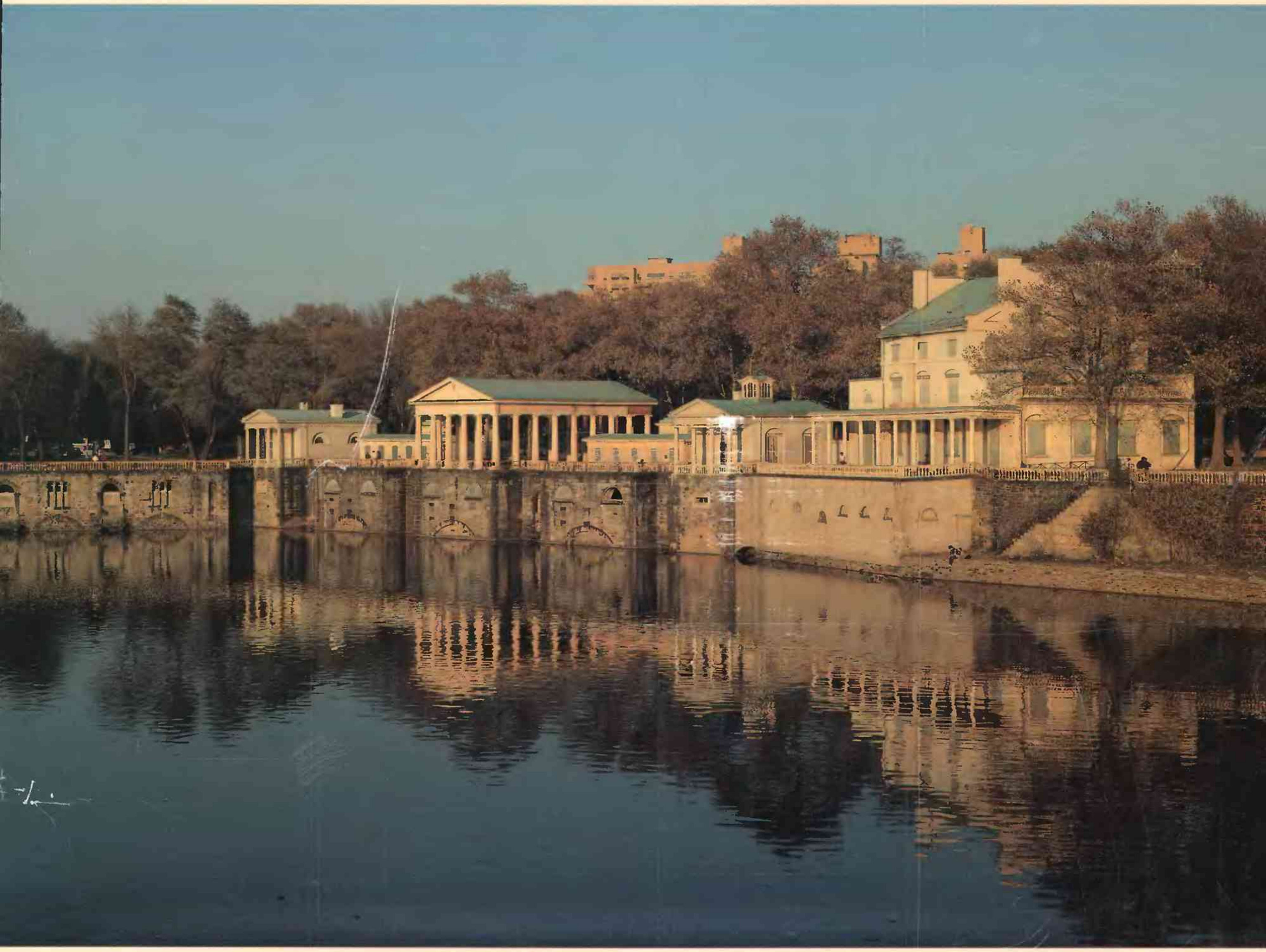
National Water Summary 1987—
Hydrologic Events and Water Supply and Use



United States Geological Survey
Water-Supply Paper 2350

Front cover—Fairmont Water Works (1815-1911), Philadelphia, Pa.
(Courtesy of Jack E. Boucher, National Park Service)
Frontispiece—Fairmont Water Works
(Courtesy of Eric N. Delony, National Park Service)
Mill house-Interior of the Water Works and breast wheel
(Historic American Engineering Record item 21)
(Courtesy of Free Library of Philadelphia, Philadelphia, Pa.)
Back cover—Fairmont Water Works in the winter
(Courtesy of Eric N. Delony, National Park Service)
Section through center of turbine wheel and flume
(From Philadelphia, Pa., Water Department Annual Report 1868, published with permission)
West front of mill house-ca. 1820
(Historic American Engineering Record item 18)
(Courtesy of The Franklin Institute, Science Museum, Philadelphia, Pa.)

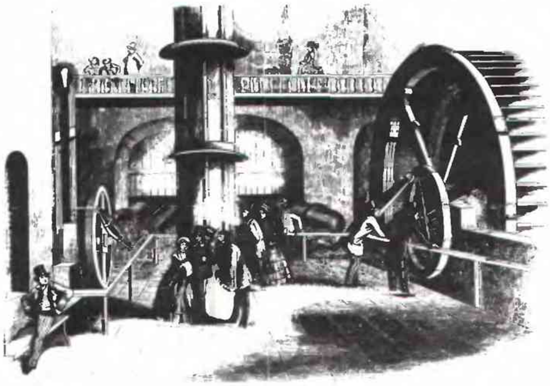
Located on the banks of the Schuylkill River in Philadelphia, Pa., the Fairmont Water Works greatly influenced the development of public water-supply systems in the United States during the 19th century. Built to supply Philadelphia with a reliable water supply, the Water Works made use of a variety of technologies to pump water to a reservoir on the top of nearby Morris Hill (now the site of the Philadelphia Art Museum), from whence the water was distributed to the city through cast-iron pipes.

The Fairmont Water Works was designed by Frederick Graff (1774–1847), who was a draftsman trained in engineering by Benjamin Henry Latrobe (later one of the architects of the Nation's Capitol). Over the course of nearly 100 years, the Water Works used steam engines, wooden and cast-iron breast wheels, and iron water turbines to power its pumps. Graff, who was also the engineer and manager of the Water Works, became a leading authority on the design and the construction of public water supplies; during his career, he provided consultation and advice to the builders of water supplies in more than 30 cities.

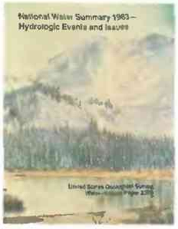
By the mid-19th century, the Fairmont Water Works had become a popular tourist attraction. Visitors came to observe the operation of the machinery and to enjoy the scenic grounds. Among the notable visitors was Charles Dickens who described the Water Works in his *American Notes and Pictures from Italy* (1873, London, Chapman and Hall, p. 47) as follows:

> Philadelphia is most bountifully provided with fresh water, which is showered and jerked about, and turned on, and poured off everywhere. The Water-works, which are on a height near the city, are no less ornamental than useful, being tastefully laid out as a public garden, and kept in the best and neatest order. The river is dammed at this point, and forced by its own power into high tanks or reservoirs, whence the whole city, to the top stories of the houses, is supplied at a very trifling expense.

In 1977, the Fairmont Water Works was designated a National Historical Mechanical Engineering Landmark by the American Association of Mechanical Engineers and in 1978 it was documented in the Historic American Engineering Record (HAER file PA-51). In 1988, the Water Department and the Fairmont Park Commission of the city of Philadelphia completed restoration of the Water Works buildings, which are cited as an outstanding example of Greek Revival style applied to early 19th century American industrial architecture.

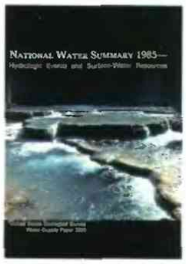


National Water Summary—



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

1984 — Hydrologic Events, Selected Water-Quality Trends, and Ground-Water Resources (U.S. Geological Survey Water-Supply Paper 2275)



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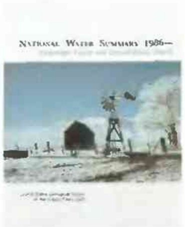
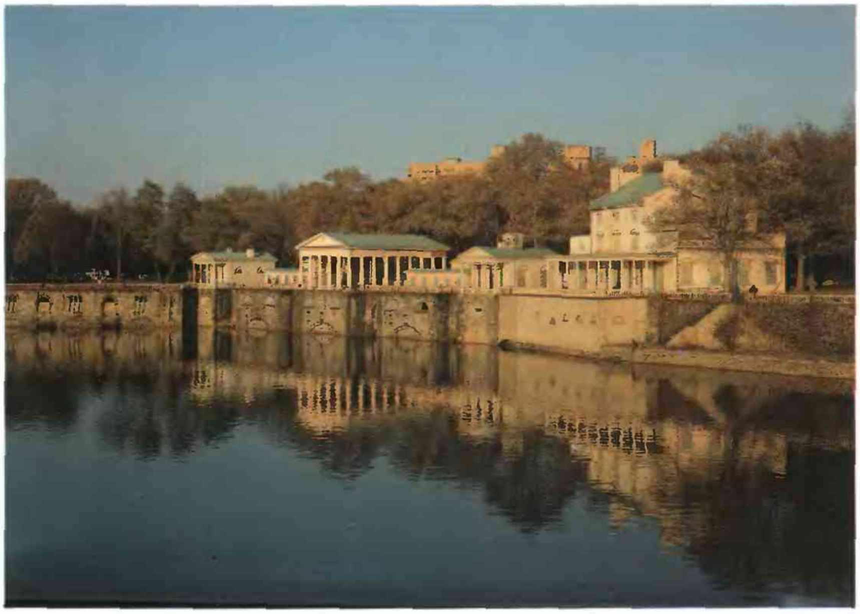


1986 — Hydrologic Events and Ground-Water Quality (U.S. Geological Survey Water-Supply Paper 2325)

National Water Summary 1987—

Hydrologic Events and Water Supply and Use



By U.S. Geological Survey

Jerry E. Carr, Edith B. Chase, Richard W. Paulson, and
David W. Moody, Compilers

United States Geological Survey
Water-Supply Paper 2350

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

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Foreword

National Water Summary 1987—Hydrologic Events and Water Supply and Use is the fifth in a series of annual reports that describe the condition and the characteristics of the Nation's water resources. This volume portrays the source, use, and disposition of freshwater in the United States for five major categories of use—public supply, domestic and commercial, industrial and mining, thermoelectric power, and agricultural. It utilizes information from the U.S. Geological Survey's National Water-Use Information Program to present water-use data by county, by aquifer, and by river basin for each State and to document the steps being taken by each State to manage water use.

The U.S. Geological Survey has published estimates of water use for the United States at 5-year intervals since 1950. In 1977, the Congress expanded the Survey's water-use activities by establishing a National Water-Use Information Program, which, in cooperation with the States, collects reliable and uniform information on the sources, the uses, and the disposition of water in the United States. The program constitutes formal recognition by the Congress of the importance of water-use information in planning and managing the Nation's water resources.

The history of water-resources development in the United States reflects the history of water use. In colonial times, local springs, shallow wells, creeks, and rainwater collected in cisterns served to meet domestic and livestock uses. These supplies were subject to the uncertainties of droughts and were vulnerable to contamination. Urban growth in the Eastern States, particularly after 1800, caused the quality of city water supplies to deteriorate noticeably. Shallow water supplies commonly were contaminated by household privies that often were located near the family well. Cistern water was contaminated by accumulations of soot, dust, and street debris that collected on roofs and in gutters.

As the population grew during the 1880's, people moved away from free-flowing creeks and rivers. But the need for adequate water supplies to fight devastating fires that frequently wrought havoc in the cities was of great concern. In addition, the use of water for washing streets increased because it was believed that the prevalent epidemics of yellow fever, typhoid fever, cholera, and smallpox were related to the filthy conditions of the streets. As a result, cities such as Boston, New York, and Philadelphia began looking for ways to ensure reliable water supplies early in the 19th century. To develop such supplies required storage reservoirs, aqueducts, distribution systems, and engineers to design and build them. It is interesting to note that more than 2,000 years ago, Native Americans in the arid West already had built and used elaborate diversion and distribution systems for irrigation. These systems were revitalized and copied by the Spanish and later European settlers.

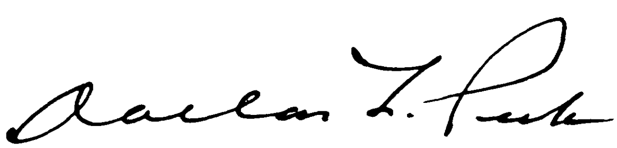
Inland navigation also was of increasing importance to the commerce of the Nation in the early 1800's. A major navigation project—the Erie Canal—was begun in 1817. Because there were few practicing engineers in the United States at that time, the construction of the canal served as a training ground for surveyors and others to learn engineering skills through an apprenticeship system. After the completion of the canal in 1825, a number of graduates of the "Erie Canal School of Engineering" went on to design reservoirs and aqueducts for Boston, New York, and a number of other cities. It is of note that one of the first hydrologic studies of water availability in the United States was made along the canal route to ensure that there was sufficient supply to meet the needs of navigation and the operation of the canal locks.

In addition to the use of water for public supplies and navigation, the demand for mechanical energy led to the design of sophisticated water wheels and turbines to power America's growing industry. The history (1815–1911) of the Philadelphia Fairmont Water Works, pictured on the cover of this report, embodies many of the characteristics of the early development of public water supplies and water power in the United States.

During the first two-thirds of the 20th century, water planners and managers sought to develop the Nation's water resources to meet the growing needs of the country. Large reservoirs and aqueducts were constructed in the West to provide water for public supply, industry, irrigation, and hydropower and to foster regional economic development. By the 1960's and 1970's, concerns about the environmental effects of large reservoirs, as well as increasing construction costs and the scarcity of suitable storage sites, curtailed the construction of significant additional reservoir capacity. Water demand continued to increase through 1980, and use of alternate supply sources, such as ground water, increased over 60 percent between 1960 and 1980. However, data for 1985 indicate that 37 States and Puerto Rico reported less water withdrawn during 1985 than during 1980 for an overall 12-percent decrease in ground-water withdrawals and an 8-percent decrease in surface-water withdrawals.

As we enter the 1990's, concerns for dependable water supplies will cause water planners and managers to place increasing emphasis on improving the efficiency with which we use existing supplies. Some of the tools that will be used to increase water-use efficiency and to make greater beneficial use of developed water resources are legislative controls on ground-water withdrawals, improved operating rules for reservoirs and reservoir systems, conjunctive use of ground and surface water, water conservation measures (such as leak-detection programs, installation of water-efficient plumbing fixtures, lining of irrigation canals, and improved irrigation techniques), reuse of water, and establishment of water markets in which to buy and sell water rights. Intensive water management by State, regional, and local agencies requires an accurate accounting of water as it moves through the hydrologic cycle. Water-use data and information, therefore, will become increasingly important as a means of evaluating the effects of human activities and climate changes on the quantity and the quality of water resources and to measure the success of water conservation and other management programs to allocate water supplies. U.S. Geological Survey scientists look forward to continued cooperation with States and other Federal and regional and local agencies to improve the reliability of water-use information and to support improved management and protection of the quality and quantity of our water resources.

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



DIRECTOR

CONTENTS

FIGURES

FIGURES—Continued

FIGURES—Continued

FIGURES—Continued

TABLES

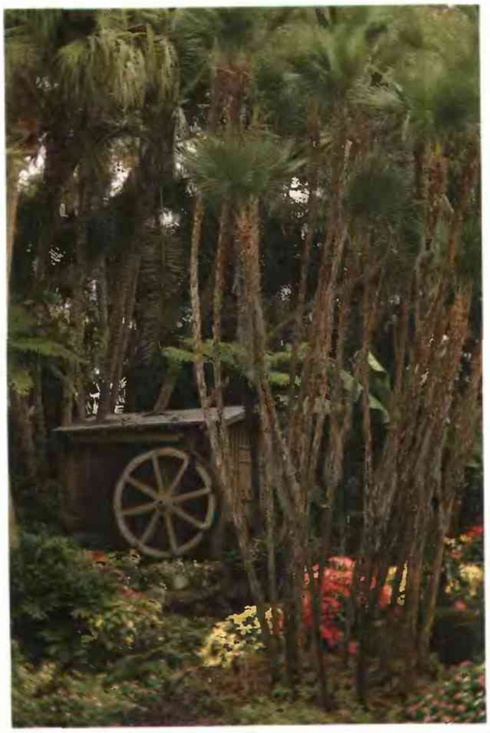
TABLES—Continued

PHOTOGRAPH CREDITS

All photographs are by U.S. Geological Survey personnel unless otherwise indicated. Untitled photographs are:

Covers: See back of front cover.
Frontispiece: See back of front cover.
Page 1. Water wheel (formerly industrial, now decorative) at Cypress Gardens, Fla. (Lee C. Trotta)
Page 11. Public water supply being used for fire protection, River Falls, Wis. (Lee C. Trotta)
Page 36. *Top* Collapsed New York State Thruway bridge over Schoharie Creek near Amsterdam, N.Y., April 1987 (Thomas J. Zembrzuski, Jr.)
Bottom Landslide damage at Bell Rapids Irrigation Company pumping plant near Hagerman, Idaho, April 1987 (U.S. Bureau of Land Management)
Page 69. Cooling tower at thermoelectric powerplant, Willmar, Minn. (Lee C. Trotta)

OVERVIEW AND INTRODUCTION



Overview

Water use in the United States, as measured by freshwater withdrawals in 1985, averaged 338,000 Mgal/d (million gallons per day), which is enough water to cover the 48 conterminous States to a depth of about 2.4 inches. Only 92,300 Mgal/d, or 27.3 percent of the water withdrawn, was consumptive use and thus lost to immediate further use; the remainder of the withdrawals (72.7 percent) was return flow available for reuse a number of times as the water flowed to the sea. The 1985 freshwater withdrawals were much less than the average 30 inches of precipitation that falls on the conterminous States each year; consumptive use accounted for only 7 percent of the estimated annual runoff of 1,230,000 Mgal/d. Nonetheless, as the State summaries on water supply and use clearly show, water is not always available when and where it is needed. Balancing water demands with available water supplies constitutes one of the major resource allocation issues that will face the United States in the coming decade.

Of the 1985 freshwater withdrawals, 78.3 percent (265,000 Mgal/d) came from surface-water sources (streams and lakes), and 21.7 percent (73,300 Mgal/d) came from ground water. Surface water provided drinking water for about 47 percent of the Nation's total population. It was the source of 59.9 percent of the Nation's public-supply systems. For self-supplied withdrawals, surface water accounted for 1.6 percent of the domestic and commercial uses; 64.0 percent of the industrial and mining use; 99.4 percent of the thermoelectric generation withdrawals, mainly for cooling water; and 65.6 percent of the agricultural withdrawals. Eight States accounted for 43 percent of the surface-water use; California, Colorado, and Idaho used surface water primarily for irrigation, and Illinois, Michigan, Ohio, Pennsylvania, and Texas used surface-water primarily for cooling condensers or reactors in thermoelectric plants.

Ground water provided drinking water for 53 percent of the Nation's total population and nearly all the rural population. It was the source of 40.1 percent of the public-supply systems withdrawals. For self-supplied withdrawals, ground water accounted for 11.3 percent of the domestic and commercial use, 17.3 percent of the industrial and mining withdrawals, less than 1 percent of the thermoelectric generation withdrawals, and 34.4 percent of the agricultural withdrawals (irrigation and livestock). Eight States—Arizona, Arkansas, California, Florida, Idaho, Kansas, Nebraska, and Texas—accounted for 66 percent of the ground water used. In each of those States, as in many other States, irrigation was the major use of ground water. Each offstream-use category described in the State summaries—public supply, domestic and commercial, industrial and mining, thermoelectric power, and agriculture (irrigation and livestock)—followed its own geographic pattern as described below.

Consumptive use of water effectively removes the water from immediate further use downstream of the withdrawal point. Of the total amount of consumptive water use in 1985, agricultural use accounted for about 82.5 percent. More than one-half (53 percent) of irrigation water is consumptively used by evapotranspiration or is incorporated into the crop. This is a good indication of the effect that irrigated agriculture can have in a river basin where irrigation is a major activity. The availability of return flows for reuse depends largely on where the water reenters the system. If the return flows are discharged to a stream, they usually can be reused; if they are discharged to a saltwater estuary, they are effectively lost to further use because of water-quality degradation just as if the water had been consumptively used. Similarly, water that recharges a highly transmissive aquifer can be available for reuse either through pumpage from a well or as discharge to a local stream. Thus, much of the water withdrawn for different uses can and does become available for further use although the quality might degrade with each additional use.

The allocation and the management of water resources are the responsibilities of the individual States and water institutions within the States. These institutions are evolving in response to the challenges of water management problems. As the individual State summaries indicate, recent State legislation deals with facilitating water transfers within the States as a means of reducing imbalances between water supplies and use, with emphasizing water conservation in times of drought and at places where ground-water depletion is a problem of long standing, and with reducing threats to public health and the environment from water pollution.

Most of the State summaries indicate the expectation that water use will continue to increase in the future and that water contamination will continue to be a major water concern. Both issues will require increasingly intensive water management in the future. Whether the water resources under management are considered to be fully appropriated or over appropriated, as in some Western States, or whether the resource could support additional development, as is the situation in most States, improved water-use information will play a key role in future water-management efforts.

HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS, WATER YEAR 1987

Hydrologic conditions during water year 1987 (October 1986–September 1987) exhibited broad regional patterns—below-normal streamflows in the western one-third of the country, above-normal flows in the central one-third, and near-normal flows in the eastern one-third. A remarkably persistent split-flow circulation pattern where the polar-front jet stream remained in Canada north of its normal position and an active subtropical jet stream crossed the Southern United States led to opposing hydrologic extremes—progressively severe hydrologic drought in Nevada and California and unusually high streamflows in the southern Great Plains. The combined flow of the Mississippi, the St. Lawrence, and the Columbia Rivers, which broadly reflects hydrologic conditions in much of the United States and parts of Canada, was 65 percent above normal during the first quarter of the year, near normal during the second and third quarters, and much below normal during the fourth quarter as the western drought intensified near the end of the water year.

Weather-related events caused more than $2.14 billion in economic losses in water year 1987. Of this amount, flood damage comprised $1.5 billion. Eighty-eight lives were lost as the result of flooding. This is well below the 10-year average (1977–86) of $2.5 billion in flood damage and 138 lives lost. Flooding in the Nation's midsection and in the Northeast accounted for 85 percent of the annual flood losses, of which 48 percent occurred in urban areas. Great Salt Lake rose to a level equal to its record-high level of June 1986 (4,211.85 feet above sea level) at the end of March, 3 months before the usual peak level in its annual cycle. Aided by below-normal inflows, increased evaporation, and pumping of the water from the lake into West Desert Pond, which began on April 10, 1987, the lake level declined during the remainder of the year. These hydrologic conditions and 87 specific events are reviewed in the "Hydrologic Conditions and Water-Related Events, Water Year 1987" part of the 1987 *National Water Summary*.

The chronological listing of significant hydrologic and water-related events in "Selected Hydrologic Events, Water Year 1987" shows that eight major floods occurred. Three of those floods were of sufficient magnitude to be described in detail.

A slow-moving storm dropped 4 to 8 inches of rain in western and central Maine at the beginning of April 1987. Several days later a second storm brought 2 to 4 inches of rain to southern Maine. Runoff from both storms, augmented by snowmelt, resulted in record to near-record peak discharges, many of which exceeded the 100-year flood recurrence interval. Twenty-six sewage-treatment plants were damaged, some seriously enough to result in the release of untreated sewage into rivers for as long as 3 months after the storms. Petroleum storage tanks were unearthed, and petroleum spills were reported in at least 15 communities, especially in the Androscoggin, the Kennebec, and the Piscataquis Rivers basins. Flood damage to 100 small dams, utilities, public buildings, and businesses exceeded well over $100 million.

Flooding in New York from the same set of storms caused flooding on Schoharie Creek, which is a tributary of the Mohawk River, and contributed to the failure of the New York State Thruway bridge near Amsterdam, N.Y. Ten people were killed when five vehicles fell off the collapsed span of the bridge.

Heavy precipitation in areas of Cook and Du Page Counties, Ill., in mid-August 1987 established a new 24-hour record of 9.35 inches of rain at O'Hare International Airport and in the Chicago suburbs. The most acute flooding from this storm occurred in the Des Plaines River basin where the recurrence intervals of peak flows ranged from 100 years to 1.4 times the 100-year flow. The heavy flooding and associated events caused four deaths and more than $77 million in damage.

Other water-related events involved water quality. Early in 1987, State and Federal wildlife biologists reported a major fish kill and die off of aquatic birds in the Carson Sink near the mouth of the Carson River, Nev. Abnormally wet years and high runoff from the Humboldt and the Carson Rivers from 1982 to 1984 inundated the sink, which normally is dry, to create a 212,000-acre lake that had a maximum depth of nearly 12 feet. Since January 1985, the size of the lake has shrunk to 180,000 acres and a maximum depth of 6 feet because of reduced inflows and evaporation. Increased dissolved-solids concentrations due to evaporation and the freezing of the lake in January 1987 is thought to have killed the fish. Avian cholera killed most of the birds when the freezing of the lake forced the fish-feeding birds to congregate near open ice holes.

A pumping valve malfunction caused more than 500,000 gal (gallons) of No. 6 fuel oil to spill over a 4-day period during offloading operations at Garden City, Ga., on the Savannah River in early December 1986. The spill affected a variety of resources. More than 60 miles of shoreline was moderately to heavily affected, 5,500 acres of intertidal wetlands was exposed to oil, aquatic birds were coated with oil, commercial fishing in the area decreased, and air pollution increased in the Savannah area because of the volitization of the hydrocarbons. The area will be monitored to determine the long-term effects on aquatic resources.

Farther south, one of the largest and most intense algal blooms ever recorded in Lake Okeechobee, Fla., took place between August 12 and 20, 1986. Preliminary evidence suggested that excessive nutrient loading from agricultural lands in the 4,500-square-mile drainage area reduced the lake's capacity to assimilate phosphorus. Concentrations of total phosphorus in Lake Okeechobee doubled between 1974 and 1984. To prevent further eutrophication of the lake, phosphorus inflows must be reduced and controlled as part of an overall lake management plan, which is directed by the South Florida Water Management District. The blue-green algae bloom has raised public awareness of the need to reduce nutrient loadings to the lake and has created wide-spread public support for proposed management actions.

Unplanned effects of human activities are demonstrated by the April 1987 landslide near Hagerman, Idaho, on the Snake River. Unlined canals operated by a local irrigation company had been leaking water, which is thought to have accumulated as perched aquifers near the rim of the Snake River canyon. The perched aquifers fed springs in the wall of the canyon and led to large-scale slumping that caused an estimated $1.5 million in damage to an irrigation pumping station and undetermined damage to fossil beds at the Hagerman Fauna Site National Landmark on adjacent BLM (Bureau of Land Management) lands. The BLM and the irrigation company jointly are funding the lining of the irrigation canals to prevent further seepage.

The last water-related event described in this volume commemorates the 50th anniversary of the construction of the Bonneville Dam on the Columbia River in Oregon and Washington. Constructed between 1933 and 1937 by the U.S. Army Corps of Engineers, Bonneville was the first of a series of

10 Federal dams to harness the enormous hydropower potential of the Columbia River system.

HYDROLOGIC PERSPECTIVES ON WATER ISSUES

The hydrologic perspectives part of the 1987 *National Water Summary* provides an introduction to some of the technical, economic, social, and institutional factors that determine the quantity of water used in the different economic sectors. It also provides background information for the "State Summaries of Water Supply and Use."

DOMESTIC AND COMMERCIAL WATER USE

Domestic and commercial water use amounted to 35,300 Mgal/d in 1985. This category includes water used by households, hotels, restaurants, office buildings, and other commercial establishments and institutions, and public use and losses in public-supply distributions systems. It depends on public supplies for 87.1 percent of its water. Almost all the remainder is self-supplied from wells that are located mostly in rural and nonurban areas. As with public supplies, the States that have the largest domestic and commercial uses are those that have the largest populations—California, Texas, and New York.

Domestic or household water use represents water used by households for drinking, bathing, cooking, and lawn watering. In 1985, about 18 percent of the population was self-supplied from privately owned wells or surface-water sources. The remaining 82 percent of the population obtained their water from public-supply systems. Water withdrawals from these systems increased 78 percent between 1960 and 1985. This is attributable to two factors—an increase in population served by these systems and an increase in water use per capita. The population served by public systems increased at an average annual rate of 1.54 percent in contrast to a 1.14-percent increase in the U.S. population. Per capita domestic use increased at an average rate of about 0.76 percent per year. The highest rates of withdrawal increases have occurred in the Southeast and the West and the lowest rates have occurred in the Northeast; these rates reflect regional patterns of population growth. Although growth in per capita use in the West recently has slowed, domestic use per capita is substantially higher in the West [138 gal/d (gallons per day) per capita] than in the Southeast (101 gal/d per capita), Northeast (85 gal/d per capita), or the East as a whole (90 gal/d per capita).

In addition to population growth, major factors thought to affect domestic water use include household size, household income, and the cost of water. Although population increased between 1960 and 1980, the average household size decreased from 3.30 persons to 2.75 persons. This decrease could be the principal cause of the growth of per capita water use because smaller households might use water less efficiently—more water per person for cooking, clothes washing, lawn watering, and car washing—than large households.

Generally it is assumed that higher income households tend to use more water because higher incomes permit better housing, more water-using appliances, and larger lawns to be watered. Median family income, however, after adjusting for inflation, remained the same for each of the years in which the U.S. Geological Survey conducted water-use surveys. The biggest changes occurred during the 1960's and undoubtedly contributed to improvements in housing conditions, such as the acquisition of indoor plumbing facilities, especially in the Southeast. The improvement in the plumbing facilities of housing units and the acquisition of dishwashers and clotheswashers during this period could have accounted for per capita water-use increases during the 1960's. However, the proportion of households owning a clotheswasher has not changed in the past 25 years, which suggests that increases in the number of water-using appliances might not be a major factor in increasing per capita use.

Finally, the cost of water to households usually is thought to be a major determinant in the quantity of water used by households. A number of factors complicate direct comparison of the prices paid by water users for service. Some 20 percent of the Nation's water suppliers do not meter water used, and those that do meter might not meter individual households. Utilities that sell water on a volume (metered) basis do so under a variety of rate schedules. The situation is further complicated by the addition of service charges and taxes to the water bill and, in many instances, the inclusion of sewer charges to cover the cost of disposing of the wastewater. An estimated average annual water bill for households that use 7,500 gal of water per month was computed from information available for 59 utilities across the country. Adjusted for inflation, this hypothetical water bill declined at an average annual rate of 1 percent between 1965 and 1984. Although the monthly bill did not decrease steadily over that period and, in fact, increased slightly between 1981 and 1984, the cost of water in each region of the country now appears to be less than it was in 1965.

The 1985 cost of water, exclusive of sewage charges, was higher in the East as a whole, and in the Northeast in particular, than in the West. The inclusion of sewer charges, however, blurred the differences between the regions; this led to the interesting finding that there is not a statistical difference between the average total water and sewer bills of any of the regions. A weighted average (based on the number of customers served by individual utilities) of the 1985 marginal price of water (that is, the expenditure required to purchase an additional unit of water) was estimated from a survey of 106 utilities across the country. The marginal cost of water in the East was not statistically different from that in the West, either with or without sewer charges. Within the East, however, the marginal price of water was about 40 percent higher in the Southeast than in the Northeast. These "direct costs" to households might not truly reflect the full cost of water to households; for example, some of the costs might be paid by taxes in areas that have government-owned utilities. In such situations, the utilities might not recover the capital costs of providing water. Most utilities do not pay for the raw water itself, although its use now imposes costs on other users, now or in the future. For these reasons, water is undoubtedly underpriced in many areas.

Industrial (Manufacturing) and Mining

Industrial (manufacturing) and mining withdrawals represent about 30,800 Mgal/d, or 9.1 percent of the Nation's total freshwater withdrawals. Most industrial water, which is used for washing, cooling, and processing, is self-supplied from surface water (64.0 percent) and ground water (17.3 percent); an additional 18.7 percent is obtained from public supplies. Indiana, Pennsylvania, and New York reported the largest freshwater withdrawals in this category for 1985; Texas had the largest saline withdrawals.

The bulk of industrial water use tends to be concentrated in a few kinds of industrial sectors and in a few firms within each sector. In 1983, for example, 3 percent of the nearly 358,000 manufacturing firms in the United States accounted for more than 95 percent of the water used in manufacturing. Major water-using manufacturing sectors include chemicals and allied products, paper and allied products, petroleum refining, steel processing, and food processing; major water-using mining sectors include oil and gas extraction, nonmetallic minerals mining (except fuels), coal mining, and metal mining.

Total intake for manufacturing use and total discharge both peaked in the late 1960's and had declined 35 percent by 1983 despite increases in industrial output over a 15-year period. Correcting for changes in production levels, 1983 intake and discharge were only one-fourth of what they had been in 1954 as a result of changes in production levels, in water-use technology, and in environmental pollution laws.

All things being equal, water use increases as production increases. However, production technology is very sensitive to changes in the price of production inputs, such as energy, and the costs of pollution control. High energy prices during the mid-1970's provided firms with an incentive to cut back on energy consumption. This led to the more efficient use of existing heat, which, in turn, led to a more efficient use of water as a result of increased recycling of the water. Similarly, environmental laws of the 1970's encouraged manufacturers to modify their production processes so that waste discharges were reduced, thus minimizing the volume of effluent that needed treatment to meet more stringent pollution discharge requirements. The money saved by recycling water instead of treating and discharging process and cooling water helped offset the increased pollution abatement costs. From 1954 to 1983, all manufacturing firms except the food industry had almost doubled their recycling rates. The petroleum industry had the highest recycling rates, and the steel and the chemical industries had the lowest. As a result, far less water was withdrawn for manufacturing during the 1980's than had been forecasted a decade or two earlier.

Water use in the mining industry is far less concentrated than in manufacturing. Figures reported for mining water use include the removal of drainage water from mines (mine water) as well as intake water. Water withdrawn from mines provides about one-third of the total mining water use and is the principal source of water for ore processing. Saline water also is extracted during the production of oil and gas. Mining water use generally is restricted to locations where minerals are extracted. California, Florida, Minnesota, Pennsylvania, Texas, and Wyoming reported the largest freshwater withdrawals for mining in 1985. Unlike manufacturing, water intake per unit of production has remained constant during the last 20 years.

Thermoelectric Power

Thermoelectric power generation represents a special type of industrial use, which, because of its magnitude, is treated as a separate category. In 1985, freshwater withdrawals for thermoelectric power generation were 131,000 Mgal/d, which was 38.7 percent of the total freshwater withdrawals for all uses and second in magnitude only to agricultural use. About 56,000 Mgal/d of saline water was used for cooling, mostly by thermoelectric plants in coastal areas. Illinois, Ohio, and Pennsylvania had the largest freshwater withdrawals for thermoelectric uses.

Agriculture

Agricultural use (irrigation and livestock) represents the largest use of water (141,000 Mgal/d, or 41.8 percent of the total freshwater withdrawals) in the United States in 1985. The vast majority of the withdrawals was for irrigation (97 percent) primarily in the western part of the country. The 22 conterminous States west of the Mississippi, for example, accounted for 95 percent of the 1985 irrigation withdrawals. California and Idaho were by far the largest users of irrigation water. In the East, Florida, Mississippi, and Georgia were the largest irrigation States. Livestock use of water for beef, dairy, poultry, and other livestock production, such as fish farming (aquaculture), amounted to only 3 percent of the water used in agriculture but these uses contribute about one-half of agricultural cash receipts.

The contribution of irrigation to the farm economy is substantial. In 1982, for example, irrigated farms comprised only 12 percent of all farms, yet they produced nearly one-third of the total value of agricultural products sold off the farm.

The decision of what, where, and when to irrigate crops is based on many factors. The most obvious factor is climate, which determines the amount and the time of crop water requirements. In many parts of the West, crop production is impossible without the application of water. In other areas, irrigation is used to increase yields; to supplement natural precipitation, especially in soils that have low moisture-holding capacity; and as a form of drought insurance.

A major factor that affects irrigation use is the availability and costs of a surface- or ground-water supply. In the West, the cost of large surface-water storage projects to develop water resources has increased greatly in recent years because the most cost-effective storage project sites have been developed. Environmental quality and dam safety concerns also have added to the cost of projects. Finally, Federal policies to increase the cost sharing of new projects have increased the cost of water to agricultural users.

The cost of ground water also increased but for different reasons. A number of regions of the country, such as the Southern High Plains, where large volumes of ground water are pumped for irrigation, are experiencing long-term declines in ground-water levels, often termed "ground-water mining" because the withdrawal rates over a long period of time exceed the natural recharge rates. As the ground-water levels decline, the cost of pumping water from greater and greater depths increases, and the quantity of water (well yield) that can be obtained from a well decreases. Thus, more wells are needed to provide a given quantity of water. Pumping costs are further increased by higher energy costs. Between 1974 and 1983, for example, energy costs increased 182 percent for electricity and 700 percent for natural gas.

Other factors being equal, as the cost of ground water increases, the farmer can install more efficient irrigation technology, improve irrigation scheduling, and grow crops that have smaller water requirements or greater financial returns. In the face of continuing ground-water declines, a shift to dryland farming or the abandonment of farming in some areas is likely.

Current and anticipated future prices for irrigated farm products are important factors in the decision to invest in irrigation equipment. The recent general decline in crop and livestock prices fosters a poor investment climate and undoubtedly has discouraged new irrigation efforts. Competition for water between instream and offstream (withdrawal) uses, between irrigation and other offstream uses, such as industrial and municipal users, and even between irrigators in different areas, such as those served by the Colorado River, has increased the value of water, especially in the West, considerably above what most agricultural users can pay.

Numerous laws, water rights, and public policies at the State and the Federal levels control the allocation of water to irrigation, municipal, and industrial uses. To meet new water demands, pressures are increasing to modify these laws and to develop policies that would facilitate the voluntary transfers of water rights. Such a policy, which was adopted recently (1988) by the U.S. Bureau of Reclamation, permits the Bureau to facilitate transfers of water stored in Bureau projects.

Irrigation played an important part in the economic development of the Western States during the first three decades of the 20th century. Ground-water irrigation became economically feasible during the 1950's when improved water pumps and center-pivot systems were developed that allowed the irrigation of rolling topography unsuitable for conventional ditch irrigation.

Between 1950 and 1978, irrigated acreage doubled; however, harvested croplands decreased by nearly 10 percent because of Federal farm programs that reduced cropland acreage. Growth of irrigation in the West was steady but slow because much irrigation development had already taken place. The development of the center-pivot systems led to rapid irrigation development in the Plains States in the 1950's and in the Southeast during the 1960's as large acreages of corn and soybeans were brought under irrigation. Rise of farm commodity prices and expanding agricultural trade in the 1970's continued to provide generally favorable economic conditions for irrigated agriculture. Since 1975, rising energy costs and declining ground-water levels have caused declines in ground-water usage for irrigation.

Although water use for irrigation had shown a long-term increase of about 54 percent between 1950 and 1985, irrigation water use was 6 percent less during 1985 than during 1980. This decline could reflect wetter conditions in 1985 than in 1980, which resulted in the use of less water, and also conservation practices. The decline also was influenced heavily by declines in farm commodity prices and a downturn in the farm economy during this period.

Livestock water use, which includes drinking water for livestock, evaporation from stock watering ponds, uses for sanitation and waste disposal, and aquaculture increased from 1,590 Mgal/d in 1960 to 2,200 Mgal/d in 1980. Between 1980 and 1985, the estimated withdrawals for livestock use doubled, primarily as a result of large increases in water use for aquaculture.

Livestock water use is determined by livestock numbers and production practices. These, in turn, are influenced by technical developments in production and marketing practices and by the demand for livestock products. The number of red meat and dairy animals declined between 1970 and 1985 but is believed to have slowly increased by 1988. Changing consumption patterns and a relative decline in the price of poultry have been important factors in the steady growth in per capita consumption of poultry over the past three decades. Aquaculture has increased significantly in Arkansas, Idaho, and Mississippi.

Livestock water use was highest in the central Midwest during the 1960's; this reflected the concentration at that time of dairy and livestock production in that region. By 1985, livestock water use in the Plains region surpassed that in other regions because of a shift in cattle feedlot operations from the Corn Belt States to a region where climatic conditions are more favorable to the confinement of cattle. This shift also was accompanied by an increase in irrigated feed and forage production.

INSTREAM USE

The offstream uses described above sometimes are called out-of-stream or diversionary uses inasmuch as the water is withdrawn (diverted) from a stream (or pumped from a well) and transported to the place of use. In the process, the quantity of water available in the stream below the point of use is reduced. In contrast, instream water use does not diminish the streamflow below its point of use.

An early instream use of water in the United States was the creation of mechanical power for grist mills and, later, for a variety of industries in the mid-19th century. At the end of the 19th century, the hydroelectric powerplant began to replace the mill as a means of converting water flow to energy, and its use gradually has increased over the years. In 1985, 3,050,000 Mgal/d (3.42 billion acre-feet) of water was used to generate hydropower. This is equivalent to passing all the surface-water runoff from the conterminous United States through a powerplant nearly 2.5 times.

Another early instream use of the Nation's water resources was for navigation. Some stream systems have been greatly modified by channelization, diking, and the construction of dams and locks to create today's 12,000-mile inland water navigation system, which transports about one-half billion tons per year. Still another use, increasingly controlled by water-quality legislation, is the dilution and transport of wastes in discharges from communities and industries and in runoff from the land.

During the 1960's, other instream uses gained new recognition as legitimate and beneficial uses of water. The use of streamflows for biological, recreational, and esthetic purposes began to emerge as legitimate uses of water under State and Federal laws and regulations. Over the past 30 years, these uses of water have been able to compete with traditional offstream uses, such as irrigation and domestic uses, and commercial instream uses, such as navigation and hydropower generation. This legal legitimacy is reflected in the continuing trend towards adoption of instream protection laws and policies by the States, although the legal approach to the allocation of flows, which differs from State to State, depends upon the abundance of water, water law, and the state of water development. As a result, traditional water-management organizations are accommodating instream uses into their day-to-day decisions and operations.

The recognition of instream flows for environmental purposes has led to the development of methods to quantify instream-flow requirements. As these methods matured, they have provided a more rigorous basis for allocating flows. Current methodological questions center on how much reliance to place on the results of simulation models of the biological response to flows based on field observations. Although every method in use is based on some instream-flow measurements, an issue remains as to the degree to which extrapolated data and model results can replace long-term field observations. Clearly, instream-flow requirements will be an increasingly important factor in future water-allocation and water-management decisions throughout the country.

Water-Use Forecasts

An essential component of water-resources planning is the water-use forecast, an estimate of the amount of water that will be used by different sectors of the economy at future points in time. The planner is motivated to make a forecast for two reasons. First, the merits of alternative investment strategies for the development of water-supply capacity and for wastewater treatment capacity must be evaluated in the light of future demands for water. Second, it is useful to anticipate water-use conflicts so that institutional mechanisms can be developed that promote efficient and equitable allocation of water.

Although water-use forecasts help structure public debate over water-policy issues, they generally are inaccurate. This is simply a reflection of the fact that the underlying technical, social, and economic factors that determine future water use are likely to change in unpredictable ways. Despite the likelihood that long-term water-use projections will prove inaccurate, these forecasts still lie at the heart of the water-resources-planning process. Some forecasts are based on the statistical extrapolation of past water use and explicitly assume certain growth rates for water use. For example, a population projection can be combined with a projection of per capita water use to obtain estimates of future domestic water use. Such a method is simple, inexpensive, and easily understood in terms of rationale and methods used. However, the underlying causes that determine water use (the facts that influence per capita use, for example), need not be specified by the planner or be made explicit for the decisionmaker.

A forecast based on a causal analysis, however, presumes that water-use demands respond to social, economic, and public policy forces that can be described and, to some extent, predicted. The relation between these factors and water use is defined and projected by assuming the causal relations that have held in the past will continue to hold in the future. Such an approach attempts to explicitly address the reasons why water use will change in the future. Causal analysis can focus on factors that are under the control of the decisionmaker, such as water-pricing strategies, and can suggest public policy actions to control and direct water use as part of the overall investment and management strategy. Thus, the analysis defines future levels of water use and suggests possible solutions for managing the capital investment problem. Most important, it permits the user to examine the conceptual reasoning, the basic assumptions, the data, and the methods that might cause the projection to be inaccurate and to form a judgement about the likelihood of projection error. Causal analysis also is amenable to sensitivity analysis, which identifies how much a particular causal variable needs to change to influence an investment decision. In this manner, the decisionmaker can determine how much error is tolerable in the causal variables.

Planning practices of the past favored acceptance and use of projections that supported the building of excess system capacity for the purpose of promoting economic growth and assuring certainty of water supply. Because the system costs are spread over time among many users and are often financed, in part, by intergovernmental grants, planners did not have incentives to examine the costs of promoting growth and reducing supply uncertainty.

The cost-burden distribution that helped reinforce past investment strategies that favored growth and assuring water-supply certainty could be changing for a number of reasons. Rising construction costs (adjusted for inflation), rising unit costs of water and wastewater treatment as a result of requirements of water-quality legislation, a decline in the availability of intergovernmental grants, the increasing use of water and sewer fees to finance expansion, and other factors have increased the costs of pursuing economic growth and water-supply certainty goals through investment in system capacity expansion. A new group of decisionmakers who directly bear the costs of capacity expansion will review the balance between the goals of economic growth and water-supply certainty and the goal of cost-saving flexibility. The response to errors in water-use projections may no longer be to construct excess capacity.

The future role of water-use forecasts could be to help illuminate issues and resolve debate over the best investment and management strategy for meeting future water demands by highlighting the tradeoffs between reduced costs, growth inducement, and assuring water-supply certainty as investment goals. Water-use forecasting need not be a prescription for future investment, rather it can be a tool to organize the factors that influence water use and to enhance understanding of these factors by decisionmakers.

STATE SUMMARIES OF WATER SUPPLY AND USE

The State summaries of water supply and use, which constitute the final part of the 1987 *National Water Summary*, are based primarily on water-use data compiled by the district offices of the U.S. Geological Survey's Water Resources Division, in cooperation with those State agencies that participate in the National Water-Use Information Program. The State summaries document water use for several categories of use, identify major sources of water, and describe the quantity consumed or returned to the ground-water or stream system. Each summary describes the available water supplies in the State, the history of water-resources development, discernable trends in water uses, and water-management approaches to the allocation of water to various uses. Multicolor illustrations show the State's water budget, the quantity of usable surface-water storage over time, freshwater withdrawals for counties, major river basins (surface-water sources), and principal aquifers (ground water). A summary diagram relating sources, uses, and disposition of water withdrawals following its use is included for each State. A glossary of water-use and related terms and a conversion table of water measurements are included as supplemental information.

INTRODUCTION

National Water Summary 1987—Hydrologic Events and Water Supply and Use is primarily an extension and exploration on a State-by-State basis of 1985 water-use information collected by the National Water-Use Information Program of the U.S. Geological Survey. If, in the judgment of the U.S. Geological Survey's water-use specialists, improved estimates of 1985 water uses were available at the end of 1987, appropriate adjustments were made to the water-use data for those individual State summaries. As with previous *National Water Summaries*, this year's report is organized into three parts. The first part, "Hydrologic Conditions and Water-Related Events, Water Year 1987," provides a synopsis of the hydrologic conditions and water-related events that occurred during the 1987 water year (October 1, 1986–September 30, 1987). 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 an unusual wildlife kill in the Carson Sink, Nev.; major floods in Illinois, Maine, and New York; the effects of an oil spill on the Savannah River, Georgia and South Carolina; a landslide near Hagerman, Idaho; algal blooms in Lake Okeechobee, Fla.; and a commemoration of the 50th anniversary of the Bonneville Dam on the Columbia River, Oregon and Washington.

The second part of the report, "Hydrologic Perspectives on Water Issues," contains articles on various aspects of water use. These articles deal with observations on domestic, industrial, and agricultural water uses; estimation techniques for determining instream-flow requirements; and the benefits and capabilities of water-use forecasts.

The third part of the report, "State Summaries of Water Supply and Use," describes the source, use, and disposition of water in each State, the District of Columbia (combined with Maryland), Puerto Rico, and the U.S. Virgin Islands. Each State summary contains an overview of water supply and use, including a simplified State water budget, a brief history of water-resources development in the State, a description of the major categories of water use and their geographic distribution within the State, and a summary of water-use-management activities. Illustrations include a multicolor diagram that shows the source, use, and disposition of freshwater and maps that show surface-water, ground-water, and total withdrawals by county. Pie charts show the percentage of withdrawals from the major river basins and the principal aquifers for each water-use category. Additional illustrations show the distribution of population in 1985, the historical growth of population, and the growth of reservoir storage in the State. The contents of the State summaries are discussed in the article "Synopsis of State Summaries of Water Supply and Use."

To supplement the information provided, bibliographic references are listed at the end of each article and State summary. Most technical terms used in this volume are defined in the "Glossary." A conversion table of water measurements also is provided for the reader's convenience.

Although numerous reports have been published during the past 40 years on the subject of water use, many of these reports pertain either to a particular category of use or to a particular geographic area. In 1950, the U.S. Geological Survey initiated a series of national water-use estimates to be published at 5-year intervals (MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977); these estimates, however, were based on a variety of sources of differing accuracy.

In recognition of the need for more uniform and reliable water-use information, the Congress in 1977 directed the U.S. Geological Survey to undertake a National Water-Use Information Program. This program, which is part of the U.S. Geological Survey's Federal-State Cooperative Program, complements the water quantity and quality data-collection programs of the Survey. As of 1988, 49 States and Puerto Rico were participating in the water-use program, which supports field data collection, evaluation of existing data, and development of State water-use information systems. As the State water-use information programs are implemented and refined the accuracy of State and national water-use estimates will continue to increase. National water-use estimates prepared by this program include those of Solley and others (1983, 1988). Reports prepared by the States are given in each State summary and in Solley and others (1988).

The 1987 *National Water Summary* complements other water-use reports such as the U.S. Bureau of the Census surveys of industrial and mining water use (U.S. Bureau of the Census, 1985, 1986a) and its surveys of farm and ranch irrigation (U.S. Bureau of the Census, 1986b). However, various agencies use different definitions of water-use categories and different information sources. These differences must be kept in mind when comparing information from the various agencies. Through the auspices of the Federal representatives to the Interagency Advisory Committee on Water Data, efforts are underway to standardize water-use categories and terminology among the Federal agencies.

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The task of preparing a *National Water Summary* requires that information be assembled by many individuals within the U.S. Geological Survey and from various Federal and State agencies. The 1987 *National Water Summary* is the fifth in this series of U.S. Geological Survey Water-Supply Papers prepared under the direction of Philip Cohen, Chief Hydrologist, U.S. Geological Survey. The report compilers gratefully acknowledge the assistance of water-resources agencies in each State in preparing and reviewing the State summaries of water use. In addition, the following Federal agencies provided data, advice, or review of parts of this report:

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Hydrologic Conditions and Water-Related Events, Water Year 1987

Review of Water Year 1987 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 1987, therefore, are described in a climatic context. Streamflow and precipitation, which are expressed as departures from long-term mean or normal conditions, are depicted on maps (fig. 1) to provide an overview of the water year. These quantities also are presented on a quarterly basis (figs. 5*A*, *B*; 6*A*, *B*; 7*A*, *B*; 8*A*, *B*) in seasonal summaries and are accompanied by maps showing

temperature as a departure from average conditions (figs. 5*C*, 6*C*, 7*C*, 8*C*,) and mean atmospheric pressure conditions near 10,000 feet (figs. 5*D*, 6*D*, 7*D*, 8*D*,). The distribution of high- and low-pressure areas across the United States at about 10,000 feet, which are 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 low- and high-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, might 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 showing geographic designations).

Hydrologic conditions across the United States during water year 1987 exhibited broad regional patterns—the western one-third of the Nation had below-normal streamflow, the central one-third, above-normal flows, and the eastern one-third near-normal annual flows (fig. 1*A*). The most anomalous conditions existed in Nevada and California, where hydrologic drought became progressively severe throughout the water year, and in the southern Great Plains, where unusually high streamflows prevailed in all seasons of the water year.

Significantly, these opposing hydrologic extremes were both associated with the same atmospheric condition—a remarkably persistent split-flow circulation pattern in which the polar-front jet stream tended to remain in Canada, north of its normal position, while an active subtropical jet stream traversed the Southern United States. The northward displacement in the polar jet carried storms and precipitation into Canada, which left the United States unusually dry. This dryness was reinforced by the position of the subtropical jet, which, by flowing northeastward across northern Mexico and the Southwestern States into the southern and central Great Plains, kept the moisture south and east of the Far West (fig. 1*B*). However, it gave rise to abundant precipitation and above-normal streamflow in Texas and Oklahoma.

Regional and local patterns of hydrologic conditions can be seen more specifically in the graphs of monthly discharges for selected rivers and month-end storage of selected reservoirs (figs. 2, 3); for example, below-normal streamflow reflected dry conditions throughout much of the Pacific Northwest and California, as seen in streamflow graphs for the Spokane and the Columbia Rivers. Both rivers were below normal during the second one-half of the water year after having reached near-normal levels at midyear. Throughout the second one-half of the water year, reservoir storage for Folsom Lake in California also reflected these dry moisture conditions and was below long-term median month-end values. In contrast, precipitation at or above the normal levels throughout the Midwest was reflected in high streamflow in the Colorado River in Utah and the Washita River in Oklahoma, as well as in above-normal conditions in several reservoir systems. Streamflow in the Washita River near Dickson, Okla., was dramatically higher than normal and reflected the very moist conditions in the areas that stretched from the Texas gulf coast to the Dakotas. The storage of water in the Salt and Verde River System Reservoirs in Arizona was about twice the long-term month-end average throughout the entire water year, whereas the

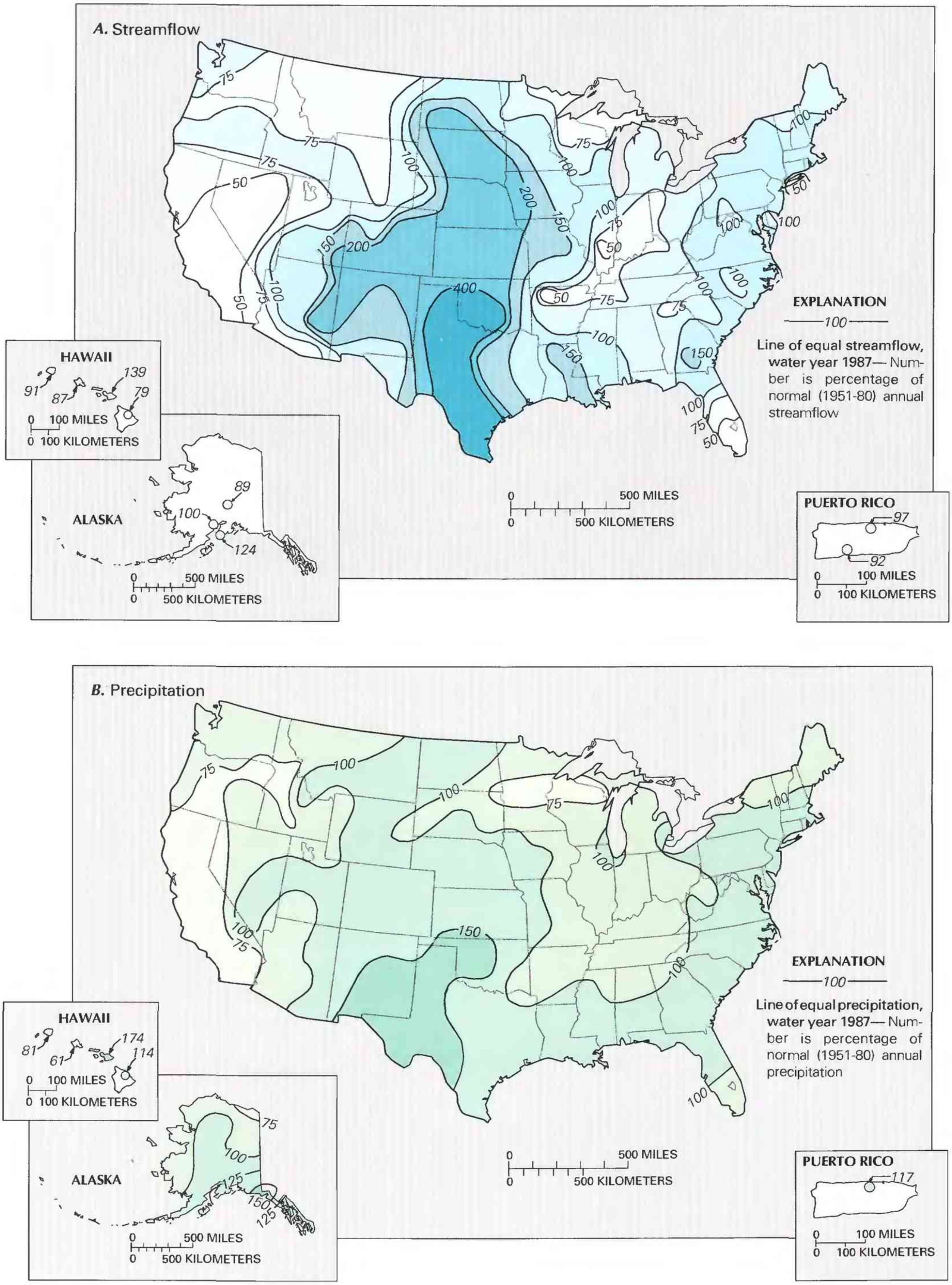


Figure 1. Streamflow (*A*) and precipitation (*B*) in the United States and Puerto Rico in water year 1987. Data are shown as a percentage of normal. (Sources: *A*, Data from U.S. Geological Survey. *B*, Data from the National Oceanic and Atmospheric Administration, National Climatic Data Center.)

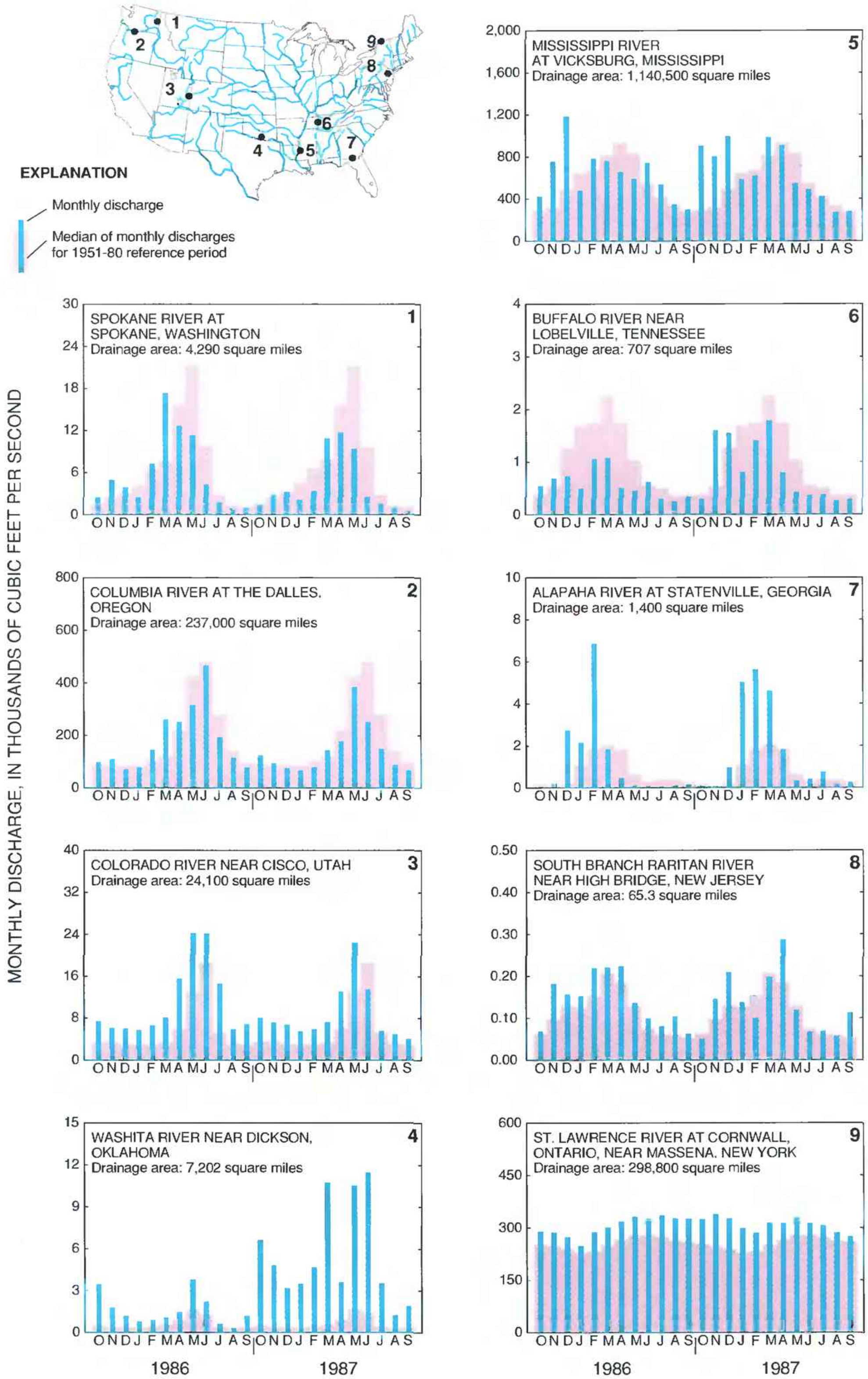


Figure 2. Monthly discharges for selected major rivers of the United States for water years 1986 and 1987 compared with monthly median discharges for the reference period water years 1951 to 1980. (Source: Data from the U.S. Geological Survey files.)

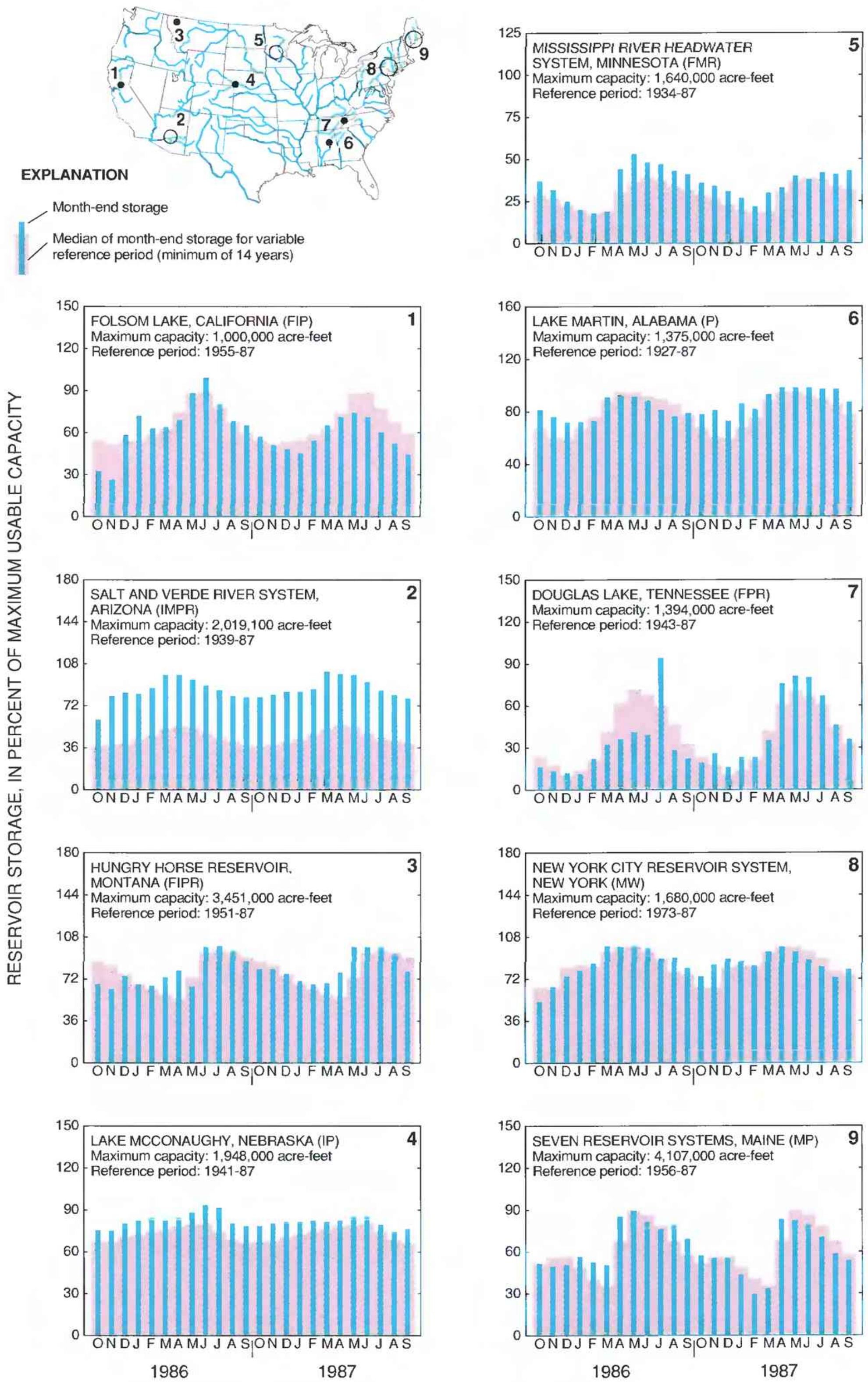


Figure 3. **Month-end storage of selected reservoirs in the United States for water years 1986 and 1987 compared with median of month-end storage for reference period.** The reference period, which varies but is a minimum of 14 water years, for each reservoir or reservoir system is shown on the graph; the beginning year for a 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 the U.S. Geological Survey files.)

Lake McConaughy Reservoir in Nebraska and the Mississippi River Headwater System in Minnesota maintained above-average storage, though not to the degree experienced in Arizona. Monthly discharge of the St. Lawrence River between Ontario, Canada, and New York was consistently high throughout the water year; this continued the trend from the previous water year and reflected record-high water levels in Lake Erie and Lake Superior and generally high water levels in the entire Great lakes system. Montana, which is located between the dry conditions of the Pacific Northwest and the wet conditions of the central part of the Nation, experienced near-normal hydrologic conditions. Storage capacity of Montana's reservoirs, such as the Hungry Horse Reservoir, was near normal because slightly above-normal storage in the middle of the water year was balanced by below-normal storage at the beginning and at the end of the water year. Storage contents of the New York City Reservoir System, which were slightly above normal at the beginning of the water year, fell a little below normal throughout the summer and closed out the water year slightly above the long-term monthly average for the system; this reflected the near-normal moisture conditions throughout the Atlantic Coastal States.

Hydrologic and moisture conditions across the Nation were a study of contrasts, especially along the boundaries between areas of the Nation where conditions were unusually moist or unusually dry. In Utah, for example, below-normal runoff generally was more severe in the western part of the State. Great Salt Lake, however, rose to record high levels even though inflow was below normal; later in the year, the lake level declined as a result of evaporation and pumping of water from the lake. Floods occurred in areas of Washington State early in the water year, despite the increasing effects of dry conditions across the West in general. Precipitation in Arizona and Nevada ranged from much below normal in the western parts of the States to much above normal in the eastern parts. These contrasts in precipitation were reflected in streamflow, which in Arizona, for example, ranged from greater than 200 percent of normal levels in the eastern part of the State to below 75 percent in the western part. In Texas, however, moisture conditions were much above normal in the western part and near normal in the eastern part; this was reflected in streamflow much as 400 percent of normal throughout the west-central part of the State and 150 percent of normal in the eastern part of the State.

Flows of the Mississippi, the St. Lawrence, and the Columbia Rivers, also known as the "Big Three," broadly reflect the hydrologic conditions in much of the United States and in parts of Canada. Variation in their combined flow over time is a measure of changing average continental hydrologic conditions. The combined flow of these rivers was 65 percent of normal during the first quarter of the water year, near normal during the second and third quarters of the year, and much below normal for the last quarter of the water year. This decrease in flow reflected the worsening of the western drought in the last quarter of the water year and also the tapering off from unseasonably high precipitation in the central part of the United States at the beginning of the year to normal or even below-normal precipitation in the Great Plains and the Mississippi and the Ohio Valleys.

During the 1987 water year, many significant water-related events, both natural and human induced, also occurred. A representative set of these events is listed chronologically in table 1, and their geographic locations are plotted in figure 4. Table 1 represents a culling of some hundreds of these hydrologic occurrences, generally omitting, for example, flood events where the recurrence interval is less than 10 years, toxic spills that involve less than 6,000 gallons or 150 barrels, 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, and 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 were based on information provided to the U.S. Geological Survey by the U.S. Environmental Protection Agency. Because the reporting of fishkills by the States to the Environmental Protection Agency is voluntary, not all States presently report such data.

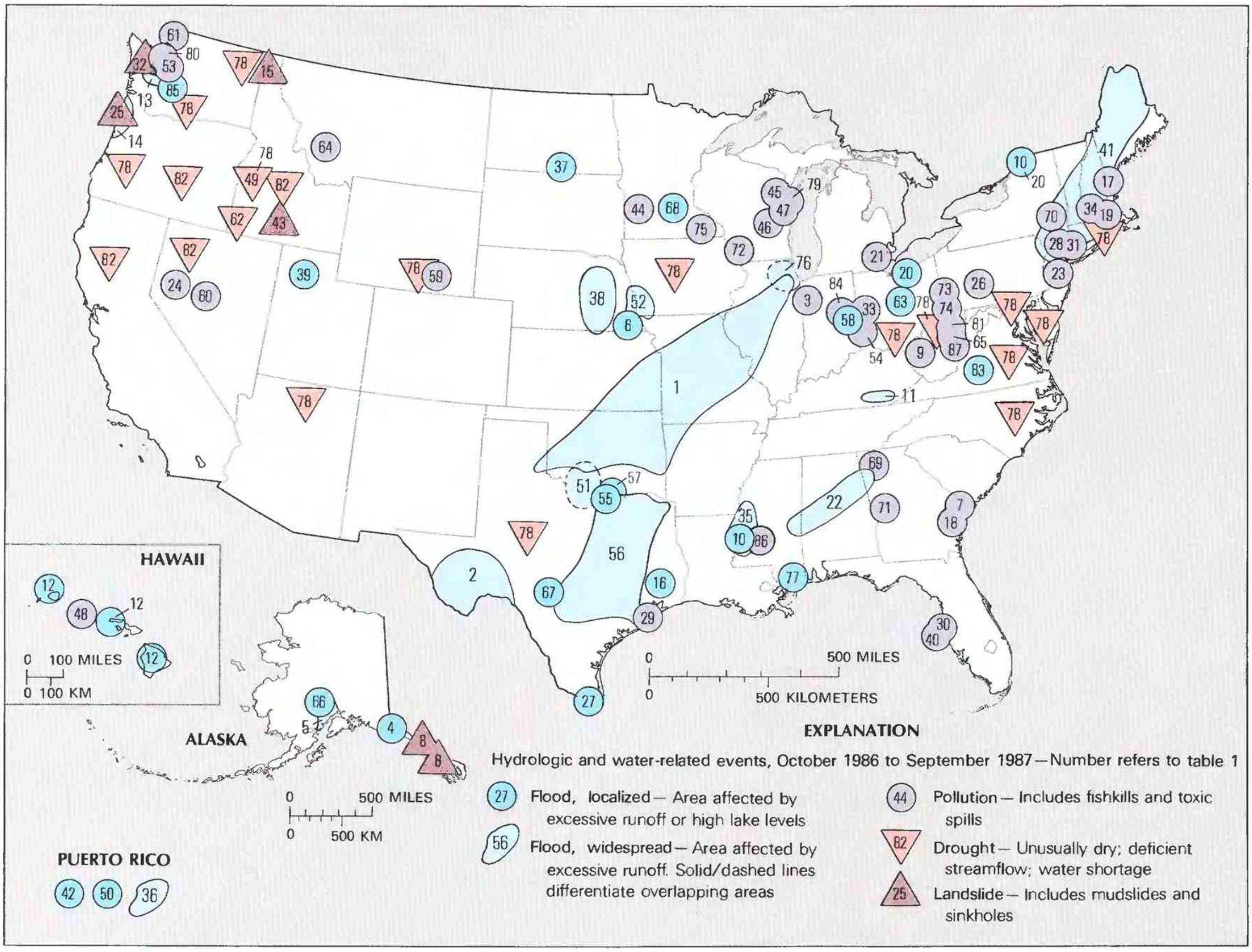


Figure 4. Location or extent of significant hydrologic and water-related events in the United States and Puerto Rico, October 1986 through September 1987 as documented in table 1.

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987

[The events described below are representative examples of hydrologic and water-related events that occurred during water year 1987. 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 are mostly from reports of the National Oceanic and Atmospheric Administration. Abbreviations used: acre-ft/year = acre-feet per year; ft^3/s = cubic feet per second; Mgal/d = million gallons per day; mi^2 = square miles; mg/L = milligrams per liter]

No. (fig. 4)	EVENT
	OCTOBER 1986
1	Between September 26 and October 5, heavy rains and flooding occurred in the Central States, especially in Kansas, Missouri, Oklahoma, and Illinois. The National Weather Service described the weather situation—"During the last four days of September and the first four days of October, the almost stationary positioning of a front resulted in a band of heavy rainfall that extended from the Texas Panhandle, through Oklahoma and southeast Kansas, and into central Missouri. By the end of September, the ground was saturated throughout most of the region, and flooding was already prevalent in many areas. Then the precipitation became further enhanced as the remnants of Pacific Hurricane Paine moved northeastward along the front on October 2 and 3 ... many locations received rainfall in excess of 20 inches during the 8-day period. Hardest hit by the flooding were north-central Oklahoma and southeast Kansas." In Kansas, the most severe flooding, which followed the 18-inch rains on October 2 and 3, occurred along the Marmaton, the Little Osage, the Neosho, the Verdigris, and the Caney Rivers and their tributaries. The Marmaton River (a tributary of the Osage River via the Little Osage River) crested at more than 14 feet above flood stage and more than 3 feet above the previous record high of 1915. At Fort Scott, the flooding of the Marmaton River damaged much of the industrial area, affected at least 55 businesses and 52 homes and reached the first-floor ceilings in some buildings. In northern Bourbon County, the Little Osage River reached a record high of 13 feet above flood stage at Fulton and washed out a section of track, where a train derailed. In southeastern Kansas, the extensive flooding caused an estimated $60 million in damage to more than 340,000 acres of farmland. In Missouri, extensive flooding occurred across the southwestern and much of the central and eastern parts of the State. A 16-year old boy drowned on October 3 while trying to rescue his dog from the swollen Moreau River near Jefferson City. On October 1, several streams in the Osage River basin reached peak flows that equaled or exceeded the 100-year recurrence interval, including the Sac River at Highway J below Stockton (north of Springfield), which peaked at 14,800 ft^3/s on October 1 (drainage area 1,292 mi^2). The Missouri River at Hermann (60 miles west of St. Louis) had a peak daily discharge of 547,000 ft^3/s (drainage area 524,200 mi^2) on October 5; this was the highest October daily discharge in the entire 89 years of record at that site. In Oklahoma, severe flooding occurred along the Arkansas, the Caney, the Canadian, the North Canadian, the Cimarron, the Washita, the Salt Fork, the Neosho, and the Verdigris Rivers and the North Fork of the Red River. More than 500 homes were destroyed, and about 30,000 people were evacuated from 25 towns. About one-half of the evacuations were from Bartlesville near Caney Creek in Washington County. On October 4, the peak discharge of the Cimarron River at Perkins, Payne County, was 160,000 ft^3/s (drainage area 17,852 mi^2) and had an estimated recurrence interval of 70 years. Much of the flooding in northeastern Oklahoma was the result of releases from the many reservoirs in the area in order to avoid the possibility of catastrophic dam
	OCTOBER 1986 (con.)
1 (con.)	failures at reservoirs that were nearly full or rapidly filling. Flooding along the Arkansas River and some of its tributaries extended downstream from Oklahoma into Arkansas. In northeastern Illinois, the late September rains caused record-breaking peak flows on October 1 along upstream parts of the Des Plaines River (a tributary of the Illinois River) that had recurrence intervals of 50 to 75 years. Additional rainfall elsewhere in the State caused flooding along many other streams. During October and November, parts of Kansas, Missouri, Oklahoma, and Illinois were declared Federal disaster areas as a result of the storms and flooding noted above.
2	The storm systems noted above also caused flooding in much of southwestern Texas early in the month; on October 5 in northern Val Verde County, about 200 miles west of San Antonio, 10 to 15 inches of rain caused severe flooding on the Devils and the Dry Devils Rivers (tributaries of the Rio Grande). The protracted and sometimes torrential rains on October 4 and 5 affected adjoining areas to the west and north in Upton, Brewster, and Crockett Counties; flash flooding occurred along the Rio Grande and its tributaries, including the Pecos River and its tributaries. A reported 16.21 inches of rain fell in 24 hours at McCamey (southwestern Upton County), which is within 10 miles of the Pecos River. One drowning occurred when a car was washed off a road east of Rankin (Upton County). In Brewster County, the Rio Grande rose 17 feet, and Terlingua Creek (tributary to the Rio Grande) rose 12 feet and sent 3 feet of water through city streets in Terlingua and Lajitas.
3	Between October 6 and 10 in northwestern Indiana, more than 10,000 fish (9 percent game fish) died along 8.5 miles of Carpenter Creek near Remington (55 miles south of Gary), Jasper County. The cause was contamination from ammonia water (high concentration of ammonia nitrogen) as a result of a truck spill. Carpenter Creek is a tributary of the Illinois River via the Iroquois and the Kankakee Rivers.
4	In southeastern Alaska on October 8 at about midnight local time, Russell Lake breached the dam that had been formed by Hubbard Glacier on May 29, 1986. The lake drained in 2 days and resumed its previous physiographic identity as Russell Fiord. 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.
5	From October 10 to 12 in south-central Alaska, runoff from record 24-hour rainfalls caused highly variable and, in some places, severe flooding. The hardest hit areas were on the Kenai Peninsula south of Anchorage and in the Susitna River valley west and north of Anchorage. The areas on the Kenai Peninsula included Seward and the Bradley Lake area at the head of Katchemak Bay east of Homer. Damage estimates of $15 million to $20 million were reported, about $4 million to $5 million of which was to the Alaska Railroad. The President declared major disaster areas in Matanuska-Susitna Borough, Kenai Peninsula Borough, the city of Cordova (about 150 miles east-southeast of Anchorage), and that part of the Alaska Railroad south of the community of Healy (80 miles

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	OCTOBER 1986 (con.)
5 (con.)	southwest of Fairbanks). Peak discharges equaled or exceeded 100-year recurrence intervals on some streams, including the Susitna River at Susitna Station (drainage area 19,400 mi²), which is within 20 miles of the mouth of the river. The maximum flow of 312,000 ft³/s occurred on October 12.
6	Rains of 2 to 5 inches fell on southeastern Nebraska between October 10 and 11 and caused extensive flooding along the Big Blue and the Little Blue Rivers and their tributaries. Many roads and thousands of acres of farmland were flooded.
7	Near the southern coastal tip of South Carolina, a fishkill of more than 2,000 fish occurred in the Wright River in Jasper County from October 10 to 12 as a result of the discharge of wastewater from a spoil area near a construction site. The Wright River is a small estuarine river that flows into the Atlantic Ocean and roughly parallels the lower reaches of the Savannah River northeast and east of Savannah, Ga.
8	Heavy rains from October 14 to 16 in the southeastern Alaska panhandle touched off mudslides in downtown Juneau and near Petersburg, about 120 miles southeast of Juneau. These rains, which followed 3 weeks of wet weather, fell on saturated ground. The mudslides caused the closing of Mitkof Highway near Petersburg and the evacuation of several families in Juneau.
9	In southwestern West Virginia from October 22 to 23, more than 8,000 fish were killed along 3.4 miles of Lens Creek near Marmet (about 5 miles south-southeast of Charleston), Kanawha County. The kill resulted from hydrochloric acid (from a gas-well drilling operation) that reached the creek by means of a diversion ditch. Lens Creek is a tributary of the Kanawha River, which flows into the Ohio River about 45 miles northwest of Charleston.
10	Unusually high streamflows for this time of year occurred in downstream parts of the Mississippi and the St. Lawrence Rivers. Monthly mean discharge of the St. Lawrence River at Cornwall, Ontario, Canada, near Massena, N.Y. (drainage area 298,800 mi²), was 323,900 ft³/s, which was the highest for October in the 126 years of record and reflected prolonged wet spells in the Great Lakes–St. Lawrence River basin. Similarly, the monthly mean flow of 905,000 ft³/s and the daily mean flow of 1,176,000 ft³/s on October 21 on the Mississippi River near Vicksburg, Miss. (drainage area 1,144,500 mi²), were the highest for October in 58 years of record.
	NOVEMBER 1986
11	In eastern and southeastern Kentucky on November 8 and 9, 3 to 5 inches of rain fell in less than 12 hours in some places and caused widespread flash flooding. The effects were intensified because the ground had been saturated by soaking rains that began on November 5. Numerous roads and bridge approaches were washed out, and many mudslides occurred. Most of the flooding occurred along small streams in headwater areas of the Licking and the Kentucky Rivers (tributaries of the Ohio River) and along the Licking River itself in Morgan County.
12	On November 10 and 11, many parts of the island chain of Hawaii received 10 to 20 inches of rain. Although the result was mostly minor flash flooding, rockslides, mudslides, and water caused the closing of roads in several areas on the island of Hawaii. On the northeastern part of the island of Kauai, rivers flowing out of the interior overflowed their banks and caused roads and bridges to be closed. On the island of Maui, the road from Kaupo to the upcountry area was washed out, stranding Kaupo's 100 residents who had lost their other road out of town (via Hana), as the result of high surf caused by Hurricane Estelle on July 23.
13	In western Washington, a Pacific frontal system stalled on November 23 and released 2 to 3 inches of rain over much of the Puget Sound lowlands and 4 to 5 inches on the western foothills of the Cascade Range. Maximum reported rainfall was 7.21 inches at Spada Lake, which is about 30 miles northeast of Seattle. The National Weather Service issued flood warnings for 13 rivers in western Washington. The Snoqualmie River basin (east and northeast of Seattle) had floods in the 15- to 50-year recurrence interval range that caused two deaths near the town of Sultan (Snohomish County) and the partial evacuation of the town of Snoqualmie (King County). Some evacuations also were necessary near Sumner (Pierce County southeast of Tacoma) as the result of 40-year recurrence flooding of the Puyallup River. By November 24 to 25, the Chehalis River (drainage area 434 mi²) had crested at a 50-year recurrence level near Chehalis (Lewis County about 50 miles south-southwest of Tacoma). On November 25, peak discharge farther downstream on the Chehalis River, near Grand Mound (Thurston County), was 51,100 ft³/s (drainage area 895 mi²), highest flow in the 59 years of record at that site. The Chehalis River flows into the Pacific Ocean on the western coast of the State, and the Puyallup River reaches the ocean via Puget Sound. The President declared six counties in western Washington major disaster areas. North of the severely flooded region near Mount Baker and about 10 miles south of the Canadian border, about 1,000 skiers were temporarily isolated on November 23 or 24 when floodwaters damaged bridge approaches (along State route 542) because a river channel had become heavily choked with silt; a temporary bridge subsequently opened the area to travel. Flood recurrence intervals in that area, however, were only 5 to 10 years.
14	From November 23 to 25, parts of the same or related storm systems that affected western Washington, as noted above, also caused numerous rains in northwestern Oregon and flooding on several of the northern and central coastal streams, principally the Nehalem and the Wilson Rivers (Clatsop, Columbia, and Tillamook Counties). Rainfall totals of more than 4 inches in 24 hours were common. Some minor flooding occurred in the central and the northern Willamette Valley.
15	On November 24, as a result of rainfall on heavy snowpack at higher elevations, Lightning Creek (tributary to Clark Fork east of Pend Oreille Lake), which is near the town of Clark Fork (Bonner County, in northern Idaho), flooded. A cabin was destroyed by the flooding, and a mudslide also occurred in the area.
16	Torrential rains and flooding occurred in southeastern Texas, especially in Hardin, Jasper, Jefferson, Newton, and

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	NOVEMBER 1986 (con.)
16 (con.)	Orange Counties at various times during the period from November 24 to 28. In southern and eastern Hardin County, 2-day rainfall totals were 10 to 12 inches, and nearly 10 inches fell at Evadale in southern Jasper County. Flooding was widespread along many streams. In Hardin County east of the Neches River, Pine Island Bayou and Village Creek and their tributaries were among the streams that flooded. A section of a bridge collapsed along a highway near Lumberton, and 3 feet of water covered a bridge that led to the town of Pinewood.
	DECEMBER 1986
17	In southern Maine, near the town of Wells (York County, 30 miles southwest of Portland), a tank truck overturned on a sharp curve while entering the Maine Turnpike (I-95) on December 4. The tank ruptured and spilled almost its entire 7,800 gallons of waste motor oil down a steep grade and into a swamp that contained high water as a result of rain on December 3; the oil-water mixture then flowed into Depot Brook, which flows into Wells Harbor, parts of which abut the Rachel Carson National Wildlife Refuge and the Wells National Marine Estuarine Sanctuary. Oil-removal operations along the brook recovered about 3,000 gallons of the oil within 24 hours and 75 percent by December 15. Cleanup operations were reportedly adequate to prevent adverse effects on the refuge and the sanctuary.
18	From December 4 to 8, a tankship spilled about 500,000 gallons of fuel oil into the tidal Savannah River during transfer operations while docked just north of Savannah, Ga. The spill, which was attributed to malfunctioning valves in the cargo and ballast piping, affected about 25 miles of the Savannah River and its tributaries, as well as 8,000 acres of the Savannah River National Wildlife Refuge. Cleanup operations were begun by the U.S. Coast Guard in the area of the spill on December 5, and, by December 30, an estimated 200,000 gallons of oil-water mixture and 160 cubic yards of oily debris had been recovered. As of January 12, 1987, no floating or recoverable oil appeared to be present on the Savannah River. [For additional details, see article in this volume "Major Oil Spill on the Savannah River, Georgia and South Carolina, December 1986." The same tankship also had lesser leakage problems in the St. Johns River near Jacksonville in northeastern Florida between December 14 and 17.]
19	In eastern Massachusetts on December 13, an overfilled tank at South Weymouth Naval Air Station (Norfolk County) about 15 miles south-southeast of Boston spilled about 6,000 gallons of jet fuel, most of which entered adjacent French Stream. The stream is a tributary of the North River (Plymouth County; via the Drinkwater and the Indian Head Rivers) that flows into Massachusetts Bay. Cleanup operations consisted of containment by using booms, flushing of affected areas, and removal of oil and contaminated soil; cleanup on French Stream, Studleys Pond, and the adjacent land area was completed by December 30.
20	Lake Erie, as measured at Cleveland, Ohio, was at its highest December level in 127 years of record (574.68 feet above sea level), and the calendar-year average level for 1986 also was a new calendar-year record. A new record-high annual average also occurred on Lake Superior as
	DECEMBER 1986 (con.)
20 (con.)	measured along its southeastern shore at Marquette, Mich. Also reflecting the prolonged wet spells in the Great Lakes–St. Lawrence River basin, the December monthly mean discharge of the St. Lawrence River at Cornwall, Ontario, Canada, near Massena, N.Y., was 327,000 ft^3/s, highest of record for the month and above average for the 23d consecutive month.
	JANUARY 1987
21	In southeastern Michigan on January 11, in the vicinity of the Detroit Metropolitan–Wayne County Airport at Romulus, 54,000 gallons of jet fuel was spilled into a diked area when an underground tank was overfilled during fuel-transfer operations. About 16,000 gallons of the fuel spilled from the dikes into a roadside ditch and thence into the Sloss and Ganong Drain, which affected 5 miles of drains. Dams and sorbent booms were used to isolate the fuel for removal and cleanup. Water in the Sloss and Ganong Drain reaches the Detroit River 9 miles to the east by way of the Sexton and Kilfoil Drain, the South Branch Ecorse River, and, finally, a 0.5-mile reach of the Ecorse River.
22	Rainfall of 2 to 10 inches that occurred from January 17 to 19 over central Alabama, east-central Mississippi, and several parts of Georgia caused flash flooding along many streams. In Alabama, the most intense rains (as much as 7 inches or more) occurred in a broad band from near Livingston, Sumter County (100 miles southwest of Birmingham), northeastward to and north of Birmingham. Flooding along the Sucarnoochee River (a tributary of the Tombigbee River) forced the evacuation of several families in the Livingston area. Flooding along the Tombigbee, the Alabama, the Cahaba, and the Black Warrior Rivers generally was confined to nearby lowlands. In adjacent east-central Mississippi, some of the most intense rains were near Meridian, Lauderdale County (80 miles west of Jackson) and resulted in some evacuations as a result of flash flooding along Sowashee Creek, which is a small stream in the Pascagoula River basin. On January 18, in northern Georgia, flash flooding occurred on many small streams from the Douglasville area (Douglas County, east of Atlanta) to northern parts of the Atlanta metropolitan area.
23	On January 19 and 20 at a Bayonne port terminal south of Jersey City, N.J., 586,000 gallons of caustic soda solution (sodium hydroxide) leaked from a ground-level crack in a 600,000-gallon storage tank. About 200,000 gallons entered Kill Van Kull, the waterway south of Bayonne that connects Newark Bay with the Hudson River estuary. The hydroxide was neutralized by using sodium bicarbonate, and contaminated soil was removed. Reportedly, there were minimal environmental affects; about 160,000 gallons of solution was recovered by excavation and vacuum trucks.
24	In west-central Nevada in late December and early January, State and Federal biologists reported that about 500,000 fish were dead and dying in the Carson Sink, which is near the mouth of the Carson River in the Fallon National Wildlife Refuge about 75 miles northeast of Carson City. The sink, which began filling in 1983 and began receding in 1986, comprised about 180,000 acres of lake area in early 1987. By early February, the number of dead fish numbered about 7 million (all tui chubs),

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	JANUARY 1987 (con.)
24 (con.)	and about 1,500 aquatic birds of many species also were reported to be dying in the sink. Major factors in the fishkill were thought to be increasing salinity (about 20,000 mg/L dissolved solids in this massive natural evaporation pan) and near-freezing temperatures. The waterfowl reportedly died of avian cholera, which is a bacterial infection. [For additional details, see article in this volume "Wildlife Kills in the Carson Sink, Western Nevada, Winter 1986-87."]
	FEBRUARY 1987
25	In western Oregon, intense rains from a January 31 to February 1 storm and the storms that followed, plus some low-elevation snowmelt runoff, caused considerable flooding of central and northern coastal rivers and of many of the Willamette River tributaries. Mudslides and highway washouts occurred.
26	In west-central Pennsylvania on February 2, drainage of farmyard manure into Warriors Mark Run near Warriors Mark, Huntingdon County (about 20 miles northeast of Altoona), killed about 13,700 fish along 10 miles of the run and downstream Spruce Creek. Spruce Creek is a tributary of the Susquehanna River via the Little Juniata and the Juniata Rivers.
27	In extreme southern Texas, torrential rains of 6 to 7 inches that fell in a 2-hour period on February 6 resulted in flooding in parts of Brownsville (Cameron County). A flood drainage system in the city was washed away. The flood waters were considered by some residents to be worse than the 1967 flooding from Hurricane Beulah.
28	On February 17 in southeastern New York State, a tank barge while being pushed upstream on the Hudson River ran aground a short distance south of the community of Highland Falls, Orange County (south of West Point and 40 miles north of New York City). About 102,000 gallons of unleaded gasoline leaked into the river from holes in two tanks of the barge. The plume of the spill extended downstream about 4.5 miles. No environmental affects were reported to have resulted from the spill. The gasoline remaining in the punctured tanks was transferred to another barge, and the damaged barge was refloated so that it could be towed to New York City for offloading and repairs.
29	On February 21 at Texas City, Tex., near the Gulf coast (about 30 miles southeast of Houston), a warehouse fire caused the melting of plastic containers holding 1 million gallons of antifreeze (ethylene glycol). The resulting spill was about 150 yards from the Texas City ship channel of Galveston Bay, but the antifreeze was prevented from reaching the channel by diked drainage ditches from which most of the liquid (diluted by rainfall) was pumped into three storage tanks. Cleanup activities were completed by February 26. The remaining diluted liquid from the ditches was released into the Texas City harbor at a rate sufficiently slow to meet environmental requirements established by the Texas Water Commission.
30	At Tampa (Hillsborough County) near Florida's gulf coast on February 23, the bottom of a 1-million-gallon storage tank failed, which resulted in the release of about 700,000 gallons of ammonia nitrate (70 percent solution) into nearby Delaney Creek. Cleanup operations, which were monitored by the Florida Department of Environmental Resources, recovered some of the contaminant. The Department reported a fishkill of several species of fish and advised that the majority of the contaminant was in the upper part of Delaney Creek and that the outgoing tide carried a minimal amount to East Bay (an inlet of Hillsborough Bay).
31	On February 25 at Bethel in southwestern Connecticut (Fairfield County southeast of Danbury), a gasket beneath 2 feet of snow blew out at a bulk storage tank during delivery from a fuel truck. About 19,000 gallons of fuel oil was released into a diked area, and some of the oil overflowed the dike into a drainage ditch. From the ditch, the oil flowed into a swamp, which is a wetland contiguous with Sympaug Brook (a tributary of the Housatonic River via the Still River). By the evening of the next day, about 13,000 gallons of oil had been recovered.
	MARCH 1987
32	Three days of rainfall totaling 2.5 to 6 inches in western Washington triggered mudslides that temporarily closed at least two highways— Highway 2 east of Monroe (northeast of Seattle) and Highway 101, 20 miles west of Bremerton (west of Seattle).
33	On March 4 near Lima, Allen County, northwestern Ohio, a pipeline leak released more than 120,000 gallons of crude oil onto the ground. The spill was contained in 1.5 miles of drainage ditches on oil company property and did not affect the Ottawa River (which flows through Lima), a tributary of the Maumee River via the Anglaize River. Within 2 days, more than 170,000 gallons of mixed oil and water had been recovered.
34	In north-central Massachusetts at Lunenburg (Worcester County, 22 miles north of Worcester) on March 6, 10,000 gallons of oil was spilled from underground storage tanks at the elementary school and entered an unnamed tributary of Lake Shirley via Catacoonamug Brook, which flows into the Nashua River (a tributary to the Merrimack River). About 8,000 gallons were recovered within 7 days. After further cleanup, final cleanup of the oil recovery area with sorbent materials was deferred until the summer.
35	On March 17, severe thunderstorms and sometimes tornadoes inflicted widespread wind and water damage in many parts of west-central and south-central Mississippi. Numerous instances of flash flooding occurred from the thunderstorms that bought as much as 6 inches of rain in 3 to 4.5 hours. Flood damages were greatest in the Vicksburg area (Warren County). Damages to homes, businesses, streets, and public utilities reportedly exceeded $5 million. More than 250 people were evacuated from their homes.
36	An upper air trough moving slowly eastward across northern Puerto Rico generated extensive showers and a few thunderstorms over the northwestern, northern, and northeastern coasts. The largest rains during the 48-hour period from March 16 to 17 ranged from about 6 to 16 inches. Flooding of small-streams was widespread. At coastal Isabela near the west end of Puerto Rico, road 112 near the town cemetery became a flooded "sinkhole"—19 houses and 2 gas stations were under water.

