of igneous or metamorphic origin.

Desorb—To free from a sorbed state; to remove a sorbed substance by the reverse of adsorption or absorption. *See also* Absorption, Adsorption, *and* Sorb.

Dewatering—Removing or draining water from a streambed, caisson, or mine shaft by pumping or evaporation.

Diffusion—Process whereby particles of liquids, gases, or solids intermingle as a result of their spontaneous movement caused by thermal agitation.

Discharge area (ground water)—An area in which subsurface water, including water in the unsaturated or saturated zone, is discharged to the land surface, to surface water, or to the atmosphere.

Dispersion—Spreading and mixing of chemical constituents in water caused by diffusion and by mixing due to variation in water velocities.

Dissolved oxygen—Oxygen dissolved in water. One of the most important indicators of the condition of a water body. Adequate dissolved oxygen is necessary for the life of fish and other aquatic organisms.

Dissolved solids—Minerals and organic matter dissolved in water.

Domestic withdrawals—Water used for normal household purposes, such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens. Also called residential water use. The water may be obtained from a public supply or may be self supplied.

Drawdown—Difference between the water level in a well before pumping and the water level in the well during pumping. Also, for flowing wells, the reduction of the pressure head as a result of the discharge of water. *See also* Pressure head.

Eolian deposits—Rocks, soils and related deposits that were transported by the wind.

Evapotranspiration—Collective term that includes water discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies and by plant transpiration.

Fall Line—Imaginary line marking the boundary between the ancient, resistant crystalline rocks of the Piedmont province of the Appalachian Mountains, and the younger, softer sediments of the Atlantic Coastal Plain province in the Eastern United States. Along rivers, this line commonly is reflected by waterfalls.

Flow—As used in this report, movement of water.

Fracture—A break in rock units due to structural stresses. Fractures may occur as faults, joints, and planes of fracture cleavage.

Freshwater—Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids; generally more than 500 mg/L is undesirable for drinking and many industrial uses.

Gangue—The valueless rock or mineral aggregates in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining.

Glacial drift—A general term applied to all materials transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier. Includes unstratified material (till) and stratified material.

Glacial fluvial—*See* Glaciofluvial.

Glaciofluvial—Relating to the combined action of glaciers and streams.

Ground water—All subsurface water, including the saturated and unsaturated zone, as distinct from surface water. More commonly used to refer to subsurface water in the saturated zone.

Ground-water divide—Ridge in the water table or other potentiometric surface; ground water moves in both directions normal to the ridge line. *See also* Potentiometric surface *and* Water table.

Ground-water reservoir—Permeable rocks in the zone of saturation. *See also* Aquifer.

Ground-water system—Ground-water reservoir and its contained water. Also, the collective hydrodynamical and geochemical processes at work in the reservoir.

Gypsum—A natural hydrated calcium sulfate, $CaSO_4.2H_2O$. A common evaporite mineral used in the manufacture of plaster of Paris and wall board.

Halite—Rock salt. A mineral, $NaCl$.

Hardness (water)—A property of water that causes the formation of an insoluble residue when the water is used with soap and a scale in vessels in which water has been allowed to evaporate. It is due primarily to the presence of ions of calcium and magnesium. Generally expressed as milligrams per liter as calcium carbonate ($CaCO_3$). A general hardness scale is:

Description	*Milligrams per liter as* $CaCO_3$
Soft	0–60
Moderately hard	61–120
Hard	121–180
Very hard	More than 180

Heap leaching—Process for the recovery of metal from weathered material from mine dumps.

Heavy leachate—Metals present in wastes that may possess long-term environmental hazards. Examples are cadmium, cobalt, chromium, copper, mercury, lead, and zinc.

Heavy metals—Metallic elements with atomic number greater than 36 in Group III through V (including transition elements) of the Periodic Table; the importance of these elements is their generally low solubility but possibly high toxicity in waters.

Hydraulic conductivity—Measure of the ease with which a fluid will pass through a porous earth material, determined by the size and shape of the pore spaces in the material and their degree of interconnection as well as by the viscosity of the fluid; a term replacing "field coefficient of permeability." Hydraulic conductivity may be expressed as cubic feet per day per square foot or cubic meters per day per square meter; hydraulic conductivity is measured at the prevailing water temperature.

Hydraulic gradient—In an aquifer, the rate of change of head per unit of distance in a particular direction. *See also* Pressure head.

Hydraulic head—The height of the column of water above a reference plane (such as sea level) that can be supported by the hydraulic pressure at a given point in a ground-water system.

Igneous rock—Any rock that solidified from molten or partly molten material; igneous rocks constitute one of the three main classes into which all rocks are divided (igneous, metamorphic, sedimentary).

Industrial withdrawals—Water withdrawn for or used for thermoelectric power (electric utility generation) and other industrial and manufacturing uses such as steel, chemical and allied products, paper and allied products, mining, and petroleum refining. The water may be obtained from a public supply or may be self supplied.

Infiltration—Movement of water into soil or porous rock.

Inorganic compounds—Chemical compounds that do not contain carbon as the principal element (excepting carbonates, cyanides, and cyanates).

Insecticide—Type of pesticide designed to control insect life.

Interface—In hydrology, the contact zone between two fluids of different chemical or physical makeup.

Ion—Positively or negatively charged atom or group of atoms. *See also* Anion *and* Cation.

Ion exchange—Reversible chemical replacement of an ion bonded at the liquid-solid interface by an ion in solution.

Irrigation return flow—Part of artificially applied water that is not consumed by evapotranspiration and that migrates to an aquifer or surface-water body. *See also* Return flow.

Irrigation withdrawals—Withdrawal of water for application on land to assist in the growing of crops and pastures or to maintain recreational lands

Isotropy—The condition of having properties that are uniform in all directions.

Karst—Type of topography that results from dissolution and collapse of limestone, dolomite, or gypsum beds and characterized by closed depressions or sinkholes, caves, and underground drainage.

Landfarm—Facility where sewage wastes are spread on the ground to undergo a washing and drying process.

Leachate—Any liquid, including any suspended components in the liquid, that has percolated through or drained from human-emplaced materials.

Leaching—Removal of materials in solution from soil, rock, or waste.

Lithology—The physical character of rocks.

Livestock withdrawals—Drinking and wash water for domesticated animals. *See also* Rural withdrawals.

Loess—Widespread, homogeneous, fine-grained blanket of wind-deposited soil consisting primarily of silt with subordinate grain sizes from clay to fine sand. Usually refers to sediments deposited by the wind.

Longwall—Method of underground mining, especially coal.

Mean—Arithmetic mean of a set of observations, unless otherwise specified; an average of quantity.

Metamorphic rock-Any rock derived from preexisting rocks in response to marked changes in temperature, pressure, shearing stress, and chemical environment at depth in the Earth's crust. Metamorphic rocks constitute one of the three main classes into which all rocks are divided (igneous, metamorphic, and sedimentary).

Metasedimentary rock—Sedimentary rock that shows evidence of having been subjected to metamorphism.

Milliequivalent per unit—Unit that expresses the chemical equivalence of ions or compounds by taking into account their formula weight and ionic charge or valence. The specific units include milligram-equivalents per kilogram if derived from parts per million, or milligram-equivalents per liter if derived from milligrams per liter.

Mining of ground water—Ground-water withdrawals in excess of replenishment. Also referred to as overdraft.

Mud cone—Small cone of sulfurous mud built up around the opening of a mud volcano or mud geyser.

Nonpoint source of pollution—Pollution from broad areas, such as areas of fertilizer and pesticide application and leaking sewer systems, rather than from discrete points.

Normal—As used by the meteorological profession, average (or mean) conditions over a specific period of time; usually the most recent 30-year period; for example, 1951 to 1980.

Offstream use—Water withdrawn or diverted from a ground- or surface-water source for use.

Organic compounds—Chemical compounds containing carbon. Other components include hydrogen, oxygen, chlorine, nitrogen, and other elements.

Outcrop—That part of a geologic unit exposed at the surface of the Earth.

Outwash—Glacially transported sediment deposited by meltwater streams beyond active glacier ice.

Oxidation—Chemical reaction in which there is a transfer of electrons from an ion or atom, thus increasing its net charge or valence. Term derives from reactions involving oxygen; oxygen generally gains electrons when bonding with other elements, thus the elements are said to be "oxidized."

Oxidizing condition—*See* Oxidation.

Perched ground water—Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.

Percolation—Slow laminar movement of water through openings within a porous earth material.

Permafrost—Any frozen soil, subsoil, surficial deposit, or bedrock in arctic or subarctic regions where below-freezing temperatures have existed continuously from two years to tens of thousands of years.

Permeability—Capacity of a rock for transmitting a fluid; a measure of the relative ease of fluid flow in a porous medium.

Pesticide—Any substance, organic or inorganic, used to destroy or inhibit the action of plant or animal pests; major categories of pesticides includes herbicides, insecticides, fungicides, rodenticides, and miticides.

Picocurie (pCi)—Picocurie is one-trillionth (1×10^{-12}) of the amount of radioactivity represented by a curie (Ci). A curie is the amount of radioactivity that yields 3.7×10^{10} radioactive disintegrations per second. A picocurie yields 2.22 dpm (disintegrations per minute).

Point source of pollution—Pollution originating from any discrete source, such as the outflow from a pipe, ditch, tunnel, well, concentrated animal-feeding operation, or floating craft.

Pollution—Presence or addition of any substance to water that is or could become injurious to the public health, safety, or welfare; or that is or could become injurious to domestic, commerical, industrial, agriculture, or other uses being made of the water.

Pollution plume—Area of degraded water in a stream or aquifer resulting from migration of a pollutant.

Porosity—Ratio of the volume of the voids in a rock to the total volume, expressed as a decimal fraction or as a percentage. The term "effective porosity" refers to the amount of interconnected pore spaces or voids in a rock or in soil; it is expressed as a percentage of the total volume occupied by the interconnected pores.

Potable water—Water that is safe and palatable for human use.

Potential evapotranspiration—Water loss by evapotranspiration that will occur if at no time is there a deficiency of water in the soil for use by vegetation.

Potentiometric surface—An imaginary surface representing the static head of ground water in tighty cased wells that tap a water-bearing rock unit (aquifer); or, in the case of unconfined aquifers, the water table.

Precipitation—Atmospheric precipitation, includes rain, snow, hail, and sleet.

Pressure head—Hydrostatic pressure or force per unit area expressed as the height of a column of water that the pressure can support, relative to a specific datum such as land surface or sea level.

Prior appropriation—A concept in water law under which users who demonstrate earlier use of water from a particular source are said to have rights over all later users of water from the same source.

Priority pollutants—A list of toxic chemicals (129 compounds and classes of compounds) prepared by the U.S. Environmental Protection Agency in response to a mandate for publication of toxic pollutants in conformance with the Federal Water Pollution Control Act Amendments of 1972.

Public-supply withdrawals—Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes such as domestic, commercial, industrial, and public supply.

Pyroclastic—Clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin.

Radionuclide—Species of atom that emits alpha, beta, or gamma rays for a measurable length of time. Individual radionuclides are distinguished by their atomic weight and atomic number.