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	MARCH 1987 (con.)
37	In North Dakota, a mild, dry, early winter coupled with above-normal precipitation and warmer temperatures during February and March combined to create flood hazards on tributaries to the Missouri River in mid-March. The town of Linton (population 1,500) in Emmons County (south-central part of State) bore the brunt of the flood damage. Overflowing waters of Beaver Creek and its tributary, Spring Creek, damaged 20 homes, caved in two basements, and forced the evacuation of more than a dozen families. Beaver Creek flows into Lake Oahe on the Missouri River west of Linton.
38	Widespread flooding occurred in central and eastern Nebraska at various times during the period between March 18 and 27 as a result of 4 to 6 inches of rain in parts of the area between March 6 and 18 and as much as 3 inches of rain on March 23 and 24. The river basins affected were mainly the lower Platte River and its tributary basins (the Elkhorn River and Salt Creek) and the Big Blue River basin (a tributary of the Kansas River), all in eastern Nebraska. On March 18, the discharge of South Fork Elkhorn River near Ewing (drainage area 314 mi^2), Holt County (northeastern part of the State), peaked at 6,750 ft^3/s, which is 1.5 times the flood discharge for a 100-year recurrence interval. The Elkhorn River at Neligh (drainage area 2,200 mi^2), Antelope County, peaked at 14,500 ft^3/s on March 19. This flow had a recurrence interval of about 50 years and exceeded the flood of June 1947 by about 2,500 ft^3/s. Peak discharges at the most downstream stations on the Platte, the Big Blue, and the Little Blue Rivers were estimated to have recurrence intervals of 20 to 30 years.
39	Great Salt Lake in northern Utah reached its seasonal peak on March 30—4,211.85 feet above sea level. This level was the same as the seasonal high level of June 3 to 8, 1986, which was the highest level in nearly 140 years of recorded and estimated levels of the lake. These high levels, which reflect a rise of 12.2 feet since September 1982, are the result of a series of years of above-normal precipitation—principally occurring as snowfall—in the region that drains into the lake. The high levels have caused estimated damages of $285 million and have flooded wildlife refuges, county roads, minerals industries, and transportation corridors. A major effort is underway to reduce peak levels in the future by pumping 800,000 acre-ft/yr or more from Great Salt Lake to West Desert Pond, which has a storage capacity of about 780,000 acre-feet and an estimated potential evaporation of about 825,000 acre-ft/yr.
40	On March 31 at the St. Petersburg–Clearwater International Airport near the gulf coast of Florida, about 100,000 gallons of wastewater (airplane stripping solution, which included cadmium, chromium, phenol, methylene-chloride, and chloroform, mixed with wastewater) spilled from overfilled storage tanks onto the ground. About 35,000 gallons of the wastewater solution was held within a concrete containment area, but the remainder flowed by natural drainage to a grass area and into a ditch that leads to the Cross Bayou Canal tributary to Old Tampa Bay on the northern edge of the airport. The ditch leading to the bayou was diked, and the wastewater was drained and pumped into holding tanks. Concentrations of the contaminants were analyzed and reported to be low. A contributing factor to the overfilling of the tanks was the 5 days of rainfall preceding the spill.
	APRIL 1987
41	Between March 31 and April 6, heavy rains—more than 10 inches in some areas—coupled with snowmelt runoff caused extensive flooding in the Northeast. In the New England area, Maine, Massachusetts, and New Hampshire were the most seriously affected. In southern New England, the Housatonic, the Connecticut, the Merrimack, and the Concord Rivers flooded; some people were evacuated in southeastern New Hampshire; and thousands fled in Massachusetts. Property damage was most serious in Maine and Massachusetts, where estimates of $100 million and $50 million, respectively, were reported. Affected parts of these two States were declared Federal disaster areas. In Connecticut, the failure of a dam undergoing repairs on Hermere Reservoir, which is the principal water supply for the city of Meriden, caused extensive flooding downstream. South-central Maine was particularly hard hit. Rainfall of 6 to 7 inches in the headwaters of the Androscoggin and the Kennebec Rivers was nearly continuous for 44 hours. Record high flows were recorded at many stream-gaging stations in Maine—flows exceeded the 100-year recurrence interval at 14 gaging stations. Recurrence intervals generally were greater than 100 years on the Piscataquis (a tributary of the Penobscot River) and the Kennebec Rivers. The peak discharge of the Kennebec River at North Sidney (11 miles upstream from the State capitol in Augusta) on April 2 (drainage area 5,403 mi^2) was 220,000 ft^3/s. On April 1, the peak discharge of the Little Androscoggin River, near South Paris (drainage area 73.5 mi^2), was 9,300 ft^3/s, which was nearly 1.5 times the 100-year flood and the highest during the 55-year period of record. On April 6, pollution-hazard warnings were issued because a large number of drums containing hydrocarbons had been released by flood waters into the Kennebec River and other streams. Fortunately, these drums were recovered without serious incident. [For additional details, see article in this volume "Flood of April 1987 in Maine."] Flooding also occurred in several parts of the Middle Atlantic States, but no major damage was reported in northern New Jersey and northeastern Pennsylvania. On April 4 and 5, New York streams that drain the Catskill Mountains flooded; the floods ranged from the 25- to the 75-year recurrence interval. The flooding was especially severe on Schoharie Creek, which is a tributary of the Mohawk River, where it contributed to the failure of the New York State Thruway bridge near Amsterdam (west of Albany) on April 5. Ten people were killed when four cars and a truck fell off the failed bridge. [For additional details, see article in this volume "Flood-Induced Collapse of the New York State Thruway Bridge Near Amsterdam, New York, April 5, 1987."]
42	Between April 11 and 13, Puerto Rico experienced serious floods that resulted from intermittent heavy rains, particularly in the northern part of the island. Some areas had as much as 14 inches of rain during the period, with a maximum-day rainfall of 9 inches reported near the town of Vega Baja on April 12. The Rio Cibrico (0.8 mile east of Vega Baja; drainage area 99.1 mi^2, of which 25.4 mi^2 does not contribute directly to surface runoff) had a record peak flow of 33,000 ft^3/s. Four people drowned and the homes of 1,450 families sustained property damage or were totally destroyed. Sixteen towns suffered flood damage; the most damage occurred in the town of Vega

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	APRIL 1987 (con.)
42 (con.)	Baja. Overall damage was estimated to be more than $2 million.
43	On April 16, ground-water seepage precipitated a landslide on the western bank of the Snake River canyon near Hagerman (Gooding County), in south-central Idaho about 30 miles west-northwest of Twin Falls. The landslide caused an estimated $1.5 million in damage to the Bell Rapids Irrigation Company's pumping plant and serious damage to the Hagerman fossil beds on U.S. Bureau of Land Management property located downslope. [For additional details, see article in this volume, ''Landslide of April 14, 1987, near Hagerman, Idaho''.]
44	On April 27, a large fishkill was reported in Byllesby Reservoir in southeastern Minnesota, near the town of Cannon Falls (Goodhue County). The kill stemmed from a scheduled drawdown of the lake for repairs to the dam gate. Lowering the water level in the lake reduced the amount of available dissolved oxygen over a 40-acre area. The action also stirred up sediment, which released ammonia from the sediment to the Cannon River below the dam and killed fish for 6 miles downstream. The low oxygen content and the ammonia reportedly combined to kill about 21,500 fish, 8 percent of which were game fish. In addition, secondary poisoning of some wildlife occurred.
	MAY 1987
45	From May 8 to 11, a fishkill occurred on Kelly Brook and its receiving stream, the Little River, a tributary of Green Bay (via Oconto River), near Lena, Wis., in Oconto County. About 18 miles of stream were affected including the 15 miles of Kelly Brook farthest downstream and 3 miles downstream on the Little River from the point of confluence of Kelly Brook and the Little River. The water in the fishkill area was being treated for sea lamprey with 3-trifluoromethyl-4-nitrophenol (TFM). Apparently, an abnormally high concentration of ammonia (from decomposition of organic matter), low dissolved oxygen, and TFM were responsible for the death of about 41,000 fish (about 10 percent game fish); also killed were various insects and crayfish.
46	Between May 9 and 22, the Fox River and Buckstaff Creek (a Fox River tributary) near Oshkosh in Winnebago County, east-central Wisconsin, were the scene of six fishkills totaling about 30,000 fish, of which about 45 percent were game fish. The Fox River is a tributary of Lake Butte des Morts, which, in turn is tributary to Lake Winnebago. From 0.5 to 2 miles of stream was affected in each of the six kills. The cause of the kills remains uncertain despite the fact that fishkills have occurred repeatedly in these streams in recent years. According to the Wisconsin Department of Natural Resources, a pollutant was suspected, but not confirmed, in the latest May occurrence.
47	On May 11, near the confluence of the Kewaunee River (tributary of Lake Michigan) and School Creek in northeastern Wisconsin, a dairy plant in the town of Luxemburg (Kewaunee County) spilled an unknown quantity of ammonia and other compounds. As a result, a 5-mile stretch of School Creek was affected, and thousands of crawfish and more than 8,000 fish (about 4 percent game fish) were killed.
	MAY 1987 (con.)
48	On May 13, 1987, an oil spill occurred when a leak in a pipeline operated by a major oil company released about 104,000 gallons of jet fuel into a stream flowing into Middle Loch, Pearl Harbor, Hawaii. Navy personnel immediately deployed a harbor boom at the mouth of the stream, and a private contractor performed recovery operations. U.S. Fish and Wildlife officials reported that, in a refuge fed by the stream, two endangered birds died from oil exposure. In addition, 1,000 mosquito fish were found dead in ponds adjacent to the spill site, and a number of mangrove trees near the mouth of the stream also were killed. Ultimately, 75 percent of the oil was recovered, and 100 cubic yards of contaminated soil was removed.
49	On May 15, the Governor of Idaho declared a state of emergency in Ada, Elmore, Washington, Blaine, and Adams Counties in anticipation of an irrigation water shortage during the summer [see events 62 and 78]. Spring precipitation throughout the area was as much as 47 percent below normal, and runoff from the existing snowpack already had been reduced by above-normal spring temperatures.
50	A stationary upper level trough over Hispaniola (about 100 miles west of Puerto Rico) produced heavy showers and thunderstorms over northeastern Puerto Rico; some rainfall intensities were as much as 4 inches in 3 hours on May 18 and 19. The towns of Rio Grande and Ceiba were the hardest hit—flooded roads, landslides, and several houses were affected. A small bridge on New Road No. 3 at the entrance to the U.S. Navy base in Ceiba was destroyed.
51	From May 26 to 29, rains totaling 10 to 13 inches caused severe flooding in the central and western parts of Oklahoma. Two persons drowned, several bridges were washed out, some highways closed, and 500 families were evacuated. Many streams and rivers in the Arkansas and the Red River basins had flows that exceeded the 50- to 100-year recurrence intervals in an area covering about 40,000 mi^2. On May 29, the Washita River (a Red River tributary) near Dickson (drainage area 7,202 mi^2) peaked at 105,000 ft^3/s, 1.8 times the 100-year flood and 7,000 ft^3/s greater than the previous maximum discharge on May 19, 1967.
52	On May 26 to 29, rains totaling 3 to 11 inches caused severe flooding in the Nishnabotna River basin in southwestern Iowa. At the gaging station upstream from Hamburg, the river reached 28 feet, which exceeded the March 1979 record height of 27.46 feet. On May 27, about 1,100 people were evacuated from Red Oak (Montgomery County), where Indian Creek enters the Nishnabotna River. Several other towns also were evacuated, and the Governor declared Mills, Montgomery, Fremont, and Page Counties disaster areas because about $5.8 million of land, property, and crop damages were sustained. The Nishnabotna River is tributary to the Missouri River from the east in northwestern Missouri.
53	On May 27, in northwestern Washington, Little North Creek, which is a tributary to North Creek and the Sammamish River and, in turn, flows into Puget Sound near the town of Bothell (King County), was contaminated by applications of pesticide (Diazinon and Guthion mix) to fruit trees in a residential area. The pesticide apparently drifted from

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	MAY 1987 (con.)
53 (con.)	the application site, and, in a period of about 12 hours, almost 2,500 fish (mostly Coho salmon and trout) were killed in a 1.5-mile section of the creek beginning at its intersection with State Route 27.
54	On May 27, at a chemical warehouse in Dayton Park, Dayton, southwestern Ohio, a lift truck accidentally spilled cans of solvent, which exploded and caught on fire. Ultimately 1,500,000 gallons of toxic chemicals was released. Because runoff water from firefighting posed an immediate threat to the adjacent Miami well field muncipal water supply and the nearby Great Miami River, the fire was allowed to burn itself out. Response crews constructed containment trenches and plugged storm sewers to prevent discharge into the river. River samples indicate that a small quantity of solvents entered the water, but tests of the Miami well field revealed no contamination, though local agencies will continue to monitor ground water for contamination in the Dayton area. The chemical company is operating several recovery wells and monitoring the volatile material on site. Water from three monitoring wells has contained solvents, and air-injection recovery wells have removed 3,700 pounds of volatile organics.
55	On May 31, flood waters on the Red River at Gainesville, in northeastern Texas (drainage area 24,846 mi^2), peaked at 1.4 times the 100-year peak discharge, which exceeded the stage of the May 1983 flood by 3.16 feet. Two people drowned, and several State highways were closed, and bridges were washed away in areas of severe flooding.
	JUNE 1987
56	Added to the heavy rains that began at the end of May in east Texas, the torrential rains that fell from June 1 to 4 caused many streams to flood. One death occurred when flood water swept a car off a road. Northeast of Wichita Falls, an oil pipeline was ruptured by flood waters, and a small volume of crude oil was dumped into the Red River, which flows into Lake Texoma; no toxic effects were reported. The eastern and southern parts of Texas continued to receive heavy rains throughout most of the month.
57	Rains during the first week of June caused Lake Texoma, which is located on the north-central Texas–Oklahoma border, to reach its highest level since 1957. As a result, most recreation and concesssion areas were closed until the water receded. At its peak on June 5, the lake surface area had expanded to 131,000 acres, which is an increase of nearly 47,000 acres over that observed on May 28. The lake, which normally has 585 miles of shoreline, expanded to more than 800 miles of shoreline by June 5.
58	On June 2, 6 to 9 inches of rain fell in Winchester, Randolph County, east-central Indiana. This rain caused flooding in 90 percent of the town; 35 to 55 persons were forced to evacuate their homes. Also, three bridges were torn from their abutments, and several others were destroyed.
59	During mid-June, near the town of Wheatland, in southeastern Wyoming, about 14,000 fish (about 1,500 game fish) were killed in the areas of the confluence of Wheatland Creek and the Laramie River. The kill affected 3 miles of Wheatland Creek and 3 miles of the Laramie River downstream of the confluence of these streams. Although the cause is unknown, pesticides were suspected.
	JUNE 1987 (con.)
60	From about June 18 to 30, about 10,000 fish died at Lead Lake in the Stillwater Wildlife Management Area near Fallon, Nev. Carp, catfish, and Sacramento black fish were the principal species affected. This is the second massive kill on the refuge in 1987. [See event 24 and article in this volume, "Wildlife Kills in the Carson Sink, Western Nevada, Winter 1986–87."]
61	On June 28, a large fishkill occurred in Padden Creek near the town of Bellingham, Whatcom County, northwest Washington. Padden Creek drains Lake Padden and, in turn, the creek empties into Puget Sound. About 7,100 fish were killed (98 percent game fish). A 1-mile section of the creek apparently was affected by a pesticide, but this could not be confirmed.
62	In Idaho, the drought continued despite some light showers during May. The lack of any precipitation in April established a historical precedent and added to the drought condition that started with below-normal snowfall in the winter 1986. The State requested Federal emergency drought relief for 10 southwestern counties. The severity of the agricultural drought was not reflected in the streamflow because of ground-water discharge and large reservoir releases.
	JULY 1987
63	From July 1 to 2 in the north-central part of Ohio, heavy rains totaling 4 to 6 inches in 24 hours or less caused severe flooding in Ashland, Richland, Marion, Crawford, Delaware, and Morrow Counties, which is an area of more than 2,000 mi^2. Damages in the area were estimated to be $30 million to $40 million. Flooding was more severe on the upstream reaches of the Scioto, the Olentangy, and the Sandusky Rivers and on the Black Fork and the Clear Fork of the Mohican River. No record peak discharges were reported, but, on July 3, the Olentangy River at Claridon, Ohio (drainage area 257 mi^2), peaked at 13,700 ft^3/s, which was 1.5 times the discharge for the 100-year flood but 12,000 ft^3/s less than the January 1959 peak of record. Downstream reaches of all but the Sandusky River are protected by reservoirs.
64	In early July, hundreds of fish were found dead along the upper Clark Fork in western Montana. The fishkill occurred between Warm Springs and Galen below the settling ponds at the headwaters of the Clark Fork; these ponds were designed to remove toxic metals from Silver Bow Creek. Although the cause of the fishkill was not determined, it occurred during summer thunderstorms when flow bypassed the settling ponds via the Mill–Willow bypass. Toxic metals carried into the river by overland flow was thought to be the cause of the fishkill.
65	On July 2, a treatment pond, which contained water from a coal-preparation plant, broke and released water into Pecks Run, a tributary of the Buckhannon River near Hodgesville (Upshur County) in the east-central part of West Virginia. The contaminated water, which contained anhydrous ammonia plus iron, manganese, aluminum, and other chemicals, resulted in a kill of about 7,500 fish, more than 25 percent of which were game fish.
66	On July 14, intense local thunderstorms near Black Rapids in the central Alaska Range caused flash flooding in

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	JULY 1987 (con.)
66 (con.)	several small (less than 7 mi^2) drainage basins. The floods washed out roadways and stream-control structures, plugged bridges and culverts with sediment, and deposited great quantities of mud and debris on the Richardson Highway. Damage to the highway, the only surface-transportation route through this part of the Alaska Range, was estimated to be about $1 million.
67	Heavy rains on July 16 caused flooding of the Guadalupe River in south-central Texas. About 25 miles upstream at Kerrville on the North Fork of the Guadalupe, rain began at 4:00 a.m. and, by dawn, 3.3 inches had fallen. Near Comfort, Tex., a church camp bus carrying 43 children was swept from a low-water crossing by flashflood water; 9 passengers were killed, and many others were injured.
68	From July 20 to 24, back-to-back storms dropped 14.49 inches of rain at Minneapolis, Minn.; this was double the amount recorded between January 1 and July 18. The first storm, which occurred overnight (July 20–21), hit the southwestern side of the Twin Cities area and dropped as much as 9 inches of rain. The second storm (July 23–24), which was centered slightly north of the first storm and was preceded by a tornado, dumped more than 11 inches of rain in some areas; 10 inches were recorded in about 6 hours at the Twin Cities area Weather Service rain gage. This exceeded the 100-year, 24-hour rainfall by about 4 inches. Combined rainfall for the two storms exceeded 16 inches in some areas of the southwest Minneapolis suburbs. Flooding on the two streams most severely affected—Purgatory Creek (drainage area about 30 mi^2) and Nine Mile Creek (drainage area 46.2 mi^2) is estimated to have exceeded the 100-year flood recurrence interval in some areas. Those streams flow southeastward through Minneapolis suburbs to the Minnesota River—Purgatory Creek in Eden Prairie and Nine Mile Creek through Edina and Bloomington. These creeks were hit by both storms, whereas Minnehaha Creek (drainage area 157 mi^2) and Bassett Creek (drainage area 37.4 mi^2) were severely affected by only the second storm, which caused flooding approaching the 100-year recurrence interval in several areas. Two people drowned in the flooding, and damages were estimated to be $40 million to $50 million.
69	On July 22, industrial waste that had a pH level of 9 or more entered Mill Creek, which is a tributary of the Conasauga River near the town of Dalton in northwest Georgia. The contamination affected almost 2.9 miles of the creek and killed about 7,800 fish, of which 73 percent were game fish.
70	Between July 23 and 24, a fishkill was discovered on Cayadutta Creek, which is in Montgomery County near the town of Berryville in east-central New York. About 17,500 fish were killed; more than one-half of these were game fish (smallmouth bass). The kill apparently was the result of ammonia in sewage waste originating from a tanning plant. A section of the creek about 2 miles long was affected.
71	On July 26, a large fishkill was reported in the area of the confluence of Peachtree Creek and the Chattahoochee River near Atlanta, Ga., in Fulton County. A pollutant was not identified, but the kill affected 6 miles of Peachtree Creek near its confluence with the Chattahoochee River and 8 miles of the Chattahoochee River downsteam of the confluence. About 6,500 fish were killed (8 percent game fish).
72	Between July 30 and 31, a fishkill was reported on Rattlesnake Creek (a tributary of the Grant River, which is a tributary to the Mississippi River), in Grant County, southwestern Wisconsin). Rainfall of about 3 inches in a 6-hour period caused overland runoff into the creek, and the dissolved oxygen dropped to minimal levels. The fishkill was extensive and involved 8 to 10 miles of stream above the intersection of the creek and Rattlesnake Road. The smallmouth bass population was reduced from more than 300 fish per mile to only 13.
	AUGUST 1987
73	On August 4, an industrial plant in Criders Corner, Cranberry Township, Butler County, western Pennsylvania, was the source of aluminum waste that entered Brush Creek and killed about 35,000 fish (1 percent game fish). Brush Creek, which is a tributary of Connoquenessing Creek, was contaminated for 2.8 miles.
74	On August 11, mine waste was discharged into Meadow Run, which is a tributary of Dunkard Creek near Davistown, Dunkard Township, Green County, southwestern Pennsylvania. One-half mile of the stream was affected, which resulted in a kill of nearly 23,000 fish (less than 2 percent game fish). The pollutant was a polymer used to settle suspended solids.
75	On August 13, manure runoff from a hog feedlot contaminated Willow Creek, which is located near the town of Preston in Fillmore County, southeastern Minnesota. A rainfall of about 1 inch caused the ruroff that affected about 4 miles of the creek. The dissolved-oxygen deficiency created by this waste load entering the shallow stream killed 5,000 fish (10 percent of which were trout).
76	On August 13 and 14, rains of 4 to 9 inches in the 24 hours ending at noon on August 14 caused severe flooding in a 750-mi^2 area of Du Page and Cook Counties (northeastern Illinois). Near Chicago (Cook County), many highways were closed, and O'Hare International Airport, which had 3 feet of water over all the roads leading into the airport, was closed and isolated. The Governor declared the counties of Du Page and Cook disaster areas. New peak-discharge and water-level records were set on eight streams in the area including the North Branch Chicago River (drainage area, 19.7 mi^2) at Deerfield, which had a recorded discharge of 900 ft^3/s on August 14; it exceeded the 100-year recurrence interval and the 1982 stage record by 0.6 foot. [For additional details, see article in this volume "Storm and Flood of August 13 to 15, 1987, in Cook and Du Page Counties, Illinois."] On August 16, rain again drenched the Chicago area and caused some suburban residents to temporarily flee their homes.
77	In southeastern Mississippi in mid-August, torrential rains caused severe flooding; the estimated damages of $4.5 million affected about 275 families. More than 10 inches of rain fell on Vancleave on August 15 (more than 31 inches for the month as a whole) in central Jackson County 13 miles from the gulf coast. Rainfall at Pascagoula, on the coast near the Alabama border, was

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—*continued*

No. (fig. 4)	EVENT — AUGUST 1987 (con.)
77 (con.)	more than 7 inches on August 15 and was more than 12 inches at Columbia (Marion County) on the Pearl River on August 13. The recurrence interval of peak discharge was equal to or greater than 50 years on some streams, including Bluff Creek (a Pascagoula River tributary) near Vancleave and Tuxachanie and Tchoutacabouffa Creeks near Biloxi, Harrison County.
78	August brought drought to many areas of the United States. The Southeastern States that had experienced severe drought in 1986 fared better in summer 1987, but parts of the region continued to suffer drought through most of the growing season. By August, it was clear that parts of the Western United States, as well as some Eastern States, also experienced harsh drought conditions. In New England, drought hurt crops in many States. Rhode Island, which experienced its worst drought in 22 years, had only 7.6 inches of rain during the main part of the growing season (May–August) compared to normal rainfall of 13.3 inches. Crop losses were estimated to be $25 million. Other States hurt by the agricultural drought were parts of Maryland, Virginia, Pennsylvania, Delaware, West Virginia, North Carolina, Texas, Wisconsin, Iowa, and Idaho. Farmers in the southwestern and south-central parts of Ohio experienced their worst water problems in more than 50 years; crop yields reportedly were cut by one-half. One community was down to a reservoir supply of only 30 days, and another community constructed a temporary 5-mile pipeline from the source of supply of a nearby community to supplement its supply. In southern Indiana, drought conditions resulted in zero flow at Indian Creek, which is the water source for the town of Corydon, from mid-August through the end of the 1987 water year. Connections were installed to neighboring water distribution systems so this community of 4,000 persons could receive its public water supply. Beginning in mid-July, dry conditions led to forest and bush fires in many areas in the Western States. A
78 (con.)	forest fire that swept across 10,000 acres southeast of Roseburg, Oreg., destroyed eight houses and killed two loggers. Somewhat smaller, but no less destructive, fires broke out near Spokane, Wash., Cedar City, Utah, Kaibab National Forest, Ariz., the Boise National Forest near Idaho City, Idaho, Libby, Mont., and Modoc National Forest, Calif. Drought conditions also contributed to low alfalfa and hay harvests in Wyoming and record crop losses in parts of Idaho. Idaho farmers started diverting water from the Snake River to irrigate fields in Lincoln, Ada, Blaine, Washington, and Elmore Counties. The Bonneville Power Authority suffered significant reduction in power output because of a 30-percent reduction in Columbia River flow through hydroelectric plants.
79	Between August 18 and 20, storm runoff from a pit on a farm caused the deaths of 20,000 fish (9 percent game fish) on Black Creek near the town of Franklin in Kewaunee County, Wis. Black Creek is a tributary of the Neshota River, which, in turn, is a tributary of the West Twin River. The kill extended 3 to 4 miles from Black Creek near its confluence with the Neshota River on into Manitowoc County near the town of Gibson. Ammonia from the runoff, which apparently reduced the level of dissolved oxygen in the water, was thought to be the cause of the kill.
80	Between August 19 and 21, a substantial fishkill occurred in Deer Creek near the town of Edmonds, Snohomish County, northwest Washington. Deer Creek drains directly into Puget Sound just south of Edmonds. Apparently, silt and fresh concrete entered the stream below a construction project, killing about 3,200 fish (80 percent game fish). The kill affected a 1-mile section of the creek.
81	Between August 23 and 25, acid mine drainage and associated metals were released accidentally from an industrial waste pond into the Buckhannon River 4.5 miles south of the town of Buckhannon, near the town of Sago in east-central West Virginia. About 6.2 miles of stream was

Table 1. Chronology of significant hydrologic and water-related events, October 1986 through September 1987—continued

No. (fig. 4)	EVENT
	AUGUST 1987 (con.)
81 (con.)	contaminated, which resulted in a kill of about 6,600 fish (about one-third game fish).
	SEPTEMBER 1987
82	Drought conditions contributed to more forest fires in early September throughout large areas of Oregon, Nevada, California, and Idaho. Lightning was responsible for the majority of fires, and the number of fires was so large that finding enough firefighting crews was difficult. Northern California, which was hardest hit, had 979 fires, most of which were reported in August and September. About 750,000 acres were burned over in California alone. Homes were destroyed by forest fires in Oregon, Idaho, and California. Campgrounds and whole communities had to be evacuated in several areas.
83	Heavy rains from September 8 to 10 caused flooding in the southwestern part of Virginia. For the week ending September 12, rainfall at Roanoke totaled 7.39 inches (5.99 inches in a 24-hour period). Peak discharge or stage at three gaging stations exceeded record highs. Discharge of the Big Otter River near Evington (drainage area 320 mi^2) peaked at 41,900 ft^3/s on September 8, exceeding both the 100-year flood and the floods of October 1937 and August 1939 by about 2 feet and 14,400 ft^3/s. (The floods of October 1937 and August 1939 were within 0.01 foot of each other and had the same published discharge.) On the Pigg River, near Sandy Level (drainage area 350 mi^2), and Goose Creek, near Huddleston in Bedford County (drainage area 188 mi^2), the stage was the highest of record by about 5.5 feet and 11.9 feet, respectively. Discharge on both streams exceeded the 100-year recurrence interval, 65,600 ft^3/s and 53,200 ft^3/s, respectively. The area of heaviest flooding was on the western Piedmont just to the east of Roanoke, in the vicinity of Charlottesville, and along the eastern slopes of the Blue Ridge. Several bridges were washed out on Goose Creek. The highest flood measurement ever on the Roanoke River was observed on September 10 at Randolph—32.4 feet, about 3 feet higher
	SEPTEMBER 1987 (con.)
83 (con.)	than the previous high measurement of 29.38 feet recorded on November 6, 1986.
84	On September 9, a substantial fishkill occurred on Pike Creek north of Muncie, Delaware County, east-central Indiana. The kill was caused by runoff from field tiles of hog manure applied to a field. Decomposition of the waste in turn reduced the levels of dissolved oxygen. The kill involved about 3,360 fish and other aquatic animals over about a 2-mile section of the stream.
85	Between June 29 and September 23, four jokulhlaups (glacial outburst floods) flowed from South Tahoma Glacier on the southwestern side of Mount Rainer, Wash. The jokulhlaups mobilized debris on the valley floor and buried the site of a picnic area 4 miles from the terminus. Several hikers who witnessed the floods were not seriously injured. Nearby, in a seperate event, a series of small rockfalls traveled down the nearly vertical headwall above South Tahoma Glacier from midmonth on and caused dust clouds that were visible from Tacoma, which is 40 miles away. The frequency and the duration of the rockfall events are uncommon because the slopes normally are frozen or covered by snow.
86	On September 24 in west-central Mississippi just south of Jackson, a leaking pressure relief valve on a chlorine-filled tank car was discovered in the Jackson railyard. Failing in efforts to relieve pressure from the car, officials decided that the least dangerous option was to empty the chlorine from the car to the river via the city sewage-treatment plant; the possible detrimental effects on the river and its aquatic life were taken into account. As a result more than 14,000 fish were killed along a 12-mile reach of the Pearl River, but the action averted a potential disaster to people living or working in the area.
87	On September 28, about 12,700 fish (2 percent game fish) were killed along a 2.4-mile section of the East Fork of the Greenbrier River, near the town of Durbin, Pocahontas County, southeastern West Virginia. The cause was sulfuric acid (1,200 gallons), which flowed from an industrial site into the river.

Seasonal Summaries of Hydrologic Conditions, Water Year 1987

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

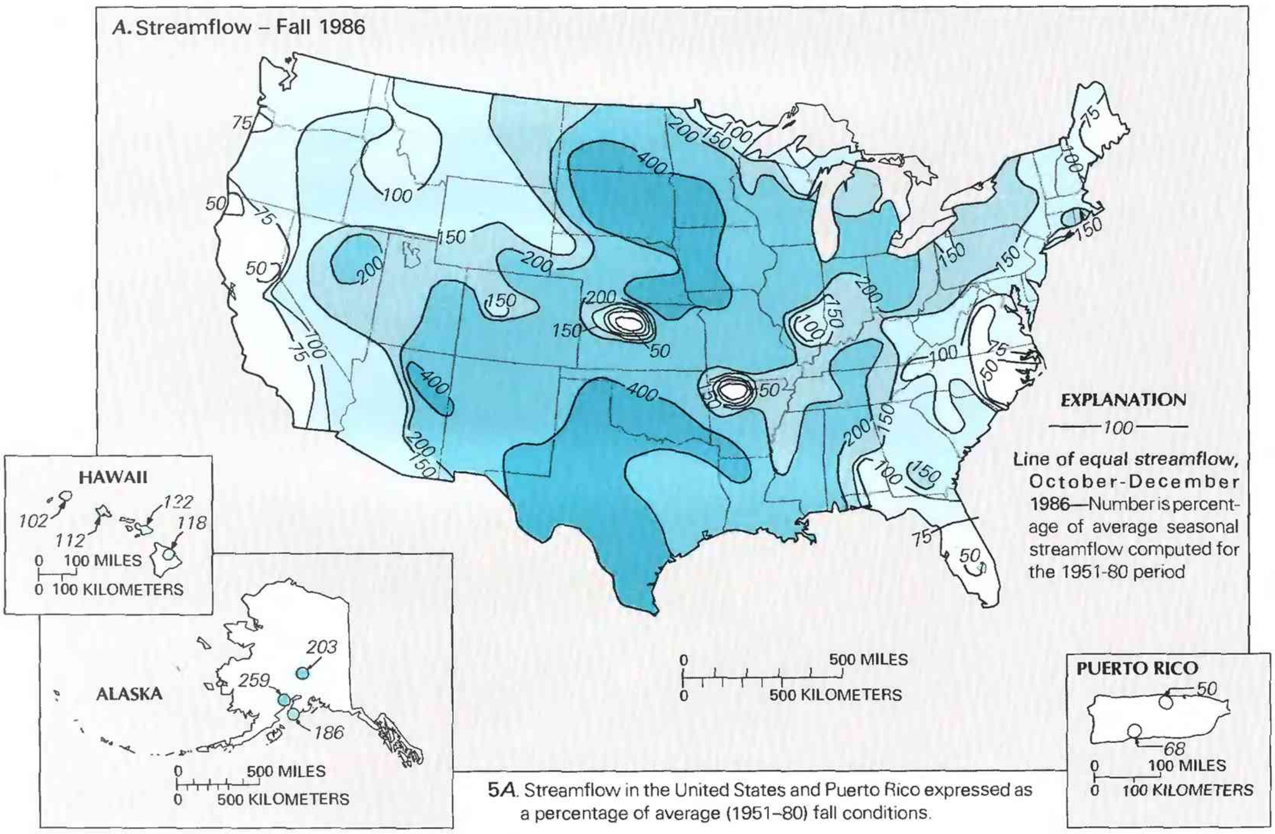
FALL 1986

The fall season of water year 1987 (October–December 1986) was characterized by very high streamflow in the northern and the southern Great Plains and somewhat lower flows in the central Great Plains. This pattern exhibited remarkable persistence, having appeared in each season of the previous water year. Other notable features of the autumn months included the progressive development of dry conditions in the Far West and a continuation of drought in eastern North Carolina. However, recovery from the severe drought that pervaded much of the Southeast during most months of the 1986 water year (fig. 5*A*) was significant. The general hydrologic condition of the Nation, 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 above normal. For the season, the combined mean discharge of the Big Three rivers was 1,327,900 ft^3/s (cubic feet per second), a 56-percent increase over the summer season (July–September 1986) flow and 65 percent above the fall season median combined flow.

Autumn began with major flooding across much of the central Midwest. Numerous rivers flooded in Oklahoma, Kansas, Missouri, and Illinois. The floods, which had recurrence intervals in excess of 50 years, were the result of intense rainfall that had been generated by the combined effects of a stationary front and the advection of moisture associated with the remnants of Pacific Hurricane Paine from the Southwest. Also in October, extremely severe flooding occurred in south-central Alaska. Record flows were recorded at nearly a dozen gaging sites in the Susitna River valley and on the Kenai Peninsula.

Rainfall also was widespread in November, and streamflow was in the normal to above-normal range at more than 90 percent of the 192 index gaging stations (190 in the United States and 2 in southern Canada). In Washington, a series of unusually intense rainstorms coupled with melting mountain snows generated floods on rivers and creeks in the Chehalis, the Puyallup, and the Snohomish River basins and on Lake Washington in late November. Moreover, new maximum monthly mean discharges for November were recorded at seven index gaging stations in the Great Basin, the northern High Plains, and on the St. Lawrence River.

By December, seasonal increases in streamflow were occurring in Nevada, Texas, Louisiana, and Georgia and throughout much of the Ohio Valley,



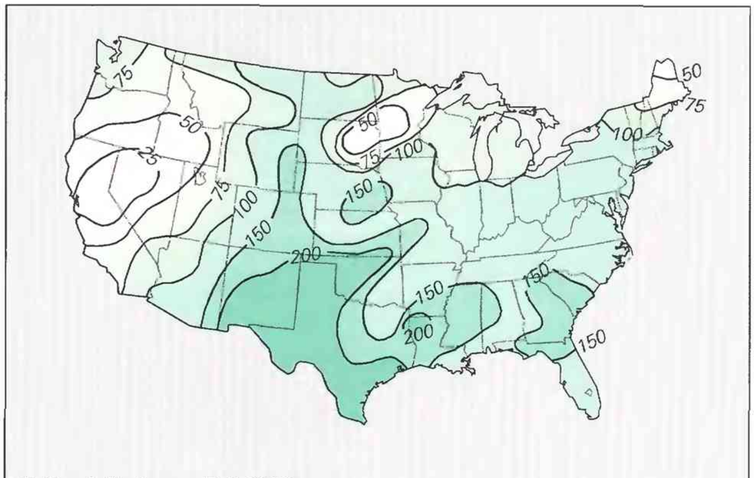
5*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) fall conditions.

Figure 5. Hydrologic conditions during the fall (October–December 1986) of water year 1987. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

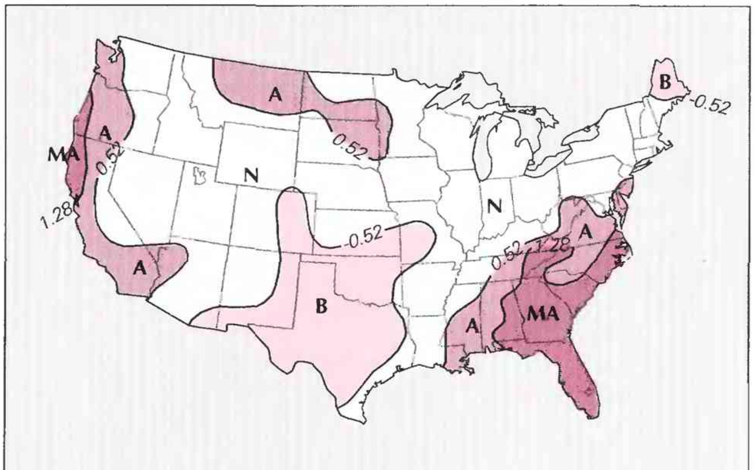
[1]U.S. Geological Survey. [2]National Oceanic and Atmospheric Administration, National Climatic Data Center.

Middle Atlantic and New England States. However, a significant unseasonal decrease began affecting parts of Washington, Oregon, and northern California. Record monthly high flows for December occurred on the St. Lawrence, the Colorado, and the San Juan Rivers. Notably, the flow of the St. Lawrence River at Cornwall, Ontario, for calendar year 1986 was the highest in 126 years of record. Also, at the end of December, new water-level records had been set on two of the Great Lakes. Lake Erie experienced new highs for both December (at 574.68 feet above sea level) and the annual average for a calendar year (at 574.76 feet above sea level, which exceeded the old record of 574.28 feet set in 1973). Lake Superior also set a record high annual average level at 602.65 feet above sea level; this exceeded the previous record of 602.46 feet set in 1951.

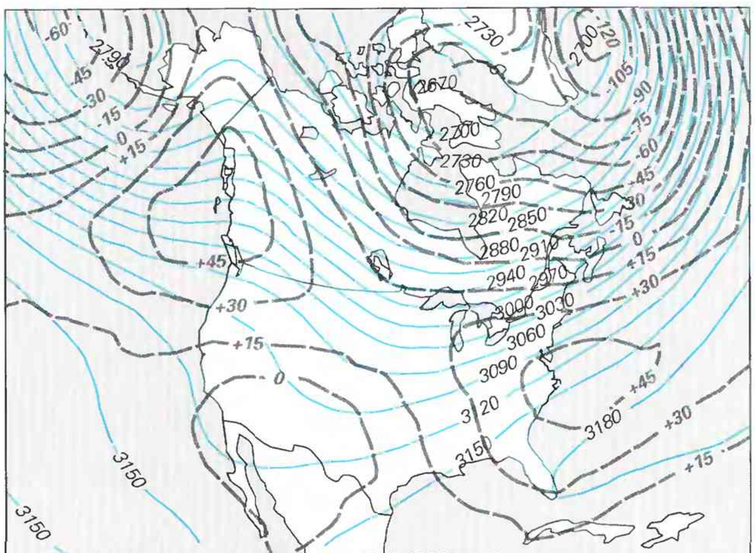
The fall season in the conterminous United States was the 13th wettest autumn in the past 92 years, and much of the season's flooding could be attributed to intense precipitation (fig. 5*B*). Not every month was wet, however. The season began with an October that was wet nearly everywhere in the United States except along its northern, western, and northeastern boundaries. November also was wet across much of the Nation, except for the Far West and Midwest, but, by December, all but the southern and eastern parts of the Nation were dry. This transition coincided with a major circulation change that was to manifest itself frequently over the next two seasons as extreme warmth dominated much of the country, especially the northern Great Plains. Despite the warm December and the lack of snow cover in the Plains States, the seasonal temperatures were tempered by the cool November as much of the Nation had near-normal temperatures when averaged over the season (fig. 5*C*). The major circulation feature that dominated the last month of the fall season can be seen on the 700-mb (millibar) height pattern (fig. 5*D*). A split flow, combined with an active subtropical jet, developed in the southern parts of the country, while the polar jet remained north of its normal position. As a result, below-normal 700-mb heights occurred in the Southwest and above-normal heights occurred over the rest of North America.



B. Precipitation — Fall 1986



C. Temperature — Fall 1986



D. 700-millibar pressure surface – Fall 1986

Figure 5. Continued.

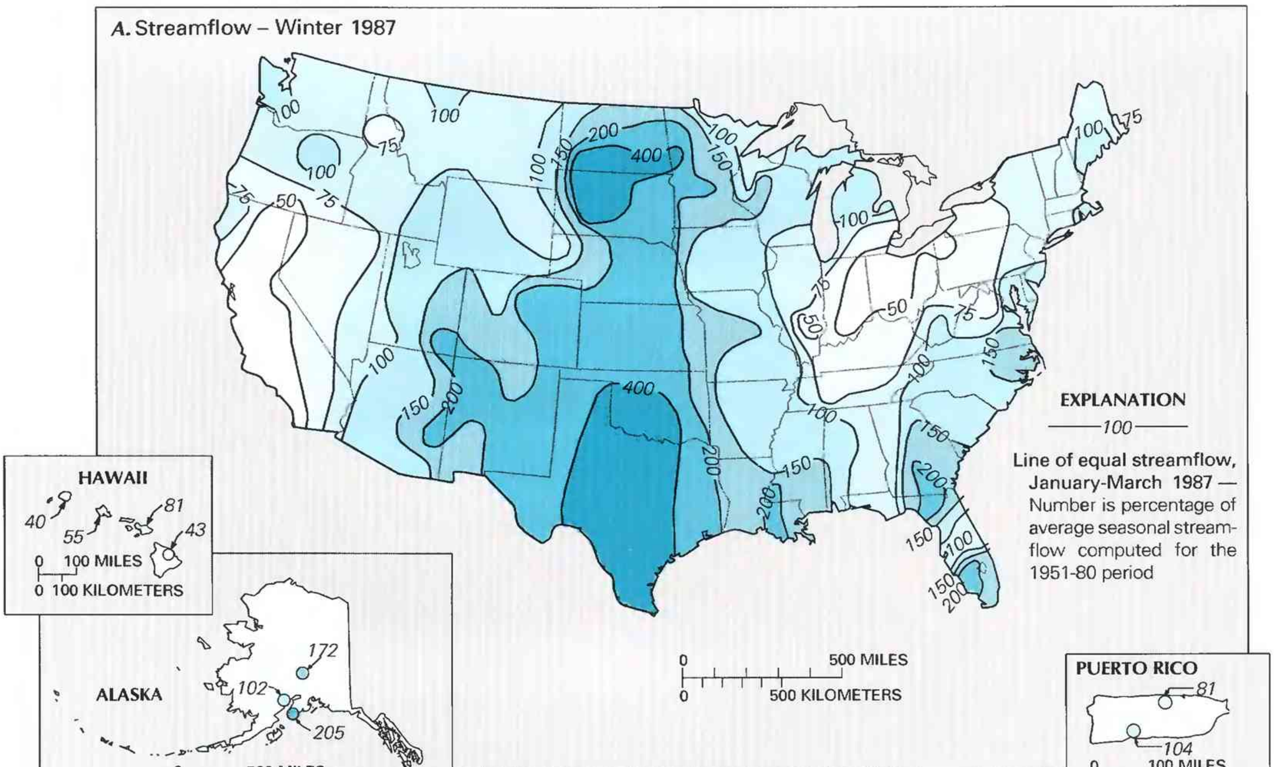
5*B*. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) fall total precipitation.
5*C*. Temperature in the conterminous United States expressed as a departure from average (1951–80) fall conditions. (MA = much above, at least 1.28 standard deviations above 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 above the mean; B = below, between 0.52 and 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.

WINTER 1987

The winter season (January–March 1987) brought a continuation of extremely moist conditions in the Central United States, an expansion and intensification of the dryness of the West, and a change from above- to below-normal streamflow in the Ohio Valley and the eastern Great Lakes regions and from below- to above-normal streamflow across most of Florida (fig. 6*A*). The expanded dryness during the winter months was reflected in the seasonal mean combined flow of the Big Three rivers, which at 1,124,600 ft³/s was down 15 percent from the fall combined flow.

Although, as a whole, the Nation had near-normal precipitation during this season, the spatial variability was considerable (fig. 6*B*). The Central States remained wet, while the dryness continued in the West and intensified and expanded in the Great Lakes. The near-record and record dryness across the Great Lakes helped to reverse their recent rise. Despite this general deficiency in moisture supply, one of the more notable hydrologic events of the winter season was the continued rise of the Great Salt Lake. After undergoing a typical seasonal decline from the June 1986 record high level, the dramatic 5-year increase in the lake's level continued; by the end of March (3 months before the usual peak in its annual cycle), the Great Salt Lake stood again at its record high of 4,211.85 feet above sea level. The anomalously high precipitation that occurred in the Great Plains and parts of the Southeast also was notable. The wettest winter of the century occurred in much of Nebraska and parts of South Dakota, Kansas, and northern Florida.

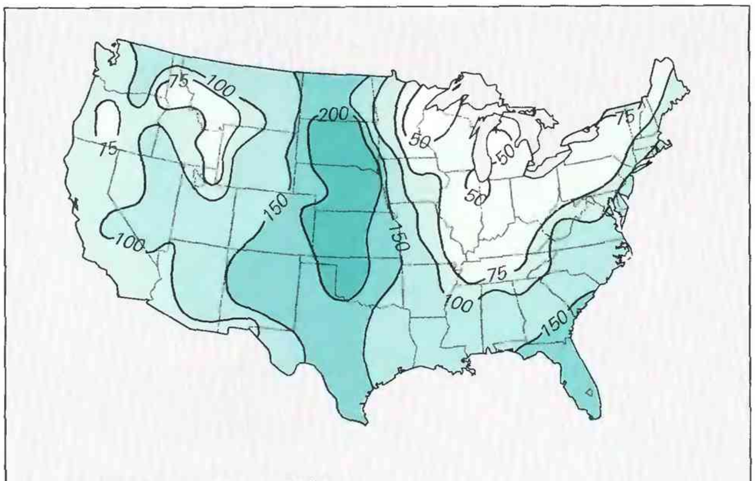
The most persistent pattern throughout the winter was the extreme warmth in the northern one-half of the Central States (fig. 6*C*). It was the warmest winter of the century in all areas north of a line from eastern Montana southeast to Iowa and northeast to lower Michigan. Such warmth prevented the substantial buildup of snow on the ground so typical of these areas. Undoubtably, this lack of snow helped to prevent flooding in many of these areas when two to five times the normal precipitation fell during February and March. In general, no extreme or damaging hydrologic events occurred during the winter months. In January, new monthly maximum mean flows were recorded at five index stations scattered through the eastern and southern conterminous United States and at one station in Alaska. During February, only four new monthly maximums occurred—two in New Mexico and one each in Utah and Florida. The growing dryness in the upper Ohio River valley gave rise to a record monthly minimum mean flow on Oil Creek at Rouseville, Pa. Similarly, in March, only five new monthly high flows were recorded at the 190 index stations around the country.



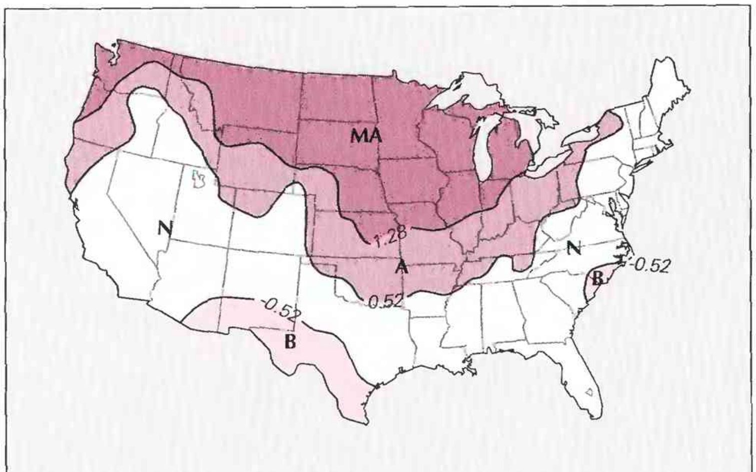
6*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) winter conditions.

Figure 6. Hydrologic conditions during the winter (January–March 1987) of water year 1987. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

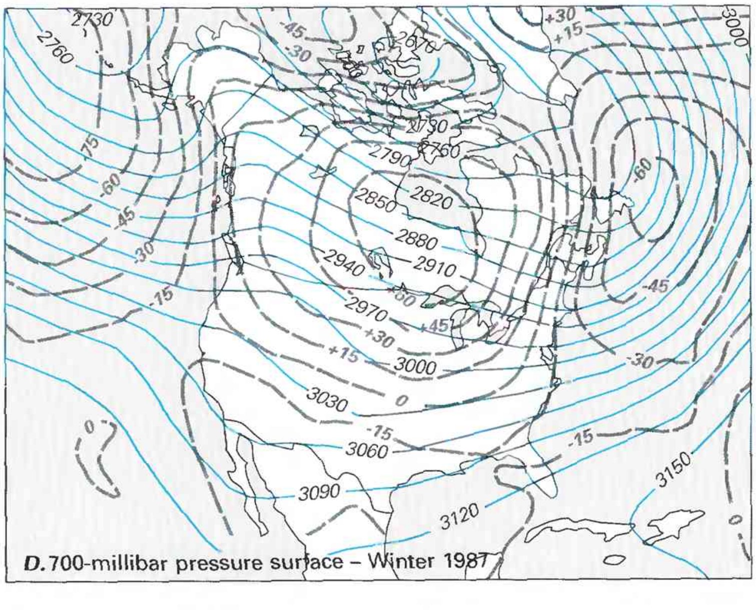
The dryness in the Far West during this normally wet season can be attributed to the continuation of the split-flow pattern that developed the previous December. Storms moving in from the Pacific were taken well north of their normal track by the polar jet into Canada. At the same time, the subtropical jet was most active south and east of the Far West (fig.6*D*), thus moving moisture into the Great Plains. In fact, several of the major precipitation events in the Central and Southern States could be attributed to a well-developed subtropical jet across Mexico and the Southwestern States. As several upper air disturbances moved along this jet, they intensified in the Central and Southern States to such an extent that they altered the normal west-to-east flow. A strong southerly flow, which developed ahead of these disturbances, advected considerable moisture well into the central and northern Great Plains. However, much of the energy in these systems was expended by the time they moved farther east, thus leaving the Eastern States dry.



B. Precipitation — Winter 1987



C. Temperature — Winter 1987



D. 700-millibar pressure surface – Winter 1987

Figure 6. Continued.

6*B*. Precipitation in the conterminous United States 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 above the mean; B = below, between 0.52 and 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.

SPRING 1987

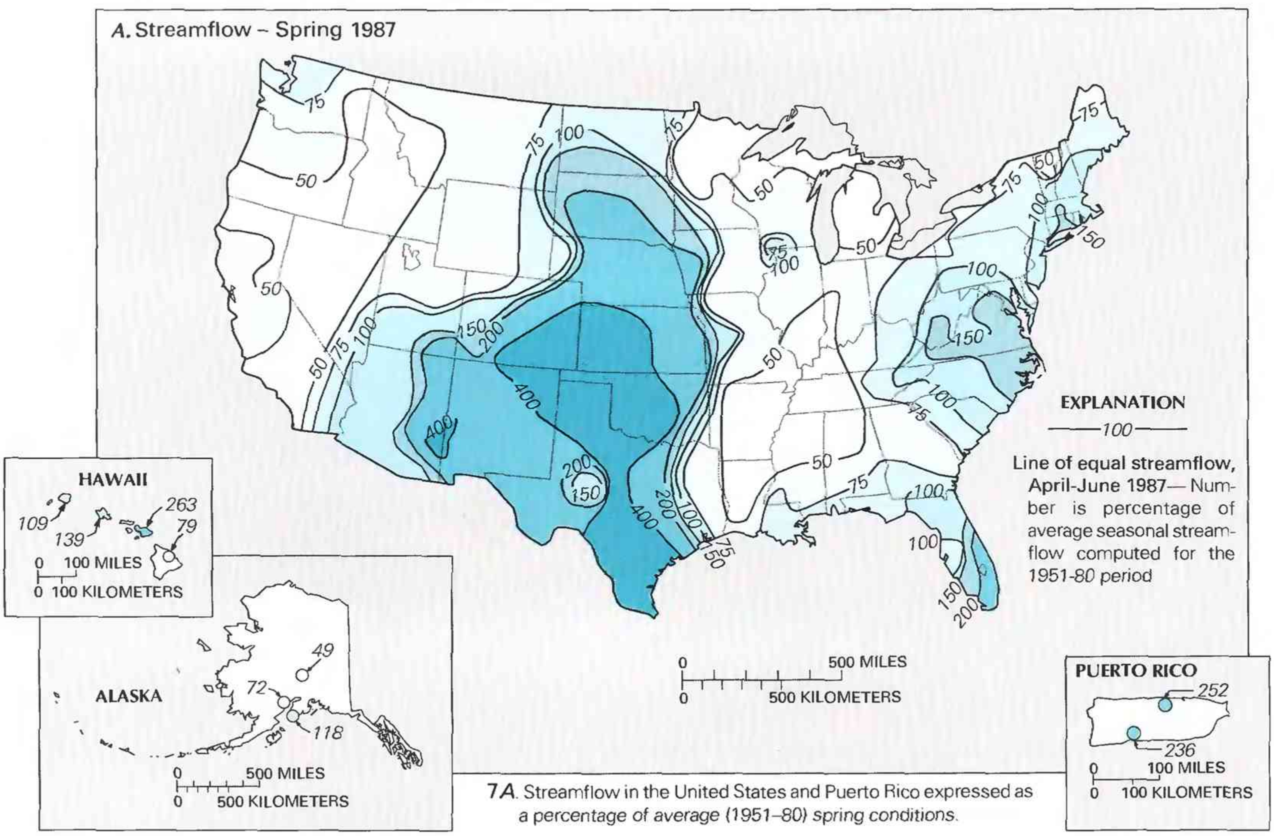
The general geographic pattern of positive and negative streamflow anomalies prevailing during the winter months persisted through the spring season (April–June 1987). The region of above-normal flows in the Central States remained fairly stable, although the areas of diminished flows in both the East and the Far West underwent considerable expansion (fig. 7*A*). The combined seasonal flow of the Mississippi, the St. Lawrence, and the Columbia Rivers, at 1,235,000 ft^3/s, was 10 percent above the winter flow, although still roughly 10 percent below its seasonal median.

Above-normal precipitation during this season was limited to the South Central States, parts of New England, and the Great Basin (fig. 7*B*). Wet weather continued in southern New Mexico and in western Texas, parts of which had their second wettest spring of the century. Overall, however, the spring of 1987 across the United States was on the dry side, which ranks it in the lower quartile of all springs since 1895. Eastern South Dakota had its driest spring on record. This is of particular importance inasmuch as spring normally is the wettest time of year in this region of the country. The Far West continued to be dry; parts of the Southeast were very dry, and southwestern Florida had its second driest spring of the century.

From another perspective, the most notable aspect of the spring season of water year 1987 was the extreme warmth. The above-normal temperatures led to early heat waves across much of the Northern States, and it was the warmest spring of the century from eastern Washington eastward to Wisconsin (fig. 7*C*). The hot weather placed added demands on the reduced streamflow and water supply in the Northwest and upper Midwest. The only relatively cool weather that could be found was in southwestern Texas, where the rainfall had been unusually heavy.

The remarkable persistence in the split-flow atmospheric circulation pattern contributed to the wet weather in the South and, because the polar jet already was beginning its seasonal retreat from its existing abnormal northward displaced position, did little to help the dry conditions that had developed in the Far West. The subtropical jet again was active during this season as indicated by the below-normal 700-mb heights (fig. 7*D*).

The season began with heavy rains combining with melting snow to produce widespread flooding in New England. The most severe conditions occurred between April 1 and 3 in the Penobscot, the Sheepscot, the Kennebec, and the Androscoggin River basins of Maine, in the Piscataquis and the Merrimack River basins of New Hampshire, and in the Parker, the Ipswich, and the Connecticut River basins of Massachusetts. Maine was declared a Federal disaster area on April 8. Peak discharges on the Piscataquis, the Sebec, the Sandy, the Sebasticook, and the Little Androscoggin Rivers in Maine exceeded those of record and also were greater than the 100-year



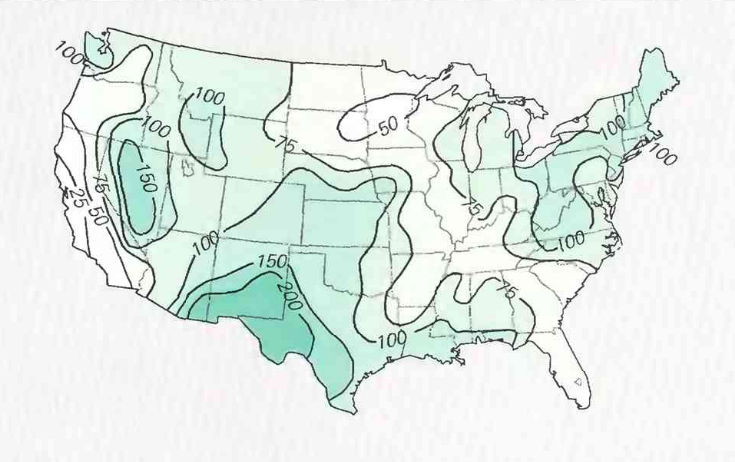
7*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951–80) spring conditions.

Figure 7. Hydrologic conditions during the spring (April-June 1987) of water year 1987. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

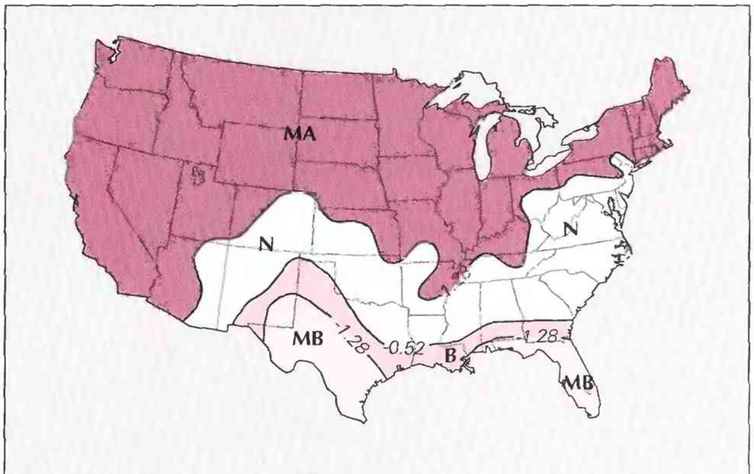
recurrence interval. Peaks of record also were measured at more than a dozen other gaging stations in Maine, New Hampshire, Massachusetts, and New York. A flow in excess of the 100-year recurrence interval occurred on Schoharie Creek near Amsterdam, N.Y., and caused the collapse of a New York State Thruway bridge. Ten people died in the incident when their vehicles plunged into the flood-swollen creek. (See articles in this volume, "Flood of April 1987 in Maine" and "Flood-Induced Collapse of the New York State Thruway Bridge Near Amsterdam, N.Y., April 5, 1987".)

Spring streamflow in Idaho was extremely low. In April, the Governor of Idaho declared a state of emergency in Ada, Canyon, Elmore, Washington, Blaine, and Adams Counties because surface water was so deficient that a shortage of irrigation water was expected during the coming summer. Precipitation since the beginning of the water year was only 47 percent of normal for the Boise River basin and 58 percent of normal for the entire State. Moreover, as of April 1, the snowpack was less than one-half of normal for that date. By season's end, record low flows had been recorded on the Salmon and the Clearwater Rivers.

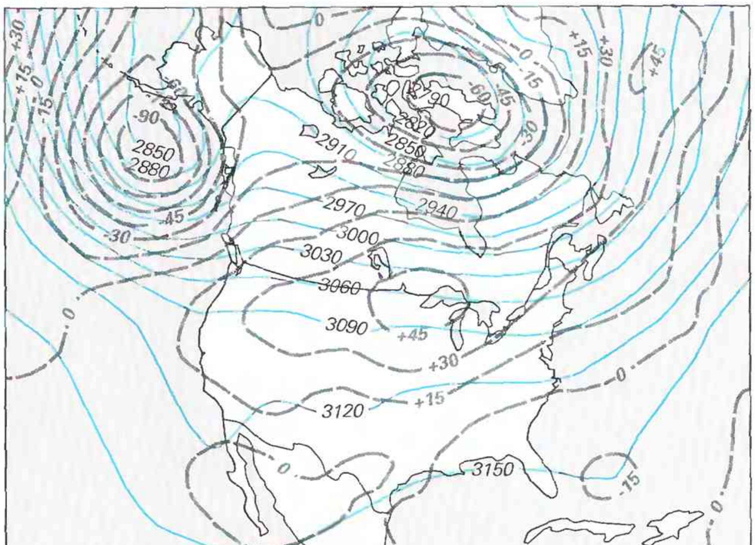
Notably, on June 30 the level of Great Salt Lake was at 4,211.20 feet above sea level, which represented a 0.65-foot fall since the end of March when the lake stood at its record-equaling high. The volume of the south arm of the lake decreased about 606,000 acre-feet during the spring while that of the north arm declined about 404,000 acre-feet. Although precipitation in the region was below normal during the winter and the spring months, the decline in the level of the lake also was affected by the West Desert Pond Pumping Project. An estimated 450,000 acre-feet was pumped from the lake to the pond between April 10, 1987, when the project began operation, and June 30.



B. Precipitation — Spring 1987



C. Temperature — Spring 1987



D. 700-millibar pressure surface - Spring 1987

Figure 7. Continued.

7B. Precipitation in the conterminous United States expressed as a percentage of average (1951–80) spring total precipitation.
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; N = near normal, between −0.52 and 0.52 standard deviations above 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.

SUMMER 1987

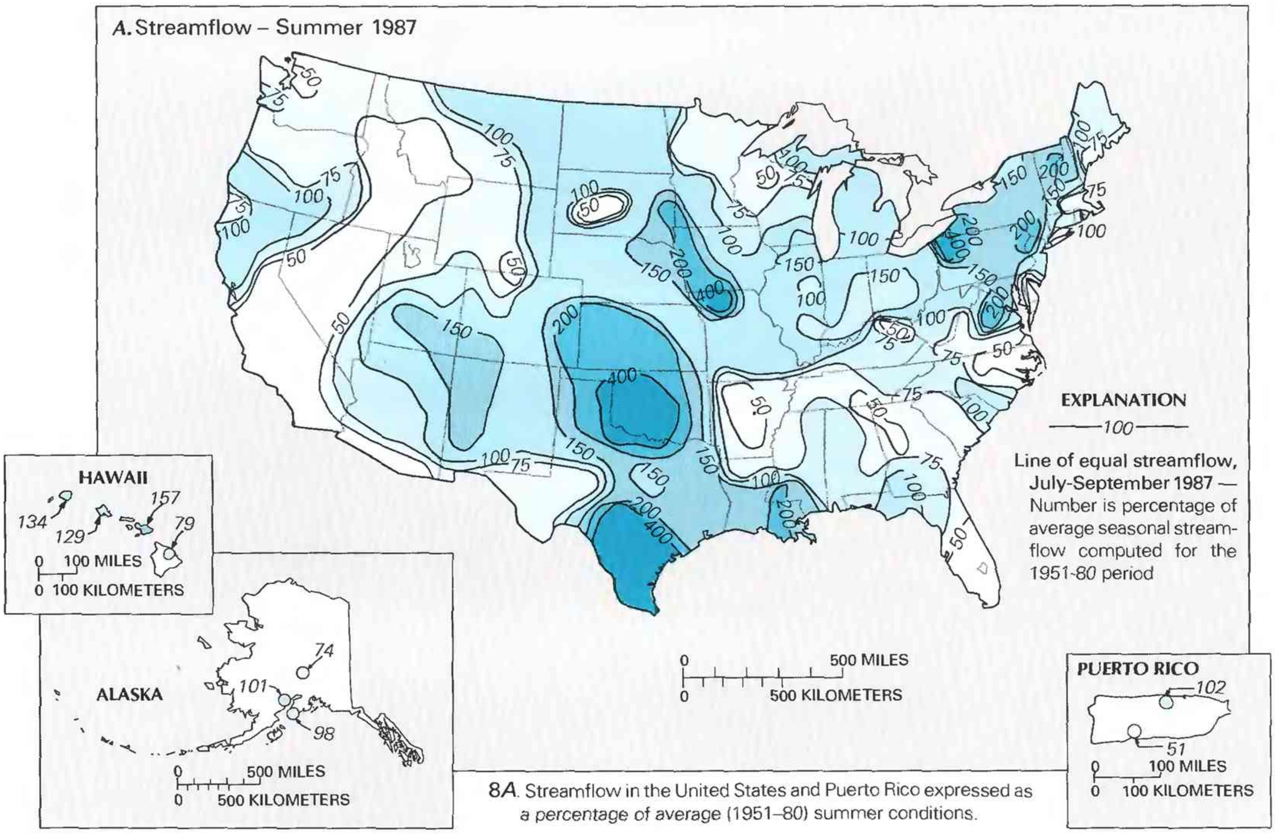
The areas of unusually high and low spring streamflow remained anomalous through the summer season (July–September 1987). The acute dryness in the West, much-above-normal flows in the central and the southern Great Plains, and low-flow conditions in the middle Mississippi Valley and western Great Lakes continued during each summer month (fig. 8*A*). The most notable differences between the two seasons occurred along the east coast. The spring high flows that prevailed in parts of the Middle Atlantic region and in southern Florida were replaced by very low discharges, and the dry spring conditions in the southern and eastern Great Lakes area recovered with above-normal summer streamflow. The seasonal decline in the flow of the Big Three rivers during the 1987 summer was stronger than normal, which reflected the unusual moisture deficit over much of the Columbia and the Mississippi River basins. The combined flow of the Big Three was 712,400 ft^3/s, which was down 42 percent from the spring flow and 13 percent below the combined seasonal median flow.

Despite the dryness in the Northwest and the lower Mississippi Valley, the total summer precipitation across the Nation was very close to normal because of the abundant rainfall across the rest of the country (fig. 8*B*). As is so often the case, however, much of this summer precipitation was not well distributed throughout the season. Several heavy rainstorms contributed to the total seasonal precipitation; for example, parts of the Minneapolis–St. Paul area received over 9 inches of rain in one night during July; the Greater Chicago area received as much as 9 inches of rain in one 24-hour period during August; and La Cross, Wis., had over 5 inches of rain in a one-day event.

The lack of tropical storms and hurricanes in the Southeast during the summer months contributed to the below-normal precipitation in this region. Typically, tropical storms and hurricanes contribute as much as 5 to 20 percent of the total summer precipitation along the gulf coast and the southeastern Atlantic coast as far inland as several hundred miles. The only substantial rainfall directly related to tropical activity during the season occurred when a weak tropical disturbance along the gulf coast dropped more than 7.5 inches of rain on Baton Rouge, La.

Temperatures across the country finally broke from the broad patterns that began during the previous December. Near-normal temperatures returned to the northern Great Plains and much above normal temperatures were found farther east in the Middle Atlantic and the Great Lake States and in southern Florida (fig. 8*C*). Below-normal temperatures occurred in much of the Southwest.

The 700-mb height pattern for the summer reflected the warmth in the East and cooler conditions in the Southwest (fig. 8*D*). In the Southeast, the higher-than-normal heights associated with the Bermuda High contributed to the warm, dry summer in this region. In the Southwest, the below-normal 700-mb heights



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

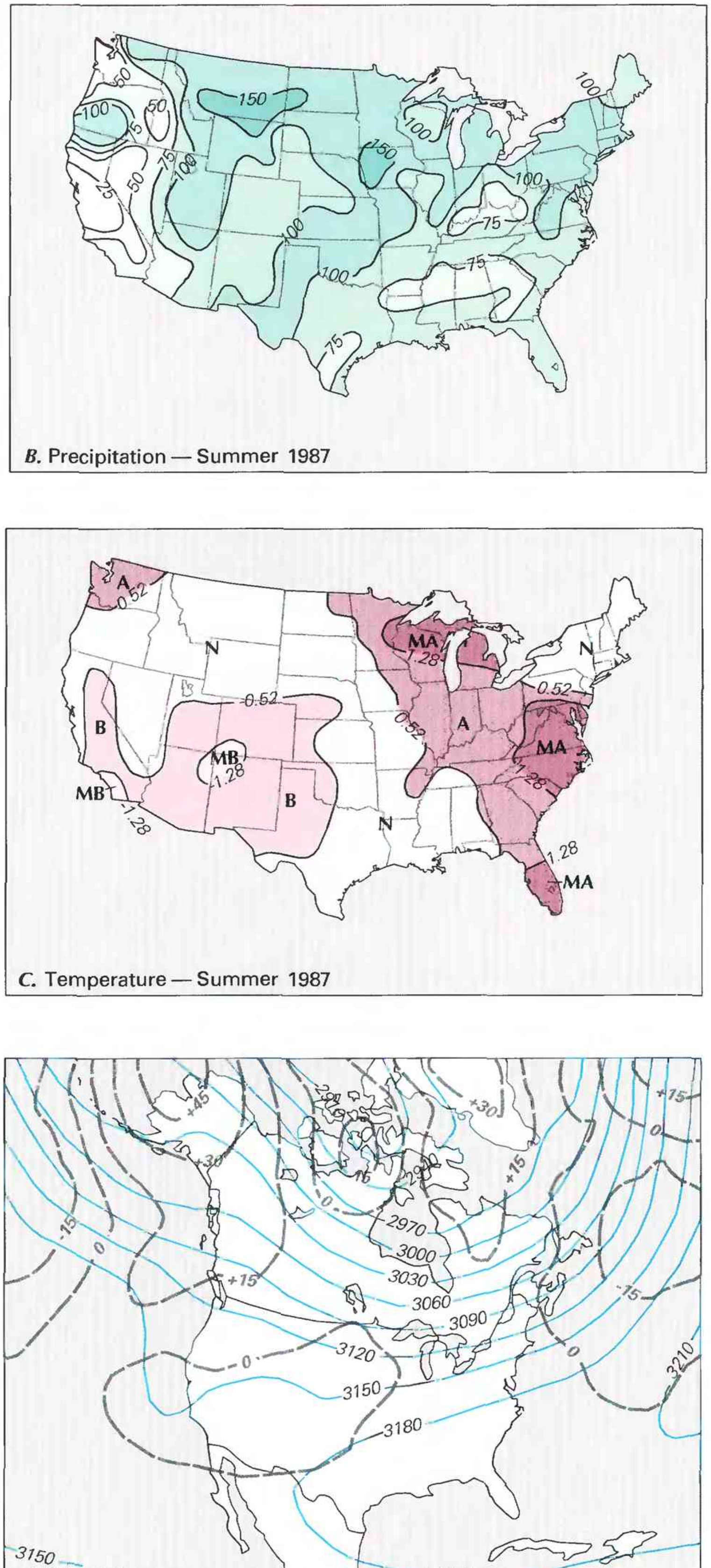
Figure 8. Hydrologic conditions during the summer (July–September 1987) of water year 1987. (Sources: Meteorological data from the National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data from the U.S. Geological Survey.)

were associated with the cooler-than-normal weather. The area between such anomalies often tends to have enough instability so that, when adequate atmospheric moisture occurs, the result is above-normal precipitation (fig. 8*B*).

Several significant hydrologic events occurred across the Nation during the summer season. In mid-August, severe flooding was generated by very heavy rainfall over a 24-hour period in northeastern Illinois. New peaks of record were set, and the 100-year flood was equaled or exceeded at nine gaging stations in the Illinois River basin—from 4 to 9 inches were recorded across Du Page and Cook Counties. (See article in this volume, "Storm and Flood of August 13 to 15, 1987, in Cook and Du Page Counties, Ill.") Additional rain at the end of the month gave this area the wettest August on record and the fourth wettest month of the century (three Septembers were wetter). Farther west, in southwestern Iowa, more moderate flooding occurred in late August in the Nishnabotna, the Grand, the Chariton, and the Skunk River basins. The flow on the Nishnabotna River set a new record for the month, and the discharge of 7,800 ft^3/s on the Platte River at Diagonal, Iowa, on August 25 was a record peak.

Of more widespread significance were the low-flow conditions that affected a number of basins around the country. Record or near-record low flows were recorded at many stations in Washington, Oregon, and Idaho. Most notable were the low-flow records—set on the Columbia River at The Dalles, Oreg., in August and September, both of which were roughly 10 percent lower than their previous recorded lows. New low discharges for September also were recorded at index stations on the Skykomish and the Spokane Rivers in Washington and on the Clearwater River in Idaho. Inasmuch as the summer is typically the dry season in these areas, the below-normal rainfall certainly contributed to the record low flows. The antecedent dry conditions resulting from the fall, winter, and spring seasons, when the largest percentage of annual precipitation typically occurs, undoubtedly were important factors in the severity of the hydrologic drought. Moreover, the added stress of increased seasonal evaporation and transpiration, coupled with the existing low soil moisture and snowpack, only served to exacerbate the surface-water conditions.

At season's end, the level of the Great Salt Lake had fallen to 4,210.10 feet above sea level, which was down 1.75 feet from the record-tying 4,211.85 feet reached on March 30. Although the lake level at the end of water year 1987 was 1.20 feet below the level of a year ago, it was still 5.23 feet above the level of 4 years ago.



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 above 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 1987

Floods, droughts, and other water-related events that occurred during water year 1987 are documented in the previous section of this volume ("Review of Water Year 1987, Hydrologic Conditions and Water-Related Events"). Seven of those events are described in more detail in the following pages. They were selected because they illustrate the range of events that can affect large numbers of people or require a variety of management actions to mitigate their effects.

Weather-related events caused more than $2.1 billion in economic losses during water year 1987. Of this amount, flood damages were more than $1.5 billion—well below the 10-year (1977–86) average of $2.5 billion. Flood-related fatalities totaled 88, which was well below the 10-year average of 138 lives. Flash floods accounted for more than 75 percent of the water-year 1987 deaths, and at least 80 percent of those deaths took place in moving vehicles. Flooding of some degree occurred in every region of the country; the most economically damaged area was in the Nation's midsection, and the second was in the Northeast. Those two regions accounted for more than 85 percent of the annual losses and, of that amount, 48 percent occurred in metropolitan areas (U.S. Army Corps of Engineers, 1988). Eight major floods occurred in water year 1987—the same number that occurred in water year 1986. These floods are summarized briefly in the previous section in table 1 (events 1, 2, 13, 41, 51, 52, 55, 63, 67, 76, 77). Three of those events are discussed more fully in this section—"Flood of April 1987 in Maine," "Flood-Induced Collapse of the New York State Thruway Bridge near Amsterdam, New York, April 5, 1987," and "Storm and Flood of August 13 to 15, 1987, in Cook and Du Page Counties, Illinois."

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 $5.2 billion in economic damages. However, this amount is well below the 10-year (1977–86) average of $10.3 billion; the record was set in water year 1986 when $27.3 billion in flood damages were prevented (U.S. Army Corps of Engineers, 1988; U.S. Geological Survey, 1988, p. 34).

Other significant water-related events—both human induced and naturally occurring—in water year 1987 that required a diversity of management actions are described in three articles: "Wildlife Kills in the Carson Sink, Western Nevada, Winter 1986–87," "Major Oil Spill on the Savannah River, Georgia and South Carolina, December 1986," and "Algal Blooms in Lake Okeechobee, Florida, and Management Strategies to Mitigate Eutrophication." Another event was of scientific interest because it caused an undetermined amount of damage to fossil beds at the Hagerman Fauna Site National Landmark in Idaho. The fossils at this site are of major paleontological significance because they are considered to be one of the most complete assemblages of Pliocene fauna in the world. This event is described in the article "Landslide of April 14, 1987, Near Hagerman, Idaho." Water year 1987 also was a significant year for the Bonneville Power Administration, as described in the article "Bonneville Dam—Fifty Years of Public Service."

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Wildlife Kills in the Carson Sink, Western Nevada, Winter 1986–87

By Timothy G. Rowe and Ray J. Hoffman

In late December 1986 and early January 1987, State and Federal wildlife biologists reported that about 500,000 fish were dead or dying near the mouth of the Carson River, in the Carson Sink, which is a part of the Fallon National Wildlife Refuge and is about 75 miles east of Reno, Nev. (fig. 9). By early February 1987, the estimated number of dead fish had increased to about 7 million. Fish carcasses were found along 40 miles of shoreline (fig. 10), and about 1,500 aquatic birds of many species were found dead in the sink, mainly near the Humboldt Slough (Steven P. Thompson, U.S. Fish and Wildlife Service, oral commun., 1987).

The U.S. Fish and Wildlife Service asked the U.S. Geological Survey to collect and analyze water and bottom-material samples near the wildlife kills in the Carson Sink to help determine the cause of the wildlife deaths. Background information and the results of studies by the two agencies are presented in this article.

The Carson Sink is the northeastern terminus and ultimate discharge area of the Carson River basin. During abnormally wet years, such as the period 1982–84, the Humboldt River also discharges into the sink by way of the Humboldt Slough. Normally, the sink is a dry, nearly flat, 400-mi^2 (square mile) playa that is entirely barren and, in many places, salt-encrusted. However, during the 3-year period of 1982–84, the Carson and the Humboldt Rivers had much greater than normal flows into the sink; for example, at the Carson River stream-gaging station nearest the sink (below Fallon), the average flow for the 3-year period was 264 ft^3/s (cubic feet per second), or 191,000 acre-ft/yr (acre-feet per year) (U.S. Geological Survey, 1976–85). This flow was 300 percent of the average for the 17 years of record, 1968–84 (U.S. Geological Survey 1967–75, 1976–85). The gage farthest downstream on the Humboldt River (below Rye Patch Reservoir) recorded an average flow of 1,110 ft^3/s, or 804,000 acre-ft/yr, for the 3-year period. This flow was 450 percent of the average for 70 years of record (1943–84 and several periods during 1899–1941; U.S. Geological Survey, 1960, 1963, 1970, 1967–75, 1976–85).

Because of unmeasured losses or gains, or both, in flow between the gages and the sink, inflow to the sink is not just the total of the flow measured at the two gages. For example, on the lower Humboldt River, within a distance of about 50 miles between the gage and the sink, substantial water is lost as a result of diversions and evaporation in the Humboldt Sink (fig. 9), and only a small amount of flow is regained as a result of irrigation returns. In contrast, on the lower Carson River, return flows from irrigation drainage through the Stillwater Wildlife Management Area can be significant (fig. 9). U.S. Fish and Wildlife Service records indicate that more water was received (496,000 acre-ft) in the Stillwater Wildlife Management Area in the 1983 calendar year than in any of the previous 38 years. This amount is about eight times more than the 58,060 acre-ft received in 1985, which was a normal year.

By September 1984, the abundant inflow had raised the water-surface altitude in the Carson Sink to 3,876.2 feet above sea level (fig. 11), which is possibly the highest level in more than 100 years. This level was maintained until mid-January 1985, when it started to decline (Morris C. LeFever, U.S. Fish and Wildlife Service, written commun., 1986). Between July 1984 and February 1985, the surface area of the Carson Sink was the largest of any water body in the State of Nevada; the lake inundated about 212,000 acres to a maximum depth of nearly 12 feet.

Since January 1985, the sink has continued to shrink as a result of evaporation and the lack of major inflow, which has caused an increase in salinity (dissolved-solids concentration). By mid-January 1987, at the time of the wildlife kill, the lake level had declined more than 6 feet, and the water covered less than 180,000 acres to an average depth of 2 feet and a maximum depth of 6 feet. The increase in salinity near the Humboldt Slough is reflected by an increase in specific conductance, from 4,700 μS (microsiemens per centimeter at 25°C) in July 1983 to 31,300 μS in January 1987. For comparison, the specific conductance of sea water is about 50,000 μS, which is equivalent to a dissolved-solids concentration of about 35,000 mg/L (milligrams per liter).

In January 1987, the lake froze, which probably further raised salinity in the water beneath the ice; the temperature of the brackish water dropped below 30°F. Wildlife biologists speculate that the salinity and the sudden drop in temperature were the probable causes of death of the fish, whose initial population was swept into the sink during the previous high flows. (Norman Saake, Nevada Department of Wildlife, oral commun., 1987).

The fish that were killed during winter 1986–87 included three age classes of tui chubs (*Gila bicolor*); this fish is a member of the minnow–carp family (*Cyprinadae*). Interestingly, a fishkill of similar magnitude occurred 1 year earlier in much the same area (Steven P. Thompson, U.S. Fish and Wildlife Service, oral commun., 1987); however, those fish were almost exclusively carp (*Cyprinus carpio*). Apparently, the carp died earlier than did the tui chub because they are less tolerant of increasing salinities. The tui chubs apparently gained tolerance to the high salinity over time because a large tui chub population remained trapped in the sink in mid-1987.

The water in the Carson Sink at the time of the wildlife kill was brackish (about 20,000 mg/L of dissolved solids, dominated by sodium and chloride), cool (36–47°F), supersaturated with respect to dissolved oxygen (135–182 percent), and highly alkaline (pH 9.5). The laboratory determinations for water samples

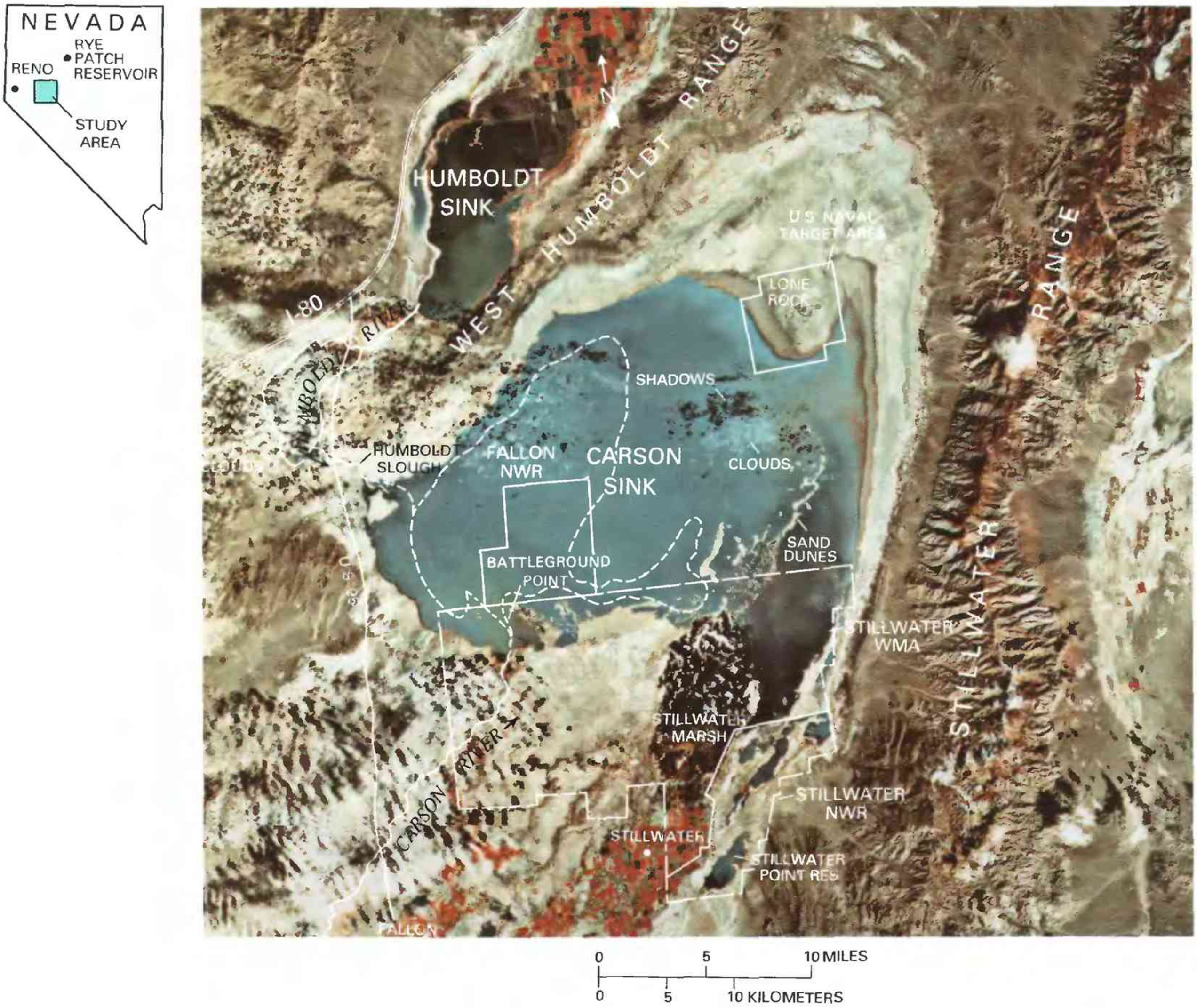

Figure 9. Landsat image of the Carson Sink, Nev., on October 27, 1984, at time of maximum lake level (3,876.2 feet above sea level). Dashed line is lake level as of January 1987 (about 3,870 feet). Note numerous clouds and their shadows across the image. Abbreviations: NWR, National Wildlife Refuge; Res., Reservoir; WMA, Wildlife Management Area. (Source: Image from U.S. Geological Survey, Flagstaff, Ariz.)

consisted of dissolved inorganic constituents, nutrients, and trace elements; bottom materials were analyzed for trace elements and organochlorine compounds.

Concentrations of arsenic, boron, copper, and dissolved solids in the lake [800 μg/L (micrograms per liter), 40,000 μg/L, 80 μg/L, and 20,100 mg/L, respectively] were high enough to be potentially stressful to aquatic organisms (U.S. Environmental Protection Agency, 1986). Arsenic and boron occur naturally, commonly in high concentrations, in the soils and ground water of the lower Carson River basin.

With the exception of DDE, DDT, and endosulfan, the organochlorine compounds in the bottom material were at or below detection limits. The concentrations of DDE, DDT, and endosulfan were low—0.3, 0.2, and 0.1 μg/kg (micrograms per kilogram), dry weight, respectively.

not necessarily mean that such concentrations will result in adverse biological effects (Dennis Lemly, U.S. Fish and Wildlife Service, written commun., 1987).

Water samples also were analyzed by the U.S. Geological Survey for toxin-producing blue-green algae. None were expected because of the seasonally cool water, and none were found. The single-celled diatom (*Cyclotella meneghiniana*) was by far the most abundant alga in the lake in terms of numbers (76 percent of the total) and biovolume (77 percent of the total).

The deaths of the aquatic birds and the fish were the result of different physiological causes. Pathologists at the U.S. Fish and Wildlife National Wildlife Health Research Center, Madison, Wis., determined that the major cause of the bird kill was avian cholera.

Figure 10. Dead tui chubs of three age classes on the shoreline of the Carson Sink near the Humboldt Slough, Nev., February 7, 1987. (Source: Steven P. Thompson, U.S. Fish and Wildlife Service.)

Trace-element concentrations found in the bottom material, except those for mercury and lithium—0.48 and 190 μg/g, (microgram per gram) dry weight, respectively—were less than those commonly found in soils in the Western United States (Shacklette and Boerngen, 1984, p. 6). The high concentrations of lithium are typical for arid, saline environments. In contrast, mercury-contaminated sediments are distributed widely in the lower Carson River basin because about 7,500 tons of mercury was lost during the milling of gold and silver in the late-1800's (Smith, 1943).

Analysis of nine tui chubs for trace elements by the U.S. Fish and Wildlife Service showed arsenic and copper totals (0.67 and 1.0 μg/g of whole fish, wet weight, respectively) that exceeded the baseline values of the National Contaminant Biomonitoring Program (Lowe and others, 1985). According to the U.S. Fish and Wildlife Service, even if concentrations are high in relation to the baseline values, this does

The ice cover on the lake was a major factor in this bacterial outbreak because the ice reduced the feeding areas, which caused the birds to congregate. This crowding of birds allowed avian diseases to spread easily and quickly (Kathy A. Converse, U.S. Fish and Wildlife Service, oral commun., 1987).

Selected birds were sent to the U.S. Fish and Wildlife Service, Patuxent Wildlife Research Center, Laurel, Md., for analysis of trace elements. Several migratory bird species had high levels of mercury and selenium (220 and 51 μg/g, dry weight, in their livers, respectively). These levels are potentially harmful to aquatic birds; for example, laboratory feeding studies have shown that 72 μg/g of mercury in soft tissues of wild birds (Finley and others, 1979, p. 108) and 9.4–43 μg/g of selenium in livers of adult mallards (Heinz and others, 1987, p. 5) can cause significant reproductive failure. About 1,500 birds died in the sink during January 1987 (Steven P. Thompson, U.S. Fish and Wildlife Service, oral commun., 1987). California gulls were the most numerous of the bird fatalities.

In summary, an unusual natural event occurred during 1986 and early 1987 after the Carson Sink, a normally dry, salty playa, was inundated with water from unusually high runoff in the Carson and the Humboldt River basins (from 1982 through 1984). The high flows flushed in the initial fish populations along with a large amount of dissolved salts. These fish flourished in their new nutrient-rich environment until the lake began to recede after the high inflows ceased and evaporation continued. This recession caused the lake to increase in salinity, which, in turn, caused the tui chubs to die as they reached their maximum salt-tolerance levels, as happened to the carp in 1986. The fishkills in 1987 also were intensified by a sudden freeze-over of the lake, which further increased the salinity of the water beneath the ice and further stressed the fish. The freezing also forced the abundant fish-feeding birds to congregate near open ice holes. This crowding allowed an outbreak of avian cholera to spread easily.

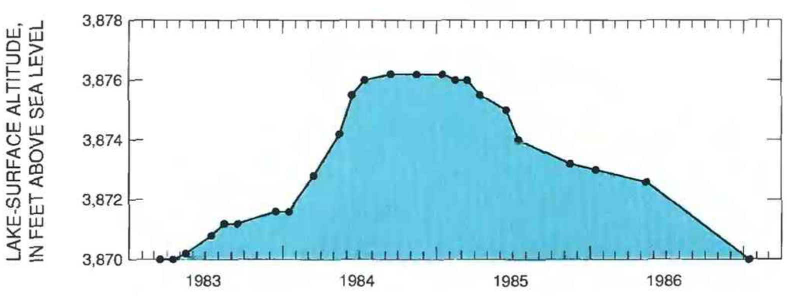

Figure 11. Surface altitude of lake in the Carson Sink, Nev., 1983–87. (Source: Data from Otto Moosburner, U.S. Geological Survey, written commun., 1987, and Morris C. LeFever, U.S. Fish and Wildlife Service, written commun., 1986.)

In April 1988, the former 330-mi² lake became a dry, salty playa (Steven P. Thompson, U.S. Fish and Wildlife Service, oral commun., 1988), as has happened countless times before over geologic time.

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FOR ADDITIONAL INFORMATION

Timothy G. Rowe or Ray J. Hoffman, U.S. Geological Survey, Room 224, Federal Building, 705 N. Plaza Street, Carson City, NV 89701

Flood of April 1987 in Maine

By Richard A. Fontaine and Thomas J. Maloney

The New England States were subjected to severe rainstorms between March 31 and April 8, 1987. Heavy rainfall, more than 10 inches in some areas, coupled with snowmelt runoff, caused extensive flooding especially in Maine, Massachusetts, and New Hampshire. Particularly hard hit was south-central Maine where between 6 and 7 inches of rain fell in the headwaters of the Androscoggin and the Kennebec Rivers (fig. 12). The flooding was the climax to a series of meteorologic and hydrologic extremes experienced in Maine during winter–spring of 1987.

In Portland, Maine, January brought 50.7 inches of snow—31.5 inches more than normal for the month and also the fourth highest total for any January in the last 100 years. In sharp contrast to January, February had only 0.04 inch of precipitation, which was the lowest monthly precipitation total for any month since March 1871 when records began (Fred Ronco, National Weather Service, oral commun., 1987). March was characterized by pleasant spring weather—daytime high temperatures ranged from about 55 °F to about 65 °F.

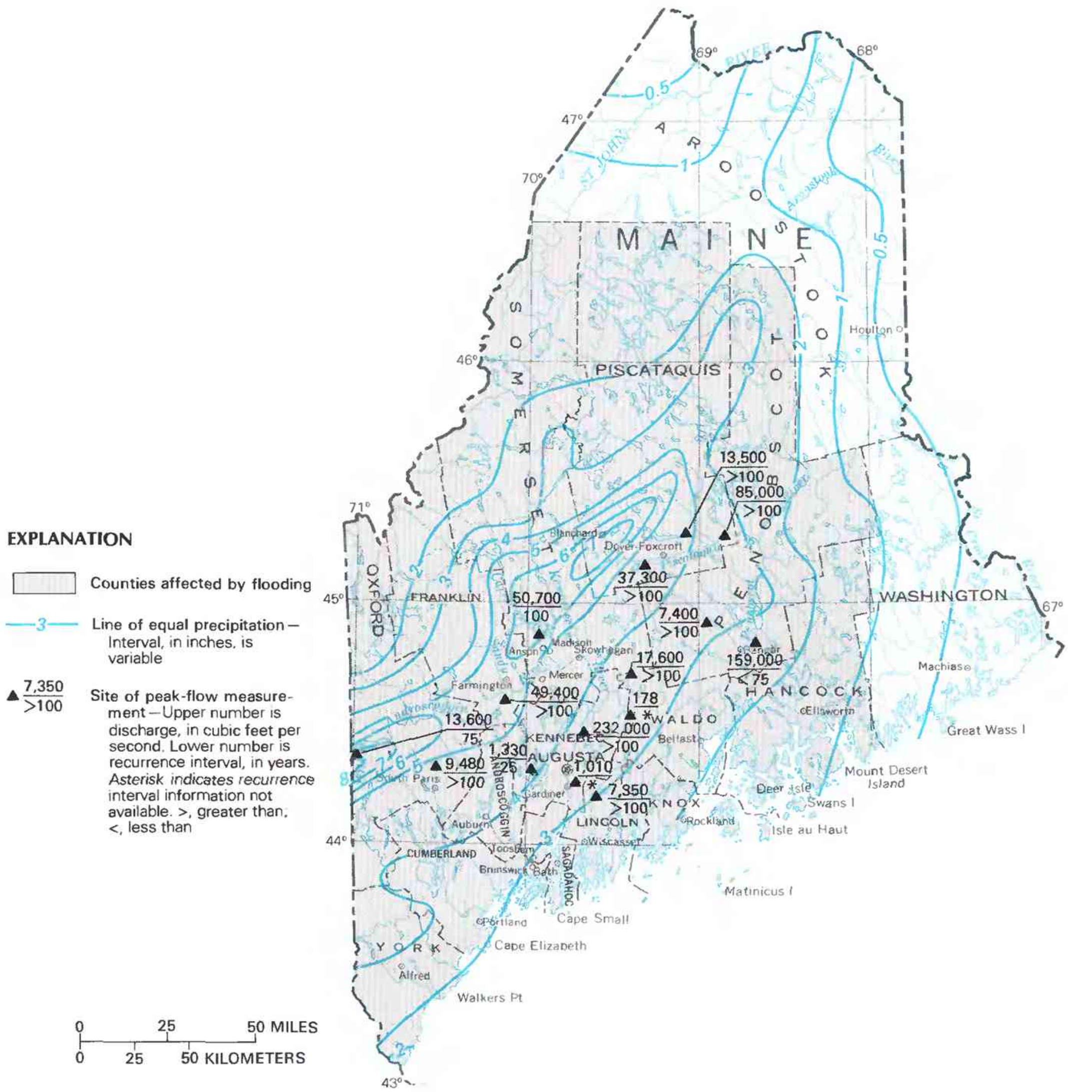

Figure 12. Precipitation, selected peak flows, and counties in Maine that were declared Federal disaster areas as a result of the storms of April 1987. (Source: Precipitation data compiled by National Weather Service; peak-flow data from U.S. Geological Survey files.)

Rapid snowmelt, coupled with rainfall that began on March 30, produced increased runoff but gave no warning of the floods that would follow in early April.

On March 31, a storm system that moved northeastward into the Province of Quebec, Canada, brought heavy snowfall to the central parts of the United States. Over Virginia, a new area of low pressure formed on the cold front that trailed from the storm center in Canada and moved slowly toward Maine bringing heavy rain to the area. By the time this slow-moving storm reached Maine, it was traveling in a path almost perpendicular to the mountainous region in the western part of the State. The slow speed of the storm and orographic effects combined to cause extreme rainfall totals in the headwater areas of several river basins, such as the Piscataquis, the Sandy, the Carrabassett, the Wild, and the Little Androscoggin. The storm, which began to affect Maine on March 30 and continued through the morning of April 2, dropped 4 to 8 inches of rain in the central and western parts of the State (fig. 12). The highest rainfall totals observed during this storm were 8.30 inches at Pinkham Notch, N.H., and 7.33 inches at Blanchard, Maine. Runoff from the storm was augmented by meltwater from a snowpack that contained a water equivalent of 5 to 7 inches, and as much as 10 inches of water equivalent in the higher elevations (Fred Ronco, National Weather Service, written commun., 1987).

A *C*

B *D*

Figure 13. Lows Bridge, a National Historic Landmark completed in 1857, succumbs to the floodwaters of the Piscataquis River, April 1, 1987. Lows Bridge had been the site of the U.S. Geological Survey stream-gaging station, Piscataquis River near Dover-Foxcroft, Maine, since 1902. *A*, The rising flood water exerting pressure on the bridge, 7:15 a.m. The national historic dedication plaque is shown in right center of photograph. *B*, The bridge has broken in half and has moved off the abutments, 7:40 a.m. The U.S. Geological Survey gage is just out of the photograph near the lower left corner. *C*, The broken bridge has been swept well downstream. *D*, The dedication plaque is all that remains of the bridge that had stood for 130 years. (Source: Courtesy of Dwinal Hall, resident, Dover-Foxcroft, Maine.)

From April 4 to 8, before water levels in rivers had a chance to recede from the March 30 storm, another low-pressure area formed over the Carolinas, moved to the northeast, and brought an additional 2 to 4 inches of rain, primarily to southern Maine. Runoff from the second storm prolonged recessions from the maximum flood peaks caused by the combined effects of heavier rainfall and snowmelt from the first storm.

These storms, combined with snowmelt runoff, resulted in record to near-record flood peaks. Recurrence intervals of many peak discharges exceeded 100 years. Record peaks occurred at 15 of the 25 U.S. Geological Survey stream-gaging stations in western and central Maine. Peak-discharge and recurrence-interval data for the April 1987 flood are summarized in figure 12 for all gaging stations in Maine where new record peaks were measured (Fontaine, 1987). Flood peaks on the Piscataquis River near Dover–Foxcroft (fig. 13), the Carrabassett River near North Anson, and the Sandy River near Mercer were 63, 65, and 28 percent higher, respectively, than those of any flood peak previously recorded at these sites. Damage from the storm was estimated to exceed $100 million in Maine (figs. 14, 15) (Hasbrouck, 1987), and 14 of Maine's 16 counties (fig. 12) were declared Federal disaster areas (Federal Emergency Management Agency, 1987).

In addition to damage from high water levels, the flood affected water quality throughout much of central Maine. Twenty-six sewage-treatment plants were damaged. Plants in the Anson–Madison area and in Augusta, Brunswick, Farmington, and Skowhegan suffered severe damage, which resulted in the release of untreated sewage into rivers for as long as 3 months after the flood (Dennis Keshel, Maine Department of Environmental Protection, oral commun., 1987).

Petroleum spills were reported in at least 15 communities. These ranged from relatively minor spills from automobiles and homes to major spills of many thousands of gallons from automobile-service stations and fuel-storage yards. At least 30 underground gasoline-storage tanks were unearthed, and more than 600 55-gallon drums were recovered from rivers after the flood. The total amount of petroleum spilled was estimated to be greater than 8,500 gallons in the Androscoggin River basin, at least 100,000 gallons in the Kennebec River basin, and at least 15,000 gallons in the Piscataquis River basin (Fred Brann, Maine Department of Environmental Protection, oral commun., 1987). Fumes from the oil spills lingered for days along the rivers of central Maine.

Severe erosion was reported along the major rivers. According to Hasbrouck (1987), "About 100 small dams were damaged by the flood through erosion of banks and support structures. Many roads throughout the flooded areas were severely eroded or

Figure 14. A lone boater surveys the flood damage on Water Street in Gardiner, Maine. Flooding was caused by the Kennebec River on April 2, 1987. (Source: Courtesy of Lewiston, Maine, *Sunday Sun Journal*.)

Figure 15. The flood-swollen Androscoggin River threatens the Route 201 highway bridge connecting Brunswick and Topsham, Maine, on April 2, 1987. (Source: Courtesy of Richard Connelly and Brunswick, Maine, *Times Record*.)

washed out and with 200 miles of track under water, there was much damage to railroad banks and foundations. A small number of farms, mostly on the Sandy River below Farmington, were damaged through erosion or deposits of debris on cropland." The Maine Department of Human Services (1987) reported erosion damage at six water utilities and a significant amount of sedimentation in reservoir pools at two utilities.

The April 1987 flood also caused extensive structural damage in Maine. Twenty-five water utilities reported such flood damages as loss of pipeline river crossings, structural damage to reservoirs and dams, and damage to pump houses. Individuals and businesses reported damages estimated to be $70 million, including $16 million to homes; $45 million to small businesses; $8 million to electric utilities, railroads, paper mills, and other industries; and $0.5 million to farms (Hasbrouck, 1987). Public buildings and facilities had estimated damages of $33 million, including $17.1 million to roads and bridges, $3.6 million to sewage-treatment plants, more than $1 million to public water supplies, $1.8 million to public buildings, more than $5 million to small dams, and about $3 million for other miscellaneous categories (Hasbrouck, 1987).

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FOR ADDITIONAL INFORMATION

Office Chief, U.S. Geological Survey, 26 Ganneston Drive, Augusta, ME 04330

Flood-Induced Collapse of the New York State Thruway Bridge near Amsterdam, New York, April 5, 1987

By Thomas J. Zembrzuski, Jr.

The two center spans of the New York State Thruway (Interstate 90) bridge near Amsterdam, N.Y., collapsed into flood-swollen Schoharie Creek at 9:48 a.m. EST[1] on Sunday, April 5, 1987, when one of the piers supporting the bridge span failed (fig. 16*A*). In the ensuing moments, before motorists could react or be warned, five vehicles plummetted 80 feet into the stream below and carried 10 people to their deaths. During the next several hours, search-and-rescue efforts were thwarted by deep water and swift currents and, consequently, were unsuccessful in rescuing any victims. Subsequently, an additional span of the bridge collapsed into the creek (fig. 16*B*). Preliminary investigations of the accident implicated scour around one of the four bridge piers as the cause of the failure.

A

The bridge collapse marked the climax of a weekend of widespread devastating flooding in the Schoharie Creek basin and in the Catskill Mountains of southeastern New York. Two days of sometimes heavy rain from a slow-moving coastal storm brought many streams in the region to their highest levels in 32 years, and the resulting flood damages prompted the Governor to declare five counties—Delaware, Greene, Montgomery, Schoharie, and Ulster—to be major disaster areas (fig. 17). Homes, farms, businesses, roads, and bridges sustained direct damages in excess of $65 million (Anthony Germano, New York State Emergency Management Office, written commun., 1987). On May 15, the President declared the five counties eligible for Federal disaster assistance (New York State Disaster Preparedness Commission, 1987).

The rain began falling late on April 3, 1987, and, by the time the storm ended on April 5, 6 to 8 inches of rain had fallen over the headwaters of the drainage basins of Schoharie, Esopus, Catskill, and Rondout Creeks and the Neversink and the East Branch Delaware Rivers (fig. 17). Stream levels, which already were high as a result of snowmelt and a storm during the preceding week, rose quickly in response to the heavy rain. By late evening of April 4, when the storm began to weaken, the discharge of most rivers in the mountains had peaked near or above the 25-year recurrence interval.

Schoharie Creek is a northward-flowing tributary to the Mohawk River and drains the northwestern Catskill Mountains (fig. 18). The flood crest traveled quickly down the steep, forested headwater channels to the broad agricultural flood plains that begin between North Blenheim and Breakabeen, which is 40 miles downstream. Along the way, it passed virtually unattenuated and undelayed through the Schoharie Reservoir, which is part of the New York City water-supply system, because the reservoir already was filled to overflowing before the flood began. (It has no provision for regulation of floodwaters.) Five and one-half miles further downstream, the lower reservoir of the New York Power Authority Blenheim–Gilboa pumped-storage hydroelectric project also passed incoming floodwaters without modification, as is required by its Federal Energy Regulatory Commission license. Less than 2 hours separated the crests recorded at the U.S. Geological Survey gaging stations at Prattsville (upstream from the reservoirs) and North Blenheim (downstream from

B

C

Figure 16. Collapsed New York State Thruway bridge over Schoharie Creek near Amsterdam, N.Y. *A*, View from the east following collapse, afternoon of April 5, 1987. *B*, View from east bank as bridge section collapses, about 11:15 a.m. (EST), April 5, 1987. *C*, View from west bank of collapsed bridge, April 14, 1987. (Sources: *A*, *B* courtesy of Sid Brown, *Schenectady Gazette*; *C* Thomas J. Zembrzuski, Jr.)

[1]April 5 was the day the United States went on daylight saving time, and all public accounts of the times involved in the bridge collapse are daylight saving time. However, to maintain hydrologic integrity in discussing peak-flow traveltime, all times used in this article are eastern standard time (EST).

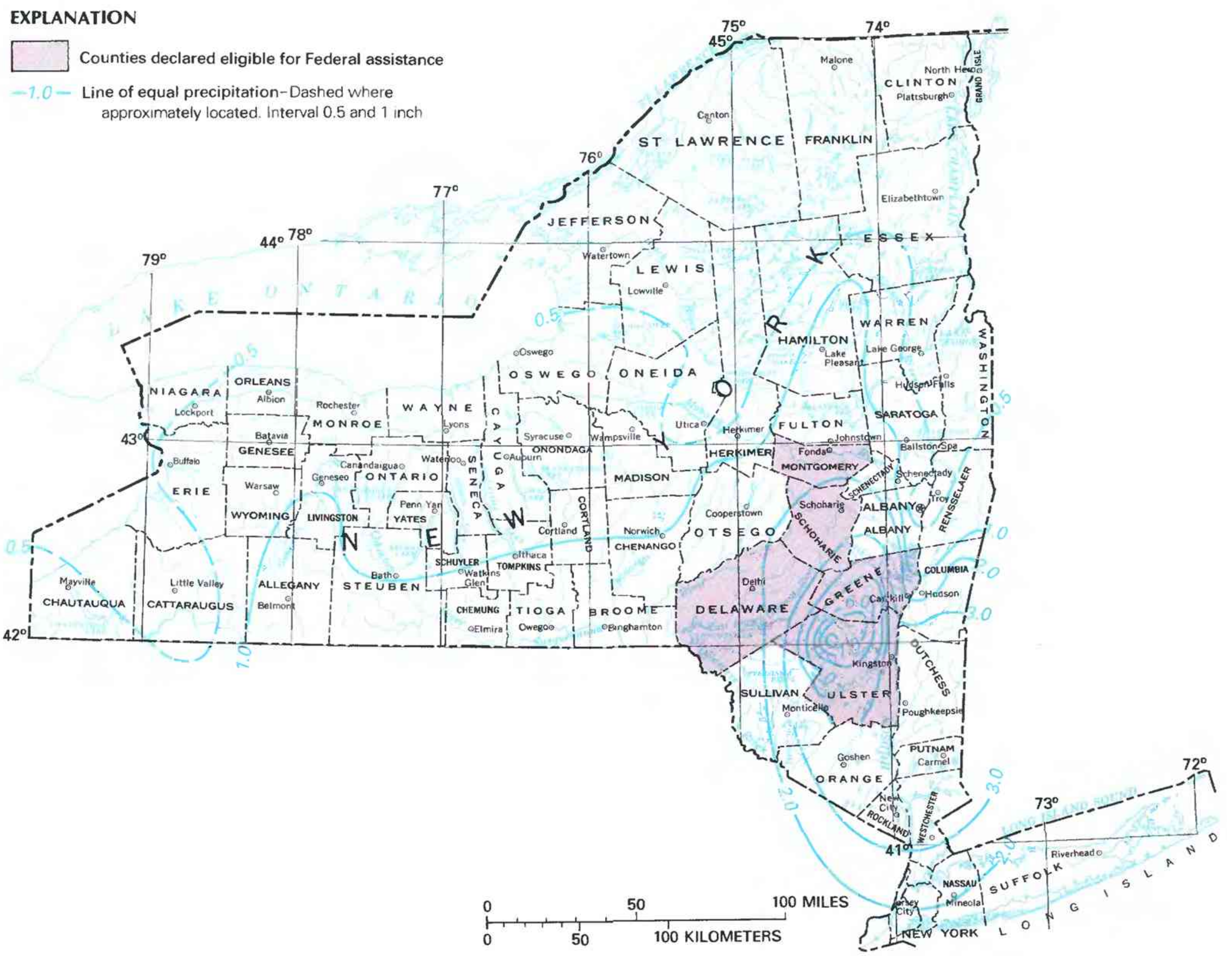

Figure 17. Lines of equal 48-hour precipitation through 7:00 a.m. EST, April 5, 1987, and counties declared eligible for Federal disaster assistance. (Source: Precipitation data from an unpublished map compiled by the New York State Department of Environmental Conservation.)

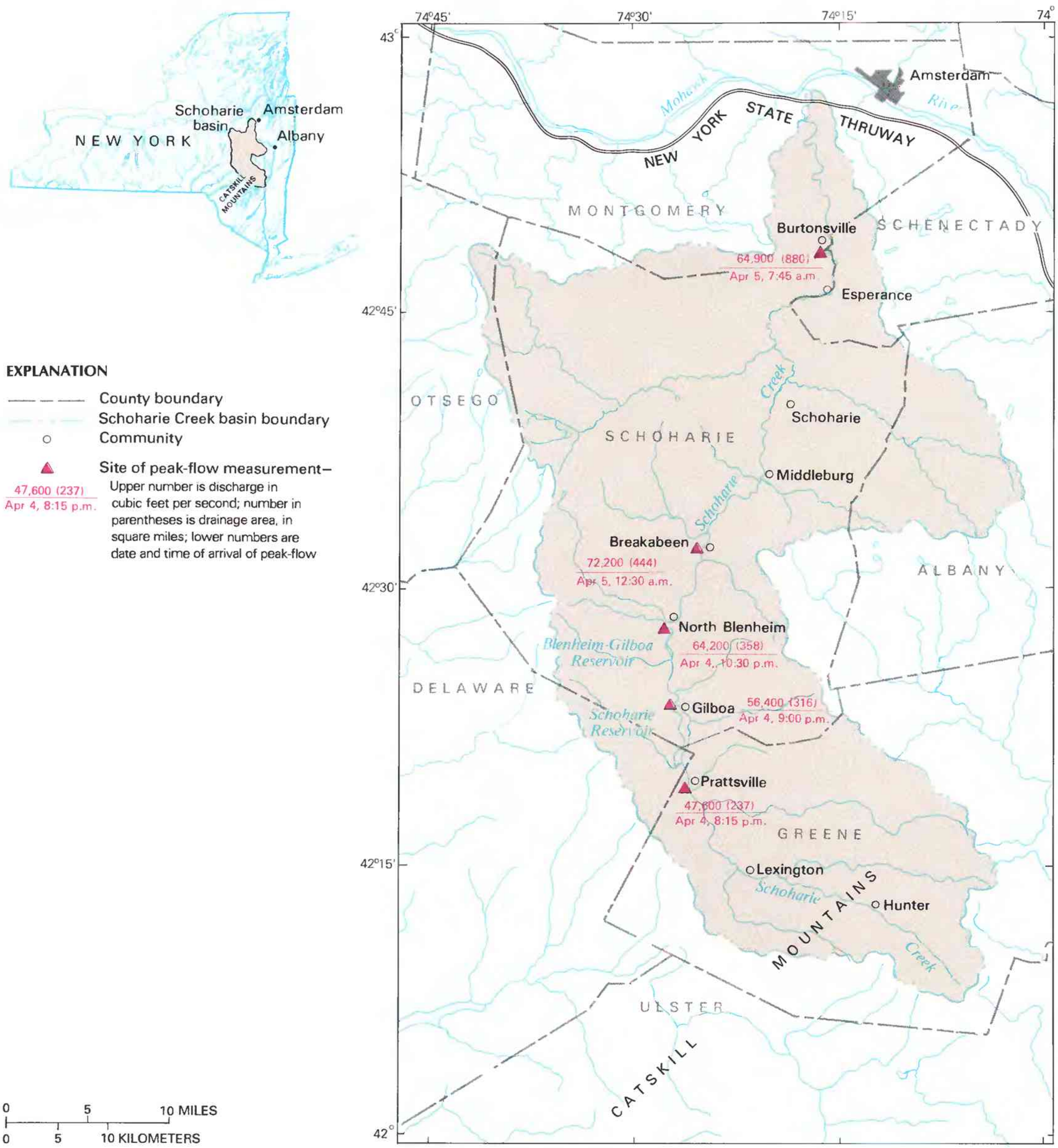

Figure 18. Major geographic features of the Schoharie Creek basin and peak-flow measurements from the storm of April 4–5, 1987.

the reservoirs), where the stream discharged maximum flows of 47,600 ft^3/s (cubic feet per second) and 64,200 ft^3/s, respectively. (Tributary inflow accounted for the increase in discharge between the two stations.)

During the early morning of April 5, flood waters continued to rise further downstream (north) of the gage at Breakabeen, where a peak flow of 72,200 ft^3/s was recorded. The progression of the crest slowed as it moved down the more gently sloped channel between Breakabeen and the gage at Burtonsville. Thousands of acres of farmland along the creek were inundated, as were low-lying areas in the villages of Middleburg and Schoharie. The smaller streams that are tributary to the lower Schoharie Creek already were receding, and, as more water spilled onto the wide flood plains, the crest began to attenuate. The peak discharge of 64,900 ft^3/s at the Burtonsville gage arrived at 7:45 a.m. EST.

In the Schoharie Creek's last 17 miles of descent to the Mohawk River, the channel again steepens. Estimates of traveltime (based on wave-speed calculations) indicate that the crest arrived at the mouth of the creek between 90 and 120 minutes after the crest passed the Burtonsville gage. Accordingly, the collapse of the Thruway bridge probably occurred within 30 minutes of the cresting of Schoharie Creek.

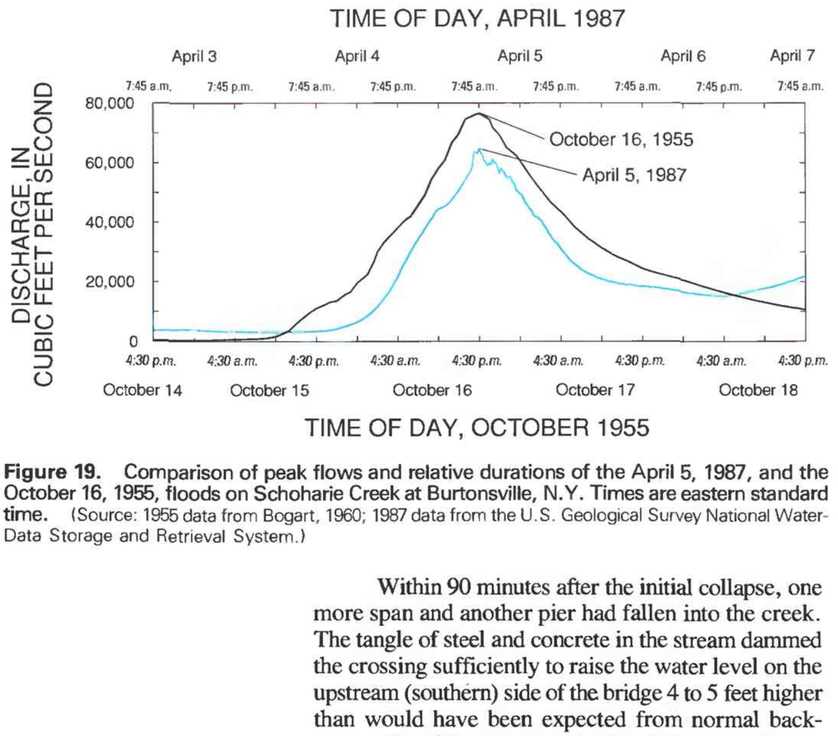

Figure 19. Comparison of peak flows and relative durations of the April 5, 1987, and the October 16, 1955, floods on Schoharie Creek at Burtonsville, N.Y. Times are eastern standard time. (Source: 1955 data from Bogart, 1960; 1987 data from the U.S. Geological Survey National Water-Data Storage and Retrieval System.)

Within 90 minutes after the initial collapse, one more span and another pier had fallen into the creek. The tangle of steel and concrete in the stream dammed the crossing sufficiently to raise the water level on the upstream (southern) side of the bridge 4 to 5 feet higher than would have been expected from normal backwater. The difference in water levels between the upstream and the downstream sides of the bridge was later determined from highwater marks to have been 7 feet.

The piers of the Thruway bridge were founded on spread footings set 5 to 8 feet into compact cobbly silty to clayey glacial till. The footings were not supported by piles. Investigations after the collapse determined that the average depth of scour in the bridge vicinity was about 13 feet and that the maximum depth of scour was 25 feet (Dineen, 1987). Patterns of local scour resulting from the bridge debris in the channel extended beyond the area near the pier where the failure originated; this obscured definitive reconstruction of the sequence of events leading to the failure. The floating and partly submerged debris (such as logs and utility poles) carried by the current might have aggravated the situation by piling up around the piers (Hearings testimony, National Transportation Safety Board, oral commun., July 1987). In its investigation, the National Transportation Safety Board (1988) concluded that the footings were vulnerable to the erosive force of the flood waters because of inadequate riprap around the base of the piers.

The recurrence interval of the April 1987 flood at the Burtonsville gage was estimated to be 75 years. This flood was exceeded only once in the 84 years since stream gaging began in the Schoharie basin—on October 16, 1955, when a peak flow of 76,500 ft^3/s was recorded (fig. 19; Bogart, 1960). The 1955 flood occurred only 1 year after the opening of the New York State Thruway.

Scour around bridges is a serious problem on many rivers (Jarrett and Boyle, 1986, p. 1), and the collapse of the New York State Thruway bridge has focused national attention on the vulnerability of other bridges to failure from scour. In its final report, the National Transportation Safety Board (1988) recommended revision of Federal and State bridge design, maintenance, and inspection guidelines as they relate to the threat posed by scour. The Board also recognized a need for continuing research into the scour phenomenon, particularly with respect to the stability of riprap in fast-flowing waters.

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FOR ADDITIONAL INFORMATION

District Chief, U.S. Geological Survey, P.O. Box 1669, Albany, NY 12201.

Storm and Flood of August 13 to 15, 1987, in Cook and Du Page Counties, Illinois

By George W. Curtis

Heavy rainfall on August 13 and 14, 1987, caused severe flooding of urban areas by streams in Cook and Du Page Counties, Ill. The storm was caused by the interaction of warm, moist air from the Southeast and Southwest with a cold-air mass from the Northwest. This interaction created a stationary weather pattern over northeastern Illinois that caused the heavy rain.

An all-time 24-hour rainfall record was established for the Chicago area when 9.35 inches of rain fell at O'Hare International Airport between 9:16 p.m. Thursday, August 13, and 2:45 p.m. Friday, August 14. This surpassed the previous record of 6.24 inches for a 24-hour period that was set on July 13, 1957. Record rainfall amounts also occurred in Chicago and in the suburbs within a 15-mile radius of the airport (R.R. Waldman, National Weather Service, written commun., 1987). An additional 2 to 3 inches of rain fell over the area during the following 2 days (fig. 20).

EXPLANATION

— 4 — Line of equal precipitation—Interval 1 inch

▲ 2,370 Site of peak-flow measurement—Number is discharge in cubic feet per second

● Community

✈ O'Hare International Airport

0 10 MILES

0 10 KILOMETERS

Figure 20. **Precipitation and selected peak flows of the Des Plaines River and Salt Creek as a result of the storm of August 13 to 15, 1987, Cook and Du Page Counties, Ill.** Precipitation, in inches, for the 48-hour period ending at 1 p.m. on August 15, 1987. (Source: Precipitation data provided by the National Weather Service and Wayne M. Wendland, Illinois State Climatologist; peak-flow data from U.S. Geological Survey files.)

The areas most acutely affected by flooding were communities along the Des Plaines River, which traverses the metropolitan area from north to south (fig. 20), and its tributary, Salt Creek. On August 14, flash flooding on the Des Plaines River occurred between 7 a.m. and about 11 a.m. The Des Plaines River crested near Des Plaines at midnight on August 14 and downstream at Riverside at noon on August 15 (R.R. Waldman, National Weather Service, written commun., 1987). General flooding continued after that time.

Suburban communities in the heavily urbanized Cook and Du Page Counties that were affected by the flooding include Arlington Heights, Bensenville, Buffalo Grove, Des Plaines, Elk Grove Village, Elmhurst, Mount Prospect, Rolling Meadows, Roselle, Schaumburg, and Wheeling. On August 14, access to O'Hare Airport was halted in the afternoon, and the first floor of the National Weather Service Forecast Office, which is located near the airport, was covered by 3 feet of water. The office lost electrical power and, after exhausting their emergency power, transferred their forecasting responsibilities to backup offices in Michigan, Wisconsin, and Illinois.

Figure 21. Flooded homes in Cook County, Ill., as a result of the storm of August 13 to 15, 1987. (Courtesy of *Chicago Tribune*.)

At least four deaths in the Chicago area and extensive damage were associated with the flooding (fig. 21). No deaths, however, were reported in the suburban residential areas located in the Des Plaines River basin (Federal Emergency Management Agency, 1987). Du Page County and parts of Cook County were declared major disaster areas by the President. Preliminary damage assessments indicate that about 8,900 buildings were affected by flooding or sewer backup in Cook County and about 7,500 buildings were affected in Du Page County. The total number of homes affected was about 11,500, almost all of which were owner-occupied, single-family units. The Small Business Administration's estimate of damages to private property was $53.0 million. The estimate damages to public property was $9.4 million (Jane E. Norton, Federal Emergency Management Agency, oral commun., 1989).

The intense rainfall produced record maximum peak flows at 10 stream-gaging stations on the Des Plaines River and its tributaries, including Salt, Addison, and McDonald Creeks, and the West Fork of North Branch Chicago, the West Branch Du Page, the North Branch Chicago, and the Skokie Rivers. Recurrence intervals for peak flows at the 10 gages ranged from 100 years to 1.4 times greater than a 100-year flow. [See Curtis (1977), for computation techniques.]