Rainfall—Quantity of water that falls as rain only. Not synonymous with precipitation.

Reaeration—The replenishment of oxygen in water from which oxygen had been removed.

Real-time data—Data collected by automated instrumentation and telemetered and analyzed quickly enough to influence a decision that affects the monitored system.

Recharge (ground water)—Process of addition of water to the ground-water system by natural or artificial processes.

Recharge area (ground water)—An area over which recharge occurs.

Recurrence interval—The average interval of time within which the magnitude of given event, such as a flood or storm, will be equaled or exceeded.

Reduction—Chemical reaction in which there is a transfer of electrons to an ion or atom, thus decreasing its net charge or valence.

Reducing condition—*See* Reduction.

Regulation of a stream—Artificial manipulation of the flow of a stream.

Renewable water supply—Rate of supply of water (volume per unit time) potentially or theoretically available for use in a region on an essentially permanent basis.

Return flow—Amount of water that reaches a ground- or surface-water source after release from the point of use and thus becomes available for further use. Also called return water. *See also* Irrigation return flow.

Riparian rights—A concept of water law under which authorization to use water in a stream is based on ownership of the land adjacent to the stream.

Runoff—That part of the precipitation that appears in surface-water bodies. It is the same as streamflow unaffected by artificial diversions, storage, or other human works in or on the stream channels.

Rural withdrawals—Water used in suburban or farm areas for domestic and livestock needs. The water generally is self supplied and includes domestic use, drinking water for livestock, and other uses such as dairy sanitation, evaporation from stock-watering ponds, and cleaning and waste disposal.

Safe yield (ground water)—Amount of water that can be withdrawn from an aquifer without producing an undesired effect.

Safe yield (surface water)—Amount of water that can be withdrawn or released from a reservoir on an ongoing basis with an acceptably small risk of supply interruption (reducing the reservoir storage to zero).

Saline water—Water that generally is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. Salinity is generally expressed as milligrams per liter (mg/L) of dissolved solids, with 35,000 mg/L defined as seawater. A general salinity scale is:

Description	*Dissolved solids, in milligrams per-liter*
Saline:	
Slightly	1,000 - 3,000
Moderately	3,000 - 10,000
Very	10,000 - 35,000
Brine	More than 35,000

Salinity—*See* Dissolved solids.

Saltwater intrusion—Replacement of freshwater by saline water in an aquifer or body of water.

Saprolite—A soft, earthy, typically clay-rich, rock material formed in place by thorough decomposition by chemical weathering of igneous, sedimentary, or metamorphic rock.

Saturated zone—A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

Schist—Strongly foliated crystalline rock that can be readily split into thin flakes or slabs.

Sea level—Refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929). The NGVD of 1929 is a geodetic datum derived from a general adjustment of the first-order level of nets of the United States and Canada.

Sea water— *See* Saline water.

Sediment—Particles derived from rocks or biological materials that have been transported by water or air.

Sedimentary rock—Rocks formed by the accumulation of rock fragments or particles of various sizes, remains of organisms, precipitation of chemicals, or mixtures of the above.

Seep—Generally small area where water or oil percolates slowly to the land surface.

Semiconfined aquifer—An aquifer that is partially confined by a layer (or layers) of lower permeability material through which recharge and discharge may occur.

Shield volcano—A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava or by rhyolitic ash flows.

Shut-in pressure—Reservoir pressure as recorded at the well head when the valves are closed and the oil or gas well is shut in.

Silviculture—A branch of forestry dealing with the development and care of forest.

Sinkhole topography—*See* Karst.

Skimming well—Well used to skim freshwater from above saline water.

Sludge—Any semi-solid waste, as from a chemical process or sewage treatment plant.

Soft water—*See* Hardness (water).

Sole-source aquifer—An aquifer designated as the "sole" water-supply source in an area for the purpose of protecting the water quality in the aquifer. The aquifer must be the principal source of water and supply 50 percent or more of the drinking water for the area. Designation is by petition to the U.S. Environmental Protection Agency under the Safe Drinking Water Act.

Sorb—To take up and hold either by absorption or adsorption. *See also* Absorption *and* Adsorption.

Spoil—Non-ore or other waste material removed in mining, quarrying, dredging, or excavating.

Specific capacity (of a well)—The rate of discharge of a water well per unit of drawdown, commonly, expressed in gallons per minutes per foot.

Specific discharge—Rate of discharge of ground water per unit area of the porous medium measurement at right angles to the direction of flow.

Specific yield—Ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity from that mass.

Stage—Height of the water surface in a reservoir or a river above a predetermined point (may be on or near the channel floor). Used interchangeably with gage height.

Storage coefficient—The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

Strip mining—*See* Surface mining.

Stripper well—An oil well that produces such small quantities of oil that the cost of operation is nearly as great as the revenue from the sale of the oil produced.

Subcrop—Areal limits of a buried rock unit at a surface of unconformity.

Surface mining—Mining method whereby the overlying materials are removed to expose the ore for extraction.

Swallet—Sinking stream (surface stream that disappears underground in a karst region).

Thermal loading—The amount of waste heat discharged to a water body.

Thermoelectric power—Electrical power generated by use of fossil-fuel (coal, oil, or natural gas), geothermal, or nuclear energy.

Till—Dominantly unsorted and unstratified drift, generally unconsolidated, deposited directly by and beneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

Toxic—*See* Toxicity.

Toxicity—The toxic hazard of a material may depend on its physical state and on its solubility in water and acids. For example, some metals that are harmless in solids or bulk form are quite toxic as fume, powder, or dust.

Transpiration—Process by which water passes through living organisms, primarily plants, and into the atmosphere.

Transmissivity—The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Trough—In meteorology, an elongated area of relatively low atmospheric pressure; the opposite of a ridge. This term commonly is used to distinguish a feature from the closed circulation of a low (or cyclone). A large-scale trough, however, may include one or more lows, and an upper-air trough may be associated with a lower-level low. In ground water, an elongated depression in a potentiometric surface.

Turbidity—The opaqueness or reduced clarity of a fluid due to the presence of suspended matter.

Unconfined aquifer—Aquifer whose upper surface is a water table free to fluctuate.

Underground water—*See* Ground water.

Unsaturated zone—A subsurface zone in which not all interstices are filled with water; usually the interval between the land surface and the water table.

Upconing—Process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone as a result of pumping water from the freshwater zone.

Volatile organic compounds (voc's)—A group of lightweight, synthetic organic compounds, many of which are aromatic; sometimes referred to as "purgeable organic compounds" because of their low solubility in water.

Water budget—An accounting of the inflow to, outflow from, and storage changes of water in a hydrologic unit.

Water content of snow—*See* Water equivalent of snow.

Water demand—Water requirements for a particular purpose, such as irrigation, power, municipal supply, plant transpiration, or storage.

Water equivalent of snow—Amount of water that would be obtained if the snow could be completely melted. Free-water content is the amount of liquid water in the snow at the time of observation.

Water exports—Artificial transfer (pipes, canals) of water from one region or subregion to another.

Water imports—Artificial transfer (pipes, canals) of water to one region or subregion from another.

Water-resources region—Natural drainage basin or hydrologic area that contains either the drainage area of a major river or the combined areas of a series of rivers. In the United States, there are 21 regions of which 18 are in the conterminous United States and one each in Alaska, Hawaii, and the Caribbean.

Water-resources subregion—The 21 water-resources regions of the United States are subdivided into 222 subregions. Each subregion consists of the area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin(s), or a group of streams forming a coastal drainage area.

Water rights—Legal rights to the use of water. *See* Prior appropriation *and* Riparian rights.

Water table—Top of the saturated zone in an unconfined aquifer. The water level in wells that penetrate the uppermost part of an unconfined aquifer marks the position of the water table. *See also* Saturated zone.

Water-table aquifer—*See* Unconfined aquifer.

Water year—A continuous 12-month period selected to present data relative to hydrologic or meteorologic phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30.

Withdrawal (of water)—The art of removing water from the ground or diverting it from a surface-water source for use.

NATIONAL DRINKING-WATER REGULATIONS

The U.S. Environmental Protection Agency's National Primary Drinking-Water Regulations and National Secondary Drinking-Water Regulations are summarized in the following tables. The primary regulations specify maximum contaminant levels (MCL), recommended maximum contaminant levels (RCML), and health advisories. The MCL's, which are the maximum permissible level of a contaminant in water at the tap, are health related and are legally enforceable. If these concentrations are exceeded or if required monitoring is not performed the public must be notified. The RMCL's are the maximum levels of a contaminant in drinking water at which no known or anticipated adverse effect on the health of persons would occur; they are nonenforceable health goals. The secondary drinking-water regulations specify the secondary maximum contaminant levels (SMCL). The SMCL's are for contaminants in drinking water that primarily affect the esthetic qualities related to public acceptance of drinking water; they are intended to be guidelines for the States and are not federally enforceable. Health advisories are guidance contaminant levels that would not result in adverse health effects over specified short-time periods for most people.

As provided by the Safe Drinking Water Act of 1974, the U.S. Environmental Protection Agency has the primary responsibility for establishing and enforcing regulations. However, States may assume primacy if they adopt regulations that are at least as stringent as the Federal regulations in levels specified for protection of public health and in provision of surveillance and enforcement. The States may adopt more stringent regulations and may establish regulations for other constituents. As of January 1987, all States and territories have assumed primacy except Indiana, Oregon, Wyoming, and the District of Columbia.

Primary Drinking-Water Regulations

[Extracted from U.S. Environmental Protection Agency, 1986, Maximum contaminant levels (subpart B of part 141, National primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 524–528, 567–568. Data are given in milligrams per liter (mg/L) unless otherwise indicated; mL = milliliters; tu = turbidity; pCi/L = picocurie per liter; mrem = millirem (one thousandths of a rem)]

Constituent or property	Level
Maximum Contaminant Level (MCL)	
Inorganic:	
Arsenic	0.05
Barium	1.0
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate (as N)	10.0
Selenium	0.01
Silver	0.05
Fluoride[1]	4.0
Organic:	
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005
2,4-D	0.1
2,4,5-TP Silvex	0.01
Total trihalomethanes [the sum of the concentrations of bromodichloromethane, dibromochloromethane, tribromomethane (bromoform) and trichloromethane (chloroform)]	0.10
Microbiological:	
Coliform bacteria	1 per 100 mL (mean)
Turbidity:	
Turbidity	1–5 tu
Radionuclides:	
Radium 226 and 228 (combined)	5 pCi/L
Gross alpha particle activity	15 pCi/L
Gross beta particle activity	4 mrem/yr
Recommended Maximum Contaminant Level (RCML)	
Benzene	0.0
Carbon tetrachloride	0.0
p-Dichlorobenzene	0.75
1,2-Dichloroethane	0.0
1,1-Dichloroethylene	0.007
1,1,1-Trichloroethane	0.20
Trichloroethylene	0.0
Vinyl chloride	0.0

[1] A secondary maximum level of 2.0 mg/L also has been established.