The severe flooding in the lower reach of the Des Plaines River basin was caused partly by the large inflow from Salt Creek. The Des Plaines River near Des Plaines, (24 miles upstream from Salt Creek), peaked at 3,370 ft^3/s (cubic feet per second), which is equivalent to a 10-year recurrence-interval discharge. The Des Plaines River at Riverside (0.9 mile downstream from Salt Creek) peaked at 9,750 ft^3/s, which is equivalent to a discharge 1.2 times greater than a 100-year discharge.

Salt Creek gages at Rolling Meadows and Western Springs set new peaks of record on August 14 of 1,670 and 3,230 ft^3/s, respectively, which are equivalent to discharges 1.4 times greater than a 100-year discharge. Additional heavy rains on August 16 caused the stream at Western Springs to rise again and peak at 3,540 ft^3/s on August 17, thus breaking the peak of record set 3 days earlier.

In summary, the heavy rainfall and associated flooding in Cook and Du Page Counties in August 1987 caused extensive damage to this heavily urbanized area. Four people died, and more than 11,000 private residences and nearly 5,000 business establishments were affected by the flood; damages were in excess of $62.4 million. The rainfall set 24-hour precipitation records, which caused peak flows on some of the streams to have recurrence intervals equal to or greater than 100 years.

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FOR ADDITIONAL INFORMATION

District Chief, U.S. Geological Survey, 102 East Main Street, 4th Floor, Urbana, IL 61801

Major Oil Spill on the Savannah River, Georgia and South Carolina, December 1986

By Whitney J. Stringfield

An oil spill, initially of unknown origin, was detected on the Savannah River in the evening of December 4, 1986. The source was determined later to be the *Amazon Venture*, a 700-foot tanker whose valve system malfunctioned while offloading No. 6 fuel oil at the Georgia Ports Authority (GPA) (fig. 22). More than 500,000 gal (gallons) of fuel oil eventually spilled into the river and affected about 25 miles of the Savannah River and its tributaries, wetlands, a wildlife refuge, recreational facilities, economic and cultural areas, and commercial river traffic. A total settlement of $1.2 million was awarded to South Carolina, Georgia, and the Savannah River National Wildlife Refuge (SRNWR) for damages caused by the oil spill and for studies to evaluate such accidents (The State Newspaper, 1987).

The *Amazon Venture*, carrying 13 million gal of No. 6 fuel oil from Pointe-a-Pierre, Trinidad, docked on December 4, 1986, at the GPA Garden City Terminal

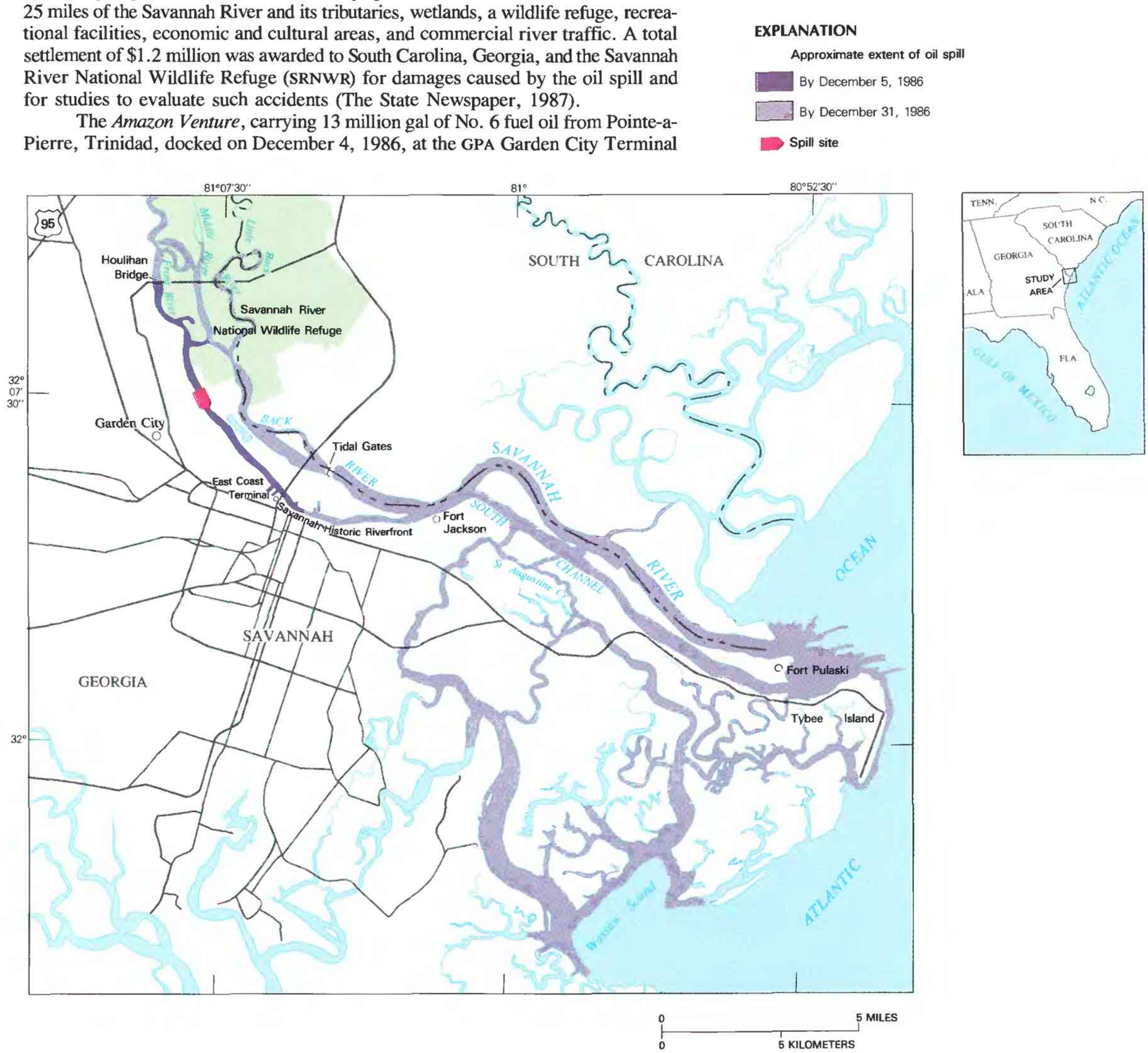

Figure 22. Areas affected by the oil spill on the Savannah River, Georgia and South Carolina, in December 1986.

in Garden City, Ga., to offload 3.5 million gal of oil to an oil-storage facility. Oil began to leak into the river after a pumping valve malfunctioned during offloading, and oil continued to spill into the Savannah River for the 4 days it took to complete the offloading (fig. 23).

Later in the day, the U.S. Customs Service became aware of this oil and notified the U.S. Coast Guard Marine Safety Office (MSO) in Savannah, Ga., of an oil spill in the Savannah River. The initial assessment of the size of the spill was 2,000 gal, which qualified it as a Federal spill. Emergency response personnel from several State and Federal agencies were alerted. Oil samples were taken from all probable vessels in port, and the samples were sent to the South Carolina Department of Health and Environmental Control for chemical analysis. The analysis indicated that the spilled oil originated from the *Amazon Venture*. It was later determined that the U.S. Customs Service had detected the spill 3 hours after the *Amazon Venture* began transferring its cargo of oil.

To assess the extent of the oil contamination, an aerial survey of the Savannah River, which is tidal affected, was conducted by personnel of the MSO and Coastal Divers and Pollution Control Inc. at daylight on December 5. Concurrently, shoreline and water surveys were conducted by Coast Guard personnel. These surveys indicated that patches of oil were as far upriver as the Houlihan Bridge and downriver of the East Coast Terminal, a total of about 8 miles (fig. 22). It was difficult to estimate the amount of the spill because northerly winds kept much of the oil that was under wharf and dock areas along the south bank of the river hidden during the first 2 days of the spill. Subsequently, the initial estimate of a minor spill of 2,000 gal was increased by the Coast Guard to a medium spill of 11,000 gal.

The Savannah River shoreline at the spill site is composed of numerous marshes and wetlands that are important habitats for wintering birds, anadromous fish, and shellfish; consequently these areas are sensitive to the effects of oil. When the spill was first noticed, the principal concern of Federal and State offices was the protection of the fish and wildlife habitat of the SRNWR, whose southern boundary was less than 1 mile upstream from the spill site (fig. 22). This 25,608-acre refuge contains freshwater marshes, tidal rivers and creeks, river bottom hardwood swamps, and diked impoundments. About 3,000 acres of former rice fields are managed by the U.S. Fish and Wildlife Service as freshwater impoundments for migratory waterfowl, wood ducks, and wading and shore birds. Within the refuge boundaries are important spawning areas for striped bass, American shad, and other anadromous fish. Also inhabiting the wetland areas of the refuge are five federally listed endangered or threatened species—the southern bald eagle, the wood stork, the red-cockaded woodpecker, the Arctic peregrine falcon, and the shortnose sturgeon.

Flood tides in the Savannah River area of the spill and the refuge commonly are strong during December, and mean tides can exceed 7 feet. High southerly winds also occurred at the same time as the spill, and the fuel oil moved quickly into the southern part of the refuge. The winds and tides carried oil-contaminated water up the Front and the Middle Rivers during the first few days after the spill occurred and as far as 6 miles into the refuge.

On December 5, containment and recovery efforts were begun by the Coast Guard who deployed booms in the area of the spill, and, by the next day, the fuel oil began to be recovered. The deployment of booms across the river channels in the SRNWR also was attempted on December 5, but the deployment failed as a result of the high tidal velocities. Booms were placed at several locations during the next 4 days, and, as of December 11, five booms were in the SRNWR, several booms were deployed in the vicinity of the *Amazon Venture*, and one boom was deployed across St. Augustine Creek, which is downstream from the spill area. Due to the strong tidal currents in the Savannah River, only small amounts of fuel oil were contained by the booms, which were not effective in preventing the spread of oil.

To slow the movement of the oil up the Middle River and into the refuge, the U.S. Army Corps of Engineers opened the tidal gates in the Back River for a limited period of time between December 9 and 16 (fig. 22). The gates normally are closed on the ebb tide to increase flushing in the main river channel. Opening the tidal gates was successful in reducing the upstream velocity in the Savannah River, which made oil containment and recovery more effective. The containment and cleanup of the oil was under the supervision of the U.S. Coast Guard and involved six private contractors, two of whom were hired by the ship's owner. About 60 people worked to contain and cleanup the oil by using nine vacuum trucks, 15,000 feet of containment boom, and 6,000 feet of absorbent boom. Two of the contractors worked exclusively on cleaning up the oil in the SRNWR, where 6,500 feet of the total 21,000 feet of boom was deployed.

To monitor the extent of oil in the river and along the shoreline, daily aerial surveys were conducted by personnel from the National Oceanic and Atmospheric Administration and the Coast Guard. It became evident from these surveys that the magnitude of the spill was more severe than had been estimated originally; this prompted a request for assistance from one of the Coast Guard's three Gulf Strike Teams (GST) whose members have received special training to manage the cleanup of oil spills. Five GST members from Mobile, Ala., were detailed to assist the MSO, to conduct aerial surveys, and to further assess the spill. Based on the assessment of the strike team, MSO officials on December 7, 1986, increased the estimate of the spilled oil from 11,000 to 50,000 gal, which is still considered to be a medium oil spill. Four days later, on December 11, 1986, the medium oil spill was upgraded to a major spill of 500,000 gal.

The containment procedures, which continued to be hampered by the strong currents in the Savannah River and Wassaw Sound, were ineffective because the booms could not extend the width of the river. Thus, incoming and outgoing tides continued to spread some of the fuel oil. The ineffectiveness of the booms was evidenced by the presence of oil on both sides of the booms and was verified by oil found in shellfish meats at locations originally thought to have been protected. Also, because the source of the spill went undetected and unreported for 4 days, the oil had time to spread over a wide area, which made containment difficult. By December 30, an estimated 200,000 gal of oil-water mixture and 160 cubic yards of oily debris had been recovered. As of January 12, 1987, no floating or recoverable oil appeared to be on the Savannah River. Ultimately, 8,000 acres of the SRNWR, the entire estuarine area of Wassaw Sound, the Savannah River and its tributaries from I-95 to the Atlantic Ocean, areas nearshore and offshore of Tybee Island, and Wassaw Sound were affected by the spill. Oil not reclaimed by the cleanup efforts was allowed to dissipate naturally as a result of biodegrading and dilution. The long-term effect on the environment is still unknown.

This oil spill created a variety of environmental, historical, economic, and recreational effects. More than 60 miles of shoreline was moderately to heavily affected, and an additional 124 miles was lightly affected. Within the SRNWR, 58 miles of shoreline had a moderate to heavy coating of fuel oil, and 5,500 acres of intertidal wetlands and 1,200 acres of surface water also was exposed to oil. Wildlife was affected by the introduction of oil into food chains and the direct oiling of wading birds, waterfowl, crabs, and mammals. Commercial shad, shellfish, catfish, and sturgeon fishing decreased while the river was inaccessable during cleanup. Air pollution, another environmental effect not commonly associated with oil spills, increased along the Savannah harbor as the result of volatilization of the hydrocarbons.

During the spill, tourism decreased at the Fort Jackson and the Fort Pulaski National Monuments and the Savannah Historic Riverfront. Recreational activities, such as pleasure boating, recreational fishing, shellfish harvesting, and migratory waterfowl hunting, also decreased.

Several different types of relevant data that are collected routinely will help in the evaluation of the long-term effects of the oil spill. One source of data is a U.S. Fish and Wildlife Service study of the vegetation density, composition, and biomass of study plots in the SRNWR. Striped bass egg and larval data have been collected from the Savannah River by the Georgia Department of Natural Resources during the last 10 years. Additionally, the South Carolina Wildlife and Marine Resources Department has data on the size and age of the shad population migrating up the

Figure 23. Downstream view of the spilled fuel oil spreading along the Savannah River near the East Coast Terminal, Ga., December 8, 1986. (Source: Jane Settle, South Carolina Wildlife and Marine Resources Department.)

Savannah River from 1977 to 1985. Other data on the economic value of commercial fishing and crabbing, the number of tourists visiting the Historic Riverfront, and the number of hunters and fishermen who use the SRNWR provide a baseline against which to compare future use of the Savannah River and its neighboring wetlands. Research studies by various organizations are underway to determine the effects of the oil spill on oyster beds, aquatic habitat, fish populations, and other organisms that might have been affected in the contaminated areas of the Savannah River and its tributaries.

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FOR ADDITIONAL INFORMATION

Whitney J. Stringfield, U.S. Geological Survey, 1835 Assembly Street, Suite 677A, Columbia, SC 29201–2492

Landslide of April 14, 1987, near Hagerman, Idaho

By R. E. Lewis

INTRODUCTION

A landslide on April 14, 1987, near the town of Hagerman, Idaho (fig. 24), caused an estimated $1.5 million in damages to the southernmost of two irrigation pumping stations and an undetermined amount of damage to fossil beds at the Hagerman Fauna Site National Landmark on adjacent U.S. Bureau of Land Management (BLM) lands. Some soil slumping and scars from several small recent landslides have been observed in this same area, but none are of the magnitude of the April landslide nor did they in any way affect the pumping stations. Damage to the southern pumping station was extensive; the northern station was undamaged. No injuries were reported, but the landslide crushed the pumphouse, scattered several hundred feet of pipeline, overturned an electrical transformer, and buried two trucks. Two 36-inch diameter pipes called penstocks twisted and collapsed because of the movement of soils and rock, which created concern that repairs could not be made in time to prevent crop losses. However, the irrigation company was able to avert such losses by increasing the volume of water pumped at a nearby downstream plant and by installing pipe to transport water to the canal that had been serviced by the damaged pumping plant. Figure 25 shows rubble from the slide on the left bank of the river near the pumping plant at the base of the canyon wall.

Figure 24. Location of the town of Hagerman, Idaho, and the Snake River where landslide of April 14, 1987, occurred.

The fossil beds at the Hagerman Fossil Site National Landmark were first discovered in the early 1900's and were excavated in the 1930's by scientists from the Smithsonian Institution. The site contains fossils of 11 species of animals that inhabited the area nearly 3.5 million years ago, including a zebralike horse known as the Hagerman Horse, camels, beavers,

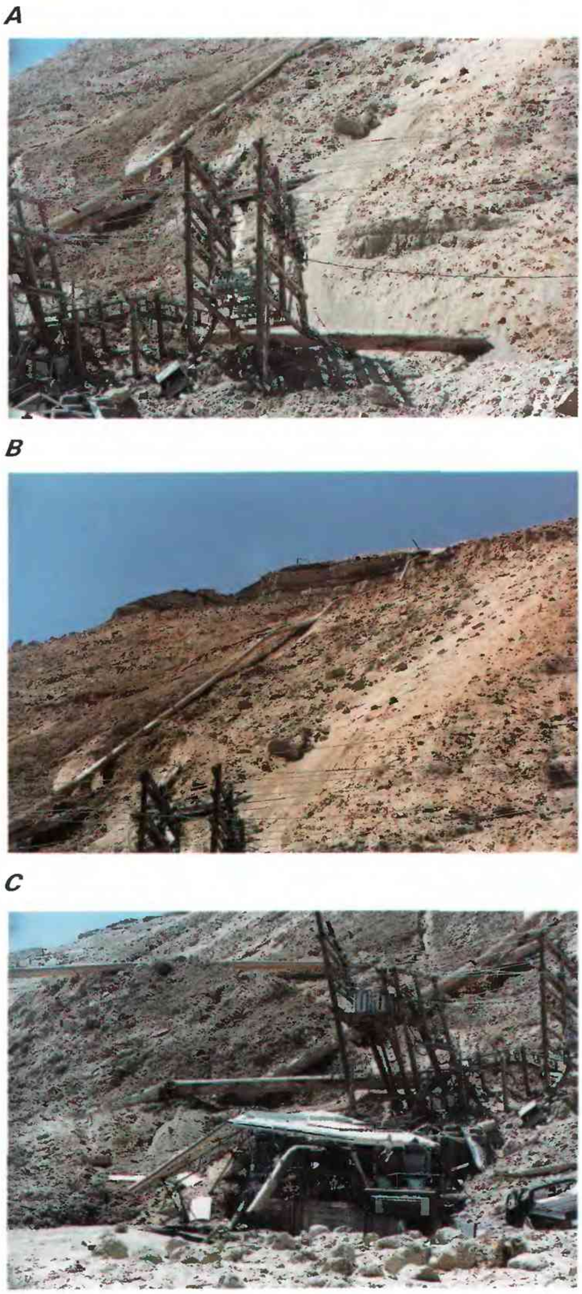

Figure 25. Bell Rapids Irrigation Company pumping plant damaged by landslide near Hagerman, Idaho, April 1987. *A*, Damaged penstock at base of canyon. *B*, Damaged penstock on canyon wall. *C*, Pumping plant. (Source: U.S. Bureau of Land Management.)

ducks, and fish. The fossils are of major paleontological significance and are considered to be one of the most complete assemblages of Pliocene fauna in the world. Although the monetary loss from the landslide is difficult to assess, future scientific work could be impaired.

The town of Hagerman, which has a population of about 650, is located in a 3-mile-wide valley of the Snake River in south-central Idaho. The Snake River flows generally northwestward in this area and is deeply incised into basalt and sedimentary rocks of Pleistocene and Pliocene age; the rims of the canyon wall are about 450 feet above the valley floor. Most of the land is used for farming, although aquaculture, which is the commercial raising of fish, in this case trout, is a major industry in south-central Idaho. Irrigated crops on the valley floor receive water diverted from the Snake River through a system of canals and ditches or from the many springs that discharge from basalt on the northern side of the canyon. Farms on the plateaus above the valley on the southern side of the canyon rely on high-volume pumping plants to pump water from the river through the penstocks to the canyon rim 450 feet above. In 1986, about 100 pumping stations were operating on the Snake River between Twin Falls and Hagerman.

Two pumping stations are operated by the Bell Rapids Irrigation Company near Hagerman. Water from the Snake River is pumped through 36-inch penstocks to the canyon rim and is discharged into two unlined canals for distribution to irrigate about 36,000 acres of cropland.

CAUSATIVE FACTORS

Cause of the landslide was not determined, although BLM officials speculate that the landslide was caused by moisture in the ground that resulted from unusually wet conditions during 1985 and 1986 and by water that seeped into the ground from unlined canals. It is thought that water accumulated in shallow perched aquifers near the canyon rim. Discharge from the aquifers as small springs in the canyon wall might have saturated the adjacent rock and sediment and caused the slide.

In 1984, the BLM requested the U.S. Geological Survey to obtain geologic and water-level data for the perched aquifers of the area so that they could determine whether leakage from the unlined canals was causing water to accumulate in the shallow sedimentary material. The BLM was concerned that the perched aquifers were the sources of the small springs that issue from the canyon wall above the Hagerman fossil beds.

As a result of the data-collection work, the BLM requested the U.S. Geological Survey to drill 11 test holes to monitor water levels in the perched aquifers. The test holes were installed, and, beginning in March 1986, continuous water-level recorders were operated at five of the holes, and monthly water-level measurements were made in the others. Preliminary results of the monitoring confirmed the presence of shallow perched aquifers just beneath the unlined canals. Hydraulic gradients, which were determined from the water-level measurements, indicated that the water in the perched aquifers was moving toward the Snake River canyon and was the source of water discharging as springs in the canyon wall. Discharge measurements in the canals at several sites during the irrigation season verified that a significant amount of water was being lost in the upper parts of the canals during transport. Water lost from the canals was thought to be percolating through mostly unconsolidated sedimentary material until it encountered a less permeable material and accumulated in the perched aquifers.

MANAGEMENT ACTIONS

On the basis of these preliminary results and before the landslide occurred, the BLM had decided to line the canals with cement for about 1 mile from the canyon rim to prevent further recharge to the perched aquifers and, ultimately, undesirable discharge from the springs. After the landslide, an agreement was reached between the BLM and the Bell Rapids Irrigation District to jointly fund the work, and lining of the southern canal was begun after the 1987 irrigation season. When the work was completed in mid-November 1987, the canal was lined for nearly 2,200 feet away from the canyon rim. No plans were formulated for the immediate lining of the northern canal or to repair the destroyed pumping station and to replace the penstocks. As of July 1989, crops on plateau lands above Hagerman were still being irrigated by pumping Snake River water at the existing northern pumping station for distribution through existing pipes to the newly lined southern canal and the unlined northern canal.

In September 1988, a bill was passed by the Congress declaring the Hagerman Fossil Beds a national monument. Funds will be appropriated to develop and protect the resource and to provide for its management by the National Park Service.

FOR ADDITIONAL INFORMATION

R.E. Lewis, U.S. Geological Survey, 230 Collins Road, Boise, ID 83702

ALGAL BLOOMS IN LAKE OKEECHOBEE, FLORIDA, AND MANAGEMENT STRATEGIES TO MITIGATE EUTROPHICATION

By David R. Swift[1], Cathy Anclade,[1] and I. H. Kantrowitz[2]

INTRODUCTION

One of the largest and most intense algal blooms ever recorded in Lake Okeechobee occurred from August 12 to 20, 1986, and covered more than 120 mi^2 (square miles) of lake surface. The filamentous blue-green *Anabaena circinalis* was the dominant alga comprising the bloom. Although previously reported as an abundant species in the summer of 1970, this nitrogen-fixing species had not been observed as a major bloom-forming species in Lake Okeechobee in such magnitude. Fall 1986 and spring 1987 brought a recurrence of *Anabaena* blooms. The sudden appearance of massive algae blooms has been interpreted by many individuals as a sign that the ecological health of the lake is being threatened by excessive nutrient inflows and has increased both government and public awareness of the lake-eutrophication issue.

Water-quality data collected over the last decade by the U.S. Geological Survey and, more recently, by State water-management agencies have shown a steady increase in lakewide phosphorus concentrations, which has created concern that the sediments in the lake might be losing their capacity to assimilate phosphorus. Additionally, ratios of total nitrogen to total phosphorus have shown a downward trend that could indicate a shift in the composition of phytoplankton species toward nuisance nitrogen-fixing blue-green algae, such as *Anabaena* (Brezonik and others, 1987).

HYDROLOGIC FEATURES AND LAND USE

Lake Okeechobee is a large shallow eutrophic lake in south-central Florida and is a major feature of the highly productive Kissimmee-Okeechobee-Everglades ecosystem (fig. 26). In surface area, Lake Okeechobee covers 730 mi^2 and is the second largest freshwater lake wholly contained within the conterminous United States. (Lake Michigan is larger.) It has an average depth of only 9 feet, but its storage capacity of 1 trillion gallons of water represents the heart of southern Florida's water-supply and flood-control systems for more than 3.5 million persons living in highly urbanized coastal areas. The lake is used for a variety of purposes—a direct drinking-water source for 32,000 persons living in five cities surrounding the lake; a partial source of water (Caloosahatchee River) for urban western coast areas; a source of aquifer recharge for eastern coast municipal well fields; a source of irrigation water for a $1.5-billion-per year crop of sugarcane, rice, and winter vegetables; and a source of water for the ecologically unique Everglades National Park. Lake Okeechobee is nationally known for its duck hunting and sport fishing, particularly largemouth bass and black crappie; it also supports a viable commercial fishing industry.

Lake water levels are regulated by a complex system of pumps and locks collectively known as the South Florida Flood Control Project. The system is managed jointly by the South Florida Water Management District (SFWMD) and the U.S. Army Corps of Engineers. The water-regulation schedule attempts to achieve the multiple-use purposes stated above, as well as to provide for seasonal lake-level fluctuations. As protection against hurricane flooding, the lake is encircled by a 25-foot-high earthen levee (the Hoover Dike).

The lake's drainage area is more than 4,500 mi^2 (fig. 26). Land use within the area is predominately agriculture—cattle and dairy pasture to the north and northwest and sugarcane, rice, and vegetable crops grown in organic (peat) soils to the south and east. Major inflows into the lake include rainfall (39 percent), the Kissimmee River (33 percent), and numerous other smaller inflows, the largest of which are from the Everglades Agricultural Area (9 percent), Harney Pond and Indian Prairie basins (6 percent), Fisheating Creek (6 percent), and Taylor Creek-Nubbin Slough (4 percent) (Federico and others, 1981). Major outflows are evapotranspiration (66 percent), the Caloosahatchee River to the west (12 percent), and several canals draining to the east and south (22 percent).

Along the shallow western shore, an extensive marsh (bulrush, cattail, maidencane) occupies 150 mi^2 of the lake's surface. Aquatic life within these marshes supports sizable populations of wading birds and migratory waterfowl; the marsh is the nesting and feeding habitat of the endangered snail kite.

ENVIRONMENTAL QUALITY

Between 1974 and 1984, concentrations of total phosphorus in Lake Okeechobee about doubled (fig. 27). Preliminary evidence suggests that excessive nutrient loading has reduced the lake's capacity to assimilate phosphorus. In addition, the ratio of total nitrogen to total phosphorus has shown a significant downward trend, which possibly indicates a shift in species composition from the lake's normal algal flora to less desirable nitrogen-fixing blue-green algae, such as *Anabaena* (Brezonik and others, 1987). If these trends continue, then it is possible that eutrophication will accelerate and that the lake will suffer an ecological collapse of its food chain and fishery resource (Jones, 1987). Such a collapse would be a major environmental and economic loss to the region.

Although numerous blue-green algal blooms have occurred in the lake in the past, the August 1986 bloom was the most severe (fig. 28) and was distinguished by its magnitude and by the algal species involved. *Anabaena circinalis* is a filamentous, nitrogen-fixing blue-green alga that frequently is dominant in highly eutrophic lakes. Although this

[1]South Florida Water Management District. [2]U.S. Geological Survey.

Figure 26. Lake Okeechobee drainage basin (Kissimmee-Okeechobee-Everglades ecosystem) and major hydrologic features of South Florida. (Source: Landsat 4 multispectral scanner mosaic, 1982.)

species had been documented as an abundant member of the lake's phytoplankton community in summer 1970 (Joyner, 1974), it had not been observed recently as a bloom-forming species in Lake Okeechobee. The bloom, which had been building since mid-July, attracted national attention after strong southeasterly winds concentrated the algal mass along the western shore marsh where the *Anabaena* cells ruptured, thus releasing a rich source of nutrients for bacterial growth. Bacterial populations increased rapidly; this depleted the water of oxygen and released high concentrations of ammonia, which turned the water a milky white color. The toxic effects of high ammonia concentrations and near-zero dissolved-oxygen levels caused the death of thousands of apple snails (fig. 29). The bloom threatened the snail kite, which is an endangered species that feeds almost exclusively on apple snails.

Although *Anabaena* has been known to release an endotoxin that is lethal to aquatic organisms, laboratory bioassays conducted during the bloom showed no apparent toxicity in this case. No fishkills were observed, presumably because the fish had moved out of the area. Snail kite populations also appeared unaffected by the bloom. Within 2 weeks, the bloom cycle was completed and dissipated. A number of other less-severe blooms have occurred since August 1986, with *Anabaena* becoming established as a common component of the lake's plankton community.

In addition to the increased frequency of *Anabaena* blooms, the lake is also experiencing a luxuriant infestation of attached algae (periphyton) along the lake's southern, northern, and western shores. To the south, localized infestations of the filamentous blue-green *Lyngbya birgei* have hindered fishermen, and, on the northern and western shores, massive growths of the filamentous green *Cladophora glomerata* periodically have formed bright-green floating mats along the lakeward fringe of the marsh. Although the cause of these algal growths is not yet fully understood, they, too, are suspected to be another sign of excess nutrient loading to the lake.

Studies of the lake's fishery by the Florida Game and Fresh Water Fish Commission (FGFWFC) report that the recent *Anabaena* blooms have had no direct impact on the lake's fishery (Fox, 1987). However, increased nutrient loading over recent years is thought to be generally linked to a lakewide increase in fish abundance. From 1984 through 1986, black crappie, which is an important game fish, increased dramatically within the lake, although the average harvestable size of individual fish has declined in response to increased fish density and competition. Furthermore, ratios of rough-fish to game-fish species indicate that, in 1986, game fish were still predominant in the lake.

The significance of the recent *Anabaena* blooms is a point of debate. Some scientists believe the algal blooms signal the death of the lake as a productive sports fishery unless drastic measures are taken immediately; others maintain that, although the lake ecology is not in immediate danger of collapse, to keep the lake healthy appropriate action must be taken to control nutrient inflows. Most agree that the recent blooms are a clear sign that the lake ecology currently

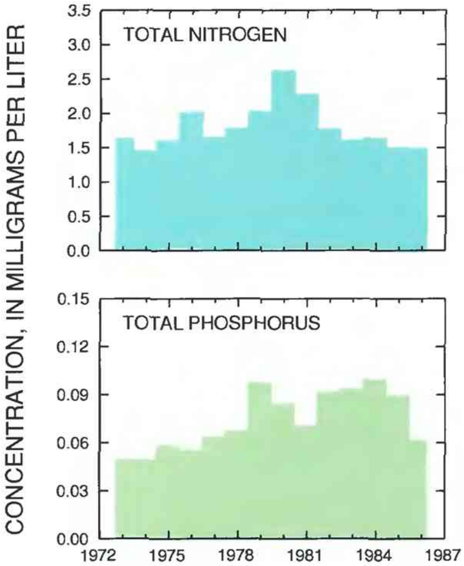

Figure 27. Mean annual concentrations of total nitrogen and phosphorus in Lake Okeechobee, Fla., 1973–86. (Source: Data from the South Florida Water Management District.)

A

B

Figure 28. Algal bloom in Lake Okeechobee, Fla., August 1986. *A*, Aerial photography; *B*, microphotograph. (Source: *A*, Pat Partington, and *B*, David R. Swift, South Florida Water Management District.)

is stressed by excessive nutrient inputs and that action should be taken as soon as possible to control them.

DATA AVAILABILITY AND SCIENTIFIC UNDERSTANDING

Studies of Lake Okeechobee began in 1940 when the U.S. Geological Survey initiated data collection as part of its water-quality-monitoring program. However, it was not until 1969 that a comprehensive water-quality study of Lake Okeechobee was undertaken. In that year, the U.S. Geological Survey, in cooperation with the SFWMD (then known as the Central & Southern Florida Flood Control District), began a program to assess the nutrient balance of the lake. This study concluded that the lake's chemical and biological characteristics were in an early eutrophic condition (Joyner, 1974). A related study documented nutrient loadings to the lake from the channelized Kissimmee River (Lamonds, 1975).

In 1973, the SFWMD followed these initial limnological investigations with a program of long-term collection of water-chemistry data at all major inflows and outflows and at eight in-lake sites. This continuing program, which had sampling frequencies of 2 to 4 weeks, was designed to develop nutrient budgets; to monitor water-quality trends and relations among chemical, biological, and physical factors; and to assess the biological and chemical state of the lake over time (Davis and Marshall, 1975; Federico and others, 1981; Jones and Federico, 1984).

In 1979, the SFWMD, in cooperation with the Florida Department of Environmental Regulation (FDER), used an empirically based water-quality model (Vollenweider, 1976) to establish the maximum loadings of nitrogen and phosphorus that could be safely discharged into the lake. Modeling results indicated that total annual average loading of nutrients entering the lake from all sources should be lowered by 34 percent for nitrogen and 40 percent for phosphorus (Federico and others, 1981). Despite some initial declines in 1980 and 1981 (fig. 27), which resulted from efforts to divert agricultural runoff away from the lake, total in-lake phosphorus concentrations generally have increased, and nutrient-loading targets have not been met.

As a result of the August 1986 *Anabaena* bloom, the monitoring program begun in 1973 was expanded from 8 to 42 sites (fig. 29). The purpose of the expanded program is to examine lakewide areal differences in water quality, to understand the effects of nutrient inflows from various sources, to examine algae-nutrient relations, and to measure the effects of various water-management programs on the lake's water quality. Several contracts with State universities have been initiated to investigate nutrient loading and recycling processes, such as sediment resuspension, within the lake; export of phosphorus from the littoral zone; and algal-nitrogen fixation processes and their overall contribution to lake eutrophication.

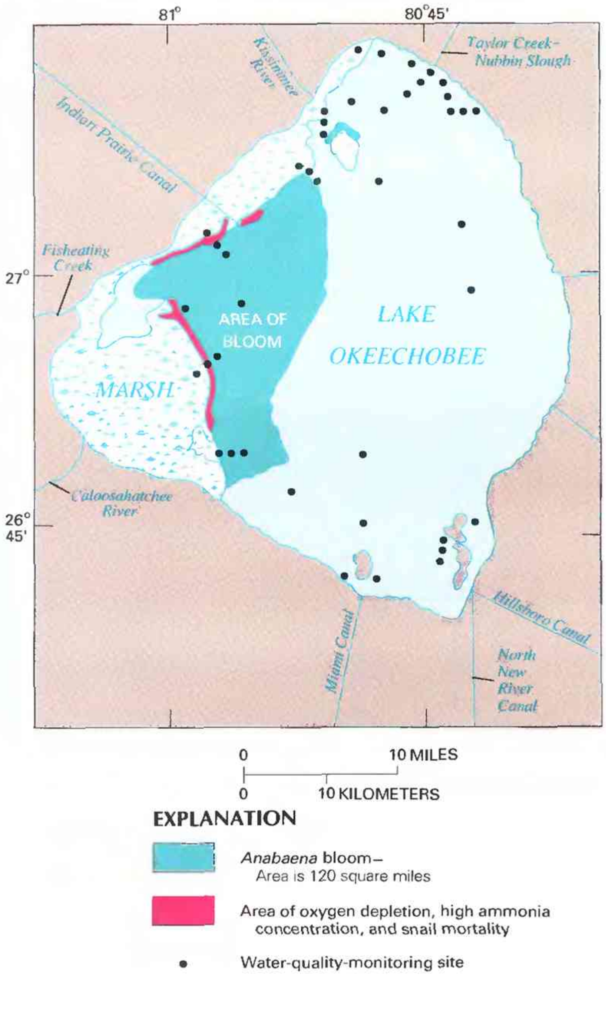

Figure 29. Areas of algal bloom and snail mortality and location of water-quality-monitoring sites, Lake Okeechobee, Fla., August 1986. (Source: Data from David R. Swift, South Florida Water Management District.)

MANAGEMENT STRATEGIES TO MITIGATE EUTROPHICATION

The element that most often limits or controls algal growth in freshwater lakes is phosphorus, although nitrogen can be growth-limiting in some grossly polluted and phosphorus-enriched lakes. Phosphorus commonly is assumed to be the growth-limiting nutrient in Lake Okeechobee, although nitrogen has been shown to stimulate algal growth in some instances. Phosphorus is less difficult to control than nitrogen because blue-green algae can fix nitrogen from the atmosphere. Therefore, to prevent further eutrophication of the lake, the primary management strategy is to reduce and control phosphorus inflows. Although the SFWMD considers the control and the management of phosphorus to be the key elements to mitigate eutrophication, control of nitrogen inputs also is important and is viewed as an essential component of the overall lake-management plan.

In 1985, the Lake Okeechobee Technical Advisory Committee (LOTAC) was established by the Secretary of the FDER at the request of the Governor. The LOTAC, which is composed of scientists, representatives of local, State, and Federal agencies, and agricultural and conservationist groups, was charged with recommending how best to conserve water and to protect and improve Lake Okeechobee's water quality. The committee's final report (Florida Department of Environmental Regulation, 1986) recommended the following measures to enhance water quality, water supply, and water conservation:

Water quality—

- Reduce annual phosphorus loadings to the lake by 40 percent.
- Divert Taylor Creek–Nubbin Slough water away from the lake and divert the Everglades Agricultural Area (EAA) water that would normally be "backpumped" to the lake. (Backpumping is the practice of mechanically pumping water against gravity to provide flood protection for low-lying farmland and urban areas within the EAA.)
- Reduce the need for backpumping by enlarging and improving the conveyance system of canals south of the lake.
- Implement advanced Best Management Practices (BMP) (economically, technologically, and institutionally appropriate methods of controlling nonpoint sources of pollution) in the Taylor Creek–Nubbin Slough and the lower Kissimmee River basins.
- Restore the natural wetland functions of the Kissimmee River by means of pool-stage manipulation, flooding historic oxbows, and creating overland sheet flow.

Water supply—

- Conduct a feasibility study of aquifer storage and recovery of diverted runoff.
- Conduct a feasibility study of diverting (backpumping) water from largely undeveloped and pristine areas east of the lake if acceptable water quality can be maintained.

Water conservation—

- Endorse a SFWMD water-conservation plan and an integrated protection plan to monitor, conduct research, and manage the lake.

Although implementation of these recommendations requires coordinated multiagency efforts, the SFWMD was recognized as the lead agency responsible for carrying out Lake Okeechobee protection plans. Since the LOTAC released its recommendations, the SFWMD has taken steps to implement the lake-protection plan and to control phosphorus and nitrogen inflows.

Phosphorus Control

Reduction and control of phosphorus entering the lake from cattle and dairy operations within the Taylor Creek–Nubbin Slough basin are key components of the protection strategy. Nutrient budgets (Federico and others, 1981) show that this basin annually contributes about 29 percent of the phosphorus inflows to the lake, although it contributes only 4 percent of the inflow water (fig. 30). Strategies for controlling phosphorus in this basin include BMP's, such as fencing cattle away from waterways and collecting dairy-barn runoff in wastewater lagoons, that focus on controlling phosphorus runoff from dairy barns and cattle pastures. This program, which is nearing completion, is expected to reduce phosphorus runoff from the basin by 50 percent. Recent data (1987) indicate these initial efforts have already reduced phosphorus loadings into the lake by 15 percent.

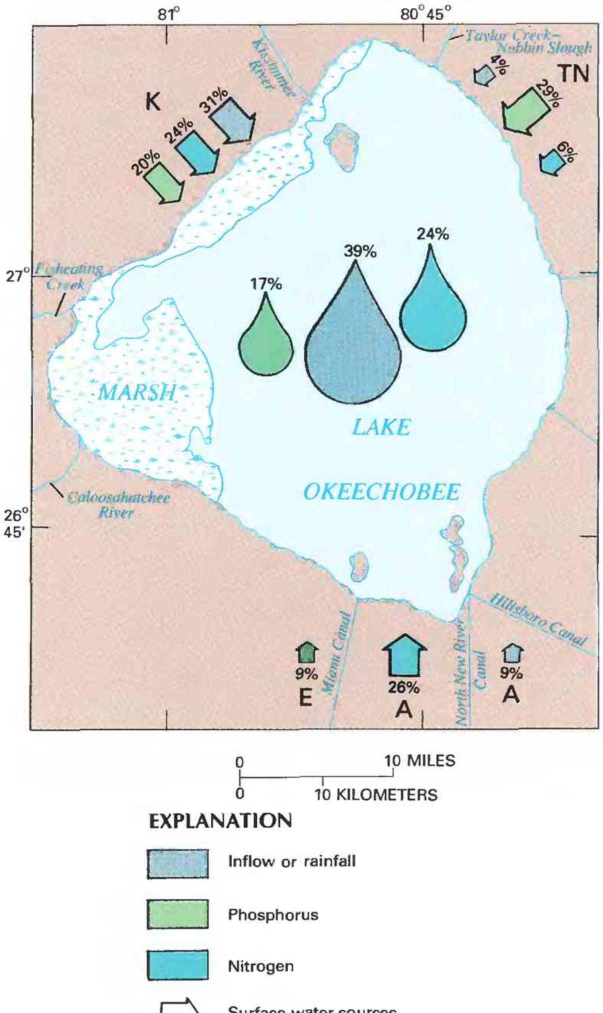

Figure 30. Major sources of water and nutrient loads to Lake Okeechobee, Fla., 1973–84. All inflows to the lake are not shown, therefore the values shown do not add to 100 percent. K, Kissimmee River basin; TN, Taylor Creek–Nubbin Slough basin; EAA, Everglades Agricultural Area. (Source: Data compiled by B.L. Jones from South Florida Water Management District data and from Federico and others, 1981.)

Other efforts by the SFWMD to reduce phosphorus loading in the Taylor Creek–Nubbin Slough basin include developing a low-phosphorus fertilizer management program for cattle pastures, lowering the phosphorus content of dairy-cattle feed, and developing onsite wastewater management of dairy-barn and feedlot waste. Similar BMP programs are being implemented in the Kissimmee River basin, which contributes 20 percent of the phosphorus loading to the lake.

Another option under consideration is the possible diversion of phosphorus-enriched runoff from the Taylor Creek–Nubbin Slough basin into a 13,500-acre reservoir that would be constructed northeast of the lake by the U.S. Army Corps of Engineers. Diverted waters would be stored in the reservoir during the wet season and released during the dry season for citrus operations on the eastern coast. Diversion of phosphorus-enriched water also is being considered in combination with several other options, such as Aquifer Storage and Recovery (ASR), treatment at the source, and, possibly, a small secondary reservoir.

ASR is a promising water-management measure in which surface water is injected into the underlying limestone saline-water aquifer and stored for later recovery and use (Merritt, 1985). In addition to water conservation, another benefit of using surface water from the Taylor Creek–Nubbin Slough basin is the reduction of phosphorus concentrations that would result from bacterial activity and chemical interaction with the limestone. After a period of time, injected water could be recovered and returned to the lake or used in agriculture. Test wells have been constructed by the SFWMD to measure the feasibility of pursuing the ASR water-management option.

Mechanical harvesting of aquatic weeds to reduce phosphorus concentrations in the lake by simple physical removal was tested by the SFWMD in 1986. Initial results of the pilot-scale program were disappointing; however, the SFWMD currently is investigating new ways to improve the efficiency and cost effectiveness of the project and is planning a larger scale demonstration project. Physical removal of phosphorus by commercial harvesting of rough-fish species, such as gizzard shad, is another option that is being investigated in cooperation with the FGFWFC.

Restoration of the Kissimmee River also is an essential component of the overall plan to reduce phosphorus loadings in the Kissimmee–Okeechobee–Everglades ecosystem. During the 1960's, channelization of the river enhanced flood protection and contributed to the rapid expansion of intensive dairy-cattle operations in the lower basin. Channelization degraded the natural phosphorus removal capabilities of the river's historic oxbows and wetlands. Changes in land use and loss of the Kissimmee River wetland system contributed to increased phosphorus loadings to the lake (Lamonds, 1975). In 1987, the SFWMD, in cooperation with the FDER and the FGFWFC, completed phase 1 of a demonstration project to restore some of the natural wetland functions along a 12-mile reach of the river. One of these natural functions is the uptake and removal of phosphorus by marsh vegetation. By diverting floodwaters through historic oxbows and by creating overland sheet flow across adjacent river marshlands, the natural flow regime will help to restore wildlife habitat and to reduce phosphorus loading to Lake Okeechobee. A detailed physical model of the river is being developed by the University of California in cooperation with the SFWMD. Results from the testing of the physical model will be combined with field data collected in the reach of the river that is being restored to develop and calibrate a numerical model of the river. This numerical model, in turn, will be used to simulate riverflow conditions under various future restoration options.

Nitrogen Control

Reduction of nitrogen inflows into the lake focuses on the highly productive agricultural region known as the EAA located south of the lake. Nitrogen-rich organic (peat) soils and the warm subtropical climate permit year-round farming of sugarcane, rice, and winter-vegetable crops; however, these low-lying areas require extensive drainage in the wet season and irrigation during the dry season. The EAA contributes about 26 percent of the total nitrogen load to the lake, although it contributes only 9 percent of the water inflow (fig. 30).

In 1979, the SFWMD instituted a revised operating schedule for the water-control structures located on the southern shore of the lake. Known as the Interim Action Plan (IAP), the operating schedule was intended to divert nitrogen-enriched EAA surface runoff away from the lake and to route it south to the Water Conservation Areas and the Everglades National Park (fig. 26). The IAP might be suspended to protect the EAA from flooding during major storms or to store water in the lake during droughts. Back-pumping from the EAA to the lake under these emergency conditions has occurred three times since 1979—twice for water-supply purposes and once for flood control. Even during periods of backpumping, intensive monitoring of nutrient levels is used to choose pumping periods that will minimize nitrogen loadings to the lake. Although not achieving its goal of a 90-percent reduction in nitrogen loading from the EAA, the EAA has significantly reduced lakewide nitrogen concentrations since 1980 (fig. 27).

The IAP does, however, have several major drawbacks. As a natural biological filter, the 1,500-mi² Everglades marsh comprising the Water Conservation Areas assimilates nutrients more efficiently than does the lake, but it, too, has shown recent signs of degradation and loss of its assimilative capacity. Phosphorus-uptake and plant-vegetation studies conducted by the SFWMD and the National Park Service over the past decade show that excessive nutrient loading of the sawgrass marsh eventually alters plant vegetation, causes changes in the species composition of marsh algae (the base of the Everglades food chain), lowers dissolved oxygen levels, and ultimately reduces the natural phosphorus retention capability of the ecosystem (Davis and Harris, 1978; Davis, 1984; Flora and others, 1986; Swift and Nicholas, 1987). To date, nutrients have effected more than 20,000 acres of Everglades marsh. A second drawback is that more water is lost through evapotranspiration when it is stored within the shallow sawgrass marshes of the Water Conservation Areas than when it is stored in southern Florida's deepest, most efficient reservoir—Lake Okeechobee.

A proposal to mitigate affects of the IAP on the Water Conservation Areas and the Everglades National Park involves diverting EAA runoff to the Holey Land tract, which is a 40-mi² marsh south of the EAA (fig. 26). This former Everglades sawgrass marsh area has been degraded by overdrainage and muck fires, which have affected its vegetation and soil characteristics, thus greatly reducing the natural resource value of the marsh. To restore the tract to a more natural Everglades condition, the SFWMD, in cooperation with FDER and the FGFWFC, began construction in 1985 of pump stations, canals, levees, and culverts to redirect water flow into the overdrained marsh. Diversion of nutrient-rich EAA runoff into the tract would alter the proposed Holey Land marsh vegetation in much the same way it has altered vegetation in the Water Conservation Areas. Consequently, LOTAC recommended that any plans to use the Holey Land tract to reduce IAP effects be designed within the constraints of habitat-restoration objectives developed by the FGFWFC.

Several other measures also have been taken in the EAA to reduce nitrogen inflows into Lake Okeechobee. Hydraulic constrictions in the Miami, North New River, and Hillsboro Canals have been removed to improve the conveyance capacity of these primary canals to route more water southward, thereby reducing the potential for flood-control backpumping into the lake. The diversion of nutrient-enriched waters in the western part of the EAA away from the lake to the Caloosahatchee River during major storms has been considered by the SFWMD. Water that normally would be backpumped into the lake would be diverted to the river under this plan, thus reducing nutrient loading to the lake from the western EAA by more than 50 percent. Measures that involve water diversions and reduced backpumping unfortunately also reduce water inflows to the lake, thereby reducing its capability to function as a water-supply reservoir. One way of increasing water inflow while reducing nutrient loading to the lake would be to backpump low-nutrient water from a largely undeveloped area east of the lake. Backpumping would dilute nutrient loadings to the lake if the current quality of the water in the area can be maintained in the future.

SUMMARY AND CONCLUSIONS

The August 1986 algae bloom was the largest ever recorded in Lake Okeechobee and stimulated government and public awareness of the need to reduce nutrient loading to the lake. As a result of the bloom, previously identified control measures received support from a broad spectrum of public and private agencies and interest groups. Among the management actions taken or intensified following the bloom are:

- Reduction of phosphorus loading from cattle and dairy operations by implementing best-management practices such as use of alternate fertilizer and feed, fencing cattle away from water courses, and developing onsite wastewater management;
- Restoration of wetlands and oxbows along the Kissimmee River to take advantage of their capability to remove phosphorus;
- Diversion of nitrogen-enriched agricultural runoff away from the lake into managed wetland systems; and
- Improvement of the conveyance capacity of southward-draining canals to reduce flood-control backpumping and to increase diversion of agricultural runoff.

Additional management strategies being considered or studied are:

- Diversion of phosphorus-enriched runoff from cattle and dairy operations to a temporary holding reservoir or to a deep-well injection facility;
- Removal of nutrients by physical harvesting of aquatic weeds and rough-fish species;
- Diversion of nitrogen-enriched agricultural runoff to a restored wetland south of the lake and to the Caloosahatchee River west of the lake; and
- Reduction of nutrient loading by backpumping water from undeveloped wetland areas east of the lake.

The appearance of massive *Anabaena* blooms on the lake during the summer of 1986 may prove to be the catalyst for the implementation of strategies to protect the long-term health and vitality of this multiuse and ecologically unique natural resource.

Epilogue

Passage of the Surface Water Improvement and Management (SWIM) bill by the Florida legislature in 1987 led to the development of a comprehensive regional water-management plan for Lake Okeechobee (Swift and others, 1989) that was approved by the SFWMD's Governing board on March 1, 1989. Utilizing a modification of Vollenweider's (1976) nutrient-loading model, the plan sets forth performance standards for all tributary inflows based on a goal of reducing phosphorus loading to the lake by 40 percent by 1992. All lake inflows will be required to meet the 0.18 mg/L (milligrams per liter) performance standard for total phosphorus or their present discharge concentration, whichever is less. Basins that exceed the 0.18 mg/L standard must reduce their phosphorus concentrations and achieve compliance by 1991. The plan identifies priority basins that must meet the 0.18 mg/L standard and are required to obtain water-management permits from the SFWMD. The FDER will enforce effluent discharges from all dairy operations through implementation of the "Dairy Rule" and BMP's within the Taylor Creek–Nubbin Slough and the Kissimmee River basins. The SFWMD will monitor dairy-discharge water quality to ensure that BMP's are working. All non-dairy land uses that discharge to the lake also must meet the 0.18 mg/L performance standard and obtain permits. In 1989, the Florida legislature designated $5.5 million to fund SWIM enforcement, BMP monitoring, lake research projects, and public education programs for Lake Okeechobee.

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FOR ADDITIONAL INFORMATION

David R. Swift, South Florida Water Management District, P.O. Box 24680, West Palm Beach, FL 33416

Irwin H. Kantrowitz, U.S. Geological Survey, 227 North Bronough Street, Suite 3015, Tallahassee, FL 32301

BONNEVILLE DAM—FIFTY YEARS OF PUBLIC SERVICE

By William F. Willingham[1] and Larry L. Hubbard[2]

The 50th anniversary of the Bonneville Dam on the Columbia River (fig. 31) in 1987 brought public attention to the economic benefits that it provides and to the designers, engineers, and workers who constructed the dam. The Columbia River averages 2 feet of fall per mile over its 1,200-mile length, and streamflow averages 262,000 ft^3/s (cubic feet per second) at its mouth. It has the largest potential for producing hydroelectric power on the North American continent, and has 40 percent of the Nation's total potential for hydropower (Willingham, 1987). The Bonneville Dam was the first Federal dam to start harnessing this power.

The Bonneville Dam, which was constructed by the U.S. Army Corps of Engineers between 1933 and 1937, was designed to employ large numbers of out-of-work laborers and engineers during the Depression and to produce long-term hydropower and navigation benefits (fig. 32). In compliance with House Document 308 (U.S. Congress, 1926), the Corps of Engineers prepared the landmark 308 report recommending construction of the Bonneville Dam as part of a 10-dam project to tap the enormous hydropower potential of the Columbia River.

In August 1937, President Roosevelt signed the Bonneville Power Act, which assigned the responsibility for generating power to the Corps of Engineers and also created a new agency—the Bonneville Power Administration (BPA)—to market and distribute the power. By December 1939, the BPA had completed its first high-tension transmission lines between the Bonneville Dam and the Portland metropolitan area. In 1940, the BPA was assigned to market and distribute power produced by the Grand Coulee Dam. In response to the high power demands during World War II, the BPA integrated the power produced by the Bonneville Dam with that produced by other public and private power systems to become the chief distributor of electric power in the Northwest. Revenues from the sale of the hydropower are used to repay the costs of constructing and operating Federal hydropower projects to the U.S. Treasury and to cover the costs of BPA marketing and distributing the power. The BPA marketing and transmission system has continued to grow, and excess power produced from the Columbia River during high flows is available to utilities in southern California.

Engineering and building the Bonneville Dam in the heart of the Columbia River Gorge was a monumental task. The complex geology of the gorge, combined with the great volume of the swift Columbia River, presented many complex problems of site selection, construction techniques, and equipment design. The project consisted of a spillway dam, a powerhouse, a navigation lock, and fish-passage facilities.

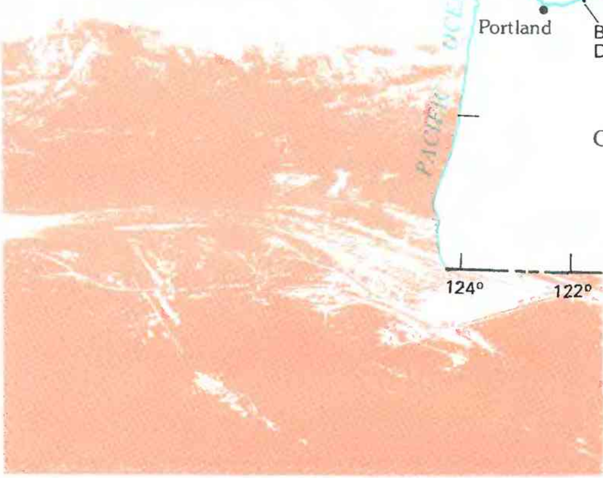
The spillway structure stretches 1,450 feet and contains 18 vertical-lift gates 50 feet wide. When the gates are raised to their full open position, the spillway can pass a discharge of 1.6 million ft^3/s, which is 37 percent greater than the discharge of the maximum recorded flood of 1894 and 60 percent greater than the 1 million ft^3/s discharge of the flood of May 1948. The width of the dam crest is 132 feet, and the height above the lowest point is 197 feet. Construction of the spillway required that the river be divided in half and that the river flow be directed from each half successively by means of massive timber cofferdams. A U-shaped cofferdam was built to enclose the southern one-half of the spillway section site to allow for construction of the lower part of the spillway and the piers for that section of the dam. Workers then removed the cofferdam, thus permitting the river to flow between the piers and over the uncompleted crest sections while another cofferdam was constructed to permit completion of the northern section of the dam (fig. 33). Following completion of the entire northern section, another cofferdam was built over the crest section between the piers of the uncompleted southern part so that the crest could be brought to final elevation.

The original powerhouse, which was 1,027 feet long and 190 feet both wide and high, was designed to support two hydroelectric-generating units and a substructure for four additional units. By 1943, regional power demands led to the expansion of the substructure to support 10 units capable of generating 558,000 kilowatts. As additional hydropower projects were built upstream, the flow of the Columbia became more controlled, and the original powerhouse could not handle all the released water. The BPA requested that the Corps of Engineers build a second powerhouse on the Washington shore.

To make room for the second powerhouse, the Corps of Engineers had to relocate the town of North Bonneville, Wash., and to remove carefully the artifacts from an important archaeological site. The addition of the new powerhouse more than doubled the previous electric output of the project. When the new powerhouse was completed in 1983, the Bonneville Dam combined the oldest and newest Federal powerplants on the Columbia.

At the time of its construction, the navigation lock at the Bonneville Dam was the highest single-lift lock in the world (fig. 34). Located adjacent to the southern end of the powerhouse, the lock measures 500 feet long and 76 feet wide and can accommodate small ocean-going ships and barges up to 8,000 tons. The lock, which has an annual capacity of 13 million tons, served the shipping needs of the Columbia River until the 1980's. To more efficiently handle current and anticipated increases in river traffic, the Corps of Engineers is constructing a larger lock, which will have an annual capacity of 30 million tons; this lock is scheduled to be completed in 1992.

[1]U.S. Corps of Engineers, Portland District. [2]U.S. Geological Survey.



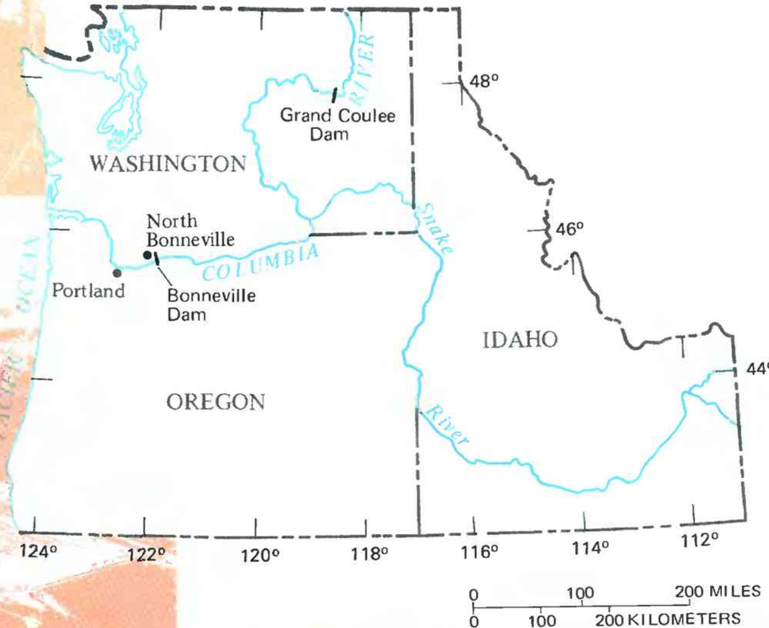


Figure 31. Location of the Bonneville and the Grand Coulee Dams, Columbia River basin, Oregon and Washington.

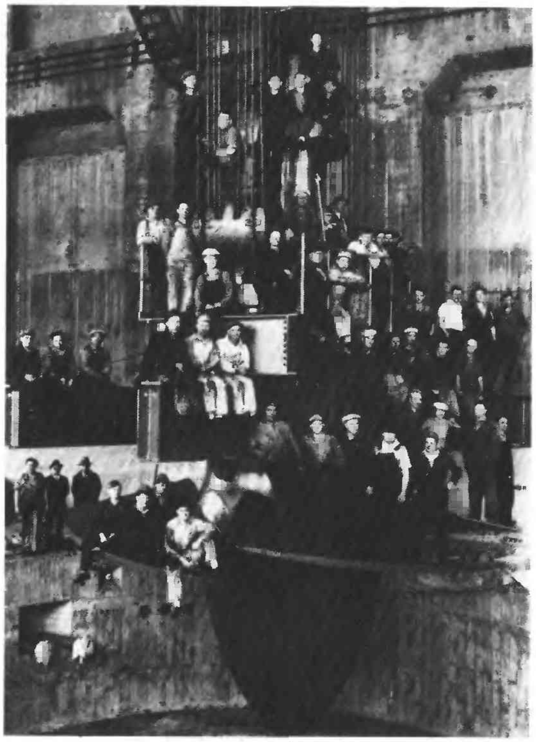


Figure 32. Workers on a turbine impeller being installed in the powerhouse, Bonneville Dam, 1937. (Source: U.S. Army Corps of Engineers.)

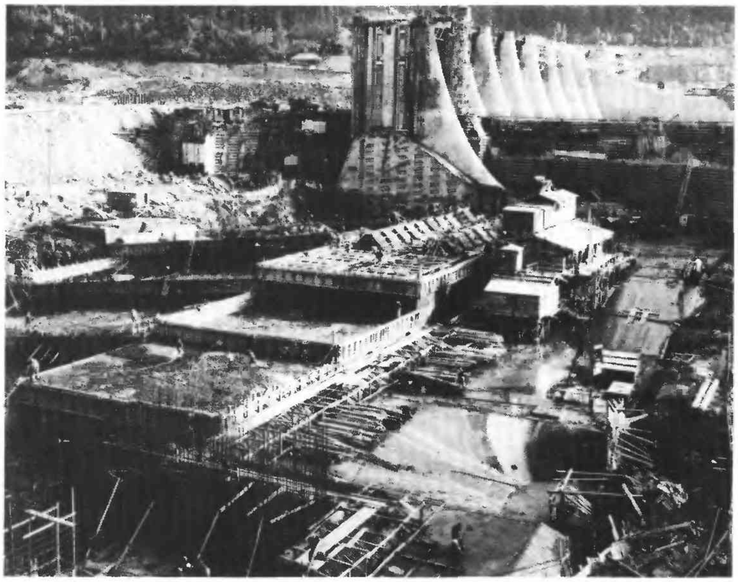


Figure 33. View of the Bonneville Dam northern spillway under construction (the southern spillway is behind the cofferdam), 1935. (Source: U.S. Army Corps of Engineers.)

Figure 34. Aerial view of the Bonneville Dam, 1940. The spillway, the powerhouse, and the fish ladder can be seen from right to left across the complex. (Source: U.S. Army Corps of Engineers.)

The Bonneville Dam also was designed to provide fish-passage facilities for the annual Columbia River runs of anadromous fish. The fish-management system had to accommodate both adult fish migrating upstream and fingerlings headed downstream to the ocean. The principal component of the unprecedented fishways system at Bonneville consists of three fish ladders. They resemble long stairways of pools 16 feet long, 40 feet wide, each 1 foot higher than the last and leading to the 72-foot-high pool behind the dam. Novel collection systems attract the fish migrating upstream to the ladders at the spillway and the powerhouse, and several bypass systems attract the fingerlings migrating downstream to the ladders around the powerhouse turbines. Over the years, the Corps of Engineers has continued to improve the fish-management system.

The Bonneville Dam was an economic investment by the Nation and a wonder of engineering when it was constructed 50 years ago. There is every reason to believe that it can continue to provide vast benefits to the Nation and to serve the people of the Northwest for many years to come.

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FOR ADDITIONAL INFORMATION

William F. Willingham, U.S. Army Corps of Engineers, P.O. Box 2946, Portland, OR 97208

Larry L. Hubbard, U.S. Geological Survey, 10615 SE. Cherry Blossom Drive, Portland, OR 97216

Hydrologic Perspectives on Water Issues

INTRODUCTION

The "Hydrologic Perspectives on Water Issues" part of the 1987 *National Water Summary* provides an introduction to some of the technical, economic, social, and institutional factors that affect water use in various sectors of the economy. These factors influence the amount of water used for various purposes and, as they change over time, influence the trends in water use that are observed in the historical data. Collectively, the five articles in this part provide different perspectives for better understanding the descriptions of water use in the "State Summaries of Water Supply and Use" and provide some explanation of the regional variations in water use observed in the State data. Three of the articles examine trends and associated factors in offstream water use; the fourth describes the increasing emphasis on instream water use; and the fifth discusses the benefits and pitfalls of long-term forecasting of water use.

TRENDS AND ASSOCIATED FACTORS IN OFFSTREAM WATER USE

"Domestic Water Use in the United States, 1960–85" examines changes in domestic water use and in some of the factors thought to affect water use in the home over the past 25 years. Factors thought to influence domestic use include median family income, household size, and the direct cost to households of purchasing water. Median family income, adjusted for inflation, has not changed more than a few percentage points since the 1970's; it is doubtful that this factor has had a major influence on domestic water since the 1960's. Similarly, water use per household appeared to be about the same in 1980 as it was in 1960 because increases in per capita use were offset by corresponding decreases in household size. Perhaps most interesting is the finding that, after adjusting for inflation, water was cheaper in 1985 than it was in 1960. It appears that the direct cost of water to households often is less than the full cost of providing the water to the users. Thus, water may be underpriced in many areas.

"Manufacturing and Mining Water Use in the United States, 1954–83" discusses a large and important water-using sector of the economy—industry. Industries make substantial use of the Nation's water resources for cleaning, cooling, dilution of wastes, transportation, and incorporation into products. Industrial water use is concentrated heavily in only a few kinds of industrial sectors and in a relatively few firms within each sector. The article examines water use in five major manufacturing sectors and four mining sectors. Adjusting for changes in production levels, intake and discharge in 1983 were only one-fourth of what they had been in 1954 as a result of improvements in water-use technology, changes in production, and changes in the law, especially the environmental pollution laws of the 1970's. In particular, the Clean Water Act of 1972 encouraged manufacturers to modify their production processes to reduce the discharge of pollutants by recycling water and adopting water conservation measures. Similarly, higher energy prices of the mid-1970's provided economic incentives to cut back on energy use. In mining, most water use occurs in oil and gas extraction and nonmetallic (chemical and fertilizer) mining, and includes the removal of drainage water from mine workings, which is the largest source of water for ore processing. Saline water also is extracted in the production of oil and gas, and more than 50 percent of the water used in mining is saline. Compared to manufacturing, mining is a relatively small water user and its use has remained relatively constant for the past 20 years.

"Agricultural Water Use in the United States, 1950–85" discusses irrigation and livestock. In 1985, agriculture accounted for 42 percent of all freshwater withdrawals in the United States; 97 percent of the withdrawals was for crop irrigation and 3 percent was for livestock use. Decisions of what, where, and when to irrigate are based on many factors. The most obvious are climate, water-supply costs, crop and livestock prices, competition for water resources by other economic sectors, and public policies. Irrigation water use appears to have peaked for at least three reasons—the cost of additions to surface-water systems has exceeded the agricultural sector's ability to pay, concerns about environmental quality and dam safety have increased costs, and Federal water policy has continued to reduce the level of subsidy of irrigation water supply.

Although livestock water-use withdrawals amount to only 3 percent of the withdrawals for agriculture, livestock production makes up about one-half of agricultural cash receipts. Livestock water uses include drinking water for livestock, evaporation from stockwatering ponds, and uses for sanitation and waste disposal. A rapidly increasing use of water in this category is the production of fish (aquaculture). Factors determining the amounts of water use for livestock production include technical developments in production techniques, marketing practices, and the demand for livestock products.

INSTREAM WATER USE

In times of water shortage, a potential conflict is possible between offstream and instream uses, such as hydropower generation, navigation, recreation, and fish and wildlife needs, that require the water to remain in the stream. The article " Instream Water Use in the United States—Water Laws and Methods for Determining Flow Requirements" provides a brief history of the recognition of instream flows as a beneficial use of water and attempts to quantify the streamflows necessary to support various instream uses.

WATER-USE FORECASTING

"Water-Use Forecasting—Benefits and Capabilities" summarizes a number of issues surrounding attempts to forecast water uses. Although water-use forecasting is a fundamental part of water-resources planning, its accuracy depends upon the ability of the forecasters to anticipate changes in population growth, economic shifts, and institutional modifications, which are beyond the control of water managers. The problem of knowing the unknowable limits the forecaster's ability to estimate accurately future water use. Despite this limitation, forecasts can and will play a significant role in developing water resources.

TRENDS AND ASSOCIATED FACTORS IN OFFSTREAM WATER USE

DOMESTIC WATER USE IN THE UNITED STATES, 1960–85

By John E. Schefter

INTRODUCTION

Over the past quarter-century, steadily increasing incomes have afforded a higher standard of living, which, in turn, has resulted in increased domestic water use even in the face of ever-higher water prices. Although this statement is true, it also is misleading. In the United States, 1985 disposable income per capita (adjusted for inflation) was higher than ever, but the median family income had not changed appreciably since 1970. Domestic water use per capita also was higher than ever, but domestic water use per household was about the same as it was during 1960. Water prices, too, were higher than ever, but they had not kept pace with inflation. Adjusted for inflation, water was cheaper in 1985 than it was in 1965. More water was used during 1985 for domestic purposes, that is for household purposes such as bathing, cooking, and lawn watering, because of increased population and per capita use. Water use per capita increased primarily because our population is living in more but smaller households.

This article examines changes in domestic water use and in some of the factors thought to have influenced domestic use from 1960 through 1985. These factors include median family income, household size (number of persons), and the direct cost to households of purchasing a given quantity of water. Geographic regional differences in water use and in 1985 water and sewer rates also are compared.

For purposes of this discussion, the conterminous United States is divided into three regions (fig. 35)—the humid Northeast; the warmer, humid Southeast; and the mostly arid West. Estimates of water use and of the other variables are presented for each of these regions, for the East as a whole (Northeast and Southeast), and for the United States as a whole (the conterminous States, Alaska, and Hawaii). Although much of the difference in domestic water use per capita among the regions undoubtedly is attributable to climatic differences, the role of climate in domestic water use is not explicitly considered here.

DATA SOURCES

The water-use estimates in this article are from the series of U.S. Geological Survey reports entitled "Estimated Use of Water in the United States." These reports, which have been published every 5 years since 1950, provide estimates of total water withdrawals in each State for five categories of use; they also provide separate estimates of withdrawals for domestic use. Before 1985, domestic use, as reported by the Survey, included losses from supply systems and water withdrawn for public use in addition to residential use—single and multifamily housing. (In this article, the terms "domestic" and "residential" are used interchangeably.) Losses include actual leakage from supply systems as well as accounting losses that result from inaccurate water meters. Public use includes, for example, water for such purposes as firefighting, street washing, and municipal parks and golf courses. To maintain comparability with previous estimates, the estimates of public uses and system losses are included in the 1985 domestic-use estimates. The Survey reports also contain estimates of the population served by public-supply systems.

The domestic water-use estimates in this article do not include water used by self-supplied households. During 1985, about 18 percent of the Nation's total population was self-supplied from private wells and surface-water sources. In the East, 22 percent of the population was self-supplied whereas in the West only 11 percent was self-supplied. Self-supplied households withdrew about 3,300 Mgal/d (million gallons per day) or about 78 gal/d (gallons per day) per capita (Solley and others, 1988).

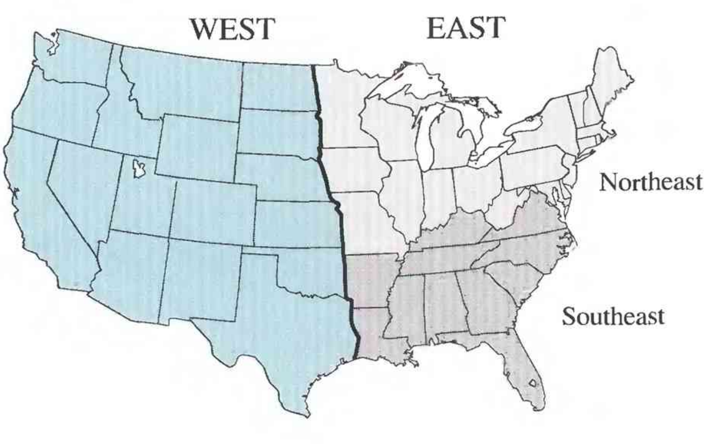

Figure 35. Geographic regions used in domestic water-use article.

Regional income estimates, estimates of household size, estimates of improvements in plumbing facilities, and estimates of population growth rates were either taken directly or derived from publications of the U.S. Bureau of the Census (1962, 1967, 1978, 1980, 1982, 1983, 1986, 1987). Estimates of the U.S. median family income were obtained from the Economic Report of the President (1987). The consumer price index (Economic Report of the President, 1987) was used to adjust income and price estimates for inflation. Unless otherwise noted, all dollar estimates are in 1982 dollars.

The American Water Works Association's (AWWA) series of reports (1973, 1979, 1981, 1986) entitled "Operating Data for Water Utilities" provided data for estimating changes in water rates over time. The AWWA conducted five surveys over the past 20 years (1965, 1970, 1976, 1981, 1984). The 1965 and

1970 surveys applied only to utilities that served 10,000 or more people. A review of these reports identified 59 utilities that responded to each of the five surveys. Thus, it was possible to assemble time-series estimates of the cost of water from 59 municipal water-supply systems. These estimates are of the cost of purchasing 1,000 ft^3/mo (cubic feet per month) [7,480 gal/mo (gallons per month)] or the monthly cost of purchasing about 90, 000 gal/yr (gallons per year).

Because the AWWA data present very limited information on water costs to customers and no information on sewer rates, the U.S. Geological Survey field offices were used to collect supplementary information for the purpose of this article. This information included water-rate schedules for 106 water-supply utilities across the Nation, an estimate of the number of residential customers served by each utility, and sewer-rate schedules for at least one sewer district within each water-supply utility's service area.

The 106 utilities ranged in size from very small ones serving only a few hundred residential customers to very large ones serving hundreds of thousands of residential customers. According to a survey by the U.S. Environmental Protection Agency (1982), one-third of the water-supply systems in the Nation serve less than 100 people each, and 75 percent of them serve less than 1,000 people each. However, the utilities serving less than 1,000 people each serve less than 5 percent of the total population served by water-supply utilities. The 106 utilities discussed here are more representative of the larger utilities serving over 1,000 people each and over 95 percent of the population served by public water-supply systems. The average number of residential customers was 69,000, but one-half of the utilities had under 21,000 customers. The population served averaged 328,000 people, but one-half of the utilities served under 69,000 people. One-fourth of them served under 13,000 people, and one-fourth of the utilities served over 375,000 people. These water and sewer utilities provide their services under a wide variety of rate schedules that range from flat fee schedules, under which payment of a fee entitles the customer to unlimited amounts of water at no additional cost, to block rates, under which the price of water varies with the amount of water used.

PUBLIC-SUPPLY SYSTEM WITHDRAWALS

TOTAL WITHDRAWALS

Public-supply systems withdrew 36,300 Mgal/d for all categories of use in 1985, up 78 percent from 20,400 Mgal/d withdrawn during 1960 (fig. 36). More water was withdrawn daily in the Northeast than in the entire West, although the West had been gaining on the Northeast, especially since 1975. Withdrawals increased 107 percent in the West over the past quarter-century, while they increased only 43 percent in the Northeast. Although the Southeast had the lowest daily rate of withdrawal, the percentage increase in withdrawals was the highest in the East—136 percent.

The 78-percent increase in public-supply system withdrawals is attributable to two factors—an increase in the population served by public-supply systems and an increase in the use of water per person. The population served by public-supply systems increased primarily because of growth in the general population, but also because the proportion of the population served by water utilities had increased. Between 1960 and 1985, the U.S. population grew at an average annual rate of 1.14 percent and the population served increased at a rate of 1.54 percent. Although the West has had a higher annual rate of growth in the general population (1.93 percent) than the Southeast (1.57 percent), the Southeast had the highest rate of growth in population served by utilities (2.68 percent).

While the total population served by public-supply systems increased at an average annual rate of 1.54 percent during the period 1960–85, per capita use increased at an average annual rate of 0.76 percent. The combination of population growth, an increase in the percentage of the population served by public-supply systems, and an increase in per capita use resulted in an average annual rate of increase of

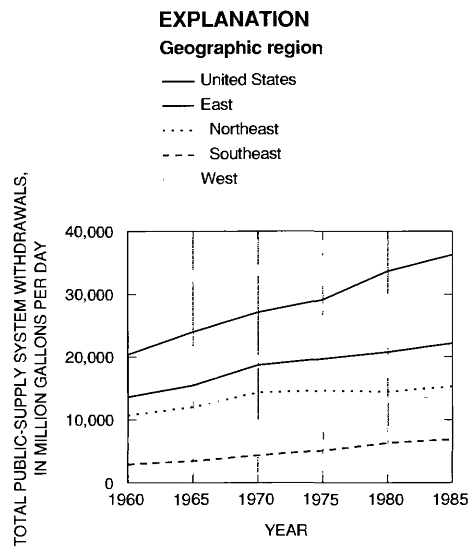

Figure 36. Total withdrawals by public-supply systems in the United States, by geographic region, 1960–85. (Source: Data from MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988.)

2.30 percent in total water withdrawals by public-supply utilities (fig. 37).

Geographically, the Southeast had the highest rate of withdrawal increase (3.43 percent), primarily because of the rapid rate of increase in population served. The Northeast had the lowest rate of increase in withdrawals, even though per capita use grew at a higher rate (0.80 percent) than in the other regions. The West, which had a higher rate of increase in withdrawals than in the East, primarily because of a higher rate of growth in population, had a lower rate of per capita use increase than the other regions.

Although the average annual rate of increase in withdrawals per capita has been lower in the West than in other parts of the Nation, total withdrawals

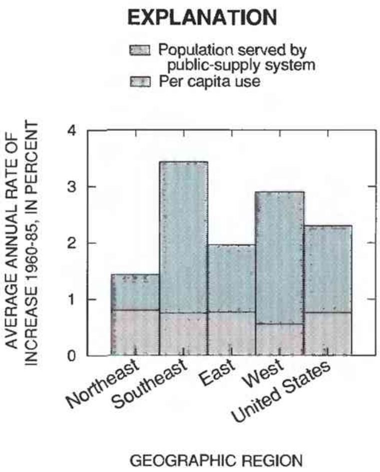

Figure 37. **Average annual rate of increase in total withdrawals by public-supply systems in the United States, by geographic region, 1960–85.** The increase is the sum of average annual rates of increase in the population served and in per capita use. (Source: Data from MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988.)

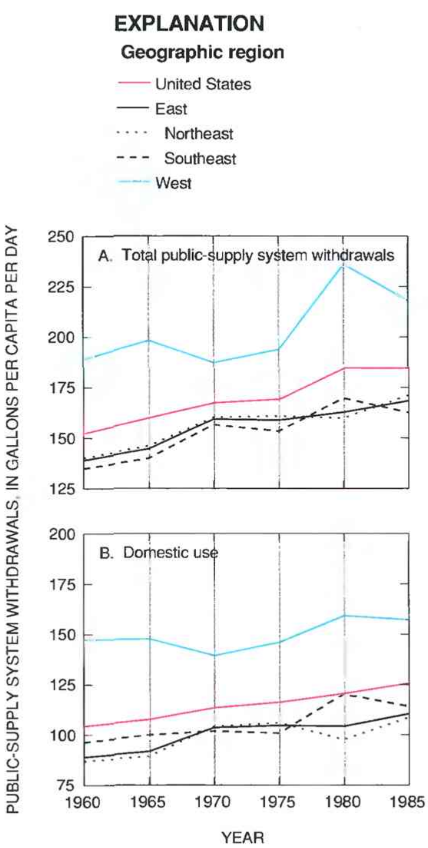

Figure 38. **Average daily per capita water withdrawals by public-supply systems in the United States, by geographic region, 1960–85.** *A*, Total withdrawals from public-supply systems. *B*, Domestic use. (Source: Data from MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988.)

per capita have been substantially higher in the West than in the East over the past quarter-century (fig. 38). Between 1980 and 1985, however, total withdrawals per capita declined in the West and they increased in the Northeast.

Changes in per capita withdrawals in the Southeast follow a pattern similar to those of the West. In both regions, per capita withdrawals were estimated to be higher in 1980 than they were in either 1975 or 1985. This pattern illustrates the pitfalls of basing predictions and statements as to trend on estimates at only two points of time.

Domestic Water Use

Most of the water withdrawn by public-supply systems is delivered for domestic use. Since 1960, domestic use has averaged about two-thirds of total public-supply system withdrawals in the Nation. Domestic use has accounted for a larger percentage of public-supply system withdrawals in the West (72–77 percent) than in the East (64–66 percent) since 1960.

The average annual rate of growth in domestic use over the past quarter-century followed the same regional pattern as that in total public-supply system withdrawals. Domestic deliveries from public-supply systems increased at a faster rate in the Southeast and the West than elsewhere, primarily because of the relatively rapid growth in population in those regions. It is of interest to note, though, that domestic use per capita increased at a slower rate in the Southeast (0.68 percent) and the West (0.26 percent) than in the Northeast (0.90 percent). For the Nation as a whole, the average annual rate of growth of domestic use was about equal to that of the total public-supply system withdrawals (2.28 percent) as a result of a 1.54-percent rate of increase in population served and a 0.74-percent rate of increase in domestic use per capita.

Although domestic use per capita increased at a slower rate in the West than elsewhere, it was larger in the West (fig. 38). In 1960 and 1965, domestic use per capita in the West was higher than total public-supply system withdrawals per capita in the East; in 1985, it was nearly as high.

Before 1985, the U.S. Geological Survey estimates of public-supply deliveries for domestic purposes were combined with deliveries for public uses (municipal parks and golf courses, street washing, fire-fighting, and other public uses) and system losses. In 1985, separate estimates of public uses and losses were made, and they accounted for about 12 percent of domestic deliveries in the Southeast and the West and 22 percent in the Northeast. Deducting public uses and losses from the domestic use estimates resulted in residential use estimates of 85 gal/d per capita in the Northeast and 101 gal/d per capita in the Southeast. The Nation averaged 106 gal/d per capita for residential use, the East averaged 90 gal/d per capita, and the West averaged 138 gal/d per capita.

Based on 1980 data from the U.S. Bureau of the Census, there was an average of 2.75 persons per household in the United States, 2.76 persons per household in the East, and 2.72 in the West. The number of persons per household was slightly higher in the Southeast than in the Northeast (2.77 and

2.75, respectively). Given these estimates of household size and the estimates of residential water use per person, 1985 residential use per household averaged 106,000 gal/yr in the United States, 91,000 gal/yr in the East (85,000 gal/yr in the Northeast and 102,000 gal/yr in the Southeast), and 137,000 gal/yr in the West.

In summary, between 1960 and 1985, total withdrawals by public-supply utilities in the United States increased at about 1.5 times the rate of growth in the population served by utilities. This ratio was higher in the East (1.6) and lower in the West (1.2). Total public-supply system withdrawals per capita have increased at a slower rate in the Southeast and West where populations are growing more rapidly than in the Northeast.

About two-thirds of the total withdrawal by public-supply systems was for domestic use. Deliveries for domestic use have increased at a faster rate in the West and Southeast than in the Northeast due to higher rates of population growth. However, domestic use per capita increased at a slower rate in the Southeast than in the Northeast.

FACTORS AFFECTING DOMESTIC WATER USE

Factors that are considered to affect domestic water use are household size, household income, and cost of water to households. Each of these factors is discussed below.

HOUSEHOLD SIZE

A major influence on domestic water use has been the diminishing size of households and the growth in their number. Average household size in the United States decreased to 2.75 persons in 1980 from 3.30 persons in 1960. Over the same period, the total population increased. Thus, the number of households increased at a faster rate than the general population. Geographically, the number of households increased at 2.4 times the rate of population growth in the Northeast, at 1.8 times the rate of population growth in the Southeast, and at 1.4 times the rate of population growth in the West. Note that domestic water use per capita has increased most rapidly in the Northeast, followed in turn by the Southeast and the West. The decreasing size of households probably has resulted in an increase in water use per person. Smaller households might use more water per person for cooking, for washing dishes, clothes, and cars, and, especially, for lawn and garden irrigation than do larger households. Therefore, smaller households might result in more domestic water use per person but less total water use per household.

HOUSEHOLD INCOME

Higher income households tend to use more water. Higher incomes allow more water-using appliances, larger lawns to be watered, and, in some instances, swimming pools to be filled. Also, there might be a tendency for higher income households to be less concerned about the size of the water bill and to be less frugal in the use of water. This might be offset to some extent by the fact that a higher percentage of lower income households lives in apartments where water service usually is not metered individually and there is little immediate incentive, in the form of a monthly water bill, to use less water.

Many studies have examined the relationship between water use and, among other things, income; Boland and others (1984) summarized about 50 such studies. One measure of the relationship between water use and income is the income elasticity of demand. This measure indicates the percentage increase in water use that is associated with a 1-percent increase in income. Estimates of income elasticity vary considerably, ranging from about 0.2 to 2.0. However, most of the estimates fall between 0.4 and 1.0, which means that a 1-percent increase in income results in a 0.4- to 1-percent increase in water use. Estimates for the East tend to fall closer to the lower part of this range, and for the West toward the upper part. Foster and Beattie (1979) estimated the income elasticity to be between 0.46 and 0.63 for the Nation as a whole.

Estimated income elasticities for the arid West, where lawn irrigation is more prevalent, tend to be greater than 1.0. Studies that have examined lawn-sprinkling demand separate from other domestic uses have found the income elasticity of demand for lawn irrigation to be much higher than for in-house domestic use [see, for example, Howe and Linaweaver, (1967)].

Although higher income households tend to use more water than lower income households, it is doubtful that changes in income levels have had much effect on average domestic water use per household since 1970. Family incomes have increased very little, after adjusting for inflation. Household incomes have increased even less (all families are households, but not all households, as defined by the U.S. Bureau of the Census, are families). The biggest change in incomes from 1960 to 1985 occurred during the 1960's.

Between 1959 and 1979, the median income, adjusted for inflation, of U.S. families increased 41 percent. The increase was greatest in the Southeast (66.6 percent) and smallest in the Northeast (38.5 percent), although the Southeast still had the lowest and the Northeast the highest median family income. The increase for the East as a whole (42.6 percent) was slightly greater than that for the West (40.9 percent).

Between 1969 and 1979, the rate of increase in median family income slowed considerably, and the median family income increased only 5 percent for the Nation, compared to about 35 percent during the 1960's. Geographically, the Southeast fared better with a 12-percent increase between 1969 and 1979 in contrast to a 2.5-percent increase in the Northeast and a 7.4-percent increase in the West during that period.

For the Nation as a whole, median family income (adjusted for inflation) peaked in 1973 and fluctuated considerably between then and 1985 (fig. 39). In 1985, it was only slightly higher, in constant (1982) dollars, than in 1970. The U.S. median family income was virtually the same in each of the years since 1970 for which the U.S. Geological Survey has published water-use estimates.

The largest effect of generally higher incomes on domestic water use probably occurred at the lower end of the income scale and, especially, during the 1960's. During that decade there was substantial improvement in the plumbing facilities of housing units, especially in the Southeast. In 1960, 13 percent of the housing units in the Nation lacked complete plumbing facilities. A housing unit is considered by the U.S. Bureau of the Census to have complete plumbing facilities if it has hot and cold running water, a flush toilet, and a bathtub (or shower) for the exclusive use of the occupants. By 1970, less than 6 percent of the occupied, year-round housing units lacked complete plumbing, and by 1980 only about 2 percent did so. The biggest improvement during the 1970's occurred in the Southeast where the percentage of housing units without complete plumbing dropped to 3.5 percent in 1980 from 12.5 percent a decade earlier. In 1980, 1.9 percent of the households in the Northeast and 1.5 percent of those in the West still lacked complete plumbing facilities, down from 3.9 and 3.4 percent, respectively, in 1970.

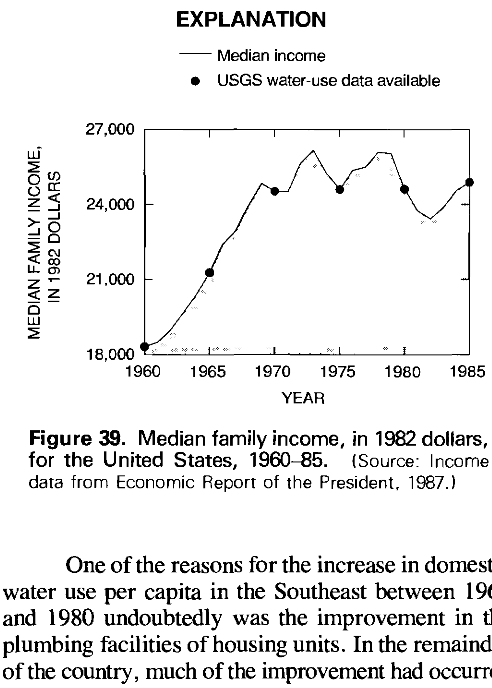

Figure 39. Median family income, in 1982 dollars, for the United States, 1960–85. (Source: Income data from Economic Report of the President, 1987.)

One of the reasons for the increase in domestic water use per capita in the Southeast between 1960 and 1980 undoubtedly was the improvement in the plumbing facilities of housing units. In the remainder of the country, much of the improvement had occurred before 1970. Some of this improvement most likely occurred in housing units not supplied by public-supply systems, and some probably occurred as the result of the development of public-supply systems in rural areas.

Improved housing facilities are one result of higher incomes. Higher incomes also make possible more water-using appliances such as dishwashers, but it is not evident that such appliances greatly increase household water use. Moreover, many of the appliances already were in homes by 1960. The percentage of households owning a clotheswasher (74 percent) did not change between 1960 and 1985 (U.S. Bureau of the Census, 1962, p. 6; 1987, p. 826). As noted previously, another result of higher incomes is simply more use of water for the same purposes, especially if households purchase the water on a volume basis.

Cost of Water to Households

Not all households served by public-supply systems purchase their water on a volume basis. Some systems do not meter the water used by any of their residential customers, and some meter only part of their residential customers. Even those systems that meter all residential customers do not necessarily individually meter all households because some residential customers (and meters) might serve more than one household.

Using the results of a U.S. Environmental Protection Agency (1982) survey, it is estimated that 20 percent of the public-supply systems in the Nation, with 7 percent of the population served by such systems, do not charge any of their residential customers on a volume basis for any of the water they use. Some of these systems charge a flat fee regardless of the amount of water used, some base their water bill on a non-use measure such as residential lot frontage or the number of water-using fixtures in the residence, and some that provide water in conjunction with other services (such as mobile home parks with their own water systems) do not bill for water separately. These systems typically do not meter the water used by their individual customers.

Some public-supply systems meter only a portion of their residential customers. The water-supply systems serving areas in or around, for example, Denver, Fresno, Greeley, New York City, Reno, Sacramento, Saint Louis, and Schenectady did not meter most of their residential customers in 1984 and thus were not charging them on a volume basis for water used.

Those systems that meter all residential customers do not meter all households. Some households reside in structures containing more than one housing unit, and those units often are not metered individually. The U.S. Bureau of the Census estimated that, in 1980, 34 percent of the housing units in the Nation were in multifamily structures and 18 percent of them were in structures containing five or more units. An unknown, but surely very large, percentage of housing units in multifamily structures is not metered individually, and the households residing in them do not purchase water on a volume basis.

Utilities that sell water on a volume basis do so under a variety of rate schedules. Most such utilities also have a service charge that households must pay regardless of the amount of water used, and some utilities include the first few thousand gallons of water as part of the service charge at no additional cost. Some utilities charge the same price per unit (gallons or cubic feet) of water used regardless of the amount used during the billing period. However, under most rate schedules, the price per unit changes (increases or decreases) if the amount of water used during the billing period exceeds some specified amount. In addition, some utilities have different rates for the summer and the winter months. Because of the complexity of the rate schedules, there usually is not a single price that applies to all of the water used by a household. A household's water bill seldom can be calculated by multiplying the total number of gallons used by the price per gallon.

To further complicate calculation of the cost of water to households, the expenditure to purchase the water is only a part of the cost to the household. Households on public water-supply systems usually are served by a public sewer system, and, generally, sewer utilities have a separate rate schedule for disposing of the used water. The variety of rate schedules used by sewer utilities is as wide as that used by water utilities, and some sewer utilities also have winter and summer rates. The direct cost of water to a household is determined by the combined water and sewer rate schedules. In some places, one water utility might serve a large area that has many different sewer utilities, each with its own rate schedule. More commonly, several water utilities provide water within one sewer utility's service area. Thus, the cost of water to households can vary considerably within any one water utility's service area.

In this section, two pieces of information on the cost of water to households are provided—the average water bill for a specified quantity of water, and the price households pay for an additional 1,000 gal of water (that is, the marginal price) provided that it has already purchased a given quantity of water. This marginal price is one of the few variables that a water utility can manipulate to influence both its revenue from the sale of water and the amount of water that households use.

A number of studies have examined the effect of the price of water on the quantity of water used by customers; Boland and others (1984) summarized about 50 such studies. Gibbons (1986), who provided a review of many studies, discussed some of the issues that arise in estimating the effect of price on the demand for water. Schefter and David (1985) and Schefter (1987) provide a more technical discussion of some of the problems that arise in estimating the effect of price on water use when water is sold under block-rate structures that have multiple prices.

Estimates of the price elasticity of demand for residential water vary widely, but in recent years most estimates for average annual water demand fall in the range of −0.2 to −0.7. That is, a 1-percent increase in price is estimated to result in a 0.2- to 0.7-percent decrease in average annual water use.

Outdoor uses of water tend to be more responsive to price than do indoor uses. Studies that have estimated the sensitivity of water use for lawn watering to price or the responsiveness of summer use of water to price have found them to be more responsive than winter or in-house use. Estimated price elasticities for summer use indicate that a 1-percent increase in price results in more than a 1-percent decrease in use, especially in the more humid East. Lawn watering is perhaps used more for supplemental irrigation in the East and is less necessary to keep a lawn alive than in the West. Estimates of the price elasticity of demand for seasonal use are in the range of −1.1 to −1.6 in the East, whereas, for the West, they are in the −0.7 to −0.8 range.

The estimates of the price elasticity of demand appear to be moving closer to zero over time; that is, the estimates appear to indicate that demand is becoming increasingly inelastic. This is probably due to technical reasons involving more accurate estimation techniques.

Water does not command a large share of household income. In 1965, a household that had the U.S. median family income of $21,284 and that used 7,500 gal/mo would have had an estimated average annual water bill of $120, which is equal to 0.6 percent of its income. In 1984, a household that had the U.S. median family income of $25,729 and that used the same amount of water would have had an average annual water bill of $99, which is equal to 0.4 percent of its income. (All dollar estimates are in 1982 dollars.)

The preceding estimates of average annual water bills for households using 7,500 gal/mo are for the 59 utilities that responded to each of the AWWA surveys as described in the section entitled "Data Sources." The populations served by the utilities ranged from 15,000 to 1.4 million in 1984. Twenty-one of the utilities are in the Northeast and served a total of 4.6 million people in 1984, 11 are in the Southeast and served 3.8 million people, and 27 are in the West and served 7.9 million. Statistically, the total withdrawals per capita for these utilities, averaged by geographic region, are not significantly different at, at least, the 95-percent confidence level from the average total withdrawals per capita by public-supply systems in the corresponding regions as estimated by using the U.S. Geological Survey data. The 59 utilities sold water under a variety of rate structures, including flat fee.

Between 1965 and 1984, the average monthly water bill in nominal (unadjusted for inflation) dollars for 7,500 gal/mo increased over 170 percent, to $8.92 from $3.26. (The averages are weighted by the populations served by the utilities.) The largest increase was in the Northeast—191 percent to $9.53 from $3.28; the smallest was in the West where it increased 162 percent to $8.75 in 1984 from $3.33 in 1965. Over this same period, however, the consumer price index increased over 229 percent. Although the average bill for 7,500 gal/mo increased at an average annual rate of 5.3 percent for the 59 utilities over the period, inflation ran at an average annual rate of 6.3 percent.

Adjusted for inflation, the average monthly bill for 7,500 gal (1,000 ft^3/mo) of water, calculated across the 59 utilities, declined at an average annual rate of 1 percent between 1965 and 1984. In every region, the cost to households of 7,500 gal/mo was less in 1984 than it was in 1965 (fig. 40).

The monthly bill did not decrease steadily over the 19-year period. During the first one-half of the 1970's, rate increases outran inflation, and the monthly bill for 7,500 gal increased in constant dollar terms in all regions except the West. During the latter one-half of the 1970's inflation outstripped rate increases and the inflation-adjusted monthly bill plummeted. Between 1981 and 1984, the monthly bill for 7,500 gal increased but it remained below 1965 levels after adjusting for inflation.

Both the largest and the smallest average monthly bills were for utilities in the East—in the Northeast and Southeast, respectively (fig. 40). After 1970, the average monthly bill for 7,500 gal was larger for those in the East, considered as a whole, than in the West, but the difference is not large in any year except 1976. In both 1965 and 1984, the average monthly bills for 7,500 gal were within $1 across all regions.

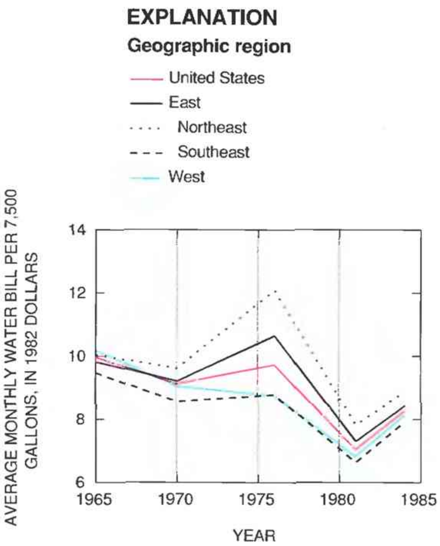

Figure 40. Average monthly water bill for 7,500 gallons (1,000 cubic feet), in 1982 dollars, in the United States, by geographic region, 1965–84. (Source: Data from American Water Works Association, 1973, 1979, 1981, 1986.)

All households do not, of course, use 7,500 gal/mo, and the average monthly water bill generally varies with the amount of water used. The 1985 average monthly bills at different rates of water use were estimated by using the rate schedules from 106 utilities around the Nation (fig. 41). The rate schedules were obtained as described in the section entitled "Data Sources." The estimates are weighted averages, where the weights are the number of residential customers served by the individual utilities. Forty-two of the utilities are in the Northeast and served 3.2 million residential customers during 1985, 21 are in the Southeast and served 0.8 million, and 43 are in the West and served 3.3 million. Estimates of the average monthly bill for water service alone and for combined water and sewer service are graphically shown in figure 41.

The 1985 average monthly bill for 7,500 gal of water, without sewer charges, was higher in the East than in the West, and, within the East, the Northeast was more expensive than the Southeast. This is the same pattern observed using the AWWA data for 1984 (fig. 40). However, the estimates in figure 40 indicate that the West was slightly more expensive than the Southeast whereas figure 41 indicates the opposite. However, at 7,500 gal/mo (90,000gal/yr), the difference between the Southeast and the West is not statistically significant.

When the cost of water alone is considered, the East as a whole and the Northeast separately were both more expensive than the West. This difference is statistically significant at rates of water use up to about 180,000 gal/yr or 2,000 ft³/mo. A significant difference did not exist between the average monthly bills in the Southeast and the West at any rate of water use up to at least 224,000 gal/yr.

Adding the monthly sewer charges to the water bills further blurs the differences between the regions. There was virtually no difference between the regions in the average monthly total bills for 1,000 ft³/mo or 90,000 gal/yr (fig. 41). A statistically significant difference does not exist between the 1985 average monthly total bills of any of the regions at any rate of water use, with two minor exceptions—at rates of water use below 45,000 gal/yr, the Southeast was significantly less expensive than the Northeast, and the Northeast was more expensive than the West.

Sewer costs accounted for a substantial portion of the monthly cost of using water. In the Southeast and the West, sewer costs accounted for between 45 and 50 percent of the average monthly bill at all rates of water use in 1985. In the Northeast, they accounted for 30 percent of the monthly bill at about 90,000 gal/yr and approached 40 percent as water use increased toward 225,000 gal/yr.

The total expenditure or monthly bill for a given rate of water use is a historical accounting. It tells how much a household spent to purchase a given quantity of water, including any fixed fees or service charges that do not vary with water use. The monthly bill also reflects the prices paid per gallon or cubic foot up to any given rate of water use; if an increasing or decreasing block rate structure was in effect, then water could have been purchased under several different prices. A household purchasing water under a flat fee rate structure may have a relatively large monthly bill, but the price for an additional gallon would be zero regardless of the amount of water used. Monthly bills or total expenditure estimates (fig. 41) do not directly indicate the expenditure necessary to purchase an additional unit of water, that is, the marginal price.

The marginal price of water in 1985 to households in the different regions (fig. 42) was estimated by using the same 106 rate schedules used to derive the total expenditure estimates (fig. 41). These estimates of marginal price are weighted averages, where the weights are the number of residential customers served by the individual water-supply utilities. Estimates of the marginal price of water to households with and without the sewer charges are shown in figure 42.

By using regional averages, the marginal price of water in the East in 1985 was very close to that in the West. Without sewer charges, it averaged between $0.81 and $0.83 per 1,000 gal at a rate of use of 45,000 gal/yr and climbed to between $0.90 and $1.00 per 1,000 gal at 224,000 gal/yr. With sewer charges, the marginal price in both the East and the West averaged between $1.50 and $1.60 per 1,000 gal at a 45,000 gal/yr rate of use and between $1.59 and $1.71 per 1,000 gal at 224,000 gal/yr. (All estimates are in 1985 dollars.) Though the marginal price averaged higher in the West than in the East, the difference is not statistically significant at, at least, the 95-percent confidence level.

Within the East, the marginal price, both with and without sewer charges, was 40 percent higher in the Southeast than in the Northeast at use rates of between 45,000 and 180,000 gal/yr. At use rates of between 180,000 and 224,000 gal/yr, the marginal price increased slightly in the Northeast and decreased slightly in the Southeast. The differences in marginal price between the two regions, both with and without sewer charges, are statistically significant.

At use rates of above 45,000 gal/yr, the

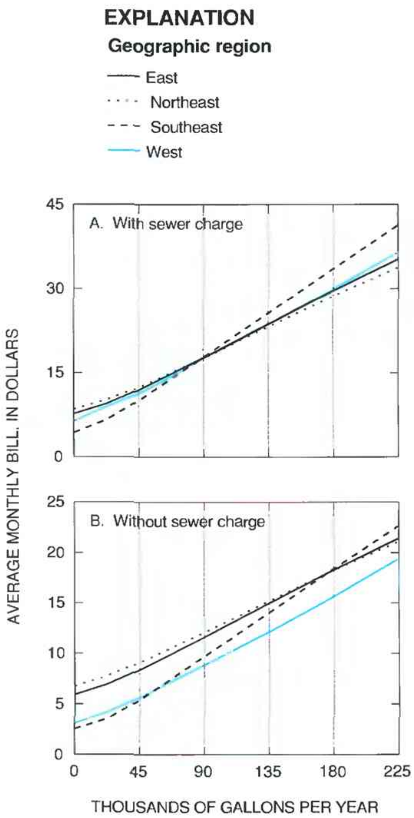

Figure 41. Average monthly household water and sewer bill at different rates of water use in the United States, by geographic region, 1985. *A*, With sewage charge. *B*, Without sewer charge. (Source: Estimated from rate schedules of 106 water utilities.)

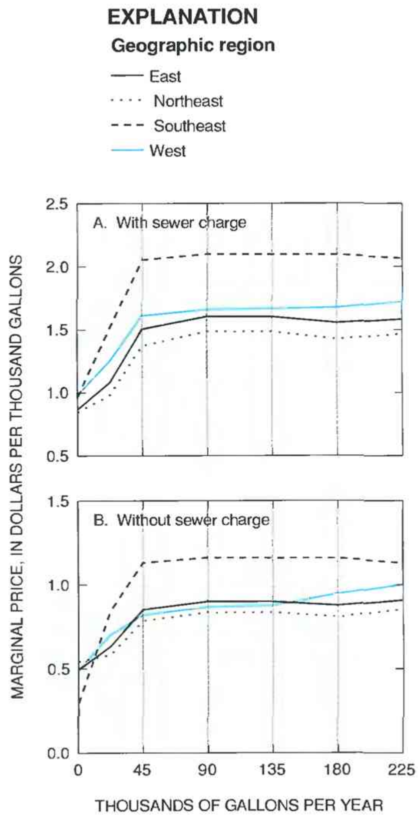

Figure 42. Marginal price of water to households in the United States, by geographic region, 1985. *A*, With sewage charge. *B*, Without sewer charge. (Source: Estimated from rate schedules of 106 water utilities.)

marginal price of water to households was remarkably constant. The rapid increases in marginal price occurred at use rates of below 45,000 gal/yr. Many utilities have a minimum monthly charge that entitles customers to a certain amount of water at zero marginal price. This practice results in relatively low average marginal prices toward the lower end of the use scale.

SUMMARY

Three factors thought to influence domestic water use have been discussed—household size, household income, and the cost of water to households. Adjusted for inflation, the median family income in the United States increased 43 percent between 1960 and 1973 but had declined to such an extent by 1982 that it was less than that in 1968. The median family incomes in 1975, 1980, and 1985 were all within $400, or 1.5 percent, of the 1970 median family income. It is doubtful that changes in income have had a major influence on water use by households using public-water systems.

There is not much information on the change in the cost of water to households over time. Data available for 59 cities indicates that, adjusted for inflation, the cost of purchasing 1,000 ft^3/mo (7,480 gal/mo) was 17 percent lower in 1984 than in 1965. Water rates simply did not keep pace with inflation, especially during the late 1970's. Sewer costs accounted for about 40 percent of the direct cost of water to households in 1985, but data on sewer rate changes over time were not available.

In describing the cost of water to households, a distinction was made between the total expenditure required for a given amount of water and the marginal price paid to use an additional unit of water. Differences across the geographic regions—East (Northeast and Southeast) and West—in the total expenditures for a given quantity of water were quite small in 1985 and, in general, were not statistically significant. The total expenditure for 90,000 gal/yr averaged about the same in all three regions. The marginal price paid for an additional gallon or cubic foot, given that a household is already using, for example, 90,000 gal/yr, was highest in the Southeast and lowest in the Northeast, and it was higher in the West than in the East as a whole.

Household size declined during the 1960's and 1970's. There are no direct measures of the effect of this on household water use, nor are there any direct measures of the changes in household water use over this period. Between 1960 and 1980, domestic water use per capita increased at an average annual rate of 0.7 percent while the number of persons per household decreased at an average annual rate of 0.9 percent. As a crude estimate, this implies that domestic water use per household decreased at an average annual rate of 0.2 percent. If so, then average water use per household was about 4 percent lower in 1980 than in 1960. Given the uncertainty in an estimate based on these broad averages, it is probably best to conclude that domestic water use per household was essentially the same during 1980 as during 1960.

This conclusion, which is based on 20-year averages, masks the contrast between the 1960's and the 1970s. During the 1960's, domestic water use per capita increased at an average annual rate of 0.9 percent while household size decreased at a 0.6 percent annual rate. During the 1970's, domestic water use per capita increased at a slower rate of 0.6-percent while household size decreased at an annual rate of 1.2 percent. This implies that water use per household increased during the 1960's and then declined at an average annual rate of 0.6 percent during the 1970's. If the trends of the 1970's in per capita use and household size have continued into the 1980's, then average water use per household (not per capita) was lower in 1985 than it was a quarter-century earlier.

CONCLUSIONS

Domestic water use per capita was higher during 1985 than during 1960, but it is not evident that domestic use per household increased over that period. During 1980, domestic water use per occupied housing unit in the United States was within 4 percent of the use per unit in 1960.

After adjusting for inflation, water alone was cheaper in 1985 than it was in 1965. Households also must pay the cost of disposing of the water, and sewer costs accounted for about 40 percent of the households' average water bill in 1985. Because information on sewer costs to households over time was not available, it was not possible to get an accurate estimate of changes in the total direct cost of water to households over time.

The household water and sewer bill represents only the direct cost of water to households, and, for several reasons, it could be somewhat misleading as an indicator of the full cost of water to households. First, in some areas served by government-owned systems, a part of the water or sewer costs might be paid through taxes. Second, some utilities, especially government-owned ones, do not price water sufficiently high to recover the capital costs of providing the water (Congressional Budget Office, 1987). Third, most water-supply utilities do not purchase the raw water. They pay only pumping, treatment, and distribution costs; the raw water is considered to be a free good. In some instances, however, the raw water is not really free or costless. Its withdrawal now imposes costs on other water users, either now or in the future. The withdrawal of ground water at a rate faster than an aquifer is recharged could mean that someday an alternative water source will have to be found. The withdrawal of more surface water by one utility could mean that other water users might have less water available and will have to either make do with less water or seek an alternative source. In either instance, a cost is associated with using the water now. In some instances, water has scarcity value; however, this value usually is not considered in pricing the water. For these reasons, the direct cost of water to households often is less than the full cost of providing the water. Water undoubtedly is underpriced in many areas.

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FOR ADDITIONAL INFORMATION

John E. Schefter, U.S. Geological Survey, 410 National Center, Reston, VA 22092

TRENDS AND ASSOCIATED FACTORS IN OFFSTREAM WATER USE

MANUFACTURING AND MINING WATER USE IN THE UNITED STATES, 1954–83

By Elizabeth L. David[1]

INTRODUCTION

Industries make substantial demands on the Nation's water resources. They use water for cleaning, cooling, dilution, transportation, and incorporation into products. Their water demands are met mostly by withdrawing water from surface- and ground-water sources and by recycling that water many times; for example, during 1983, the five major manufacturing water-using sectors withdrew about 27,500 Mgal/d (million gallons per day), but some of this quantity was recycled a number of times for a gross water use of 92,700 Mgal/d. In the same year, the mining sector withdrew about 3,280 Mgal/d and had a gross water use of about 9,120 Mgal/d.

Industrial water use is concentrated heavily in only a few kinds of industrial sectors and in a few firms within each sector. This article discusses how much water is used and how much can be expected to be required in the future by the five major water-using manufacturing sectors (chemicals and allied products, paper and allied products, petroleum refining, steel processing, and food processing) and the four major water-using mining sectors (oil and gas extraction; nonmetallic minerals mining, except fuels; coal mining; and metal mining).

Water used by these industries is defined by the following three general terms. (1) Water intake, which is the quantity of water either withdrawn from a natural water source (ground- or surface-water withdrawals) or delivered by a public-supply system and is used for all processes within the industry. (2) Water discharge, which is the quantity of water that is discharged, or returned, to a surface- or ground-water source or to another entity (usually a municipal wastewater treatment plant) and thus becomes available for further use. (3) Gross water use, which is an estimate of the total quantity of water used by a firm. For example, a firm withdraws a gallon of water and reuses it many times by recirculating it as cooling water or treating it and reusing it as process water. Gross water use, then, is a measure of the quantity of water that would have been required if no water had been recirculated or reused.

Information about trends in industrial water use is available for the period 1954 to 1983 from the "Census of Manufactures—Water Use in Manufacturing" and the "Census of Mineral Industries—Water Use in Mineral Industries," both of which are published by the U.S. Bureau of the Census at 5-year intervals. Information also is available from the series "Estimated Use of Water in the United States" published by the U.S. Geological Survey at 5-year intervals since 1950 (MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988). Because these agencies use different data sources and publish in different years, the data in these reports are not comparable without some adjustments; for example, the Bureau of the Census does not collect data on water use for thermoelectric power generation or consumptive use.

The data used in this article are derived mostly from U.S. Bureau of the Census publications, which report on firms using more than 20 million gallons per year. In discussions of the various manufacturing and mining processes, comparisons are made of water use per unit of production to compensate for variations in industrial output. Coefficients to adjust 1983 statistics are published by the U.S. Department of Commerce, Bureau of Economic Analysis (1983, 1985). Also, the Bureau of the Census has aggregated regional statistics by different State groupings and by water-resources regions (fig. 43).

MANUFACTURING WATER USE

During 1983, 3 percent of the nearly 358,000 manufacturing firms in the United States accounted for more than 95 percent of the water used in manufacturing; of the five major manufacturing sectors, 10 percent of those firms provided more than half of the industrial employment and accounted for 99 percent of the water use (U.S. Bureau of the Census, 1986a, p. 5). In that same year, the five major water-using manufacturing sectors had a gross water use of about 92,700 Mgal/d. That amount represented an intake of about 27,500 Mgal/d, reuse of the water several times within the plant, and discharge of about 24,400 Mgal/d. About 60 percent of the intake was self-supplied from streams and lakes; the remainder was about equally divided among ground water, tidewater, and public-supply deliveries.

Manufacturing water use peaked in the late-1970's. Gross water use, which had increased annually by about 3,000 Mgal/d between 1954 and 1973, plateaued at about 122,000 Mgal/d in the late-1970's and declined by 29,300 Mgal/d between 1978 and 1983. Total intake and total discharge peaked in the late 1960's at about 42,400 Mgal/d and 39,100 Mgal/d, respectively; 15 years later the annual total intake had decreased to about 27,500 Mgal/d and the annual discharge had decreased to about 24,400 Mgal/d. (See table 2.)

Although the decrease in gross water use by the manufacturing sector occurred between 1968 and 1983, the quantity of water used per unit of production had decreased consistently since about 1960. Gross water use per unit of production, which stayed relatively constant in the 1950's, declined by about 20 percent in the 1960's and by 66 percent in the

[1]Wisconsin Department of Natural Resources.

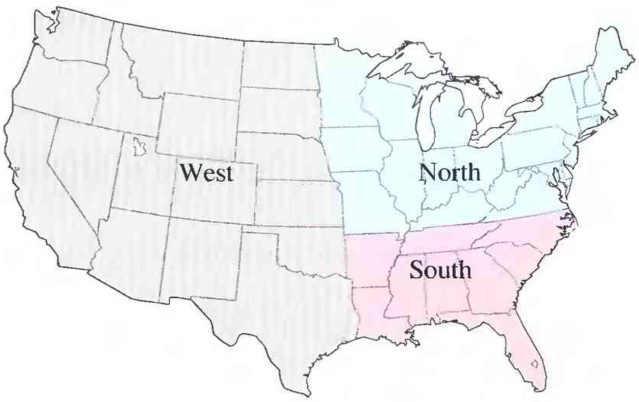

Figure 43. Geographic regions used in manufacturing and mining water-use article. Before 1972, the U.S. Bureau of the Census considered Delaware, Kentucky, Maryland, Virginia, and West Virginia to be part of the South, and Iowa and Minnesota to be part of the West. The water-resources regions referenced in this article are shown in the maps in the Supplemental Information part of this volume.

Table 2. Trends in industrial (manufacturing and mining) water use in the United States, 1954–83

[Data in million gallons per day; includes all water sources—surface, ground, fresh, and saline water. NA = not available. Sources: Manufacturing data from U.S. Bureau of the Census, 1956, 1961, 1966, 1971a, 1975, 1981a, 1986a; mining data from U.S. Bureau of the Census, 1957, 1971b, 1976, 1981b, 1985a]

Water use	Quantity of water						
	1954	1959	1964	1968	1973	1978	1983
Manufacturing industry (Five major manufactures water-using sectors)							
Gross (intake plus reuse)	57,600	71,900	81,800	97,800	119,000	122,000	92,700
Intake:							
Total	31,700	33,200	38,400	42,400	41,200	35,600	27,500
Process	8,300	8,600	10,100	11,800	10,700	10,200	8,500
Cooling	23,900	22,200	25,700	27,100	27,200	21,600	16,400
Discharge:							
Total	29,600	31,400	35,900	39,100	38,800	32,000	24,400
Untreated	25,800	24,100	25,500	27,200	21,900	19,100	13,400
Treated	3,760	7,300	10,400	11,900	16,900	12,900	11,000
Mining industry (All sectors)							
Gross (intake plus reuse)	5,950	NA	NA	10,100	10,900	9,740	9,120
Intake:							
Total	1,980	NA	NA	3,860	4,560	4,040	3,280
Process	NA	NA	NA	2,410	2,380	1,860	1,440
Cooling	NA	NA	NA	729	852	814	523
Discharge[1]:							
Total	2,700	NA	NA	3,740	4,400	4,360	2,840
Untreated	NA	NA	NA	2,950	2,390	2,930	907
Treated	NA	NA	NA	792	2,010	2,090	1,930

[1]Volume of water discharged could be greater than water intake because of mine water that is drained and discharged.

1970's. This decline began accelerating between 1973 and 1978, dropping from 914 Mgal/d to 830 Mgal/d, and was even steeper between 1978 and 1983, dropping to 278 Mgal/d (U.S. Bureau of the Census, 1986a, p. 6–7).

Intake and discharge per unit of production began to decline earlier than gross water use did; in fact, manufacturing water withdrawals and discharge per unit of production declined consistently since the mid-1950's when the data were first collected. After correcting for changes in production levels, intake and discharge per unit of production during 1983 were only one-fourth of what they were during 1954 (fig. 44).

These differences in manufacturing water use are the result of three major factors—changes in production, in technology, and in law. All other things being equal, an increase in water use accompanies an increase in production. Changes in technology and more careful use of materials have important effects on the volume of water needed to produce a unit of product. Technological changes occur for a number of reasons. Shifts in relative prices, for example, change the amounts of raw materials required. Higher energy prices in the mid-1970's provided an incentive for firms to cut back on their use of energy. This resulted in a more efficient use of heat, which, in turn, resulted in more efficient use of water, which was the result of increased recycling of the water. Changes in laws and regulations affect water use. The environmental pollution laws of the 1970's, such as the Clean Water Act of 1972, encouraged manufacturers to modify their production processes to reduce the discharge of pollutants by increasing water recycling and by adopting conservation measures. To meet the pollutant discharge limits, firms minimized water use to reduce the volume of effluent that needed treatment. As a result, cooling-water needs were reduced by using more efficient heat exchangers and by recirculating cooling water more frequently. Discharges will continue to cause some pollution problems, but the nature of the problem has changed; for example, although the discharge of degradable, oxygen-demanding waste probably has been reduced considerably, the harder-to-control toxic and hazardous substances are still discharged to the environment.

The demand for water is not independent of its price. Projections of water use cannot be made without also taking into account possible changes in the price of water. Straight-line projections of past trends in water use are inappropriate predictors of future water use inasmuch as the price of water is a major determinant of the demand for water. This is true for agricultural and industrial water users, because those users are accustomed to taking prices into account. It also is true of domestic use; a number of studies have demonstrated that as the price of water increases, domestic water use declines. (For examples, see articles in this volume, "Domestic Water Use in the United States, 1960–85," and "Agricultural Water Use in the United States, 1950–85.")

The price effect can be direct, as when the price of water purchased from a municipality rises. These price effects also can be indirect, as when a change in regulations changes the costs of doing business; for example, as a result of the 1970's clean water legislation, the cost to discharge each gallon of water increased. The requirement that no process water could be discharged into a lake or stream without being treated forced most of the larger manufacturing firms to build their own wastewater-treatment systems. Manufacturers reported capital expenditures for water pollution abatement of more than $1 billion per year during each year between 1974 and 1981 and nearly that much during 1983 (U.S Bureau of the Census, 1980, p. 1; 1986b, p. 1). Although wastewater treatment amounts to less than 5 percent of most firms' total production costs, the cost increase that resulted from the 1970's water pollution abatement legislation was large enough to cause a decrease in water intake and discharge. The money saved by recycling water, such as when process and cooling water is treated and reused instead of being discharged, helped offset the increase in costs of pollution abatement.

As mentioned above, recycling of water within a plant can reduce the quantity of water withdrawn and discharged. The recycled water sometimes can be used for another purpose without treatment, but, in many instances, it needs to be treated before it can be reused. In the mid-1950's, most firms used their water no more than twice (table 3). The petroleum sector had the highest recycling rate, and the steel and the chemicals sectors had the lowest. By 1983, all manufacturing sectors, except food, had almost doubled their recycling rates—petroleum had the highest ratio of gross water use to intake, about 7.5:1, and food, steel, and chemicals were below average, less than 3:1 (U.S. Bureau of the Census, 1986a, p. 6–7).

As a result of the factors discussed above, far less water was used for manufacturing in 1983 than had been predicted a decade or two before. Although necessary, water-use forecasting is difficult. (See article in this volume "Water-Use Forecasting—Benefits and Capabilities.") Specific examples of inaccuracies in water-use forecasting are given in Osborn and others (1986). Those authors compared water-use forecasts for 1980 made by the Senate Select Committee (U.S Congress, Senate Select Committee on National Water Resources, 1959, 1960) and by the U.S. Water Resources Council (1968) to the 1980 water-use estimates published by the U.S. Geological Survey (Solley and others, 1983). For comparison to Osborn and others, a third forecast, based entirely on U.S. Bureau of the Census data, is included here. The Senate Select Committee in 1960 overestimated water intake for 1980 by nearly 2.5 times the reported intake—an estimated 104,000 Mgal/d in comparison to a reported 44,000 Mgal/d. Using Census data and basing the forecast of industrial intake on straight-line extrapolation of water-use changes between 1954 and 1964, would have led to a forecast of 1983 intake of about 200 percent of the 1983 reported intake—53,000 Mgal/d versus 27,000 Mgal/d. The Water Resources Council's 1968 forecast of 1980 manufacturing water use (intake) was 74,000 Mgal/d, which is an overestimate of nearly twice the actual intake reported by the U.S. Geological Survey. As discussed in the sections below that deal with specific manufacturing sectors, it seems likely that, for the foreseeable future, gross water use and use per unit of production will continue to decline in most of these sectors, although probably not as sharply as in the recent past.

Chemical Manufacturing

The chemical manufacturing sector encompasses a great many diverse products and processes. The U.S. Department of Commerce classifies the chemical sector as industrial organics and inorganics; plastic materials and synthetics; agricultural chemicals; drugs; soaps, cleaners, toilet goods, and detergents; paints and allied products; and miscellaneous chemical products. As shown in table 4, firms manufacturing industrial organic chemicals accounted for nearly one-half (4,150 Mgal/d) of the intake water that was used by the chemical sector during 1983. This is in contrast to the 2,420 Mgal/d used for industrial inorganic chemicals, the 1,170 Mgal/d used for plastics and synthetics, and the 836 Mgal/d used for agricultural chemicals.

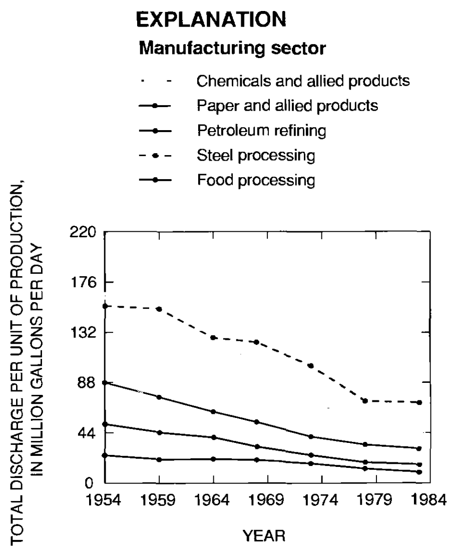

Figure 44. Water discharge per unit of production for five major water-using manufacturing sectors in the United States, 1954–83. (Sources: Data from U.S. Bureau of the Census, 1986a, p. 6-7, and U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 6-7.)

The most prevalent use of water in the chemical industry is for cooling. "Many chemical reactions generate heat, and the reaction vessel is cooled so that the temperature is controlled at the desired limit and the reaction does not get out of control. Other chemical reactions require heat ***" (Kemmer, 1979, p. 26–1). Generally, excess heat is dissipated in cooling towers before the water is returned to the plant. During 1983, water intake in the chemical sector was 9,310 Mgal/d, of which nearly 7,700 Mgal/d was for cooling. Of the 17,000 Mgal/d of water recirculated (the difference between intake and gross water use), 15,500 Mgal/d was used for cooling (U.S. Bureau of the Census, 1986a, p. 41).

Trends in Water Use

Between 1954 and 1973, gross water use, primarily for cooling, increased constantly from about 11,000 Mgal/d to 27,000 Mgal/d and peaked at 34,000 Mgal/d during 1978. By 1983, despite continued increases in production, gross water use had decreased to 26,400 Mgal/d. Meanwhile, water use per unit of production decreased steadily over the period of record (U.S. Bureau of the Census, 1986a, p. 7). This decline in water use per unit of production occurred, in part, because of increased efficiencies in production, especially increased water recycling and, in part, because air cooling had been substituted for some water cooling (S.H. Chiang, University of Pittsburgh, written commun., 1987).

Regional Water Use

When the first water-use statistics were gathered by the U.S. Bureau of the Census in the 1950's, most of the chemical industry was concentrated in the North (fig. 43). This is no longer true. As firms moved from the North to the South water use decreased in the North, and the South needed increasing volumes of water to keep up with the expanding production of its chemical sectors. By 1978, water use by the chemical sector in the South exceeded that of the North. This was the result of increases in the number of firms and increases in production. The West's share of the chemical industry's water use remained constant at

Table 3. Ratio of gross water use to water intake for the manufacturing industry in the United States, 1954–83
[Source: Data from U.S. Bureau of the Census, 1956, 1961, 1966, 1971a, 1975, 1981a, 1986a]

Manufacturing sector	Recycling ratio						
	1954	1959	1964	1968	1973	1978	1983
All manufacturing	1.8	2.2	2.1	2.3	2.9	3.4	3.4
Five major water-using manufacturing sectors:							
Chemical and allied products	1.6	1.6	2.0	2.1	2.7	2.9	2.8
Paper and allied products	2.4	3.1	2.7	2.9	3.4	5.3	3.9
Petroleum refining	3.3	4.4	4.4	5.1	6.4	7.0	7.5
Steel processing	1.3	1.5	1.5	1.6	1.8	1.9	2.5
Food processing	2.1	2.1	1.6	1.7	2.0	1.9	2.2

about one-third until 1973 when it decreased to about 20 percent. Since 1973, it has remained constant (U.S. Bureau of the Census, 1975, p. 58–60; 1981a, p. 31–33; 1986a, p. 24–26).

Pollution Abatement

Wastewater pollution abatement is more expensive for the chemical sector than for other manufacturing sectors, such as food and paper, which use biological treatment systems to neutralize their waste. Activated carbon, one of the most expensive treatment processes, frequently is needed to remove organic chemicals used in the production processes from the effluent. During 1983, the chemical sector spent more on all forms of pollution abatement than any other manufacturing sector. In most categories of pollution abatement expenditures, the chemical sector spent nearly one-third of the total spent by all manufacturing sectors. Operating costs for pollution abatement equipment are particularly high. Table 5 shows pollution abatement expenditures for the manufacturing industry for water pollution abatement and hazardous and nonhazardous solid-waste disposal; the latter includes disposal of the sludges removed in the wastewater-treatment processes (U.S. Bureau of the Census, 1986b, p. 11, 26).

PAPER AND ALLIED PRODUCTS MANUFACTURING

The paper industry manufactures a variety of products that are classified as either paper or paperboard. Paper includes printing papers, such as newsprint; packing papers, such as brown paper and the glassine papers used inside cereal boxes; and tissues, such as toilet tissue, facial tissue, napkins, and towels. Paperboard includes unbleached products,

Table 4. Water use in the chemical and allied products manufacturing industry in the United States, 1983

[Source: Data from U.S. Bureau of the Census, 1986a, p. 10]

Chemical sector subdivision	Water use, in million gallons per day			Recycle ratio (gross water use to intake water)
	Gross (intake plus reuse)	Intake	Discharge	
Industrial chemicals:				
Organics	11,300	4,150	3,780	2.7
Inorganics	5,930	2,420	2,080	2.4
Plastic materials and synthetics	3,930	1,170	1,070	3.4
Agricultural chemicals	3,780	836	556	4.5
Drugs	658	249	238	2.6
Soaps, cleaners, and toilet goods	285	178	167	1.6
Paints and allied products	11	5	5	2.0
Miscellaneous chemical products	490	301	263	1.6
Total	26,400	9,310	8,160	....
Recycle ratio for chemical industry	.....	....	....	2.8

Table 5. Pollution abatement expenditures by the manufacturing industry in the United States, 1983

[Data in million dollars per year. Source: Data from U.S. Bureau of the Census, 1986b]

Manufacturing sector	Expenditures for—							
	Water				Solid waste			
	Capital expenditures				Hazardous		Nonhazardous	
	Total	End-of-line treatment	Production changes	Operating costs	Capital expenditures	Operating costs	Capital expenditures	Operating costs
All manufacturing	$818.9	$718.0	$100.9	$3,258.6	$60.9	$573.5	$136.0	$1,438.9
Five major water-using manufacturing sectors:								
Chemical and allied products	187.4	156.5	30.9	1,013.3	25.6	189.9	23.3	262.1
Paper and allied products	65.9	53.2	12.7	438.1	1.3	9.7	26.6	155.1
Petroleum refining	164.7	146.2	18.5	542.5	7.7	64.5	4.3	67.9
Steel processing	100.2	93.4	6.8	420.8	3.2	82.7	4.6	165.8
Food processing	105.1	95.0	10.1	186.6	.3	3.4	10.6	121.5

such as linerboard and corrugated boxes; bleached products, such as milk cartons, paper plates, and cups; combinations of bleached and unbleached material, such as shipping containers; and construction products, such as construction paper and wet-machine board products, which includes items such as manila folders.

To produce paper, wood is first converted into pulp. This is done by first chipping the logs and then either chemically dissolving the lignin, which binds the fibers, or mechanically rubbing the fibers to separate them, or by a combination of the two. The two most frequently used chemical-pulping processes use alkali to dissolve the wood binders. The pulp then is made into paper or paperboard products.

Water is used in various ways by the paper industry. In the initial process of converting the wood to chips, much water is needed to clean the wood of dirt and debris, to transport the wood from one place to another in the facility, to cool the machinery used for conveyors, to debark, and to chip. In most pulping, the chips are steam cooked, then washed and screened. The resulting pulp, a slurry of about one-half water and one-half fiber, is used either as is without bleaching, or it is bleached.

To make paper, the pulp is further diluted to a concentration of about 1 part fiber to 100 parts water (E.C. Jordan Co., Inc., 1979, p. III–14). This slurry is spread over the belts or cylinders where it is moved along while being drained, heat-dried, and pressed. The water that drains off is recycled and combined with incoming slurry, which saves both fiber and water. A number of additives are used in the papermaking process. Clay might be added to improve brightness and opacity; alum and rosin are added to help size the paper sheets; and dyes are added either in the papermaking process or as a coating applied after the paper has been formed. Other coatings, such as starch, also are used to improve writing and printing characteristics. All these additives could appear in the wastewater that is treated before being discharged.

Trends in Water Use

In the paper industry, gross water use per unit of output has declined over the years (fig. 45). In the early 1950's, a pulping and papermaking mill using a kraft (chemical) process to produce "fine" writing paper needed about 60,000 gal (gallons) of water to produce a ton of paper; about 30 years later, water use per ton of paper was about one-half that amount (E.C. Jordan Co., Inc., 1979, p. III–11). This decrease in water use was accomplished by small adjustments in the pulping and papermaking processes rather than by major changes in production techniques.

Per unit water intake and wastewater discharge also have declined (fig. 44). This has occurred because dry production processes have been substituted for wet processes, as evidenced by the decrease in gross water use per unit of production mentioned above, and more water is now recovered, treated, and reused within the plant. This in-plant treatment reduces the need for intake water, saves chemicals, and, in some instances, reduces heat losses. Reusing in-plant water instead of using intake water does not necessarily decrease the volume of water the plant must treat; rather it changes the point at which the water treatment occurs. Most intake water must be treated before use to remove the dirt and the algae that otherwise might color the paper (U.S. Bureau of the Census, 1986a, p. 7).

Regional Water Use

During 1954, more than one-half of the water used by the paper manufacturing industry was in the North; water use in the North was about twice the use in the South. Since about 1964, however, the South has steadily increased the quantity of water used in paper manufacturing as the industry moved from the North to the South. By 1983, the two regions were about equal; each region accounted for about 40 percent of the water used in the paper industry (U.S. Bureau of the Census, 1961, 1986a). The remaining 20 percent of paper production occurs in the West, principally in the Pacific Northwest, in part, because water, which is so important to paper production, is not as scarce or expensive there.

Pollution Abatement

Wastewater from a pulp or paper mill has about the same characteristics as municipal sewage; consequently, similar treatment systems are used. Typically, a secondary treatment system uses aerobic digestion, in which microorganisms consume the biological wastes to reduce the biochemical oxygen demand in the wastewater. In the simplest system, wastewater is pumped into an aerated lagoon where it remains for 30–60 days before being discharged. However, because a lagoon needs space and relatively warm temperatures, most mills use either trickling filters or an activated sludge process. This industry spends about $66 million on capital expenditures per year, the smallest amount of the five major water-using sectors, and about $438 million on operating costs (table 5).

Petroleum Refining Industry

Petroleum refining involves separating the various components of crude oil and chemically changing them into other products. Distillation and extraction are the processes used to separate the components. Each process requires heat, and many processes require specific temperatures to induce separation and chemical changes.

As in the chemical industry, and in sharp contrast to the paper industry, cooling is the most prevalent use of water in the petroleum industry. Petroleum production used 10 times as much cooling water as process water (fig. 46). However, water is recirculated more times in the petroleum industry than in the chemical industry. The chemical industry reused water on average about three times, whereas, in the petroleum industry, the recycling ratio is about 7.5:1 (table 3). Water reuse has a long history in the petroleum industry. Even during 1954, when no other major manufacturing water-using industries had a ratio of more than 2.4:1, the petroleum industry had a ratio of 3.3:1 (U.S. Bureau of the Census, 1986a, p. 7).

Trends in Water Use

Annual gross water use increased from about 11,000 Mgal/d to nearly 22,000 Mgal/d during the 1950's and 1960's but decreased to about 16,000 Mgal/d during 1983. Intake similarly decreased from about 3,600 Mgal/d to about 2,100 Mgal/d between 1973 and 1983. Water use per unit of production decreased consistently between 1954 and 1983, almost entirely as the result of the decline in cooling water intake; intake per unit of production declined by 30 percent from 1973 to 1983. This decline occurred largely because of the substitution of dry (air) for wet cooling processes (U.S. Bureau of the Census, 1986a, p. 7). However, the most important reason for the decline in water needed by the petroleum industry was production cutbacks. Between 1978 and 1983, production decreased by more than 20 percent—from a production index of 145 to only 118 (using the production levels of 1967 as the base index—1967 = 100).

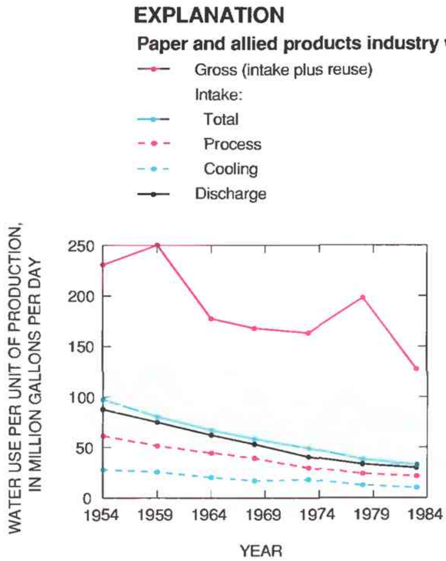

Figure 45. Water use per unit of production in the paper and allied products manufacturing industry in the United States, 1954–83. (Sources: Data from U.S. Bureau of the Census, 1986a, p. 6–7, and U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 6–7.)

Regional Water Use

Until the early 1970's, production was concentrated in the North and the West, which had about 50 percent and 40 percent of total production, respectively. A decade later, the North had maintained its share of about one-half of the production, but the South had grown from about 10 percent to 20 percent, offset by a decline in production in the West. Recently, because production cutbacks have been greater in the South than elsewhere, its share of the industry has fallen to less than 20 percent (U.S. Bureau of the Census, 1975, 1986a).

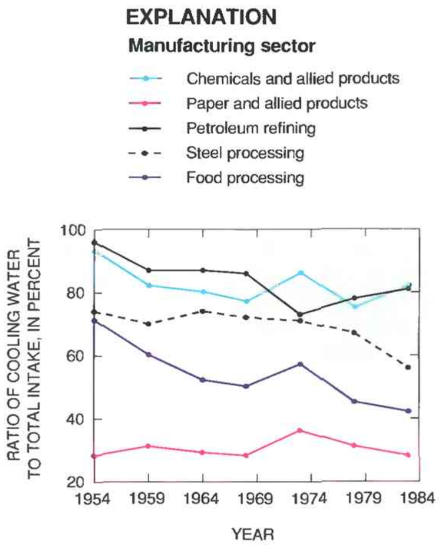

Figure 46. Cooling water intake as a percentage of total water intake in the five major water-using manufacturing sectors in the United States, 1954–83. (Sources: Data from U.S. Bureau of the Census, 1986a, p. 6–7, and U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 6–7.)

Pollution Abatement

The petroleum refining industry, unlike the paper industry, has been unable to change its production methods to meet the water pollution abatement requirements. In 1983, as in 1977, about 90 percent of their capital expenditures was for treatment at the end of the production line rather than for changes in their production processes (table 5; U.S. Bureau of the Census, 1985b, p. 11; 1986b, p. 11).

In 1977, the industry spent $195.6 million for capital equipment for water pollution abatement. Their expenditures for operations and maintenance were $285.2 million, of which some part, perhaps 25 percent, was recovered through the sale or reuse of materials and heat taken from the wastewater (U.S. Bureau of the Census, 1985b, p. 48). During 1983, the industry was still spending about the same amount, $165 million, for capital equipment (U.S. Bureau of the Census, 1986b, p. 11), but their net operations and maintenance expenditures had increased to $543 million (U.S. Bureau of the Census, 1986b, p. 26).

Steel Processing Industry

Geographically, steel production is concentrated to a greater extent than other industries. About 85 percent of the production occurs in western Pennsylvania, Ohio, Indiana, and Michigan. Thus, changes in water use in the steel industry are felt in only a small part of the country.

Trends in Water Use

From 1954 to 1973, the volume of water used by the steel industry increased steadily, directly paralleling the growth in steel production. Gross water use increased from about 14,000 Mgal/d during 1954 to nearly 25,000 Mgal/d during 1973; intake water increased from less than 11,000 Mgal/d during 1954 to about 14,000 Mgal/d during 1973. However, since 1973, world steel production has grown very little. In the United States, raw-steel output peaked at about 150 million tons during 1973 and by 1983, output was less than 90 million tons (U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 111). As a result, water use declined; intake water withdrawals decreased by 50 percent between 1973 and 1983 (table 6).

The drop in the demand for steel is not the only

Table 6. Water use in the steel processing industry in the United States, 1954–83
[Source: Data from U.S. Bureau of the Census, 1956, 1961, 1966, 1971a, 1975, 1981a, 1986a]

Water use	1954	1959	1964	1968	1973	1978	1983
	Quantity of water, in million gallons per day						
Gross (intake plus reuse)	13,600	15,500	18,400	21,300	24,200	17,800	16,100
Intake:							
Total	10,500	10,100	12,600	13,700	13,500	9,290	6,470
Process	2,180	2,390	2,730	3,310	3,350	2,640	2,460
Cooling	7,800	7,140	9,280	9,870	9,620	6,190	3,590
	Recycling ratio						
Process to intake	0.21	0.24	0.22	0.24	0.25	0.28	0.38
Cooling to intake	.74	.70	.74	.72	.71	.67	.56
Gross water use to intake water (recycling)	1.3	1.5	1.5	1.6	1.8	1.9	2.5

cause of the decrease in water use in the industry. Changes in production methods and, more importantly, changes in recycling rates caused substantial reductions in water use per unit of production during the last 30 years. Gross water use, intake, and discharge, which have been corrected for changes in production, decreased consistently until 1978. Between 1959 and 1978, both intake and discharge per unit of production decreased by one-half. Between 1978 and 1983, intake and discharge per unit of production remained constant, and gross water use per unit of production increased. These later changes are attributable to the decreases in production and the changes in production processes described below.

The first step in the steelmaking process is to create iron in a blast furnace. Typically, a blast furnace uses about 11,000 gallons of water per ton of "hot metal" (iron) produced. Iron is turned into steel by one of three processes—open hearth, basic oxygen, or electric arc. The open-hearth process dominated steel production until the mid-1960's. By 1980, the basic oxygen furnace was the dominant process in the large integrated mills (Russell and Vaughan, 1976, p. 104; Barnett and Crandall, 1986, p. 3). More recently steel production processes shifted again from basic oxygen furnaces at large integrated mills to electric arc furnaces at what are called "minimills." In 1970, electric arc furnaces accounted for 20 million tons of steel, or about 15 percent of raw-steel production. Between 1975 and 1985, the share of steel production produced by electric arc furnaces rose from about 20 percent to 35 percent (Barnett and Crandell, 1986, p. 7).

The shift from steelmaking at large integrated mills to the small minimills reduced the need for water in the steelmaking process; for example, the basic oxygen furnace uses a mixture of hot metal (iron produced in a blast furnace that requires 11,000 gal of water per ton of hot metal) and scrap; the ratio is about 70 percent hot metal and 30 percent scrap (iron and steel). In contrast, the minimills, because they use only scrap, need only 2,600 gallons of cooling water per ton of steel produced. Therefore, it takes substantially less water to make a ton of steel in an electric arc furnace than in a basic oxygen furnace (Kemmer, 1979, p. 32-2).

Steel mills also have begun to recycle their process and cooling water through settling ponds and back into the production lines. Between the 1950's and the 1970's, recycling gradually increased, and the rate of gross water use to intake increased from 1.3:1 to 1.9:1. By 1983, recycling had increased by 25 percent to 2.5:1 (table 6; U.S. Bureau of the Census, 1986a, p. 7).

In summary, unless steel production in the United States increases, the total volume of water needed by the steel industry will continue to decrease, as will intake and discharge per unit of production. To the extent that reductions in intake and discharge are caused by production changes rather than by increased recycling, the decline will be limited because the relative share of production at minimills probably will level off at about 40 percent of the market (Stanley Margolin, Network Consulting, Inc., written and oral communs., 1987).

Pollution Abatement

Part of the impetus for the recent increase in recycling is due to the air- and water-quality regulations enacted by the U.S. Environmental Protection Agency (EPA). To meet their air-quality limits, most steel plants have installed wet scrubbers. These scrubbers use substantial quantities of water that can be recycled. The water-quality regulations also affected the industry because the limits imposed on discharged water quality increased the cost of pollution abatement and, thereby, the cost of water use (Earle Young, American Iron and Steel Institute, written commun., 1987). The increased costs put pressure on the firms to reduce water discharge by reusing the water several times before treating it for final discharge. Although the recycling ratio in the steel industry is still not large, it appears likely that there should be a small but steady decline in the volume of water intake and the effluent discharge.

Food Processing Industry

The food processing industry is comprised of firms that process meat and dairy products, preserve fruits and vegetables, make grain mill and bakery products, refine sugar, make confections, produce edible fats and oils, make beverages, and make miscellaneous products, such as canned seafood, packaged fish, and macaroni. Water is used for washing food, such as fruit and vegetables; for transporting food within the factory; for processing food, usually by steaming the raw food in the can or bottle; and for combining with food in making syrups and in canning and preserving. Water also is used to clean processing equipment and food containers; for example, to wash beer bottles returned for refilling (Kemmer, 1979, p. 28-1–28-14).

Sugar production is the largest water user within the food processing industry. Sugar refineries use about one-half of their intake water for cooling and 20 percent or less for processing. Cooling water, which can be reused without treatment other than cool down, is recycled several times for cooling purposes. It also can be reused several times as process water, which requires treatment between uses, before final treatment for discharge. Beverage manufacturers also use large quantities of water for cooling, although they also incorporate water into the products. Beverages, which are sterilized by heating and then rapidly cooled to preserve their flavor, also require more process water than cooling water but in a smaller quantity. In contrast, meat processing and the preservation of fruits and vegetables require more process water—about 60 percent of the intake water—than cooling water (table 7).

Trends in Water Use

Unlike the steel industry, the food industry has not made major changes in its production techniques. However, water use per unit of production has decreased since the mid-1950's when the statistics were first collected. Even though production has increased, total discharge has steadily decreased from its peak of 2,100 Mgal/d during 1968, to 2,000 Mgal/d during 1973, to 1,800 Mgal/d during 1978, and to 1,500 Mgal/d during 1983 (U.S. Bureau of the Census, 1985b, p. 6). This decline probably was accelerated, as noted below, by the water pollution abatement legislation.

Water use in food processing probably will not significantly decline during the 1980's and 1990's; rather, water use per unit of production might decline somewhat, but it will tend to follow production changes. Inasmuch as food processing firms are located where the food is grown, future regional changes in their pattern of water use are unlikely. Thus, the forecast is for a gradual decline in food processing water use with regional water use continuing its existing pattern.

Regional Water Use

Food processing firms are located throughout the Nation. About 85 percent of the water use in this industry is divided about equally between the North (44 percent) and the West (41 percent); the remaining 15 percent occurs in the South. The relative regional water use has remained remarkably constant except between 1954 and 1964 when food processing in the West nearly doubled.

Pollution Abatement

One of the first manufacturing industries to feel the effects of the water pollution abatement legislation of the 1970's was the food industry because some of the first limits established by the EPA pertained to oxygen and solids in discharge water. These discharge limits are strict because most food processing is done during the summer and the fall when streamflow is low and water temperature is high, conditions that contribute to low dissolved-oxygen levels in lakes and rivers. Inasmuch as most food processing wastewater contains organic material that uses oxygen as it decomposes, treatment of the wastewater lessens the depletion of the oxygen levels in the streams receiving the effluent.

The food industry responded to the EPA regulations and reduced its levels of discharge by switching from wet to dry processes and by building or improving wastewater-treatment systems. The change from wet to dry processes is illustrated by the decrease in gross water use per unit of production—from 13.1 gal to 8.6 gal between 1968 and 1983. However, recycling changed very little—it stabilized at 2:1 for those years. Most of the industry's wastewater-treatment systems, which are biologically based and are similar to municipal sewage treatment systems, provide primary and secondary treatment by using either activated sludge or trickling filters. Although the proportion of the total discharge that is treated changed very little, the level of treatment improved significantly (U.S. Bureau of the Census, 1986a, p. 6).

MINING WATER USE

The mining industry is classified into four major sectors by the U.S. Bureau of the Census. In order of their relative water use, these sectors are oil and gas extraction; nonmetallic minerals, except fuels; coal mining; and metal mining. Most water use occurs in the oil and gas extraction and nonmetallic (chemical and fertilizer) minerals mining. Of firms included in the Bureau of the Census statistics, those that have an annual water intake of 20 Mgal/d or more account for about 30 percent of the employment and 50 percent of the value added in the mining industry. This is in contrast to the major water-using manufacturing industries where the Census statistics include a large portion of the water use and output in each industry.

Water use in the mining industry involves both the removal of drainage water from the mines (mine water) and intake water. Water that flows into the mine from surface infiltration or from adjacent aquifers needs to be collected and removed from the mine workings. Some of this mine water is used in the mines to help extract the ore. Once the ore has been brought to the surface, its processing, like all manufacturing, requires water. Water removed from the mine workings is the largest single source of intake water for ore processing, and it provides about one-third of the

Table 7. Water use in the food processing industry in the United States, 1983

[Data in million gallons per day. Source: Data from U.S. Bureau of the Census, 1986a]

Water use	Quantity of water by food type			
	Meat	Fruit and vegetable preservation	Sugar	Beverages
Gross (intake plus reuse)	329	551	1,030	847
Intake:				
Total	255	274	490	244
Process	159	173	145	121
Cooling	52	66	263	[1]82

[1]Estimated from 1978 data; 1983 data not available.

total mining intake. Saline water also is extracted during the production of oil and gas. Oil-field brines often are injected back into the oil and gas reservoir to enhance the recovery of the petroleum products. During 1983, gross water use in the mining industry was about 9,120 Mgal/d, with an intake of about 3,280 Mgal/d (table 2). As compared to manufacturing water uses, the mining industry uses more water than the food processing industry but less than the other major water-using manufacturing sectors. Also in contrast to manufacturing, where 85 percent of the water intake is freshwater, more than 50 percent of the water used in mining during 1983 was saline.

Statistics on water use in mining were collected in 1954 and then again in 1968 and every 5 years thereafter. In mining, unlike the manufacturing industries, both gross water use and intake, which are measured per unit of output, have remained constant during the past 20 years. However, between 1978 and 1983, discharge decreased (fig. 47). Recycling ratios, which are low, average about 3:1 (U.S. Bureau of the Census, 1985a, p. 6).

Inasmuch as the location of mineral deposits determines where mining activities are located, operations are not necessarily concentrated in the water-rich areas of the United States. Substantial volumes of water are used in mining in the water-rich Great Lakes region (Minnesota, Illinois, Michigan, Ohio, and Pennsylvania) and in the South (the South Atlantic–Gulf and Lower Mississippi water-resources regions). Substantial amounts of water also are used in the arid West (States such as Arizona, California, New Mexico, and Texas).

The mining industry has difficult water pollution abatement problems. In the last few years, pollution abatement expenses have increased for wastewater treatment and for sludge disposal. Between 1973 and 1983, annual operating costs increased from $124 million to nearly $500 million (U.S. Bureau of the Census, 1985b, p. 6).

Treatment of mine water involves settling to remove the solids and then treatment to neutralize the acids and to remove heavy metals primarily from coal and sulfide-metal mines. The solids from process water settle out in tailings ponds. In the newer mills, water is recycled from the settling ponds back to the ore processing mill where it is treated and reused. Excess water is treated and discharged to a surface-water source (B.J. Hansen, consultant, written and oral communs., 1987).

Oil and Gas Extraction

In oil and gas extraction, most of the water use is for subsurface injection. Water is pumped into wells to force the residual oil and gas to the surface as part of secondary recovery operations (Kemmer, 1979, p. 43- 3). Processing petroleum products accounts for only 5 percent and cooling about 25 percent of the water intake.

Annual gross water use for oil and gas extraction has remained at about 4,000 Mgal/d since 1968. Intake also has been relatively constant—around 1,600 Mgal/d during 1973, 1978, and 1983. This constancy in the use of water occurred despite a 25-percent increase in production between 1968 and 1978 and a 10-percent decline from 1978 to 1983 (U.S. Bureau of the Census, 1985a, p. 6).

Nonmetallic Minerals

Nonmetallic minerals mining includes stone quarrying, mining for clay, and mining for chemical and fertilizer minerals, such as phosphate, potash, soda, and borate. Water is used in various ways; for example, in phosphate mining, to convert the ore into phosphoric acid for fertilizer, large amounts of water are used to dissolve the phosphate from the host rock. Water also is used for steam to heat the solution to encourage maximum leaching (Kemmer, 1979, p. 29-9).

Between 1968 and 1983, the nonmetals part of the mining industry had an average gross water use of about 2,500 Mgal/d. Average gross water use was 2,300 Mgal/d between 1968 and 1978, but, by 1983, it had increased to 2,700 Mgal/d. However, despite a growth in production of about 25 percent between 1968 and 1983, intake decreased from 1,300 Mgal/d during 1968 to 1,000 Mgal/d during 1983 (U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 5).

Coal

Although coal mining is not a large water user, water is important to extraction and to the separation of the coal from other rock. In underground mining, most of the water is used to suppress dust from the drilling operations. Water under high pressure also is sometimes used to remove the coal from the seam, wash it, and transport it to a collection system. Most of the water used for these purposes comes from seepage into the mines. Once the ore has been brought to the surface, water is used to separate the coal from the associated host rock. Screens are used to dewater the coal before shipping (Kemmer, 1979, p. 29–1, 29–3).

Coal production has been increasing steadily since 1954, and it increased especially quickly between 1978 and 1983 (U.S. Bureau of the Census, 1985a, p. 5). Total water use, however, stayed constant—gross water use at about 343 Mgal/d since 1968 and intake at about 140 Mgal/d since 1972. Discharge, however, followed the increase in production; it increased from 220 Mgal/d during 1978 to 340 Mgal/d during 1983 (U.S. Bureau of the Census, 1985a, p. 7).

(*Note:* Discharge can be greater than water intake because of mine water that is drained and discharged.)

Metals

The metals industry uses extraction techniques similar to those used in coal mining. The metal-bearing rock is ground to a fine flourlike powder by using water as the lubricant. This rock flour is then suspended in a water solution. Magnets are used to extract the iron, and various chemicals are added to the slurry so that other minerals float in a foam that can be skimmed (Kemmer, 1979, p. 29-6).

Until 1983, gross water use in the metals industry was about the same as that used for the oil and gas extraction industry—4,000 Mgal/d and 4,100 Mgal/d, respectively. However, during 1983, the gross water use of 2,000 Mgal/d reflected the sharp drop in metals production. Metals mining, which grew in spurts until 1973, was cut so much that, during 1983, production was no more than it had been during 1954. The production index, which was 73 in 1954, declined from 130 in 1973 to 74 in 1983 (U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 5).

Gross water use per unit of production remained constant between 1968 and 1983. No new technology has changed the volume of water needed in production. What did change are the rates of recycling and discharge. Between 1968 and 1983, discharge per unit of production decreased by one-half (fig. 48). Water use per unit of production also decreased because many metals-mining firms are in the Southwest where water is expensive and because innovations in recycling have resulted from the requirements imposed by the water pollution abatement legislation, which made discharge more expensive and thus forced recycling at new metals mines (B.J. Hansen, consultant, oral commun., 1987).

Although further innovations in water-treatment technology could result in small reductions in discharge, major changes in metals processing are unlikely without a stronger world demand for metals. Inasmuch as international metals prices and, therefore, domestic prices are not expected to rise in the next 20 years or so, water use in the metals industry also is not likely to change (Chase Econometrics' Metals Price Forecast, 1985).

SUMMARY

During 1983, the five major water-using manufacturing industries in the United States had a total intake of about 27,500 Mgal/d, which was reused several times in the plant for a gross water use of about 92,700 Mgal/d; discharge was about 24,400 Mgal/d. About 60 percent of the intake was self-supplied from surface-water sources (lakes and streams), and the remainder was about equally divided among ground water, tidewater, and public-supply deliveries (U.S. Bureau of the Census, 1986a, p. 6, 18). During the same year, the mining industry's water intake was about 3,280 Mgal/d and gross water use was 9,120 Mgal/d.

Of the manufacturing industries, the chemical sector was the largest gross user of water during 1983—26,400 Mgal/d. The three next largest manufacturing sectors together used about the same gross quantity of water—paper and allied products, 21,000 Mgal/d, and petroleum and steel, about 16,000 Mgal/d each. Food processing used the least water—less than 4,100 Mgal/d (U.S. Bureau of the

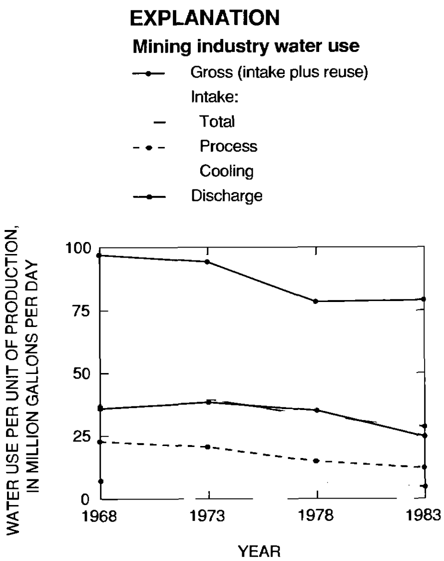

Figure 47. Water use per unit of production in the mining industry in the United States, 1968–83. (Sources: Data from U.S. Bureau of the Census, 1986a, p. 6–7, and U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 6–7.)

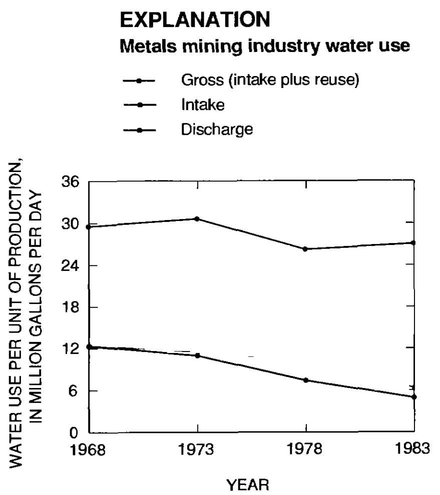

Figure 48. Water use per unit of production in the metals mining component of the mining industry in the United States, 1968–83. (Sources: Data from U.S. Bureau of the Census, 1986a, p. 6–7, and U.S. Department of Commerce, Bureau of Economic Analysis, 1985, p. 6–7.)

Census, 1986a, p. 7). As compared to manufacturing, the mining sector used more water than the food processing sector but less than the other major water-using manufacturing sectors. Also in contrast to manufacturing, where 85 percent of the intake water is freshwater, more than 50 percent of the water used in mining during 1983 was saline.

Geographically, about one-half of the water used by manufacturing firms occurred in the North. The West accounted for about 20 percent, and the South for the remaining 25 to 30 percent. Despite some shifts from North to South in the chemical manufacturing and the paper processing industries, the overall regional pattern remained remarkably constant from 1954 to 1983. Regional patterns for the mining industry also were constant because of the location of mineral deposits.

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FOR ADDITIONAL INFORMATION

Elizabeth L. David, Wisconsin Department of Natural Resources, Box 7921, Madison, WI 53707

TRENDS AND ASSOCIATED FACTORS IN OFFSTREAM WATER USE

AGRICULTURAL WATER USE IN THE UNITED STATES, 1950–85

By Michael R. Moore[1], William M. Crosswhite[1], and John E. Hostetler[1]

INTRODUCTION

Water use in agriculture includes the water applied in the irrigation of crops and the water used in beef, dairy, poultry, and other livestock production. In 1985, agriculture accounted for 42 percent of all freshwater withdrawals in the United States—a total withdrawal of about 141,000 Mgal/d (million gallons per day) of which 137,000 Mgal/d (97 percent) was for irrigation and 4,470 Mgal/d (3 percent) was for livestock production (table 8). Availability of low-cost water has been a major feature in the development of a productive agriculture in arid areas of the United States. In the West, public development of surface-water supplies encouraged the growth of irrigated agriculture, whereas in the Plains States, private development of ground-water supplies provided the principal source of water for irrigation development. In the humid East, irrigation of a small but growing acreage prevents periodic crop losses from drought and frosts, improves productivity of sandy soils in the coastal plain, and increases the production and quality of highly valued fruit, vegetable, and specialty crops.

This article includes discussions of factors that affect the uses (and variations in use) of water in agriculture and of estimates of agricultural water uses. It examines the influence and the effects of water sources, water institutions, economic factors, technological developments, trends in water use, and public policies on water use in agriculture. Irrigation and livestock production are discussed separately.

IRRIGATION WATER USE

Irrigation has been an important factor in the increasing productivity of the Nation's agriculture. Irrigated farms contribute proportionally more to farm crop production than do nonirrigated farms. Based on 1982 data, irrigated farms comprise only 12 percent of all farms but produce nearly one-third of the total value of agricultural products sold off the farm (table 9). Although irrigation is practiced to some degree in all States, most major irrigated areas are located in the West.

The line of 20 inches of average annual rainfall from southwest Texas to the extreme northwestern corner of Minnesota divides the conterminous United States about equally into major irrigated and nonirrigated areas (fig. 49). In the western half of the Nation, irrigated farms produce a larger percentage of agricultural products than are grown on nonirrigated farms. These irrigated farms account for more than 50 percent of the value of agricultural products sold in 10 of the Western States. California's irrigated farms produce 82 percent of the value of that State's agricultural product sales. California leads all other States in farm products sold from irrigated farms.

For purposes of this article, the conterminous United States has been grouped into humid and dry regions; the dry region is further subdivided into the Plains and the West. About two-thirds of the water used in the United States for irrigation was withdrawn in the six western water-resources regions. (See table 12.) Irrigation is required to sustain high-yielding agricultural production under the arid and semiarid conditions that exist throughout most of these regions.

In the three water-resources regions (Missouri, Arkansas-White-Red, and Texas Gulf) that encompass the Central Plains, irrigated agriculture competes with a highly productive dryland agriculture. Irrigation has increased crop yields and has been effective in extending both the geographical area and the variety of crops produced in the Plains States; for example, irrigated crop production has contributed to shifts in cattle feeding from the Corn Belt (Iowa, Illinois, Indiana, Missouri, and Ohio) and cotton production from the Southeast (Alabama, Florida, Georgia, and South Carolina) to the drier areas of the Plains. About 30 percent of the total irrigation water used in the United States is used in the Plains.

In the humid parts of the United States, irrigation is used to supplement normal precipitation as a way of improving crop yields and reducing year-to-year variability in yields and product quality. The only States in the humid regions considered as major irrigation States are Florida (South Atlantic-Gulf Region) and Arkansas and Louisiana (Lower Mississippi Region). Large acreages of rice, orchards, vegetables, and cotton are irrigated in these States.

Most major crops in the United States are irrigated to some degree, but the percentage of acres irrigated varies widely from crop to crop (fig. 50). In 1982, for example, 100 percent of the rice-growing acreage, just over 70 percent of land in orchards, and more than 50 percent of the acreage in vegetables,

Table 8. Estimated water use in agriculture in the United States, at 5-year intervals, 1950–85

[Data in thousands of million gallons per day. NA = not available. Sources: Data from MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988]

Year	Livestock	Irrigation
1950	NA	89
1955	1.5	110
1960	1.6	110
1965	1.7	120
1970	1.9	130
1975	2.1	140
1980	2.2	150
1985	[1]4.5	137

[1]The large change in livestock water use results from the inclusion of aquaculture, which is a growing, large water-using industry.

[1]U.S. Department of Agriculture, Economic Research Service.

Table 9. Irrigated farms and value of agricultural products sold by irrigated farms in the conterminous United States, 1982

[Irrigated farms are those with any agricultural land irrigated in the specified calendar year. Figures might not add to totals because of independent rounding. Source: Data from U.S. Bureau of the Census, 1984]

State	Farms			Agricultural products sold		
				In million dollars		In percent, by irrigated farms
	Total	Irrigated	Percent irrigated	All farms	Irrigated farms	
20 major irrigation States:						
Arizona	7,334	4,437	60	1,527	1,067	70
Arkansas	50,525	6,678	13	2,826	1,069	38
California	82,463	58,389	71	12,491	10,271	82
Colorado	27,111	15,232	56	2,941	1,718	58
Florida	36,352	10,550	29	3,522	2,488	71
Idaho	24,714	17,355	70	2,232	1,763	79
Kansas	73,315	7,257	10	6,191	1,843	30
Louisiana	31,628	3,693	12	1,406	411	29
Montana	23,570	9,226	39	1,547	695	45
Nebraska	60,243	22,190	37	6,626	4,125	62
Nevada	2,719	2,154	79	203	184	91
New Mexico	13,484	6,918	51	851	419	49
North Dakota	36,431	762	2	2,294	103	4
Oklahoma	72,523	3,069	4	2,530	372	15
Oregon	34,087	15,334	45	1,641	1,184	72
South Dakota	37,148	1,814	5	2,478	334	13
Texas	185,020	19,775	11	8,936	2,912	33
Utah	13,984	11,174	80	555	440	79
Washington	36,080	16,252	45	2,831	1,755	62
Wyoming	8,861	5,284	60	606	427	70
Total or percent	857,592	237,544	28	64,235	33,579	52
Other States	1,383,384	40,733	3	67,665	6,135	9
Conterminous United States	2,240,976	278,277	12	131,900	39,714	30

potatoes, berries, and sugar beets were irrigated. In contrast, only a small percentage of wheat and soybean acreage was irrigated.

Between 1900 and 1935, the number of farms that had irrigated land increased rapidly (fig. 51) because of public development of surface-water supplies in the West and improvements in pump technology. Then, for the next three decades, the number of irrigated farms leveled off. During the late 1960's, the number decreased, and during the 1970's the number increased again in response to rising farm-commodity prices and expanding agricultural trade. However, during the 1980's, the number of farms that had irrigated land declined again as a result of the pressures of higher energy prices, lower commodity prices, and widespread economic distress in the farm economy.

In contrast, a long-term upward trend in the number of irrigated acres persisted from 1900 to 1979 (fig. 51). Irrigated acreage doubled from 1950 to 1978, during a period when harvested cropland decreased by nearly 10 percent and the number of irrigated farms dropped significantly. This has resulted in the growth of irrigated acres per farm from 80 acres in 1950 to 176 acres in 1982. Since 1982, total irrigated acreage has fluctuated with changes in farm programs.

Regional Patterns of Irrigation Development

Irrigation in the conterminous United States is concentrated in the 17 Western States plus Arkansas, Louisiana, and Florida. In 1984, about 94 percent of the irrigated acreage was in these 20 States (table 10). About 41 million acres of cropland and 3.8 million acres of pasture and other land were irrigated. In 1984, about 50 percent of the irrigated acreage was in California, Nebraska, Oregon, Texas, and Washington. Another 29 percent of total irrigated acreage was in the States surrounding the Rocky Mountains. The percentage of harvested cropland that was irrigated in each State was lowest in the humid East and greatest in the semiarid and arid regions of the West (fig. 52). In humid areas, however, irrigated acreage, although relatively small, has been increasing.

Large regional differences in the pattern of irrigation development have occurred since 1900. Federal water development in the West supported rapid growth in irrigation during the first one-third of this century, whereas improvements in ground-water pumping technology around the middle of the century provided a basis for the rapid irrigation development in the Plains States. Irrigated acreage has continued to increase in the Great Plains, especially in Nebraska, but the number of acres irrigated in Texas and Oklahoma has declined in recent years because of declining ground-water levels, rising energy costs, and, more recently, a declining farm economy.

Between 1959 and 1969, the South Atlantic-Gulf and the Lower Mississippi Regions experienced a surge of growth in irrigation. Ground-water development in Georgia and Alabama brought large acreages of corn and soybeans under irrigation. Irrigation contributed to the increased use of double cropping in these regions—more than 10 percent of the total harvested acres in these regions in 1982 (Hexem and Boxley, 1986).

Trends in irrigated acreage have not always followed the trends in harvested cropland in the United States (fig. 53). Irrigated acreage increased at a rate higher than that for harvested cropland from 1920 to 1945, except in 1934, when both showed a decline that was probably due to the effects of the Great Depression. The gap between changes in irrigated acreage and harvested cropland widened from 1950 to 1970, when Federal farm programs were directed at reducing cropland acreage. Expansions in irrigated cropland have been very responsive to favorable economic conditions, especially during the period of high commodity prices that followed both World Wars I and II and that also occurred along with expanded world trade in the 1970's. Conversely, irrigated acreage in some locations has been declining because of lower commodity prices, declining ground-water levels, and nonagricultural users purchasing water rights from agriculture.

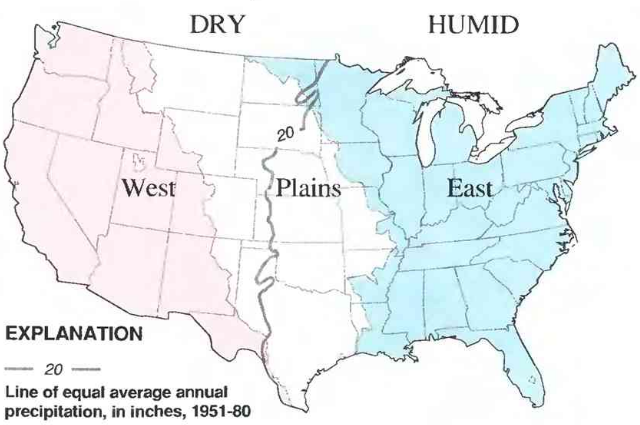

Figure 49. Regions used in the agricultural water-use article. The line of 20 inches of average annual rainfall is the boundary between the humid region and the dry region as used in this article. Most irrigation occurs west of this line. The water-resources regions referenced in this article are shown in the maps in the Supplemental Information part of this volume. (Source: Line of 20 inches of average annual rainfall from U.S. Geological Survey, 1986, fig. 27.)

Factors Affecting Irrigation Water Use

The amounts and distribution of water use for irrigation in the Nation are affected by many factors beyond the basic physiological needs of crops for water and the availability of such water from precipitation in different parts of the country. Other factors include water-supply costs, crop and livestock prices, nonfarm competition for the water resources, and public policies.

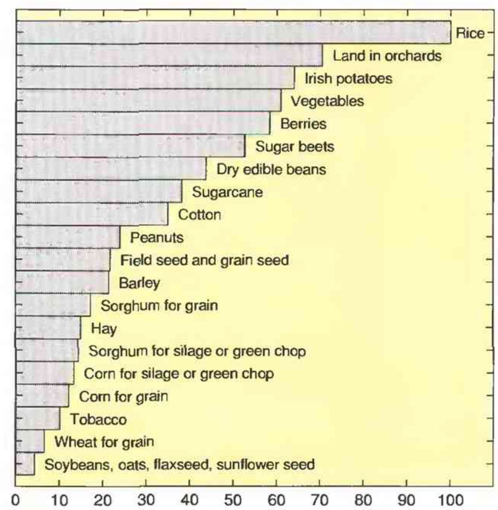

Figure 50. Selected crops and the percentage of the harvested acreage that was irrigated in the conterminous United States, 1982. (Source: U.S. Bureau of the Census, 1984.)

Water-Supply Costs

Water-supply costs depend on the availability and location of surface-water storage and conveyance facilities, stability of ground-water levels, and energy costs. Irrigation surface-water storage reservoirs have been constructed to smooth out the natural variations in streamflow and thus to make irrigation water available throughout the cropping season. As a way of expanding agricultural production, water-conveyance facilities are used to transport water to fertile soil in arid lands that are not adjacent to a stream. Today, many western river systems have a complex network of large mainstem dams and reservoirs, smaller on-stream and offstream reservoirs, major aqueduct links between river basins, and thousands of diversionary canals and ditches. Of the total western irrigated acreage, about 20 percent was developed as projects of the U.S. Bureau of Reclamation and about 80 percent was developed as non-Federal (primarily private) investments.

Construction of large-scale irrigation facilities, which peaked in the 1960's, is declining for at least three reasons. First, the present cost of additions to the surface-water-supply network exceeds the agricultural sector's ability to pay, in part because the most cost-effective storage project sites already have been developed. Second, concerns for environmental quality and dam safety have increased the costs of water projects by imposing more stringent environmental and

Table 10. Irrigated lands, by type, in the conterminous United States, 1984

[Figures might not add to totals because of independent rounding. Source: Data from U.S. Bureau of the Census, 1986]

State	Irrigated land, in thousand acres			Percentage of irrigated land in conterminous United States
	Cropland	Pasture[1]	Total	
20 major irrigation States:				
Arizona	837	56	893	2.0
Arkansas	1,870	2	1,872	4.2
California	7,214	591	7,805	17.4
Colorado	2,740	365	3,105	7.0
Florida	1,260	178	1,438	3.2
Idaho	2,781	474	3,255	7.2
Kansas	2,281	34	2,315	5.2
Louisiana	578	1	579	1.3
Montana	1,430	447	1,877	4.2
Nebraska	5,727	101	5,828	13.0
Nevada	525	173	698	1.6
New Mexico	611	63	674	1.5
North Dakota	143	1	144	.3
Oklahoma	424	16	440	1.0
Oregon	1,310	466	1,776	4.0
South Dakota	336	3	339	.8
Texas	4,727	194	4,921	11.0
Utah	856	198	1,054	2.4
Washington	1,372	110	1,482	3.3
Wyoming	1,194	356	1,550	3.4
Total or percent	38,216	3,829	42,046	94.0
Other States	2,681	4	2,685	6.0
Conterminous United States	40,897	3,833	44,731	100.0

[1]Pasture includes soil-improvement crops, failed acres, summer fallow, idled acres, and cropland planted but to be harvested after the census year.

safety regulations. Finally, Federal policy has continued to reduce the level of subsidy of irrigation water supply.

Experts on the subject of western water agree that the West is in transition from the era of water development to an era of water management and conservation. (See Weatherford, 1982, and Wilkinson, 1985.) Attention is now centered on optimizing the use of existing surface-water projects rather than on the further development of large storage reservoirs and major aqueducts, on developing more efficient water application techniques, and on developing other water conservation measures such as lining irrigation canals.

The widespread use of ground water for irrigation, other than the use of artesian (free flowing) wells, had to await the development of efficient deep-well pumps. Breakthroughs in pumping technology and adoption of center-pivot irrigation systems since World War II have allowed more ground water than surface water to be used for irrigation in some arid and semiarid areas. Center-pivot systems also allowed water to be applied to land where the rolling topography was unsuitable for conventional gravity irrigation. Favorable crop prices, tax incentives for capital investment, and depletion allowances in some States for the pumping of ground water also fostered the increased use of ground water for irrigation.

Many regions of the country where ground water is used heavily for irrigation are experiencing declines in ground-water levels. This is sometimes called ground-water mining, a term analogous to the extraction of a mineral deposit that is applied to an aquifer system where the sum of the withdrawal rate and the natural discharge rate exceeds the recharge rate. Figure 54 highlights areas of the United States that have had water-level declines in excess of 40 ft (feet) in at least one aquifer (see also Mann, 1985). Except for the large areas in the North-Central United States, most of the declines have resulted from withdrawals for irrigation.

Ground-water-level declines increase the pumping lifts (the distance from the ground-water pumping level to the land surface) and, thus, the pumping costs of raising water to the surface. In a comprehensive study of the economic aspects of ground-water mining in the United States, Sloggett and Dickason (1986) reported average pumping lifts and average decline rates in the States of chronic ground-water mining (table 11). The long-term consequence of mining is a reduction in individual well yields and an increase in pumping costs; the cost of water to the farmer gradually increases.

As the cost of pumping ground water increases, three strategies might be attempted before the farm operation reverts to dryland farming—install water-efficient irrigation technology, grow crops that require less water, and improve irrigation scheduling, which also might improve the efficiency of water use. Recent research by Caswell and Zilberman (1986) verified that farmers who use large pumping lifts employed relatively efficient irrigation technology, such as a drip or sprinkler system. Kim and others (1989) demonstrated that as ground-water levels declined in the High Plains area of Texas, it was financially beneficial for farmers to stop growing irrigated grain sorghum but to continue growing irrigated cotton. These research results demonstrate the resiliency of irrigated agriculture. Although significant acreage has been converted from irrigated to dryland farming in the High Plains region of Texas, where irrigation is dependent upon the High Plains aquifer system (El-Ashry and Gibbons, 1986; Schefter, 1985), the increased crop yields that result from ground-water irrigation could continue well into the next century. The transition back to dryland agriculture, which is the ultimate consequence of continued ground-water mining, is likely to be a gradual one.

Increases in energy costs have directly influenced the costs of pumping ground water to the land surface and surface water to higher elevations. Since 1973, increases in fuel costs have reduced the profitability of pumping ground water for irrigation. A parallel can be drawn between increasing energy prices and declining ground-water levels—both increase the cost of bringing ground water to the surface. The effects of increasing energy prices, therefore, are similar to the effects of ground-water mining. Sloggett (1985) documented increases in energy costs from 182 percent for electricity to 700 percent for natural gas between 1974 and 1983. These increases raised annual on-farm water-pumping costs by $1.4 billion. About 90 percent of this, or $1.26 billion per year, is attributable to the increased cost of ground-water pumpage.

Energy costs can decline as well as rise.

Although many experts agree that energy prices ultimately will continue to increase, the first one-half of the 1980's initially represented a period of energy-price stability; then prices declined. Such fluctuations in energy costs complicate long-term planning of irrigation investments that rely on ground water. For the farmers who had invested in ground-water withdrawal and distribution systems, however, the recent decrease in energy costs was beneficial.

Crop and Livestock Prices

Investments in irrigation infrastructure and equipment for both surface- and ground-water use are based on the prospect of a reasonable financial return over the useful life of the equipment (often 15–20 years). Current and anticipated future prices for irrigated farm products, therefore, are important to the investment decision. The recent general decline in crop and livestock prices fosters a poor investment climate and undoubtedly has discouraged investments in irrigation. This economic environment is affected strongly by Federal policy. The Food Security Act of 1985 (Public Law 99–198), for example, was an attempt to counter the decline in market prices with specific commodity-price-support programs and farm-income-support programs for several farm commodities through 1990 (Glaser, 1986). Recent initiatives by the Federal government to increase international competition in agricultural products also could increase market prices by opening up foreign markets. This would improve agriculture's financial environment, thus providing incentives for expenditures on irrigation equipment and facilities.

Competing Demands for Water Resources

As the Nation's population and industrial centers have grown and shifted during the last several decades, so has competition for available water supplies. Competition for water occurs between instream and offstream (withdrawal) uses, between uses for irrigation and other offstream uses, and even among irrigation uses in different regions; for example, despite the large distances separating them, farm operations in northeastern Colorado, central Arizona, and southern California compete for water from the Colorado River. Instream water uses, such as hydroelectric power generation, river-based recreation, maintenance of fish and wildlife habitat, and transportation and dilution of wastes, compete with irrigation for surface-water resources. Urban water needs in some regions of the country, such as central Arizona (Saliba, 1986), also compete with irrigated agriculture for ground water.

With the growth in western water use by the municipal and industrial sectors and the associated growth in water demands for recreation, esthetic enjoyment, and hydroelectric power by an expanding population, irrigated agriculture generally cannot compete economically for available water supplies. Municipal and industrial sectors can afford to pay much more for water than the agricultural sector. Folk-Williams and others (1985) have documented the pattern of increased urban water use in the Southwest and its correlation to population growth. A leveling of agricultural water use combined with growing population, urbanization, and industries suggests that, for the foreseeable future, new balances will have to be struck in water use between the rural and urban areas in the American West.

Numerous laws, water rights, and public policies at the State and Federal levels control distribution of water between irrigation and other uses. Voluntary transfer of farm water rights to cities and businesses is an important consideration in this period of increased water management and water reallocation.

Public Policies

The Federal government has long maintained a policy of promoting the settlement of the West through subsidized irrigated agriculture. The

Table 11. Pumping lifts and rates of water-level decline for areas of ground-water mining in selected major ground-water-irrigated States

[The amount of lift and the annual rate of decline are the ranges of averages in the States. These figures do not indicate that the State average is between the rates. Source: Modified from Sloggett and Dickason, 1986]

State	Aquifer	Range in average pumping lift (feet)	Average annual rates of decline (feet)
Arizona	Alluvial aquifers	75–535	2.0–3.0
Arkansas	.....do	50–120	.5–1.3
California	Alluvium and older sediments–Central Valley.	100–260	.5–3.5
Colorado	High Plains aquifer	175–275	2.0
Florida	Floridan aquifer	250	2.5
Idaho	Basalt, sedimentary and volcanic, and valley fill aquifers.	200–375	1.1–5.0
Kansas	High Plains aquifer	190–275	1.0–4.0
Nebraska	.....do	25–250	.5–2.0
New Mexico	Basin and valley fill and limestone aquifers.	100–200	1.0–2.5
Oklahoma	High Plains, Rush Springs, and Dog Creek–Blaine aquifers.	100–275	1.0–2.5
Texas	High Plains, Gulf Coast, and Carrizo–Wilcox aquifers.	50–300	1.0–4.0

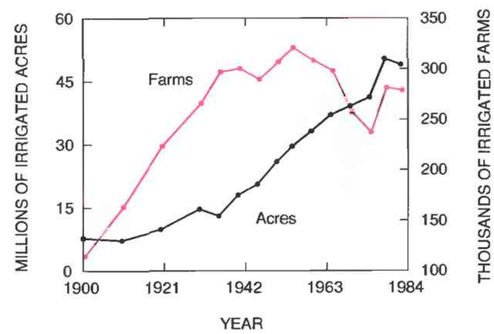

Figure 51. Trends in farms that had irrigated acreage and in the number of irrigated acres in the conterminous United States for census years 1900–82. (Source: Data from Census of Agriculture (selected years) published by the U.S. Bureau of the Census at 4-year intervals between 1900 and 1982.)

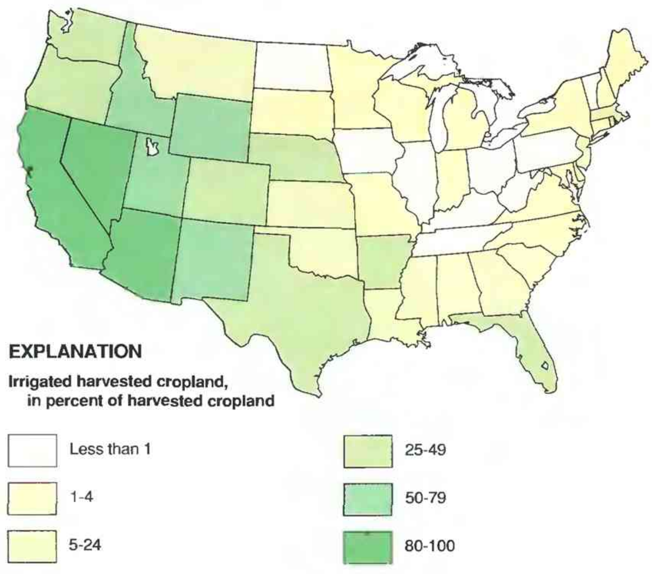

Figure 52. Irrigated harvested cropland in the conterminous United States, 1982. (Source: Data from U.S. Bureau of the Census, 1984.)

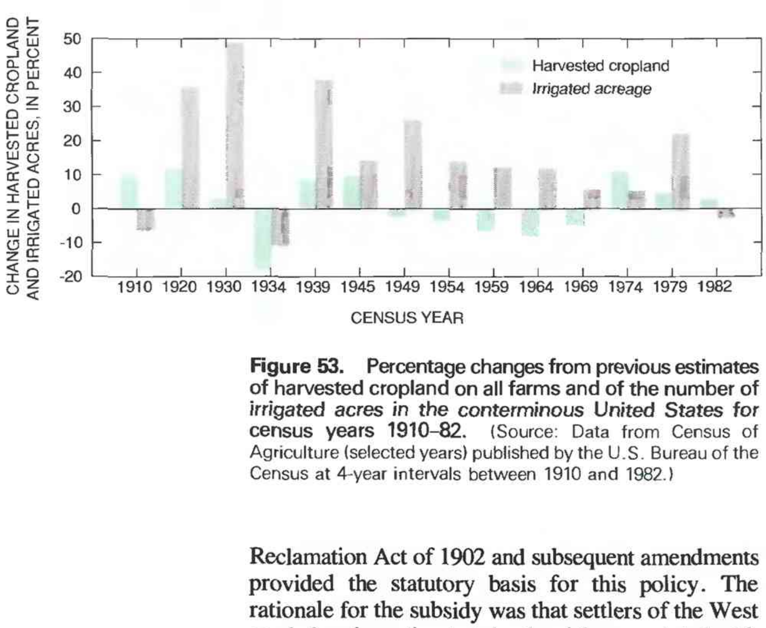

Figure 53. Percentage changes from previous estimates of harvested cropland on all farms and of the number of irrigated acres in the conterminous United States for census years 1910–82. (Source: Data from Census of Agriculture (selected years) published by the U.S. Bureau of the Census at 4-year intervals between 1910 and 1982.)

Reclamation Act of 1902 and subsequent amendments provided the statutory basis for this policy. The rationale for the subsidy was that settlers of the West needed an incentive to take the risks associated with establishing a sustainable western agriculture and that their activity served the welfare of the Nation (Sax, 1965). The U.S. Bureau of Reclamation implemented the Federal policy by planning and constructing major water storage, diversion, and conveyance projects throughout the West. It continues to administer the reclamation program by completing projects under construction, maintaining existing facilities, and collecting revenue generated from long-term water-supply contracts held by irrigation districts and other water-distribution organizations.

The U.S. Bureau of Reclamation provides water to farmers at less than full cost by financing project construction without interest, which results in a sizable financial loss to the Federal treasury. In addition, a portion of power revenues from hydroelectric-power generation at the Bureau's mainstem dams also subsidizes irrigation by covering project costs allocated to irrigation. In a chronicle of historical reclamation-water-pricing policy, Burness and others (1980) calculated that repayment by irrigators averaged only 26 percent of the total expenditures allocated to irrigation-water supply at Bureau of Reclamation water-development projects between 1949 and 1977.

During the 1970's, a heightened public awareness of Federal expenditures and of the effects of water development on environmental quality, along with concerns about subsidizing an agricultural economy that already was over-producing, brought into question the need for additional project development. In 1977, the Carter Administration initiated a shift in irrigation-water policy by halting the planning and the construction of many prospective water projects. Since then, Federal funding of irrigation-water projects has continued, but at a very low level, and only one new major project has been started.

Two public policies are now being implemented that affect the current Federal relation to western surface-water development and use. The first requires local and regional sharing of water-project planning and construction costs with the Federal government. This transfers a higher proportion of the planning and investment costs of new projects to the direct and indirect project beneficiaries; for example, the Colorado River Basin Project Act Amendments of 1982 (Public Law 97–373) require that non-Federal interests pay 20 percent of the cost of some features of the Central Arizona Project. Maxey and Starler (1987) documented the subsequent negotiations that finalized the entire cost-sharing agreement for that project and analyzed the negotiations as a case study of how the policy of cost-sharing could operate.

A second policy, defined in the Reclamation Reform Act of 1982, attempts to increase prices of Federal irrigation water deliveries closer to their actual costs, thereby reducing the Federal subsidy. This policy, which applies only to farms and leaseholdings exceeding 960 acres, will meet the original goal of the reclamation program of not providing subsidies to large farms. The 1982 legislation could force some large irrigated farm operations to reduce the scale of their businesses. As a way of avoiding full-cost prices, some large farms have been subdivided into management units of 960 acres or less, which might be a legal way of negating the intent of the Act. Even if this is determined to be illegal, other legal challenges of the Act are expected. The Reclamation Reform Act also could quicken the ongoing transfer of water use from irrigation projects to the urban sector.

Most of the authority for allocation and administration of the Nation's freshwater resources rests with the individual States. The cornerstone of such administration has been the granting and the regulation of water rights—the right of access to and use of water from a specific source, usually a specified amount for a particular purpose. Usually, an agency (such as the Division of Water Resources or a State Engineer's Office) or a State water court administers the use of both surface- and ground-water resources. However, the States' policies regarding water rights differ widely. The Federal government generally accedes to State law by applying for the water rights associated with each project in the reclamation program.

Of the States that have significant irrigated acreages, most have adopted the doctrine of prior appropriation to govern the apportionment and the use of surface water and, to a lesser extent, ground water. This commonly is described as "first in time, first in right" as, in water-short years, senior appropriators receive their entire water entitlement before junior appropriators receive any water. Most of the senior water rights in many areas of the country are for irrigation water. However, this does not assure a sustained supply of irrigation water in times of drought when the supply has been over-allocated. Because they represent large amounts of water, irrigation water rights are obvious targets for competing demands in areas where existing water resources are fully allocated or, in places, over-allocated. Some States use a doctrine that is based on the water needs and supplies in the region (Sax and Abrams, 1986) and allocate or reallocate water rights according to a hierarchy of beneficial uses, some of which stand higher than irrigation in priority.

Many recent claims to water supplies or minimum streamflows have been established for such purposes as fish habitat or other environmental concerns, largely at the expense of irrigation diversions. In addition, some Western States, such as Arizona, Colorado, Kansas, and Nebraska, have adopted legislation that addresses the specific issue of ground-water mining (Sloggett and Dickason, 1986). The intent of these statutes is to reduce the decline in ground-water levels by limiting irrigation withdrawals. As competition for limited water supplies increases, water becomes a valued commodity, and the economic value of water for irrigation cannot compete with the value of water for some other uses, such as industrial or municipal supplies. The growing competition for the water available to agriculture and the decline in ground-water supplies have created pressures to increase water-use efficiency in agriculture, to change water laws to make it easier to reallocate water supplies to nonagricultural users, and to increase State and local involvement in managing water resources.

Each of the Western States provides for the formation of quasi-public agencies to act as wholesale or retail suppliers of water to farms. Their description as "quasi-public" originates in their power to tax both rural and urban property owners and, in some instances, in their power of eminent domain or their ability to issue tax-exempt bonds. Various names—conservancy district, irrigation district, or water agency—are applied to these agencies. Beginning in 1926, Congress required that such organizations be formed to serve as contracting agents with the Federal government before a Federal reclamation project could be constructed (Leshy and others, 1982, p. 360). Because the quasi-public irrigation organizations provide more than one-half of the irrigation water delivered by water organizations (U.S. Bureau of the Census, 1982), they play a powerful, central role in the allocation and the management of surface-water resources.

Many Western States also have statutes authorizing the formation of local ground-water-management districts. In Texas, for example, the High Plains Underground Water Conservation District No. 1 educates farm operators about the techniques, the practices, and the technology of water conservation. The District appears to have been a factor in slowing the decline of water levels in the major aquifer in that region. Other States, such as Colorado and Kansas, give ground-water-management districts authority to adopt reasonable standards and rules for ground-water use (Massey and Crosswhite, 1987).

The growth in the transfer of water supplies and (or) water rights as a means of meeting new water demands has led to an emergence of organizations that serve as "water banks" or "clearinghouses" between the sellers and buyers of water. The transfers that are facilitated by these organizations are voluntary transactions. In addition, isolated water-rights transfers and short-term water exchanges to alleviate drought conditions have been negotiated directly between buyers and sellers. According to Wahl and Osterhoudt (1986, p. 113), the prior-appropriation system of water rights, which predominates in the West, has been conducive to voluntary transfer of water; the possibilities for water transfers are just emerging in the Eastern States, where other systems are used. Of the 10 case studies of water transfers described by those authors, at least 5 involved the transfer of irrigation water for other uses, including electric power generation, industrial use, and municipal supplies.

Irrigation Water-Use Patterns

The distribution of irrigation water use reflects wide regional differences in climate across the country (table 9). The 17 Western States accounted for 85 percent of the irrigated acreage in 1984 (U.S. Bureau of the Census, 1986) and 91 percent of the water used in irrigation. About two-thirds of the irrigation water use in the Nation occurs in the six water-resources regions identified as the West in table 12.

Quantity of Irrigation Water

Between 1950 and 1985, water use for irrigation increased about 54 percent from an estimated 89,000 Mgal/d in 1950 to 137,000 Mgal/d in 1985. During that period, irrigation water use apparently declined during only two 5-year periods—by 3 percent between 1955 and 1960 and by 6 percent between 1980 and 1985. The recent decline in irrigation water use probably was influenced heavily by, among other factors, declines in farm commodity prices and a downturn in the farm economy in the early 1980's. Solley and others (1988, p. 71) noted that rainfall (and, consequently, streamflow), generally was more plentiful in 1985 than in 1980, which would have reduced the need to irrigate in some areas and would have reduced the dependence on ground water where surface water was an alternative choice. In addition, part of the apparent decline in irrigation water use could be the result of more reliable estimates.

In 1985, an average of 54 percent (73,800 Mgal/d) of the water withdrawn for irrigation was consumptively used by evapotranspiration or incorporated into crops and 17 percent (23,600 Mgal/d) was lost

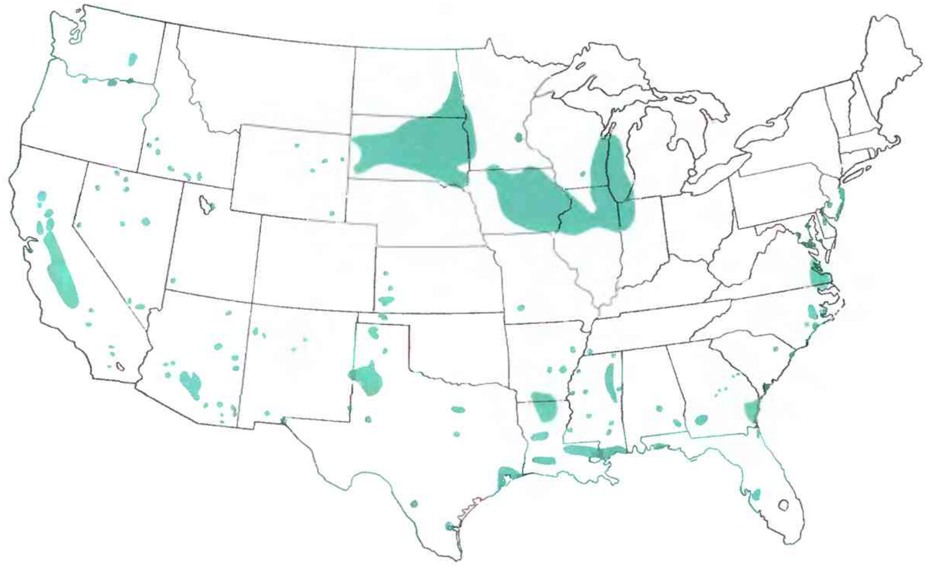

Figure 54. Areas of water-table decline or artesian water-level decline in excess of 40 feet in at least one aquifer, in the conterminous United States. (Source: U.S. Geological Survey, 1984, fig. 20.)

in conveyance (evaporation or leakage to the ground-water system). The remaining 29 percent of the water withdrawn was returned to streams or infiltrated into the soil to reach the ground-water system. Irrigation consumptive use accounted for 80 percent of the total consumptive water use in the Nation. Geographically, consumptive use as a percentage of total irrigation withdrawal is highest in the humid regions (76 percent) because of low application rates for supplementing precipitation during dry periods. It is nearly average in the Plains regions (61 percent) because of the dryness of the climate and the large quantities of irrigation water used on row crops, such as corn and sorghum. Consumptive use is lowest in the West (48 percent) because of the very large quantities of water applied and the large return flows.

Surface-water supplies often are moved long distances to the point or area of use. As a result, a large quantity of water is lost during the conveying process (conveyance losses) as a result of leakage into the ground and evaporation from canals and other open conduits. Conveyance losses were estimated to be 28,900 Mgal/d [32,400 million acre-ft/yr (acre-feet per year)] in 1955 and about 23,000 Mgal/d (25,800 million acre-ft/yr) in 1960, a level that has persisted since. However, much of this conveyance loss percolates down to the ground-water system and could become available for further downstream use. With the increase in the competition for water, measures to reduce such conveyance losses also have increased because reducing such losses is viewed as one way to increase the immediate availability of water.

Sources of Irrigation Water

The main sources of water used in irrigation are surface and ground water, although a small quantity of reclaimed sewage also is used (table 12). Nearly two-thirds of the water used in irrigation comes from surface-water sources and one-third comes from ground-water sources (fig. 55*A*).

The dependency on either a surface- or a ground-water source for irrigation varies geographically (fig. 55*B*–*D*). Although the West generally is much more dependent upon surface water than ground water for irrigation (fig. 55*B*), ground-water sources supply a higher percentage of total irrigation water use in the Lower Colorado and the California Regions than in other parts of the West. The water-resource regions in the Plains rely much more on ground water than on surface-water sources (fig. 55*C*). Irrigation in the Plains is supported largely by water from the 170,000-square-mile Ogallala aquifer. In parts of six States—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas—ground water is the principal source of water for irrigation. Recharge to that aquifer system in most areas is lower than withdrawals, and use of ground water for irrigation water from that source has declined in the High Plains of Texas and Oklahoma. However, in other parts of the Plains, irrigation from the Ogallala has increased. The humid regions rely much more heavily on ground water than on surface-water sources for irrigation (fig. 55*D*). Contrary to trends in other parts of the country, the use of ground water for irrigation in the South Atlantic–Gulf Region increased over the past decade.

Rates of Applying Irrigation Water

The quantity of water applied per acre varies with the crop, the method of application (irrigation system), and the geographic location. Application rates for the two major irrigation systems—sprinkler and gravity flow—for four crops are shown in table 13. The water applied per acre tends to be higher for gravity systems than for sprinkler systems in Arizona and California; otherwise, the application rates seem to depend more on the crop than on the State or region. The crop receiving the highest rate of application commonly is alfalfa. In the relatively dry, irrigated areas of Arizona and California, most of the irrigated crops received comparatively large applications of water—around 3 ft or more of water during the year. In the humid regions, applications are much lower. Application rates of water in the humid regions are only about 10–30 percent of those in Arizona or California (table 13).

Water-Quality Effects of Irrigation

Water-quality degradation of surface- and ground-water resources by agricultural production activities, a type of nonpoint-source (nonlocalized) pollution, has long been recognized. Only recently have attempts been made to quantify and regulate them. Salts, dissolved from the soil by irrigation return flows, are the principal pollutant from western irrigated production. However, agricultural chemicals and sediment from irrigation-caused erosion also find their way into the Nation's water resources. Environmental effects of irrigation agriculture are not all negative, however. Results that could be considered beneficial include induced wetlands and seeps, where irrigation return flows are trapped in low spots or appear as springs; improved wildlife habitat from phreatophytes and other riparian vegetation that grow along irrigation canals; more visually diverse landscapes from vegetation supported by return flows; and the maintenance of dry season streamflow by irrigation return flows.

Several management practices can be effective in reducing the effects of agricultural chemicals on surface and ground waters. Improvement in timing and methods of applications of fertilizers, pesticides, and irrigation water often allow reductions in the amounts applied. Such reductions not only lessen production costs, but also reduce contamination in receiving waters because of the overall reduction in potential contaminants applied and the smaller return flow that is available to carry the contaminants directly to streams (as surface drainage) or to the ground water (as downward percolation beyond the root zone).

In warm climates, double cropping can provide almost continuous soil cover, which reduces field erosion, and an additional crop for the farmer. However, double cropping increases the amounts of chemicals applied per acre and encourages the use of irrigation to ensure the second crop. Conservation-tillage practices reduce sediment runoff by retaining crop residues on the land, but they concentrate pesticides and increase water and pesticide infiltration of the soil profile. Some of these practices also provide immediate benefits by reducing production costs. Limited general knowledge of the benefits, along with start-up costs for the farm operators (mainly for equipment) and insufficient financial or technical assistance, have constrained the adoption of these beneficial practices (U.S. Environmental Protection Agency, 1984).

The magnitude and effect of irrigation practices on salinity levels, including salt concentration and salt loading, are well understood. Under typical soil and water conditions, irrigation return flows are more saline than the applied irrigation water. Salinity problems are associated with nearly one-fourth of all irrigated lands in the United States. Most of the land stretches in a band through Arizona, eastern Utah, and western Colorado. Small and severe occurrences of salinity also exist in the San Joaquin and the Imperial–Coachella Valleys of California and the Yakima Valley of Washington (El-Ashry and others, 1985).

Salinity, which can come from several sources, tends to increase as water passes through the steps of storage, conveyance, irrigation, and return flow. Those sources, which generally are both natural and artificial, include minerals dissolved in the native water; salts added as a result of previous uses of the water; minerals leached from the soil and rock materials that the water comes in contact with during conveyance, use, and drainage; and fertilizer and other farm chemicals. Thus, return flows are more saline than the withdrawn waters, and, with repeated use, the water source itself may become more saline. This has occurred in the lower Colorado River basin, where a desalting plant on the United States–Mexico border is used to remove salts derived from irrigation return flows. This plant was built to meet international agreements concerning salinity levels in Colorado River water that flows into Mexico (El-Ashry and others, 1985). Effects of high salinity levels in water supplied to agricultural, industrial, and municipal users include poor crop yields and inability to grow some crops, high costs of treating water before use, and corrosion of plumbing, boilers, irrigation sprinkler systems, and household appliances.

Concentrations of salts, such as chloride, sulfate, and bicarbonate, increase whenever water is lost by evaporation and transpiration; for example, reservoir water becomes increasingly saline during warm weather because of evaporation losses. When diversions of water further reduce the amount of water available to dilute salts in the reservoirs, salt concentration increases. Virtually all reservoirs in the West are susceptible to this salinity buildup in summer, when evaporation and withdrawals for irrigation are greatest.

As irrigation water is lost through evaporation and transpiration, salts that are left behind in the soil can accumulate and cause a decline in agricultural productivity. Salt-resistant crops can be substituted for less tolerant plants, but if the salts are allowed to accumulate in the soil, the lands eventually will become unsuitable for agriculture. Depending on the types of salts involved, the soil might be improved by chemical treatment or application of extra water or both. Excess irrigation water leaches soils, dissolves naturally occurring and accumulated salts, and carries the salts away in the return flows to ground- or surface-water sources. Thus, the leaching process, which might improve the soil, can degrade the receiving waters if more water is applied than is needed to carry salts below the root zone.

The disposal of irrigation drainage water laced with naturally occurring toxic salts is a major problem in extensively irrigated areas (Lindsey, 1985). Selenium, boron, and nitrogen concentrated by evaporation can result in environmental hazards to wildlife and, rarely, to humans (U.S. Bureau of

Table 12. Irrigation water use by water-resources region in the United States, 1985

[Data in million gallons per day. Figures might not add to totals because of independent rounding. Source: Modified from Solley and others, 1988, p. 23]

Water-resources region	Withdrawals, by source			Reclaimed sewage	Conveyance losses	Consumptive use, freshwater
	Ground water	Surface water	Total			
Humid:						
New England	4.6	21	25	.0	.0	25
Mid-Atlantic	100	148	248	1.3	1.7	229
South Atlantic-Gulf	1,950	1,690	3,630	79	61	2,700
Great Lakes	118	136	254	21	.0	274
Ohio	19	21	40	.0	.3	38
Tennessee	1.3	8.9	10	.1	.0	7.7
Upper Mississippi	293	65	358	4.2	12	345
Lower Mississippi	4,410	1,390	5,810	.0	471	4,400
Souris-Red-Rainy	38	36	75	.6	8.3	63
Plains:						
Missouri	8,170	16,100	24,300	3.5	8,810	11,600
Arkansas-White-Red	6,860	1,980	8,840	3.1	898	7,230
Texas-Gulf	3,600	1,340	4,950	34	681	4,390
West:						
Rio Grande	1,250	3,730	4,970	2.1	608	1,970
Upper Colorado	34	7,140	7,170	.0	1,090	2,220
Lower Colorado	2,590	3,640	6,240	37	1,240	3,610
Great Basin	1,170	6,200	7,370	18	1,310	3,370
Pacific Northwest	4,370	26,400	30,800	4.6	7,370	12,000
California	10,300	20,500	30,800	224	942	19,200
Other:						
Alaska	.0	.0	.0	.0	.0	.0
Hawaii	336	570	906	1.4	91	21
Caribbean	50	107	157	.0	16	102
Total	45,700	91,300	137,000	434	23,600	73,800

Reclamation, 1986). High selenium concentrations, which are found in some irrigated regions of California such as the San Joaquin Valley, have caused bioaccumulation in plants and animals that has resulted in reproductive abnormalities (Ogg and others, 1988).

The more recent recognition of ground-water contamination from widespread agricultural practices has caused considerable health concern among the general public and is one of the factors that prompted the establishment of the Ground-Water Protection Strategy by the U.S. Environmental Protection Agency (1984). The U.S. Department of Agriculture also has recently issued a policy for ground-water quality (U.S. Department of Agriculture, 1987).

LIVESTOCK WATER USE

The agricultural water use with the greatest economic return for the water withdrawn is the use for livestock production. Although water use for livestock amounts to only about 3 percent of the withdrawals for irrigation (table 8), livestock makes up more than one-half of the agricultural cash receipts. Total cash receipts from crop and livestock marketing and other farm-related income in 1984 totaled $138 billion, of which $76 billion was from livestock (U.S. Department of Agriculture, 1988a). Receipts from marketing livestock products—red meat, poultry, eggs, and dairy products—typically make up one-half of cash farm receipts.

Livestock water uses include drinking water for livestock, evaporation from stock-watering ponds, and related sanitation and waste disposal. The livestock category comprises several livestock groups including dairy, cattle, hogs, sheep, goats, and poultry. Also included is water use by animal specialties such as horses, rabbits, bees, pets, and fur-bearing animals in captivity. Water used to produce fish in captivity (aquaculture) also is included in livestock water use in the U.S. Geological Survey's estimates of livestock water use, which accounts for the large change in use between 1980 and 1985 (Solley and others, 1988, p. 26).

Factors Affecting Livestock Water Use

Livestock water use is determined by livestock numbers and production practices. Those, in turn, are influenced by technical developments in production and marketing practices and by the demand for livestock products. Production techniques have benefited from modern technology that increases production and lowers costs (U.S. Department of Agriculture, 1985); for example, beef-cattle feeding has become more efficient by the use of feed additives and genetic improvements, which have reduced the time required to bring a steer to market from 3 or 4 years to 18 months. Poultry and pork producers have increased production efficiencies and similarly reduced the time required to bring animals to market weights. Such production improvements reduce both the quantity of water required to produce a pound of meat and the water requirements per animal.

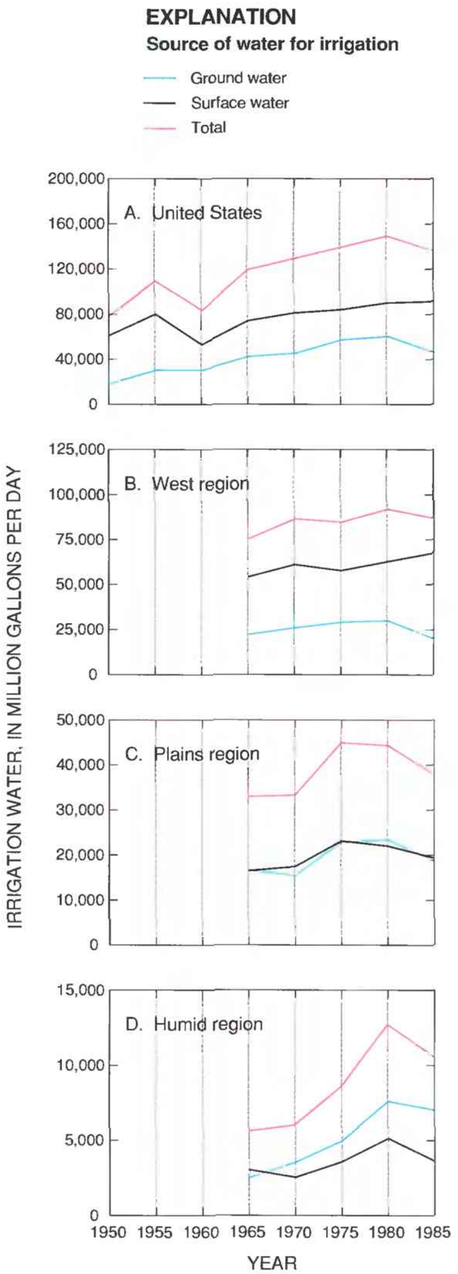

Figure 55. Sources of irrigation water, by geographic region, in the United States, 1950–85. (Source: Data from MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988.)

Demand for Livestock Products

Demand for livestock products is a major factor affecting livestock water use because of its large influence on livestock and poultry production and on changes in the market shares of various meats. Statistics from the U.S. Department of Agriculture (1988b) show large changes in the per capita consumption of meat and poultry during the past decade. The per capita consumption of all red meats was at record or near-record levels during the mid-1970's but has since declined, while both the per capita and total consumption of poultry continues to grow steadily. Total meat consumption was at a record high in 1986 (fig. 56) because of higher consumer incomes and relatively low product prices. Changing consumption patterns and a relative decline in the price of poultry have been important factors in the steady growth in per capita consumption of poultry over the past three decades.

Livestock Numbers and Production

The number of dairy and red-meat animals, including milk cows and heifers, beef cattle and calves, hogs and pigs, and sheep and lambs, showed a downward trend from 1970 to 1985 (table 14). The Federal Dairy Termination Program of 1986 sharply reduced the number of milk cows. The effects of this program are expected to stabilize by the end of the 1980's. Beef-cattle production likely will continue its current decline, but by the end of the 1980's it could slowly begin to increase. Pork production, which fluctuates in fairly consistent 4- to 5-year market cycles, will continue to lose market shares to other meats as in the past. Both chicken broilers and turkeys are trending upward in production.

The chicken broiler industry grew rapidly during the 1970's, but expansion slowed during the 1980's. However, broiler and turkey production is expected to continue its steady rise as poultry meats gain a larger share of the market. The number of laying hens and other chickens has declined steadily in recent years because of increases in the number of eggs produced per bird and a decline in the human consumption of eggs for health reasons.

Quantity, Sources, and Regional Distribution

The estimated withdrawals of water for livestock use in 1985, by water source and water-resource region, are shown in table 15. Livestock water use strongly reflects dairy production in humid regions and in the California Region. Aquaculture activities have a major effect on water use in the Lower Mississippi, South Atlantic-Gulf, and Pacific Northwest Regions.

Of the total water used in livestock production in 1985, one-third was from surface water (1,450 Mgal/d) and two-thirds was from ground-water sources (3,020 Mgal/d); differences, however, were large among the regions. Overall, consumptive use was 53 percent of total water withdrawals for use in livestock production.

The total quantity of water withdrawn for livestock use across the Nation increased progressively from 1,590 Mgal/d during 1960 to 2,200 Mgal/d during 1980, a time during which the proportions of livestock water derived from surface water and ground water changed very little (fig. 57). Between 1980 and 1985, the estimated withdrawals for livestock use nearly doubled (increased 93 percent) primarily as a result of large increases in water use for aquaculture, which uses large quantities of ground water. Excluding aquaculture, the overall level of livestock production

Table 13. Average acre-feet of irrigation water applied per acre, by crop type for selected States and irrigation systems, 1984

[NA = not available. Source: Data from U.S. Bureau of the Census, 1986, table 17]

State/region and irrigation system	Crop			
	Corn	Wheat	Cotton	Alfalfa
Arizona:				
Sprinkler	2.5	2.9	3.9	4.5
Gravity flow	3.1	3.5	4.8	5.3
Arkansas:				
Sprinkler	1.9	NA	NA	NA
Gravity flow	1.1	.9	.8	NA
California:				
Sprinkler	3.0	1.5	2.9	2.9
Gravity flow	3.3	2.1	3.1	4.2
Montana:				
Sprinkler	NA	1.0	NA	2.0
Gravity flow	2.2	1.6	NA	1.6
Texas:				
Sprinkler	1.6	1.1	.7	2.7
Gravity flow	1.6	1.0	1.0	1.7
Humid region[1]				
Sprinkler	.7	.3	.6	.6
Gravity flow	.9	.5	.4	NA

[1]Excludes Arkansas shown above and Florida and Louisiana, which are considered to be the only States in the humid region that are major irrigators.

has remained fairly constant since 1980, even though the annual production of individual livestock products has varied (U.S. Department of Agriculture, 1985, p. 29–31).

Livestock water use in 1960 was highest in the Upper Mississippi, Great Lakes, and Ohio Regions, reflecting the concentration at that time of dairy and livestock production in those regions. By 1985, however, livestock water use in the Plains regions surpassed that in the other regions (table 15) because of a decline in the number of dairy animals and a shift in beef cattle to the Plains regions. The shift in cattle feeding from the Corn Belt regions to the Plains regions was supported by climatic conditions that are more favorable for confinement in feed lots, as well as an increase in irrigated feed and forage production in the Plains regions. The steady rise in water use in the Lower Mississippi and South Atlantic–Gulf Regions resulted from the rapid growth in aquaculture; the poultry industry, especially broiler and turkey production; and expansion of cow-calf operations.

FUTURE DIRECTIONS AND ISSUES

Although specific regional or quantitative predictions of emerging or foreseeable effects on agricultural water use are beyond the scope of this article, certain qualitative assessments are possible. Major issues that are expected to significantly affect future agricultural water use include economic influences, efforts to reduce water-quality degradation attributed to agricultural activities, expansion of water marketing, and growing competition for water supplies.

ECONOMIC INFLUENCES

As discussed previously, economic influences, such as crop and livestock demands and prices, pumping costs, and other expenses of agricultural activities, have major effects on agricultural water uses. The overall effects, however, are complicated by several factors that cloud the outlook; for example, the basic demands, prices, and expenses are subject to significant short-term changes that are largely unpredictable. Also, these economic factors, in turn, are largely dependent on various policy decisions. In addition, various sectors of the agricultural industry could respond differently to economic changes; for example, lower crop prices might lead one farm operator to eliminate his irrigation costs by shifting to dryland farming, whereas another operator might increase irrigation to achieve greater yields. Moreover, emerging trends, such as drip application technology in the case of irrigation or expansion of aquaculture in the case of livestock water use, could exert unexpected major influences.

Livestock producers' financial stress likely will persist through the end of the decade (U.S. Department of Agriculture, 1985). Animal numbers, production, and consumption will change in response to health-based consumer preferences, market changes in meat and poultry prices, grain prices, and interest rates. Both the cycles in livestock production and the competition between meats for consumer dollars are well recognized.

REDUCTION OF POLLUTION

Agricultural activities have contributed to pollution of surface and ground water. This is an issue of great national concern. Agricultural sources of pollution include point (localized) sources, such as feedlots, and nonpoint sources, such as agricultural runoff that carries pesticides, sediment, and nutrients from fertilizer. Although considerable progress has been made in the control of point sources of surface-water pollution, further improvements in surface-water quality are thought to require increasing attention to nonpoint sources, including agricultural runoff (U.S. Geological Survey, 1984, p. 75).

Because of growing concerns, more information has been gathered and disseminated about instances of ground-water contamination that can be attributed to agricultural activities (U.S. Geological Survey, 1988). Successes in containing surface-water pollutants, ironically, have contributed to ground-water contamination; for example, agricultural chemical residuals in holding ponds can percolate downward into and contaminate ground-water systems.

Available technology for measuring contaminant levels, although limited, exceeds our knowledge of the associated health effects of continuously using contaminated water or the costs of mitigating the problem. It is clear, however, that water-quality-control measures could preclude the use of some agricultural chemicals and could impose higher cost production practices on farmers, raise food costs, and reduce irrigation water use.

WATER MARKETING

The term "water marketing" is defined as any voluntary transfer of water-right ownership. Water marketing raises a set of complex legal, policy, social, and economic issues that are receiving an increasing amount of attention, as summarized below. More detailed analyses of many of the issues are provided by El-Ashry and Gibbons (1986), Frederick (1986), Howe and others (1986), Saliba and Bush (1987), Wahl and Osterhoudt (1986), and Weatherford (1982).

Economists have been persistent advocates of water markets because they provide a mechanism for facilitating the reallocation of water to more economically valuable uses. Voluntary transfers generally are advantageous to the seller and the buyer; otherwise, they would not occur. Advocates of water markets believe that the markets also would help to meet urban water needs in a cost-effective and environmentally benign way.

However, there are a variety of impediments to water transfers. Third-party effects of water marketing, known as externalities (downstream users of return flows), have long been the basis in western water laws for the review of a transfer by a State Engineer or a State water court (Hartman and Seastone, 1970). A classic example depicts a water user who relies on the return flow from an upstream user's water application and who could be harmed if the upstream user transfers the water right. Generally, State water laws protect the third party by allowing for an objection to be raised. Many States' laws prohibit or impede a transfer when a third party objects rather than arranging for a mediation process among the parties to balance the various financial interests.

Secondary economic effects to water marketing result when businesses that participate with farmers in the production and distribution of farm commodities are dislocated by the discontinuation of irrigated agriculture. Water marketing can have negative effects on the local economy, although, from a national perspective, gains in one region could balance losses in another. State water laws and interstate water agreements, though, clearly emphasize the regional perspective by impeding transfers from existing regional allocations of water. A variety of methods is used to accomplish this—several river compacts, including the Colorado River Compact, appear to prohibit interstate water marketing; a number of Federal and State laws limit the transfer of water outside of the service area of irrigation districts, conservancy districts, and other water-service agencies; basin-of-origin statutes impede transbasin transfers; and, finally, many State ground-water laws limit water use to the land overlying the aquifer.

Other concerns exist over the potential effect of widespread water marketing on a distinct western social fabric and cultural diversity. Original reclamation law limited the farm size eligible for reclamation water to 160 acres to promote the family farm (Worster, 1985). The Reclamation Reform Act of 1982 affirms this social goal by pricing water at a lower rate for relatively small farms (less than 960 acres). Some evaluators fear that water marketing, left unrestrained, will accentuate current trends of replacing family farms with agribusinesses in excess of 960 acres.

Mumme and Ingram (1985) discussed another facet of western culture that water marketing could affect—the survival of traditional Hispanic and Native American communities in the Southwest. Many of these communities rely on traditional methods of irrigation that are technologically inefficient by modern standards. Mumme and Ingram (1985, p. 377, 379)

Table 14. Trend in livestock animals and poultry production in the United States, 1970–85

[Source: Data from U.S. Department of Agriculture, 1985]

Category	Unit	Year				Percentage change 1970–85
		1970	1975	1980	1985	
Milk cows and heifers...	1,000	12,091	11,220	10,758	10,819	−11
Beef cattle and calves...	1,000	112,369	132,028	111,242	109,802	−2
Hogs and pigs............	1,000	67,385	49,267	64,462	54,073	−20
Sheep and lambs.........	1,000	20,428	14,515	12,699	10,443	−49
Poultry production:						
Chicken broiler.........	Million pounds	10,819	11,096	15,539	18,623	72
Turkey....................	..do....	2,198	2,277	3,077	3,513	60

Table 15. Estimated livestock freshwater use by water-resources region, 1985

[Data in million gallons per day. Figures might not add to totals because of independent rounding. Source: Data from Solley and others, 1988, p. 27]

Water-resources region	Withdrawals, by source			Consumptive use
	Ground water	Surface water	Total	
Humid:				
New England.................	13	31	44	30
Mid-Atlantic..................	106	36	142	85
South Atlantic-Gulf.........	199	78	277	227
Great Lakes..................	64	14	78	69
Ohio............................	98	87	184	155
Tennessee....................	35	24	59	28
Upper Mississippi...........	257	43	300	279
Lower Mississippi...........	634	257	892	348
Souris-Red-Rainy...........	8.8	3.8	13	13
Plains:				
Missouri........................	222	151	373	364
Arkansas-White-Red.......	110	145	255	199
Texas-Gulf....................	63	113	176	176
West:				
Rio Grande....................	16	24	40	39
Upper Colorado..............	3.9	35	39	13
Lower Colorado..............	26	43	69	14
Great Basin...................	48	21	69	16
Pacific Northwest...........	1,060	32	1,090	150
California......................	41	160	201	156
Other:				
Alaska..........................	10	146	156	.2
Hawaii..........................	.7	3.1	3.8	2.2
Caribbean......................	8.6	.0	8.7	8.7
Total.........................	3,020	1,450	4,470	2,370

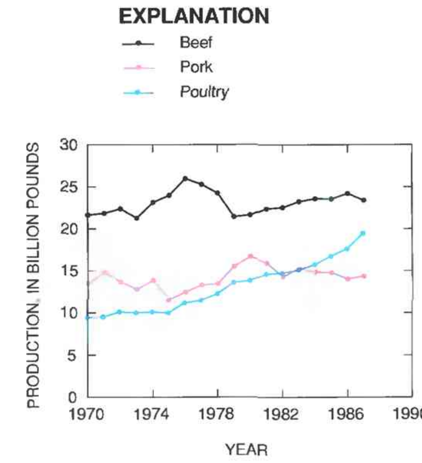

Figure 56. Trends in commercial beef, pork, and poultry production in the United States, 1970–87. (Source: U.S. Department of Agriculture, 1988b.)