Secondary Drinking-Water Regulations

[Extracted from U.S. Environmental Protection Agency, 1986, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1986, p. 587–590. Data are given in milligrams per liter (mg/L) unless otherwise indicated]

Constituent or property	Level (SMCL)
Chloride	250
Color	15 color units
Copper	1
Corrosivity	Noncorrosive
Dissolved solids	500
Fluoride	2.0
Foaming agents	0.5
Iron	0.3
Manganese	0.05
Odor	3 (threshold odor number)
pH	6.5–8.5 units
Sulfate	250
Zinc	5

Health Advisory

[Extracted from U.S. Environmental Protection Agency, 1985, National primary drinking-water regulations—Proposed rules: Federal Register, v. 50, no. 219, p. 46943 and 46980]

Constituent	Level (mg/L)
Sodium	20

SELECTED LISTING OF CHEMICAL AND COMMON NAMES OF ORGANIC COMPOUNDS

Chemicals have a variety of names—chemical names, common names, trade names—that often are used interchangably. As a result, no attempt was made to consistently use the same name(s) throughout the 1986 *National Water Summary*. This listing is an alphabetical presentation of the organic compounds used in the report (1st column), their synonyms (2d column), and their principal uses. Trade names are given in both the 1st and 2d columns and are set in small capital letters (for example, BROCIDE). The numbers in parentheses in the 1st column are Chemical Abstract Service (CAS) registry numbers. These numbers uniquely identify every element and compound of known composition and structure. The CAS registry numbers first were used in American Chemical Society publications and now are prevalent in the technical literature.

Name used in 1986 *National Water Summary* (CAS No.)	Selected synonyms	Principal use
Acetone (67-64-1)	Dimethyl ketone; 2-propanone dimethyl formaldehyde; pyroacetic ether.	Industrial manufacturing chemical, solvent, laboratory reagent.
Alachlor (15972-60-8)	ALONEX; LASSO; metachlor; methachlor.	Herbicide.
Aldicarb (116-06-3)	OMS 771; TEMIK; UC 21149.	Insecticide, acaricide, nematocide.
Aldrin (309-00-2)	Compound 118; HHDN; OCTALENE.	Insecticide.
Ametryn (834-12-8)	Ametrex; EVIK; G-34162; GESAPAX.	Herbicide.
Atrazine (1912-24-9)	AATREX; G 30027; PRIMATOL A.	Herbicide.
Benzene (71-43-2)	Benzol; cyclohexatriene.	Manufacture of medicinal chemicals, and in the production of dyes and other organic compounds; solvent; reagent.
BHC (58-89-9)	APARASIN; APHTIRIA; benzene hexachloride; ent 7796; lindane (gamma-BHC); HCH; hexachlorocyclohexane.	Insecticide, pediculicide, ectoparasiticide.
Bromacil (314-40-9)	BOREA; du Pont herbicide 976, HYVAR URAGON.	Herbicide.
Bromoform (75-25-2)	Methyl tribromide, tribromomethane.	Chemical intermediate in organic synthesis, industrial solvent, mineral separation, sedative.
Butylate (2008-41-5)	S-ethyl N, N-diisobutylthiocarbonate; Sutan.	Herbicide.
Carbaryl (63-25-2)	SEVIN.	Insecticide.
Carbofuran (1563-66-2)	BAY 70143; FURADAN; NIA 10242.	Insecticide, acaracide, nematocide.
Carbon tetrachloride (56-23-5)	BENZINOFORM; NECATORINA; perchloromethane; tetrachloromethane.	Industrial solvent, degreasing agent, organic reagent.
Chlordane (57-74-9)	BELT; CHLOR KIL; chlordan; CORODANE; KYPCHLOR; OCTACHLOR; ortho-klor; VELSICOL 1068.	Insecticide, acaracide.
Chlorobenzene (108-90-7)	Benzene chloride; MCB; monochlorobenzene; phenyl chloride.	Manufacture of a variety of chemical compounds, solvent, heat-transfer medium.
Chlorobenzilate (510-15-6)	ACARABEN; AKAR; compound 338; G23992.	Acaracide.
Chlorodibromomethane (124-48-1)	Dibromochloromethane.	Organic synthesis.
Chloroform (67-66-3)	Trichloromethane.	Fumigant for treatment of agricultural products, industrial solvent, manufacturing chemical.
Chlorothalonil 1897-45-6)	BRAVO; DAC 2787; DACONIL 2878; TERMIL.	Fungicide, bacteriacide, nematocide.
Creosote (8021-39-4)	Beechwood creosote; creasote.	Antiseptic, wood preservative, expectorant, parasiticide.
Cyanazine (21725-46-2)	BLADEX; DW 3418; FORTROL; SD 15418; WL 19805.	Herbicide.
Cyanide (57-12-5)	Carbonnitride ion; cyanide anion; isocyanide; hydrocyanic acid; hydrogen cyanide; prussic acid (74-90-8).	Used in a variety of compounds as a pesticide and rodenticide; manufacturing chemical; leaching and gold plating; laboratory reagent.