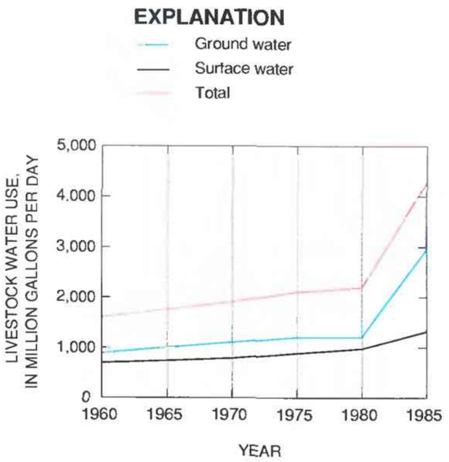

Figure 57. Trends in livestock water use and sources of water in the United States at 5-year intervals, 1960–85. (Sources: Data from MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988.)

wrote that water markets "can only diminish what control these communities presently have over their water resources and erode their viability as culturally distinct societies" because "low-income communities would find themselves subject to increasing pressure to surrender their water rights to outside bidders as market prices rose." These issues exemplify the intermittent conflict between economic efficiency and social goals.

The Federal government and State governments are adopting laws and policies to handle some of the dilemmas of water marketing. For example, the State of New Mexico might sell ground water to El Paso, Tex., as a means of resolving the court battle between the two entities over the property rights to the ground water (DuMars, 1985). This decision to allow water to be sold out-of-State is in contrast with the traditional western belief that water is absolutely necessary for a State's economic development and, thus, should be retained at almost any cost. The U.S. Bureau of Reclamation has adopted a policy not to impede voluntary sales of reclamation water rights; however, others in the field of water rights (beginning with Sax, 1965) have raised the question about the equity of such transfers: Why should farmers, who receive the reclamation water at a highly subsidized price, receive the full value of the water as a result of transfer? Finally, States in the Great Lakes basin are developing a unified protective policy on prospective transfers of Great Lakes water to the arid West. The common aspect of the various approaches is to anticipate the dilemmas of water marketing and to design institutions that will balance a variety of social and economic goals in this new environment.

New Competition for Water

Irrigated agriculture has been the largest consumer of western water since minerals mining subsided in the 19th century. Two new competitors for irrigation water have emerged—Native Americans with tribal lands and instream-flow requirements. These new competitors rely partly on legal doctrines that question the primacy of the prior-appropriation doctrine as the sole basis of western surface-water allocation.

In the case of Native American water rights, the U.S. Supreme Court found, in *Winters v. United States* in 1908, that water was reserved implicitly in the treaties or treaty substitutes that created the separate Indian reservations. That decision reserved sufficient water for the "present and future needs" of the reservation communities. Although Native American water rights represent clear legal entitlements, they were ignored during the period when most western water development occurred (Moore, 1989). In *Arizona v. California*, in 1963, the U.S. Supreme Court explicitly allocated to Indian reservations more than 10 percent of the apportionment of the lower Colorado River. The outstanding Native American water rights that exist throughout the West have encumbered the water-rights system for every major western river basin. Folk-Williams (1982) documented more than 60 claims that totaled more than 45 million acre-ft/yr. Because the water in most western rivers already is completely appropriated, accommodating "new" Indian water rights will reduce traditional water rights in all economic sectors, including agriculture.

Maintaining river flow serves many uses—recreation, esthetic enjoyment, fish and wildlife, hydroelectric power generation, navigation, and pollution removal and dilution. Most of the Western States have adopted policies to reserve water for these purposes. The Federal government also can, and does, reserve river flow to meet the requirements of Federal reservations, such as national forests and national parks. The authority for this originates in the *Winters v. United States* ruling. Graff (1986) noted that the institutional mechanisms only now are forming to minimize conflict in reallocating water to instream use from diversionary use. Because of public support of uses of instream flow, it can be expected that the demand for instream flow will continue to compete strongly with other sectors of the economy. (For more details, see article in this volume "Instream Water Use in the United States—Water Laws and Methods for Determining Flow Requirements.")

In summary, surface-water use for irrigation is expected to decline because of the growing water demand by nonagricultural users, the lack of additional suitable surface-water storage sites, the need for expensive conveyance facilities, and concerns about the environmental affects of agricultural practices. Increases in ground-water use will be constricted severely in the West by declining ground-water levels and by competition with urban areas for the rights to those resources. Ground-water use for irrigation in the humid regions is expected to continue to experience modest increases as a form of drought insurance for crops and as a means of increasing yields. Water use for livestock production is likely to remain fairly constant, except for use associated with aquaculture, which is expected to increase.

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FOR ADDITIONAL INFORMATION

Michael R. Moore, William M. Crosswhite, and John E. Hostetler, U.S. Department of Agriculture, Economic Research Service, 1301 New York Avenue, N.W., Washington, D.C. 20005–4788.

Instream Water Use in the United States—Water Laws and Methods for Determining Flow Requirements

By Berton L. Lamb[1] and Harvey R. Doerksen[2]

INTRODUCTION

Water use generally is divided into two primary classes—offstream use and instream use. In offstream use, sometimes called out-of-stream or diversionary use, water is withdrawn (diverted) from a stream or aquifer and transported to the place of use. Examples are irrigated agriculture, municipal water supply, and industrial use. Each of these offstream uses, which decreases the volume of water available downstream from the point of diversion, is discussed in previous articles in this volume. Instream use, which generally does not diminish the flow downstream from its point of use, and its importance are described in this article.

One of the earliest instream uses of water in the United States was to turn the water wheels that powered much of the Nation's industry in the 18th and 19th centuries. Although a small volume of water might have been diverted to a mill near streamside, that water usually was returned to the stream near the point of diversion and, thus, the flow was not diminished downstream from the mill. Over time, the generation of hydroelectric power replaced mill wheels as a means of converting water flow into energy. Since the 1920's, the generation of hydroelectric power increasingly has become a major instream use of water. By 1985, more than 3 billion acre-feet of water (3,050,000 million gallons per day) was used annually for hydropower generation (Solley and others, 1988, p. 45)—enough water to cover the State of Colorado to a depth of 51 feet.

Navigation is another instream use with a long history. The Lewis and Clark expedition journals and many of Mark Twain's novels illustrate the extent to which the Nation originally depended on adequate streamflows for basic transportation. Navigation in the 1980's is still considered to be an instream use; however, it often is based upon a stream system that has been modified greatly through channelization, diking, and construction of dams and locks. The present (1987) inland water navigation system in the conterminous United States consists of about 12,000 miles of maintained waterways, over which about 500 million tons of cargo is carried each year (U.S. Army Corps of Engineers, 1988, p. 16).

Although not so widely practiced in recent years, streams have been used to dispose of raw waste products from homes, communities, and factories. This use has been discouraged by law and public policy because of public health concerns and the damage it causes to the environment.

Beginning in the mid-1960's, other instream uses gained new prominence in the water-resources arena—the assertion of a legal right to a free-flowing stream for biological, recreational, and esthetic purposes. These uses themselves, however, are not new. Riverine habitat always has produced fish, and the beauty of flowing water always has evoked a strong sense of esthetic appreciation. What is new is the emerging legitimacy and awareness of these non-economic uses under State and Federal laws and regulations. In the past, environmental uses of flowing water were ignored, for the most part, under a long-standing legal tradition that favored offstream uses and certain instream uses that had a strong economic basis.

The history of the instream-flow policy debate really concerns these recently recognized types of instream uses. Although the more traditional water uses have been protected by law, the recognition of other instream uses has resulted in substantial changes in State water laws. Although methods for determining the volume of water needed for most traditional water uses are relatively straight-forward and well-established, methods for determining water requirements for the instream uses have been developed only recently and are continuing to evolve.

Water laws that have favored the more traditional water uses, the inherent nature of conflict between instream and offstream water uses, and the special kinds of technological and philosophical problems posed by the "newer" types of instream uses are described below. Water laws that have been passed to accommodate the more recently recognized instream uses are summarized.

WATER-LAW CHANGES—THE WEST

Water is a finite but renewable resource. In times and places of plentiful supply or small demand, major conflict over the available supply is not common. In the Western States, however, because of the chronic scarcity of water, it is not surprising that "water wars" are common. It also is not surprising that the water laws in this arid region evolved to protect those who "got there first."

In the arid West, two early and major water uses were hydraulic mining and irrigated agriculture. These uses, which often required water to be transported for long distances from the stream to the point of use, also often consumed a large part of the diverted water (Gould, 1977, p. 4–5). To recognize this offstream nature of water use and to protect the earliest users, a body of water law, known as the appropriation doctrine, evolved. This law has two primary principles—first in time is first in right, and beneficial use of water is the basis of the right. First in time means that the earliest water-right holder has a right to all the water needed to fulfill the right, and then the second, the third, and so forth, can claim their rights. Each water right depends upon supplies available after all prior rights have been satisfied (Gould, 1977, p. 5). Thus, as the supply decreases, lower priority water right holders must stop using water until the more senior users can be satisfied.

[1]U.S. Fish and Wildlife Service. [2]U.S. Department of the Interior, Office of Program Analysis.

As applied in most Western States, the beneficial-use principle requires the user who diverts water to comply with State procedural requirements and to apply water to beneficial uses. State constitutions generally identify those uses considered beneficial, such as municipal, irrigation, industrial, mining, and livestock watering, and frequently list them in descending order of priority. The beneficial-use requirement, as defined by State laws, provides the basis for the legitimacy of a water right. However, for most water uses, the key determinant of the value and the reliability of a water right has been the priority date.

Conflict over such an essential resource as water has been almost a natural part of water-resources management over the years. The system of water law serves two important functions—it provides a means for resolving the myriad of conflicts among water users and it serves to protect the integrity and reliability of established water uses. However, the water-law system has proved to be an adversary to the so-called new instream water uses that emphasize a nondevelopmental, qualitative emphasis upon moving water within natural watercourses for esthetic enjoyment, instream recreation, fish and wildlife habitat, and enhancement of the quality of life. This point was emphasized by Dewsnup and Jensen (1977, p. 1), who wrote,

> To fully understand and appreciate the programs that are emerging in the various Western States to protect instream values, it is important to remember the circumstances surrounding the development of the appropriation doctrine of the West. The important point to keep in mind here is that the basic water law of the States was developed at a time when the prevailing theme was to divert and utilize as much water as was necessary to sustain agriculture, promote and maintain industrial growth, and satisfy community needs. The public interest was primarily an economic one.

As a consequence of existing water laws in many States, instream flows for these new uses were not considered beneficial, were unable to meet the diversion requirement, and (or) were given a priority date so junior that the authorized right could be rarely exercised. However, during the past 20 years State water laws and the interpretation of Federal laws have undergone significant changes to accommodate the newer, nondevelopmental instream uses of water.

The earliest formal legislative recognition of the need to protect instream uses of water occurred in 1915 when the State of Oregon prohibited the diversion of water from certain streams because they fed the spectacular falls in the Columbia River Gorge. Because this provision for instream flows protected esthetics as a legitimate water use, it was, in one sense, a clear departure from the past. The waterfalls in the gorge, however, provided a strong economic base for Oregon's important tourism industry. Consequently, the legal provision could be seen as the protection of an economic resource rather than as the explicit recognition of esthetic purposes as a beneficial use of instream flows. Furthermore, the legislature simply sheltered the stream from diversion; it did not provide a water right for the instream use.

In a similar situation only 2 years earlier (1913), the courts in the State of Colorado relaxed somewhat the requirement that a legal water right must be based on a diversion from a stream. Cascade Town was a resort area for tourists who were attracted to the local waterfall and the luxuriant vegetation nurtured by the spray from the fall. A power company planned to divert the stream above the falls through a turbine, thus depriving the falls of water. In an attempt to protect the falls, a lawsuit was filed (*Empire Water and Power Co. v. Cascade Town Co.*). The court maintained that the use of the falls for purely esthetic purposes was not a beneficial use. However, the court decided that the spray from the falls, which watered the vegetation, was a diversion, and that human diversion was not necessarily required. This decision became an important precedent for instream flows, even though its application was quite limited and indirect (Gould, 1977, p. 7).

Oregon took the lead among Western States in establishing more generalized protection of instream flows. In 1955, the State legislature established a policy recognizing the importance of instream uses. The law permits the water administrative body of the State to establish flow quantities that will minimize the effect of altered flows on the salmon fishery. This important law, however, still fell short of actually granting a water right for fishery use of water.

The establishment of a water right for instream use is vitally important because of the nature of western water law. First, the acquisition of a water right means that a use has passed all the tests of legal legitimacy and that the terms of the right are spelled out. Second, the acquisition of a water right provides each use with a priority date, so that it is superior to all subsequent rights. Third, even if the right is junior in time to many other rights, a junior water user can legally prohibit a change in stream conditions from those existing at the time that the junior right was established if the change would damage the junior right (Gould, 1977, p. 9).

In 1969, Montana became the first State to provide for the legal acquisition of a water right for instream uses, and the State Department of Fish, Game, and Parks was allowed to acquire such rights (Revised Code of Montana, Sec.89-801). Since then, other States have followed suit. At the present time (1987), water rights can be obtained by a State agency or other entity in Arizona, California, Idaho, Kansas, Montana, Nebraska, Nevada, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming (Lamb and Meshorer, 1983; McKinney and Taylor, 1988). The diversity of forms that the instream-flow programs in selected Western States have taken is shown in table 16.

WATER-LAW CHANGES—THE EAST

In the East, water quality is the problem, whereas in the West, prevailing wisdom long maintained that the volume of water is the problem. This follows from the fact that the West is sparsely settled, arid,

Table 16. Programs providing an appropriative water right in selected Western States as of 1987

[This is a partial listing; all States west of the Mississippi River, except New Mexico, have some sort of instream-flow program. Sources: As indicated by footnotes]

State	Program purpose(s)	Scope	Approach	Instream-right holders
Alaska[1]	Fish and wildlife; recreation; water quality; navigation.	Statewide	Stream-by-stream	Any public or private entity.
Arizona[2]	Fish and wildlife; recreation.	do	By stream segment	Do.
California[2]	Fish and wildlife; wild and scenic river; public trust.	do	Stream-by-stream; review of each diversionary water right.	Conditions on new water rights.
Idaho[1]	Fish and wildlife; recreation; visual quality; water quality; navigation.	do	Stream-by-stream	Idaho Water Resources Board.
Montana[1]	Fish and wildlife; recreation; water quality; future consumptive uses.	do	Basin-wide planning	Any political subdivision of the State.
Nevada[2]	Fish and wildlife; recreation; water quality.	do	By stream segment	Any public or private entity.
Oregon[2]	do	do	Basin-wide planning	Departments of Fish and Wildlife and Environmental Quality.
Utah[1]	Fish and wildlife	Limited	Stream-by-stream	State Division of Wildlife Resources.
Washington[1]	Fish and wildlife; recreation; visual quality; water quality; navigation.	Statewide	Basin-wide planning	State Department of Ecology.
Wyoming[1]	Fish and wildlife	Limited	Stream-by-stream	State of Wyoming.

[1]McKinney and Taylor (1988). [2]Shupe, 1988.

Table 17. Programs providing for instream flows in selected Eastern States as of 1987

[This is a partial listing; most Eastern States have some sort of statutory provision that could be used to protect streamflows. Source: Lamb, 1986]

State	Program purpose(s)	Scope	Approach	Type of protection
Iowa	Natural environment	Statewide	Stream-by-stream	Administrative rule.
Maine	River resources	16 streams	Important streams	Governor's executive order.
Michigan	Natural rivers; natural environment.	Statewide	Stream-by-stream	State and local administrative rules.
Minnesota	Natural environment	do	do	Administrative rule.
Pennsylvania	Fish habitat	Hydroelectric projects.	do	Do.
Wisconsin	Natural environment; navigation.	Statewide	do	Do.

and relatively free of pollution, whereas the East is more densely populated, water rich, industrial, and subject to pollution.

In the East, water law is based on the riparian doctrine, in which (in its purest form) owners of land along a watercourse are entitled to have the stream flow through their land not perceptibly retarded, diminished, or polluted by others (Ausness, 1983, p. 548). Unlike the appropriation doctrine, the early riparian system was consistent with the concept of instream flows; thus, instream flow as an issue in the East did not exist until recently, as explained below.

Population pressures, industrial growth, and an increase in irrigated agriculture in the Eastern United States and their attendant requirements for water have challenged the assumption that this region is "water rich." The concept of "natural flow" gave way to "reasonable use" as the guiding principle governing the exercise of a water right. Under the reasonable-use principle, any particular riparian land owner was entitled to use water for any beneficial purpose if that use did not unreasonably interfere with the water rights of others on the watercourse (Ausness, 1983, p. 549). In addition, many of the Eastern States have been moving toward a form of permit, or water-allocation system, as a means of providing water to persons who do not own riparian lands.

As a result of these increasing pressures on available supplies for offstream uses of water, several States in the East, as well as the Midwest, have established, or are considering, instream-flow protection programs. In 1949, Iowa became one of the first States to implement such a program by passing legislation to set flow standards on its streams. These standards limit the ability of riparian users to take water in times of shortage. This is accomplished, in part, by administratively designating streams as "protected." Iowa's instream-flow program is the most comprehensive of any Eastern State and has had long-standing success. Other Eastern States and their form of instream-flow protection are listed in table 17.

FEDERAL RESERVED WATER RIGHTS

As a matter of public policy, the States traditionally have been given precedence in the development of water laws. During the 1970's, a new legal concept in water rights, which is called the Federal Reserved Water Rights, emerged that was long thought to apply only to Indian reservations. This doctrine allows the Federal government to claim early priority dates for water rights on certain Federal lands. As described by the U.S. Supreme Court (*Cappaert v. United States, 1976*):

> This Court has long held that when the Federal Government withdraws its lands from the public domain and reserves it for a Federal purpose, the Government, by implication, reserves appurtenant water then unappropriated to the extent needed to accomplish the purpose of the reservation. In doing so the United States acquires a reserved water right in unappropriated water which vests on the date of the reservation and is superior to the rights of future appropriators.

Under this doctrine, the lands that are set aside (reserved) from the public domain for a particular purpose, such as national forests, national parks, national wildlife refuges, and wild and scenic rivers, are inferred to have a water rights to carry out the purposes of the reservation.

The quantity of the water right is limited to the quantity needed to accomplish the purpose(s) of the reservation. The priority date, as it relates to water rights created under State laws, is the date on which action was initiated to create or change a Federal reservation (President's Task Force on Non-Indian Federal Water Rights, 1980).

The Federal Reserved Water Rights doctrine for instream-flow purposes is important for two reasons—it establishes as legitimate certain instream uses of water (for example, watershed management, fishery maintenance, recreation, and esthetics) that otherwise might not have been recognized as "beneficial" under State water laws, and it gives these instream uses a priority date much earlier than would have been possible by using State water-rights procedures. Because Federal Reserved Water Rights apply to future as well as present water needs and might supersede senior rights in some cases, the doctrine introduces considerable uncertainty for State water managers and existing water users. To date (1987), claims under the doctrine have been for very small amounts of water.

METHODS FOR DETERMINING INSTREAM-FLOW REQUIREMENTS

As both State and Federal water laws have recognized various types of instream uses, technical methods have been developed and refined to determine quantities of water to meet the needs of each use. One of the "new" instream uses—fish-habitat maintenance—actually has been part of the water-management scene for a number of years. Before the concept of instream flow became widely known in the 1970's, State and Federal fishery agencies had negotiated for "fish flows" for the operation of a number of dams, under provisions of the Fish and Wildlife Coordination Act of 1943 (first passed in 1934 and subsequently strengthened through amendment). These fish flows typically were expressed as "minimum flows."

These efforts to obain fish flows challenged the dominance of economically oriented, diversionary uses of water. Nevertheless, from the perspective of today's understanding, there were six serious flaws in the concept of minimum flows for fish-habitat maintenance.

- These early "minimum flows" were considered to be just that—a minimum-flow level below which fish populations (or other values, such as recreation) would be seriously harmed. In fact, if true minimum flows were maintained for extended periods of time, fisheries and other instream uses would be seriously curtailed and might cease to exist. The ability of a fish population to survive a single 1-in-10-year low-flow event might give the false impression that the fish population could remain viable even if this minimum flow (drought) condition was imposed continuously.

The long-term effects of continuously maintaining these artificial minimum flows seldom are the same as the infrequent, naturally occurring, short-term effects that appear in the historic record. As water projects were built and operated, it became apparent that, in many instances, the fishery resources were decimated as a result of imposing minimum-flow standards (Trihey and Stalnaker, 1985, p. 177).

- Long-term imposition of low flow ignores the importance of periodic flushing events to the maintenance of fish habitat. The channel shape and bedforms to which fish have adapted has formed in response to cycles of flooding and low flows. Continuous low flow could drastically alter the nature of a channel so that it no longer is a viable habitat (Tennant, 1976, p. 7).
- Minimum flows for fisheries were perceived as limits imposed on legitimate water uses rather than as legitimate uses in their own right. Within the water development community, instream flow tended to be viewed as water wasted.
- Minimum flows were unenforceable because they were not based on water rights. They were only as good as the word of the operator of a dam or diversion. Even if minimum flows were provided, they were available for appropriation for other uses just below the dam or diversion.
- The concept of minimum flows was too rigid to be a useful negotiating tool. It had an "all or nothing at all" ring to it. Water developers asked such questions as, "How much would a fishery be improved by a little additional water?" or "What would happen to the fishery with a little less water?". Biologists could not answer these questions.
- The minimum-flow concept, as practiced in earlier years, failed to recognize the different water-flow requirements of the various instream uses. A commonly held belief was that fish required a greater minimum flow than all other uses. Therefore, according to the prevailing wisdom, if there is enough water for fish, there is enough water for other instream uses.

During the early 1970's, as streamflows for fishery maintenance and management, recreation, water-quality maintenance, esthetics, and maintenance of estuarine ecosystems were recognized as legitimate uses of water, the terms "instream flow" and "instream-flow needs" began to replace the concept of minimum flow. Instream uses now were thought to have their own set of flow requirements that could not be satisfied by water "left over" after other uses were satisfied; for example, flow requirements for a particular instream use might not be just a single minimum, but could vary seasonally or even daily. Further, instream needs were found to be different for each use and often were in conflict with one another (fig. 58). Until 1976, the hydrographs shown in figure 58 for fish and wildlife, estuary inflow, waste assimilation, and recreation would have appeared as straight lines (constant minimum flow), if included at all, in an analysis of streamflow allocation.

Two conferences—one on a description of existing instream-flow methodologies and the other on the major legal, institutional, and technical problems associated with instream flows—that were held in the 1970's focused national attention on this issue (Orsborn and Allman, 1976; Stalnaker and Arnette, 1976). Of the problems identified in both conferences, one was emphasized over and over—the need for an incremental methodology. A means was needed to determine the value of an increment of flow to assess adequately needs and to negotiate flow releases sufficient to satisfy those needs.

Since the mid-1970's, instream-flow methodology has advanced significantly; it now includes the development of incremental approaches for assessing

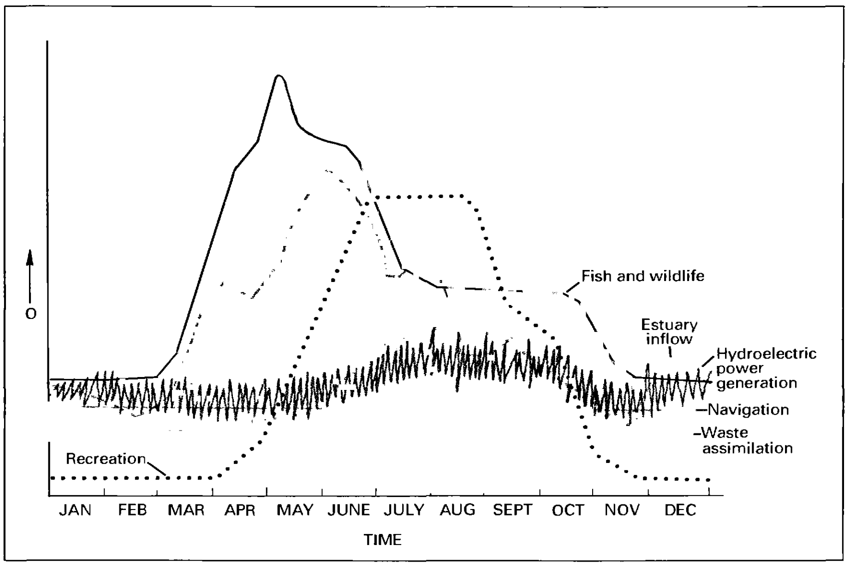

Figure 58. Schematic of the nature of streamflow requirements for instream uses throughout a calendar year. (Source: Modified from U.S. Water Resources Council, 1978, v. 1, p. 42.)

the effects of varying flow regimes on fish habitat, recreation, and other instream values. Several important research reports reflect past research and also serve as references for future methodological advances. Bovee (1982) addressed instream-flow assessments for fish habitat; his report has become the baseline for discussion of emerging technologies. Tennant (1976, p. 10) described the need for periodic flushing events to maintain certain hydrologic characteristics of the channel necessary to protect the environment for fish. Hyra (1978) analyzed the streamflow requirements of recreational activities.

The technologies developed since 1978 fall into two categories—those appropriate to preliminary planning and those designed for project impact assessment. The preliminary planning methods are related most closely to the traditional concept of minimum flow. These methods typically use a streamflow characteristic that represents the minimum flow for a particular instream use. Examples include 40 percent of mean annual flow, the point at which the size of wetted perimeter begins to fall sharply with small reductions in flow, flows equaled or exceeded 90 percent of the time, 10 percent of the mean annual flow, or the lowest flow on record (Trihey and Stalnaker, 1985).

Project impact assessment requires a different approach. During the 1970's, instream-flow assessment methods that attempted to evaluate fish habitat in terms of changes in the environment were developed. These "incremental" methods estimate the quality of fish habitats at different increments of streamflow. Early investigators of these approaches used depth, velocity, and substrate criteria to evaluate the influence of incremental changes in streamflow on the quality of spawning habitat for salmon in Washington streams (Collings and others, 1972). Waters (1976) applied weighted criteria for depth, velocity, and substrate/cover and introduced computer simulation to evaluate the response of rainbow trout habitat to streamflow in California.

The application of hydraulic modeling methods in conjunction with streamflow-dependent criteria for fish habitat began with single transect methods in which the stream model was based on the measurements taken at a single cross-section of the stream. The U.S. Forest Service introduced one such method called R-2 CROSS (Isaacson, 1976).

Single transect methods were followed by more sophisticated multiple transect methods in which the stream models were based on several representative cross sections of the stream channel. Fishery impact assessment methods were adapted from water-surface profile (WSP) simulation models that were used by the U.S. Bureau of Reclamation, the U.S. Soil Conservation Service, and the U.S. Army Corps of Engineers. The multiple transect techniques support predictions of depth and velocity at points across a transect and changes in the wetted perimeter of the channel as a function of flow (Dooley, 1976). The development and refinement of hydraulic simulation models to facilitate evaluation of habitat conditions under a wider range of streamflow conditions has continued to the present (Milhous, 1984). The Physical Habitat Simulation Model (PHABSIM) is an important analytical component of the Instream Flow Incremental Methodology (IFIM) described by Bovee (1982).

In general, project impact assessment approaches are more labor and data intensive, and more costly, than preliminary planning methods. Thus, the first question facing the manager is which of the two approaches to use. The decision is based on the magnitude and nature of the problems being addressed. Generally, preliminary planning methods would be appropriate whenever a specific project has relatively benign effects; fisheries, recreational, and other instream values are limited; or development is not anticipated for several years in the future (Trihey and Stalnaker, 1985).

The more complex and data-intensive project impact assessment methods are used when alteration of the streamflow, stream temperature, channel structure, or water chemistry is anticipated and there are concerns about the effects of these alterations on instream values. These methods can help answer the question, "What will happen if the minimum flow standards are violated?". These methods also might provide useful guidance to resource agencies seeking opportunities to improve existing fish populations or to alter the species composition of a stream.

Once the decision is made as to the type of method to use, the manager has an array of specific methods available. The choice of method depends on the resource agency's management policy, the region of the country, the type of instream uses to be provided, and, for fishery uses, the species of concern.

The more frequently used methods of determining instream flows are listed in table 18. Two conclusions can be drawn from those data. First, they show the diversity of available methods. This diversity is the result of many people independently attempting to solve the technological problems associated with assessing appropriate streamflow levels for instream uses and also of the variation of instream uses. Second,

Table 18. Methods for determining instream-flow requirements and number of States using method

[Source: American Fisheries Society survey conducted by Dudley Reiser in 1987 (unpublished). More complete information on each method can be obtained from Lamb, 1989]

Method	Number of States using method
Instream flow incremental methodology (IFIM)	38
Tennant method	16
Wetted perimeter	6
Aquatic Base Flow (ABF)	5
7-Day, 10-Year Low Flow (7Q10)	5
Professional judgment	4
Single Cross Section (R-2 CROSS)	3
USGS Toe-Width	2
Flow records/duration	2
Water quality	2
Average Depth Predictor (AVDEPTH)	1
Arkansas	1
Habitat quality index	1
Oregon	1
Vermont fish-flow	1
U.S. Army Corps of Engineers Hydraulic Modeling (HEC-2)	1

the data demonstrate that some methods are beginning to be accepted as "standard"; for example, the IFIM (a project impact assessment method) and the Tennant Method (a preliminary planning method) are used by 38 and 16 States, respectively.

CONCLUSIONS

Since the mid-1960's, instream uses of water for fisheries and environmental purposes have gained legal legitimacy along with the traditional offstream water uses, such as irrigation and domestic uses, and the commercially oriented instream uses, such as navigation and hydroelectric power generation. There is a continuing trend toward adoption of instream protection laws and policies by the States, although the legal approach to instream flows differs from State to State. Each State appears to adjust its water program to fit the circumstances of abundance, allocation law, and development. As a result, traditional water-management organizations are accommodating instream uses in their day-to-day operations. The Federal Reserved Water Rights doctrine has opened the door for water rights to be claimed to carry out the purpose of certain Federal lands. However, the actual quantities of these rights typically are determined in State water-adjudication procedures.

Instream uses for environmental purposes also have gained scientific legitimacy, as certain methods of determining instream flow are becoming broadly recognized as "standard," in contrast to the earlier regionally oriented approaches. Questions currently under discussion center around the issue of how much reliance should be placed on the results of simulated models as compared with field observations. Although every method is based on some stream measurements, there is a question of the extent to which extrapolations from existing data can take the place of long-term field observations.

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FOR ADDITIONAL INFORMATION

Berton L. Lamb, U.S. Fish and Wildlife Service, National Ecology Center, Aquatics System Branch, 2627 Redwing Road, Fort Collins, CO 80526-2899 and Harvey R. Doerksen, U.S. Department of the Interior, Office of Program Analysis, 18th and C Streets, N.W., Washington, DC 20240

Water-Use Forecasting—Benefits and Capabilities

By Leonard Shabman[1]

Water-resources planning requires a view of the future; that is, a forecast of the water situation that might exist with or without a particular investment, policy, or program. Only with a view of the future can problems be anticipated and solutions defined. Thus, one task of water-resource planning is to evaluate the merits of alternative capital investment and management strategies for water-resource development and for providing wastewater treatment. Another task, no less important, is to anticipate water-use conflicts so that initiatives capable of promoting efficient and equitable distributions of scarce water can be developed.

Water-use forecasts, which are an essential part of water-resource planning, are estimates of the quantity of water that will be used by different sectors of the economy at future points in time. In water-supply and wastewater-system planning, the water-use forecast is compared with the existing capacity to collect, treat, and distribute water and wastewater for average- and peak-use periods. This comparison helps determine if there might be a water shortage and, if so, helps initiate a planning activity that might include a capital facility investment strategy. Similarly, water-use forecasts might initiate an investment in water development for irrigation or hydroelectric power if a comparison of the anticipated seasonal need for water to grow a particular mix of crops or to produce electricity with the storage capacity of the existing water system suggests that a water shortage will occur. In planning for future water allocations, water-use forecasts help identify the potential for future conflicts over water rights and also help define the merits of alternative reforms of water law and administrative organization for water management.

Clearly, water-use forecasts help structure the public debate over such fundamental water-policy questions as

- How much money shall be spent, and who shall pay, for water-system expansion?
- Should allocation processes for water-use rights be modified?

Although the projection of water use lies at the heart of water-policy and investment planning (Gardiner and Herrington, 1986), the ability to project future water use is limited, at best, even for the short term of less than 10 years (Black, 1988). For the longer term, it is likely that a precise projection will prove inaccurate with the passage of time. This conclusion is not an indictment of the quality of water-resource planning, rather it is a realistic acknowledgment of the fact that the underlying technical, social, economic, and political factors that determine future water use are likely to change in unpredictable ways.

To determine the accuracy of past water-use forecasts, Osborn and others (1986) studied two predictions for 1980 water use in the Nation's major river basins—one by a Senate committee (U.S. Congress, Senate Select Committee on National Water Resources, 1960) and the other by the U.S. Water Resources Council (1968). Both of these basin-level predictions were substantially in error as a result of events in the economy and in the political and social arenas that could not reasonably have been anticipated. Examples of such events are the environmental movement, the decline in comparative advantage for United States steel production in the world economy, and the shift of population to the South and the West. On the national level, most projections in the past have proved inaccurate (fig. 59).

The inability to predict with accuracy is not unique to the water-resources area. In a comprehensive review of the reliability of forecasting, Ascher (1978) concluded that, more often than not, forecasts in the areas of population, economic activity, energy, transportation, and technological change have been inaccurate. More recent articles continued to raise questions about the ability to accurately forecast economic activity (Kolata, 1986; McNees and Ries, 1983). The difficulty of accurately forecasting such fundamental factors as population and economic activity affects the accuracy of estimates of future water use.

The water-resource planner, thus, is faced with a problem—projections lie at the heart of the planning process, yet, with the benefit of hindsight, projections over any long period of time are likely to prove incorrect. This problem, which is recognized among water-resource planning professionals, usually results in water-use forecasts that are based in part on statistical methods and data and in part on professional judgment and planning philosophy. The uses of and philosophical underpinnings for water-use forecasts are discussed in this article. The challenges of making capital investments in water-supply and wastewater-treatment facilities are used as examples.

WATER-USE FORECASTS—RATIONALE AND METHODS

In forecasting water use, two projection philosophies and methods can be defined—extrapolation of past trends and causal analysis. Each of these is described below.

Extrapolation of Past Trends

Extrapolation of past water-use trends assumes that future water use will increase at the same rate as past water use. The planner can use simple time-series extrapolation graphs to plot past water use in relation to time. Alternatively, the planner might employ a statistical estimate of the historical relation between water use and time and use this estimated relation to project future water use.

A variation on the time extrapolation is to develop a simple model of the factors that are expected to determine water use; for example, residential or domestic water use can be estimated to be the product of per capita water use and population. A time

[1]Virginia Polytechnic Institute and State University.

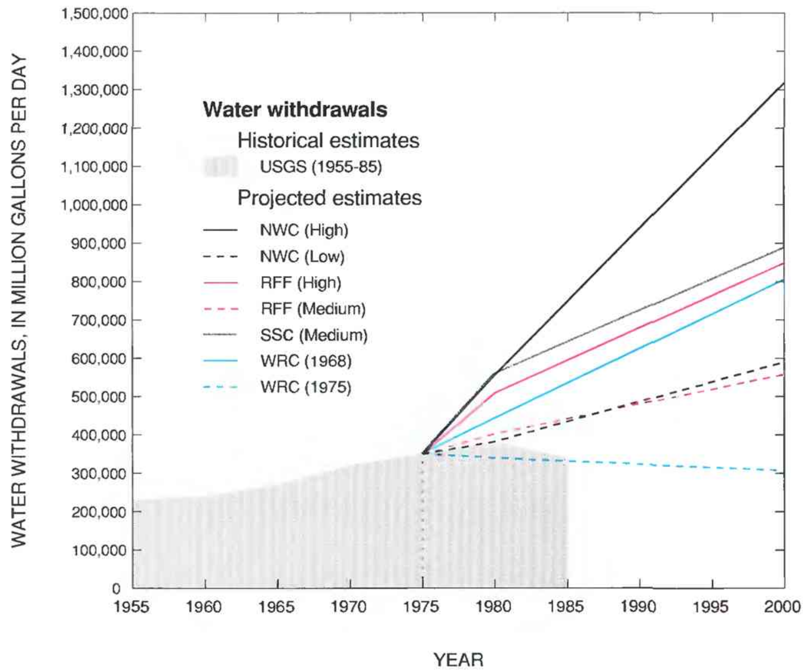

Figure 59. Historical and projected water withdrawals in the conterminous United States, 1955–2000. NWC, National Water Commission (1973); RFF, Resources for the Future (Wollman and Bonem, 1971); SSC, Senate Select Committee on National Water Resources (U.S. Congress, Senate Select Committee on National Water Resources, 1961); WRC, U.S. Water Resources Council (1968, 1978); USGS, U.S. Geological Survey (MacKichan, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988). Note: Starting point for projected estimates was 1975, the most recent year for which USGS data were available. USGS data for 1980 and 1985 added here to update historical estimates. Data for NWC, RFF, WRC (1968) are for fresh and saline water; data for SSC, WRC (1978), and USGS are for freshwater only. (Source: Modified from Viessman and DeMoncada, 1980, p. 236.)

extrapolation of these two factors and the resulting projections are combined to form a water-use projection; for example, a trend extrapolation of per capita water use might be combined with general regional planning estimates of population growth in an area to form the water-use projection.

Trend extrapolation has several characteristics that might make it attractive as a projection method. First, because it is simple and inexpensive, it could be used by a planner who has a limited planning budget, limited data base, or limited access to sophisticated analytical tools. Second, the end user of the projection—the client of the planner—could find this approach intuitively appealing and easily understood both in terms of its rationale and the analytical methods employed. Third, trend extrapolation might yield a result that the planner and the client feel supports their prior judgment on the appropriate investment decision; for example, the projection might suggest an expenditure that confirms their views on the needed capital investment for the area. This third point is discussed later in this article.

Causal Analysis

A characteristic of the trend extrapolation approach is that the underlying causes that determine water use need not be specified by the planner or made explicit for the investment decisionmaker. As a result, the reasons why water use will change in the future and the possible shifts in economic trends and public policy actions that might alter future water use are not addressed explicitly. An increased understanding of the factors that determine a water-use projection result can be achieved if the planner makes a causal analysis.

A causal analysis presumes that water-use levels are a response to social, economic, and public policy forces that can be described and, to some extent, predicted. After the underlying causal factors are hypothesized to affect water use, the relation between these factors and water-use levels is determined. Finally, by projecting future trends in these factors, predictions of future water use can be made by assuming the causal relation that has held in the past will continue to hold in the future; for example, average-day residential water demand could be hypothesized to be a function of water price, billing method, household income, number of customers, and weather variables. By using historical data for one area or data at a point in time from several areas, a statistical estimate, which quantitatively measures how each causal determinant affects the level of water use, can be made. Then a water-use forecast is made by applying projections of the causal variables to the estimated relations between those variables and water use.

This approach can be superior to time extrapolation as a decisionmaking aid for two reasons. First, a causal analysis can focus upon factors that might be under the control of the decisionmaker (for example, pricing strategies) and can suggest public policy actions to control and direct water use as part of the overall investment and management strategy. Therefore, a causal analysis will not only define future use levels, but also can suggest possible solutions for managing the capital investment problem. Second, a causal analysis will be open to detection of the possibility of error involved in the forecast. Past reviews of forecast accuracy have found that basic assumptions and conceptual logic are the most important sources of forecast error (Ascher, 1978; Osborn and others, 1986). Because conceptual reasoning, statements of basic assumptions, and data and methods must be clearly stated for causal projection, a causal analysis can increase the credibility of the resulting forecast among planners and decisionmakers, if not the potential accuracy.

A causal analysis of water-use determinants, rather than time extrapolation, can increase confidence in a water-use forecast for investment decisionmaking. However, the planner still faces the question of how far to partition a water-use model into its causal factors. This is a critical decision because, as noted above, the underlying logical components of the projection model are the key determinants of projection accuracy. Although the degree of disaggregation will be a function of available analytical time and resources, there is a basic analytical question of how far to go. Consider the following example.

At the first level of detail, water use might be considered to be a simple function of time. This is the "time extrapolation" approach.

$$\text{Average-day residential water use} = f(\text{time}). \quad (1)$$

If this approach is considered to be too simple, then a more detailed model could be developed; for example, population and per capita use, which are two factors considered to be determinants of water use, might be used to build a model of water use,

$$\text{Average-day residential water use} = \text{population} \times \text{per capita use}. \quad (2)$$

A still more detailed causal analysis is possible by further disaggregating these causal factors. First, consider the determinants of population change—

$$\text{Average-day residential water use} = h\,[(\text{initial population} + \text{births} - \text{deaths} + \text{net migration}) \times \text{per capita use}]. \quad (3)$$

Equation 3 includes a more detailed causal description of the factors affecting population growth. However, equations 4, 5, and 6 offer still more detail, which in turn can be included in equation 7—

$$\text{Births} = j\,(\text{age distribution}), \quad (4)$$

$$\text{Death} = k\,(\text{age distribution}), \quad (5)$$

$$\text{Net migration} = l\,(\text{economic activity}), \quad (6)$$

$$\text{Average-day residential water use} = [\text{initial population} + j\,(\text{age distribution}) - k\,(\text{age distribution}) + l\,(\text{economic activity})] \times \text{per capita water use}. \quad (7)$$

The effort to disaggregate the causal factors underlying population change also can be extended to the various factors that determine per capita water use; for example, per capita water use might be expressed in functional form—

$$\text{Per capita water use} = m\,(\text{marginal price of water, household income, climate factors}). \quad (8)$$

Then substitution of equation 8 into equation 7 yields a more complete casual model shown in the following equation 9.

$$\text{Average-day residential water use} = [\text{initial population} + j\,(\text{age distribution}) - k\,(\text{age distribution}) + l\,(\text{economic activity})] \times m\,(\text{marginal price of water, household income, climatic factors}). \quad (9)$$

As the level of detail is increased from equations 1 through 9, the causality imbedded in a water-use projection becomes clearer. Once the causal model is fully specified, statistical analysis of the available data would be used to estimate the separate relations between each of the causal variables and the variable of interest, water use. The estimation of these statistical relations might be based upon the historical data for one area or data at a point in time for several areas. The statistical model allows the planner to determine how much water use will change in response to specific changes in one or more causal variables; for example, the effects of increases in household income on water use might be determined. The planner must recognize that changes in social values and public policy could alter the statistical estimates of the relations between the causal factors and water use; for example, the response of water use to marginal price could change as housing styles and landscaping practices change in response to social trends.

Of course, no matter how much detail is considered in a causal model or how confident the planner is in the statistical estimates, the accuracy of the water-use projection will depend upon how well the most basic causal factors themselves are projected. Often the projections of the causal factors will be based upon a trend extrapolation or an educated or expert guess. Therefore, a causal analysis differs most significantly from a trend extrapolation in the opportunity that it offers to assess and review the underlying logic and assumptions behind a projection. Because the key factors that might make a projection wrong can be identified, the user of the forecast has a basis for forming a judgment about the likelihood of projection error.

Sensitivity analysis is a useful tool for establishing confidence in a water-use projection. A sensitivity analysis identifies how much a particular causal factor needs to vary from the projected level in order for the water-use projection to be significantly in error; that is, sufficient to change the investment decision. This analysis is of greatest use if the causal determinants of the demand forecast are highly disaggregated. Consider the example of population as a determinant (equation 2). A sensitivity analysis that concludes that a 15-percent error in the population projection will sufficiently alter the water-use projection enough to change the investment decision is of limited decisionmaking value. The decisionmakers need to understand the core assumptions that underlie the population projection in order to determine whether they believe a 15-percent error in the population projection is likely. Equation 9 serves the decision process better than equation 2, but there is no guarantee that the projection that uses equation 9 will prove any more accurate in hindsight.

ACCEPTABILITY OF WATER-USE FORECASTS

Water-demand projections are an integral part of a public decisionmaking process for water-resource management. Therefore, estimates of future water demands will be accepted by decisionmakers when the estimates have both technical credibility and support the goals of water-resource decisionmakers. Two goals that typically are considered in accepting a projection as a basis for water-system investment and management decisions are local desires for economic growth and the desire to avoid surprise.

WATER FOR ECONOMIC GROWTH

Time-trend extrapolation and causal analyses both assume that future water use is determined by population and by economic change, which usually are considered to be independent of the chosen water-system management and investment strategy. However, many decisionmakers believe that investing in capacity in excess of projection will induce growth that would not otherwise be realized. Thus, projected water demands will be exceeded because an investment in water and wastewater facilities is made. Water-system investment is considered to be an instrument of economic growth and, as such, it can create a future demand that might not be reflected in a projection. An acceptable water forecast will be one that includes the possibility of this occurring and, therefore, that supports the possibility of investing in what, from the planners' best projection, appears to be excess capacity.

AVOID SURPRISE—RISK ATITUDES AND PROJECTION

Projection accuracy is elusive. Therefore, decisionmakers, recognizing the high likelihood of a projection being wrong, must make a judgment on the acceptable direction for projection error and then choose a management and investment strategy accordingly. One strategy is to favor projection assumptions, logic, and methods that tend to err on the so-called high side. If investment is made for a high-side projection, then the result is to assure certainty of supply. A corollary benefit is that the prospects for induced growth are maintained.

An alternative strategy for dealing with surprise is to maintain flexibility in water-system management and investment decisions. This strategy deals with projection uncertainty by continuously monitoring water use and making adjustments over time through a combination of demand management and incremental additions to capacity as the demand becomes more certain. If maintaining flexibility is a goal for dealing with forecast error, then the projection at any time is a tentative guide to near-term investment and water-use management and serves as a framework for understanding the factors affecting water-use patterns. Causal analysis is essential for the strategy.

Each strategy for dealing with projection error has potential benefits and costs. As a benefit, flexibility offers a financial cost-savings opportunity because a time pattern of investments that is well-matched to demands is being pursued and because system capacity is developed only in the amount and at the time it is needed. As a cost, there are several potential adverse consequences of pursuing a flexible or a wait-and-see investment strategy. First, this strategy could leave system capacity inadequate if demand unexpectedly increased. Second, in seeking to maintain flexibility, a water system could lose an investment opportunity; for example, a possible reservoir site might be used for another purpose. Third, many system planners consider excess capacity a hedge against future inflation. Of course, for this inflation hedge to be valid, the cost of the construction should be expected to rise faster than the ability of the system customers to pay. Fourth, a strategy of flexibility often requires making decisions that politically are more difficult than raising revenues for a capacity expansion. These decisions, which include the need to implement successful demand management by water pricing, land-use controls, and drought-emergency planning, could require repeated applications, reviews, and legal challenges to facility construction plans.

The benefits and costs of the certainty-of-supply strategy can be considered to be the inverse of those of the flexibility strategy. An investment approach favoring certainty promises that a water system will be less likely to be caught short by sudden demand shifts. Also, this strategy assures that an investment opportunity, which could be lost by delay, is taken as soon as possible. As a corollary benefit, this strategy often promotes local growth.

A certainty strategy favors a projection that is likely to err on the high side. However, if, with hindsight, the projection proves to be too high, than the adverse affect is excess system capacity over time and a misallocation of investment funds. The cost of excess capacity could result in inadequate system revenues to retire a debt incurred to finance the system and in less funds available for other private and public uses.

A CHANGING INVESTMENT CLIMATE?

Planning practices in the past favored acceptance and use of projections that supported the building of excess system capacity for the purpose of promoting economic growth and assuring certainty of supply. Because forecast error was inevitable, it was presumed to be better to err on the high side by having too much capacity for the demand that materialized. In the words of the Senate committee (U.S. Congress, Senate Select Committee on National Water Resources, 1960, p. 9), which published the first set of comprehensive regional water projections, "it is generally better to overbuild than to underbuild."

This planning practice was supported, in part, by the manner in which the cost burden of investment decisions was distributed. For many years, the system users did not bear the entire cost burden because costs were spread over numerous persons and governments. This fact reduced the incentive for system planners to examine the costs of certainty and growth promotion as decision goals.

Although significant aggregate costs of excess capacity might be a consequence of high-side projections, the cost to the individual customer might not be significant if that cost is spread over time and many customers. Thus, from one perspective, large, perhaps excessive, capacity investment could be seen as a potential white elephant, whereas from another perspective, it could be argued that excess capacity is a low-cost (per customer) insurance policy against inadequate capacity for the community, a low-cost (per customer) local economic growth strategy, and a hedge against possible real cost increases for future investment.

Not only might costs be spread over a large customer base, but also the costs that are incurred might not be borne fully by the system users. When costs are shared with others through intergovernmental cost sharing and by cost recovery from general revenue sources, such as sales and property taxes rather than user fees, growth and certainty goals will be pursued more vigorously. A recent Congressional Budget Office (1985) study illustrates this effect. That study compared the capacity investment decisions of localities for wastewater treatment as those decisions were influenced by the amount of intergovernmental grants available for the system. The study found (p. xii) that

> ***if local costs were low, fewer cost-saving decisions were made. But as greater financial responsibility was placed on the municipality, expected sewer fees grew and citizens become more concerned, increasing pressure on local officials to reduce costs. This process led to the selection of simpler treatment technologies, limited construction of reserve capacity, rigorous cost oversight, and, ultimately, shorter construction periods.

The cost-burden distribution that helped reinforce past investment strategies favoring certainty and promotion of growth could be changing. Nonetheless, because institutional developments remain unsettled, the following discussion is offered.

- The 1970's began a period of real construction-cost escalation. The Engineering News-Record (1986) (ENR) index of construction costs rose faster than the rate of general inflation (U.S. Bureau of the Census, 1987) during the period and raised the inflation adjusted cost of building excess capacity. Specifically, from 1967 to 1984, the ENR index rose 384 percent, and the gross national product (GNP) price deflator rose 301 percent.
- Federal legislation, such as the Clean Water and the Safe Drinking Water Acts, have resulted in construction changes for wastewater-treatment systems and water-supply systems. By raising the unit costs of water and wastewater treatment, these laws have increased the cost of building excess capacity into a system.
- Intergovernmental grants, as a source of revenues for the construction of water-supply and wastewater-treatment systems, have declined. This has forced an increasing cost burden onto local governments, which must increasingly seek to finance their investment costs through either the private bond market or the special revolving funds that are developed at the State level (Snyder and others, 1984). The use of sinking funds paid into accounts of special districts as a form of nondebt financing also has received attention as an alternative to debt financing.
- The availability of general revenues, such as property taxes, to support water-capacity expansion has been sharply reduced (Moreau, 1988). This reduction in tax availability has increased the use of water and sewer fees and development impact fees to retire debts incurred by special-purpose districts.
- The private bond market is pessimistic rather than optimistic about the justification for public-works expenditures. The financial market will pay particular attention to the question of whether or not the system customers and revenue will materialize during the time of the bond repayment—often less than 20 years. To avoid risk, the market will finance only capacity expansion projections that appear justifiable on the basis of technically sound projections of relatively short term water-use revenues.

The combined result of the above changes in the planning environment is to increase the cost of pursuing certainty and local economic growth as goals of water-system investment and to shift such costs onto the direct users of the project. If the preceding arguments are valid, then a new set of decisionmakers will be introduced into the capacity-investment process—those who will directly pay an increasingly larger bill for capacity expansion. The balance between the goals of flexibility for cost-saving efficiencies and of growth promotion and certainty will be reviewed by these new decisionmakers, and the response to the risk of projection error may no longer be to construct excess capacity.

IMPLICATIONS FOR WATER-USE FORECASTS

A water-use forecast will be used if it supports a politically acceptable investment and management strategy and if the technical approach is understood and considered to be valid by the responsible decisionmakers. The preceding section suggests that preferred water-investment strategies could be altered as a result of changes in the institutional environment. However, the capital-investment problems still require that a multiyear perspective be taken. Investment decisions will depend upon the content and the use of water-use forecasts because the question of revenue potential for the recovery of costs through user fees will force greater attention to defining forecast rationales and because the resulting projections will be more carefully reviewed.

Perhaps if more sophisticated causal models were used, more accurate water-use forecasts would be possible. However, the accuracy of long-term forecasting always will depend upon anticipating changes, such as population shifts, that are beyond the control of water managers. The unsurmountable problem of knowing the unknowable remains and will continue to limit the accuracy of long-term forecasts.

Nevertheless, the process of making projections can play a significant role in the development of a political consensus among the direct project users who will pay a larger bill than in the past for capacity expansion. The projection process helps illuminate issues and resolve debate over the best investment and management strategy by highlighting the trade-offs between reduced cost, growth inducement, and certainty as investment goals. Within this context, the test of forecast accuracy might be in achieving a consensus of professional and political judgment on the validity of the logic, data, and techniques that are used to establish a projection and then an investment strategy.

This perspective means that

- Water-use forecasting need not be a prescription for future investment, but rather it can be a tool to organize the understanding of factors that might influence water use.
- Forecasters should be more attentive to the effects that their forecasts would have in directing the public-investment process and less concerned about whether or not the forecasts will prove ''accurate.''

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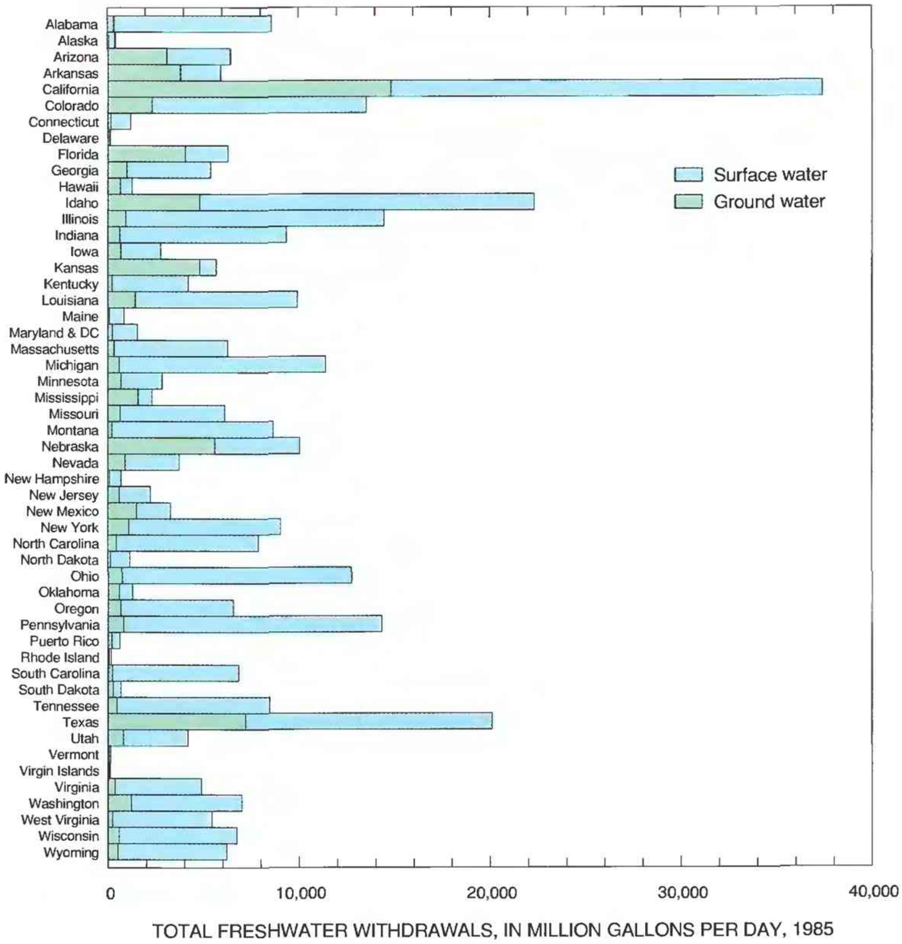
FOR ADDITIONAL INFORMATION

Leonard Shabman, Department of Agricultural Economics, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

STATE SUMMARIES OF WATER SUPPLY AND USE



SYNOPSIS OF STATE SUMMARIES OF WATER SUPPLY AND USE

INTRODUCTION

The State summaries of water supply and use in this volume are based primarily on water-use data compiled by the district offices of the U.S. Geological Survey's Water Resources Division, in cooperation with the State agencies that are involved in the National Water-Use Information Program. Data for 1985 were summarized in "Estimated Use of Water in the United States in 1985" (Solley and others, 1988) by State and water-resources region; in this 1987 *National Water Summary*, the data are summarized by county, river basin, and aquifer for each State. If, in the judgment of the U.S. Geological Survey water-use specialists, improved estimates of 1985 water use were available for some States at the end of 1987, appropriate adjustments were made to the water-use data for those State summaries.

Water-use estimates are given for several categories of water use. The State summaries document withdrawals of fresh surface and ground water, amounts of water temporarily lost to the immediate area (consumptive use), and amounts returned to the ground-water or stream system (return flow). Where significant, use of saline water and reclaimed sewage wastewater is described. The State summaries emphasize offstream water uses that require diversion or withdrawal rather than instream uses. Instream uses, which include hydroelectric power generation, fisheries, recreation, navigation, and waste transport, are very difficult to quantify and evaluate. At present, hydroelectric power generation is the only instream water use quantified by the U.S. Geological Survey.

In addition to providing more detail than is given in Solley and others (1988), the State summaries also provide additional kinds of information relating to water use. Each State summary describes available water supplies (resources), history of water development, discernible trends in water use, and water-management approaches that relate to allocation and use of the water. In addition, the information about water use and trends is given in the context of the State's present and future water supplies. Multicolor illustrations portray the State's—

- Water budget (fig. 1*A*),
- Cumulative normal surface-reservoir storage (fig. 1*B*),
- Population trends (fig. 1*C*) and distribution (fig. 1*D*),
- Surface-water, ground-water, and total withdrawals by county (fig. 2),
- Withdrawals by hydrologic units and categories of use (fig. 3), and
- Source, use, and disposition of freshwater withdrawals (fig. 4).

The National Water-Use Information Program has markedly improved standardization of methods and techniques for collecting and compiling water-use data. However, in comparing water-use data of one State with the data of another State, the reader should be aware of the following complications:

- Water use in a specific year and region varies considerably with the availability of precipitation and streamflow. The uses most affected by these variations are irrigation and hydroelectric power generation;
- Differences in the availability of surface-water supplies affect the demands for ground-water supplies, especially for irrigation and public-supply uses;
- Differences in the cost and, particularly, the price structure of water affect the types and amounts of water used over time from region to region. Costs of water to the user are affected by such variables as declining ground-water levels and increased pumping costs, the degree to which water must be treated before and after use, and public policies;
- Economic conditions and commodity prices affect the requirements for industrial (manufacturing and mining) and agricultural (irrigation and livestock) withdrawals, as more or fewer products and crops are produced; and
- The derivation of water-use estimates involves some subjective judgments that can vary from State to State.

Water for offstream uses typically is diverted from a stream or withdrawn from a well and conveyed to the place of use. During most conveyances, some water is lost as a result of leakage from pipelines and canals and evaporation from open-water surfaces. Therefore, for nearly all uses, more water is withdrawn than is actually used. During the various uses, a portion of the water withdrawn is consumptively used by being incorporated into products, by evaporation, or by transpiration. The water that remains after the various uses typically is returned to a surface-water body, with or without some form of treatment, or infiltrates into the ground, and is referred to as return flow.

Consumptive use should not be thought of as a permanent loss of the water resource. In the context of the global water supply, there are virtually no losses attributable to human uses of water resources; there are only changes in the physical state and location of the water. In the Western United States, for example, although water that is evaporated or transpired by plants during irrigation is effectively eliminated (at least temporarily) from further use at that site, the moisture could fall as precipitation that nourishes crops in the Midwest a few days later. Even the moisture incorporated into a product—grain, for example—is not "used up," because the moisture in the grain ultimately will be released back to the environment.

It is instructive to compare consumptive use of water with the amount of water occurring naturally in a State and with the amount of water used for human activity; two water budgets in each State summary support such comparisons. The first water budget (shown as figure 1*A* in each State Summary) estimates the total natural flux of water in and out of the State, plus consumptive water use—

Precipitation + Surface-water inflow
= Evapotranspiration + Surface-water outflow + Consumptive use

Additionally, there is a net change of ground water in storage in a few States, which also becomes a term in the budget. A national estimate of this type of water budget is reflected in figure 60. Although there is considerable uncertainty in calculating some of the terms in the equation (especially evapotranspiration), the estimates provide an order of magnitude comparison of consumptive use in the context of the natural water regime. The second water budget (shown as figure 4 in each State summary), which consists of—

Withdrawals (surface water + ground water)
= Use + Disposition (consumptive use + return flow)

and shows the intermediate allocation of water to various uses, supports a comparison of surface- and ground-water withdrawals with consumptive use and return flow. This approach commonly is used to estimate return flow, which is the least measurable factor of this equation, or to check the reasonableness of estimates made independently for each of the factors. A national estimate of this type of water budget is reflected in figure 61. Water-use values expressed as average daily quantity used are derived from annual totals and generally are rounded to three significant figures. A conversion table is given at the end of this volume to assist those readers who might wish to convert the data to other units of measurement. The bases for estimates of the various categories of water use are discussed in Solley and others (1988).

NATIONAL PERSPECTIVE

The aggregate use of water in the United States is very large, in keeping with a highly developed nation that has generally abundant water supplies. The estimated total withdrawals of

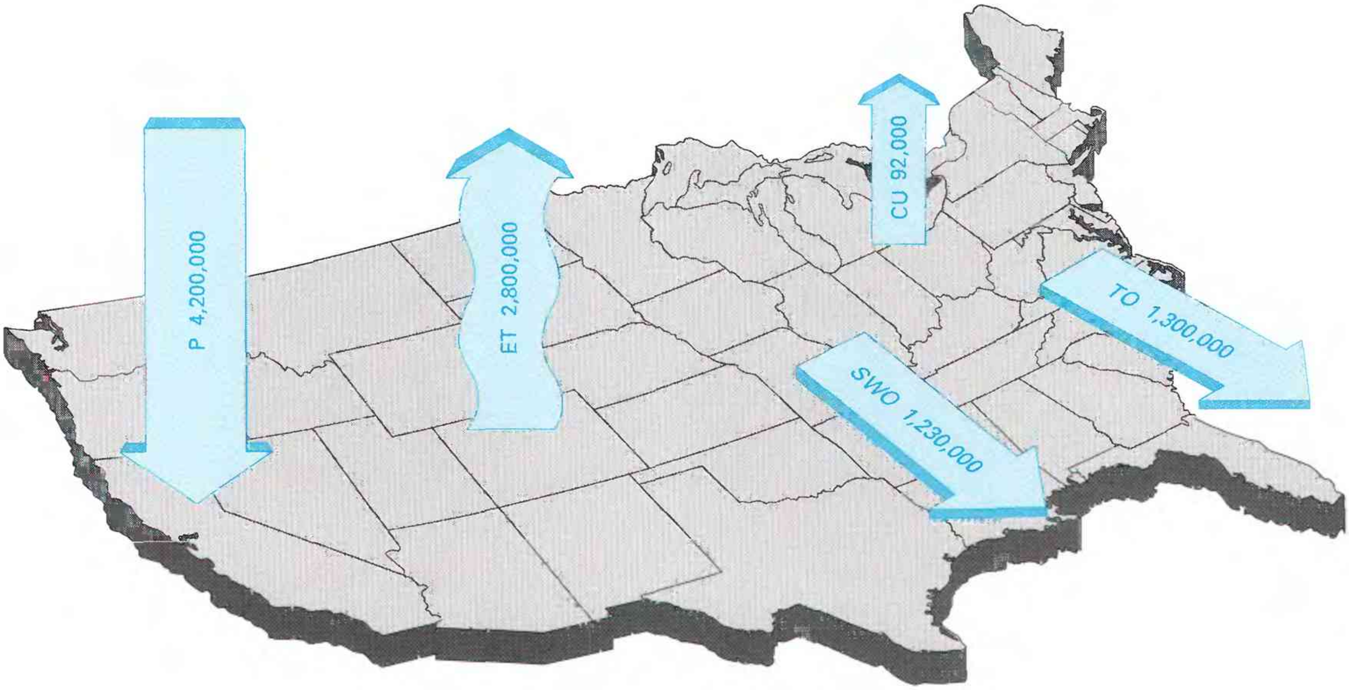


Figure 60. Estimated water budget, in million gallons per day, for the conterminous United States. Abbreviations: CU, consumptive use; ET, evapotranspiration; P, precipitation; SWO, surface-water outflow to the oceans, Canada, and Mexico; TO, total surface- and ground-water outflow to the oceans, Canada, and Mexico. (Source: Modified from U.S. Geological Survey, 1984, p. 9.)

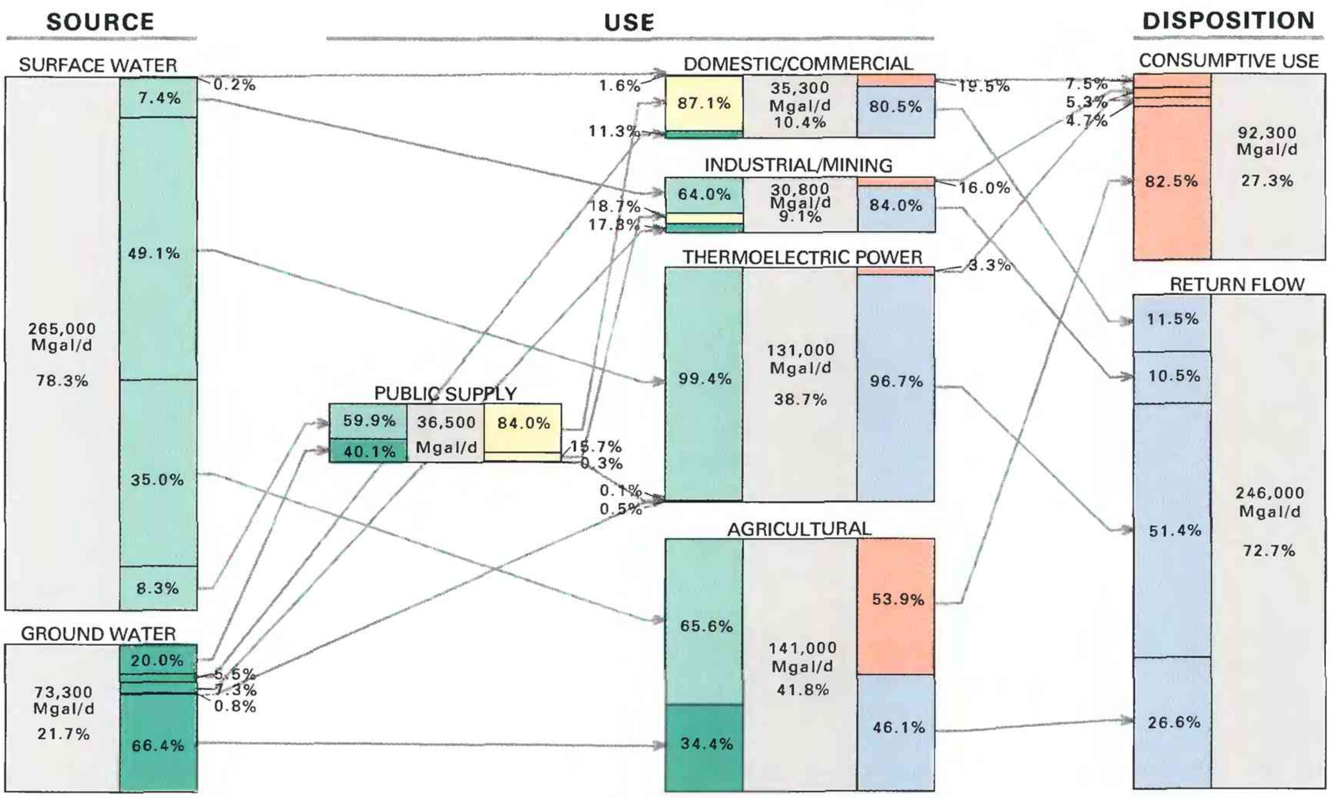


Figure 61. Source, use, and disposition of an estimated 338,000 Mgal/d (million gallons per day) of freshwater in the United States, 1985. The lines and arrows indicate the distribution of water from source to disposition for each category. For example, surface water was 78.3 percent of the freshwater withdrawals, and, going from the "Source" to "Use" columns, the line from the surface-water block to the domestic and commercial block indicates that 0.2 percent of all surface water withdrawn was the source for 1.6 percent of total water use (self-supplied withdrawals and public-supply deliveries) for domestic and commercial purposes. In addition, going from the "Use" to the "Disposition" columns, the line from the domestic and commercial block to the consumptive use block indicates that 19.5 percent of the water for domestic and commercial purposes was consumptive use, which represented 7.5 percent of total consumptive use. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Table 19. Summary by State of freshwater withdrawals by source and category of use, 1985

[Withdrawal data are rounded to three significant numbers and might not add to totals because of independent rounding. Mgal/d=million gallons per day; <=less than. Sources: Withdrawal and delivery data from figure 4 in respective State summary, 1987 *National Water Summary*; percentage of total State withdrawals and national rankings calculated from unrounded numbers.]

State	State withdrawals		Source						Use		
			Surface water			Ground water			Public supply		
	Total fresh surface and ground water (Mgal/d)	Rank nationwide	Withdrawals (Mgal/d)	Percentage of total State withdrawals	Rank nationwide	Withdrawals (Mgal/d)	Percentage of total State withdrawals	Rank nationwide	Withdrawals (Mgal/d)	Percentage of total State withdrawals	Rank nationwide
Alabama	8,590	14	8,250	96	12	340	4	35	615	7	19
Alaska	406	48	334	82	48	72	18	48	76	19	49
Arizona	6,420	21	3,330	52	29	3,090	48	8	618	10	18
Arkansas	5,910	26	2,100	36	33	3,810	64	7	257	4	36
California	37,400	1	22,600	60	1	14,800	40	1	5,310	14	1
Colorado	13,500	6	11,200	83	7	2,310	17	9	737	5	14
Connecticut	1,200	42	1,060	88	38	144	12	44	362	30	30
Delaware	139	50	60	43	51	79	57	47	77	55	48
Florida	6,280	22	2,230	36	31	4,050	64	6	1,680	27	5
Georgia	5,370	29	4,370	81	26	1,000	19	15	836	16	11
Hawaii	1,270	41	613	48	44	655	52	24	204	16	40
Idaho	22,300	2	17,500	78	2	4,800	22	4	212	1	39
Illinois	14,400	4	13,500	94	3	930	6	16	1,780	12	4
Indiana	9,360	11	8,720	93	9	635	7	26	575	6	22
Iowa	2,760	36	2,090	76	34	671	24	22	350	13	32
Kansas	5,670	27	866	15	40	4,800	85	5	316	6	33
Kentucky	4,200	31	3,990	95	27	205	5	41	404	10	28
Louisiana	9,900	10	8,470	86	10	1,430	14	12	628	6	16
Maine	849	44	783	92	41	66	8	49	108	13	44
Maryland and District of Columbia	1,540	39	1,320	86	37	219	14	39	771	50	12
Massachusetts	6,260	23	5,940	95	18	315	5	36	767	12	13
Michigan	11,400	8	10,800	95	8	596	5	28	1,250	11	8
Minnesota	2,840	35	2,150	76	32	685	24	21	473	17	25
Mississippi	2,320	37	736	32	42	1,580	68	10	312	13	34
Missouri	6,110	25	5,470	90	22	640	10	25	645	11	15
Montana	8,650	13	8,450	98	11	203	2	42	158	2	41
Nebraska	10,000	9	4,450	45	25	5,590	56	3	248	2	37
Nevada	3,740	33	2,830	76	30	905	24	17	288	8	35
New Hampshire	687	45	603	88	45	84	12	46	89	13	46
New Jersey	2,230	38	1,630	73	36	600	27	27	961	43	9
New Mexico	3,290	34	1,780	54	35	1,510	46	11	226	7	38
New York	9,050	12	7,950	88	14	1,100	12	14	2,860	32	3
North Carolina	7,880	16	7,450	95	15	435	6	33	595	8	20
North Dakota	1,170	43	1,040	89	39	127	11	45	69	6	50
Ohio	12,700	7	12,000	94	6	730	6	20	1,420	11	7
Oklahoma	1,280	40	707	55	43	568	44	30	521	41	24
Oregon	6,540	20	5,880	90	19	660	10	23	416	6	27
Pennsylvania	14,300	5	13,500	94	4	799	6	18	1,600	11	6
Puerto Rico	598	47	423	71	47	175	29	43	391	65	29
Rhode Island	147	49	120	82	49	27	18	51	116	79	43
South Carolina	6,810	18	6,600	97	16	214	3	40	359	5	31
South Dakota	674	46	425	63	46	249	37	37	80	12	47
Tennessee	8,450	15	8,010	95	13	444	5	32	627	7	17
Texas	20,100	3	12,900	64	5	7,180	36	2	2,990	15	2
U.S. Virgin Islands	7.1	52	5.7	80	52	1.4	20	52	4.5	63	52
Utah	4,180	32	3,390	81	28	790	19	19	447	11	26
Vermont	126	51	89	71	50	37	29	50	53	42	51
Virginia	4,870	30	4,530	93	24	341	7	34	579	12	21
Washington	7,000	17	5,780	83	20	1,220	17	13	955	14	10
West Virginia	5,440	28	5,210	96	23	227	4	38	151	3	42
Wisconsin	6,740	19	6,170	92	17	570	8	29	576	9	23
Wyoming	6,200	24	5,700	92	21	504	8	31	98	2	45
Total	338,000		265,000			73,300			36,500		

[1]Includes conveyance losses from public-supply systems.

Table 19. Summary by State of freshwater withdrawals by source and category of use, 1985—Continued

[Withdrawal data are rounded to three significant numbers and might not add to totals because of independent rounding. Mgal/d=million gallons per day; <=less than. Sources: Withdrawal and delivery data from figure 4 in respective State summary, 1987 *National Water Summary*; percentage of total State withdrawals and national rankings calculated from unrounded numbers.]

Use—Continued											
Domestic and commercial			Industrial and mining			Thermoelectric power			Agricultural		
Withdrawals and deliveries (Mgal/d)[1]	Percentage of total State withdrawals	Rank nationwide	Withdrawals and deliveries (Mgal/d)	Percentage of total State withdrawals	Rank nationwide	Withdrawals and deliveries (Mgal/d)	Percentage of total State withdrawals	Rank nationwide	Withdrawals (Mgal/d)	Percentage of total State withdrawals	Rank nationwide
436	5	26	1,070	12	10	6,920	81	6	165	2	30
78	19	49	141	35	38	31	8	42	157	39	32
583	9	20	204	3	32	53	1	41	5,580	87	9
325	5	32	175	3	35	1,090	18	23	4,310	73	12
4,980	13	1	1,090	3	9	511	1	29	30,800	82	1
731	5	14	197	1	34	123	1	36	12,500	93	3
346	29	31	141	12	39	701	58	26	11	1	48
72	52	50	36	26	48	1.6	1	48	28	20	46
1,850	29	4	795	13	15	656	10	27	2,980	47	15
828	15	10	759	14	16	3,280	61	19	501	9	21
241	19	39	27	2	50	90	7	38	910	72	19
311	1	34	340	2	25	<0.1	0	51	21,600	97	2
1,760	12	5	857	6	13	11,700	81	1	129	1	33
642	7	18	2,820	30	1	5,800	62	9	95	1	36
410	15	27	301	11	27	1,810	66	21	239	9	25
316	6	33	135	2	40	416	7	32	4,800	85	11
301	7	36	433	10	23	3,410	81	18	58	1	39
674	7	15	2,070	21	4	5,470	55	10	1,690	17	17
155	18	42	559	66	21	103	12	37	31	4	44
804	52	11	150	10	37	529	34	28	57	4	40
967	15	9	200	3	33	5,070	81	13	18	0	47
1,160	10	8	1,630	14	6	8,390	74	4	235	2	26
583	21	21	504	18	22	1,480	52	22	277	10	24
302	13	35	259	11	28	481	21	30	1,270	55	18
583	10	22	249	4	30	4,930	81	14	347	6	23
173	2	41	61	1	44	67	1	39	8,350	97	5
224	2	40	216	2	31	2,210	22	20	7,380	74	6
298	8	37	38	1	47	26	1	43	3,370	90	14
94	14	47	255	37	29	336	49	33	1.8	0	51
804	36	12	575	26	20	725	33	25	129	6	34
269	8	38	85	3	42	59	2	40	2,870	87	16
2,170	24	3	2,100	23	3	4,720	52	15	57	1	41
660	8	16	661	8	17	6,400	81	7	167	2	29
82	7	48	15	1	51	892	76	24	176	15	27
1,270	10	7	881	7	12	10,500	83	2	57	0	42
372	29	30	317	25	26	136	11	35	450	35	22
445	7	24	353	5	24	12	0	45	5,730	88	7
1,570	11	6	2,450	17	2	10,200	71	3	81	1	37
396	66	28	31	5	49	6.6	1	47	165	28	31
102	69	46	40	27	46	<0.01	0	52	5.7	4	50
376	6	29	1,220	18	8	5,180	76	12	44	1	43
109	16	45	51	8	45	7.2	1	46	507	75	20
604	7	19	1,710	20	5	6,060	72	8	74	1	38
2,810	14	2	1,390	7	7	7,480	37	5	8,380	42	4
6.3	89	52	<0.1	0	52	0.7	10	50	<0.1	0	52
439	11	25	99	2	41	24	1	44	3,620	87	13
51	40	51	68	54	43	0.8	1	49	6.1	5	49
655	13	17	649	13	18	3,460	71	17	105	2	35
767	11	13	828	12	14	427	6	31	4,970	71	10
151	3	43	1,050	19	11	4,210	77	16	30	1	45
510	9	23	614	9	19	5,440	81	11	174	3	28
123	2	44	165	3	36	238	4	34	5,670	91	8
35,300			30,800			131,000			141,000		

freshwater from streams and aquifers for offstream uses in 1985 averaged 338,000 Mgal/d (million gallons per day) (fig. 61; table 19), or about 123 trillion (million-million) gallons for the year.

The significance of this large quantity is best understood in the context of the Nation's overall supply of water. The precipitation that falls on the 48 conterminous United States during an average year is equivalent to about 30 inches of water (U.S. Geological Survey, 1984). In contrast, the 1985 freshwater withdrawals would cover the 48 States to a depth of about 2.4 inches. Moreover, of the 338,000 Mgal/d, only 92,300 Mgal/d, which would cover the 48 States to a depth of about 0.65 inch, was estimated to be consumptive use, or effectively lost to further use in that area for the year. The remainder (246,000 Mgal/d) was return flow, largely available for further use and, indeed, part of a water supply that could be reused repeatedly as it flows along its path to the sea. For the Nation as a whole, therefore, the consumptive use (0.65 inch), and even the freshwater withdrawal (2.4 inches), is much less than the supply from precipitation (30 inches). As the various State summaries show, however, the water is not always available where and when it is needed, and the many demands and competitions for limited water supplies constitute one of the major resource-management issues facing the United States.

Sources of the Water

Of the freshwater withdrawn in 1985, 78.3 percent came from surface-water sources (streams and lakes) and 21.7 percent came from ground water. The greatest offstream use of surface water, which accounted for nearly one-half of the surface-water withdrawal, was for thermoelectric power generation, mainly for cooling. The second largest offstream surface-water use was for irrigation. Ground water was used mostly for irrigation and livestock watering, and its second greatest use was for public supplies (fig. 61). Figures 62, 63, and 64 show, respectively, total freshwater withdrawals, surface-water withdrawals, and ground-water withdrawals for each county in the United States. (Withdrawal data for independent cities in Virginia are included in the tabulation in the map explanation, but the cities are not shown on the maps.) Population distribution is shown in figure 65.

For eight States, withdrawals of fresh surface water in 1985 averaged more than 10,000 Mgal/d each, and those States together accounted for 43 percent of the nationwide withdrawals from fresh surface-water sources during the year (table 19). Four of the States—California, Colorado, Idaho, and Texas—are in the Western United States, and the other four—Illinois, Michigan, Ohio, and Pennsylvania—are in the Eastern United States. Irrigation was the predominant water use in three of the Western States; the exception was Texas, where the use of fresh surface water for irrigation was large (2,700 Mgal/d) but nonetheless subordinate to its use for cooling at thermoelectric generating plants (7,400 Mgal/d). In the Eastern States, by far the major use of fresh surface water was for condenser and reactor cooling in thermoelectric powerplants.

Eight States, mostly in the West, also dominated the 1985 withdrawals of ground water. Together, these States—Arizona, Arkansas, California, Florida, Idaho, Kansas, Nebraska, and Texas—accounted for nearly two-thirds of the reported nationwide ground-water withdrawals in 1985. In all of these States, as in many others not in the "top eight," the major use of the ground water was for irrigation. In all but Arkansas and Idaho, the second largest use was for public supplies; in those two States the second largest use was in the livestock category, mainly for offstream fish farming (aquaculture).

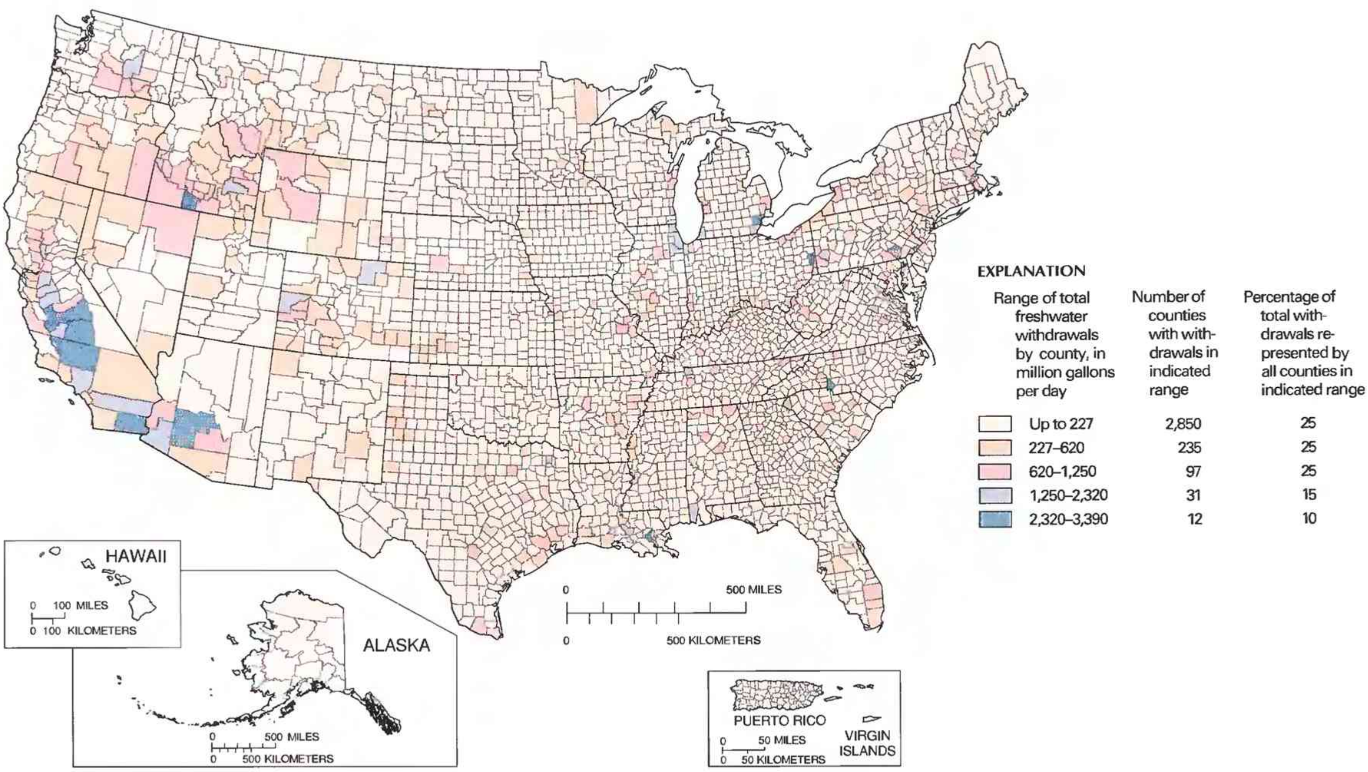


Figure 62. Total freshwater withdrawals (338,000 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands, and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

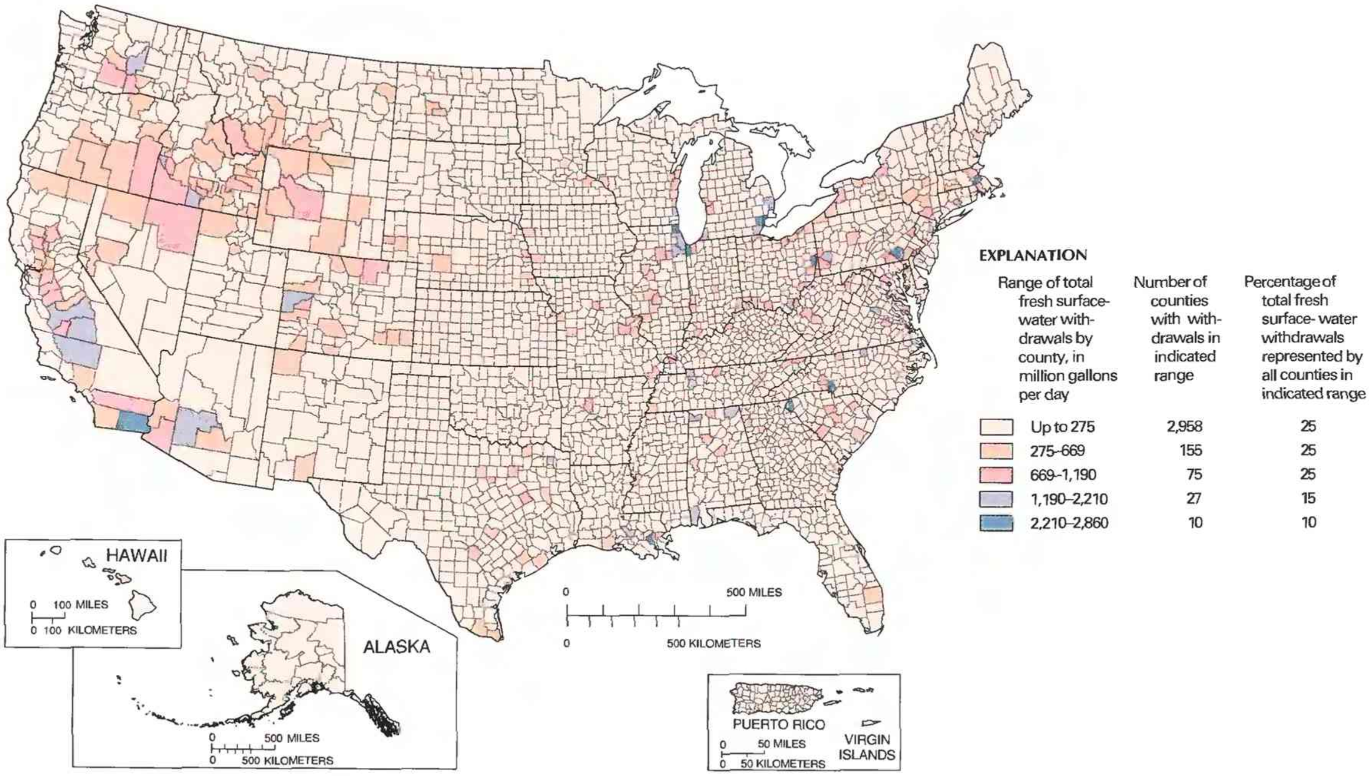


Figure 63. Total fresh surface-water withdrawals (265,000 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

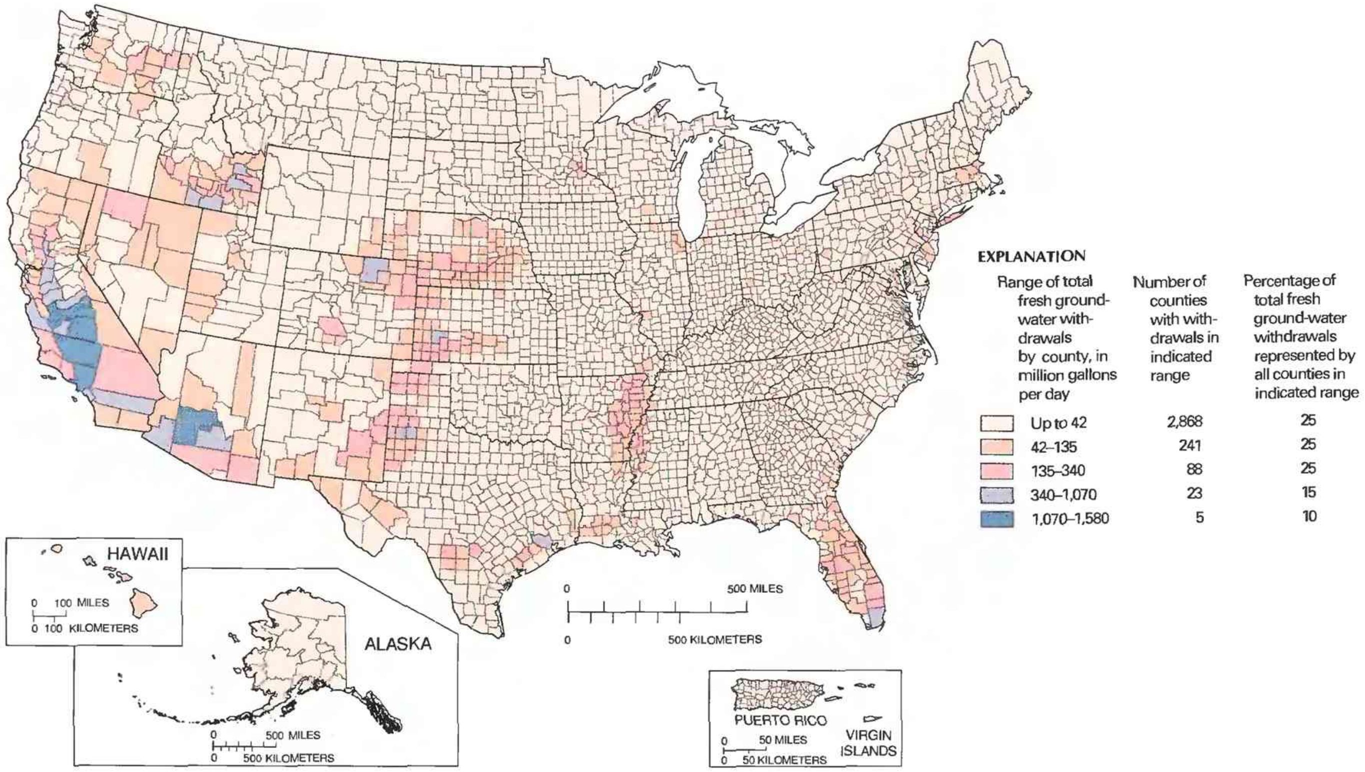


Figure 64. Total fresh ground-water withdrawals (73,300 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

The withdrawals mentioned above and discussed in the individual State summaries do not include withdrawals from saline surface- and ground-water sources and reclaimed sewage. In 1985, saline-water withdrawals amounted to about 60,300 Mgal/d, mostly in coastal States and mostly from seawater (Solley and others, 1988, tables 24, 28, and 30). Most of the saline water was withdrawn for cooling in thermoelectric energy generation, for industrial (manufacturing) processes, and for mining or processes incidental to mining. The reported use of water from reclaimed sewage was small—an average of about 579 Mgal/d nationwide—mostly for irrigation and, to a lesser extent, for industrial purposes (Solley and others, 1988, tables 8, 12, and 24).

WATER USE BY MAJOR CATEGORIES

Water use is described in the State summaries according to the same offstream water-use categories that were defined and used in "Estimated Use of Water in the United States in 1985" (Solley and others, 1988). However, in this 1987 *National Water Summary*, these categories are grouped somewhat differently for convenience of description as public supply, domestic and commercial, industrial and mining, thermoelectric power, and agricultural (irrigation and livestock). With the exception of mining and agricultural use, these categories of use include water obtained from public-supply and self-supplied systems; all water for mining and agricultural use is self-supplied. Hydroelectric power, the only instream use for which data are compiled by the U.S. Geological Survey is reported as the average rate of water flow through the generating turbines and as the average amount of power produced (Solley and others, 1988, p. 44–47); hydroelectric power is discussed in the text of the State summaries but is not included in the illustrations.

Public Supply

Public-supply use refers to water withdrawn by public and private water suppliers and delivered to a variety of users for domestic, commercial, industrial, thermoelectric power, and public uses. As used here, it includes water-supply systems that serve at least 25 people or that have a minimum of 15 service hookups.

The quantity of freshwater withdrawn for public supplies nationwide during 1985 was estimated to be 36,500 Mgal/d (fig. 66), or about 9 percent of withdrawals for all offstream uses. Surface water was the source for about 59.9 percent of public-supply withdrawals, and ground water was the source for the other 40.1 percent. The source relations, which differ greatly among the individual States, range from 100 percent surface water for District of Columbia public supplies to about 89 percent ground water for Florida.

Most public-supply use is for domestic and commercial use, and therefore it is not surprising that it is related closely to population distribution (fig. 65). California reported by far the largest withdrawal of ground water for public supplies during 1985 (about 3,730 Mgal/d), as well as the largest total public-supply withdrawal (5,310 Mgal/d). The California total was nearly 78 percent greater than the total public-supply withdrawal for Texas, which was second (2,990 Mgal/d), and 86 percent greater than that for New York (2,860 Mgal/d). The U.S. Virgin Islands, which has the smallest population of the States and areas reported, also had the smallest withdrawal for public supplies (4.5 Mgal/d). The sources, deliveries, populations served, and per capita uses of the public supplies for each State and area are summarized in Solley and others (1988, table 2) and described in more detail in each of the State summaries in this volume. (See also table 19 in this volume.)

As shown in figure 61, 84.0 percent of the public-supply withdrawals was for domestic and commercial use, such as street washing and firefighting; distribution losses, such as pipeline leaks; and other unaccounted-for losses (in the individual State summaries, these public uses and distribution losses are included in the domestic and commercial use category). The remaining distribution was 15.7 percent for industrial and mining use and 0.3 percent for use in thermoelectric power generation (mostly in California, Colorado, and Texas).

Domestic and Commercial

Domestic water use includes water for normal household purposes such as drinking, food preparation, bathing, washing clothes and dishes, and watering lawns and gardens. Commercial water use includes water for hotels and motels, restaurants, office buildings, retail and other commercial facilities, and civilian and military institutions. These two types of water use are closely related because they both are largely dependent on public supplies and their wastewaters are disposed of largely through communal sewer systems. Moreover, both types of use are concentrated in urban and suburban areas.

Although most of the freshwater for domestic and commercial use is delivered from public supplies in urban areas, a considerable amount of water for these purposes is used in rural or nonurban areas and is self-supplied. Solley and others (1988, p. 14) estimated that domestic water for about 42.5 million people (18 percent of the Nation's population) was self-supplied and accounted for about 3,320 Mgal/d of the total 24,300 Mgal/d withdrawals and deliveries for domestic use. Self-supplied withdrawals for commercial purposes were estimated to be 1,230 Mgal/d of the total 6,940 Mgal/d withdrawals and deliveries for commercial use.

The total amount of freshwater withdrawn and delivered (self-supplied and public-supply systems) for domestic and commercial uses nationwide averaged 31,200 Mgal/d during 1985, or about 9.3 percent of the total freshwater withdrawal in that year. (As shown in figure 67, self-supplied domestic and commercial withdrawals amounted to 4,550 Mgal/d.) If the more than 4,000 Mgal/d estimated to be for public use or lost in the public-supply distribution system is included in the domestic and commercial use category, then the national average would be 35,300 Mgal/d or 10.4 percent of the Nation's total freshwater withdrawal. (See figure 61.)

Figure 68 shows the percentage distributions of the sources, the domestic versus commercial uses, and the disposition of the water withdrawn for domestic and commercial uses nationwide in 1985. Of the freshwater supplied for these uses, 87.2 percent came from public supplies; of that, 81.4 percent was delivered for domestic use and 18.6 percent for commercial purposes. Of the self-supplied water, about 88 percent was from ground-water sources, and about 12 percent was from surface water and was mostly for commercial use. Florida reported the largest amount of self-supplied domestic use (259 Mgal/d, all from ground water), but Pennsylvania reported the largest population (3.68 million) using self-supplied domestic water. Massachusetts reported the largest self-supplied commercial withdrawal (238 Mgal/d). The States for which the largest total domestic and commercial freshwater use was reported were California (4,980 Mgal/d), Texas (2,810 Mgal/d), and New York (2,170 Mgal/d) (table 19).

The estimated disposition of the water used for domestic and commercial purposes was 80.5 percent return flow and 19.5 percent consumptive use. Wastewater from domestic and commercial use accounted for most of the 30,800 Mgal/d of treated wastewater

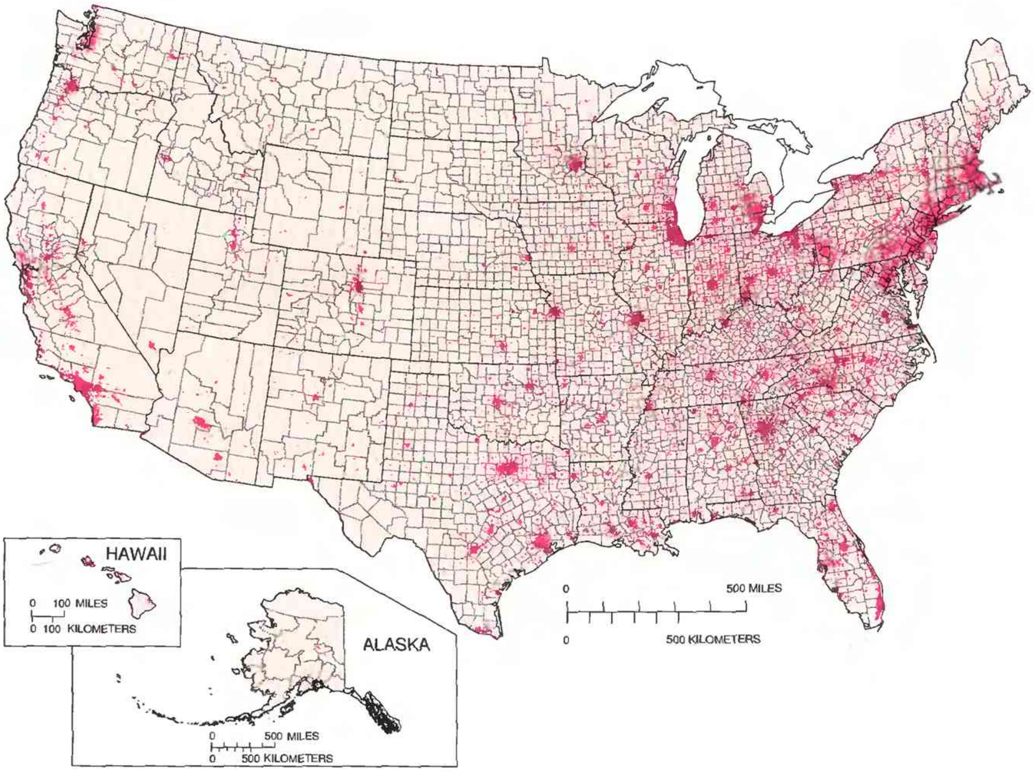


Figure 65. Population distribution in the United States, 1985. Each dot on the map represents 1,000 people within a census tract. (Source: Data compiled by the U.S. Geological Survey from U.S. Bureau of the Census data.)

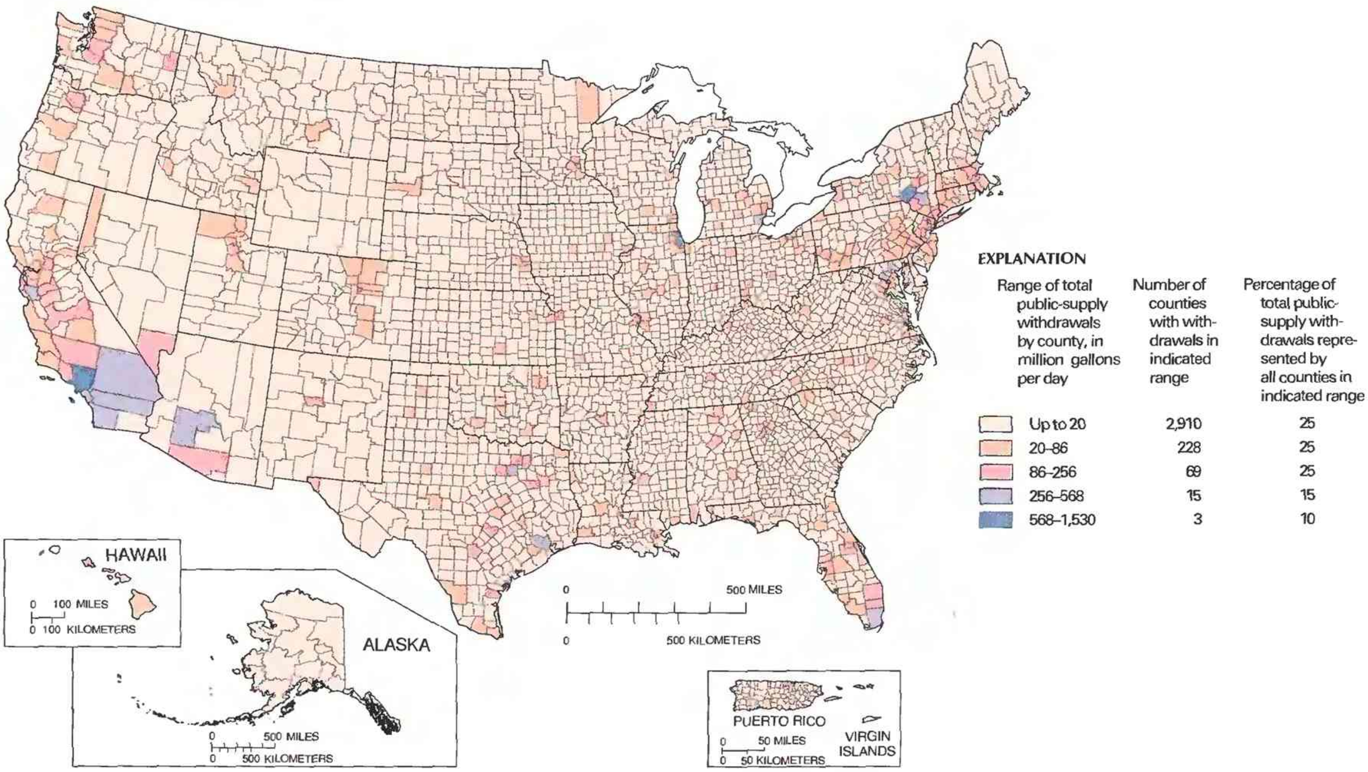


Figure 66. Total public-supply withdrawals (36,500 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

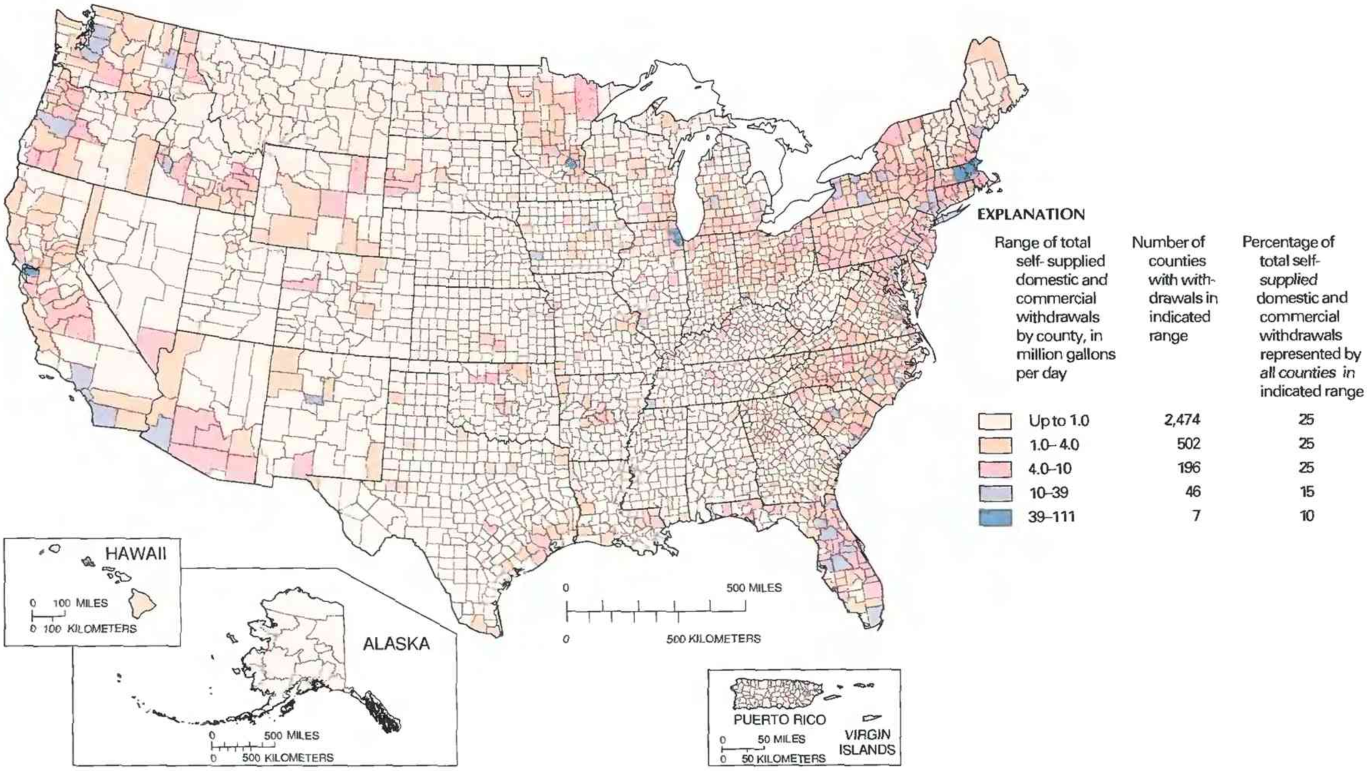


Figure 67. Total self-supplied domestic and commercial withdrawals (4,550 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

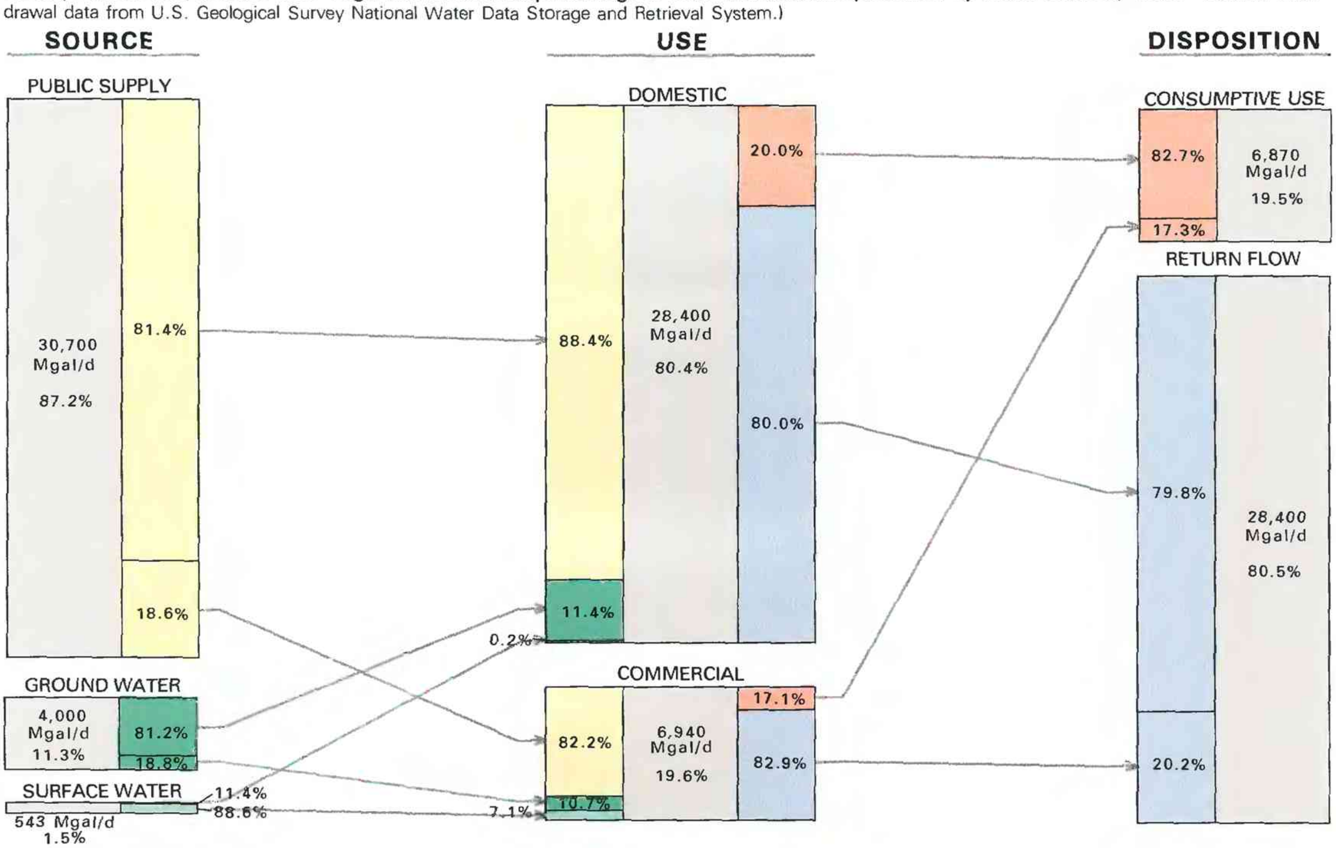


Figure 68. Source, use, and disposition of an estimated 35,300 Mgal/d (million gallons per day) of domestic and commercial withdrawals in the United States, 1985. Conveyance losses in public-supply systems and some public water uses, such as firefighting, are included in this category. All numbers have been rounded, and values might not add to totals. Percentages have been rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

that reportedly was released from about 20,600 public sewage-treatment facilities nationwide during 1985 (Solley and others, 1988, p. 48).