Name used in 1986 *National Water Summary* (CAS No.)	Selected synonyms	Principal use
DACTHAL (1861-32-1)	Chlorthal-methyl; DAC-893; DCPA.	Herbicide.
DBCP *See* 1,2-Dibromo-3-chloropropane.		
DCPA *See* DACTHAL.		
DDD (72-54-8)	1, 1-dichloro-2, 2-bis (p-chlorophenyl) ethane; TDE; RHOTHANE.	Insecticide.
DPA (87209-56-1)	BAY 30130; propanil; ROGUE; STAM; SURCOPUR.	Herbicide.
Diazinon (333-41-5)	BASIDUN; G-24480; SPECTRACIDE.	Insecticide, nematocide.
Dibenzofuran (132-64-9)	Diphenylene oxide.	Insecticide.
Dieldrin (60-57-1)	DIELDREX; DIELDRITE; HEOD.	Insecticide.
1,2-Dibromo-3-chloropropane (96-12-8)	DBCP; FUMAZONE; NEMAFUME; NEMAGON.	Soil fumigant.
Dibromochlorometane See Chlorodibromomethane.		
Dichlorobenzene (25321-22-6)	1,2-Dichlorobenzene (95-50-1); 1,4-dichlorobenzene (106-46-7); o-dichlorobenzene; p-dichlorobenzene.	Herbicide, insecticide, solvent, soil fumigant, insecticidal fumigant.
1,1-Dichloroethane (75-34-3)	Chlorinated hydrochloric ether; ethylidene chloride; ethylidene dichloride.	Solvent for plastics, cleaning agent, fumigant, insecticide.
1,1-Dichloroethene (75-35-4)	1,1-Dichloroethylene; vinylidene chloride.	Monomeric intermediate in the production of plastics.
1,1-Dichloroethylene *See* 1,1-Dichloroethene.		
cis-1,2-Dichloroethylene (156-59-2)	Actylene dichloride; cis dichloroethylene; cis-1,2-dichloroethene; DIOFORM.	Industrial solvent, organic synthesis.
1,2-Dichloropropane (78-87-5)	Propylene chloride; propylene dichloride.	Fumigant, insecticide for stored grain, dry-cleaning liquid and solvent.
1,2-Dichloroethane (107-06-2)	BROCIDE; DUTCH LIQUID; ethylene chloride; ethylene dichoride; EDC.	Agricultural fumigant, industrial solvent, laboratory solvent.
trans-1,2-Dichloroethylene (156-60-5)	Acetylene dichloride; trans-dichloroethene; DIOFORM.	Solvent and reagent.
Dichloropropene (542-75-6)	Dichloropropylene; 1,3-dichloropropene (542-75-6); 1,1-dichloro-1-propene (563-58-6), 1,2-dichloro-1-propene (563-54-2); 1,3-dichloro-1-propene (542-75-6); TELONE II.	Soil fumigant.
Dinitrobutylphenol (88-85-7)	DNBP; dinoseb; dinitro; VERTAC.	Herbicide, dessicant.
Dinitrotoluene (2532-11-46)	2,4-Dinitrotoluene (121-14-2); 2,6-dinitiotoluene (606-20-2).	Organic synthesis, dyes, explosives.
Dinoseb *See* Dinitrobutylphenol.		
Dioxane (123-91-1)	1,4-Diethylene dioxide; diethylene ether; diethyene oxide.	Organic solvent.
Dioxin (1746-01-6)	TCDBD; TCDD.	Potential contaminant in the manufacture of trichlorophenol.
DYFONATE (944-22-9)	Fonofos; stauffer 2790.	Insecticide.
Endrin (72-20-8)	Compound 269; hexadrin; mendrin.	Insecticide.
Ethylbenzene (100-41-4)	Phenyl ethane.	Solvent, chemical in the manufacture of rubber.
Ethylene dibromide (106-93-4)	BROMOFUME; dibromoethane, DOWFUME; EDB; E-D-BEE; ethylene bromide.	Chemical catalyst and reagent, fumigant.

Name used in 1986 *National Water Summary* (CAS No.)	Selected synonyms	Principal use
Ethylene dichloride *See* 1,2-Dichloroethane.		
FREON (11126-05-9)	Trade name for a series of fluorocarbon and chlorofluorocarbon compounds, such as trichlorofluoromethane (75-69-4).	Refrigerant, propellant compounds in aerosols, fire extinguisher, solvent.
Gamma-BHC *See* BHC.		
Heptachlor (76-44-8)	3-Chlorochlordene; drinox; heptachlorane, VELSICOL 104.	Insecticide.
Isopropyl benzene (98-82-8)	Cumene; cumol.	Manufacturing chemical reagent, solvent.
Isopropyl ether (108-20-3)	Diisopropyl ether; 2-isopropoxypropane.	Extraction solvent.
Methyl ethyl ketone (78-93-3)	2-Butanone; MEK.	Solvent, manufacturing chemical organic synthesis.
Methanol (67-56-1)	Carbinol; methyl alcohol; wood alcohol; wood spirit.	Industrial solvent, feedstock for the manufacture of a large number of organic chemicals, fuel, fuel additive, laboratory reagent.
Methoxychlor (72-43-5)	MARLATE; CHEMFORM.	Insecticide.
Methyl chloride (74-87-3)	ARTIC, chloromethane; monochloromethane.	Local anesthetic, refrigerant, reagent, solvent.
Methyl isobutyl ketone (108-10-1)	Isopropylacetone hexone; 4-methyl-2-pentanone.	Solvent for paint, lacquer, and varnish; organic synthesis.
Methyl parathion (298-00-0)	Metafos; parathionmethyl; phosphodroithioic acid.	Insecticide.
Methylene chloride (75-09-2)	Dichloromethane; methylene dichloride.	Fumigant, industrial solvent, cleaning fluid, laboratory reagent, degreasing fluid.
Metolachlor (51218-45-2)	BICEP; CGA 24705; DUAL.	Herbicide.
Metribuzin (21087-64-9)	Bay 94337; LEXONE, SENCOR.	Herbicide.
Nitrobenzene (98-95-3)	Nitrobenzol; oil of mirbane.	Manufacturing chemical, solvent, reagent.
Nitrofen (1836-75-5)	NIP; nitrophene; TOK.	Herbicide.
Oxamyl (23135-22-0)	DPX 1410; oxamimidic acid; VYDATE THIOXAMYL.	Insecticide, nematocide, acaracide.
Paraquat (4685-14-7)	Methyl viologen.	Herbicide.
PCB's (1336363)	AROCLOR; CLOPHEN; chlorinated biphenyls; polychlorinated biphenyls; polychlorinated diphenyls.	Past use includes electrical capacitors, transformers, hydraulic fluids, fire retardant, cutting oil, and in heat-transfer systems.
PCNB (82-68-8)	AVICOL; FOLOSAN; pentachloronitrobenzene; quintozene; TERRACHLOR.	Fungicide.
Pentachlorophenol (87-86-5)	DOWICIDE; PCP, penta.	Pre-harvest defoliant, wood preservative, molluscicide, herbicide, bactericide.
Pentane (109-66-0)	Amyl hydride; n-pentane; SKELLYSOLVE.	Fuels, propellant.
Phenanthrene (85-01-8)		Research chemical, manufacture of dyes and explosives, wood preservative.
Phenol (108-95-2)	Carbolic acid: phenic acid; phenylic acid; phenyl hydroxide; hydroxy benzene, oxybenzene.	Disinfectant; used in organic synthesis, in the production of many medical and industrial compound; pesticide.
Picloram (1918-02-1)	TORDON.	Herbicide.