Specific details on State domestic and commercial use is provided in each State summary. General factors that influence the use of domestic water are described in this volume in the article "Domestic Water Use in the United States, 1960–85."

Industrial and Mining

Industrial water use as used in this volume includes water for manufacturing processes and mining activities. The largest water-using industries reported in the States include those that manufacture steel and primary metals, chemicals and allied products, paper and allied products, and petroleum refining. Total self-supplied withdrawals for these purposes is shown in figure 69. The water for manufacturing use includes self-supplied and public-supply deliveries of freshwater and self-supplied saline water, which is mostly from surface-water sources. Mining water use includes water for the extraction of naturally occurring mineral materials, including petroleum, and withdrawals for dewatering and for milling, washing, and other mineral-preparation steps that are part of mining activities. Fresh and saline water are used in mining, but all the water is self-supplied. Thermoelectric power generation also is an industrial use, but because of the quantity of water it requires it is described below as a separate category.

The source, use, and disposition of freshwater withdrawals for industrial and mining use are shown in figures 61 and 70. Figure 61 shows that total freshwater withdrawals (30,800 Mgal/d) for industrial and mining use were 9.1 percent of the Nation's total freshwater withdrawals. Figure 70 shows that of the 30,800 Mgal/d withdrawn, 91.3 percent was for manufacturing use and 8.7 percent was for mining use. Freshwater withdrawals for manufacturing use were 65.6 percent self-supplied surface water, 14 percent self-supplied ground water, and 20.4 percent from public supplies. An estimated 16 percent of the freshwater withdrawn for manufacturing and mining uses was consumptive use; the remaining 84 percent was return flow to streams or ground-water systems. The large percentage of return flow reflects the major utilization of the water for washing and cooling, which results in relatively little actual consumptive use.

In addition to freshwater, an estimated 3,500 Mgal/d of saline water was withdrawn for manufacturing use, and nearly 800 Mgal/d was withdrawn for mining use (Solley and others, 1988, tables 12 and 14). Also, a comparatively small quantity of reclaimed sewage water (144 Mgal/d) reportedly was used by industries; about 94 percent of that usage was in Maryland and Texas (Solley and others, 1988, table 12).

The largest freshwater withdrawal for industrial and mining use reported for a State was about 2,820 Mgal/d in Indiana, of which all but about 73 Mgal/d was self-supplied. Pennsylvania reported the second-largest withdrawal (about 2,450 Mgal/d). For mining use alone, the two largest quantities of freshwater withdrawals were reported for Minnesota and Florida—273 and 258 Mgal/d, respectively.

For the specific processes and how water is used by manufacturing and mining industries, see the article "Manufacturing and Mining Water Use in the United States, 1954–83" in this volume. See also the State summaries for more detail.

Thermoelectric Power

The thermoelectric power category refers to the water used in the production of electrical power by steam using fossil-fuel, nuclear, or geothermal energy. It represents a special type of industrial use, which, because of its magnitude and other special characteristics, is presented as a separate category in the State summaries. The self-supplied freshwater withdrawals for this use during 1985 were about 131,000 Mgal/d (fig. 71), which was about 38.7 percent of the total freshwater withdrawn for all uses and was second only to that for agricultural use. Nearly all (99.5 percent) of this water was from surface-water sources. Nationwide, about 96 Mgal/d was supplied for this use from public supplies and was used mainly in California, Colorado, and Texas. In addition to the use of freshwater, about 56,000 Mgal/d of saline water was withdrawn for thermoelectric use, mostly in coastal States (Solley and others, 1988, table 16).

The States with the largest freshwater withdrawals for thermoelectric power use were Illinois (11,700 Mgal/d), Ohio (10,500 Mgal/d), and Pennsylvania (10,200 Mgal/d). Together they accounted for about 25 percent of the freshwater thermoelectric power use in 1985.

Because the main use of water in the generation of thermoelectric power is for cooling, relatively little (4,350 Mgal/d), or only 3.3 percent of the freshwater for this purpose, was consumptive use. The remaining 96.7 percent was return flow, mostly to surface-water bodies. This constituted the largest percentage of return flow among all the offstream water uses. The use of the freshwater for thermoelectric power generation was distributed by energy source as follows: fossil fuels, 105,000 Mgal/d, or 80.6 percent; nuclear, 25,200 Mgal/d, or 19.3 percent; and geothermal (all ground water), 61 Mgal/d, or less than 0.1 percent (fig. 72).

Agriculture

Agricultural uses described in the State summaries include irrigation and livestock. In these summaries, irrigation includes all artificial application of water to field, vine, and tree crops, to pastures, and to golf courses. (See "Glossary" for definitions of irrigation methods.) Livestock use is described as water used for stock watering, feed lots, dairy operations, fish farming (aquaculture), and other on-farm purposes (except household and irrigation uses).

During 1985, freshwater withdrawals for agricultural uses averaged about 141,000 Mgal/d (fig. 73), and constituted 41.8 percent of the total freshwater withdrawals nationwide (fig. 61). Surface water was the source of 65.6 percent of the withdrawals, and ground water was the other 34.4 percent (fig. 61). In addition, about 434 Mgal/d of water reclaimed from sewage was used for irrigation, more than one-half used in California (Solley and others, 1988, table 8). In the State summaries, all withdrawals for agriculture are considered to be self-supplied, even though much of the irrigation water is supplied by irrigation companies or irrigation districts.

The withdrawals for agricultural uses were 96.8 percent for irrigation (137,000 Mgal/d) and only 3.2 percent for livestock use (4,470 Mgal/d). (See figure 74.) Irrigation was by far the largest water use in the West and also was sizable in the Southeast. The 22 conterminous States west of the Mississippi River accounted for more than 95 percent of the irrigation withdrawals in 1985. California and Idaho, by far the largest users of irrigation water, withdrew about 30,600 and 20,600 Mgal/d, respectively, and together accounted for more than 37 percent of the national total. In the Southeast, the States that reported the largest irrigation withdrawals were Florida (2,910 Mgal/d), Mississippi (886 Mgal/d), and Georgia (453 Mgal/d).

Nationwide, an estimated 57.2 million acres was irrigated during 1985. In the arid regions, irrigation was the primary source of water for crops. In the wetter regions, irrigation water supplemented rainfall.

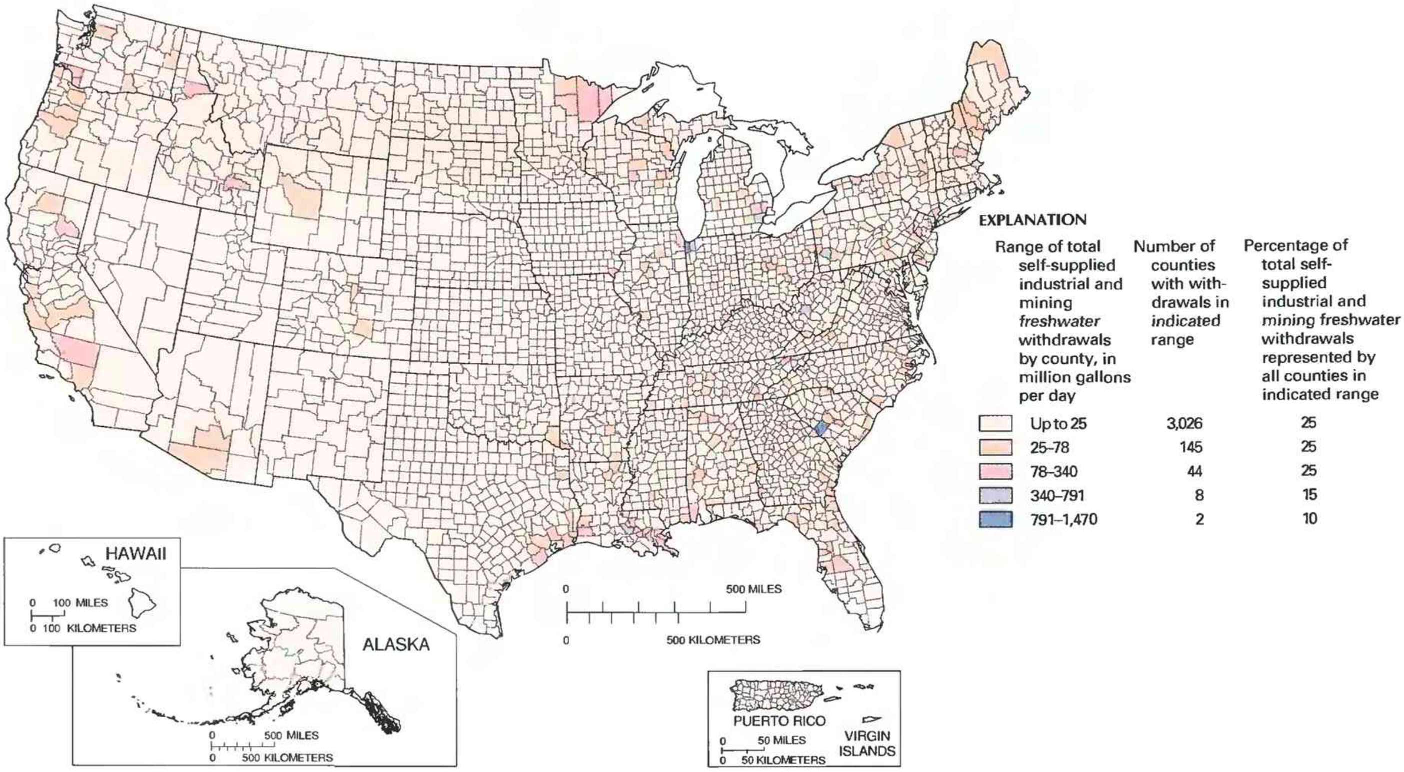


Figure 69. Total self-supplied industrial (manufacturing) and mining freshwater withdrawals (25,000 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

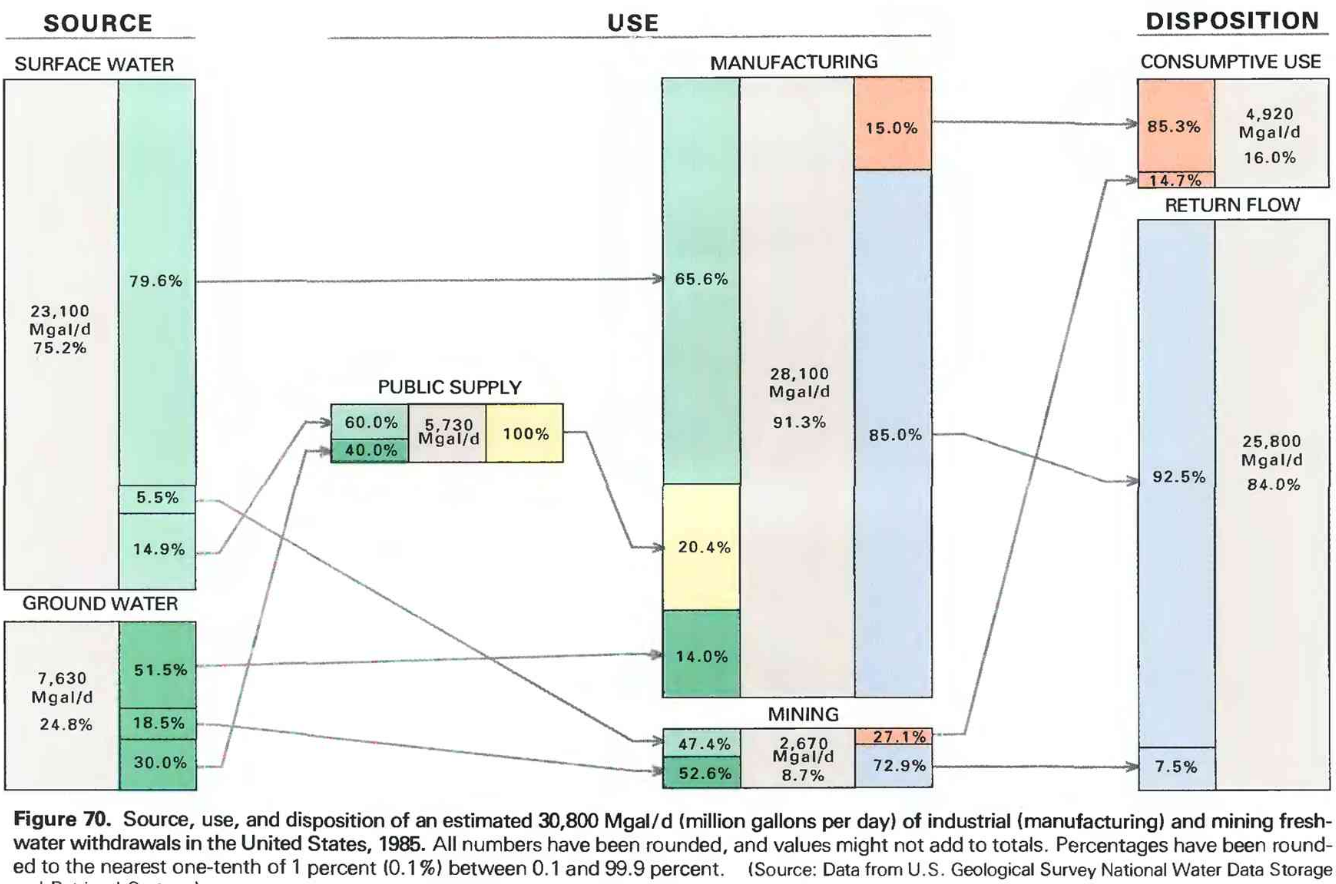


Figure 70. Source, use, and disposition of an estimated 30,800 Mgal/d (million gallons per day) of industrial (manufacturing) and mining freshwater withdrawals in the United States, 1985. All numbers have been rounded, and values might not add to totals. Percentages have been rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

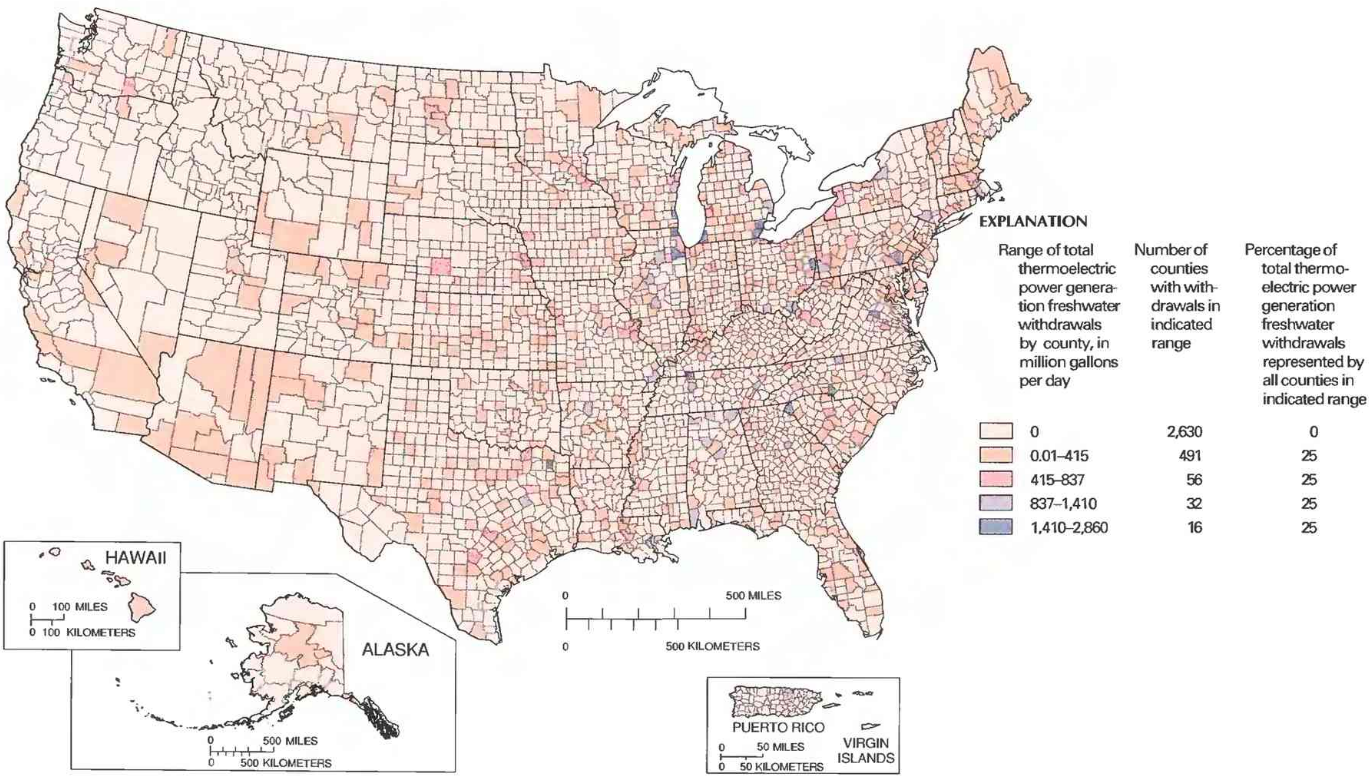


Figure 71. Total self-supplied thermoelectric power generation freshwater withdrawals (131,000 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. Because the majority of the counties do not have withdrawals for thermoelectric power generation, they were excluded from the column "Percentage of total thermoelectric power generation freshwater withdrawals represented by all counties in indicated range." (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

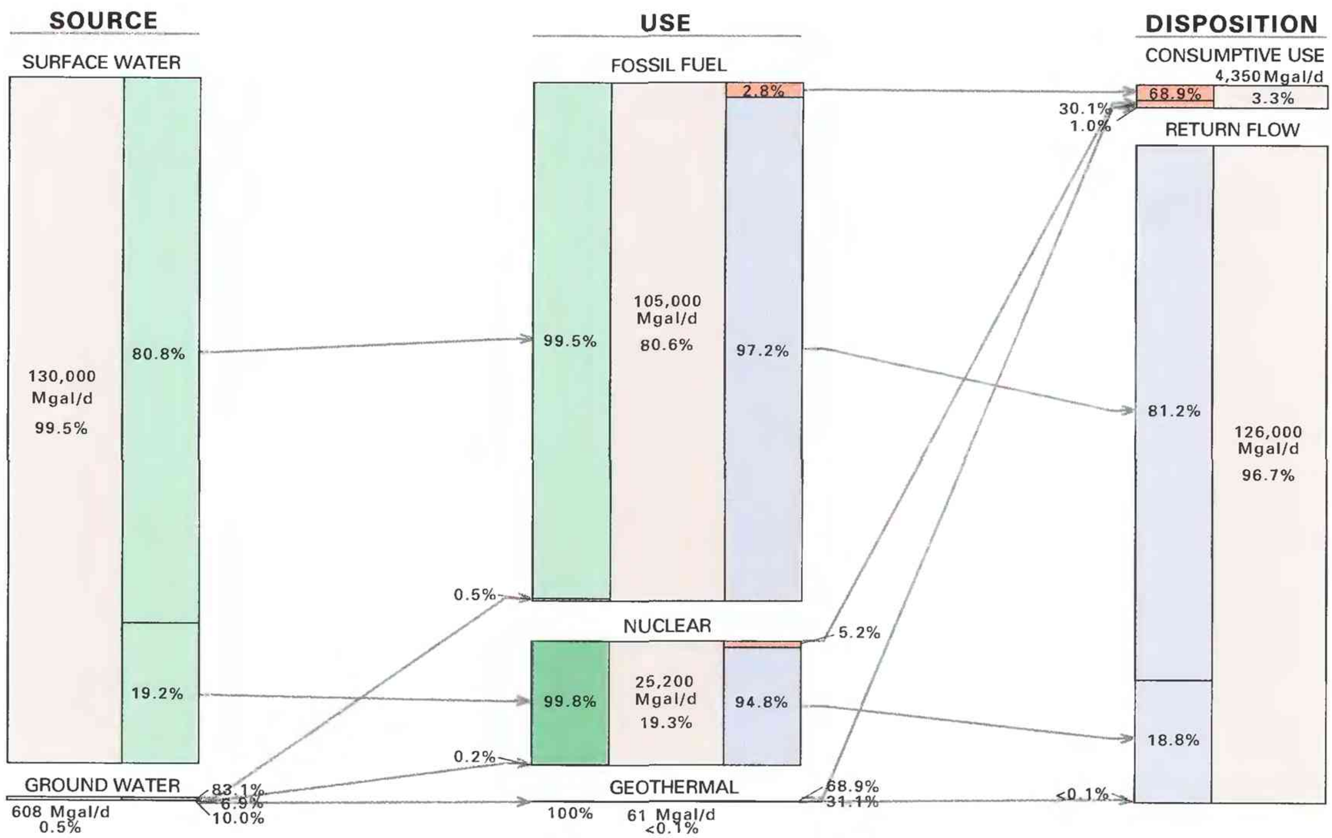


Figure 72. Source, use, and disposition of an estimated 131,000 Mgal/d (million gallons per day) of thermoelectric power generation self-supplied freshwater withdrawals, by fuel type, in the United States, 1985. All numbers have been rounded, and values might not add to totals. Percentages have been rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. In addition to the freshwater withdrawals, 56,000 Mgal/d of saline surface water was withdrawn for thermoelectric power generation. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Although livestock use constituted little more than 3 percent of the total estimated withdrawals for agriculture, the nationwide livestock use was a sizable 4,470 Mgal/d—nearly as large as the self-supplied domestic and commercial use withdrawals (4,550 Mgal/d). Ground water was the source of about 67.6 percent of livestock use withdrawals, and surface water was the source of the remaining 32.4 percent. Idaho (1,040 Mgal/d), Arkansas (440 Mgal/d), and Mississippi (385 Mgal/d) accounted for about 42 percent of the Nation's livestock use total for 1985, largely because of major withdrawals for fish farming. The remaining livestock use withdrawals were distributed fairly evenly among other States (Solley and others, 1988, table 10).

As shown in figure 61, the disposition of the freshwater withdrawal for irrigation and livestock uses was 53.9 percent consumptive use and 46.1 percent return flow. Figure 74 shows that return flow and consumptive use are about equally divided for both irrigation and livestock. Included in the return-flow percentage is water loss during the conveyance of irrigation water from points of withdrawal to places of application. This represented an estimated 17 percent of the total irrigation withdrawals.

The reported amounts of agricultural withdrawals that go to consumptive use vary greatly from State to State. For example, several States reported that consumptive use accounted for all or nearly all the irrigation withdrawals, whereas several major irrigation States reported consumptive use as less than 50 percent of the water withdrawn, and Idaho estimated that only 25 percent of the water withdrawn went to consumptive use (Solley and others, 1988, table 8). Consumptive use of irrigation water includes water incorporated into the products, as well as evaporation of water during application, evaporation from the wetted soil and plant materials, and transpiration from the plants themselves. The remainder of the withdrawals becomes return flow that includes runoff from the land as a result of irrigation and water that infiltrates the soil and percolates past the root zone and eventually reaches the groundwater system or is intercepted by artificial drains.

The comparison of agricultural withdrawals from State to State during any one year (such as 1985) is complicated by differences in water demands that are caused by climatic abnormalities (wet or dry) during the growing season. The same kinds of uncertainties pertain to the State-to-State comparisons of irrigated acreages because regional differences exist in the amount of precipitation during the growing season, the types of crops and their water needs, and whether the irrigation was primary or supplemental. The amount of water used for specific crops in specific areas of the Nation and other factors related to agricultural water use are described in this volume in the article "Agricultural Water Use in the United States, 1950-85."

Return Flow and Reuse Potential

The availability of return flows for reuse depends largely on where the return flow reenters the freshwater hydrologic system. If, for example, the return flow discharges into a salt-water estuary, then it becomes as effectively unavailable to satisfy further needs for freshwater as if it had evaporated directly. Conversely, if the return flow enters a stream in its upstream part, then it has the potential for repeated reuse as the water flows downstream through the basin. Indeed, as is pointed out in the Colorado summary, the irrigation water withdrawals in the Colorado River system are cumulative summations of repeated reuses (withdrawals and return flows) of the water as it passed downstream. The same is true for withdrawal amounts presented for other States that contain or border large river systems. Similarly, the availability of return flow to the ground-water system for reuse depends on the aquifer. If return flow percolates downward to an aquifer that has low transmissivity, then the return flow could be effectively lost to further use for the foreseeable future. Conversely, if the return flow reaches a highly transmissive aquifer, then the return-flow water could become available again within a short time, either for withdrawal through wells or as discharge to an adjacent stream.

Suitability for reuse is determined mainly by the chemical quality of the return flow or by some other characteristic such as temperature or sediment content, in relation to the intended use. For example, the repeated reuse of stream water for irrigation in a long river system ultimately can add such a load of dissolved solids that the water in the downstream part of the basin is no longer suitable for irrigation or other common uses. Similarly, if freshwater return flow recharges a body of saline ground water, then that return flow is effectively lost as freshwater.

The concept of return flow is very useful quantitatively in the water-budget analysis of hydrologic basins. As aggregated by the State summaries, it is perhaps most useful as a general reassurance that water use is not the same as water loss and that, in fact, much of the water that is used can, and does, become available for further use.

Management of Water Allocation and Use

Management of the allocation and use of most of the Nation's water resources lies with the individual States and institutions within the States. The Federal government, as part of its constitutionally based responsibilities, has entered into treaties concerning water management with Canada and Mexico and holds "reserved water rights" for use in conjunction with certain federally managed public lands. Also, the Federal government has water-related duties and responsibilities under treaties and other agreements with Native Americans (U.S. Geological Survey, 1984, p. 71). In addition, Federal courts have adjudicated many disputes over water, and the Congress has consented to many interstate compacts among States that share boundary rivers and other water resources. With those exceptions, however, the States have primacy over most aspects of water management within their respective boundaries.

Each State has its own set of institutions for the management of water allocation and use; these are in addition to environmental and other institutions that also influence water management. These water-management institutions were established and are evolving in response to water-management problems. The responsibilities of the State agencies involved with water are mainly to regulate the allocation of water among competing users, to resolve disputes, and to promote public health and safety. Also, responsibilities relating to waste disposal and its effects on water resources are becoming increasingly important in many States.

In each State, a variety of local administrative agencies, municipalities, water-supply districts, irrigation districts, and other local governmental and quasi-governmental groups are involved with water management. These entities, which operate according to State and Federal regulations, perform such local functions as withdrawing, treating, supplying, and distributing water; making local water exchanges; imposing water-conservation measures; collecting and treating wastewaters; and maintaining surveillance of quality of public supplies. The degree of water-management authority of these local institutions varies considerably.

The duration and the degree of overall water management, which differs greatly from State to State, depends mainly on the abundance of water in relation to water demands. In arid Arizona, for example, territorial laws governing the rights for withdrawal and use of surface waters were first established in 1864, and regulation is relatively intense. In contrast, for some water-rich States in the Southeast, there is little or no regulation of surface-water withdrawals except in times of drought. Even in these States,

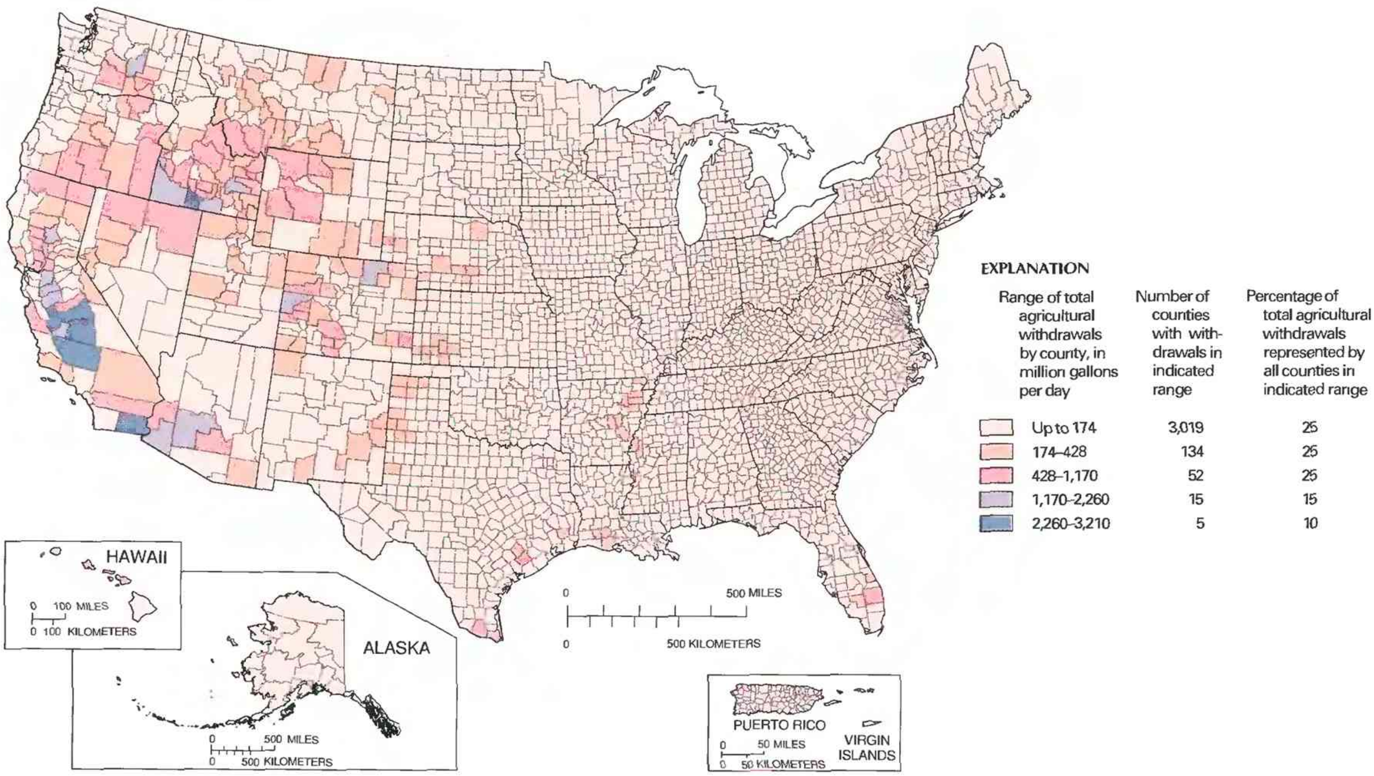


Figure 73. Total agriculture (irrigation and livestock) freshwater withdrawals (141,000 million gallons per day) by 3,225 counties comprising the United States, Puerto Rico, and the U.S. Virgin Islands and the percentage of total withdrawals represented by those counties, 1985. (Source: Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

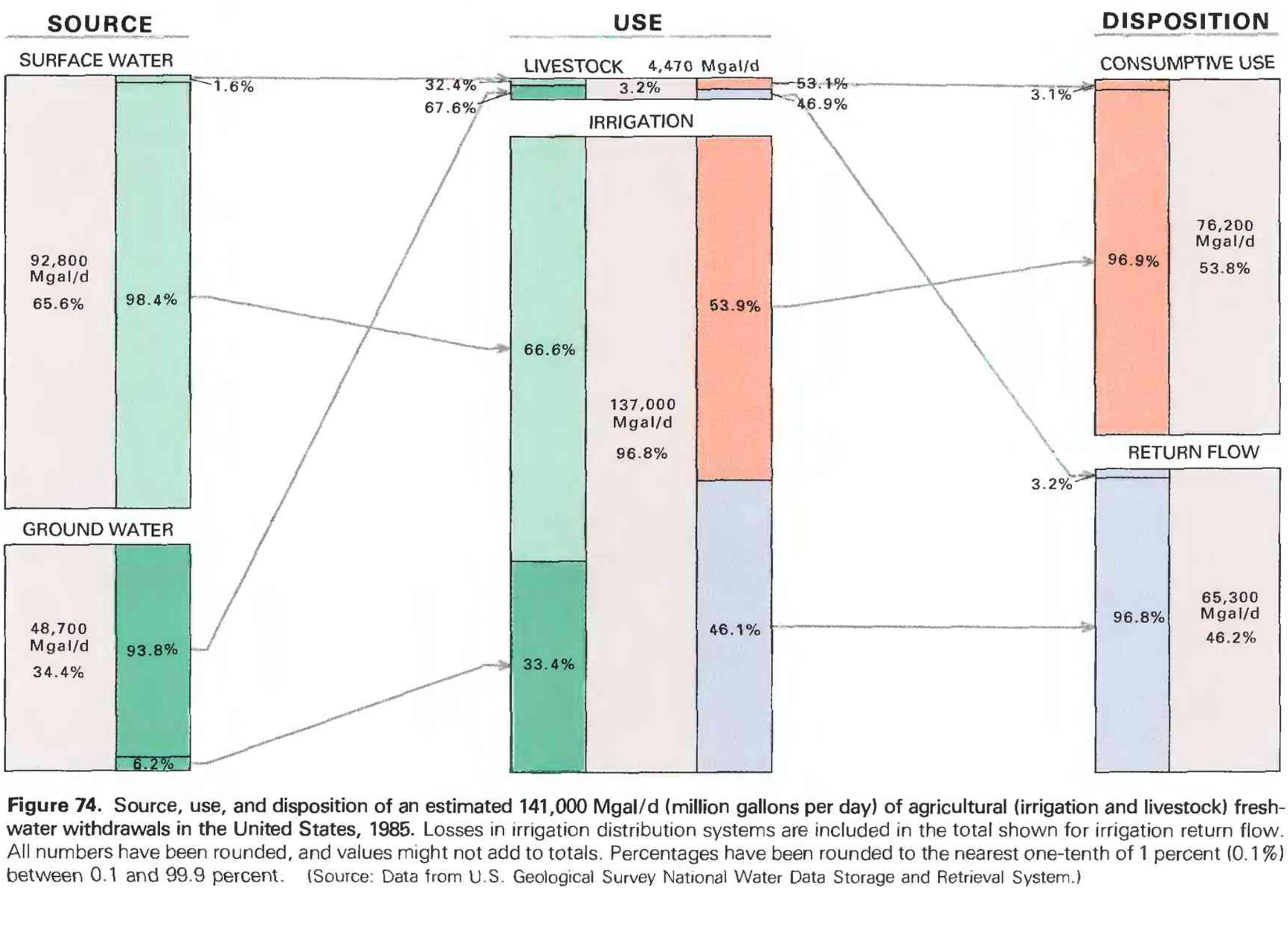


Figure 74. Source, use, and disposition of an estimated 141,000 Mgal/d (million gallons per day) of agricultural (irrigation and livestock) freshwater withdrawals in the United States, 1985. Losses in irrigation distribution systems are included in the total shown for irrigation return flow. All numbers have been rounded, and values might not add to totals. Percentages have been rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

however, there is regulation of public-supply withdrawals, which reflects a high concern for public health.

Some uses and levels of use are exempted from regulation. Most States have some regulatory threshold that is based on withdrawal rates and is aimed at excluding small rural water uses from regulation. Also, in some States (see, for example, Georgia and Tennessee), certain types of water use, such as agricultural, have been specifically excluded from regulation.

The principal State water laws are those that relate to water rights governing the allocation of water among competing users. These water-rights laws differ widely because they have evolved in different historical and hydrologic settings and reflect different customs and traditions of the people involved. Because of the differences and complexities of the various State laws and administrative approaches, few general comments can be derived from the State summaries.

In general, management and regulation of surface water came before regulation of ground water. This reflects the order in which water resources were developed in the States. Stream and lake waters were obvious and readily utilized, whereas the knowledge of ground water and methods for its efficient withdrawal evolved more slowly. Once begun, however, the regulation of ground water generally has outpaced that of surface water. In some States, recent increases in ground-water use, largely for irrigation, have resulted in State legislation that regulates the withdrawal and the use of ground water to a greater degree than surface water.

Historically, most water-rights systems considered water rights to be valid only where the water was used initially on a farm or by a factory or city. More recently, however, water rights are more likely to be treated as separate property that can be transferred by sale, loan, or trade (see summaries for Arizona, New Mexico, and Colorado, for example). In various States, reallocation of water rights can be achieved by means of regulatory-agency decisions, special water courts, the general courts, or simply free-market transfers.

As indicated in many of the State summaries, the water-management efforts continue to evolve. Recent legislation is directed at—

- Facilitating water transfers within and among States as a means of reducing imbalances between water supply and demands,
- Emphasizing water conservation in times of drought and at places of long-standing ground-water depletion, and
- Reducing the threat to public health and environmental quality from water pollution, with recent emphasis on ground water.

History of Water Use

The history of water use in the United States, as outlined in the State summaries, closely parallels the history of settlement and development of the Nation. For Native Americans and early European immigrants, the streams were routes of navigation for exploration and seasonal migration and provided access to fish and game. As settlement and interior migration proceeded, so did water-resource development. The types and the pace of water development, however, differed greatly, as they depended primarily on local climatic conditions and secondarily on population density and industrial pursuits.

Most early domestic supplies were from streams and springs, although European explorers and settlers brought a basic knowledge about wells. Consequently, water for many early settlements was obtained from shallow dug wells.

The first significant diversion and development of stream water by Europeans in what is now the Eastern United States was to power gristmills and for other waterpower uses. However, as pointed out in the Arizona and New Mexico summaries, Native Americans had built and used elaborate diversion and distribution systems for irrigation more than 2,000 years ago. These abandoned prehistoric distribution systems were rehabilitated and copied by early Spanish and other European settlers in the arid West. In the Southeast, early settlers diverted water from coastal rivers in Georgia to flood fields for rice cultivation by using a system of dikes and gates.

In the eastern States, where water from precipitation tends to be distributed fairly evenly during the year and generally is adequate for crops during the growing season, the next stage of water development was the extension and the improvement of navigational waterways. The Connecticut River was one of the first to be developed for navigation by construction of dams, locks, and canals. Many of the improved waterways in the eastern and the central parts of the Nation continue to be essential transportation routes for commerce, but the spread of railroads, which began about 1830, reduced the role of some canal systems, such as the Delaware–Raritan Canal in New Jersey, to serving as routes for interbasin water transfers or as sources of emergency water supplies.

The water that was impounded to operate navigational locks also was used for other purposes, including municipal water supplies and, later, hydroelectric power generation. As mentioned in the Connecticut and the Minnesota summaries, the development of some of the first city water supplies from streams was for fire protection rather than for public convenience or public health. Indeed, during the 19th century, diseases such as typhoid fever and cholera, which were transmitted through some municipal supplies from polluted streams, apparently led to widespread preference for well water as a source of drinking water. At some places, however, just the opposite was true. In Maryland and the District of Columbia, for example, communal water supplies were developed from stream sources after shallow ground-water supplies became polluted.

In a few of the western mining districts (see California, Montana, and Nevada summaries), some of the first major water developments were diversions of stream water for sluicing of metalliferous deposits. As placer deposits played out and mining declined, some of the flumes and ditches that had been built to convey sluicing water were rehabilitated and extended for irrigation use.

Ground-water development, which at first was limited to places where supplies could be obtained from springs or shallow dug wells, was spurred during the late 19th century by the following developments:

- Rapid improvement of well-drilling methods following the discovery of petroleum near Oil Creek, Pa., in 1859;
- Ground-water prospecting along the westward-spreading railroads, where dependable supplies of water were needed for the steam locomotives and railroad workers;
- Geologic and ground-water studies by the U.S. Geological Survey and State counterparts, especially in the arid West where several major artesian basins were thus defined;
- The invention and rapid application of internal-combustion engines as a source of power; and
- Major improvements in water pumps.

Irrigation and other large-scale uses of ground water became practical for the first time in the early 20th century as new and better engines and large-yield pumps allowed irrigators to tap aquifers at depths of hundreds of feet. In many rural areas, however, ground-water development was minor until the 1940's and 1950's when rural-electrification programs extended electrical transmission lines into these areas. According to the North Dakota summary, ground water was obtained almost exclusively by windmills and handpumps in rural areas before the arrival of electricity in the late 1940's.

The main water-development emphasis during the mid-20th century, however, has been the construction of large, federally sponsored water projects. These include dams and reservoirs; extensive irrigation and land-drainage systems; flood-control works; waterway construction and maintenance (including channel modification and dredging); and aqueduct systems for interbasin water transfer. Many of these developments were in response to the Newlands Act, which the Congress passed in 1902. This act established a fund for planning, constructing, and maintaining dams and irrigation works in 16 Western States and Territories and lead to the establishment of the U.S. Bureau of Reclamation in 1907.

The earliest dams and reservoirs constructed generally were for one and at most for two purposes. Economics of scale, made possible by the development of multipurpose projects and the increasing use of earth-fill dams, spurred the growth of reservoir capacity, especially after 1930 (fig. 75). Today, for example, surface-water reservoirs are operated to produce hydroelectric power, to control floods, to enhance fish and wildlife resources, to augment low flows in rivers, and to provide recreational opportunities as well as to supply water for irrigation, municipal, and industrial uses.

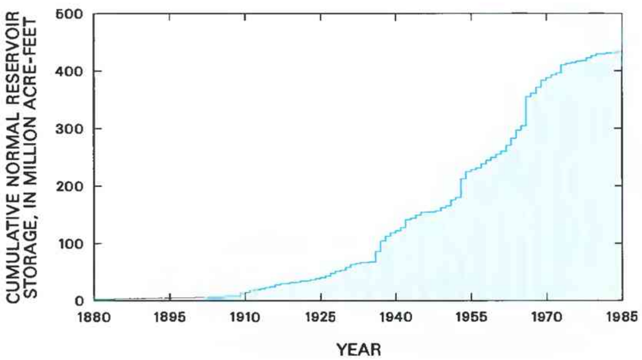


Figure 75. Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity in the United States, 1880 to 1985. (Source: Data from U.S. Army Corps of Engineers, 1981.)

Since the last period of rapid construction in the 1960's, and especially after about 1977, the addition of new reservoir capacity has slowed dramatically. At least three factors contributed to this slowing trend: A paucity of remaining good reservoir sites; the recent change in Federal water policy, which requires increased non-Federal contributions to the funding of Federal water projects; and the increased concerns about the environmental cost of additional damming of free-flowing streams.

As mentioned in some of the State summaries, the high degree of water development that has been achieved in the United States has not been without its environmental price. In addition to the water-quality degradation caused by the use of the water, several of the State summaries list silting of reservoirs and estuaries and adverse effects on esthetics, recreational opportunities, and anadromous fish populations of streams. For these and other reasons, the emphasis on large water-related developments has diminished in recent years (fig. 75).

TRENDS IN WATER USE

After progressive increases in water use from 1950 to 1980, total freshwater offstream withdrawal and instream use for hydroelectric power generation were less during 1985 than during 1980 (Solley and others, 1988, p. 68). Exceptions to the general decrease, however, were reported increases in withdrawals for public supplies, self-supplied domestic use, and livestock use. Also, a small increase in the use of reclaimed sewage water was reported. A summary of the major trends in freshwater use from 1950 to 1985 is provided in figure 76.

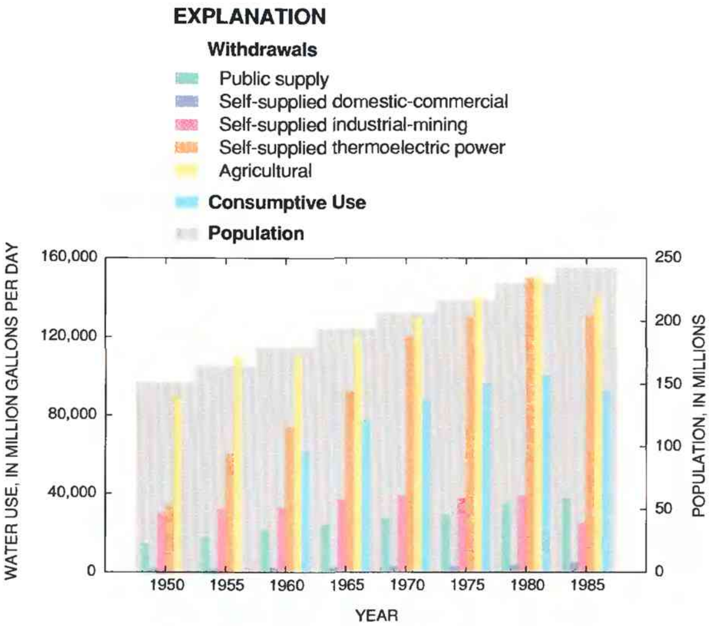


Figure 76. Trends in freshwater use and population in the United States, 1950–85. (Sources: Water-use data from MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988. Population data compiled by the U.S. Geological Survey from U.S. Bureau of the Census.)

Public-supply withdrawals increased about 7 percent in 1985 over those for 1980 and reflected continuing increases reported for each water-use compilation year since 1950. During the latest 5-year interval, the Nation's population grew an estimated 6 percent, or 1 percent less than the increase in withdrawal for public supplies. This relation, which is discussed in several of the State summaries, has been attributed to a general trend of increasing per capita domestic water use, greater commercial demands, and increased amounts of public-supply water delivered to industry.

The total industrial and mining water use shown in figure 76 apparently had been declining for several years as a result of water-pollution control efforts, which have led to improvements in water-use efficiency in many industrial processes. Part of the decline in 1985 (fig. 76), however, could be the result of better reporting and compilation methods for that year (Solley and others, 1988, p. 70). As shown by the graph, the amount reported for 1985 was the lowest since 1950.

Total irrigation withdrawals were reported to be about 6 percent less in 1985 than in 1980—the first apparent reduction in that use since 1960. This reduction, which was mainly in ground-water withdrawals for irrigation, was attributed partly to increased availability of surface-water supplies in 1985 that resulted from above-average rainfall over large areas and weak commodity prices. Both the irrigated acreage and the reported amount of water application per acre were less in 1985 than in 1980, by about 1 percent and 8 percent, respectively (Solley and others, 1988, p. 69). Withdrawals for livestock use show a steady increase from 1950 to 1985. The large increase in 1985 reflects the inclusion of aquaculture with livestock for the first time in the U.S. Geological Survey's water-use reports.

The 1985 estimates for water withdrawn for thermoelectric power generation represented a decline of about 13 percent from that of 1980. This was the first decline in this category since the water-use compilations were begun. According to several State summaries, decreases in thermoelectric withdrawals were attributed to a decrease in the use of water for "once-through" cooling, which requires large withdrawals but results in a low rate of consumptive use, and to an increase in "closed-loop" cooling, which requires much lower withdrawals but results in very high consumptive use by evaporation at cooling towers.

Although the consumptive use for thermoelectric power generation increased, the nationwide total consumptive use of freshwater is reported to have decreased by about 9 percent from 1980 to 1985 (Solley and others, 1988, table 31). This decrease in consumptive use was attributed largely to the aforementioned decreases in the estimated withdrawals for irrigation and industrial uses.

Estimated water use for hydroelectric power generation—the only instream water use discussed in the State summaries—was less for 1985 than for 1980 by about 7 percent nationwide. This was the first decline in use for hydroelectric power generation that has been reported in the series of U.S. Geological Survey water-use compilations (Solley and others, 1988, table 31). The amount of hydroelectric power generated during 1985, however, reportedly was greater by the same amount (7 percent). The increase in power generation and the decrease in estimated water use probably resulted from an increase in installed generator capacity and more efficient utilization of available surface-water supplies (Solley and others, 1988, p. 44).

Most of the State summaries indicate that an expectation of increased water demand and responses to water contamination will require more intensive management in the future. Whether the water resources are considered to be fully appropriated or over-appropriated, as in California or Arizona, or still able to support additional development, as in many other States, increased water-resources management is certain to increase the demand for water-use and other hydrologic information.

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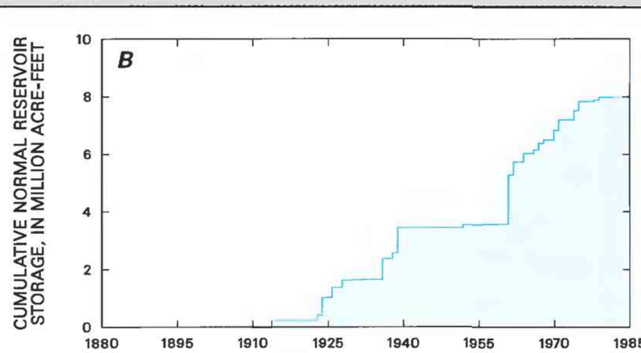
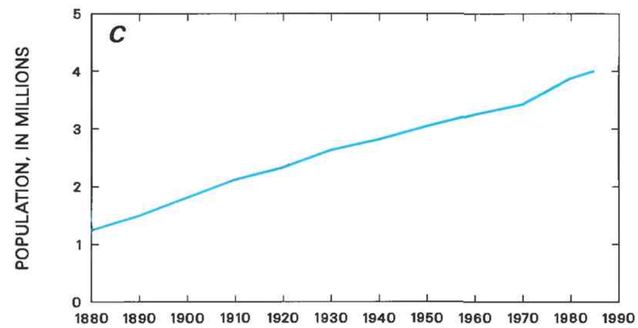
Alabama
Water Supply and Use

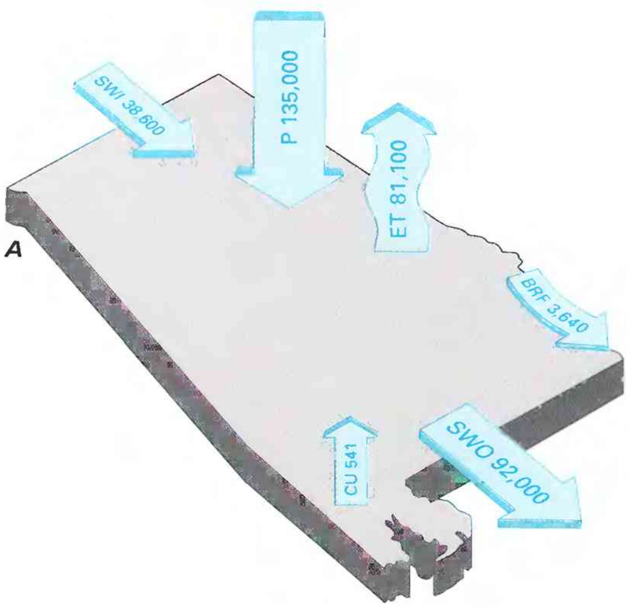
Alabama has abundant water resources that are suitable for public supply, industry, agriculture, navigation, hydropower, and recreation. The average annual precipitation ranges from 48 inches in west-central and east-central parts of the State to 68 inches on the Gulf Coast (Lineback and others, 1974, p. 10). Of the average annual precipitation of 135,000 Mgal/d (million gallons per day), most of it (92,000 Mgal/d) moves to streams and flows from the State or is returned to the atmosphere by evapotranspiration (81,100 Mgal/d) (fig. 1*A*). About 3 to 6 inches of the annual precipitation recharges the ground-water system and supplies base flow to streams (U.S. Geological Survey, 1985, p. 123). During 1985, 8,590 Mgal/d of freshwater was withdrawn from the rivers, streams, lakes, and aquifers in Alabama. Of this quantity, about 541 Mgal/d was accounted for by consumptive use, and 8,050 Mgal/d was return flow to streams or lakes.

Most of the population obtains their water supply from surface water; however, many of the public-supply systems also utilize ground water because it is generally cheaper and more convenient. Tuscaloosa and Birmingham are two of the larger cities that have impounded streams for their primary water supply. Parts of east-central and north-central Alabama have inadequate ground-water supplies and, therefore, rely more on surface water than on ground water. Communities in the southern part of the State rely mostly on ground-water sources for public supply. One exception, Mobile in southwestern Alabama, uses a surface-water reservoir for public supply even though ground-water supplies in the area are abundant.

The largest withdrawals of water in 1985 were for thermoelectric power generation; however, the largest consumptive uses of water were for industrial and mining purposes (44.9 percent of







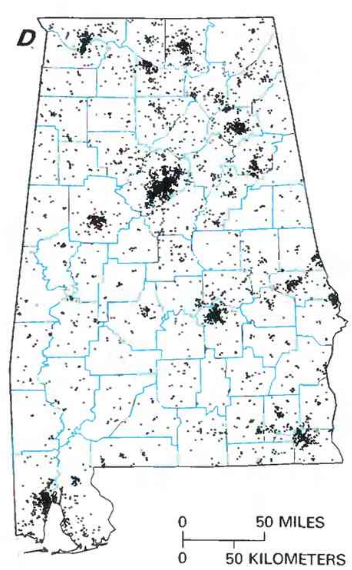


Figure 1. Water supply and population in Alabama. *A,* Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from various reports of the U.S. Geological Survey and State agencies. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

total). Water used for thermoelectric power generation was 80.6 percent of total surface- and ground-water withdrawals but accounted for only 20.8 percent of all consumptive use in the State. Combined domestic, commercial, industrial, and mining water uses in 1985 were 1,510 Mgal/d.

Because Alabama has abundant water resources, water management in the past has consisted primarily of limited development of reservoirs to meet needs. However, such issues as water quality and efficient use of water are becoming increasingly important and will need to be addressed in the future.

HISTORY OF WATER DEVELOPMENT

The extensive river systems and abundant ground water have contributed greatly to the development of Alabama. However, the State's largest city, Birmingham, was built around the local coal and iron ore deposits and did not have a navigable waterway until a network of locks and dams was developed on the Black Warrior River. The numerous rivers and streams provided power to operate several types of mills, although river rapids in areas north of the Fall Line (line approximately from Lee County to Bibb County to Franklin County) prevented upstream travel during the early industrial development of the 1800's. Beginning with the construction of locks and dams around 1910, the number of navigable waterways increased dramatically, as did opportunities for hydroelectric power generation. These and other dams also provided a system for flood control, which made development nearer the rivers more feasible. Since 1910, the cumulative normal storage of the State's reservoirs has increased to 8 million acre-ft (acre-feet) (fig. 1*B*). The large increase in reservoir capacity that occurred in 1961 was primarily due to the completion of Lewis Smith Lake in Winston, Cullman, and Walker Counties. This lake has a normal storage capacity of 1.39 million acre-ft. Alabama currently has four lock-and-dam, or slackwater navigation, systems that have a total of 14 locks.

The completion of the Tennessee–Tombigbee Waterway in 1985 opened an avenue of trade from the Gulf of Mexico through Alabama to the Tennessee, the Ohio, and the Mississippi Rivers. The waterway, which follows the Tombigbee River in Alabama, also provides opportunities for industrial and recreational uses.

In 1823, Huntsville became the first city in the South and the second in the Nation to have a public-water supply (Christensen and others, 1975, p. 40). Plans for a public-supply system for Mobile date as far back as the mid-1700's, although one was not constructed until the 1830's.

Alabama's population has increased from 3.89 million in 1980 to 4.02 million in 1985 (fig. 1*C*), and most major cities in Alabama are near one of the navigable waterways (fig. 1*D*). Population trends indicate that the population will increase by about 50,000 people annually through the year 2000 (Alabama Department of Economic and Community Affairs, 1984, p. 71). Such an increase in population would cause increased demand for water supplies. Some areas, though, already have experienced problems with water quantity or quality, or both. The severe drought of 1986 heightened public awareness of the limits of the water resources.

An expansion of irrigated acreage began in the late 1960's and continued into the 1980's. This expansion was due primarily to increased irrigation of corn and peanuts. The irrigated acreage of soybeans and cotton is also increasing. Withdrawals for all agricultural uses (irrigation and nonirrigation) increased from about 79 Mgal/d during 1975 to 165 Mgal/d during 1985. Because the number of livestock has not increased greatly in recent years, the increase in withdrawals primarily reflects increased irrigated acreages.

Since 1965, some effort has been devoted to comprehensive planning for land and water resources development. The need for future management of the water resources was addressed in "Alabama's Water Resources Policy" (Alabama Development Office, 1973), along with a brief comment on the abundance of surface and ground water in the State. Being water-rich, Alabama historically has enjoyed abundant surface and ground water, and the primary water-management concern has been the protection of human health. During the mid-1970's, concern for environmental protection led to rapidly broadening of the regulation of discharges into surface-water bodies.

WATER USE

The water budget for the State (fig. 1*A*) provides an indication of the quantities of water that flow to and from the State. As abundant as water is in Alabama, some water-supply problems are developing or already have developed. One example is in an area in Houston and Dale Counties in southeastern Alabama. Improper well spacing and overpumping of the aquifers have caused a serious decline in water levels in the past 40 years (Scott and others, 1984, p. 3).

The distribution of withdrawals by county is given in figure 2*A*. Limestone, Jackson, Colbert, Walker, Shelby, and Mobile Counties have the largest withdrawals in the State. These counties are the largest users of surface water (fig. 2*B*); all have thermoelectric powerplants that use large quantities of surface water for cooling purposes. Walker and Mobile Counties also have large withdrawals of surface water for public supply and industrial use. The counties that have the largest ground-water withdrawals (fig. 2*C*) reflect the major population centers in the State (fig. 1*D*) and the use of ground water as a source of public supply. The one exception is Hale County, where the large ground-water withdrawals are used for agriculture, specifically aquaculture.

The distribution of surface-water withdrawals by major drainage basin is shown in figure 3*A*. The largest withdrawals are in the Middle Tennessee–Elk and the Mobile–Tombigbee basins, which are the most industrialized and the most populous in the State.

Most of the State has aquifers capable of producing fairly large quantities of freshwater from properly constructed wells. The major aquifer systems in Alabama and the withdrawals for various uses from each of them are shown in figure 3*B*. Except for east-central and north-central Alabama, most of the State is underlain by thick sand or limestone aquifers that have well yields as large as 2,000 gal/min (gallons per minute). East-central Alabama has extensive igneous and metamorphic rocks that yield inadequate supplies of water for most purposes. North-central Alabama is underlain by sandstones that yield only small quantities of water. In some parts of the State where aquifers are productive, surface-water resources sometimes provide an economic alternative to drilling for ground water where large quantities of water are required.

Hydroelectric power is the largest instream use of water. Power companies have capitalized on this cost-effective method of producing electricity. During 1985, about 114,000 Mgal/d of water was used to generate more than 7,000 gigawatthours of electricity. Consumptive water use during hydroelectric power generation is considered to be negligible.

The numerous surface-water impoundments that are used for navigation and hydroelectric power generation also provide excellent locations for recreation and fish and wildlife habitats. Recreation also is a major instream use, and the retail sales associated with recreation make it important to the State's economy. Recreational use is measured in terms of the number of annual visits per facility. The number of visitors in 1980 to Tennessee Valley Authority, U.S. Army Corps of Engineers, State, local, and commercial recreational areas was estimated to be more than 23 million (Baker and Mooty, 1987).

The source, use, and disposition of freshwater are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that the

8,250 Mgal/d of surface-water withdrawals represent 96.0 percent of the total withdrawals in Alabama. Of that quantity, 5.4 percent (442 Mgal/d) is withdrawn by public-supply systems, none is for domestic and commercial use, 9.8 percent (804 Mgal/d) is self-supplied by industrial and mining facilities, 83.9 percent (6,920 Mgal/d) is withdrawn for thermoelectric power generation, and 1.0 percent (80 Mgal/d) is self-supplied for agricultural purposes. The use data indicate, for example, that domestic and commercial use was 436 Mgal/d, which represented 5.1 percent of the State's total freshwater withdrawals. Of that 5.1 percent, 90.4 percent (394 Mgal/d) was from public supply, and 9.6 percent (42 Mgal/d) was self-supplied from ground-water sources. From the total of 436 Mgal/d, 17.5 percent (76 Mgal/d) of the water was consumed use and was no longer readily available for reuse, and 82.5 percent (360 Mgal/d) was returned to natural water sources. The disposition data indicate that, of all water withdrawn, 6.3 percent (541 Mgal/d) was consumed and 93.7 percent (8,050 Mgal/d) was returned. Domestic and commercial use accounted for 14.1 percent (76 Mgal/d) of all consumptive use and 4.5 percent (360 Mgal/d) of all return flow.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. Public-supply systems in Alabama furnish water for domestic and commercial use, and industrial and mining use (fig. 4). Ground- and surface-water withdrawals for public-supply distribution increased from 29 percent of total water withdrawals (excluding that for thermoelectric power generation) during 1980 (Baker and others, 1982, p. 35) to 37 percent during 1985 (Baker and Mooty, 1987, p. 36). From 1960 to 1985, Alabama's population increased 101 percent (fig. 1*C*), and public-supply withdrawals increased 167 percent. This discrepancy indicates an increasing dependence of commercial and industrial facilities on public-supply systems. However, despite an increase in population between 1980 and 1985, public-supply withdrawals did not increase. The closing of some large industries decreased public-supply deliveries to industrial users, offsetting the increase in domestic and commercial deliveries.

Total public-supply withdrawals during 1985 were about 615 Mgal/d, of which 71.9 percent (442 Mgal/d) was surface water and 28.1 percent (173 Mgal/d) was ground water. Most public-supply systems use ground water as their source of supply because it is usually more convenient and requires less treatment than surface water. However, more surface water is withdrawn because the largest centers of population in the State use it as their source of supply owing to the great quantities of water needed.

Some public-supply systems in recent years have begun to consolidate or interconnect. In many instances, this minimizes the effects of water shortages by increasing the number of water sources. The incorporation of the smaller systems into a larger system generally provides better service to the customers because the larger systems generally are more modern.

Domestic and Commercial

Domestic and commercial water users receive water from public and self-supplied systems; total freshwater use during 1985

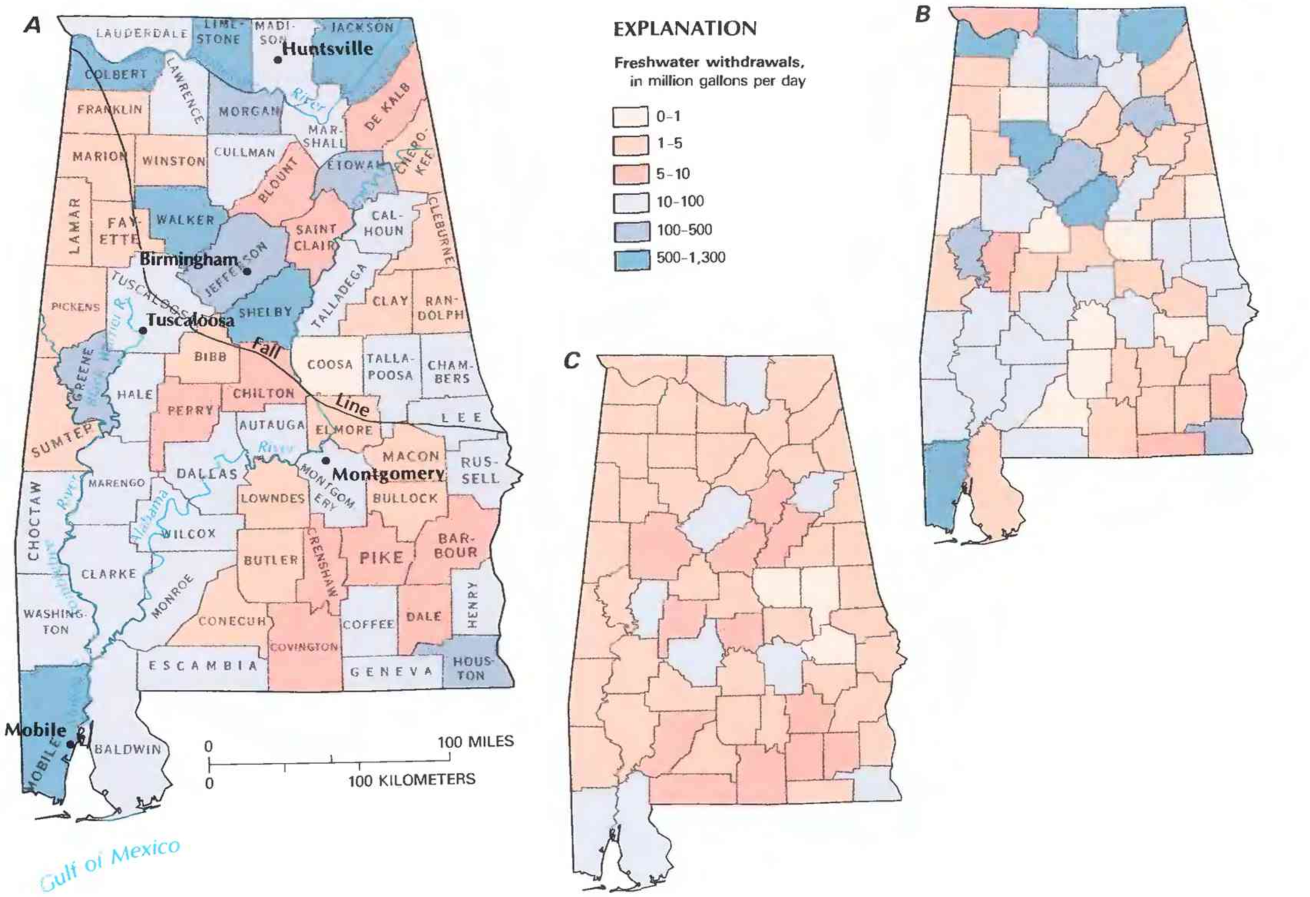


Figure 2. Freshwater withdrawals by county in Alabama, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

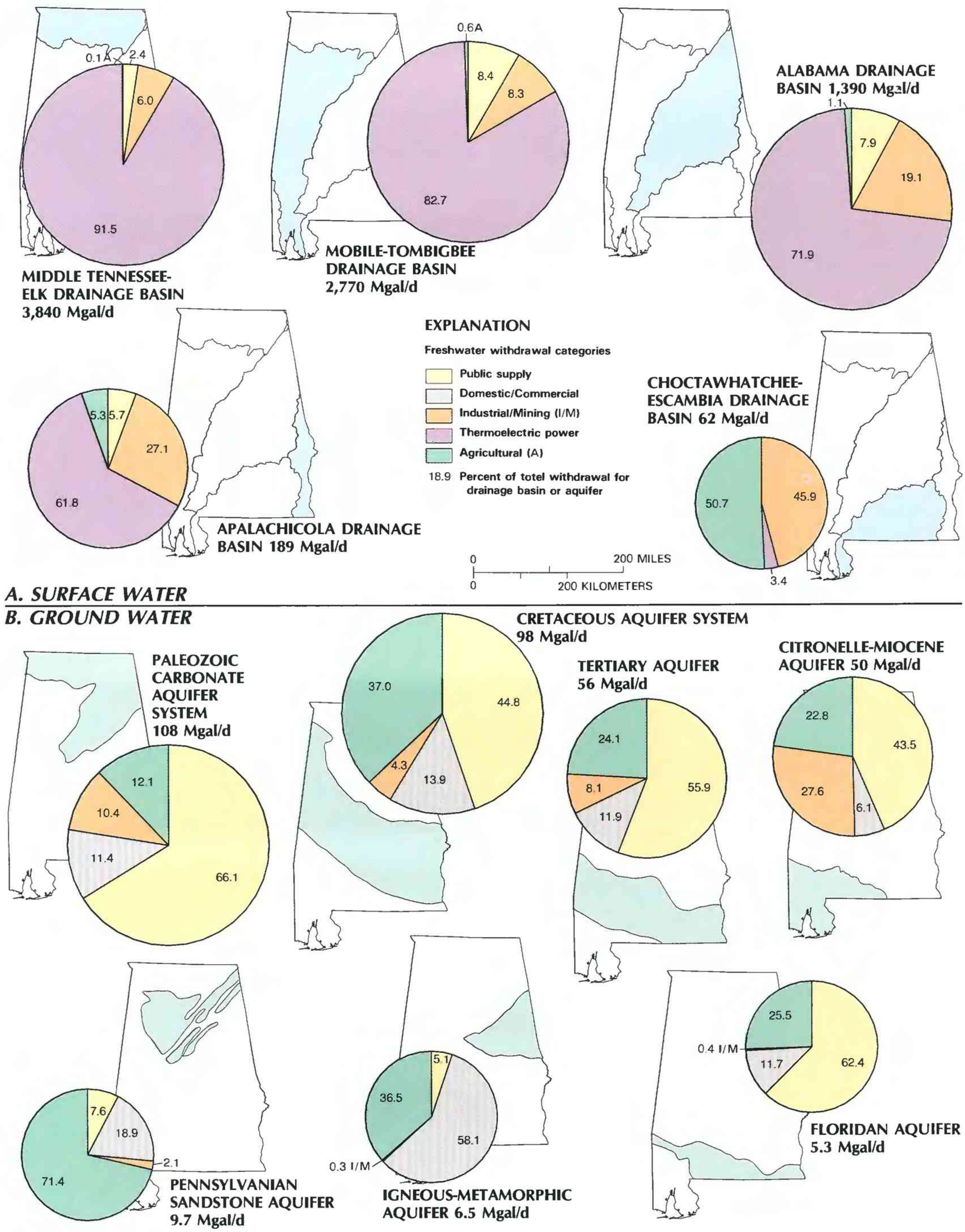


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Alabama, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey and State agencies.)

was 436 Mgal/d (fig. 4). Domestic use was about 371 Mgal/d, of which 62 Mgal/d was consumed. Of the total, 332 Mgal/d was from public-supply systems, which served 87 percent of the population, and 39 Mgal/d was self-supplied. Per capita use from public-supply systems was 175 gal/d (gallons per day) (Baker and Mooty, 1987, p. 7). In contrast, per capita use from domestic self-supplied systems was 75 gal/d during 1985; this value has been estimated to be 100 gal/d in previous water-use surveys (Baker, 1983; Baker and Moore, 1983).

Commercial use during 1985 was 65 Mgal/d, of which 3.2 Mgal/d was self-supplied and 62 Mgal/d was provided by public-supply facilities. Consumptive use for commercial purposes was 14 Mgal/d.

INDUSTRIAL AND MINING

During 1985, water withdrawals and deliveries for industrial and mining use were about 1,070 Mgal/d (fig. 4). Self-supplied industries used 804 Mgal/d of surface water and 43.8 Mgal/d of ground water. Public-supply systems delivered an additional 221 Mgal/d. Self-supplied mining activities relied totally on ground water as their source of supply. About 14 Mgal/d of ground water was withdrawn for mining, of which 3.4 Mgal/d was saline water that was not included in the quantities in figure 4.

The majority of industrial water use is by chemical and paper companies. Most of the larger companies are located along the major waterways. Industrial water use decreased 17 percent from 1980 to 1985 because some large water-use industries were closed. Other industries have decreased their water demand by using water more efficiently.

THERMOELECTRIC POWER

Water use at thermoelectric powerplants is a major part of Alabama's total water use. The withdrawal of water for cooling during thermoelectric power generation accounts for 80.6 percent of all water withdrawn. Alabama has 14 thermoelectric powerplants—11 fossil fueled and 3 nuclear powered; of the three nuclear plants, one is fully operational, one was shut down indefinitely in 1985 for repairs, and one is currently (1987) under construction. During 1985, thermoelectric powerplants used 6,920 Mgal/d of fresh surface water for cooling purposes (fig. 4). Of this quantity, 5,640 Mgal/d was used by the fossil-fueled plants, and 1,290 Mgal/d was used by the nuclear plant. Consumptive use was 75 Mgal/d for fossil-fueled plants and 38 Mgal/d for the nuclear plant. Because only 2 percent of the withdrawals is lost through evaporation during the cooling processes, most of the water is returned to the rivers.

AGRICULTURAL

Agricultural water use during 1985 was 165 Mgal/d (fig. 4). Irrigation withdrawals were 42 percent of agricultural water use, and nonirrigation agriculture (such as livestock watering and aquaculture) withdrawals were 58 percent. Consumptive use for all agricultural activities was about 66 percent of withdrawals.

Use of water for irrigation increased from 18 Mgal/d in 1970 (Peirce, 1972) to 69 Mgal/d (283 percent) in 1985. About 74 percent of the water used for irrigation is surface water. Most irrigation occurs in Baldwin County and in southeastern Alabama. To date, available surface and ground water in these areas has been

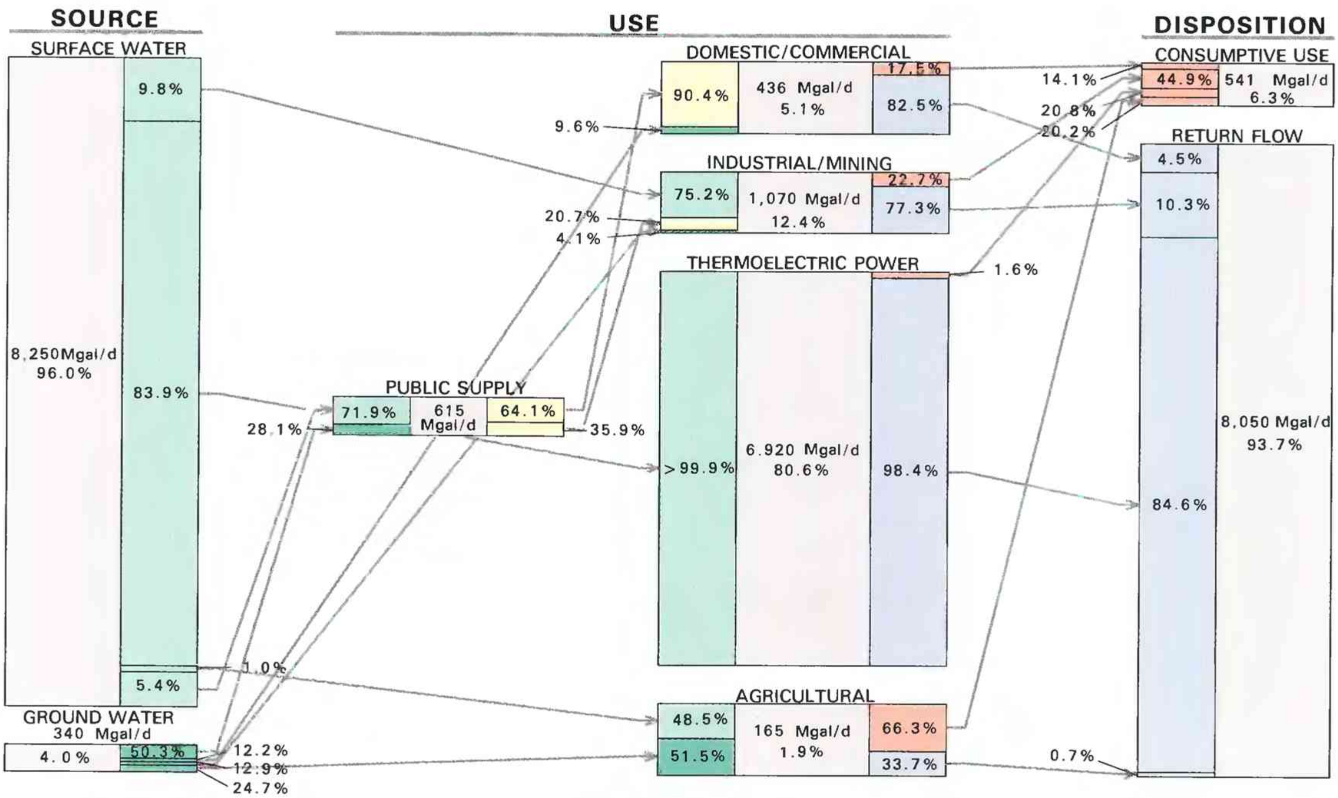


Figure 4. Source, use, and disposition of an estimated 8,590 Mgal/d (million gallons per day) of freshwater in Alabama, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Supercritical-flow flume constructed to calibrate a precipitation-runoff model for a small basin coal hydrology study in Boxes Creek near Howard, Alabama.

sufficient to support use. However, as a result of irrigation, some areas could have water-supply problems in the future. The unpredictable rainfall during recent years, and especially during the drought of 1985–86, probably will encourage more farmers to irrigate.

Water use for aquaculture, livestock, and other farm purposes was 96 Mgal/d during 1985 compared to 88 Mgal/d during 1980. This increase is due to the development of the aquaculture industry in the west-central part of the State. Of the total withdrawals for nonirrigation agriculture during 1985 (96 Mgal/d), 29 Mgal/d was surface water, and 67 Mgal/d was ground water.

WATER MANAGEMENT

The ownership of surface water and lands overlain by water in Alabama is based on the distinction between navigable and nonnavigable waters. Title to surface waters and streambeds of navigable waterways is retained in trust by the State for the people of Alabama. The legislature has the authority to establish laws pertaining to the use of public surface waters and lands underlying them and to establish authorities that can regulate the use of these waters.

Title to nonnavigable waters and streambeds may be vested in private landowners. Water rights of the landowners are subject to the riparian reasonable use doctrine. The courts' interpretation of the "reasonable use" rule allows the use of water for agricultural, industrial, mining, and other purposes, provided that the water is not wasted or allowed to affect others adversely. A water user may not divert, dam, or otherwise alter the course of a stream flowing across the land if upstream or downstream landowners will be deprived of their right to use the water or if the lands of others will be adversely affected.

Judicial decisions are used in solving conflicts over water use and water rights. Court decisions are made on a case-by-case basis and are governed by the circumstances and facts associated with each case. These decisions are binding only to the parties of each case.

Permits are required for the construction of public-supply wells and wells that will produce 50 gal/min or more within the Coastal Area Zone (Mobile and Baldwin Counties). These permits must be obtained from the Water Supply Branch of the Alabama Department of Environmental Management (ADEM). The ADEM develops well standards for public-supply wells but does not assist in the selection of well sites or regulate the spacing of wells. These standards attempt to ensure that water-supply systems meet demands. Operators of public-supply systems are required to report water withdrawals to the ADEM.

All water-supply wells (public, domestic, industrial, irrigation) must be completed by a driller licensed by the State. The State also requires that drillers submit well-completion forms to the Water Supply Branch of the ADEM and to the Water Resources Division of the Geological Survey of Alabama to ensure that the wells are completed by a licensed driller, and that information for well inventories is available when needed and to assist in locating sites for new wells.

Water-management, water-allocation, or drought-management plans have not been written by the State; solutions to water-supply shortages generally are the responsibility of local governments. Some local governing bodies have established limited control over ground-water management in their areas of jurisdiction; a few cities have adopted ordinances that require a permit for the construction and the use of a water well. The State provides local governments with advice and informal assistance. During water shortages, cities often adopt ordinances to prevent waste or to conserve water. In emergency situations, the governor may call upon the U.S. Army National Guard and the Department of Emergency Management to provide water to communities. Fines and jail sentences are used to discourage the waste of water in some cities.

During the severe drought of 1986 in the Southeastern United States, the Governor of Alabama formed a Drought Task Force. The Task Force continually monitored drought conditions and made recommendations to water users, public and private, on measures to conserve water.

The Geological Survey of Alabama and the Alabama Department of Environmental Management, in cooperation with the U.S. Geological Survey, maintain a statewide water-data network and conduct investigations of Alabama's water resources. The research, data collection, and analyses provided by this cooperative program provide an information base upon which water-management decisions can be made.

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Prepared by W.S. Mooty, U.S. Geological Survey; History of Water Development section by J.C. Warman and D.H. Block, Alabama Water Resources Research Institute; Water Management section by J.D. Moore, Geological Survey of Alabama

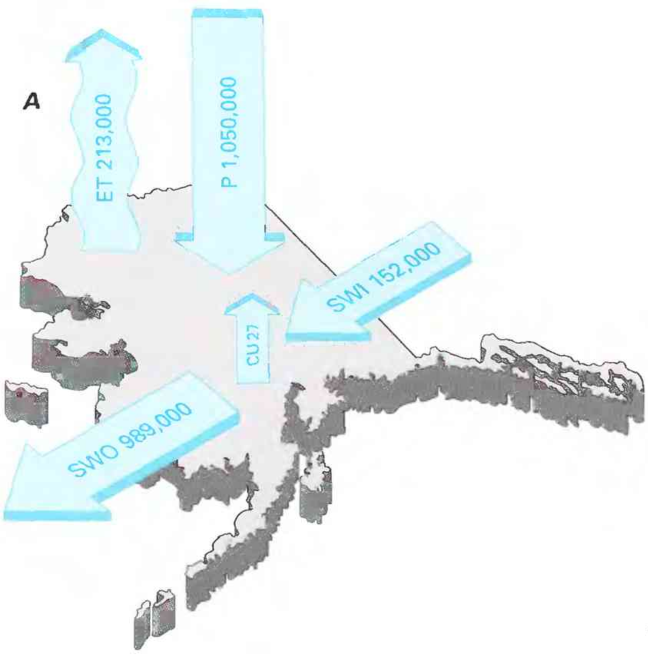
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 520 19th Avenue, Tuscaloosa, AL 35401

ALASKA
Water Supply and Use

Alaska's water supplies might appear to be unlimited because of the large quantities of precipitation received in the State (fig. 1*A*). Statewide average annual precipitation is about 1,050,000 Mgal/d (million gallons per day), and average annual runoff is about 989,000 Mgal/d. Alaska contains more than 40 percent of the Nation's surface-water resources. Three rivers (the Yukon, the Kuskokwim, and the Copper) are among the 10 largest in the United States. More than 3 million lakes range in area from pond size to about 1,000 mi² (square miles). Also, large amounts of water are stored within two principal aquifers. Environmental conditions, legal restrictions, and technological problems, however, limit the usability of these abundant supplies.

Alaska encompasses a land area of about 586,000 mi², or about one-fifth of the area of the conterminous United States. Climates range from frozen desert in the Arctic Slope basin to maritime rain forest in the Southeast Alaska basin. Average annual precipitation and temperatures range from about 5 inches and 10° F (degrees Fahrenheit) in the Arctic Slope basin to about 300 inches and 45° F in the Southeast Alaska basin. Much precipitation occurs as snow. Glaciers and icefields cover 28,500 mi², or nearly 5 percent of the land (Post and Mayo, 1971) and affect the timing and the quantity of runoff. Many of the rivers are silt laden, are affected by midwinter overflow icing or ice-jam flooding at spring breakup, or are ice covered much of the year. The occurrence and the availability of ground water are limited by permafrost. The extent and thickness of the permafrost decrease southward from a continuous layer as much as several hundred feet thick in the Arctic Slope basin to areas that are generally free of permafrost in the South Central Alaska and the Southeast Alaska basins. Because of these conditions, there is no certainty that either surface or ground water will be available at a given time and location.

Several water issues in Alaska result from this variability in the availability and occurrence of the water resource. Additionally, the legal precedents for obtaining water rights cause conflicts. Com-



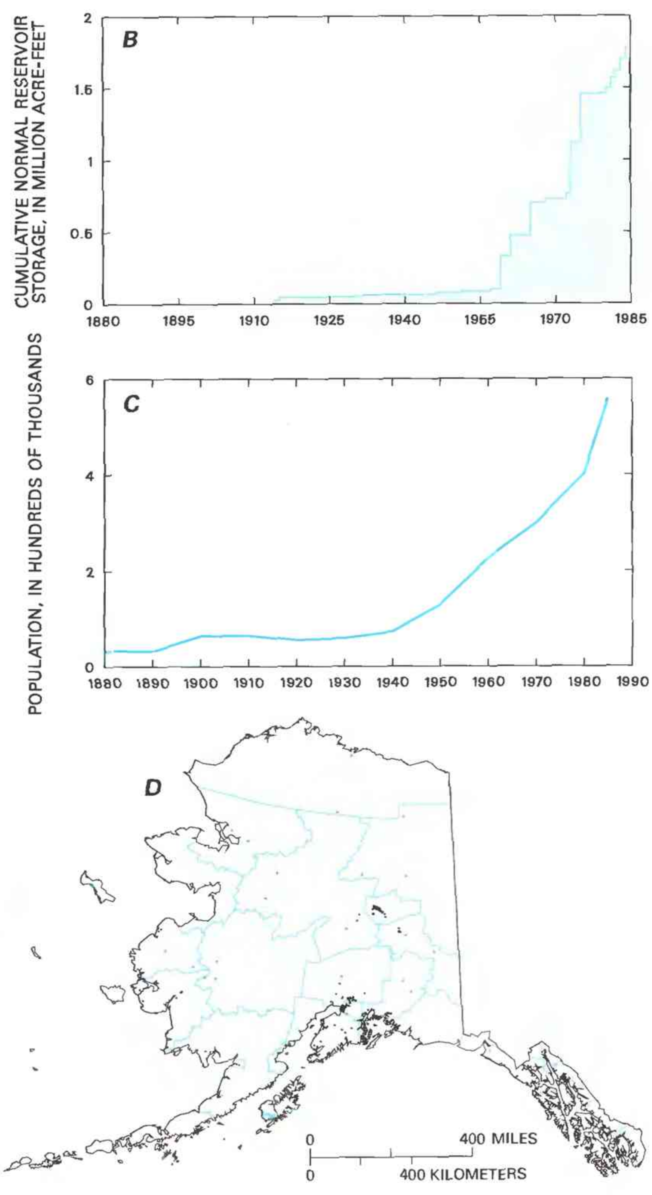


Figure 1. **Water supply and population in Alaska.** *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* R.D. Lamke (U.S. Geological Survey, written commun., 1985. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

petition for limited surface-water resources exists among industry, fish hatcheries, recreation, and fish and wildlife habitat demands. Ground-water-rights issues primarily involve public supply in basins where surface water is scarce. Currently (1987), the Arctic Slope, the South Central Alaska, and the Southeast Alaska basins are the focus of these issues.

HISTORY OF WATER DEVELOPMENT

In 1914, the first large reservoir was constructed to provide power for the mining and the timber industries in the Southeast Alaska basin. Since then, 19 additional reservoirs that have storage capacities greater than 5,000 acre-ft (acre-feet) have been built for electric power generation and public supplies. Of these 20 reservoirs, 13 are in the Southeast Alaska basin, 6 are in the South Central Alaska basin, and 1 is in the Yukon basin. These reservoirs contain a cumulative capacity of about 1.78 million acre-ft (fig. *1B*).

The first significant increase of Alaska's population occurred during the gold rushes of the late 1800's (fig. *1C*). Postwar migration and homesteading increased the population during the late 1940's and 1950's. Population growth during the 1960's and 1970's can be attributed to the development of oil fields in Cook Inlet and at Prudhoe Bay and the related pipeline-construction activities. The continued rapid population growth of the early 1980's can be attributed to the general economic well-being that oil production brought to the State. The population reached 558,000 in 1985; 77 percent of the inhabitants live within 5 of the 28 census districts, or county equivalents (fig. *1D*). Anchorage contained 44 percent of the State's population; the next largest concentrations of population were in Fairbanks (13 percent), Kenai (8 percent), Matanuska-Susitna (7 percent), and Juneau (5 percent).

Interest in Alaska's water supplies began during the gold rushes of the late 1800's; miners washed the placer deposits to extract the gold. The population growth and the corresponding urban development, especially after 1940, placed increasing emphasis on water supply. Increasing needs for water supplies for power in the Southeast Alaska and the South Central Alaska basins, for the pulp and paper industry in the Southeast Alaska basin, and for the canneries in the Southeast Alaska and Southwest Alaska basins created demands for water-resource information. Intensive development of other natural resources began during the 1960's and continued through the 1970's. Water was critical to support the oil fields in the Arctic Slope basin and the petrochemical, the seafood, and the timber production industries in the South Central Alaska and the Southeast Alaska basins. Continued population growth, especially in the South Central Alaska basin, increased the demand for public supplies; ground water became a major source of supply. Maintaining instream flows became an issue during the late 1970's, and that concern has increased during the 1980's. Instream flow for hydroelectric power generation and fish hatcheries is an additional water issue today.

WATER USE

The State's water budget is shown diagrammatically in figure *1A*. Several natural conditions limit the quantity of freshwater that can be recovered efficiently from Alaska's hydrologic environment; for example, the availability of surface water may be affected by the timing of winter freezeup and spring breakup and by the quantity and the timing of runoff derived from melting snow and glacier ice. The availability of ground water is limited by thick lenses and layers of relatively impermeable sediments and by the limited extent of coarse-grained permeable sediments. In permafrost zones, even coarse-grained sediments may be frozen. Thus, although a substantial quantity of water may be present within the State, the water may not be available when and where it is needed.

Hydroelectric powerplants used 1,480 Mgal/d to generate 18 percent, or 746 GWh (gigawatthours), of the electricity used statewide. About 90 percent of this power was generated in the Southeast Alaska basin. The water was used instream, and no water was considered for consumptive use.

Surface-water withdrawals supplied 82.2 percent of the water needed for offstream uses; ground water provided the remaining 17.8 percent. These values were determined by using the results of a cooperative survey conducted by the Alaska Department of Natural Resources and the U.S. Geological Survey in 1985, in which communities and industries estimated their water use. Where quantities of water use were not available, such data were estimated on the basis of similarities between communities and uses. The statewide distribution of total, surface-water and ground-water withdrawals is aggregated by county in figures *2A*, *2B*, and *2C*, respectively. Surface-water withdrawals by principal drainage basin and ground-water withdrawals by principal aquifer are shown in figures *3A* and *3B*, respectively. Aquifers have been grouped informally into unconsolidated alluvium and glacial outwash aquifers and bedrock aquifers (U.S. Geological Survey, 1985, p. 129–131). Major ground-water withdrawals were from the unconsolidated aquifers.

Most withdrawals occur in three of the principal river basins—Southeast Alaska, South Central Alaska, and Yukon (fig. *3A*). Withdrawals in the Southeast Alaska basin were 55 percent (221 Mgal/d) of total water use in Alaska. About 99 percent of these withdrawals was surface water. Industry and fish hatcheries were the primary users of this water. In contrast, the South Central Alaska basin accounted for about 27 percent (110 Mgal/d) of the total withdrawals during 1985. This basin withdrew about 64 percent (64 Mgal/d) of the total ground water during 1985. The large withdrawals for public supply and self-supplied domestic uses provide water to the comparatively large population of the area. Public supply, self-supplied domestic, and industry were the major water users. The Yukon basin accounted for 15 percent (41 Mgal/d) of the total withdrawals. Water used for mining and fossil-fueled powerplants was 74 percent of the 61 Mgal/d withdrawn in the Yukon basin. Surface water was used for nearly two-thirds of this quantity.

The remaining basins, the Arctic Slope, the Southwest Alaska, and the Northwest Alaska, included 8 percent of the population and used 3 percent of the total water. Public supply and self-supplied domestic and commercial uses accounted for 61.9 percent of the ground-water withdrawals within the Yukon basin.

The source, use, and disposition of Alaska's water resources are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that total freshwater withdrawals were 406 Mgal/d, of which 334 Mgal/d was surface water and 72 Mgal/d was ground water. The use data indicate that, of total freshwater use, industry and mining accounted for 34.7 percent and agriculture accounted for 38.6 percent. The disposition data indicate that most water (93.3 percent) was returned to natural sources and was available for reuse. Estimated consumptive use was 6.7 percent (27 Mgal/d).

Alaska's water is generally of sufficient quantity and acceptable quality for most uses. However, population increases during the last decade, especially in urban areas, have strained water-distribution systems and generated concern about water availability. In Anchorage, a measurable decline in ground-water levels has been attributed to increased withdrawals. Saltwater intrusion has halted further ground-water development in Auke Bay, near Juneau. In Kenai and in the Arctic Slope basin, water supply is a concern to communities near petrochemical industry activities.

Surface- and ground-water quality problems have been caused either by natural processes or by human activities. Natural processes include suspended sediment caused by glaciers, salinity, and undesirable concentrations of iron or arsenic produced by geo-chemical processes. Human activities include petrochemical contamination, the addition of nitrates through septic-tank systems, and the encroachment of saltwater in response to intensive ground-water withdrawal. Nevertheless, even in areas of water-supply difficulties, Alaska's water is generally satisfactory for most uses, although locally it may not be readily obtainable from the nearest or most economical source.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. The total withdrawals for public-supply in Alaska were an estimated 76 Mgal/d (fig. 4), which was 18.7 percent of total withdrawals in 1985. Surface water provided 46.2 percent (35 Mgal/d) of public-supply withdrawals, and ground water provided 53.8 percent (41 Mgal/d). Of total withdrawals for public supply, 40.3 percent was delivered for commercial use, and 39.0 percent was delivered for domestic use. About 60 percent (45 Mgal/d) of public-supplied water was delivered in the South Central Alaska basin.

About 62 percent of Alaska's population was served by public water suppliers in 1985. The Municipality of Anchorage supplied water to one-half of the population served by public-supply systems. The per capita use by all public-supply customers ranged from 10 to 380 gal/d (gallons per day) in 1985. Public-supplied domestic use ranged from 6 to 170 gal/d per capita. These values reflect the different types of water-distribution systems; for example, a public-supply system in the Arctic Slope basin may consist of a water-

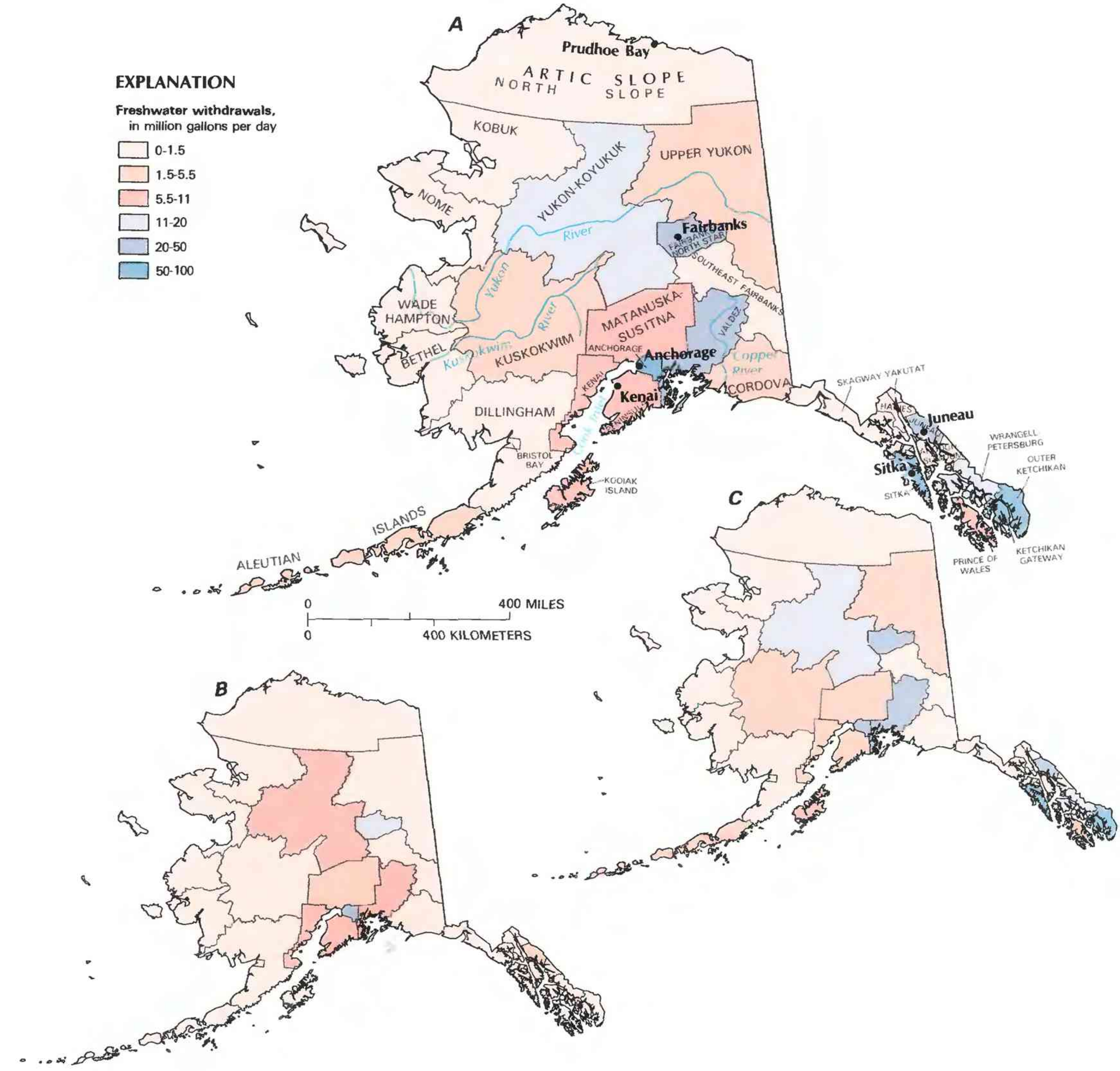


Figure 2. Freshwater withdrawals by county in Alaska, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

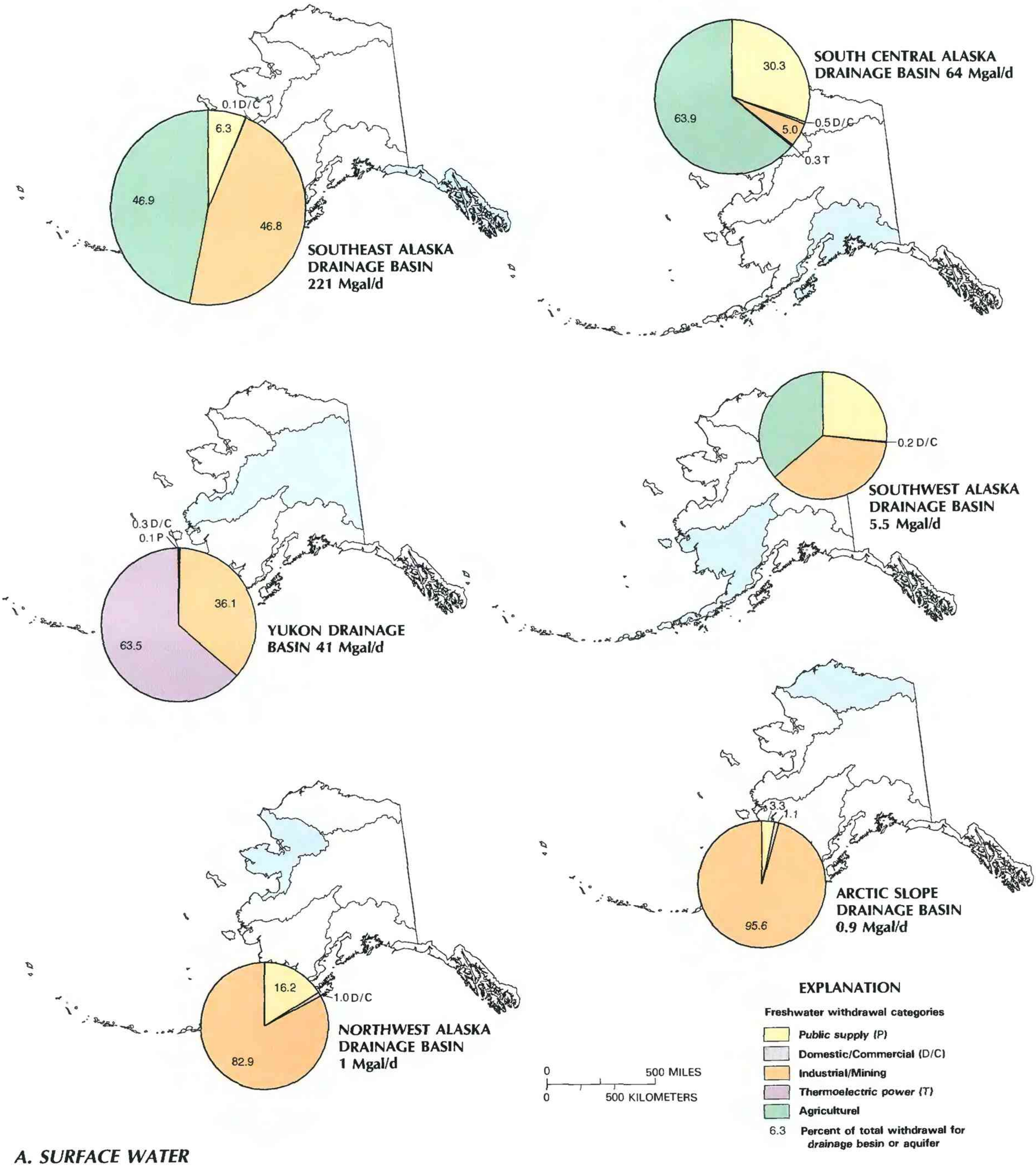


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Alaska, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

delivery truck or a common well, and the primary use is domestic. In contrast, water in the Southeast Alaska basin is abundant, and distribution systems commonly are leaky; residents, commonly leave their faucets running to prevent the pipes from freezing. In addition, water-intensive industries in the Southeast Alaska basin are served by public supply.

DOMESTIC AND COMMERCIAL

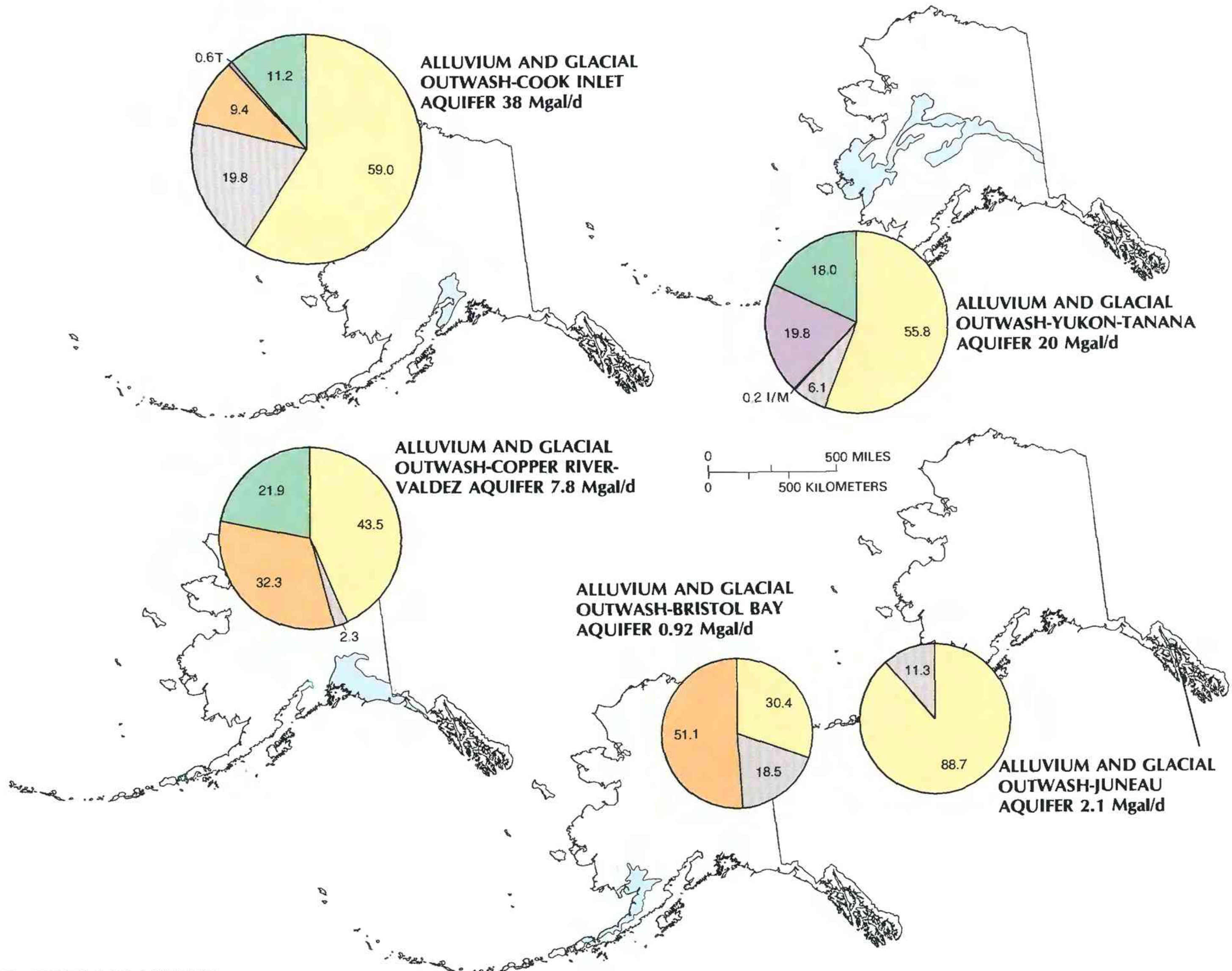
Total domestic and commercial water use, including conveyance losses and consumptive use, from public-supplied and self-supplied sources was 78 Mgal/d (fig. 4). Domestic use was about 39 Mgal/d, of which 29 Mgal/d was delivered by public-supply systems and 10 Mgal/d was self-supplied. Commercial withdrawals were about 31 Mgal/d, virtually all from public-supply sources. Conveyance losses were 7.6 Mgal/d.

The average per capita domestic use for the population served by public supply was about twice that for the population that was self-supplied. This difference can be explained, in part, by conditions under which water is delivered to homes that use these two types of supply. Public-supply systems typically serve a household that has standard plumbing. In contrast, many self-supplied households haul water from a lake, spring, river, or well and may have no plumbing.

INDUSTRIAL AND MINING

The estimated industrial and mining use was 141 Mgal/d in 1985. This represents 34.7 percent of total offstream water use (fig. 4). Industry used about 122 Mgal/d, of which 87 percent was self-supplied from surface-water sources. About 89 percent of the industrial water use was in the Southeast Alaska basin. Wood-pulp mills and seafood-processing industries in this basin used more than 100 Mgal/d in 1985. The petroleum industry was a major water user in the South Central basin.

Mining accounted for about 19 Mgal/d of water use. The Yukon basin had the largest area of mining activity and accounted for 76 percent of this water use. Adequate water supplies to support the exploration, development, and production in the Arctic Slope



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Alaska, 1985—Continued.

basin are commonly difficult to locate. Surface water is used primarily by placer-mining operations for washing sediments.

THERMOELECTRIC POWER

The fossil-fueled powerplants included in the survey used an estimated 31 Mgal/d (fig. 4) to produce 3,430 GWh of electricity during 1985. About 97 percent of the water was used by two plants in the Yukon basin, whereas 80 percent of the power produced by fossil fuel was produced by six plants in the South Central Alaska basin. These differences reflect the availability of water, the age of the powerplants, and perhaps different reporting methods. The water was used mainly for cooling purposes, and most was returned to surface-water sources.

AGRICULTURAL

Agricultural use during 1985 was an estimated 157 Mgal/d (fig. 4). Fish hatcheries dominated this category by using about 156 Mgal/d, of which 66 percent was used in the Southeast Alaska basin. Although the hatcheries in the Southeast Alaska basin exclusively use surface water, facilities elsewhere use ground water, which has a more consistent temperature and quality.

Agricultural water use for purposes other than fish hatcheries or irrigation totaled 0.21 Mgal/d, 48 percent of which was on Kodiak Island. Only 0.03 Mgal/d was used for irrigation; all of the reported irrigated farm acreage is in the Matanuska Valley, which is 40 miles north of Anchorage.

WATER MANAGEMENT

The Alaska Water Use Act (AS 46.15.010–270), which was enacted in 1966, established procedures to appropriate State water. The Act defines the doctrine of prior appropriation ("first in time, first in right") authorized by the State Constitution and delegates administration of the Act to the Alaska Department of Natural Resources (ADNR). The Act established procedures for maintaining existing water rights and for obtaining new water rights to all surface and ground water in Alaska. Water appropriations are limited to the specific use for which an individual applies. Additionally, the ADNR issues permits authorizing development and beneficial use of water. Issuance of a certificate of appropriation by the ADNR to the applicant is the final step in the water-rights process.

The original regulations implementing the Water Use Act were amended extensively on December 29, 1979, and incorporated as 11 AAC 93, Water Management. Recent amendments to the Water Use Act relate to geothermal development, reservation of water for instream uses, and administrative and judicial basinwide water-rights adjudication.

To manage the State's water resources effectively, the ADNR's Division of Land and Water Management (DLWM) requires technical descriptions and analyses and interpretations of various hydrologic conditions. The Department's Division of Geological and Geophysical Surveys (DGGS), Water Resources Section, provides the necessary data, analyses, and interpretations. Many long-term data are collected and interpreted by the U.S. Geological Survey, in cooperation with other Federal, State, and municipal agencies. Water managers of the DLWM use this information for water appropriation and water management decisions. Additionally, the DGGS, in cooperation with the U.S. Geological Survey and other State and Federal agencies, has developed and implemented the Alaska Water Resources Evaluation Plan to coordinate water-data collection and water-resource investigations in the State (Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, and U.S. Geological Survey, 1985).