Name used in 1986 *National Water Summary* (CAS No.)	Selected synonyms	Principal use
Polybrominated biphenyl (CAS numbers assigned for each isomer. Numbers range from 92-60-0 for a mono-bromo compound to 59080-411-0 for octa-bromo compounds.)	PBB; brominated biphenyl; polybromobipheyls.	Flame retardant.
Prometone (1610-18-0)	PRAMITOL; Prometon.	Herbicide.
Prometryne (7287-19-6)	Prometryn; CAPAROL; G-34161.	Herbicide.
Propachlor (1918-16-7)	RAMROD; SATECID.	Herbicide.
Propazine (139-40-2)	G-30028; GESAMIL; MILOGARD.	Herbicide.
Pyrene (129-00-0)	Benzo (def) phenanthrene.	Biochemical research, component of wood preservative.
Pyrethrin I (121-21-1) II (121-29-9)	Pyrethrum; pyrethrins.	Insecticide.
RDX (121-82-4)	Cyclonite; hexogen; T4.	Explosive.
Rotenone (83-79-4)	CHEM FISH; tubatoxin; derris; nicouline; prentox.	Insecticide, grubicide; also used to kill fish.
Simazine (122-34-9)	G 27692; PRIMATOL S; PRINCEP; SIMADOX TRIAZINE; SIMANEX.	Herbicide.
SIMETRYNE (1014-70-6)	G-32911; Gy-bon.	Herbicide.
Styrene (100-42-5)	Styron; styrofoam.	Manufacture of polystyrene.
2,4-D (94-75-7)	Acetic acid, (2,4-DICHLOROPHENOXY)-; AGROTECT; AQUA-KLEEN; CHLOROXONE; CROP RIDER; DED-WEED; 2,4-dichlorophenoxyacetic acid; DINOXOL; DORMONE; DMA-4; FERNIMINE; LAWN-KEEP; PENNAMINE D; PLANOTOX; PLANTGARD; SALVO; TRIBUTON; TRINOXOL; WEED-B-GON; WEEDONE; WEEDAR 64.	Herbicide.
2,4,5-T (93-76-5)	Acetic acid, (2,4,5-trichlorophenoxy)-; BRUSHRHAP; DED-WEED; LINE RIDER; WEEDONE.	Herbicide.
TCE *See* Trichloroethylene.		
TELONE *See* Dichloropropene.		
Temik *See* Aldicarb.		
Tetrachloroethene *See* Tetrachloroethylene.		
Tetrachloroethylene (127-18-4)	Ethylene tetrachloride; NEMA; PCE; perchloroethylene; PERCLINE; TETRACEP.	Industrial solvent, heat-transfer medium.
Tetrahydrofuran (109-99-9)	Diethylene oxide; tetramethylene oxide.	Solvent for high molecular weight polymers, and in organic synthesis.
TNT (118-96-7)	2,4,6-trinitrotoluene; trinitrotoluene; trotyl.	Explosive.
Toluene (108-88-3)	METHACIDE; methylbenzene; phenylmethane toluol.	Solvent and reagent.
Toxaphene (8001-35-2)	Chlorinated camphene; campechlor; polychlorocamphene; synthetic 3956; ALLTOX; GENIPHENE; MOTOX; PENPHENE.	Insecticide.

Name used in 1986 *National Water Summary* (CAS No.)	Selected synonyms	Principal use
Tribromomethane *See* Bromoform.		
Tribromophenol (118-79-6)	Bromol; 2,4,6-tribromophenol.	Unknown.
Trichloroethylene (79-01-6)	ALGYLEN; CHLORYLEN; ethinyl trichloride; ethylenetrichloride; TCE; TRICHLORAN; TRICHLOREN; trichloroethene.	Industrial solvent and extractant.
1,1,1-Trichloroethane (71-55-6)	CHLOROTHENE; METHYL CHLOROFORM.	Industrial solvent, coolant, lubricant, dry-cleaning agent, fumigant.
Trichlorofluoromethane *See* FREON.		
1,2,3-Trichloropropane (96-18-4)	Allyl trichloride; glycerol trichlorohydrin; glyceryl trichlorohydrin; trichlorohydrin.	Chemical intermediate, paint remover, solvent, degreasing agent, nematicide.
Trifluralin (1582-09-8)	ELANCOLAN; LILLY 36352; TREFANOCIDE; TREFLAN; TRIFLUREX.	Herbicide.
Trihalomethane	One of the family of organic compounds, named as derivatives of methane, wherein three of the four hydrogen atoms in methane are each substituted by a halogen atom in the molecular structure. *See, for example*, Bromoform; Chlorodibromethane; chloroform.	Refrigerants, solvent, organic synthesis.
Vinyl chloride (75-01-4)	Chloroethene; chloroethylene; vinyl monomer.	Chemical intermediate in plastics manufacturing, refrigerant.
Xylene (1330-20-7)	Dilan; dimethylbenzene; 1,2-dimethylbenzene (9547-6); 1,4-dimethylbenzene (106-42-3); xylol.	Chemical intermediate, industrial solvent, aviation gasoline.