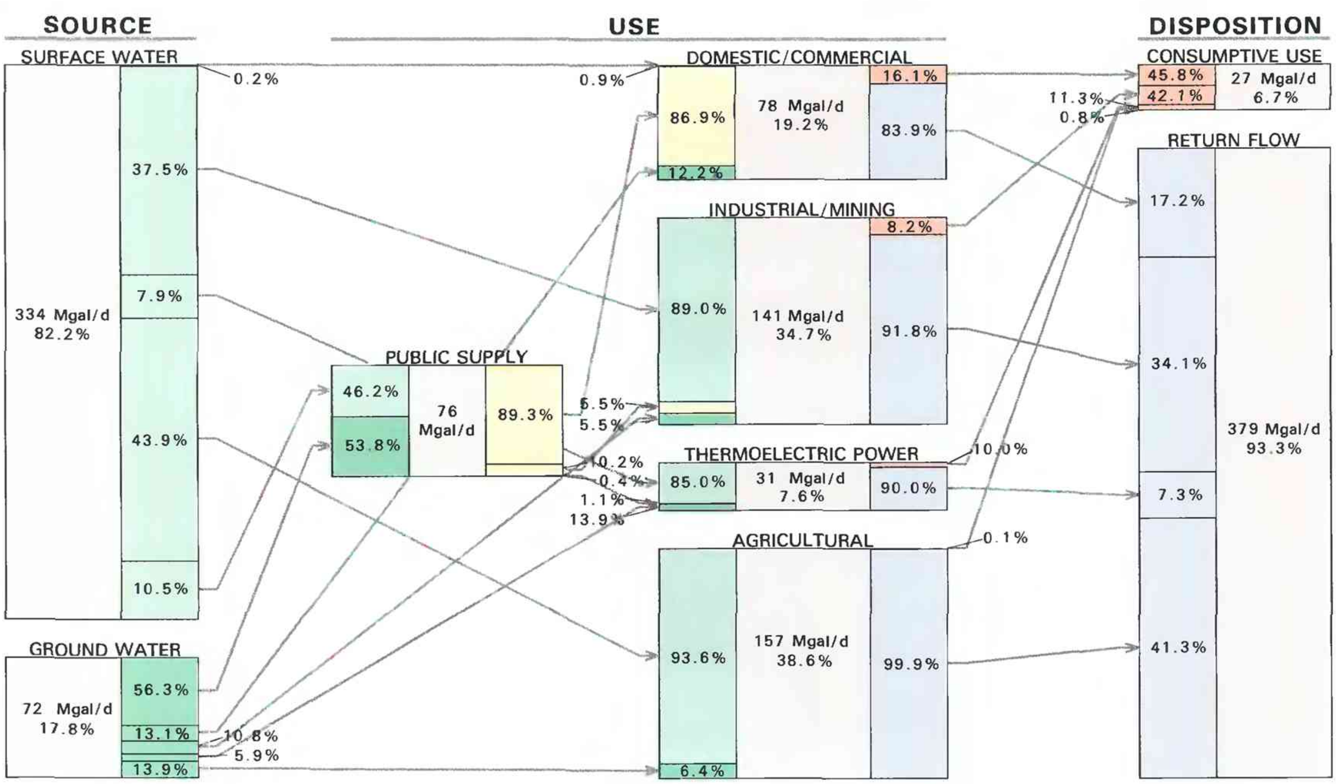


Figure 4. Source, use, and disposition of an estimated 406 Mgal/d (million gallons per day) of freshwater in Alaska, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Although few streams in Alaska are overappropriated, potential water-use problems exist. In the event of water shortages or drought, Ship Creek at Anchorage and Indian River at Sitka could possibly be examples in which the amount of legally obtainable water may exceed the water available for use. Water issues in Alaska also include hydroelectric projects, placer mining, oil development, salmon aquaculture, and proposed mining developments in the Southeast Alaska basin.

Most ground-water shortages in Alaska currently involve water for public supply and domestic use. Some areas within the Municipality of Anchorage are experiencing great ground-water demand for public and single-family domestic water supplies. As water levels declined, domestic wells become dry. The ADNR and Municipality of Anchorage are working cooperatively to solve several water-supply and distribution problems. Another area experiencing declining ground-water levels and saltwater intrusion is the Auke Bay area near Juneau (Dearborn, 1985), where the ADNR established Alaska's first "Critical Groundwater Management Area" to restrict further water-well drilling and development of ground water.

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Hydraulic "giant" used to remove overburden and expose gold-bearing gravel north of Fairbanks, Alaska. (Photograph by Gary Prokosch, Alaska Department of Natural Resources.)

Prepared by Leslie D. Patrick and Elisabeth F. Snyder, U.S. Geological Survey, and Mary Lu Harle, Alaska Department of Natural Resources

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 4230 University Drive, Anchorage, AK 99508–4664

ARIZONA
Water Supply and Use

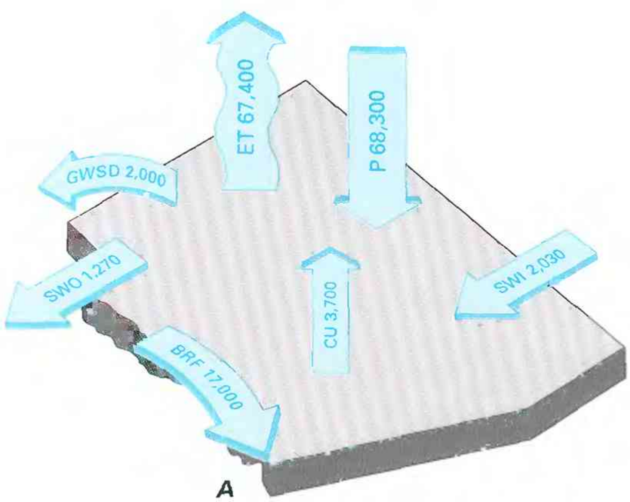
Arizona has an arid climate where the need for water is met by elaborate reservoir and canal networks that catch, store, and distribute runoff or by wells from which water is pumped from aquifers. Most of the water originates as rain and snow that falls in the State; precipitation averages about 12.6 inches per year, or 68,300 Mgal/d (million gallons per day) (fig. 1*A*). Much of the direct runoff in streams flows into reservoirs and is stored for later use, is diverted directly from the channel, or infiltrates the channel bottom and banks and recharges underlying aquifers. About 90 to 99 percent of the precipitation is lost to evapotranspiration and returns to the atmosphere. A small quantity of the water infiltrates directly into the soil and the exposed rocks and moves down into an aquifer; estimates of aquifer recharge range from zero in the driest southwestern deserts to 8 percent in some of the highland areas (Owen-Joyce and Bell, 1983).

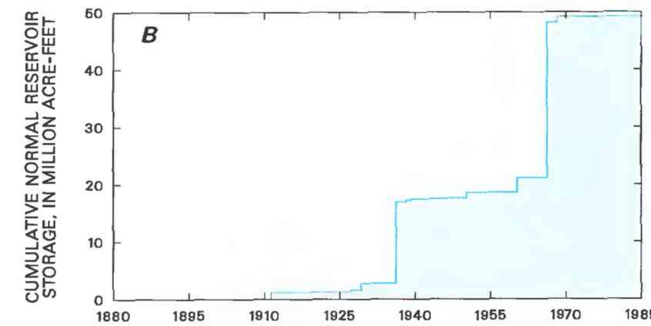
Water-use patterns in Arizona are dominated primarily by agriculture and secondarily by rapidly growing urban population centers in Maricopa and Pima Counties. Almost all field and orchard crops are irrigated because the climate is semiarid and precipitation is too little and erratic to be useful for growing crops. Land irrigated by surface water is concentrated in the valleys and basins near the Colorado, Gila, Salt, and Verde (Yavapai County) Rivers. Land irrigated by ground water is mainly in the alluvial basins in the southern and the western parts of the State.

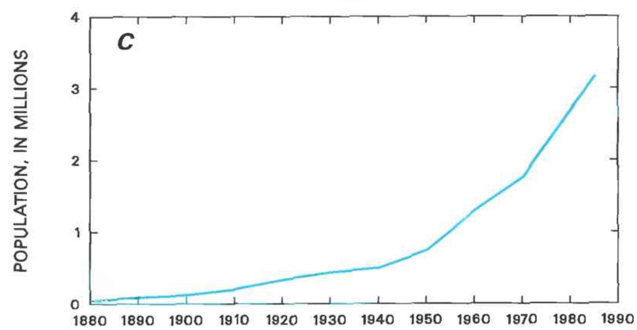
The major water problem in Arizona is the imbalance between the quantity of water consumed and the long-term dependable supply. The State used ground water for 48.2 percent of its supply in 1985. About 2.2 million acre-ft/yr (acre-feet per year) more ground water was withdrawn than was recharged to the aquifers. The overdraft has occurred for many years and, in some areas, has caused ground-water levels to decline as much as 500 feet. In Maricopa and Pinal Counties, the water-level declines have caused land subsidence. The State began a program of ground-water management in 1980 to decrease the rate of ground-water withdrawal to the annual rate of natural and artificial recharge to the aquifers.

HISTORY OF WATER DEVELOPMENT

The water resources of Arizona have been developed in four phases—prehistoric, Spanish, pioneer, and modern. The first three phases were based on the development of irrigation methods for







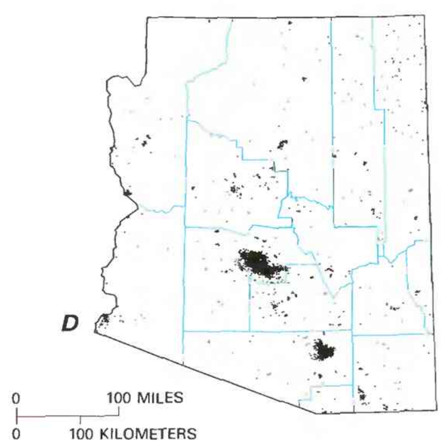


Figure 1. Water supply and population in Arizona. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **GWSD,** ground-water storage depletion; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Sellers and others, 1985. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

cooperative agriculture by using surface water. The modern phase is characterized by surface-water irrigation projects, which are coordinated by the Federal Government, and by large-scale development of ground water for irrigation and municipal use.

The prehistoric phase began in Arizona about 300 B.C. Hohokam Indians, who lived in the Salt River valley near Phoenix and Tempe (Baker and others, 1973), dug canals to divert water from the Salt River for irrigation of crops. Their irrigation system was the largest and most complex prehistoric system in the United States. The period of its maximum development was from about A.D. 700 to A.D. 1200, but, by the early 15th century, the system was abandoned.

The Spanish phase of water-resources development began with the arrival of Spanish explorers and missionaries in the 16th century. Main settlements were along the Santa Cruz River. The water-supply system for irrigation, stock watering, and most community uses was the community ditch. The Spanish settlers commonly dug wells to obtain water for domestic and stock uses.

The pioneer phase of water-resources development began in 1867 when pioneers began to divert water from the Salt River at prehistoric Hohokam sites. The census of 1890 estimated that 65,821 acres were irrigated in Arizona, 35,212 acres of which were in Maricopa County (Davis, 1897). Canals were constructed to divert water from the Gila River in central Arizona at the same time development was occurring in the Salt River valley. By 1896, 64,444 acre-ft/yr of water from the Florence Canal in Pinal County was used to irrigate 6,472 acres (Davis, 1897); five canals were in use in the lower Gila Valley.

The modern phase began with the passage of the Federal Reclamation Act of 1902. This law allowed the Federal Government to build reservoirs and canals, to operate storage and distribution systems, and to finance irrigation and reclamation projects. The development of reservoir storage in Arizona is shown in figure *1B*. The Salt River Valley Water Users' Association, organized in 1903, provided the pattern for development of cooperative irrigation projects in Arizona (Peplow, 1970). The Federal Government designed, built, and financed dams and some distribution canals. In 1917, the water users association assumed responsibility for the operation and maintainance of the system and repaid much of the original cost.

The Federal Government began construction on the first dam in the Salt River Project (SRP) in 1906. The SRP now has six reservoirs that have a combined storage capacity of almost 2.1 million acre-ft (acre-feet) (fig. *1B*). The SRP began as a system to store and distribute surface water for irrigation of crops. By the 1920's, wells were being used to supplement water withdrawn from the canals. Urbanization after World War II resulted in a substantial change in water use from irrigation of crops to irrigation of lawns and parks.

The Lower Colorado River Project is a regional water-storage and transport project constructed and operated by the U.S. Bureau of Reclamation. The Colorado River drains 244,000 square miles in seven States and is the major source of surface water for the arid Southwest. The Colorado River Compact of 1922 allocated 7.5 million acre-ft/yr of water to the upper basin States of Colorado, Utah, New Mexico, and Wyoming; the same quantity was allocated to the lower basin States of Nevada, California, and Arizona. In 1944, 1.5 million acre-ft/yr was allocated by agreement to Mexico. The combined storage of the six reservoirs of the project is 53.6 million acre-ft, which is equal to about 4 years of average flow of the Colorado River. In 1985, about 329,000 acres of land in Arizona were irrigated by using about 1.85 million acre-ft of Colorado River water.

The most recent major reclamation project on the lower Colorado River is the Central Arizona Project (CAP), which was authorized in 1968 by the Colorado River Basin Project Act. The CAP will divert as much as 1.5 million acre-ft/yr from the Colorado River and will deliver most of the water to Maricopa, Pinal, and Pima Counties. In 1985, the initial delivery to the Phoenix area was 33,500 acre-ft, and delivery of water into the Tucson area has been scheduled for 1991. Although the CAP was conceived as an agricultural irrigation project, significant volumes of water will be delivered to municipal and industrial users. In future years, continuing urbanization in Maricopa, Pinal, and Pima Counties probably will cause a shift from agricultural irrigation toward municipal and industrial uses.

The San Carlos Irrigation Project (Pinal County) was authorized in 1919 to provide water to the Maricopa and the Pima Indians. These tribes could no longer divert water from the Gila River after construction of the Florence Canal (Maricopa County) because of an insufficient water supply. Coolidge Dam (Graham County) was completed in 1928 and has a storage capacity of 935,000 acre-ft. In most years, the surface-water supply is insufficient and is supplemented by ground water pumped into the distribution canals. The project provides irrigation water to 50,000 acres of Indian land and to 52,090 acres of non-Indian land.

The large-scale development of ground-water resources has been mainly in the private sector, except for the municipal supply of Tucson. Intensive development, primarily for agricultural irrigation, began after World War II. Before that time, the depressed economy of the 1930's and the lack of efficient large-capacity deep-well pumps limited major development. Agricultural pumpage increased rapidly during the 1950's and peaked in 1974 at about 4.8 million acre-ft/yr (U.S. Geological Survey, 1986a).

WATER USE

Arizona is one of the major agricultural areas of the United States because of the extensive irrigation. Almost 86.9 percent of the total water withdrawn in the State was for agriculture. However, in the Tucson (Pima County) and the Phoenix (Maricopa County) areas, water use is changing from irrigation of crops to domestic, commercial, and industrial uses. Rapid population growth (fig. *1C*) has encouraged developers to subdivide irrigated cropland and to develop it into residential neighborhoods and shopping centers. The population of Pima County increased from 531,000 in 1980 to 626,000 in 1985 and the population of Maricopa County increased from about 1.5 million in 1980 to 1.8 million in 1985; most of the population in the State resides in Pima and Maricopa Counties (fig. *1D*). Many subdivisions and landowners in Phoenix use treated public-supply water for domestic purposes but continue to use SRP water to irrigate lawns, gardens, and playing fields. In 1985, the project withdrew 51 percent of its water for nonagricultural use—36 percent for public supply, 8 percent for subdivision irrigation, and 7 percent for institutional irrigation.

The State's water budget (fig. *1A*) shows the proportions of water that flow in and out of the State. Surface-water inflow in 1985 was 2,030 Mgal/d. The diversions along the lower Colorado River amounted to 1,640 Mgal/d. The Virgin River (Mohave County) contributed surface-water inflow of 157 Mgal/d, and the Gila River contributed 90 Mgal/d. The remainder (143 Mgal/d) was contributed by five smaller streams. The discharge of the Colorado River in 1985 was 17,000 Mgal/d, but only the amount allowed under the Colorado River Compact was diverted to Arizona users. The Colorado River flows from Utah into Arizona upstream from Lees Ferry (Coconino County), traverses the Grand Canyon, turns south, and forms the boundary between Arizona and Nevada, Arizona and California, and Arizona and Mexico. Diversion of 30 Mgal/d into the distribution system of the CAP began in 1985.

Surface-water outflow was 1,270 Mgal/d. Returns to the lower Colorado River system were 587 Mgal/d. A total of 494 Mgal/d flowed into the Colorado River from tributaries in Arizona. The Virgin River (Mohave County) conveyed 157 Mgal/d to Nevada, which later entered the Colorado River system in Lake Mead. Outside the Colorado River system, Mexico and Utah each received 16 Mgal/d.

Total water, surface-water, and ground-water withdrawals by county in Arizona are shown in figure 2. The largest total withdrawals are in the southwestern part of the State (fig. 2*A*). The major surface-water withdrawals are in La Paz, Maricopa, Pinal, and Yuma Counties (fig. 2*B*). The largest ground-water withdrawals are in Maricopa, Pima, Pinal, and Yuma Counties (fig. 2*C*).

Of the major river basins (fig. 3*A*), the largest withdrawals are in the Lower Colorado and the Lower Gila River basins and are mainly for agricultural use. Surface-water withdrawals are smallest in the northern part of the State. The largest withdrawals of ground water are from the alluvial aquifers (fig. 3*B*). Nearly all the ground water was withdrawn from the aquifers of the southern and western alluvial basins.

Ground water is a critical component of Arizona's water supply. In 1985, the 3,090 Mgal/d of ground water withdrawn was 48.2 percent of the total withdrawal of 6,420 Mgal/d. Most of the ground water is used for crop irrigation or for public supply. About 3.0 Mgal/d of ground water was transferred from Arizona by means of a pipeline that delivers slurry from a coal mine in northern Arizona to a powerplant in southern Nevada.

About two-thirds of the ground water withdrawn was pumped from storage. The depletion of about 2,000 Mgal/d was 64.7 percent of the 3,090 Mgal/d withdrawn. Depletion has occurred for many years and has removed a large volume of water from storage, which has caused water-level declines and land subsidence. The depletion for 1985 was computed by comparing ground-water withdrawal to estimates of predevelopment aquifer recharge from precipitation. Recharge components for most of the ground-water basins were derived by an iterative process of balancing inflow and outflow components for adjacent basins (Freethey and Anderson, 1986).

The source, use, and disposition of freshwater in Arizona during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 51.8 percent, or 3,330 Mgal/d, of the total water withdrawn in Arizona in 1985 was surface water. About 7 percent of this surface water was withdrawn by public suppliers, less than 0.1 percent was directly withdrawn (self-supplied) for domestic and commercial use, 0.4 percent was self-supplied for industrial and mining use, 0.6 percent was withdrawn by thermoelectric powerplants, and 91.9 percent was withdrawn for agriculture.

The use data indicate that about 9.1 percent, or 583 Mgal/d, of the State's total water use was for domestic and commercial purposes. About 92.5 percent of this water was delivered by public supplies, 0.3 percent was self-supplied from surface-water sources, and about 7.3 percent was self-supplied from ground-water sources.

The disposition data indicate that 57.6 percent of the State's total withdrawals was consumed that 42.4 percent was returned to surface-water or ground-water sources. Agricultural use accounted for 86.0 percent (3,180 Mgal/d) of the consumptive use in the State and for 88.2 percent of the return flow.

Public Supply

Public suppliers withdraw, treat, and distribute water to users. Public suppliers withdrew 618 Mgal/d in 1985, which was 9.6 percent of the total water withdrawn in the State. Surface water accounted for 37.7 percent of public-supply withdrawals, and ground water accounted for 62.3 percent. Public suppliers delivered 449 Mgal/d for domestic use, 90 Mgal/d for commercial use, and 79

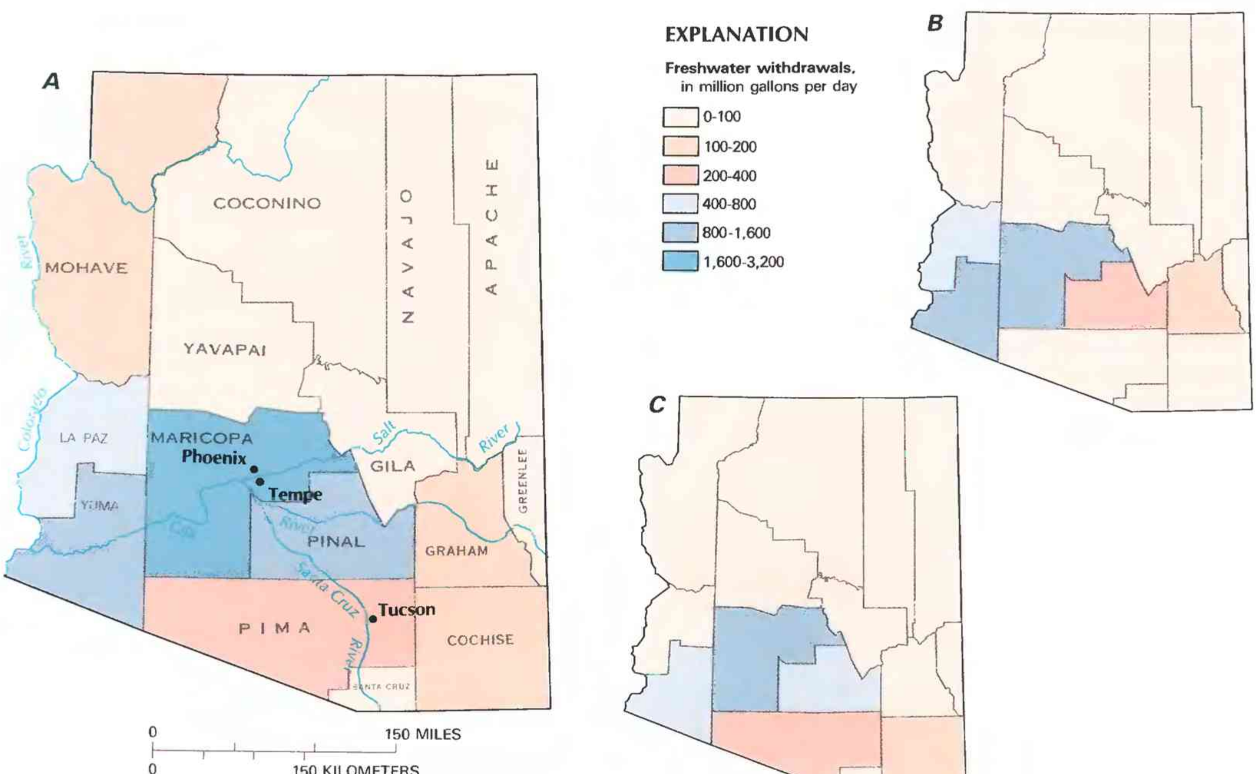


Figure 2. Freshwater withdrawals by county in Arizona, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

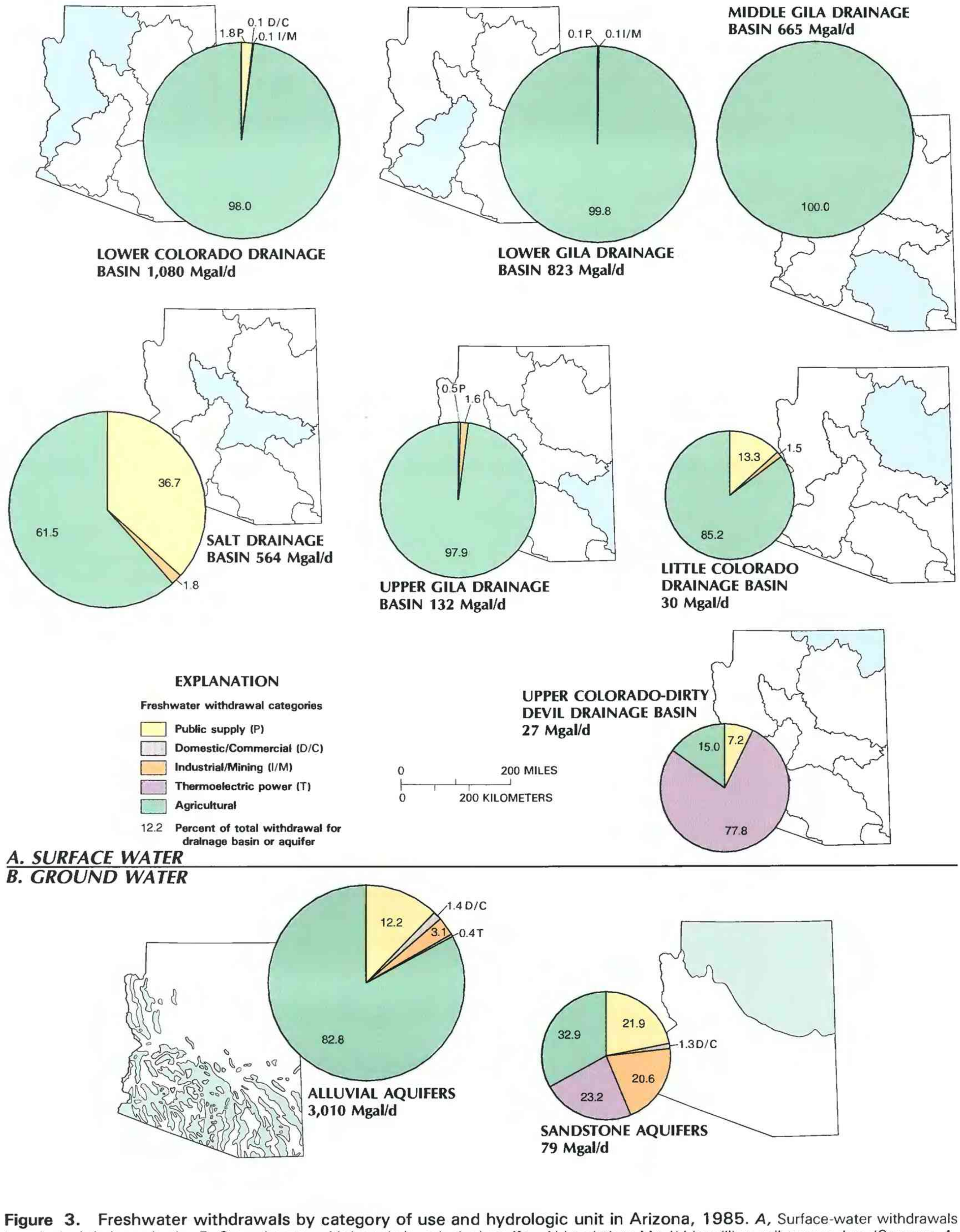


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Arizona, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987. *A, B,* data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

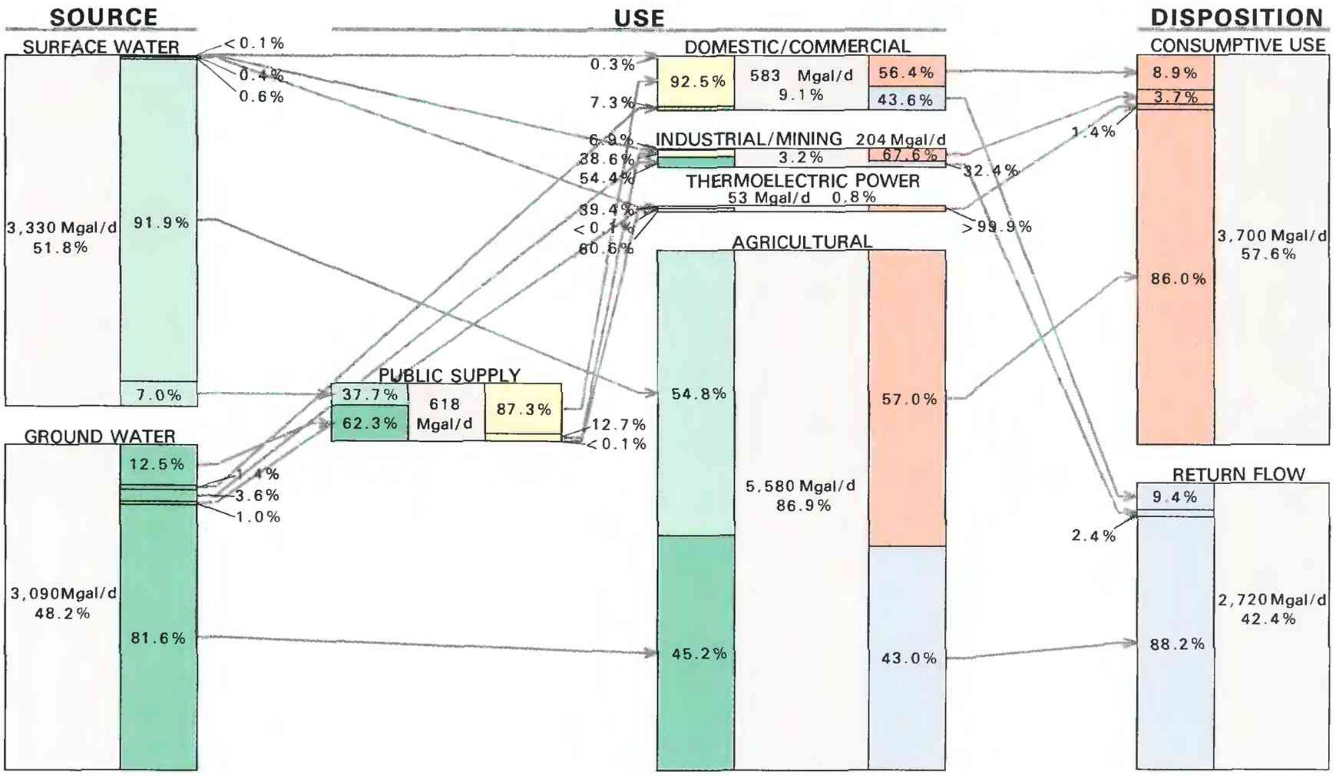


Figure 4. Source, use, and disposition of an estimated 6,420 Mgal/d (million gallons per day) of freshwater in Arizona, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Mgal/d for industrial use (Solley and others, 1988). Total withdrawal for public supply increased 10 percent from 1980 (560 Mgal/d) to 1985 because of a State population increase of 27 perent and an expanding economy. The percentage of public supply used for domestic purposes increased, although per capita use decreased from 230 to 200 gal/d (gallons per day). Per capita use probably will continue to decrease in the near future because of the increase in the costs of pumping and of distributing ground water and the increase in the costs of treatment of CAP water delivered to public suppliers.

Public-supply withdrawals probably will increase between 1985 and 1990 because of rapid population growth in existing communities and expansion of service areas for new subdivisions and communities. The percentage of public-supply water used for domestic purposes may increase more rapidly than other purposes because Arizona communities are seeking new industrial and commercial employers that require minimal quantities of water. New real-estate developments commonly are being encouraged to use reclaimed wastewater to irrigate golf courses and to fill ponds.

Domestic and Commercial

Domestic and commercial use accounted for 9.1 percent (583 Mgal/d) of the total withdrawals in 1985 (fig. 4). About 92.5 percent of this water was delivered by public suppliers. Domestic use accounted for 7.4 percent (476 Mgal/d) of water use in 1985. About 64 percent of the total was ground water. Public suppliers, including both public utilities and private water companies, provided 94 percent of the water used for domestic purposes. The remaining 6 percent is supplied primarily from private wells. Domestic use increased 25 percent from 1980 to 1985; a similar or larger increase probably will occur from 1985 to 1990 because rapid population growth is continuing. Per capita use ranged from 272 gal/d in La Paz County to 77 gal/d in Apache County. A substantial percentage of domestic water is used for irrigation of lawns and shrubs.

Commercial water use in 1985 was 107 Mgal/d, or 1.7 percent of the total withdrawal in the State. Public suppliers delivered 84 percent, and 16 percent of the water was self-supplied. About two-thirds of the water for commercial use was ground water.

Industrial and Mining

Withdrawals for industrial and mining purposes were 204 Mgal/d in 1985, or 3.2 percent of the total withdrawals. Water withdrawals for mining use were 80 Mgal/d and for industrial use were 124 Mgal/d, or 1.9 percent of the total use. About one-fourth of the withdrawals was from surface water, and three-fourths was from ground-water resources. Public suppliers delivered 38.6 percent (79 Mgal/d) of the water used for industrial and mining purposes (Solley and others, 1988). Industrial and mining use decreased 6 percent from 1980 to 1985.

Thermoelectric Power

In 1985, thermoelectric powerplants used 53 Mgal/d of freshwater and 4.6 Mgal/d of saline water for the generation of electric power. Surface-water withdrawals provided 39.4 percent, and ground-water withdrawals provided 60.6 percent. Most of the 26,200 gigawatthours generated during 1985 were in Coconino, Apache, Navajo, and Maricopa Counties. Fossil-fuel plants used 88 percent of the water, and one nuclear plant used the remainder.

AGRICULTURAL

Water use in Arizona is dominated by the agricultural sector of the economy. In 1985, about 86.9 percent (5,580 Mgal/d, or 6.3 million acre-ft) of the total withdrawals in the State was for agriculture. This amount was 91.9 percent of the total surface-water withdrawals and 81.6 percent of the ground-water withdrawals. Nearly all the agricultural water was used for irrigation of crops. Cotton, hay, and grains were grown on 415,000, 167,000, and 170,000 acres, respectively, and accounted for 78 percent of the 959,000 acres of cropland (Arizona Agricultural Statistics Service, 1986). Most cropland is in the basins and the river valleys of the southern and the western parts of the State in Cochise, Graham, La Paz, Maricopa, Pima, Pinal, and Yuma Counties. Several small irrigated areas are in the Little Colorado River drainage basin (Apache, Coconino, and Navajo counties) on the Plateau Uplands.

Large volumes of irrigation water are required to grow crops in Arizona. In 1985, the average withdrawal was equivalent to 6.5 acre-ft, or 2.1 million gallons per irrigated acre. A substantial part of the water, perhaps 40 percent, seeps from unlined canals and reservoirs, infiltrates below the root zone of crops, or evaporates from soil and open-water surfaces. Agricultural water use in 1985 was 79 percent of the 1980 use of 7,100 Mgal/d primarily because the total crop acreage decreased to 71 percent of that of 1980. From 1980 to 1985, surface-water diversions decreased 10 percent, and ground-water pumpage decreased 32 percent. Total crop acreage increased from about 1,160,000 acres in 1965 to 1,371,400 acres in 1981 but had decreased to 959,000 acres by 1985 (Arizona Agricultural Statistics Service, 1986). The volume of water withdrawn for agricultural use probably will continue to decrease in the near future because of conversion of cropland to residential or commercial uses, sale of land and its associated water rights to public suppliers, and increased pumping costs of ground water.

WATER MANAGEMENT

Territorial laws governing the right to withdraw and use surface water were first established in 1864 (Arizona Department of Water Resources, 1987). The three major principles governing water rights were that surface water was a public resource subject to appropriation, that the first person to actually use the water had a senior right and this established right must be supplied before later users, and that all water must be used beneficially. Development, withdrawal, and use of water in large-scale Federal projects were controlled by the Federal Reclamation Act of 1902. Previously developed irrigation districts remained under Territorial and then State law or were absorbed into later Federal projects.

During the period of development of large-scale irrigation for agricultural use, the connection between surface water and ground water was poorly understood. Ground water could be withdrawn by anyone without legal limitations. Ground-water depletion was recognized as a problem in the early 1930's by State and Federal officials. In 1948, the State legislature enacted the first Critical Groundwater Code, which empowered the State Land Commissioner to designate critical ground-water areas where ground water was insufficient to provide a reasonably safe supply for irrigation of lands then in cultivation. The Code prohibited the drilling of new wells to irrigate new land, but did not limit the quantity of water that could be pumped from existing irrigation wells or restrict nonirrigation users.

After 1948, Arizona ground-water law evolved through State Supreme Court rulings in individual cases. The Court adopted the "rule of reasonable use" to govern withdrawals. Under this rule, landowners had the right to use the water beneath their land for reasonable beneficial purposes on their land, but could not transport the water off the land from which it was pumped if the transportation adversely affected a neighboring landowner.

The Critical Groundwater Code and the rule of reasonable use did little to decrease the overdraft problem. In 1980, the State legislature passed the Groundwater Management Act. That Act established the Arizona Department of Water Resources (ADWR) to administer the water law and to manage the ground-water resources in the Active Management Areas (AMA's) and the Irrigation Non-Expansion Areas (INA's). The AMA's are geographical areas in which intensive ground-water management is needed because of the large and continuing overdraft. The four AMA's (fig. 5)—Phoenix, Pinal, Prescott, and Tucson—include most of the areas designated as critical by the previous Critical Groundwater Code. The AMA's contain about 80 percent of Arizona's population. About 70 percent of the depletion and 60 percent of the State's ground water are pumped from the AMA's (Arizona Department of Water Resources, 1984). Within the AMA's, the Act limits withdrawals of ground water to landowners that have ground-water rights and requires a 45-year water program of conservation and management. The three INA's are Douglas, Joseph City, and Harquahala (fig. 5). Within these areas, only land irrigated in the 5 years before the establishment of the Act may be irrigated using ground water.

The ground-water-management program established by the Act relies on continuing mandatory conservation by all water users and distributors to decrease the total annual withdrawals in the AMA's. The Act establishes a management goal for each AMA and five management periods that end in the year 2025. Before each period, the ADWR must develop for each AMA a management plan that includes conservation requirements for all agricultural, public-supply, and industrial water users and distributors. Other provisions include a ban on new irrigation in AMA's and INA's, statewide well registration, and no sales of subdivided or unsubdivided land for development in areas without an assured 100-year water supply.

The Surface Water Act of 1919 and the Groundwater Code of 1980 provide the legal basis of water use and water withdrawal rights within Arizona. Federal law and Federal case law also establish

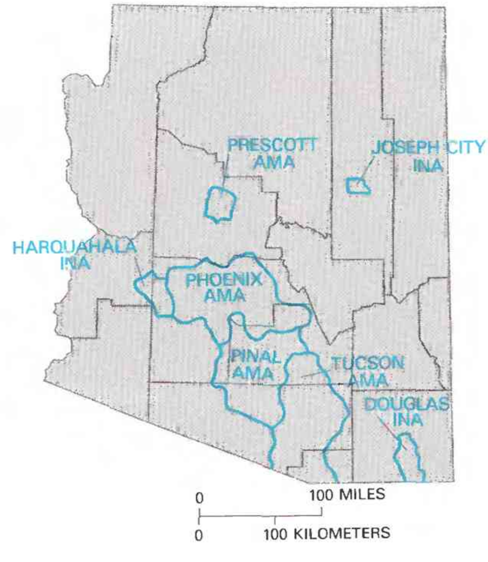


Figure 5. Active Management Areas (AMA's) and Irrigation Non-Expansion Areas (INA's) in Arizona, 1985. (Source: Arizona Department of Water Resources, 1984.)

Flood-irrigated alfalfa field in Cibola Valley, Arizona. (Photograph by Sandra Owen-Joyce, U.S. Geological Survey, June, 1983.)

rights to withdraw or use water. The conflict between Indian rights provided under Federal laws and those provided under State laws is unresolved. A general process of adjudication of all water rights in the Gila and the Little Colorado River basins is now (1988) proceeding in Maricopa County Superior Court and will eventually determine water rights for most of the State. When complete, the adjudication will provide a consistent set of rights to withdraw and use water and will create a favorable environment for management of the water resources of Arizona.

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Prepared by Richard P. Wilson

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Federal Building, FB-44, 300 West Congress Street, Tucson, AZ 85701-1393

Arkansas
Water Supply and Use

A large quantity of potable freshwater is one of Arkansas' most valuable resources. Between 1951 and 1980, the statewide average annual precipitation was about 49 inches, or 124,000 Mgal/d (million gallons per day) as shown in figure 1*A*. In 1985, about 5,910 Mgal/d of freshwater was withdrawn from Arkansas' rivers, streams, and aquifers; this amount is equivalent to more than 2,500 gal/d (gallons per day) for every person in the State. Of the total withdrawal, 3,210 Mgal/d was consumed, and 2,700 Mgal/d was returned to the hydrologic system.

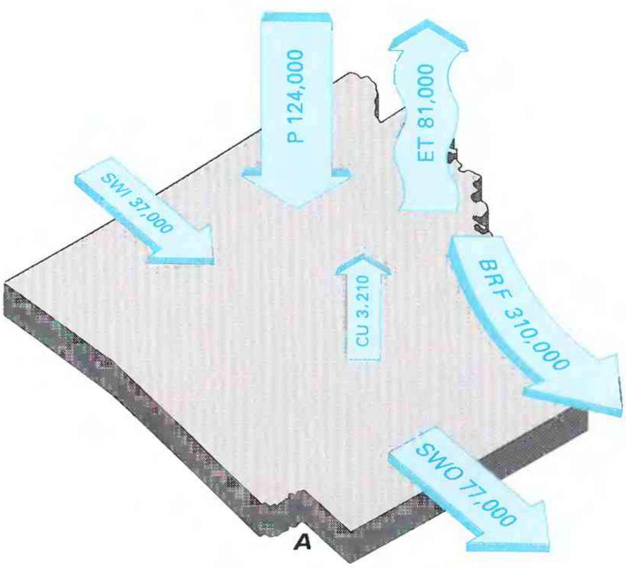
Arkansas' economy depends on agriculture as the primary economic base. Withdrawals for agricultural use account for 73.0 percent (4,310 Mgal/d) of the total quantity of water withdrawn. The pulp and paper industry and thermoelectric power generation also use substantial amounts of water.

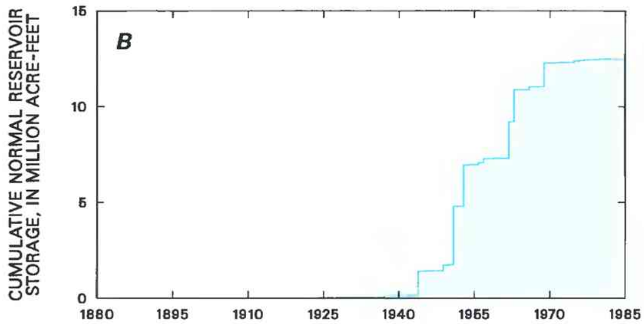
In 1985, 35.6 percent (2,100 Mgal/d) of the water withdrawn was from surface-water sources and 64.4 percent (3,810 Mgal/d) was from ground-water sources. Streams within the Lower Arkansas and the Lower Mississippi–St. Francis basins are the principal surface-water resources. Western Arkansas also relies primarily on surface-water sources for water supplies. Arkansas ranks seventh in the Nation in amount of water withdrawn from ground-water sources (Solley and others, 1988). The major sources of ground water are the alluvial and the Sparta aquifers in eastern Arkansas.

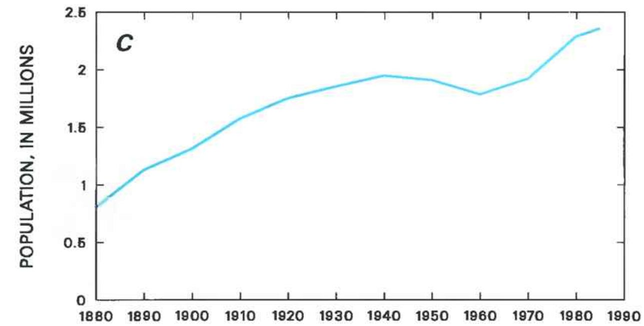
A major concern in Arkansas is the availability of water for irrigation of crops and maintenance of fish farms in the eastern part of the State. Water levels in the shallow aquifers have declined rapidly in recent years; consequently, farmers have had to drill deeper wells into the underlying aquifers at a much greater cost. Managers and planners are now investigating diversion of water from the Arkansas River into the rice-growing areas of the State.

HISTORY OF WATER DEVELOPMENT

Arkansas, which is named after the Arkansa Indian Tribe, was first explored by Hernando DeSoto in 1541, when he crossed the Mississippi River near Memphis, Tenn. The first white settlement was started by the French in 1686 at Arkansas Post near the confluence of the Arkansas and the White Rivers. The Louisiana







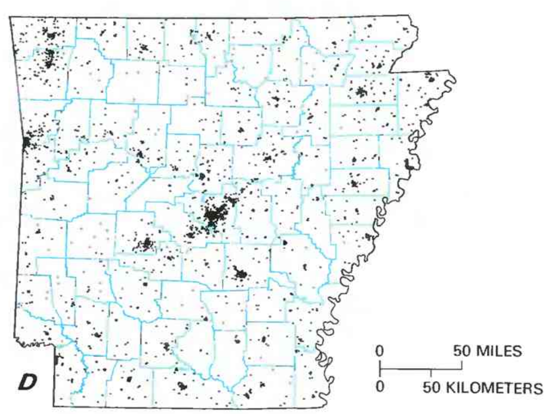


Figure 1. Water supply and population in Arkansas. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Freiwald, 1985; Thornthwaite, 1948; U.S. Geological Survey, 1985b. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Purchase, which included the Territory of Arkansas, was obtained from France in 1803; the population of the area increased from less than 1,000 in 1803 to nearly 100,000 in 1836, when Arkansas became a State. Development of water resources in the State was limited until about 1924. The Mississippi, the Arkansas, the White, and the Ouachita Rivers were some of the streams that were used as transportation routes for settlements that developed into cities.

Several major water-related events between 1920 and 1940 encouraged the beginning of water development in Arkansas. After World War I and through most of the 1920's, industrial and agricultural activity increased significantly in Arkansas. The first major dam—Remmel Dam, which created Lake Catherine near Hot Springs—was built in 1924 on the Ouachita River for electric power generation. The Grand Prairie of eastern Arkansas was becoming a large rice producer, and large quantities of water were withdrawn from the shallow alluvial aquifer. A massive flood in 1927 inundated thousands of acres in the agricultural flatlands of eastern Arkansas. This flood was followed by severe drought during the 1930's and by an economic depression.

These significant events were the catalysts for several major Federal and State programs for water development, conservation, and basic hydrologic studies from the 1920's to 1987. The U.S. Army Corps of Engineers began a development program for the Lower Arkansas, the Upper White, the Red-Sulphur and the Lower Red-Ouachita basins. This program had several purposes including navigation, flood control, hydroelectric power generation, public-water supply, irrigation, recreation, fish and wildlife propagation, and low-flow augmentation.

Several large multipurpose dams were built in and around the Ozark and the Ouachita Mountains in the western part of the State. Of the 50 dams and reservoirs represented by normal reservoir storage (fig. 1*B*), 43 were built between 1942 and 1979. The greatest single water-development project in Arkansas was the McClellan-Kerr Arkansas River Navigation System, which opened in 1970, connecting the Mississippi River to the Port of Catoosa, near Tulsa, Okla. (U.S. Army Corps of Engineers, undated).

The U.S. Soil Conservation Service has been active in Arkansas since the mid-1930's assisting farmers and communities in soil-erosion control, watershed development, natural resource surveys, and community resource protection and development. A total of 184 small watershed dams have been built with U.S. Soil Conservation Service assistance.

The Arkansas Soil and Water Conservation Commission (ASWCC) reports the activities of several agencies in the construction of lakes in Arkansas (Arkansas Soil and Water Conservation Commission, 1981). The U.S. Forest Service has constructed 10 lakes, which have a total capacity of 17,598 acre-ft (acre-feet). The Arkansas Department of Parks and Tourism has constructed 10 lakes, which have a total capacity of 3,690 acre-ft. The Arkansas Game and Fish Commission has constructed 31 lakes, which have a total capacity of 189,211 acre-ft.

Several State and Federal agencies are actively involved in the development and management of water. Increasing population (fig. 1*C*) and population distribution (fig. 1*D*) affect the withdrawal and the distribution of water used for various purposes. The urban population in Arkansas now exceeds the rural population. As the State population continues to grow and competition for water increases, the resulting challenge to all State and Federal agencies will become even greater.

WATER USE

Arkansas has an abundant supply of water. The State's water budget (fig. 1*A*) includes an estimate of the proportions of water that flows into and out of the State. The Mississippi River flows along the eastern boundary of the State and represents a large part of the water budget for Arkansas; however, it is negligible in terms of water use.

The distribution of surface- and ground-water withdrawals during 1985 differed substantially across the State. The counties that had the largest withdrawals (fig. 2*A*) indicate the major areas of water use within the State. Large withdrawals of water in counties in eastern Arkansas (Poinsett, Cross, Prairie, Lonoke, and Arkansas) are predominantly for irrigation. Water withdrawals in the Little Rock area (Pulaski County) for public-water supply are used by the large population, whereas water withdrawals in southern and central Arkansas (Ashley, Desha, Jefferson, Little River, and Ouachita Counties) are used by the large paper-products industry. The distribution of surface- and ground-water withdrawals by county (figs. 2*B*,*C*) shows that the surface-water withdrawals are predominant in the west-central part of Arkansas, and the withdrawals of ground water for agriculture are predominant in the eastern part of Arkansas.

Of the major river basins (fig. 3*A*), the largest withdrawals are in the Lower Arkansas basin because of the large volume of water used by the nuclear powerplant in Pope County. Large amounts of surface water are withdrawn for irrigation in the Lower Mississippi-St. Francis and Boeuf-Tensas basins. The Red-Sulphur basin had large withdrawals for the pulp and paper industry. Of the total ground-water withdrawals during 1985 (fig. 3*B*), 93.2 percent was from the alluvial aquifers, and 4.1 percent was from the Sparta aquifer. Irrigation was the primary use of water from the alluvial aquifers.

Instream use is important in Arkansas, and the availability of water for instream use has affected the placement of many industries in Arkansas. The largest instream use of water is for hydroelectric power generation, which supplies 17 percent of the State's electricity. In 1985, more than 59,900 Mgal/d was used to generate about 4,430 gigawatthours of electricity. The consumptive use of water in this process is mostly from evaporation, and the amount involved is considered to be negligible.

The source, use, and disposition of water in Arkansas in 1985 are diagrammatically shown in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that surface-water withdrawals are 35.6 percent (2,100 Mgal/d) of the total withdrawals. Of the total surface water withdrawn, 7.4 percent (156 Mgal/d) is diverted to public-supply systems, 0.1 percent (1.9 Mgal/d) is self-supplied for domestic and commercial use, 5.2 percent (110 Mgal/d) is self-supplied for industrial and mining use, 52.0 percent (1,090 Mgal/d) is self-supplied for thermoelectric power generation, and 35.2 percent (739 Mgal/d) is for agricultural use.

The public-supply data mainly show water conveyed for domestic and commercial use. For example, 257 Mgal/d of water is distributed through public-supply systems, which is nearly 100 percent of the water delivered by public-supply systems.

The use data indicate, for example, that agricultural use accounted for 73.0 percent (4,310 Mgal/d) of the State's total withdrawals. Of the water used for agricultural purposes, 17.1 percent (739 Mgal/d) was obtained from surface-water sources, and 82.9 percent (3,570 Mgal/d) was from ground-water sources. About 71.7 percent (3,090 Mgal/d) of the water used for agricultural purposes was consumed; 28.3 percent (1,220 Mgal/d) was returned to the hydrologic system.

The disposition data indicate the amount of water from each use category that is consumed or returned to natural sources. Of all the water withdrawn in the State, 54.3 percent (3,210 Mgal/d) was consumed, and 45.7 percent (2,700 Mgal/d) was returned.

Total water use for domestic and commercial, industrial and mining, and agricultural purposes had increased steadily since it was first reported in 1960 until 1980 (fig. 5). In 1985, water withdrawals were slightly less than in 1980 because the 1980 growing season was drier than average and more water was withdrawn for irrigation.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In 1985, public suppliers in Arkansas furnished 257 Mgal/d through 749 public-water systems (fig. 4). Nearly 100 percent of the water was delivered for domestic and commercial use. Of the 257 Mgal/d withdrawn, 156 Mgal/d was from surface-water sources, and 101 Mgal/d was from ground-water sources. Withdrawals by public suppliers have remained about the same since 1980.

Sources of water for public supplies differ throughout the State. Few productive aquifers exist in northern and western Arkansas, so public water supply is mainly from surface-water sources. Most public-supply withdrawals in eastern Arkansas are from the alluvial and the Sparta aquifers (fig. 3*B*). Pulaski County, the most populous county, uses the largest amount of public-supply water (49 Mgal/d).

DOMESTIC AND COMMERCIAL

Domestic and commercial water users receive water from public-supply and self-supplied systems. In 1985, combined withdrawals and deliveries for domestic and commercial use were 5.5 percent (325 Mgal/d) of total withdrawals (fig. 4). Of that 325 Mgal/d, 79.0 percent (257 Mgal/d) was distributed through public-supply systems, and 20.4 percent was from self-supplied systems using primarily ground-water sources.

In 1985, withdrawals and deliveries for domestic use were 230 Mgal/d, of which 60 Mgal/d was provided by self-supplied systems and 170 Mgal/d was provided by public-supply systems. Most of the population (72 percent) obtains water from public-supply systems. Consumptive use of water for domestic use is considered to be almost 100 percent; values for return flow are not available.

In 1985, withdrawals and deliveries for commercial use were about 95 Mgal/d, of which 8 Mgal/d was provided by self-supplied systems and 87 Mgal/d was provided by public-supply systems. Consumptive use was 6 Mgal/d. Pulaski and Sebastian Counties used the largest amount of water withdrawn for commercial purposes.

INDUSTRIAL AND MINING

In 1985, water withdrawals for industrial and mining use amounted to about 3 percent (175 Mgal/d) of total withdrawals (fig. 4). Self-supplied systems provided 2.0 Mgal/d of surface water and 1.0 Mgal/d of ground water for mining activities. Self-supplied systems also provided 108 Mgal/d of fresh surface water and 64 Mgal/d of fresh ground water for all other industrial uses. Consumptive use for all industries and mines was 24 Mgal/d.

Industrial and mining water use is dominated by the pulp and paper industry, which accounts for 71.0 percent (125 Mgal/d) of that

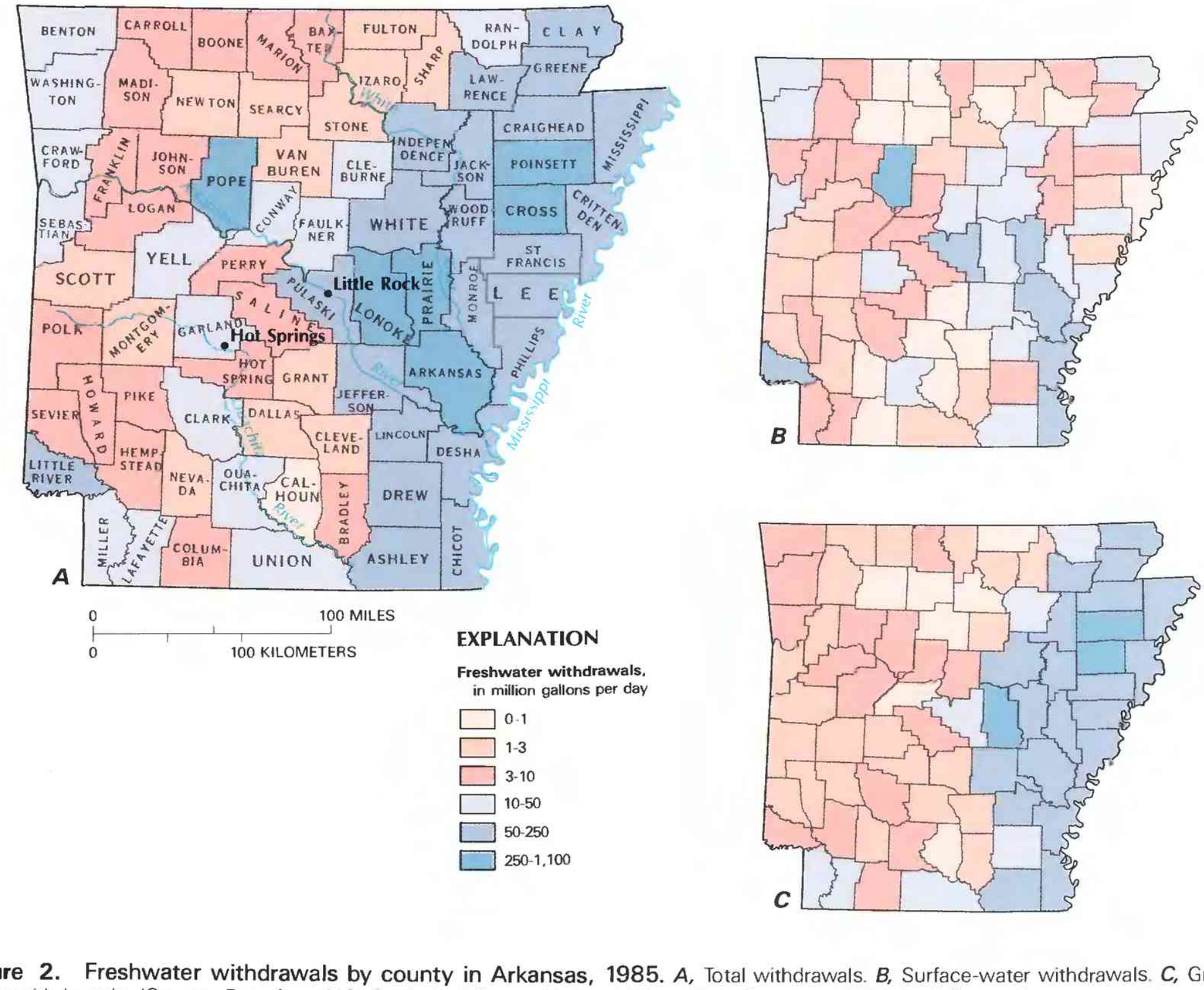


Figure 2. Freshwater withdrawals by county in Arkansas, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

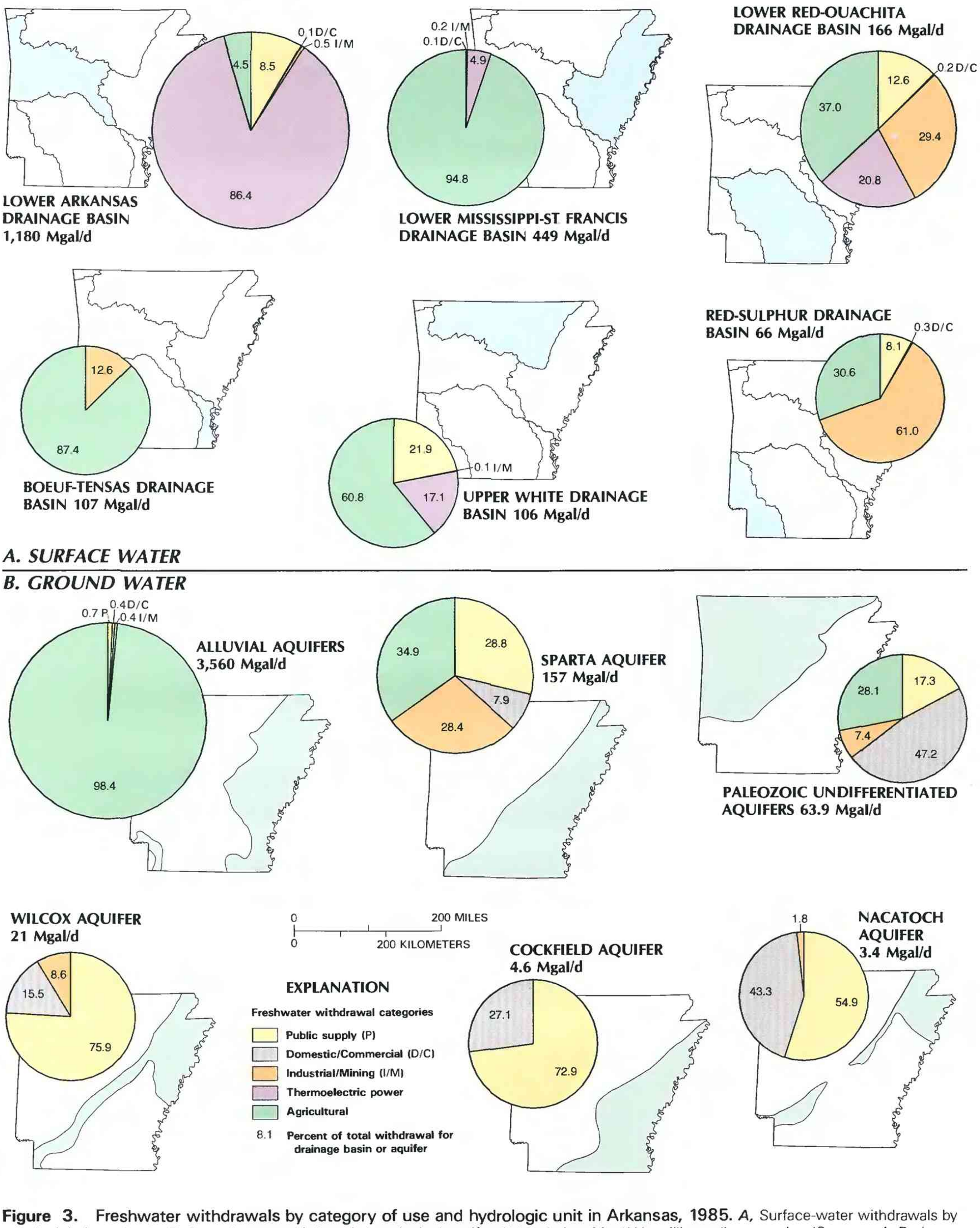


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Arkansas, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Holland and Ludwig, 1981.)

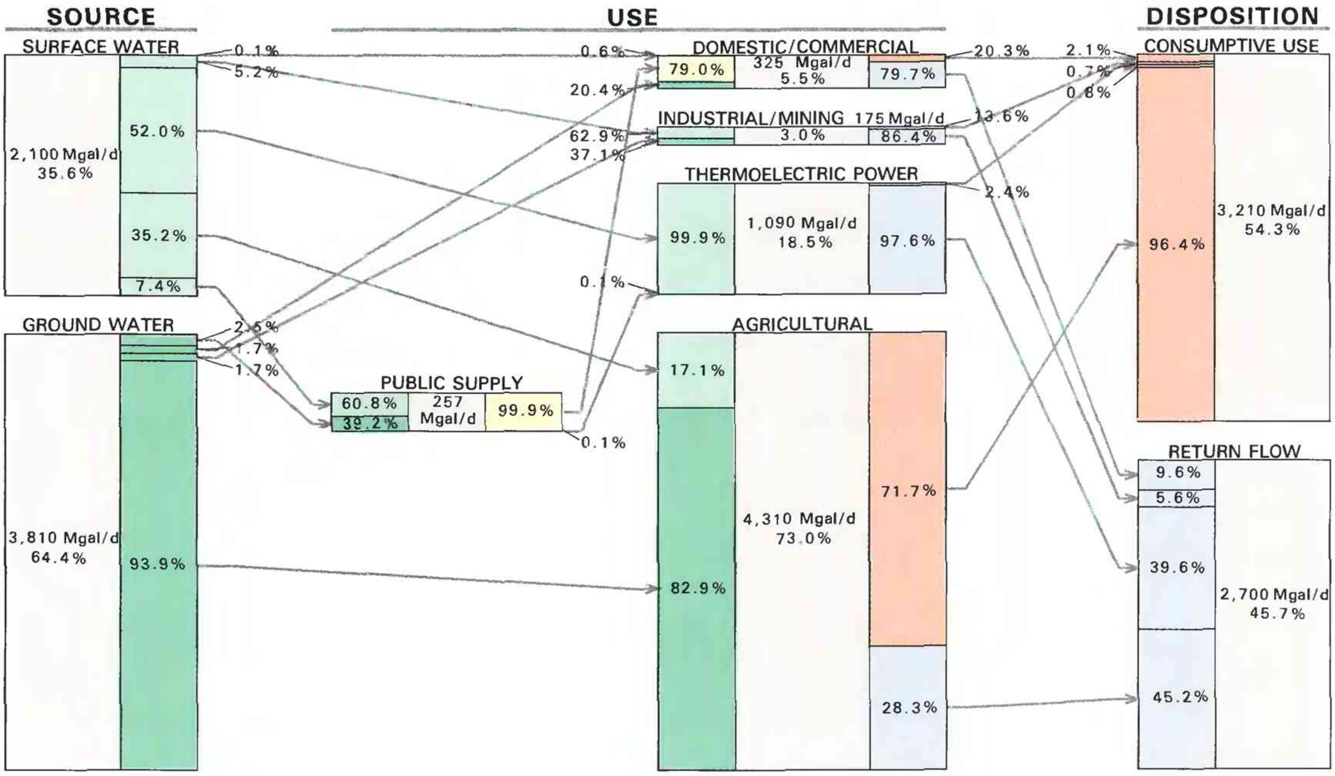


Figure 4. Source, use, and disposition of an estimated 5,910 Mgal/d (million gallons per day) of freshwater in Arkansas, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

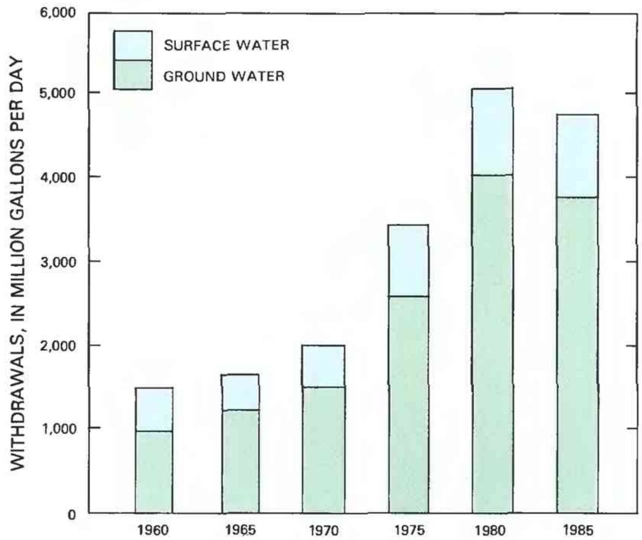


Figure 5. Total water use in Arkansas for domestic and commercial, industrial and mining, and agricultural purposes according to source of supply, 1960–85. (Sources: Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972; Halberg, 1977; Holland and Ludwig, 1981; and data from the U.S. Geological Survey National Water Data Storage and Retrieval System.)

category in Arkansas. Since 1980, industrial water use has decreased 26.0 percent, primarily because of deteriorating economic conditions in the chemical and mining industries.

THERMOELECTRIC POWER

Water used for thermoelectric power generation represents an important part of Arkansas' total water withdrawals. The State has 12 thermoelectric powerplants, of which 11 use fossil fuel and 1 uses nuclear fuel. In 1985, these plants accounted for 18.5 percent (1,090 Mgal/d) of total withdrawals for cooling purposes (fig. 4). The nuclear powerplant along the Arkansas River in Pope County accounted for 91.7 percent (1,000 Mgal/d) of the water used for thermoelectric power generation. Fossil fuel powerplants withdrew 91 Mgal/d of surface water and 1.0 Mgal/d of ground water. The 1.0 Mgal/d from ground water was used primarily to replenish water lost from "closed" cooling systems and for human use. Consumptive use was 26 Mgal/d by fossil-fuel powerplants and nearly zero by the nuclear powerplant. Withdrawal of water for thermoelectric cooling in the production of electricity accounts for 18.5 percent of all water withdrawals in Arkansas; however, most of the water is returned to streams. About 2.4 percent of the water used for cooling is lost through evaporation.

AGRICULTURAL

Agriculture is the predominant water user in Arkansas. Water withdrawn for agricultural purposes during 1985 accounted for 73.0 percent (4,310 Mgal/d) of the total withdrawals for all uses

The Joe Hogan State Fish Hatchery in Lonoke, Arkansas, is the largest State-owned, warm-water fish hatchery in the United States. Federal, State, and privately owned aquaculture facilities make Arkansas the second largest user of water in a nonirrigated agriculture category. (Photograph by N.T. Baker.)

(fig. 4). The quantity of water used for agriculture has decreased 7 percent since 1980.

In 1985, irrigation required more water (3,870 Mgal/d withdrawn) than any other type of water use. Of that amount, 540 Mgal/d was withdrawn from surface-water sources, and 3,330 Mgal/d was from ground-water sources. Irrigation is practiced extensively in the Mississippi River valley, which encompasses all or parts of 27 counties in eastern Arkansas. The largest use of water for irrigation was in Arkansas and Poinsett Counties, where total withdrawals were 357 and 297 Mgal/d, respectively. Irrigation of rice crops used 2,790 Mgal/d, which represented 72.1 percent of the water used for irrigation of all crops. Of 2.02 million total irrigated acres, 1.06 million acres was planted in rice. Cotton, soybeans, and corn are the major crops grown on the other 960,000 acres of irrigated land; however, these crops do not require the large quantities of water that are required for rice production.

In 1985, the amount of water used for irrigation was 6.0 percent less than that of 1980 because 1980 was drier and more water was used for irrigation and because rice acreage had been decreased by 1985. Rice production has decreased primarily because of the rising cost of water and a nationwide trend to decrease the quantity of surplus grains.

Large sustained ground-water withdrawals for irrigation during the early 1980's caused substantial water-level declines in some areas of Arkansas. Water levels in some wells completed in the alluvial aquifer were declining at an annual rate of 0.3 to 0.5 foot (U.S. Geological Survey, 1985a, p. 144). This decline and the resulting decrease in availability of water necessitated drilling into the deeper Sparta aquifer and resulted in greater cost.

Withdrawals for nonirrigated agriculture in 1985 were estimated to be 440 Mgal/d—198 Mgal/d from surface water and 242 Mgal/d from ground water. Although nonirrigated withdrawals for agriculture represent only 7.4 percent of total water withdrawals, Arkansas ranks second in the Nation for water use in this category (Solley and others, 1988). Aquaculture is the dominant water use for nonirrigated agriculture. Aquaculture in Arkansas consists primarily of catfish and minnow farms and, to a lesser extent, trout farms and fish hatcheries. In 1985, the largest withdrawals for aquaculture (94 Mgal/d) were in Lonoke County. Other nonirrigated agricultural water users include cattle, hog, and poultry operations.

WATER MANAGEMENT

The ASWCC is the State agency responsible for water resources planning at the State level, as designated by the State Legislative Act 217 of 1969, as amended. The Act authorizes the ASWCC to prepare a comprehensive State Water Plan in sufficient detail to serve as the basic document for defining water policy for the protection, development, and management of the State's water resources. In 1975, the first State Water Plan contained an inventory of water resources, identified major problems, and presented solutions and recommendations for water-resource problems. The ASWCC currently is revising the State Water Plan to incorporate data available from recent research. All State agencies, commissions, and public political subdivisions must consider the State Water Plan in any water-development project and must register any proposed water-development plans with the ASWCC. This statute gives the ASWCC the authority to review all water-development activity within the State.

In 1969, the General Assembly of Arkansas passed Legislative Act 180, which requires that diversions of water from streams, lakes, and ponds (except natural lakes owned by an individual) must be registered annually with the ASWCC. The registration is designed to indicate the amount, the purpose, and the location of use. The purpose of reporting surface-water diversions is to provide data to the ASWCC for water-resource planning and management.

The ASWCC does not have the authority to regulate surface- and ground-water withdrawals, except during periods of shortage.

Arkansas' water law is based on the riparian doctrine. All landowners along a stream have free and unrestricted use of streamflow, provided that use does not adversely affect other riparian water users. Similarly, landowners have the right to reasonable use of ground water as long as that use does not adversely affect other riparian water users. The ASWCC has the authority to allocate surface water among water users during periods of shortage (Legislative Act 81 of 1957, as amended). The ASWCC may administratively allocate surface water on its own initiative or on the petition of any person affected by such a shortage of water. In allocating water in such instances, reasonable preferences are given to different uses on the basis of priorities of sustaining life, maintaining health, and increasing wealth. Preference also is given to riparian users who have annually registered their diversion with the ASWCC, thereby establishing a record of historic water use.

Legislative Act 1051 of 1985, as amended by Legislative Act 460 of 1987, requires the reporting of all withdrawals of ground water, except withdrawals used exclusively for domestic use or from wells that have a potential yield of less than 50,000 gal/d. The ASWCC uses this information in conjunction with the surface-water diversion data to determine the requirements of all water users of the State. These data also are evaluated in the State Water Plan to project future water needs. In 1985, water use information was reported to the ASWCC for about 15,000 wells, which is an estimated 60 percent of the total wells in the State.

Section 5 of Legislative Act 1051 of 1985 empowered the ASWCC to authorize interbasin transfer of surplus water and transportation of excess surface water to nonriparian water uses. Surplus water is defined in the Act as being 25 percent of the quantity of water available, on an average annual basis from any watershed, that exceeds the quantity required to satisfy current and projected water needs of the basin of origin. The ASWCC is in the process of quantifying excess surface water and is developing rules and regulations to implement the application procedures.

The ASWCC also has the responsiblity to evaluate requests for out-of-State water transfer and to recommend to the General Assembly of Arkansas whether or not the transfer would be in the interest of the State. Criteria are being established for review of requests for out-of-State water transfer.

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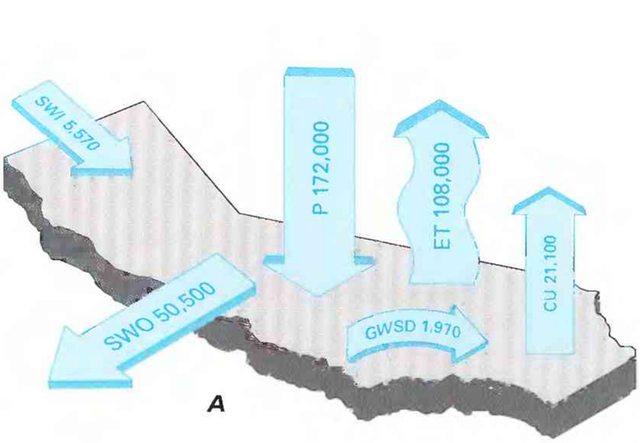
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Room 2301 Federal Building, 700 W. Capitol Avenue, Little Rock, AR 72201

CALIFORNIA
Water Supply and Use

California, which has the largest volume of offstream water use in the Nation, consistently leads all States in surface- and ground-water withdrawals. The State has retained this position for 40 years, primarily because of the large volume of irrigated agriculture (MacKichan, 1951; 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972; 1977; Solley and others, 1983; 1988). California's water budget (fig. 1*A*) shows that available water supplies originate from precipitation, ground-water storage depletion, and surface-water inflow from adjacent States. A complex water-management system has developed in response to a geographic and seasonal mismatch between supply and demand (U.S. Geological Survey, 1986, p. 157). Settlement first began near readily available sources of water such as streams, lakes, and springs. During the past 100 years, the population has increased in areas of little rainfall, and water supplies must be pumped from deep aquifers or transported from distant surface-water sources.

Water use may be divided into the broad categories of instream and offstream use. Instream use includes recreation, navigation, pollution abatement, maintenance of fish and wildlife habitat, hydroelectric power generation, and ground-water recharge from stream channels. Offstream use includes domestic, commercial, industrial, mining, thermoelectric power production (including fossil fuel, nuclear, and geothermal), and agricultural (irrigation and livestock) use (Templin, 1986, p. 3). The only instream water use now quantified under the U.S. Geological Survey's water use program is hydropower, which consistently uses the most water of all categories accounted for in California (Templin, 1986, p. 3). In 1985, the volume of instream freshwater used for hydropower was more than twice the volume used for irrigation—the largest category of offstream freshwater use.

In 1985, 37,400 Mgal/d (million gallons per day) of freshwater was withdrawn from streams and aquifers—equivalent to almost 1,420 gal/d (gallons per day) per capita. Of this water, 56.4 percent (21,100 Mgal/d) was consumed, and the balance was returned to surface and ground water. Agriculture accounted for 82.4 percent



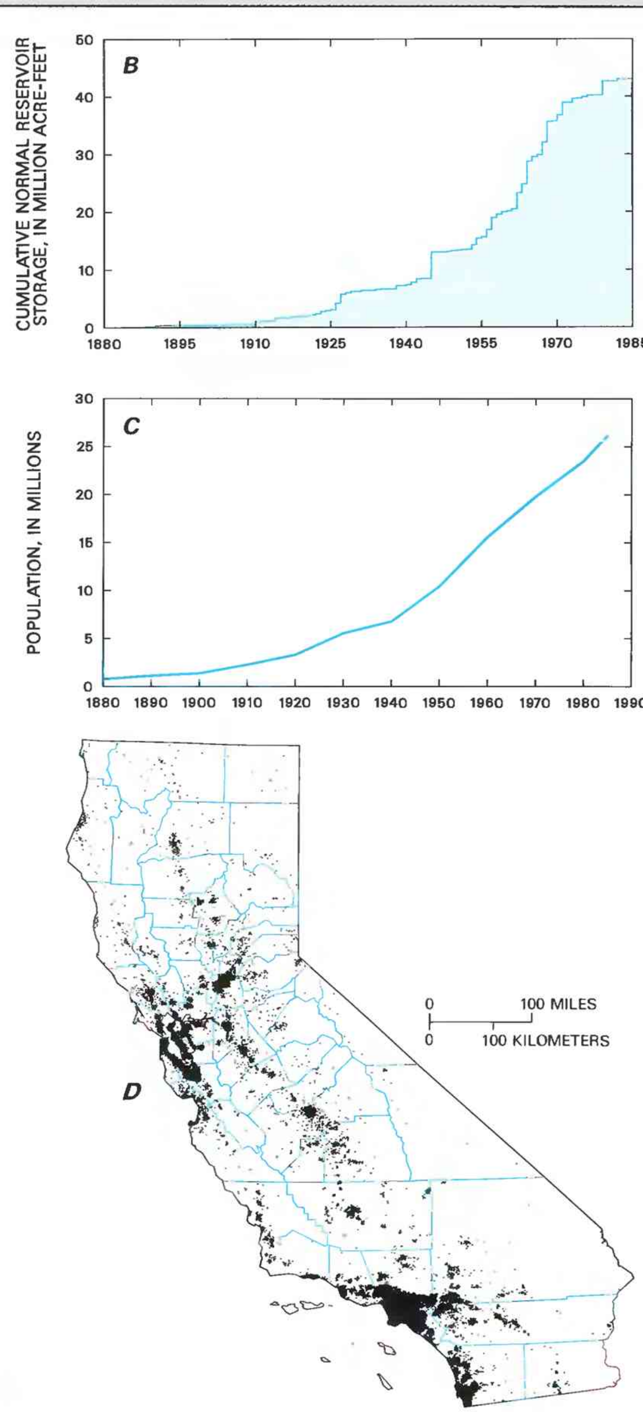


Figure 1. **Water supply and population in California.** *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **GWSD,** ground-water storage depletion; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Ralph G. Allison, California Department of Water Resources, written commun., 1987; California Department of Water Resources, 1983a; Mark Carlos, Imperial Irrigation District, oral commun., 1987; Kahrl, 1979; U.S. Bureau of Reclamation, 1986; U.S. Geological Survey data; White and Garrett, 1986. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

(30,800 Mgal/d) of total freshwater withdrawals in 1985; of this amount, 66.2 percent was surface water, and 33.8 percent was ground water. Although consumptive use cannot be quantified precisely using available information, irrigation probably accounted for about 90 percent (19,300 Mgal/d) of the consumptive use of freshwater in 1985.

Californians are concerned about many major water use issues; one of the most notable is the recurrent proposal to increase delivery of water from the north to the south and the resultant effects such action would have on water supplies and quality in northern counties. Hearings are being held now (1987) by the California State Water Resources Control Board to gather information needed to help resolve this issue. A second major issue is the use of irrigation water and return flows on the western side of the San Joaquin and Tulare–Buena Vista Lakes basins. Many investigations of the selenium problems related to the Kesterson National Wildlife Refuge in Merced County are now underway in Merced and Fresno Counties. A third issue is water marketing. Where agricultural water users are finding that the cost effectiveness of sustaining production is questionable, selling water rights is becoming increasingly attractive. The water-marketing concept, like many of the water issues mentioned above, appears to be heading to the courts for resolution.

From 1980 to 1985, the population increased 11.4 percent, from 23.7 million to 26.4 million (California Department of Finance, 1987, p. 5). The population is projected to increase to 31.4 million by the year 2000 (California Department of Finance, 1983); this would mean an average annual increase of more than 330,000 people. Available water supplies are insufficient to meet current needs without substantial ground-water storage depletion (withdrawal in excess of recharge). Delays in developing additional surface-water supplies could result in shortages or increased ground-water storage depletion (California Department of Water Resources, 1983a, p. 2).

HISTORY OF WATER DEVELOPMENT

Water-resources planning and development in California has a long and complex history dating to the 18th century (California Department of Water Resources, 1983a, p. 7). Irrigated agriculture began with crop cultivation by Indians along the Colorado River. Spanish missions expanded irrigation by diverting streams through ditches into their gardens and fields. The irrigation systems established by the missions set an example for incoming settlers who were not accustomed to the long, dry summers.

Until the California Gold Rush in the mid-19th century, little was done to develop water storage and distribution systems. The miners soon discovered, however, that water was the most effective instrument for unlocking the riches they sought. They built reservoirs and widespread networks of ditches and flumes to divert water from streams to sluice the gold-bearing deposits; these were California's first major hydraulic engineering works. By the mid-1860's, more than 4,000 miles of mining canals and ditches were operating (California Department of Water Resources, 1983a, p. 7).

After profits from the gold fields declined, some miners and new settlers turned to farming. Water for irrigation became increasingly important. In the northern and central sections of the State, irrigation practices were simple; many settlers dug ditches to convey water from streams to nearby fields. Water from flowing wells also was plentiful in many valleys and coastal plains during the late 1800's. Because of the drier conditions in southern California, however, settlers recognized the value of storage reservoirs. By the 1880's several important dams had been completed or were under construction.

Until about 1900, water development generally was undertaken by individuals and private companies. As the population and the need for water increased, public endeavor supplemented private initiative. The Wright Irrigation District Act of 1887 authorized the formation of local public irrigation districts, declaring the use of water for irrigation of district lands to be a public use and empowering districts to take over private irrigation enterprises to acquire water. By 1930, more than 100 irrigation districts were in operation. The cities of Los Angeles and San Francisco were among the early leaders in planning and developing projects to import water from other areas.

Local plans for the use of water were conceived and executed without the benefit of a statewide framework for guidance and coordination. The first statewide plan for development of water resources was established in 1920 by Colonel Robert B. Marshall, former chief geographer for the U.S. Geological Survey. Marshall's plan called for a storage reservoir on the northern end of the Sacramento River and a pair of aqueducts, one to convey water down the eastern side of the valley and one down the western side. The plan also provided for conveying water to Los Angeles. Today, the State Water Project (operated by the California Department of Water Resources) and the Central Valley Project (operated by the U.S. Bureau of Reclamation), which somewhat resemble Marshall's original proposals, form the heart of California's water-distribution network.

The history of California's reservoir storage capacity since 1880 (fig. *1B*) indicates that impoundment of surface-water sources is one of the major approaches used to manage water supplies. Most of the reservoirs in the California part of the Central Lahontan basin supply water to Nevada; storage volumes for these reservoirs, therefore, are not included in figure *1B*. Population growth and distribution since 1880 (fig. *1C*) have made water-supply management extremely important. Urban water demands are related to population distribution, which is concentrated in the southern coastal and the San Francisco areas (fig. *1D*).

WATER USE

In much of California, demand for water exceeds the natural supply. To understand the problems of supply and demand, the sources of natural supply, runoff, inflow, and outflow must first be examined. The water budget (fig. *1A*) shows an average annual statewide precipitation of 172,000 Mgal/d [193 million acre-ft (acre-feet)], which is equivalent to an average annual rainfall of nearly 24 inches. Distribution of average annual precipitation across the State, however, ranges from about 2 to 100 inches (California Department of Water Resources, 1983a, p. 8). Evapotranspiration and consumptive use accounted for about 72 percent (129,000 Mgal/d) of the total water inflow from all sources and precipitation (about 180,000 Mgal/d). Generally, about 4,100 Mgal/d (4.6 million acre-ft) percolates from stream channels to ground water (California Department of Water Resources, 1983a, p. 89). Average annual surface-water inflow and outflow rates (fig. *1A*) are about 5,570 Mgal/d (6.24 million acre-ft) and 50,500 Mgal/d (56.6 million acre-ft), respectively. An additional 1,970 Mgal/d is supplied from ground-water storage depletion. Annual average outflow rates, however, have ranged from 13,000 Mgal/d (15 million acre-ft) in 1976–77 to about 120,000 Mgal/d (135 million acre-ft) in 1982–83 (California Department of Water Resources, 1983a, p. 9).

Most of the water supply originates in the northern part of the State, but much of the demand is in densely populated and irrigated sections in the southern part. This discrepancy in source of supply and area of demand has resulted in a complex water-transportation network. Major areas of large withdrawals (fig. *2A*) are related to the water-use categories accounting for the most water use; for example, the dense populations in the urban areas of Los Angeles (Los Angeles County), Sacramento (Sacramento County), San Diego (San Diego County), and San Francisco (San Francisco

County) (fig. 1*D*) use the most public-supplied water, but the rural Central Valley counties (fig. 2*A*) use the most agricultural irrigation water.

The distribution of surface- and ground-water (fig. 2*B*,*C*) withdrawals by county indicates the availability of surface water in the northern part of the State and the reliance on surface and ground water in the southern part. Large volumes of surface water are imported into southern California from the Colorado and the Owens Rivers and the Sacramento–San Joaquin Delta. Much of the imported and local surface water is used for ground-water recharge; thus, southern California relies heavily on surface and ground water. Of the principal river basins (fig. 3*A*), the Sacramento, the San Joaquin, and the Tulare–Buena Vista Lakes basins are the source of the largest withdrawals. Part of these large withdrawals is transported

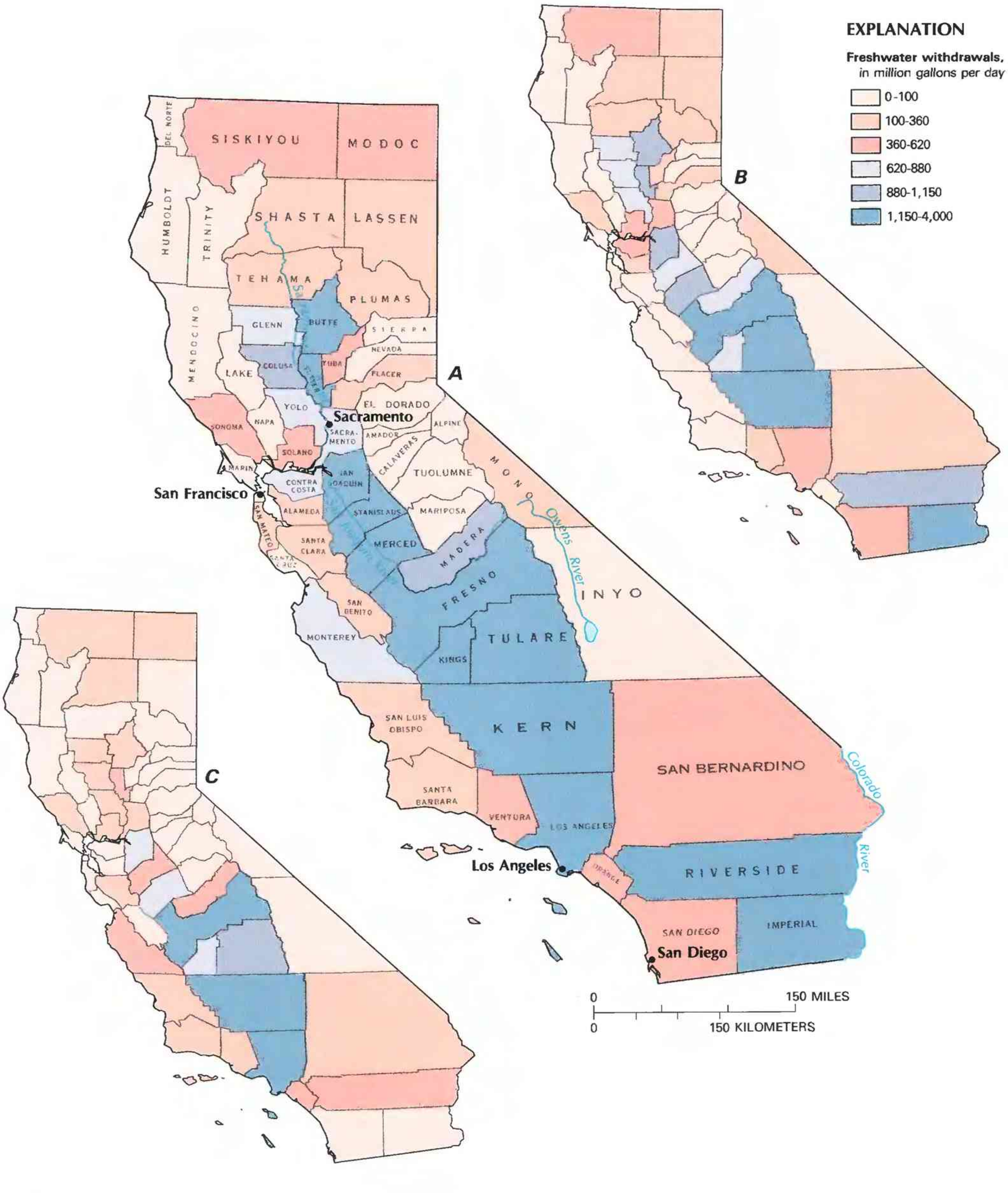


Figure 2. Freshwater withdrawals by county in California, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

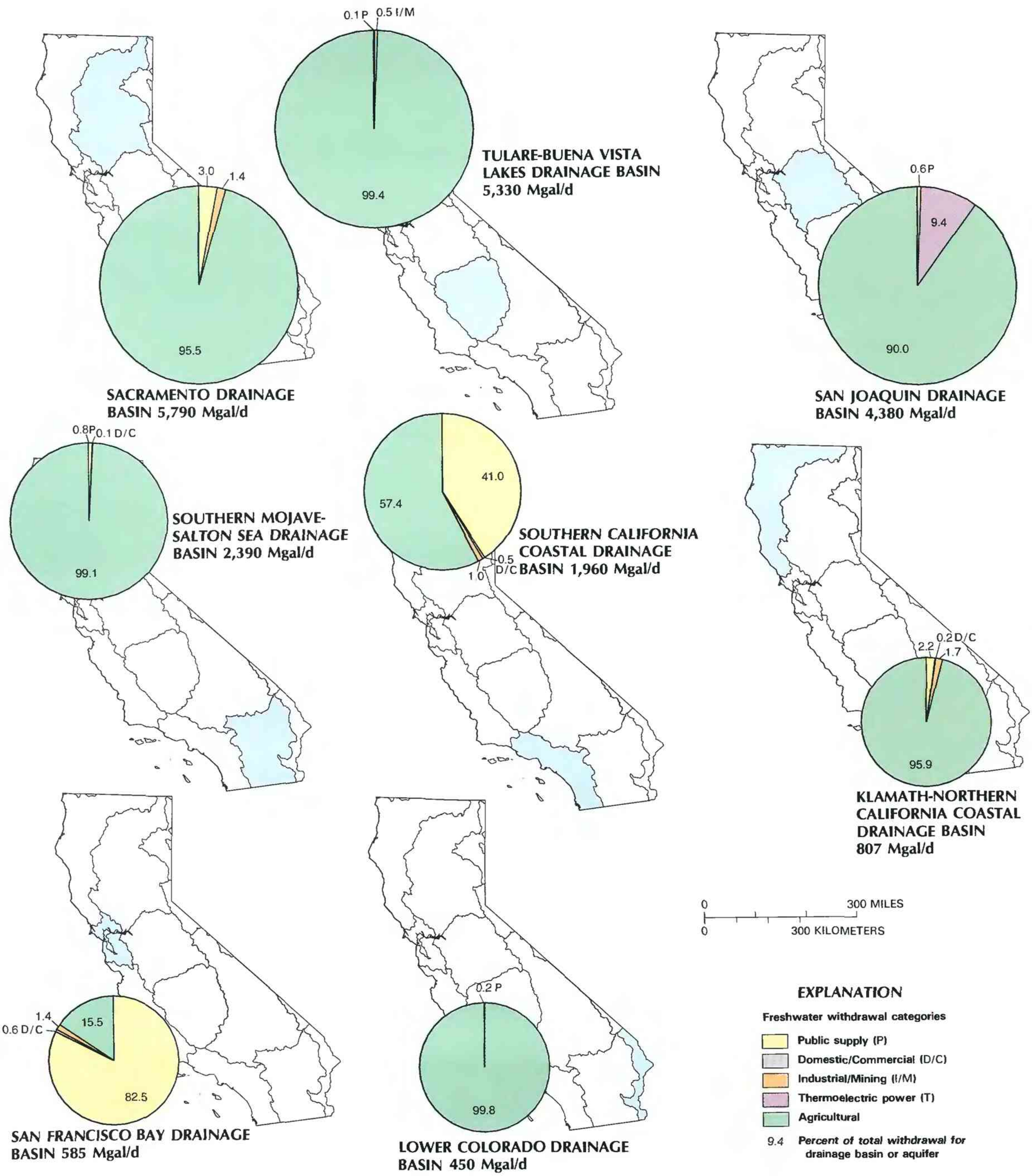


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in California, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987. *A*, *B*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

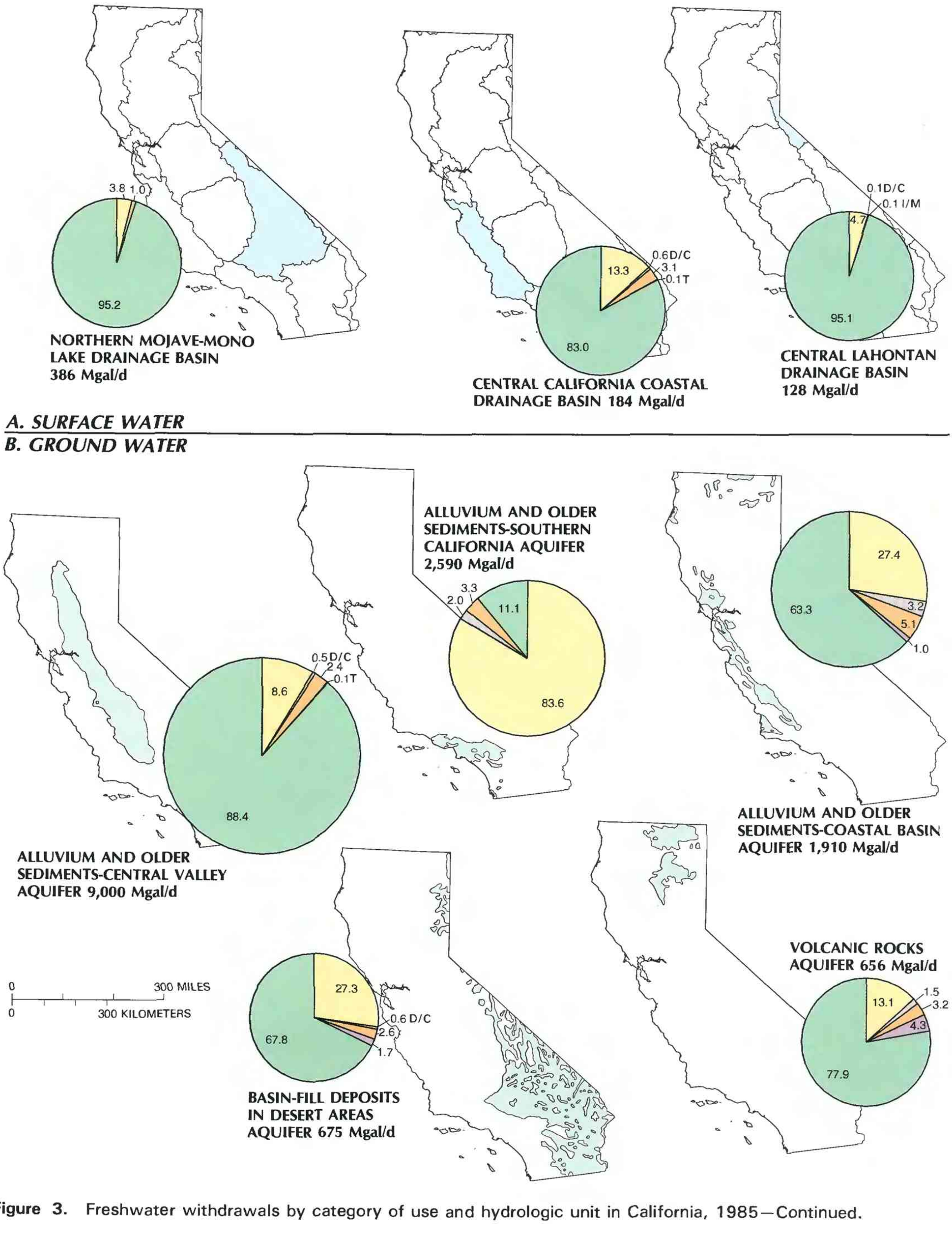


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in California, 1985—Continued.

to the southern Central Valley (including the San Joaquin and Tulare-Buena Vista Lakes Subregions) for irrigation and to southern California for public supply.

Aquifers composed of alluvium and older sediments (mostly of continental origin) and volcanic rock underlie about 40 percent of California (California Department of Water Resources, 1975, p. 7). The alluvial and other sedimentary aquifers can be divided geographically into the Coastal basins, the Central Valley, southern California, and the desert areas (U.S. Geological Survey, 1985, p. 149). These aquifers are principally related in name to the hydrologic units shown in figure 3*A*, except for a few small coastal basin aquifers north and east of Shasta Lake in northern California. The largest volumes of ground-water withdrawals occur in the Central Valley (fig. 3*B*). Ground-water withdrawals also are important in the southern California coastal subregion, where public supply is the largest use of surface- and ground-water (fig. 3*A*,*B*) withdrawals.

The source, use, and disposition of freshwater in California are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that the 22,600 Mgal/d of surface water withdrawn is 60.4 percent of the total freshwater withdrawals in California. Of that total amount, 7.0 percent is withdrawn by public-supply systems, 0.1 percent is self-supplied for domestic and commercial use, 0.7 percent is self-supplied by industrial and mining facilities, 1.8 percent is withdrawn for thermoelectric power generation, and 90.4 percent is withdrawn for agriculture. Other sources, such as saline water and reclaimed sewage wastewater, are not included in figure 4 but are included in this discussion under the appropriate subheadings. The use data indicate that domestic and commercial use accounted for 4,980 Mgal/d, or 13.3 percent of total freshwater withdrawals. Of the domestic and commercial use, 96.1 percent was from public-supply systems, 0.4 percent was self-supplied surface water, and 3.5 percent was self-supplied ground water. The use data indicate that 24.3 percent of the domestic and commercial water was consumed (not readily available for reuse) and 75.7 percent was returned to natural water sources. The use data indicate that, of all water withdrawn, 56.4 percent (21,100 Mgal/d) was consumed and 43.6 percent (16,300 Mgal/d) was returned.

At present, hydropower is the only instream water use studied under the U.S. Geological Survey's water-use program. Instream water use is not included in figure 4. Other instream uses planned for study include aquaculture, recreation, navigation, preservation of fish and wildlife habitat, water-quality improvement, and treaties (Solley and others, 1983, p. 4). The California State Water Resources Control Board (1987, p. 1) is holding hearings on the Sacramento–San Joaquin Delta and San Francisco Bay, which will provide useful information on these types of instream uses.

Hydropower has been an important part of California's history, and its availability has affected the placement of many industries. Electric power companies make every effort to use hydropower because it is a cost-effective way to produce electricity; 24.4 percent of the State's electricity is produced by hydropower. Since 1970,

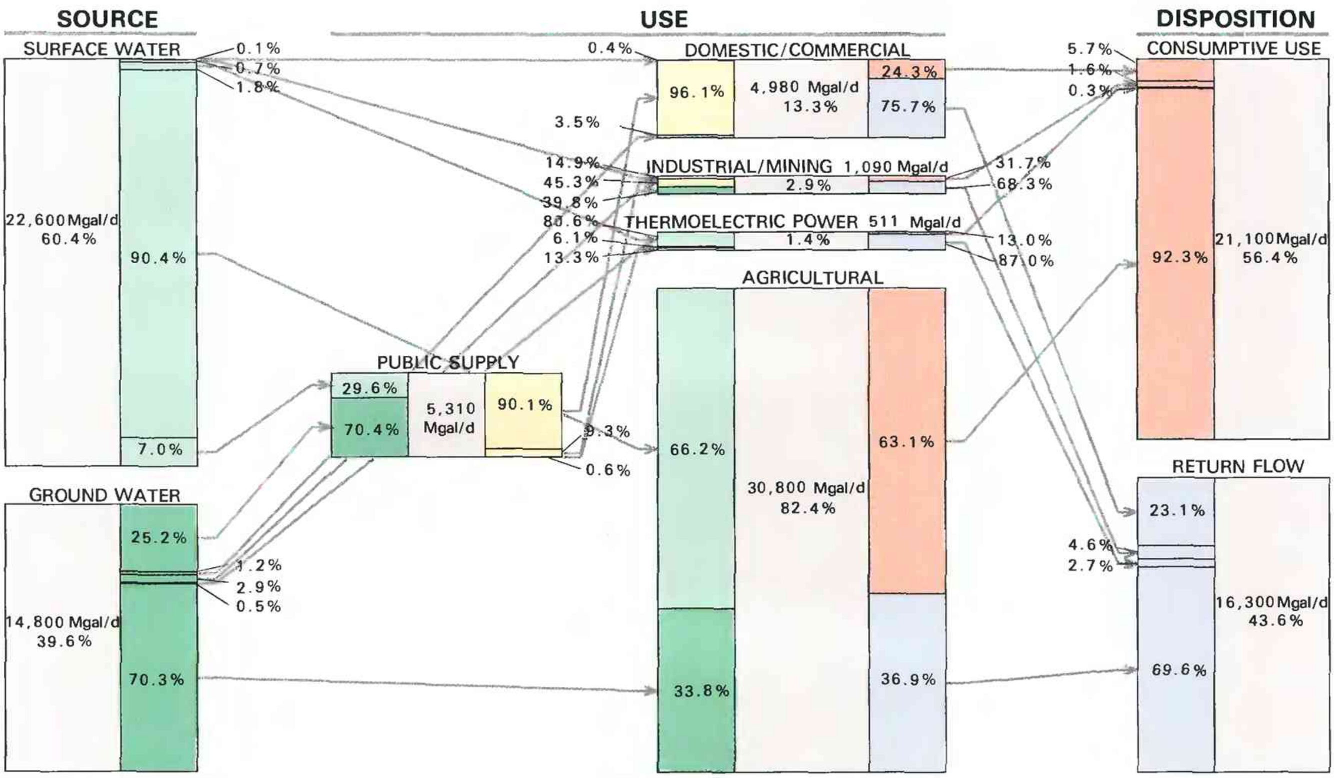


Figure 4. Source, use, and disposition of an estimated 37,400 Mgal/d (million gallons per day) of freshwater in California, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

annual water use for hydropower has been stable at between 81,000 and 84,000 Mgal/d (Murray and Reeves, 1972; 1977; Solley and others, 1983). In 1985, about 83,800 Mgal/d was used to generate about 32,000 GWh (gigawatthours) of electricity. The consumptive use of water in this process, mostly from evaporation, has not been calculated separately, but it is included in the total evapotranspiration shown in figure 1A. In 1985, about 10.6 percent of the Nation's hydropower was generated in California, but California accounted for only 2.7 percent of water used by the Nation for hydropower generation. The main reason for this small water use by hydropower plants in California relative to the quantity of power generated is that large changes in elevation are available at most hydropower sites in the State, so that a given quantity of water can produce more power. Thus, the ratio of power produced to water used is large in comparison to other States.

Saline water is used extensively (11,700 Mgal/d) for cooling of fossil-fueled and nuclear powerplants along the coast. Reclaimed sewage wastewater is used primarily for irrigation of certain crops (California Department of Water Resources 1983a, p. 80) and accounted for about 196 Mgal/d during 1980 and 233 Mgal/d during 1985 (R.G. Allison, California Department of Water Resources, written commun., 1987). In 1985, there were 892 public and 745 other wastewater-treatment plants in operation, which had a reported total discharge of 2,770 Mgal/d.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users (fig. 4). In 1985, California ranked first in the Nation in freshwater withdrawals for public-water supply, accounting for 5,310 Mgal/d (14.5 percent of the national total). California also has the largest population served by public suppliers, 24.3 million (12.2 percent of the national total). Although many water-supply systems also deliver to irrigation-water users, those deliveries are included in the irrigation category rather than the public-supply category.

Of the 5,310 Mgal/d withdrawn for public supply, about 29.6 percent (1,570 Mgal/d) came from surface-water sources, and 70.4 percent (3,730 Mgal/d) came from ground-water sources (fig. 4). The source used depends on the local availability of surface water. Public-supply deliveries during 1985 were used in the following statewide proportions: domestic and commercial, 90.1 percent; industrial and mining, 9.3 percent; and thermoelectric power, 0.6 percent (fig. 4). Statewide distribution of areas receiving public-supply water is closely related to the distribution of population centers.

In 1985, the Southern California Coastal basin accounted for 56.2 percent of the State's population served by public suppliers, compared to 25.0 percent in the remaining coastal basins; 15.8 percent in the Central Valley, including the Sacramento, the San Joaquin, and the Tulare–Buena Vista Lakes basins; and 3.0 percent in the desert areas. The Southern California Coastal basin used about 55.9 percent of the 1985 total withdrawals for public-water supply, whereas the remaining coastal subregions used about 20.0 percent, the Central Valley used about 19.8 percent, and the desert areas used about 4.3 percent. Of the population receiving public supplies in the Southern California Coastal basin during 1985, 71.8 percent was supplied from ground-water sources. By comparison, ground water supplied 47.4 percent of the population in the remaining coastal basins, 79.5 percent in the Central Valley, and 78.2 percent in the desert areas.

Domestic and Commercial

Domestic and commercial water users rely on self- and public-supply systems. Public supply delivered 96.1 percent of all domestic and commercial water used in California during 1985. The total for domestic and commercial use in 1985 was 4,980 Mgal/d (fig. 4). According to the most recent survey available (U.S. Bureau of the Census, 1983, p. 6–421 to 6–425), 89.1 percent of California's self-supplied domestic water comes from wells and springs. Domestic and commercial consumptive use during 1985 was about 1,210 Mgal/d (fig. 4). These figures are based on consumptive use coefficients from the California Department of Water Resources (1983b, p. 9). Domestic water provided by public suppliers was used at the rate of 133 gal/d per capita. Self-supplied domestic water, however, was used at an estimated rate of 75 gal/d per capita (California State Water Resources Control Board, 1977, p. 22).

Industrial and Mining

Freshwater use for industry and mining during 1985 was 1,090 Mgal/d (fig. 4) accounting for only 2.9 percent of California's total offstream freshwater use. Public supply delivered 45.3 percent (494 Mgal/d) of all industrial and mining water used during 1985, while self-supplied users provided the remaining 54.7 percent. For self-supplied users, surface water was the source of 162 Mgal/d and ground-water sources provided 434 Mgal/d. Industrial and mining consumptive use during 1985 was about 346 Mgal/d, which is 31.7 percent of this category's total water use and 1.6 percent of the total consumptive use of all categories in figure 4. Saline water was also used by industrial and mining users during 1985 at rates of 262 Mgal/d and 301 Mgal/d, respectively. Reclaimed sewage wastewater provided an additional 2.9 Mgal/d to industrial users.

The largest water-use industries are the food and kindred products and the petroleum-related industries. Almost all industry groups in food and kindred products consume large quantities of water, and the petroleum-related industries have a reported consumptive use of about 54 percent of the total withdrawals (California Department of Water Resources, 1982, p. 13, 29–30, 51–52). Oil extraction is the largest known water use related to mining. Water is extracted along with the oil and is reinjected to enhance oil recovery.

Total industrial and mining use of freshwater, saline water, and reclaimed sewage has increased from 1,170 Mgal/d in 1975 to 1,656 Mgal/d in 1985 (Murray and Reeves, 1977, p. 26; Solley and others, 1988, p. 23, 37). The volume of water used in oil extraction probably accounts for the overall increase in water use in the industrial and mining category.

Thermoelectric Power

Between 1980 and 1985, the use of fresh ground water for cooling in thermoelectric power generation apparently has decreased sharply; however, the use of saline surface water has increased. Withdrawal of fresh ground water decreased from 886 Mgal/d in 1980 to 68 Mgal/d in 1985. Withdrawal of fresh surface water also declined from 1,084 Mgal/d in 1980 to 412 Mgal/d in 1985. Withdrawal of saline surface water, however, increased from 9,189 Mgal/d in 1980 to more than 11,700 Mgal/d in 1985. The apparent decrease in use of freshwater may have resulted from the conversion of powerplants to accommodate saline surface water or from improved information gathering for 1985.

Of California's many thermoelectric powerplants, most are fossil fuel, some are geothermal, and three are nuclear. During 1985, 24.6 percent (12,200 Mgal/d) of offstream water use was for cooling thermoelectric powerplants, which produced 98,900 GWh of electricity. Thermoelectric powerplant consumptive use of cooling water was less than 0.6 percent, primarily because of the once-through closed cooling systems in many fossil-fueled and nuclear powerplants. Most of these systems are along the coast and withdraw large volumes of saline surface water—more than 11,700 Mgal/d in 1985.

During 1985, fossil-fueled powerplants withdrew 8,400 Mgal/d of saline surface water, 412 Mgal/d of fresh surface water, and 8.7 Mgal/d of fresh ground water and received 17 Mgal/d of public-supply water. Fossil-fueled powerplants' consumptive use was 19.1 Mgal/d of freshwater and 5.75 Mgal/d of saline water (primarily through their evaporative cooling towers) while producing 66,900 GWh of electricity during 1985. Nuclear powerplants withdrew about 3,340 Mgal/d of saline surface water and 0.2 Mgal/d of freshwater and received 14.0 Mgal/d of public-supplied water. Nuclear powerplants' consumptive use was 5.6 Mgal/d of freshwater and no saline water. These plants produced 19,700 GWh of electricity. Geothermal powerplants used 59.5 Mgal/d of ground water; consumptive water use was 42.0 Mgal/d. They produced 12,300 GWh of electricity.

AGRICULTURAL

Agricultural water use can be divided into two categories—irrigation and nonirrigation including livestock. Irrigation is by far the largest offstream water use in California. During 1985, about 30,800 Mgal/d of freshwater was used for agriculture; irrigation accounted for 99.4 percent (30,600 Mgal/d) of that total and agricultural nonirrigation only 0.6 percent (200 Mgal/d). Water used for irrigation in California accounted for 22.3 percent of the Nation's total irrigation water use. Trends in irrigation-water use show increases of 6 percent between 1970 and 1975, of 12 percent between 1975 and 1980, and a return to about the 1970 level in 1985. Trends in the use of fresh ground water for irrigation indicate a decline from 89 percent of the total use of fresh ground water in 1970 and 1975 to 86 percent in 1980 and 70 percent in 1985 (Murray and Reeves, 1972, p. 22; 1977, p. 24, 30; Solley and others, 1983, p. 40; Solley and others, 1988, p. 67). These trends indicate a shift from the use of ground water to a greater reliance on surface water.