CONVERSION FACTORS

[With particular reference to water-use and water-supply data]

Multiply	*By*	*To obtain*
	AREA	
acres	43,560	square feet (ft^2)
	4,047	square meters (m^2)
	0.001562	square miles (mi^2)
	FLOW	
billion gallons per day (bgd)	1,000	million gallons per day (Mgal/d)
	1,121	thousand acre-feet per year (acre-ft/yr)
	1.547	thousand cubic feet per second (ft^3/s)
	694.4	thousand gallons per minute (gal/min)
	3.785	million cubic meters per day (m^3/d)
cubic feet per second (ft^3/s)	0.646317	million gallons per day (Mgal/d)
	448.831	gallons per minute (gal/m)
	724	acre-feet per year (acre-ft/yr)
million gallons per day (Mgal/d)	0.001	billion gallons per day (bgd)
	1.121	thousand acre-feet per year (acre-ft/yr)
	1.547	cubic feet per second (ft^3/s)
	0.6944	thousand gallons per minute (gal/m)
	0.003785	million cubic meters per day (m^3/d)
thousand acre-feet per year	0.0008921	billion gallons per day (bgd)
	0.8921	million gallons per day (Mgal/d)
	0.001380	thousand cubic feet per second (ft^3/s)
	0.6195	thousand gallons per minute (gal/min)
	0.003377	million cubic meters per day (m^3/d)

SELECTED WATER RELATIONSHIPS (approximations)

1 gallon = 8.34 pounds
1 million gallons = 3.07 acre-feet
1 cubic foot = 62.4 pounds
= 7.48 gallons
1 cubic foot per second per day = 86,400 cubic feet
= 1.98 acre-feet
= 646,317 gallons
= 0.646 million gallons
1 acre-foot (1 acre covered by 1 foot of water) = 325,851 gallons
43,560 cubic feet
1 cubic mile = 1.1 trillion gallons
3,379,200 acre-feet
1 inch of rain = 17.4 million gallons per square mile
27,200 gallons per acre
100 tons per acre

GEOLOGIC-AGE CHART

MAJOR GEOCHRONOLOGIC AND CHRONOSTRATIGRAPHIC UNITS

Subdivisions in use by the U.S. Geological Survey (map symbols)						Age estimates of boundaries in million years [1, 5]
Eon or Eonothem	Era or Erathem	Period or System		Epoch or Series		
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)		Holocene		0.010
				Pleistocene		2 (1.7–2.2)
		Tertiary (T)	Neogene Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene Subperiod or Subsystem (Pɛ)	Oligocene		38 (34–38)
				Eocene		55 (54–56)
				Paleocene		63 (63–66)
	Mesozoic (Mz)	Cretaceous (K)		Late	Upper	96 (95–97)
				Early	Lower	138 (135–141)
		Jurassic (J)		Late Middle Early	Upper Middle Lower	205 (200–215)
		Triassic (TR)		Late Middle Early	Upper Middle Lower	~240
	Paleozoic (Pz)	Permian (P)		Late Early	Upper Lower	290 (290–305)
		Carboniferous Periods or Systems (C)	Pennsylvanian (ℙ)	Late Middle Early	Upper Middle Lower	~330
			Mississippian (M)	Late Early	Upper Lower	360 (360–365)
		Devonian (D)		Late Middle Early	Upper Middle Lower	410 (405–415)
		Silurian (S)		Late Middle Early	Upper Middle Lower	435 (435–440)
		Ordovician (O)		Late Middle Early	Upper Middle Lower	500 (495–510)
		Cambrian (Є)		Late Middle Early	Upper Middle Lower	~570[2]
Proterozoic (P̱)	Late Proterozoic[3] (Z)					900
	Middle Proterozoic[3] (Y)					1600
	Early Proterozoic[3] (X)					2500
Archean (A)	Late Archean[3] (W)					3000
	Middle Archean[3] (V)					3400
	Early Archean[3] (U)					
~~ (3800?) ~~~						
pre-Archean[4] (pA)						4550

[1] Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age of boundaries not closely bracketed by existing data shown by ~. Decay constants and isotopic ratios employed are cited in Steiger and Jäger (1977).

[2] Rocks older than 570 Ma also called Precambrian (p€), a time term without specific rank.

[3] Geochronometric units.

[4] Informal time term without specific rank.

[5] Age estimates for the Phanerozoic are by G. A. Izett, M. A. Lanphere, M. E. MacLachlan, C. W. Naeser, J. D. Obradovich, Z. E. Peterman, M. Rubin, T. W. Stern, and R. E. Zartman at the request of the Geologic Names Committee. Age estimates for the Precambrian are by International Union of Geological Sciences Working Group on the Precambrian for the United States and Mexico, J. E. Harrison, Chairman. The chart is intended for use by members of the U.S. Geological Survey and does not constitute a formal proposal for a geologic time scale. Estimates of ages of boundaries were made after reviewing published time scales and other data. Future modification of this chart will undoubtedly be required. The general references apply where references are not given for specific boundaries.

U.S. Geological Survey, Geologic Names Committee, 1983