Most of the withdrawals for irrigation are in the Central Valley. In 1985, the Valley used 75.3 percent (23,100 Mgal/d) of the irrigation water use. Similarly, it accounted for 72.5 percent (14,700 Mgal/d) of all surface water and 81.0 percent (8,410 Mgal/d) of all ground water used for irrigation in 1985. The volume of fresh ground water used for irrigation (8,410 Mgal/d) in the Central Valley accounted for 18.3 percent of the Nation's fresh ground water used for irrigation and 11.5 percent of the Nation's total fresh ground water used during 1985.

California accounted for 16.7 percent (9.6 million acres) of the Nation's irrigated land during 1985. This acreage reflected a decrease from 9.7 million acres in 1980 (Solley and others, 1983, p. 18); even so, the acreage was larger than in 1975 (9.0 million acres) (Murray and Reeves, 1977, p. 24) and in 1970 (8.7 million acres) (Murray and Reeves, 1972, p. 22). Federal agricultural subsidy programs, such as Payment In Kind and the Set Aside Programs, contribute to the fluctuation of irrigated acreage from year to year; for example, about 500,000 acres were part of by the Set Aside Program during 1985 (Glenn Sawyer, California Department of Water Resources, oral commun., 1987).

During 1985, total water use for agriculture was 66.2 percent surface water and 33.8 percent ground water (fig. 4), but, for nonirrigation agricultural use, it was 79.6 percent surface water (159 Mgal/d) and 20.4 percent ground water. Nonirrigation agricultural use for livestock was about 200 Mgal/d in 1985 compared to 87 Mgal/d in 1980 (Solley and others, 1983, p. 14), 100 Mgal/d in 1975 (Murray and Reeves, 1977, p. 22), and 91 Mgal/d in 1970 (Murray and Reeves, 1972, p. 20). Livestock production has been stable since 1980 (Daniel Halverson, California Crop and Livestock Reporting Service, oral commun., 1987). The increase in this water-use category probably is due to different methods of estimating or classifying livestock in the 1985 report.

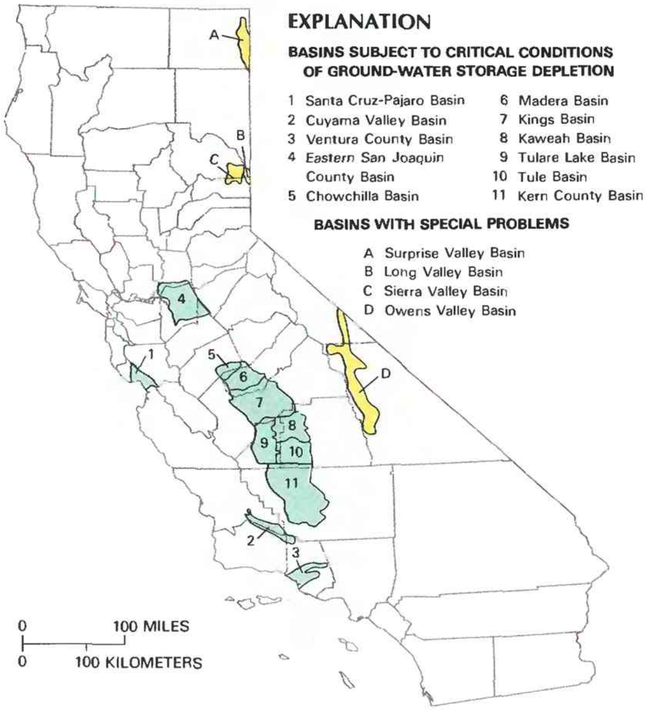


Figure 5. Basins subject to critical conditions of ground-water storage depletion and basins with special withdrawal, storage, or water-quality problems of local concern. (Source: Modified from California Department of Water Resources, 1980, p. 4.)

WATER MANAGEMENT

California has a wide range of water-rights laws. In some instances, water users have riparian rights, and reporting surface-water withdrawals is not required; in other instances, rights for surface and ground water have been set by a court of law, and withdrawal reports are required. Ground-water withdrawals are regulated only where (1) basins have been adjudicated, (2) the State Legislature has granted a local water district the power to tax pumpage, or (3) the water agencies in an area have agreed to self-regulation apart from any State regulation.

Many water agencies are responsible for surface-water management (U.S. Geological Survey, 1986, p. 165), and the number of agencies still is increasing because of continually expanding urban areas. The need for ground-water management also is increasing in response to demands. Areas subject to critical conditions of ground-water storage depletion (withdrawals in excess of recharge) and basins that have special withdrawal, storage, or water-quality problems of local concern (fig. 5) are requiring increased attention by water managers in the State (California Department of Water Resources, 1980, p. 4). The need for water-use information, therefore, has also increased. Legal resolutions typify the California water-management practices of the past and probably will continue unless an enforced statewide mandate for water management develops.

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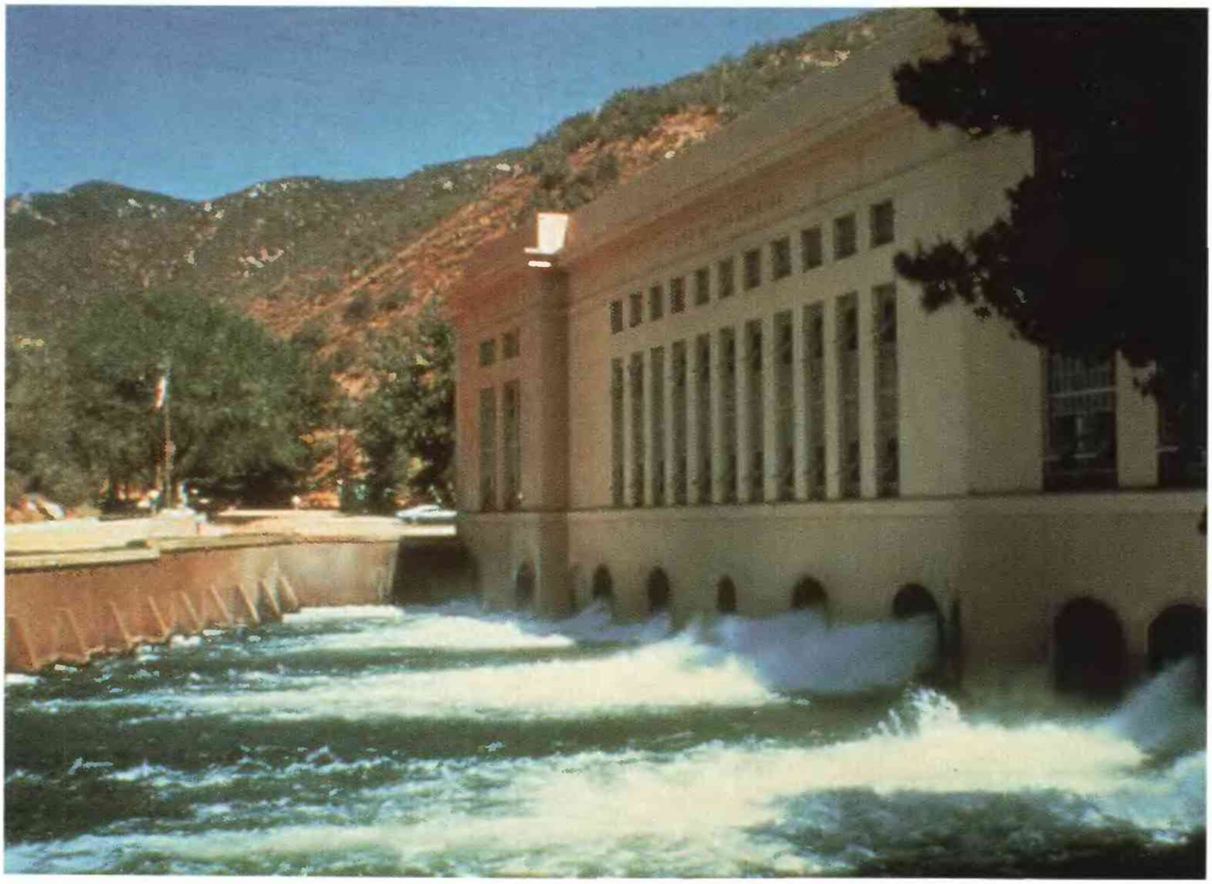

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Prepared by William E. Templin.

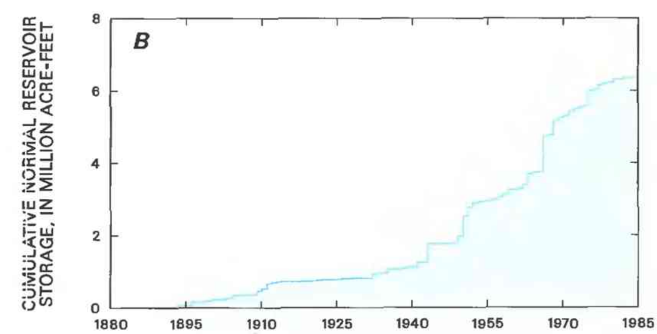
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Federal Building, Room W-2234, 2800 Cottage Way, Sacramento, CA 95825.

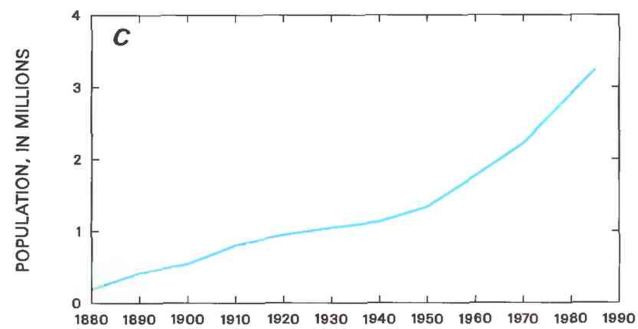
COLORADO
Water Supply and Use

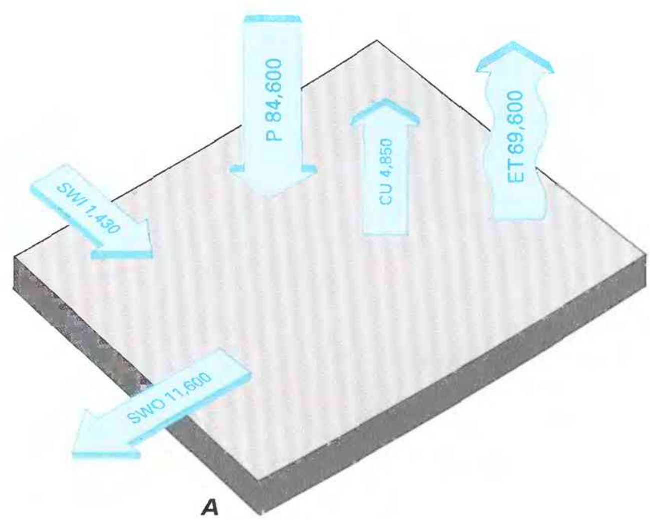
Colorado has been called "The Rooftop of the Nation" because it straddles the Continental Divide and contains more peaks higher than 14,000 feet than all the other States combined. The headwaters of four major rivers, the Colorado, the South Platte, the Arkansas, and the Rio Grande, rise within this mountainous terrain; rain and snow captured here help provide water for an area extending from Kansas to California. Still, only about 16,400 Mgal/d (million gallons per day) of the 86,000 Mgal/d received by the State is available for use; the remainder, about 81 percent (69,600 Mgal/d) returns to the atmosphere through evaporation or is transpired by natural vegetation (fig. 1*A*). Of the water available for use, about 4,850 Mgal/d is consumed within Colorado, and 11,600 Mgal/d leaves the State as surface-water outflow.

The western one-half of the State, where annual precipitation in the high mountains can exceed 60 inches, holds three-fourths of the State's surface-water resource but contains only 10 percent of the State's population. The eastern one-half of the State, which includes the populous Front Range urban corridor, must rely on scarce rainfall (8–16 inches per year), ground-water resources, and water diverted from the western part of the State to fulfill its water demands. Most demand for the principal water use categories discussed here (domestic and commercial, industrial and mining, thermoelectric power, and agricultural) is in the eastern one-half of the State.

The mismatched patterns of water availability and water demand lead to many of the principal water issues in Colorado. Diversion of water from the western part of the State to the eastern part has never been popular among west-slope residents and is becoming increasingly expensive as prospective project sites become fewer, more distant, and smaller in yield. At the same time, there is concern that the available water in western Colorado be put to beneficial use within the State rather than default to downstream users. In eastern Colorado, water debate is focused on what the magnitude of future water demand will be and whether new measures such as conservation and conversion of water rights from agricultural to municipal use are necessary and sufficient to meet this demand.







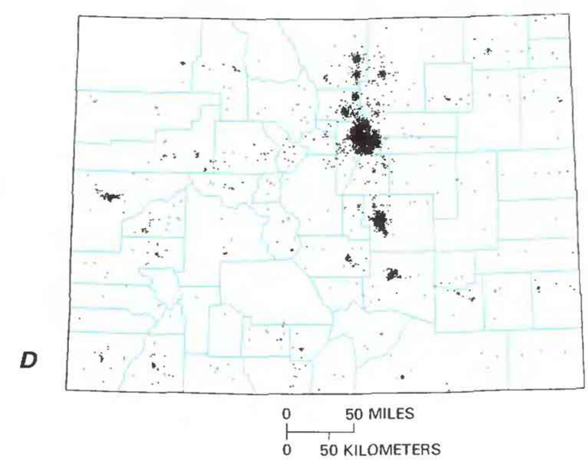


Figure 1. Water supply and population in Colorado. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Data from Colorado State Climatologist and U.S. Geological Survey files. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

HISTORY OF WATER DEVELOPMENT

The first water development in Colorado occurred in 1787, the year the Constitution of the United States was drafted in Philadelphia (Colorado Water Conservation Board and Colorado Agricultural and Mechanical College, 1952, p. 14). In cooperation with local Comanche Indians, a group of farmers, which were sent to Colorado from the Spanish Province of New Mexico, built a ditch to take water from the St. Charles River near the present city of Pueblo (Pueblo County). The project was discontinued after 2 years for political reasons.

In 1846, John Hatcher built a ditch from the Purgatoire River (primarily in Las Animas County) in the southeastern part of the State to irrigate 60 acres near the present city of Trinidad (Las Animas County). This became the first sustained irrigation project in Colorado, and eventually the water right was recognized by adjudication but with a priority date of 1864; the most senior water right in Colorado (date of 1852) is for Culebra Creek, a stream in Costilla County.

Following the Gold Rush of 1859, a great influx of people familiar with the practice of irrigation in New Mexico came into Colorado and constructed extensive irrigation works on several rivers in south-central Colorado and, to a lesser extent, along streams in northern Colorado. The development in the south was so extensive that average summer flow of the Purgatoire River, for example, was appropriated completely by 1864.

Water development in the South Platte River basin was begun in 1870 by a large group of settlers from New York under the leadership of N.C. Meeker (Maass and Anderson, 1986, p. 290). Known as the Union Colony, they established the present city of Greeley (Weld County). Two major canals were constructed from the Cache La Poudre River (primarily in Larimer County) to irrigate land around Greeley. Four years later, another group, the Fort Collins Colony, began diverting water upstream from the Union Colony's water supply. During the dry year of 1874, competition for use of the diminished water supply caused conflict between the two colonies. The Union Colony sought to have a law enacted that would recognize and protect their senior water use. The Fort Collins group became supporters of this idea when their water use was threatened by the construction of another large canal upstream from their own diversion point. These conflicts led to a provision in the first State Constitution (1876, Article XVI, Section 6), which stated "the right to divert the unappropriated waters of any natural stream to beneficial uses shall never be denied. Priority of appropriation shall give the better right as between those using water for the same purpose."

During the 1880's, water resources were developed by out-of-State corporations that had sufficient capital to build large canal systems for irrigation of extensive areas of bench lands. Although most of these ventures failed financially within a few years at considerable losses to the investors, almost all were reorganized later by farmers as mutual irrigation companies.

From 1880 to 1910, irrigated crops began to include alfalfa, potatoes, and beets, which required a longer irrigation season than hay and small grains. For this reason and because irrigation water demand in general began to exceed the resources of natural streamflow, many small reservoirs were constructed to store springtime flood flows. Innovative irrigation companies also began to construct ditches to import water from adjacent basins. At the turn of the century, these projects were of modest size and consisted of collection ditches at high altitudes leading through mountain passes across interbasin divides.

The South Platte River basin experienced such water shortages by the 1930's that large transbasin imports began to look attractive. However, even the combined resources of all irrigation interests were insufficient to develop a project of the magnitude and the cost that would be necessary to provide adequate supplemental water to the basin. At this stage, developers began looking to the Federal Government for financial and technical assistance. In 1937, the State Legislature passed the Colorado Water Conservancy District Act, which established the Northern Colorado Water Conservancy District. Because the District was given authority to assume bonded indebtedness and to levy *ad valorem* taxes, the District then was able to contract with the U.S. Bureau of Reclamation for the planning, design, and construction of a major transbasin water-import project. The resulting Colorado–Big Thompson Project now carries about 300,000 acre-ft/yr (acre-feet per year) of Colorado River water through a 13-mile tunnel under the Continental Divide into the Big Thompson River (Larimer County). Ten reservoirs also were eventually built as part of this project. Total reservoir storage capacity in Colorado increased from 1.2 million acre-ft (acre-feet) in 1945 to 6.2 million acre-ft in 1975 (fig. 1*B*); structures were built by the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, large public water suppliers, and other groups.

After World War II, Colorado's population began to grow rapidly (fig. 1*C*). Most of this growth was in the Front Range urban corridor, which is a north-south band in the central part of the State where the mountains meet the plains (fig. 1*D*). In response to increasing public-supply water demands, the cities of Aurora (a suburb of Denver), Colorado Springs, Denver, and Fort Collins constructed large projects to gather water through extensive collection systems on the west slope and to transport it to the eastern part of the State through transmountain canals and tunnels. In 1958, the Southeastern Colorado Water Conservancy District was organized to import water for domestic, agricultural, and industrial uses in the Arkansas River basin. The Fryingpan–Arkansas project, which was undertaken in cooperation with the U.S. Bureau of Reclamation, now includes five reservoirs and is authorized to divert 69,200 acre-ft/yr of water to the Arkansas River basin. Before development, the South Platte River sometimes contained dry reaches within Colorado (Boyd, 1887, p. 81). However, the application of diverted surface water on lands for irrigation has resulted in ground-water return flows to the river that have supplemented natural base flow (Hurr and others, 1975, p. 17).

Ground water has long been used in Colorado for public supply and for domestic and industrial uses. With the development of efficient pumps, engines, and electric motors, pumping of ground water for irrigation increased rapidly from the 1930's until the 1970's. The number of irrigation wells in Colorado doubled between 1940 and 1950, doubled again between 1950 and 1960, and has increased at a slower rate since that time. About 1.5 million acres presently are irrigated by ground water.

WATER USE

Surface- and ground-water resources within Colorado are distributed unevenly (U.S. Geological Survey, 1985, 1986). The eastern one-half of the State, which lies in the Great Plains physiographic province, receives only 8 to 16 inches per year of rainfall. There, surface water is available primarily along the South Platte River, which flows eastward through the northeastern quadrant of the State, and along the Arkansas River, which flows eastward through the southeastern quadrant of the State. These two river basins contain about one-fourth of the State's available surface water. The relative paucity of surface water in this region is somewhat compensated for by the extensive High Plains aquifer along the eastern boundary of the State. The Denver Basin aquifer system, which is in the north-central part of the State, also provides usable water but in more limited quantities.

The western one-half of Colorado lies partly in the Southern Rocky Mountain physiographic province (the mountainous central spine of the State) and partly in the Intermontane physiographic province (the high basins and plateaus of the extreme western part of the State). In the mountains, surface water is abundant and well distributed. However, the major rivers that drain this region, the Colorado and its many tributaries and the Rio Grande, flow to the south and west toward increasingly drier country, and the availability of surface water becomes limited away from these major channels. The San Luis Valley aquifer system in south-central Colorado is the most productive source of ground water in the western part of the State.

Leading economic activities in Colorado (in order of importance) are manufacturing, agriculture, mining, and tourism. However, the leading use of water in the State is, by far, agricultural (92.2 percent), followed by domestic and commercial (5.4 percent), industrial and mining (1.5 percent), and thermoelectric power (0.9 percent). About 60 percent of the irrigated acreage, 90 percent of the manufacturing, and 83 percent of the State's population are east of the Front Range (Erickson and Smith, 1985, p. 7).

The geographic distribution of water withdrawals by county (fig. 2) reflects the interplay between water demand and water supply. Most western counties withdraw large volumes of surface water. In eastern Colorado, only those counties along the two major rivers withdraw large volumes of surface water. Ground water commonly is used where aquifers are shallow or large sustained yields are possible; counties overlying shallow alluvial aquifers (the South Platte and the Arkansas) or overlying other major aquifers (the High Plains, the San Luis Valley, and the Denver Basin aquifer systems) withdraw significant volumes of ground water. More water is withdrawn in Weld County than in any other because surface- and ground-water resources are available. Little water is withdrawn in mountainous counties, such as Gilpin, Mineral, and Teller, where surface water is available, but rugged terrain precludes intensive water use activities. In some counties, such as Elbert, Lincoln, and Kiowa, surface and ground-water resources are meager, and little water is withdrawn.

Among major river basins (fig. 3*A*), withdrawals are largest in the South Platte (2,320 Mgal/d) and in the Colorado Headwaters (2,260 Mgal/d) basins; however, 16 percent of the withdrawals within the South Platte basin is provided by importation of water from other basins (U.S. Geological Survey, 1986, p. 168). Similarly, 1,790 Mgal/d is withdrawn in the Upper Arkansas basin; however, 6 percent of this water is imported. About 98 percent of the surface water withdrawn west of the Continental Divide is used for irrigation. East of the Continental Divide, 86 percent of the surface water withdrawn is used for irrigation, and about 10 percent is used for public supply.

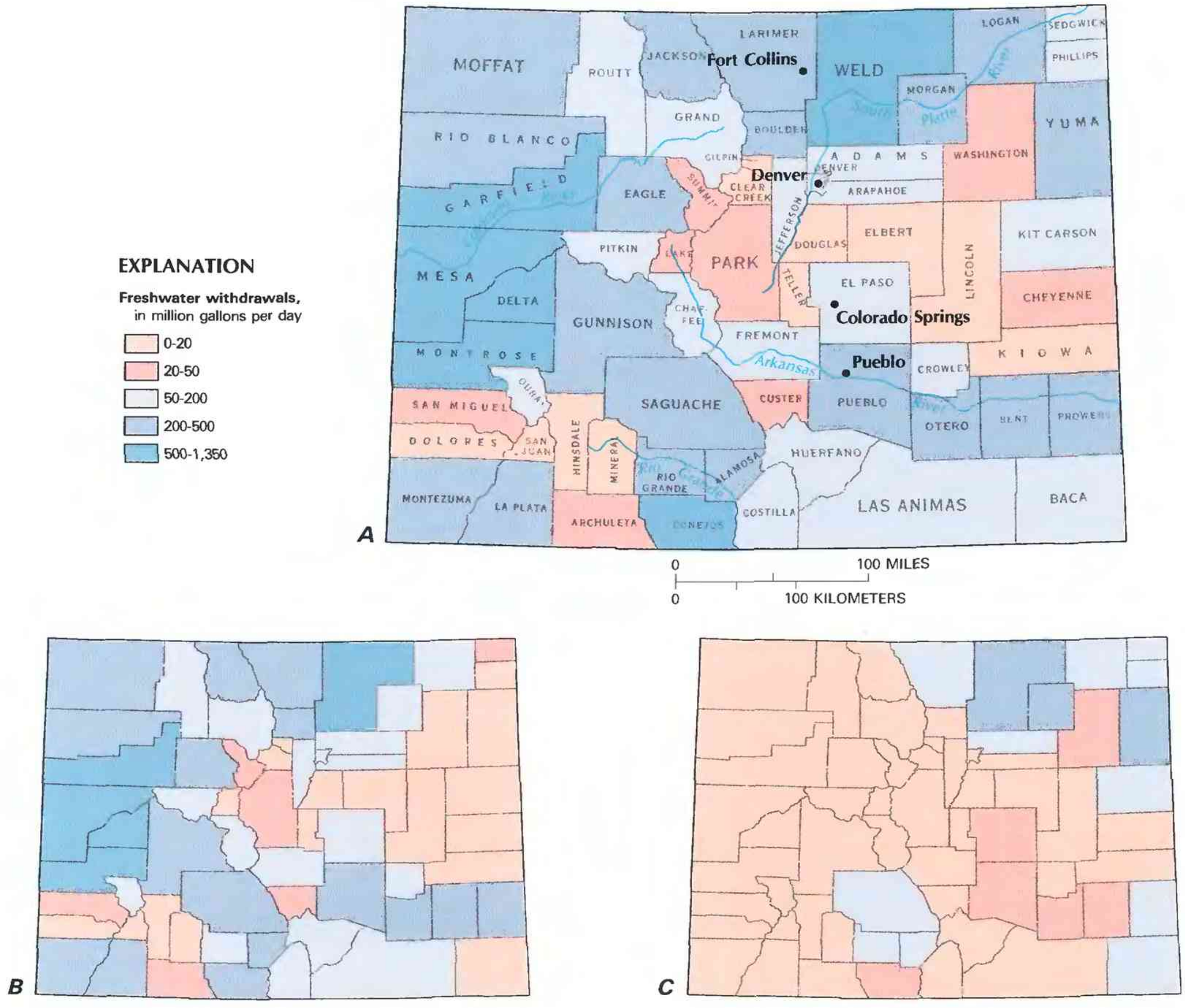
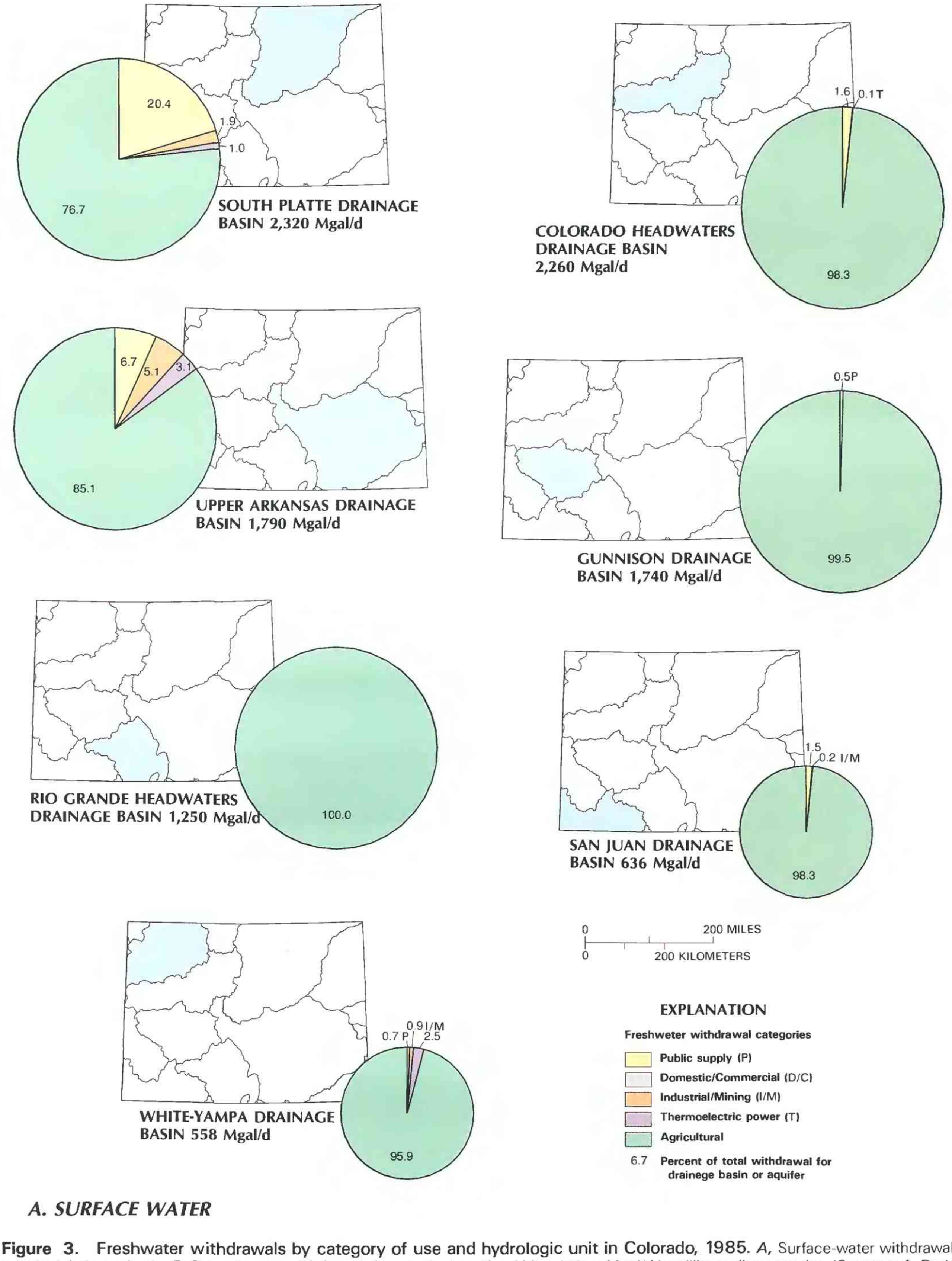


Figure 2. Freshwater withdrawals by county in Colorado, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Colorado, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files.)

The major aquifers (fig. 3*B*) also supply water primarily for irrigation; 99 percent of water withdrawn from the High Plains aquifer and 98 percent of water withdrawn from the San Luis Valley aquifer system are used for irrigation. The two principal alluvial aquifers, the South Platte and the Arkansas, provide water for multiple uses by the many towns along the rivers. The Denver Basin aquifer system and other aquifers (primarily local alluvial aquifers and deep or low-yield bedrock aquifers in western Colorado) primarily support uses other than agricultural.

The source, use, and disposition of 13,500 Mgal/d of water withdrawn in Colorado during 1985 are summarized in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. Not included in this total are saline water used in mining industries, water lost through reservoir evaporation, and instream use of water for hydroelectric power generation. The source data indicate that 83.0 percent of all freshwater used in Colorado during 1985 was from surface sources and 17.0 percent was from ground water. The data also indicate that public-supply systems withdrew 5.8 percent (651 Mgal/d) of the surface water and 3.7 percent (86 Mgal/d) of the ground water to sell to other users. The remaining withdrawals were made directly by the users (irrigation-ditch companies are not considered to be public-supply systems). Public-supply systems sold 95.8 percent (706 Mgal/d) of their water to domestic and commercial users, 2.4 percent (18 Mgal/d) to industrial users, and 1.8 percent (13 Mgal/d) to thermoelectric powerplants. Agricultural and mining water users are considered to be entirely self-supplied. The use data indicate that, among the four principal categories, agricultural use was predominant (92.2 percent of all use). About 82.8 percent (10,300 Mgal/d) of the 12,500 Mgal/d of agricultural water was surface water. The fact that this large volume of water is needed on a seasonal basis indicates how important water storage is to the water-supply system in Colorado. The disposition data in figure 4 indicate that 35.8 percent of all water withdrawn was consumed; the remainder was returned to water sources, primarily as return flows to surface channels or through infiltration to the ground-water table. Agriculture was the largest consumer of water (94.9 percent, or 4,600 Mgal/d), followed by domestic and

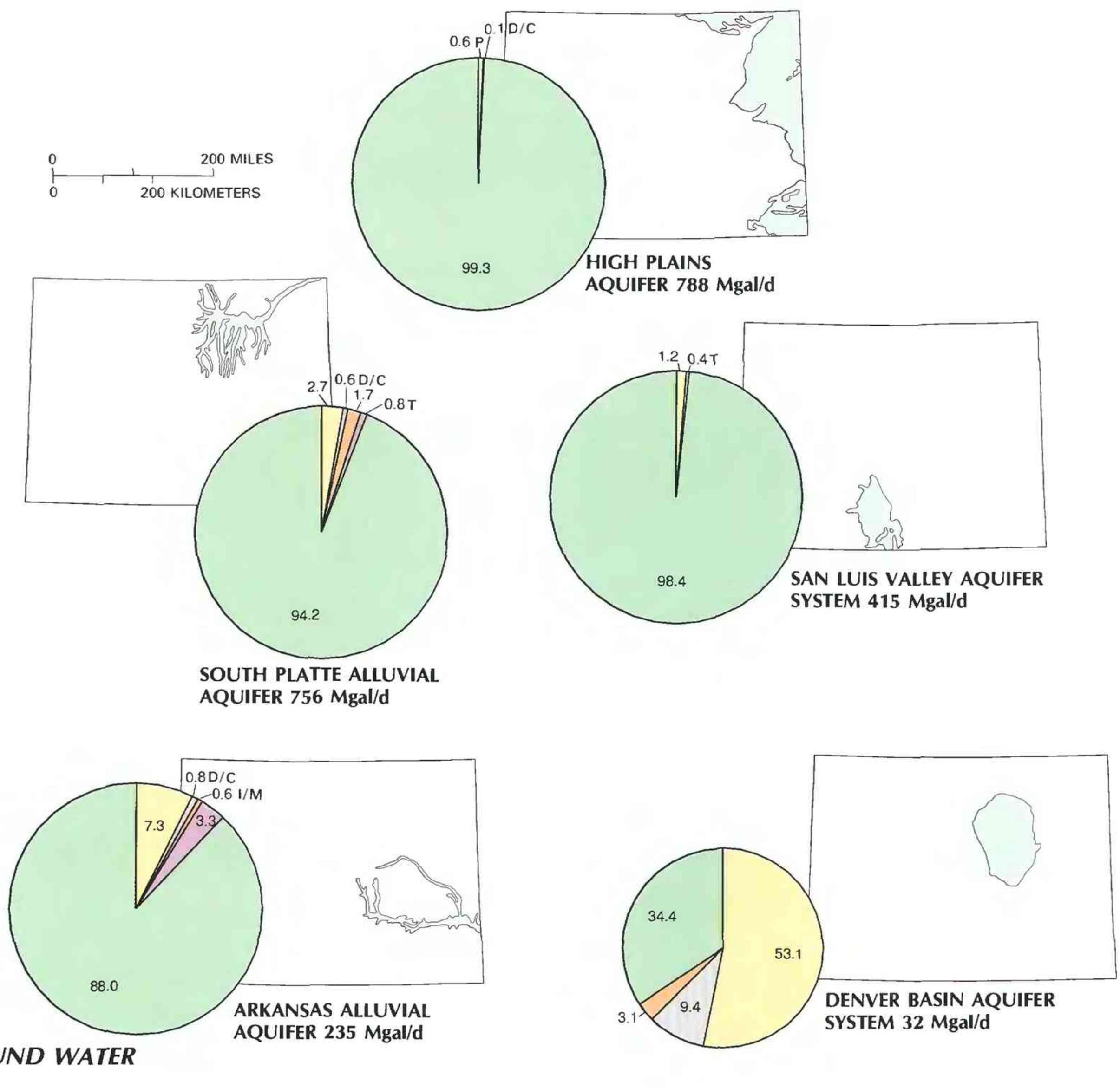


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Colorado, 1985—Continued.

commercial consumption (3.4 percent, or 166 Mgal/d); all other consumptive uses were negligible by comparison.

Evaporation from reservoirs is not included in figure 4 because it does not result from offstream withdrawal or use of water. However, a significantly large quantity of water is consumed by evaporation. During 1980, reservoir evaporation accounted for about 4 percent of all consumptive use in the Colorado River basin and was the second-largest consumptive use after agriculture (U.S. Bureau of Reclamation, 1981, p. 29).

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. About 750 public-supply systems in Colorado provide 70 percent of water used in the State for nonagricultural purposes. Withdrawals for public supply from 1950 to 1985 are shown in figure 5*A*. During this period, public-supply withdrawals increased from 170 to 737 Mgal/d; this increase reflects an increasing share of total withdrawals from 1.9 to 5.4 percent. The withdrawal of ground water has remained generally steady at about 12 percent of public-supply withdrawals, except for a slight decrease from 1970 to 1980. In general, the large metropolitan public-supply systems rely on surface water, whereas the smaller, rural suppliers use ground water. The decrease in ground-water withdrawals may have been due to expansion of the large metropolitan systems into suburban areas that previously had been supplied by ground water.

Most of the water imported into the Front Range area from western Colorado serves public-supply demand. As the population grows, the pressure for transmountain imports will continue. To protect the economic and the environmental future of the areas of water export, accommodations, such as compensatory storage and payment to the region of origin, are emerging. In recent years, public-supply systems also have examined alternatives to the traditional acquisition of surface water through large-scale diversion projects. These alternative strategies include purchase of agricultural water rights, trades of treatment-plant return flows for freshwater, reuse of water (Denver operates one of the world's largest water reuse demonstration plants), and encouragement of water-conservation practices, such as minimal water use landscaping.

DOMESTIC AND COMMERCIAL

Of all water used for domestic and commercial purposes, 96.6 percent (706 Mgal/d) is delivered by public-supply systems. During 1960, 86 percent of Colorado's population was served by public-supply systems; during 1985, 93 percent was served by public-supply systems. Still, 222,000 people in rural areas of Colorado have their own water supply, which for most is a well, but for a few is spring water, rainwater collected in cisterns, or water trucked in from an outside source. Commercial establishments that are self-supplied include motels, restaurants, schools, and dude ranches; commonly, they have their own wells and use and consume relatively small quantities of water. Two examples of commercial water use are hot-spring resorts and ski resorts. Hot-spring resorts in Garfield County use more than 4 Mgal/d of water in their pools and heating systems, although little of this is consumed. About 6 percent of the water withdrawn by ski resorts in Colorado to produce artificial snow is consumed by evaporation (Eisel, 1987).

Of the 731 Mgal/d of water used for domestic and commercial purposes during 1985, 473 Mgal/d was for domestic use, and

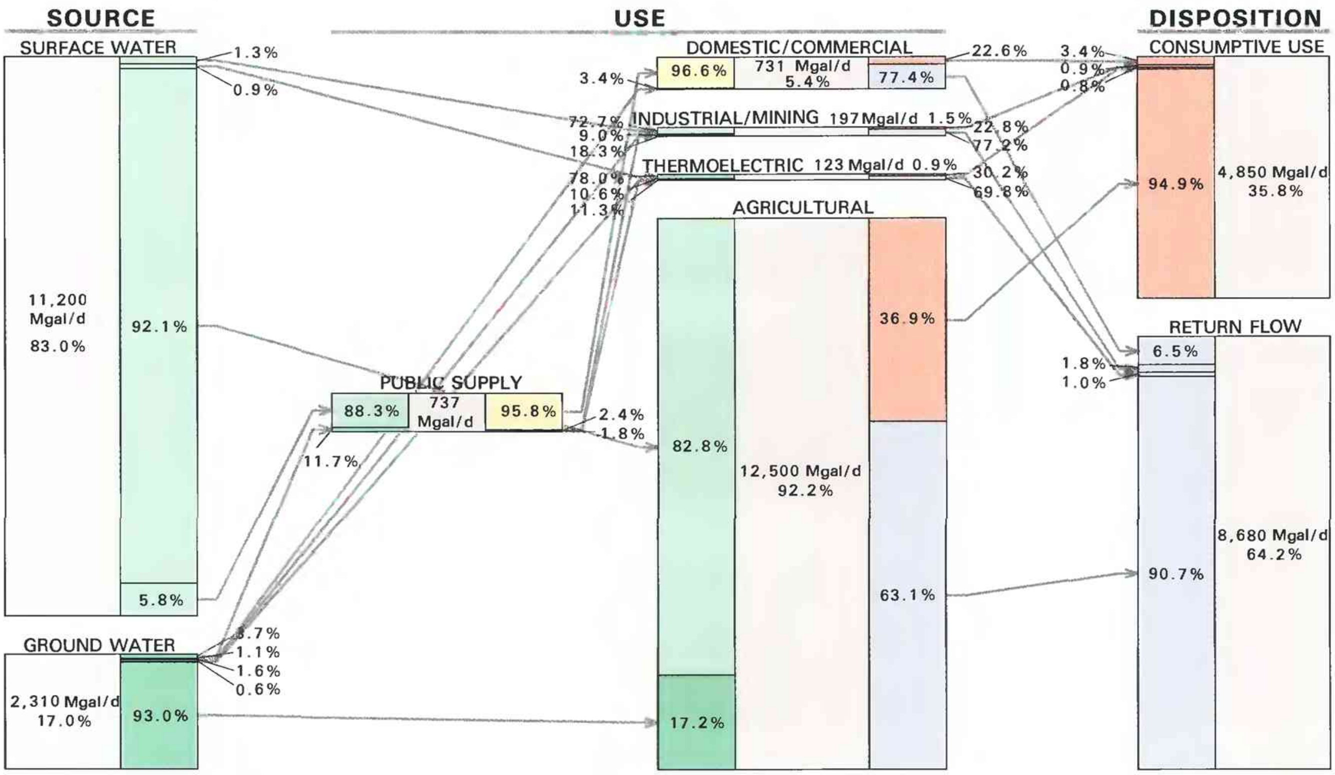


Figure 4. Source, use, and disposition of an estimated 13,500 Mgal/d (million gallons per day) of freshwater in Colorado, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

120 Mgal/d was for commercial use. The remaining 138 Mgal/d included public uses, such as fire fighting and municipal lawn watering, and losses in the delivery systems. The domestic water was used by about 3.2 million people at a rate of about 150 gal/d (gallons per day) per capita. Of this water, about one-half is used indoors and is minimally consumed, and one-half is used outdoors for lawn watering and is mostly consumed. The unconsumed water is returned to the natural system by way of sewage-treatment plants; the more thoroughly this water is cleaned, the more valuable it becomes to downstream users.

Industrial and Mining

The major industries in Colorado (based on employment) are nonelectrical machinery, food products, electric and electronic equipment, and publishing (University of Colorado Business Research Division, 1986, p. viii). Among these, the food-products industry uses the most water; included in this classification are beverage plants, produce-canning plants, and meat-processing plants. In recent years, the decline of the sugar-beet-processing industry has decreased water demand in the food-products industry. However, water used for industrial purposes has been fairly constant since the 1960's—less than 2.5 percent of total demand. During 1985, industry (excluding mining) used 138 Mgal/d of water, of which 28 Mgal/d was consumed. Older industries and facilities that require large amounts of water have tended to develop their own water supplies, but newer industries tend to purchase their water from public-supply systems.

Colorado began as a mining State and has witnessed booms and busts in mining throughout its history. Initially, gold, silver, zinc, lead, and copper were important; however, all these minerals were at peak production before 1940 (Erickson and Smith, 1985, p. 24). Since the 1950's, molybdenum and uranium have become the most important minerals, but their production also has declined in recent years. Similarly, the coal and oil industries grew during the oil embargo years of the 1970's but have decreased production as the world price of oil has decreased. The timing of cycles in this industry is difficult to predict; the large water demands foreseen during the 1970's for oil shale, coal-slurry pipelines, and coal gasification failed to materialize. The outlook could reverse quickly, however, as recent history has shown.

During 1985, the mining industry used 59 Mgal/d of freshwater, of which 17 Mgal/d was consumed. Included in withdrawals are dewatering of mines and evaporation from gravel-pit ponds, as well as production uses, such as dust control, slurry production, and process water. Not included in this data are saline ground-water withdrawals (32 Mgal/d) made in conjunction with oil production.

Thermoelectric Power

The 23 thermoelectric power generation plants in Colorado produced 26,500 GWh (gigawatthours) of net power during 1985. In addition, 27 hydroelectric powerplants in Colorado generated 2,400 GWh during 1985. Hydroelectric plants do not use water consumptively and essentially are instream users of water, so they are excluded from the data reported here. However, these plants need to be considered when estimating water demand because they have rights to and use about 7,300 Mgal/d of water that is not available for upstream consumption.

All the thermoelectric power generation plants are fossil fueled except for one nuclear-powered plant that did not generate power during 1985. The thermoelectric plants in Colorado are of a variety of types. Some are small diesel generators that use only small quantities of water in their cooling jackets. Some are "once-through" plants in which large volumes of water are withdrawn to pass through cooling structures once before being returned to the natural system and little water is consumed. Some are closed-system plants in which much less water is withdrawn than in once-through plants. Closed-system plants recycle the same water through their cooling facilities until it is essentially entirely consumed. Thermoelectric plants accounted for 0.9 percent (123 Mgal/d) of freshwater use during 1985; of this quantity, 30.2 percent (37 Mgal/d) was consumed. Most of the thermoelectric plants are near population centers, but some are near the west-slope coal mines that provide their fuel.

Agricultural

Agriculture has long been economically important to Colorado, and irrigators traditionally have held rights to most of Colorado's water. In 1982, 44 percent of the harvested cropland was irrigated (U.S. Bureau of the Census, 1984). Irrigation development in Colorado experienced bursts of growth from 1860 to 1910 and again from 1950 to 1970. Since 1970, the number of irrigated acres has been fairly static. In recent years, the location of irrigated acreage has shifted; fewer acres are irrigated in the western part of the State and along the Front Range, and more acres are irrigated in the San Luis Valley and in the High Plains of eastern Colorado. In 1985, about 3.4 million acres were irrigated (fig. 5*B*). Most irrigated acreage, 429,000 acres of corn, hay, barley, dry beans, and other crops, is in Weld County in the South Platte River basin. Weld County is the leading agricultural county in Colorado and in 1974 had the third-largest total agricultural sales in the Nation. Larimer and Morgan Counties in the South Platte River basin also have large areas of irrigated corn, hay, wheat, and barley. Jackson County in north-central Colorado is surrounded by high mountain ranges and contains large acreages of irrigated hay and pastureland. Livestock and livestock products compose 75 percent of the total farm sales in Colorado; livestock water use accounts for less than 1 percent of water withdrawals, but irrigation of pastureland and cropland to provide feed for the livestock accounts for a large part of total water use in the State. Large quantities of water are used for irrigation in the four-county area—Saguache, Rio Grande, Alamosa, and Conejos—in the Rio Grande basin, where barley, oats, and Red McClure potatoes are grown, and in three counties—Kit Carson, Prowers, and Yuma—in the High Plains area, where corn, wheat, and sorghum are specialties.

Ground- and surface-water withdrawals for irrigation from 1950 to 1985 are shown in figure 5*C*. Long-term trends in withdrawals may be masked by large annual fluctuations caused by variability in precipitation. However, ground-water withdrawals (primarily from the High Plains and San Luis Valley aquifers) generally have increased during this period. Surface-water withdrawals increased from 1955 to 1970 but may have stabilized in recent years. The maximum rate of surface-water withdrawals (about 11,000 Mgal/d) may represent a full-supply demand relative to the static level of irrigation development in western Colorado, where most supplies are from surface water.

Although 10,300 Mgal/d of surface water was withdrawn for irrigation during 1985, 36.9 percent (4,600 Mgal/d) actually was consumed. Total withdrawals are a cumulative summation of water being used repeatedly as it passes downstream. This recycling adds dissolved solids to the water as it infiltrates through soils back to streams. States within the Colorado River basin have adopted salinity standards for the Colorado River at various locations. Several salinity control projects have been initiated through the Colorado River Basin Salinity Control Act of 1974 to compensate for increases in salinity related to water development.

WATER MANAGEMENT

The system of water allocation in Colorado provides one of the best examples of free-market, prior-appropriation doctrine in the West. Water rights are granted on the basis of "first in time, first in right" and are transferable on the open market to the highest bidder. Water rights are not restricted to a single point of diversion, and application can be made to water courts to change the place and type of use.

The primary distinction relative to obtaining rights to water is whether it is tributary or nontributary. Tributary water is surface or ground water that is hydrologically connected (according to a specific legal definition) with surface water. There are few constraints on using nontributary ground water because nontributary withdrawals have small potential for injuring other rights. However, to obtain rights to tributary water, one must show that new withdrawals will not injure other senior water rights. A further distinction among types of water was made by the Groundwater Management Act of 1965. State lawmakers realized that certain aquifers already were being mined for water; that is, more water was being withdrawn than was being replenished by natural recharge. The Act allowed the establishment of designated ground-water basins, where ground-water mining was to be allowed, and instituted additional rules for granting new permits in these basins. Currently (1987), there are eight designated ground-water basins in Colorado. Groundwater Management Districts and the Colorado Groundwater Commission oversee water matters in these areas.

The State Engineer's Office of the Colorado Department of Natural Resources administers water rights through a network of water engineers and water commissioners who locally are responsible for seeing that water is distributed in accordance with the hierarchy of rights. Disagreements over water rights are handled within the judiciary branch by water judges. The water courts rule on new water-right applications and transfers of rights, give interested parties input into the process, and ensure that pre-existing rights are not injured by changes.

A second responsibility of the State is to ensure that the water resource available to Colorado is used to the fullest extent possible, which includes representing the interests of Colorado in interstate water matters. Nine interstate compacts apportion surface water flowing out of Colorado. Two of these compacts partition flows in the Colorado River basin. Depending on how these documents are interpreted, Colorado's share of Colorado River water is between 2,380 and 4,320 Mgal/d. About 1,600 Mgal/d currently is developed within Colorado; this quantity includes consumptive use, reservoir evaporation, and water export. The Colorado Water Conservation Board and three regional Water Conservation Districts have been established by the State legislature to promote water development. In addition, an enabling act allows the formation of Water Conservancy Districts and gives the Districts taxation powers to raise money for construction of specific water projects.

Beyond these two primary activities, the State has little authority to establish water policy. Three principal factors affect

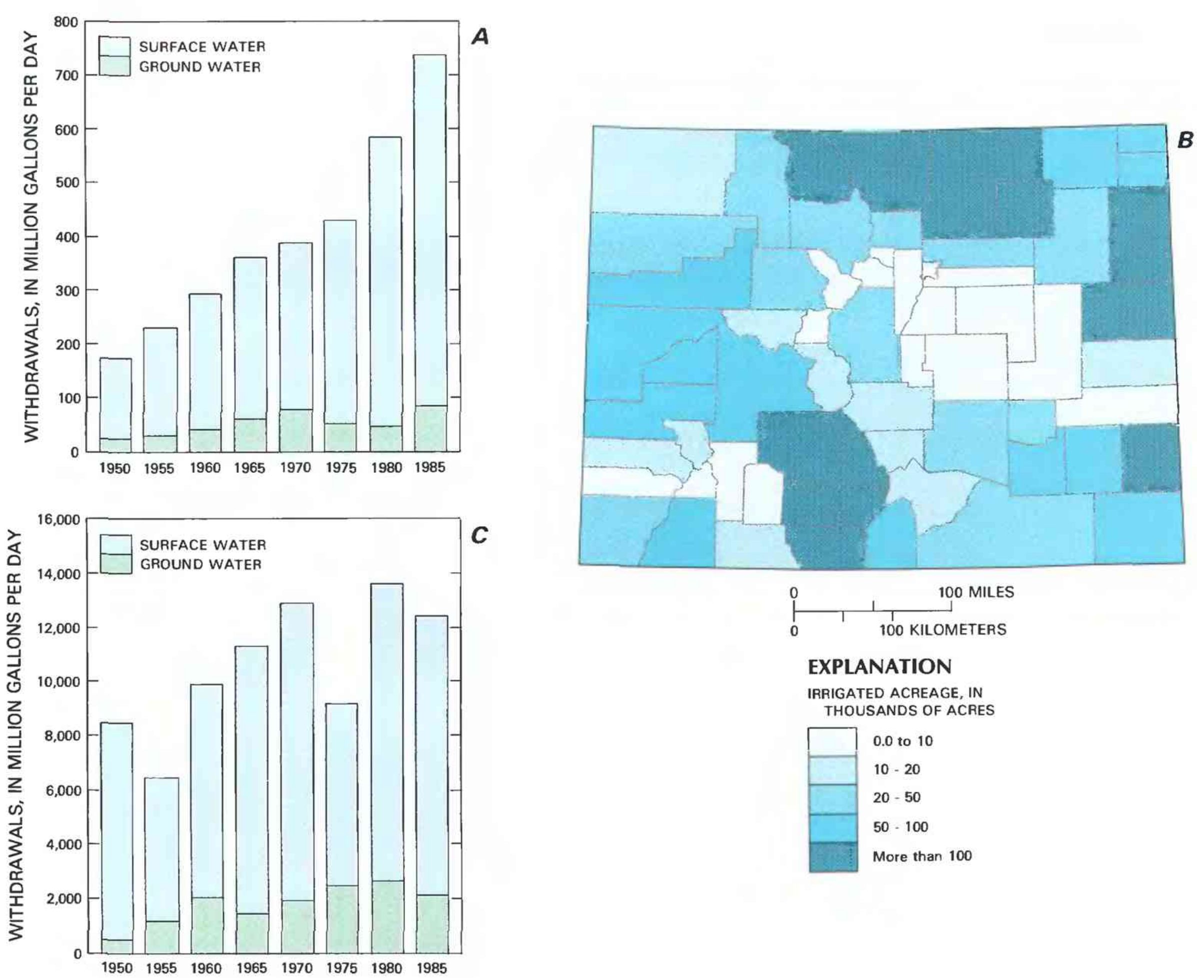


Figure 5. Selected water-use data for Colorado. *A*, Withdrawals for public supply, 1950 to 1985. *B*, Total irrigated acreage by county. *C*, Withdrawals for irrigation, 1950 to 1985. (Sources: *A*, *B*, *C*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System and U.S. Geological Survey files).

water use—free-market forces, water court rulings on water-rights disputes, and new well-permit evaluations by the State Engineer's Office. These mechanisms work well when considering offstream water use as a market-controlled commodity. However, instream uses of water, such as habitat protection and recreation, were not addressed in original appropriation doctrine. Recently, the Colorado Legislature gave the Water Conservation Board the authority to acquire instream water rights for preservation of the natural environment to a reasonable degree; however, preservation is the only instream water use currently recognized, and the State must acquire these rights through the established water-rights system.

The value of water on the open market can fluctuate widely; for example, the price of Colorado-Big Thompson project water was about $43/acre-ft in 1960, increased to about $3,000/acre-ft by 1980, then decreased to about $1,100/acre-ft in 1985 (Howe and others, 1986, p. 188). The marginal value of water for irrigation in this area is about $32/acre-ft. Consequently, most of the movement of water rights has been from agricultural to public supply. For example, in 1957, the first full year of Colorado-Big Thompson water deliveries, irrigators owned 85 percent of the water, but, by 1982, irrigators owned 64 percent of project water (Howe and others, 1986, p. 187).

Public-supply water demand within the Denver metropolitan area is projected to increase from about 275 Mgal/d in 1980 to about 700 Mgal/d in the year 2035 (U.S. Army Corps of Engineers, 1986, p. 255). This forecast is based largely on a predicted population increase from 1.4 million to 3.0 million people during this same period. These predictions have come under severe criticism by some who think the numbers are too large and by others who think the numbers are too small. Some believe that increased public-supply demands might be largely met by conversion of water from agricultural to public-supply use; others, however, believe the conversion would lead to unacceptable social and economic effects on the agricultural sector.

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Alfalfa in bloom near Sitt, Colorado. Photo courtesy of U.S. Department of the Interior, Bureau of Reclamation.

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Prepared by David W. Litke, U.S. Geological Survey; History of Water Development section by Norman A. Evans, Colorado Water Resources Research Institute

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Building 53, Denver Federal Center, Mail Stop 415, Denver, CO 80225

CONNECTICUT
Water Supply and Use

Connecticut has many different uses for its water resources, which appear to be abundant. Average annual precipitation of 47 inches exceeds average annual evapotranspiration by 23 inches, and inflow from adjacent States averages 12,000 Mgal/d (million gallons per day) (fig. 1A). Withdrawals and demands, however, are not distributed uniformly, but differ considerably geographically and temporally.

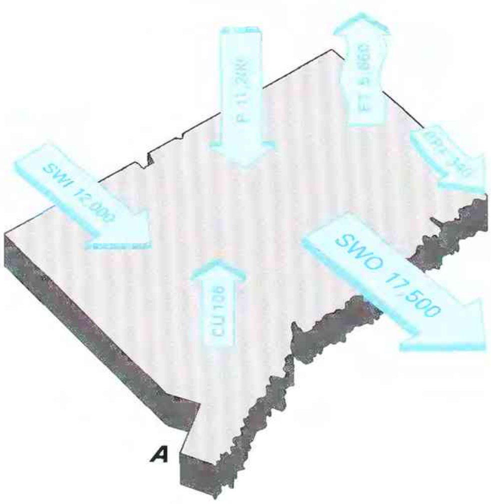
In 1985, about 1,200 Mgal/d of freshwater and 2,580 Mgal/d of saline water (total, 3,780 Mgal/d) were withdrawn from lakes, streams, estuaries, and aquifers in Connecticut. About 96 percent of this total was returned to a surface- or ground-water source after use. Cooling for thermoelectric power generation required withdrawals of more than 85 percent of this total.

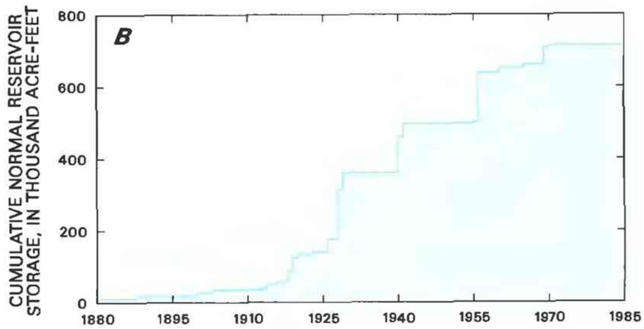
Public-supply systems served about 84 percent of the State's population and delivered 362 Mgal/d of freshwater to users. The remaining 16 percent of the population was self-supplied from ground-water sources. Domestic and commercial consumptive use accounted for 69.8 percent (74 Mgal/d) of the total freshwater consumptive use. Industrial and mining freshwater withdrawals and deliveries totaled 141 Mgal/d. Agricultural withdrawals amounted to less than 1 percent (11 Mgal/d) of total water withdrawals, but the consumptive use of 40.5 percent (4.5 Mgal/d) was the largest percentage of any category.

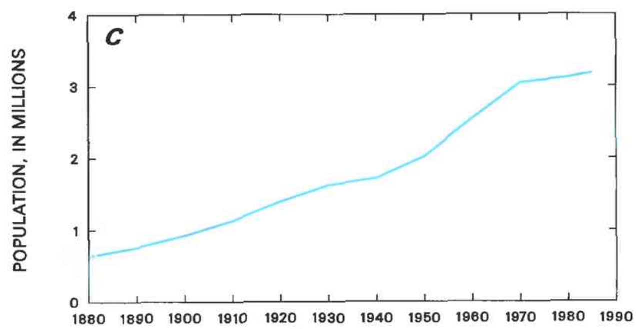
Although the State's water supply is abundant, it is not unlimited. Procedures are underway to protect aquifers and recharge areas. Seven management areas have been delineated, and committees are being formed to examine and coordinate development of public supplies in these areas. State officials are aware that the development of water supplies must be balanced and integrated with all other water uses and related land uses.

HISTORY OF WATER DEVELOPMENT

Water has been significant in Connecticut's development. Early settlers along the coast and in the Connecticut River valley used large rivers—the Connecticut, the Thames, and the Housatonic—as routes for trade and transportation. Tributaries flowing into these rivers provided power for local gristmills, which were the center of social life in these communities. The first gristmill in Connecticut was constructed in 1637, and, as the population increased, gristmills and sawmills became common along Connecticut streams (Favretti, 1976, p. 18). Population continued to increase, expanding into the eastern and western highlands, where rivers, such







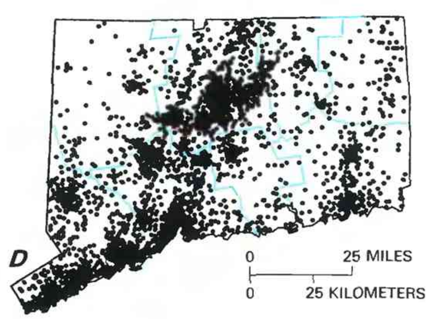


Figure 1. Water supply and population in Connecticut. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System; Hunter and Meade, 1983. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

as the Quinebaug, provided power for the mills of many hilltop farming communities.

Early industries, which relied almost entirely on water for mechanical energy, tended to cluster near water-power sites. Communities expanded around these sites and increased in number as a result of the Industrial Revolution. In the mid-1800's, there were 203 mill towns in Connecticut (Tedone, 1982, p. 57). Seymour was the first community in America entirely planned around water power (Martin, 1951, p. 146). An 1864 law gave textile mill developers the right to condemn private property to build dams and millponds; essentially, these private citizens had been given the right of eminent domain (Lewis and Harmon, 1986, p. 93). After the Civil War, steam and, later, electricity began to make inroads as sources of industrial power in Connecticut. In 1891, a hydroelectric powerplant was built on the Farmington River at Rainbow Falls in Hartford County. The 11-mile-long transmission line to Hartford was an innovation, and the plant soon became a research center for development of hydroelectric power generation and transmission (Studley, 1982, p. 95). However, in 1900, more than 50 percent of industrial energy was still from mechanical water power.

The Connecticut River became the first river in North America to be developed for navigation by construction of dams, locks, and canals (Martin, 1951, p. 142). The Farmington Canal, which traversed the State from southern present-day New Haven County to northern Hartford County, was opened in 1828. This canal ultimately connected New Haven to Brattleboro, Vt., and opened central Connecticut to water transportation. The Enfield Canal at Enfield Rapids in Hartford County opened in 1829 and allowed navigation through the first natural barrier on the Connecticut River. Both canals soon were replaced by railroads, although the Enfield Canal still is used for water power.

Community water-supply systems began to be developed in the mid-1800's. In the large cities of Bridgeport, Hartford, and New Haven, fire protection, not drinking-water supply, was the main impetus behind the construction of water systems (Minkus, 1974, p. 217).

During the 1900's, an increasing amount of water was stored behind dams (fig. 1*B*) to satisfy demands for power, water supply, and recreation for an increasing population (fig. 1*C*). From the mid-1910's to the late 1920's, storage in large reservoirs increased 1,100 percent. The Rocky River hydroelectric plant, constructed in 1928, was the first large pump-storage facility built in the United States (Studley, 1982, p. 99); its construction formed Lake Candlewood, the largest lake in Connecticut. The largest water-supply reservoir, the Barkhamsted Reservoir, was created in 1940 with the construction of the Saville Dam. Since 1955, 14 flood-detention reservoirs and 1 multipurpose reservoir have been built by the U.S. Army Corps of Engineers. Presently (1987), Connecticut has more than 3,000 dams, many of which are remnants of efforts to stabilize streamflow for mechanical hydropower.

Ground water, obtained from springs and hand-dug wells, was used initially for domestic and commercial supplies. In a successful public-supply venture in Bridgeport in 1818, spring water was transported 1.5 miles through wooden pipes for sale to ships restocking at the docks (Minkus, 1974, p. 217). As modern drilling equipment began to be used more and more, towns overlying stratified-drift and favorable bedrock aquifers began to develop these supplies. Ground water was used extensively in the New Haven area until the 1940's, when saltwater intrusion forced the development of other supplies (Mazzaferro and others, 1979, p. 69).

Continual expansion of the nonurban population has increased the demand on ground-water supplies. Currently (1987), contamination from pesticides, industrial wastes, and landfill leachate is a major concern, and the State has implemented numerous new programs to abate and prevent ground-water contamination (Connecticut Department of Environmental Protection, 1987a, p. 1).

WATER USE

Although Connecticut has abundant water resources, they are not uniformly distributed, and supplies are not always near the centers of demand. Rates of withdrawal from reservoirs, streams, and aquifers vary considerably. Freshwater withdrawals are larger in the more densely populated regions (fig. 1*D*), where domestic, commercial, and industrial demands for water are greatest. For comparative purposes, regional differences in 1985 freshwater withdrawals are shown in figures 2 and 3.

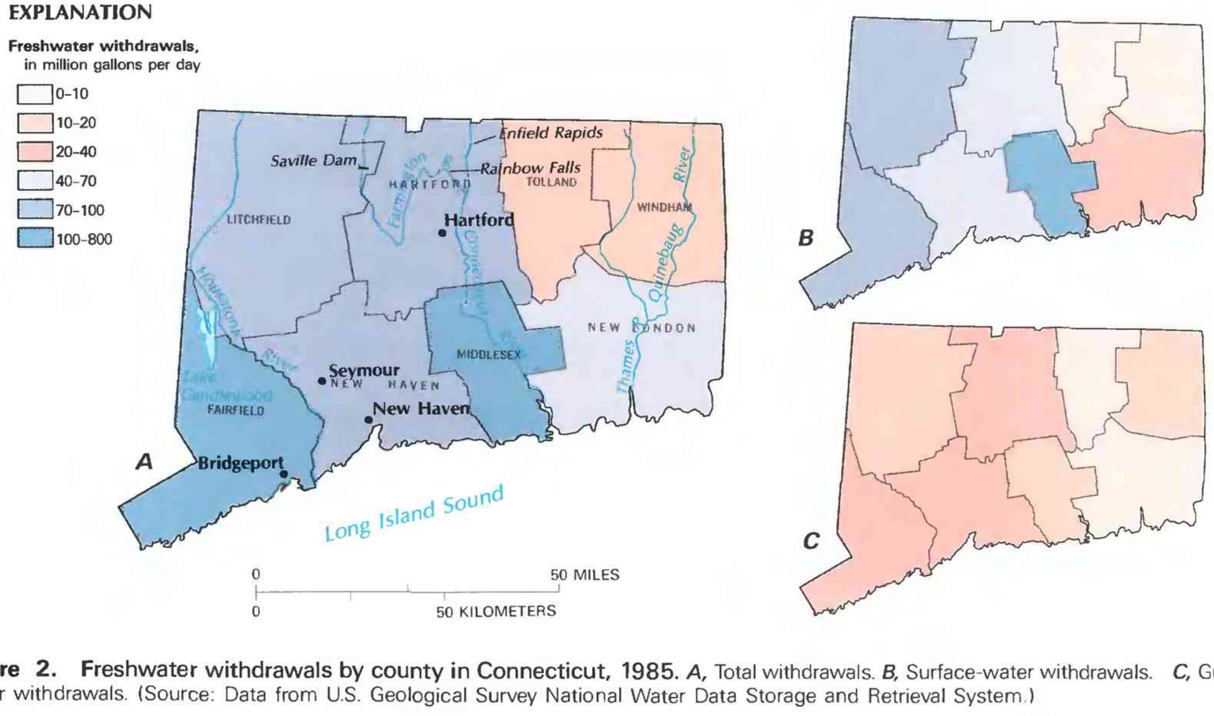


Figure 2. Freshwater withdrawals by county in Connecticut, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Total freshwater withdrawals in the five western counties far exceed those in the three eastern counties (fig. 2*A*), primarily because of the population distribution. Industrial, commercial, and residential development is concentrated within a corridor extending from the southwestern corner of Fairfield County along the coast, through New Haven County, and then northeastward through Hartford County (fig.1*D*). Two western counties (Litchfield and Middlesex) are not in this corridor but supply it with water and electric power.

Fresh surface-water withdrawals by county are shown in figure 2*B*. In 1985, the largest withdrawals in four of the five western counties (Fairfield, Hartford, Litchfield, and New Haven) were from public-supply reservoirs, whereas cooling water for thermoelectric power constituted the largest withdrawal in the fifth county, Middlesex. The major surface-water withdrawals in two of the three eastern counties also were for public supply. In Windham County, the largest withdrawals were for self-supplied industrial use, but this reflects a lack of other types of large surface-water withdrawals rather than extensive industrialization.

Fresh ground-water withdrawals by county are shown in figure 2*C*. Ground-water withdrawals exceed those from surface-water sources in only two of the counties—Tolland and Windham. Public supply was the major type of ground-water withdrawal in four of the counties, whereas the largest ground-water withdrawals in Fairfield, Litchfield, and Tolland Counties were for self-supplied domestic and commercial use. The largest ground-water withdrawals in Windham County were for agriculture.

The State has two major drainage basins—the Connecticut and the Connecticut Coastal (fig. 3*A*). Most withdrawals in the Connecticut basin were used for cooling water at the two active thermoelectric power generating stations along the Connecticut River (694 Mgal/d). Public-supply withdrawals were the most prevalent in the Connecticut Coastal basin, especially in the densely populated southwestern part of the State.

Connecticut has two major types of aquifers—unconsolidated stratified drift and bedrock (fig. 3*B*). Stratified-drift aquifers overlie the bedrock and are the most productive in the State (U.S. Geological

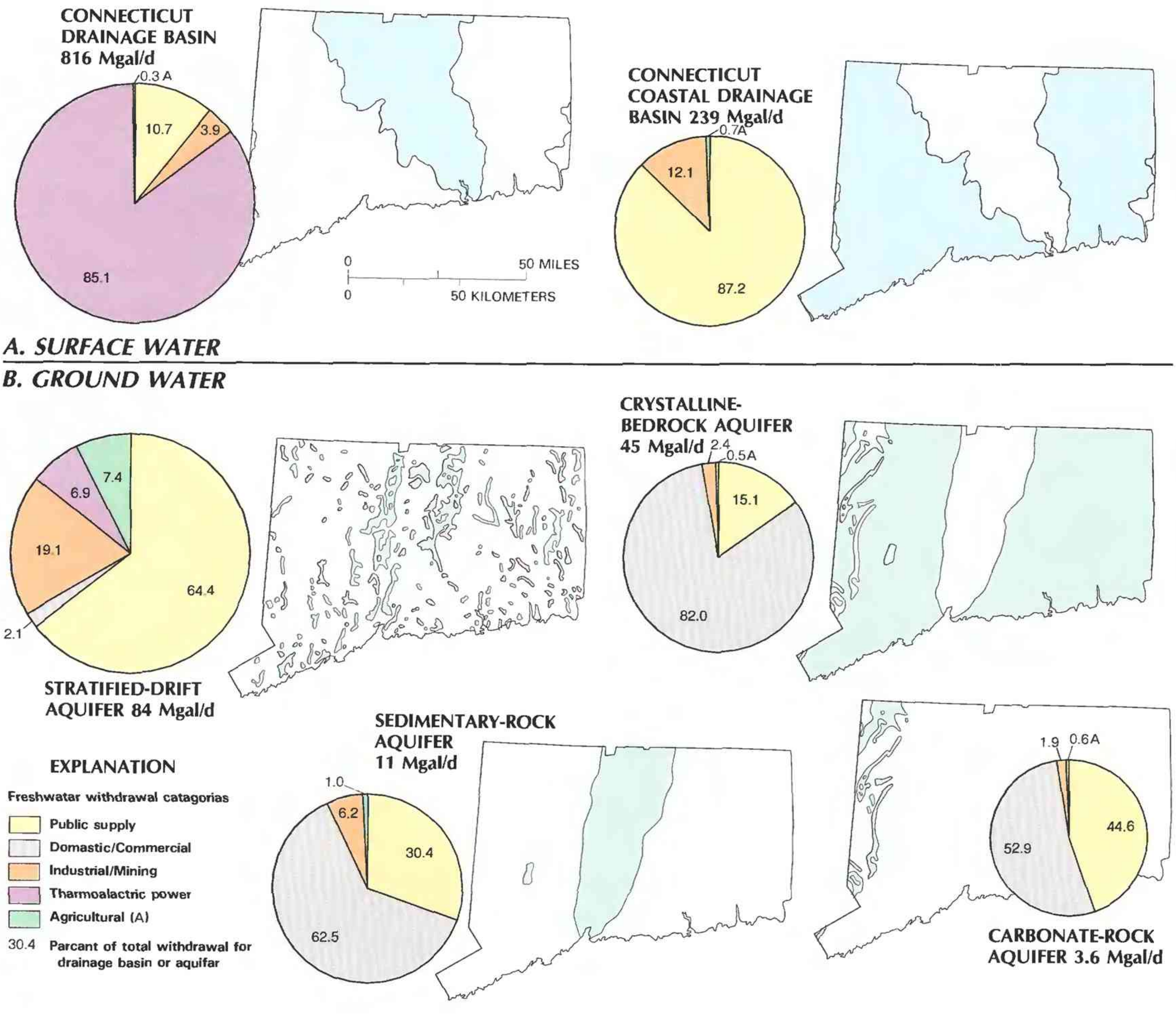


Figure 3. **Freshwater withdrawals by category of use and hydrologic unit in Connecticut, 1985.** *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files, Hartford office; and Water-Supply Shared Data Base, Connecticut Department of Environmental Protection.)

Survey, 1985, p. 161). Most large public-supply and industrial ground-water withdrawals are from these aquifers. The largest ground-water withdrawals are for public supply in the Hartford area.

Connecticut has three bedrock aquifers—crystalline bedrock (noncarbonate rocks), sedimentary rock (sandstone and shale), and carbonate rock. Crystalline-bedrock aquifers (noncarbonate), which have the largest areal extent of any aquifer type, are the major source of domestic and commercial self-supplied water, especially in southwestern areas that lie outside of public-supply-service areas. The central lowlands are underlain by the sedimentary-rock aquifers. Public suppliers distribute water from surface-water and stratified-drift sources to much of this area. Domestic and commercial self-supplied users in the northwestern part of the lowlands put the largest demand on the sedimentary-rock aquifers. Carbonate-rock aquifers underlie sections of the western part of the State. Public-supply withdrawals and self-supplied domestic and commercial withdrawals are about equal in magnitude in the southern part of the carbonate-rock aquifers and account for the greatest demand.

The source, use, and disposition of freshwater in Connecticut are shown diagrametrically in figure 4. The quantities of water given in the figure and elsewhere in this report may not add to the totals indicated because of independent rounding. In 1985, ground water accounted for 12.0 percent (144 Mgal/d) and surface water accounted for 88.0 percent (1,060 Mgal/d) of all offstream freshwater withdrawals. Freshwater either was withdrawn directly by homeowners, businesses, and industry (self-supplied users) or was withdrawn by public suppliers. Withdrawals for public supply from 250 surface-water sources and 1,500 wells comprised 28.1 percent (296 Mgal/d) of the surface water and 45.7 percent (66 Mgal/d) of the ground water withdrawn in Connecticut. Of the total offstream freshwater withdrawals, 28.9 percent (346 Mgal/d) was used for domestic and commercial purposes, 11.7 percent (141 Mgal/d) was used for industrial and mining purposes, 58.5 percent (701 Mgal/d) was used by thermoelectric powerplants, and 0.9 percent (11 Mgal/d) was used for agricultural purposes. Freshwater return flows to a stream or ground-water source after use amounted to 91.2 percent of withdrawals (1,090 Mgal/d). The remaining 8.8 percent (106 Mgal/d) was consumed by evaporation, transpiration, and incorporation into manufactured products.

Transportation and mechanical water power were once thought of as the only important instream uses of water in Connecticut. This outlook, however, has changed significantly. Navigation, hydroelectric power generation, waste assimilation, water-based recreation, and aquatic habitat are now considered to be important instream uses. Hydroelectric power generating stations produced 276 GWh (gigawatthours) of electricity, or 10 percent of all electric power generated in Connecticut in 1985. They also constituted the single largest measurable water-use category. The 4,150 Mgal/d used by hydroelectric plants is almost 3.5 times the total offstream use of freshwater summarized in figure 4.

Public Supply

Public-supply systems withdraw water, treat it, and distribute it to users. In 1985, public-supply systems provided water to about 2.7 million of the 3.2 million people in Connecticut. Total withdrawals by public supply were 362 Mgal/d, of which 81.9 percent (296 Mgal/d) was surface water and 18.1 percent (66 Mgal/d) was ground water (fig. 4). Public-supply deliveries were primarily for domestic and commercial purposes (82.5 percent). Water referred

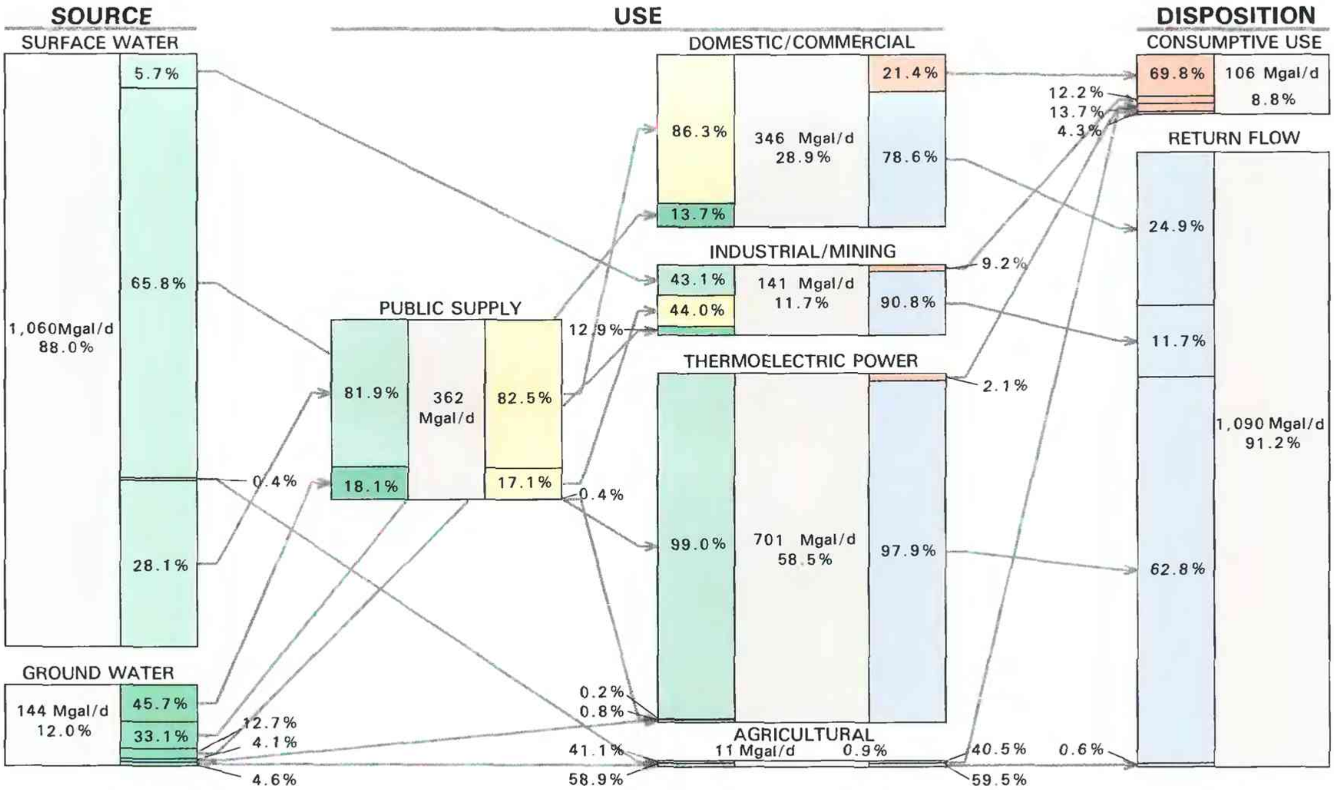


Figure 4. *Source, use, and disposition of an estimated 1,200 Mgal/d (million gallons per day) of freshwater in Connecticut, 1985.* Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

to as nonrevenue water, which was equivalent to 72 Mgal/d, also is included in the category of domestic and commercial use of figure 4. Nonrevenue water generally is water used by public suppliers for system and source maintenance, used for fire protection, and lost through leakage and main-line breaks. Excluding nonrevenue water, actual deliveries to domestic and commercial customers amounted to 227 Mgal/d—a combined per-capita use of 88 gal/d (gallons per day). Deliveries to industrial customers were 62 Mgal/d (17.1 percent), and sales of water to thermoelectric powerplants for noncooling purposes amounted to 1.3 Mgal/d (0.4 percent).

From 1955 to 1985, Connecticut's population increased nearly 45 percent (fig. 1*C*), and public-supply systems met demands by expanding reservoir and ground-water supplies (fig. 1*B*). Concurrently, withdrawals by public-supply increased 45 percent, from 250 (MacKichan, 1957, p. 13) to 362 Mgal/d. During the past 30 years, surface-water withdrawals by public suppliers increased from 240 to 296 Mgal/d, and ground-water withdrawals increased from about 10 to 66 Mgal/d. As an alternative to surface water, ground water has replaced several public-supply reservoirs that are no longer in use because of the considerable cost of treatment associated with meeting the Federal Safe Drinking Water Act. Most of the increase in demand for public supplies occurred before 1975 when rates of population and industrial growth were much larger than they are today. In fact, overall demand has remained relatively constant during the past 10 years, yet moderate increases related to continued residential and commercial development can be expected.

Demand for public supplies and the rates of surface- and ground-water withdrawals, which vary with the season, are largest during the summer. In Connecticut, summer demands are greatest because of additional outdoor water use and increased population at many lakeside and shoreline communities. In 1985, surface- and ground-water withdrawals were 405 Mgal/d in July as compared to 320 Mgal/d during the winter; ground-water withdrawals were 75 Mgal/d in July and 45 Mgal/d in December.

Connecticut has more than 600 public-supply systems, of which nearly 100 provide water service to at least 1,000 people. These systems collectively furnish water to 95 percent of the people using public supplies; many of the systems rely primarily on surface water. For example, nearly 400,000 people served in Hartford County depend on fresh surface water withdrawn from the upstream part of the Farmington River in Litchfield County. In Fairfield and New Haven Counties, two public suppliers primarily furnish surface water to 360,000 and 380,000 people, respectively. Each of these public-supply systems provides water service in at least 10 towns and sells additional water to other public suppliers through interconnections. The remaining major systems typically provide water to between 1,000 and 100,000 people in one or two towns. More than 40 of these systems depend entirely on ground water and generally serve between 1,000 and 20,000 people. Most systems serving more than 20,000 people use surface water supplemented by ground water.

Domestic and Commercial

Domestic and commercial use during 1985 was 346 Mgal/d (fig. 4). Public-supply systems delivered 86.3 percent (299 Mgal/d), whereas self-supplied ground-water users withdrew the remaining 13.7 percent (48 Mgal/d). Self-supplied surface-water withdrawals were not of significant quantity to be included in this total. Consumptive use was 21.4 percent (74 Mgal/d) of the water withdrawn and delivered.

Public-supply systems served 84 percent of the State's population at a rate of 178 Mgal/d—a per capita domestic use of 66 gal/d (gallons per day). Self-supplied systems served the remaining 16 percent of the population and withdrew 39 Mgal/d from about 225,000 wells. Per capita use for the different counties ranged from 38 to 97 gal/d; the statewide average was 75 gal/d. Total domestic consumptive use was 27 percent (59 Mgal/d) of the total domestic withdrawals and deliveries.

About 58 Mgal/d of freshwater was used for commercial purposes. Public-supply systems delivered 85 percent (49 Mgal/d) of all commercial water, and self-supplied withdrawals were 15 percent (8.6 Mgal/d). Consumptive use was 26 percent (15 Mgal/d) of commercial withdrawals and deliveries.

Industrial and Mining

Since the need to cluster near water-power sites ended, industrial water has been used mainly for cooling and processing. In 1985, 209 Mgal/d was supplied to meet industrial and mining demands; 33 percent (68 Mgal/d) was saline surface water, and 67 percent (141 Mgal/d) was a combination of fresh surface and ground water. More than 99 percent of the saline water was used by one company. That company, which manufactures chemical and allied products (U.S. Office of Management and Budget, 1972), used more water than the combined total of all other self-supplied surface-water users. About 14 Mgal/d (1.4 Mgal/d saline water and 13 Mgal/d freshwater) was consumed, mainly through evaporation and replenishment of process water.

Of the freshwater used for industrial and mining purposes in 1985, 12.9 percent was self-supplied from ground-water sources (18 Mgal/d for industry and 0.2 Mgal/d for mining) (fig. 4). As a group, transportation equipment companies had the largest total withdrawals, whereas a company producing stone, clay, glass, and concrete products was the single largest user. Self-supplied surface water accounted for 43.1 percent of the freshwater used (59 Mgal/d for industry and 1.4 Mgal/d for mining). Transportation equipment had the largest total group withdrawal and single-user withdrawal. Forty-four percent (62 Mgal/d) of the freshwater was purchased from public suppliers. The fabricated metal products group received the most water from public suppliers and included the largest industrial purchaser.

Thermoelectric Power

Cooling water for thermoelectric power generation accounted for 85 percent (3,210 Mgal/d) of all fresh and saline water withdrawn in 1985. Replenishment of feedwater and sanitary applications increase the total water withdrawn to 3,220 Mgal/d. Saline water accounts for 78 percent (2,510 Mgal/d) of total water withdrawals; fresh surface-water withdrawals (694 Mgal/d), fresh ground-water withdrawals (5.8 Mgal/d), and public-supply deliveries (1.3 Mgal/d) supplied the remainder (fig. 4). Although only 2 percent (50 Mgal/d saline and 15 Mgal/d fresh) of this water was consumed, it accounts for more than 45 percent of total consumptive use of freshwater and saline water.

In 1985, Connecticut had eight active fossil-fuel plants that withdrew 1,340 Mgal/d of saline water and 158 Mgal/d of freshwater. All had open-cycle cooling systems, except for a single unit at one plant that has a forced draft cooling tower. A ninth plant was undergoing renovation to improve resource recovery. The two nuclear powerplants withdrew 1,170 Mgal/d of saline and 537 Mgal/d of freshwater. One of these plants had two operating units and a third was under construction. Both plants employed open-cycle cooling. Total power production for all thermoelectric plants was 26,400 GWh.

Agricultural

Agricultural use is a minor component of the State's total water demand. Less than 1 percent (11 Mgal/d) of the total water withdrawn in 1985 was for agricultural purposes. Of this quantity, 41.1 percent (4.6 Mgal/d) was fresh surface water, and the remaining 58.9 percent (6.5 Mgal/d) was fresh ground water. Irrigation accounted for 56 percent (2.5 Mgal/d) of the surface water and 2 percent (0.2

Mgal/d) of the ground water withdrawn for agricultural purposes. The remaining 2.0 Mgal/d of surface water and 6.4 Mgal/d of ground water were withdrawn for other nonirrigation agricultural purposes. Consumptive use was 40.5 percent (4.5 Mgal/d).

Fish hatcheries constituted the largest single demand for water within the agricultural use category. Three hatcheries accounted for 60 percent (6.6 Mgal/d) of the total water withdrawn for agriculture. Two hatcheries relied entirely on ground water and withdrew 92 percent (6.0 Mgal/d) of the total withdrawn for agricultural purposes.

Dairy products are Connecticut's most valuable agricultural commodity (Lewis and Harmon, 1986, p. 158), and dairy farms account for most of the remaining nonirrigation use. The number of milk cows, however, is decreasing, whereas the importance of other livestock, particularly beef cattle, pigs, horses, and chickens, is increasing.

The once-dominant tobacco industry is declining. Most acreage owned by the industry now is used for growing other crops, particularly ornamental shrubs and trees, or has undergone residential, commercial, or industrial development. This decline, plus lesser declines in other irrigated crops, such as potatoes, fruits, and vegetables, has decreased the demand for irrigation water despite increasing acreage of nursery and flowering plants. Total withdrawals for irrigation decreased from 21 Mgal/d in 1980 (Solley and others, 1983, p. 18) to 2.7 Mgal/d in 1985 (Solley and others, 1988). Golf courses, as a category, probably have the largest demand for irrigation water.

WATER MANAGEMENT

The Connecticut Departments of Environmental Protection (DEP) and Health Services (DOHS) have primary responsibility for water resources management in Connecticut. The DEP is responsible for assuring the protection, enhancement, proper allocation, and utilization of water resources, whereas the DOHS has jurisdiction over the use and quality of water for potable supply. The Department of Public Utility Control (DPUC) regulates the financial and operational aspects of privately owned water utilities that operate more than 50 connections. The Connecticut Office of Policy and Management (OPM) is responsible for developing overall State land-use policy, including water-related matters.

Under Section 22a–352 of the Connecticut General Statutes, the DEP, the OPM, and the DOHS prepare and periodically update a statewide long-range plan for the management of water resources. Water-management issues also are addressed in "Environment/2000—Connecticut's Environmental Goals and Management Strategies" (Connecticut Department of Environmental Protection, 1986b). Water allocation is becoming a major issue; conflicts between water uses and competition for use of limited supplies are increasing (Morrissey, 1987, p. 4).

The Water Diversion Policy Act (Connecticut General Statutes, Secs. 22a–365 to 378), which is administered by the DEP, provides a mechanism for allocating water resources. Permits are required for new withdrawals of surface and ground water in excess of 50,000 gal/d and for modification of instantaneous flows in watercourses that have watershed areas of 100 acres or greater. Diversions operating before July 1982 were required to register with the DEP. Applications for new diversions are reviewed to evaluate the need for the diversion, alternatives to the proposed diversion including water conservation, and potential effects on other water uses. All permit applicants must submit a long-range water-conservation plan that includes procedures for limiting water use during shortages. Under provisions of the law, the Commissioner of the DOHS can declare a water-supply emergency. In this situation, the DEP is empowered to suspend permits temporarily or to authorize temporary diversions to ease emergency conditions.

The State's Water Quality Classification System (Connecticut Department of Environmental Protection, 1987b, p. 1) complements the diversion permitting process by establishing designated uses for specific surface- and ground-water resources and by identifying the criteria necessary to support those uses. The use and criteria goals help to focus the DEP's water-quality activities. Section 22a–417 of the Connecticut General Statutes prohibits waste discharges into surface waters tributary to public-supply reservoirs. Conversely, State policy, which currently prohibits the use of waste-receiving surface waters for public water supply, allows the consideration of such sources in the development of water-supply plans. Mechanisms to provide additional water-quality protection for large- and moderate-yield aquifers currently (1987) are being evaluated (Connecticut Department of Environmental Protection, 1987c, p. 2).

The DEP also administers the Minimum Stream Flow Standards (MSFS), which were adopted pursuant to Section 26–141a of the Connecticut General Statutes. These regulations require flow releases from existing impoundments on streams stocked with fish. The standards were specifically intended to protect fishery resources. However, at present (1987), they are considered to be of marginal benefit for protecting instream flows and habitat values because of the inclusion of a calculation table that requires the use of flow data that are not available for most dams. Minimum flow releases in excess of those required under MSFS can be imposed on new diversions for the protection of aquatic habitat and water quality and for recreational use or esthetic purposes under the diversion permitting process.

The DOHS requires public suppliers to submit water-supply plans for State approval (Sec. 25–32d of the Connecticut General Statutes). The water-supply plans must include an evaluation of supply needs in the service area and a strategy to meet those needs for 50 years. Contingency procedures for public drinking-water-supply emergencies also must be included.

Section 25–33 of the Connecticut General Statutes requires that the DOHS approve the location of public water-supply sources and consider the effects of a proposed new source of supply on nearby systems, including public and private wells. The DOHS also has the authority to authorize the sale, supply, or taking of any waters or the temporary interconnection of water mains in a public drinking-water-supply emergency.

The DOHS administers a program to coordinate the planning of public-supply systems under Section 25–33c of the Connecticut General Statutes. The Coordinated Planning Program is designed to ensure effective development of supply systems. Seven Public Water-Supply Management Areas (PWSMA) have been delineated (fig. 5). Water Utility Coordinating Committees (WUCC) will be established within each area according to priorities adopted by the DOHS. The WUCC must assess the existing water-supply situation within the PWSMA, establish exclusive service areas, and prepare a coordinated supply-system plan. The coordinated plans include

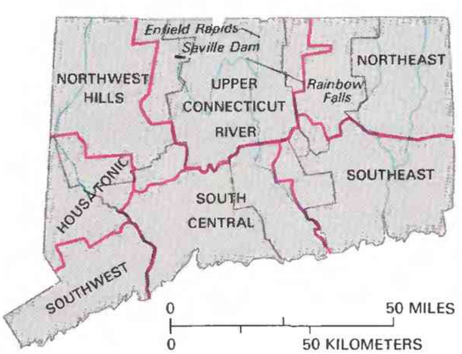


Figure 5. **Public Water-Supply Management Areas in Connecticut, 1987.** (Source: Connecticut Department of Health Services files.)

Schroeder Brook near South Marlborough, Connecticut.

provisions for integration of public-supply systems, integration of public-supplier plans, integration of water- and land-use plans, and evaluation of the effects on other water uses. In most instances, the law prohibits the approval of new public-supply systems in the PWSMA after the WUCC has convened.

Under legislation enacted during 1987, public suppliers regulated by the DPUC must submit a plan for promoting water conservation by customers during any rate proceeding brought before the Department (Connecticut Public Act 87-202). The Connecticut Basic Building Code (Connecticut Department of Public Safety, 1987, p. 46C) requires installation of water-conserving plumbing fixtures in new construction and in the alteration or addition of fixtures in existing structures.

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FOR ADDITIONAL INFORMATION: Office Chief, U.S. Geological Survey, 450 Main St., Rm. 525, Hartford, CT 06103

Prepared by Denis Healy, U.S. Geological Survey; Public Supply parts of Water Use section by Howard Sternberg, Connecticut Department of Environmental Protection; Water Management section by Carrolyn Hughes, Connecticut Department of Environmental Protection

DELAWARE
Water Supply and Use

Delaware has adequate surface- and ground-water resources to meet the present demand for freshwater. Precipitation averages 43 inches per year and provides about 4,000 Mgal/d (million gallons per day) of freshwater across the State (fig. 1A). The Delaware River and Bay border the State on the east. Excluding flow in the Delaware River, which is estuarine in the reach adjoining Delaware, the net streamflow entering the State from the bordering States of Maryland and Pennsylvania averages 385 Mgal/d.

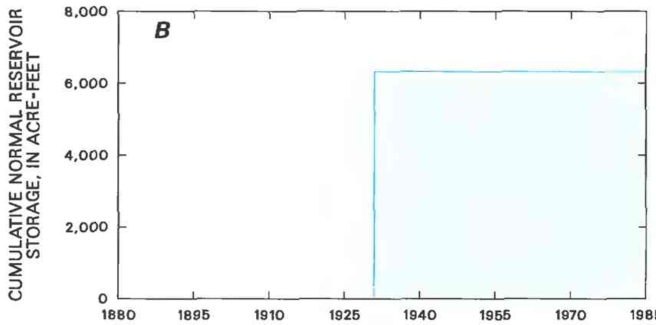
In 1985, 139 Mgal/d of freshwater and 1,500 Mgal/d of saline water were withdrawn for all uses in Delaware. Surface-water sources provided the source for 43.1 percent of the freshwater withdrawn in 1985. Most surface-water use (87 percent) was in New Castle County, the northernmost of the State's three counties. New Castle County is underlain by crystalline rocks and, to a lesser extent, by unconsolidated sediments of the Coastal Plain south of the Fall Line. Ground-water sources provided 56.9 percent of the freshwater withdrawn in 1985. Most ground-water use was in Kent and Sussex Counties. Kent and Sussex Counties, which are south of the Fall Line, are underlain by a seaward-thickening wedge of unconsolidated Coastal Plain deposits that contain several productive aquifers.

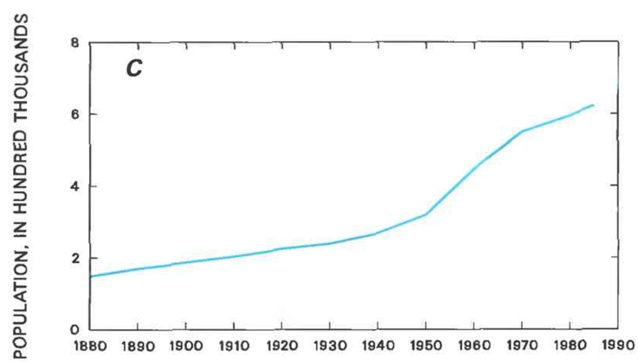
Public suppliers withdrew most of the freshwater used in Delaware in 1985—77 Mgal/d, or 56.1 percent of total withdrawals. The remaining 43.9 percent of the water withdrawn was self-supplied. Domestic and commercial use (51.9 percent of all water used) was dominant in Delaware, followed by industrial and mining use (26.4 percent), agricultural use (20.6 percent), and thermoelectric power generation (1.1 percent).

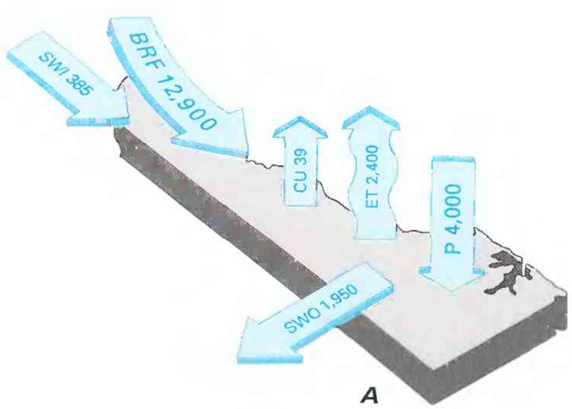
HISTORY OF WATER DEVELOPMENT

Delaware, a State that has agricultural and industrial interests, has depended on water for much of its development. In 1609, the English explorer Henry Hudson sailed into what is now called the Delaware River. The State's first permanent settlement was established in 1638, when a small group of Swedish and Finnish immigrants settled in Wilmington on the Christina River near its confluence with the Delaware River.

Water development in Delaware began with the use of gristmills. Mills were important to the early economy of New Castle County. Although most were on Brandywine Creek, records indicate a gristmill on Shellpot Creek (New Castle County) as early as 1662 and one on Naaman Creek (New Castle County) in 1701. Early residents in Kent and Sussex Counties settled land near streams and rivers for access to transportation and water power. Millponds were developed to provide water power for flourmills and other types of







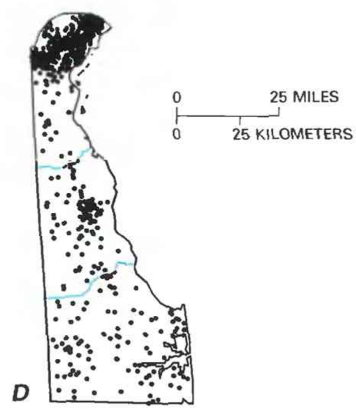


Figure 1. **Water supply and population in Delaware.** ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Data from U.S. Geological Survey files. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

mills. Most of these ponds were abandoned, but later restored to impound runoff, replenish aquifers, provide recreational and wildlife areas, and supply water for low-head hydropower generation.

New Castle County developed chiefly as an industrial area. In 1802, E.I. du Pont de Nemours established the first gunpowder works in the United States on Brandywine Creek. The water-powered machinery used to grind the components and prepare the gunpowder has been restored and is on display at the Hagley Museum in Wilmington. Kent and Sussex Counties developed important agricultural economies, with corn and soybeans as the major crops. Ground water is important for irrigation in these two counties.

Hoopes Reservoir (New Castle County) is part of the city of Wilmington water system and is the only large reservoir in the State. Its normal storage is shown in figure 1*B*.

The population of Delaware increased an average of 4,800 persons per year from 1970 through 1985 (figs. 1*C*,*D*). If this rate of growth continues, then the State's population in the year 2000 will be about 694,000 or about 12 percent larger than that in 1985. Such growth would increase the demand on Delaware's supply of freshwater, particularly in New Castle County. Future water-supply problems may be those of distance between source and point of need, rather than those of inadequate supplies within Delaware's borders.

WATER USE

Demand for freshwater in Delaware is greatest in the densely populated and industrialized northern part of the State and least in the agricultural central and southern parts. Surface-water supplies are abundant in the north, whereas ground-water supplies are abundant in the south. Withdrawals of freshwater by county (fig. 2) reflect these patterns. New Castle County, in northern Delaware, has a population density of about 940 persons per square mile and withdraws 55 percent of all freshwater used in the State; most of the water withdrawn (68 percent) is surface water. Kent County, in the central part of the State, has a population density of about 170 persons per square mile and withdraws about 19 percent of the freshwater used in the State; almost 90 percent of the water used in this county is ground water. About one-half of the water used in the county is withdrawn by the city of Dover and by Dover Air Force Base. Sussex County, in the southern part of the State, has a population density of about 110 persons per square mile and withdraws about 26 percent of the freshwater used in the State; almost 90 percent of this water is from ground-water sources.

Surface-water sources provided 43.1 percent of all freshwater used in Delaware during 1985. The Delaware basin provides most of the surface water used in the northern part of the State (fig. 3*A*). Almost 90 percent of withdrawals is made by public suppliers that deliver water for domestic and industrial uses. Surface-water withdrawals from the Upper Chesapeake basin are used for irrigation in the southern part of the State.

Ground-water sources provided 56.9 percent of all freshwater used in Delaware during 1985. Ground-water availability generally increases from north to south as the aquifers of the Coastal Plain (south of the Fall Line) thicken and become more productive. The location of principal aquifers is shown in figure 3*B*. The unconfined aquifer, whose northern boundary is at the Fall Line, provides the most water (44 Mgal/d). This aquifer attains its maximum thickness of 180 feet in Sussex County, where most withdrawals are made by public suppliers and agricultural users. Johnston (1973) estimated that a maximum of 800 Mgal/d of freshwater could be developed from this aquifer alone. Water from aquifers in the northern and central parts of the State (unconfined, Potomac, and Piney Point–Cheswold) is withdrawn primarily by public suppliers and industrial users. Water levels in the Potomac (Martin and Denver, 1982) and the Piney Point–Cheswold (Leahy, 1982) aquifers have declined more than 150 feet in response to pumping to satisfy this demand. Aquifers in the southern part of the State are not greatly stressed, however, and water levels there have not declined significantly.

The source, use, and disposition of freshwater in Delaware for 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that most surface water (81.5 percent) is withdrawn by public suppliers, whereas the remainder is withdrawn mostly by agricultural (13.4 percent) and industrial and mining (5.2 percent) users. Saline-water use is not included in figure 4, but is discussed under the appropriate categories. The 79 Mgal/d of ground water withdrawn represents 56.9 percent of total freshwater withdrawals in Delaware. Of this quantity, 15.8 percent is withdrawn directly for self-supplied domestic and commercial use; 20.2 percent is self-supplied by industry; 26.1 percent is self-supplied for agriculture; and 36.8 percent is withdrawn by public-supply systems. The use data indicate that domestic and commercial use accounted for 51.9 percent of the State's total freshwater use. Of that quantity, 17.3 percent was self-supplied from ground-water sources, and 82.7 percent was delivered by public-supply systems. About 8.4 percent of the water used for domestic and commercial purposes was consumed; the remaining 91.6 percent was returned to natural water sources for reuse. Agriculture withdrew 72.0 percent of the water from ground-water sources and 28.0 percent from surface-water sources. This water is assumed to have been consumed. The disposition data indicate that for all water withdrawn in the State,

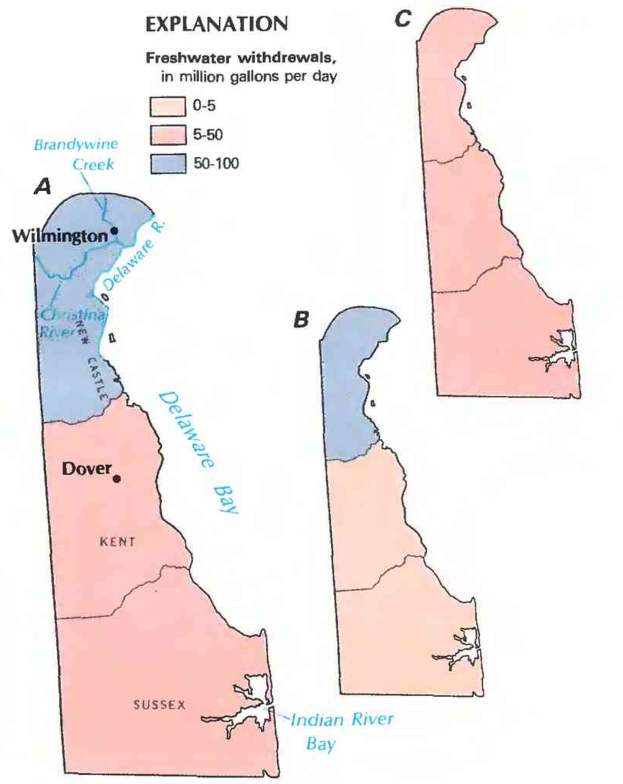


Figure 2. Freshwater withdrawals by county in Delaware, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

28.0 percent (39 Mgal/d) was consumed and 72.0 percent (99 Mgal/d) was returned to natural water resources.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. Withdrawals for public supply increased from 23 Mgal/d in 1950 to 77 Mgal/d in 1985. During this period, withdrawals for public supply increased from 32 to 56 percent of total freshwater withdrawals, reflecting the increasing urbanization of the State. During the same period, self-supplied domestic withdrawals decreased from 11 to 8.6 percent of total withdrawals.

All surface water withdrawn by public suppliers (49 Mgal/d) in 1985 was distributed in New Castle County. Ground water provided an additional 15 Mgal/d for public supply in New Castle County and all public-supplied water (14 Mgal/d) in Kent and Sussex Counties.

The city of Wilmington relies entirely on surface water for public supply. Water from Hoopes Reservoir (New Castle County) is used for supply when the primary source, Brandywine Creek, is inadequate because of diminished flow or unacceptable water quality.

Most of the water withdrawn for public supply (76.5 percent) is delivered to domestic and commercial users (fig. 4). Industry and mining use 22.7 percent of this water, and thermoelectric-power generators use the remaining 0.8 percent. The demand for public supply is expected to increase by about 7 percent between the years 1985 and 2000 (Water Resources Agency for New Castle County, 1983).

DOMESTIC AND COMMERCIAL

Domestic and commercial use in 1985 was 72 Mgal/d (fig. 4). Included is 11 Mgal/d that was for public use or was lost

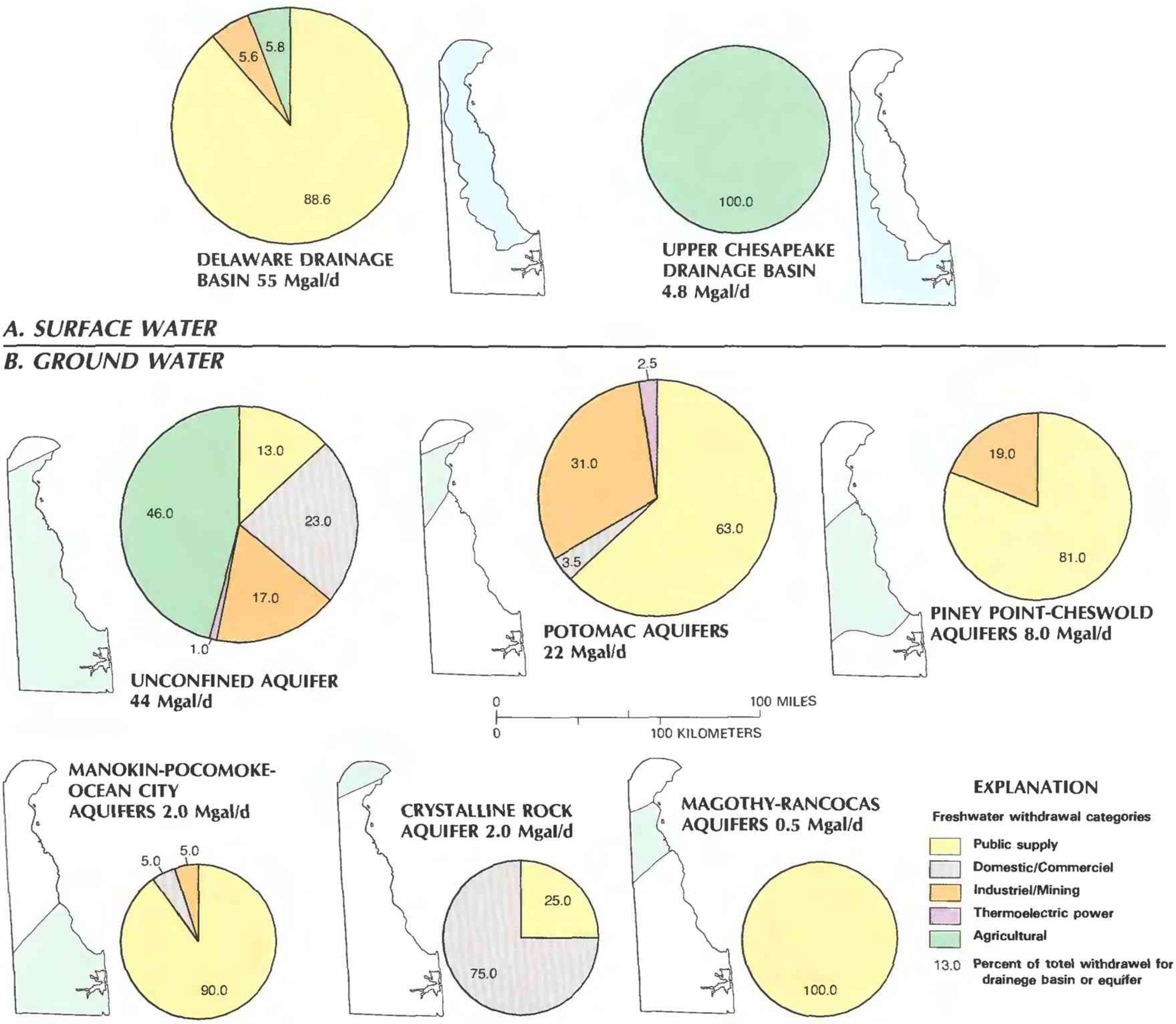


Figure 3. **Freshwater withdrawals by category of use and hydrologic unit in Delaware, 1985.** *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* River basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from Delaware Department of Natural Resources and Environmental Control and U.S. Geological Survey files.)

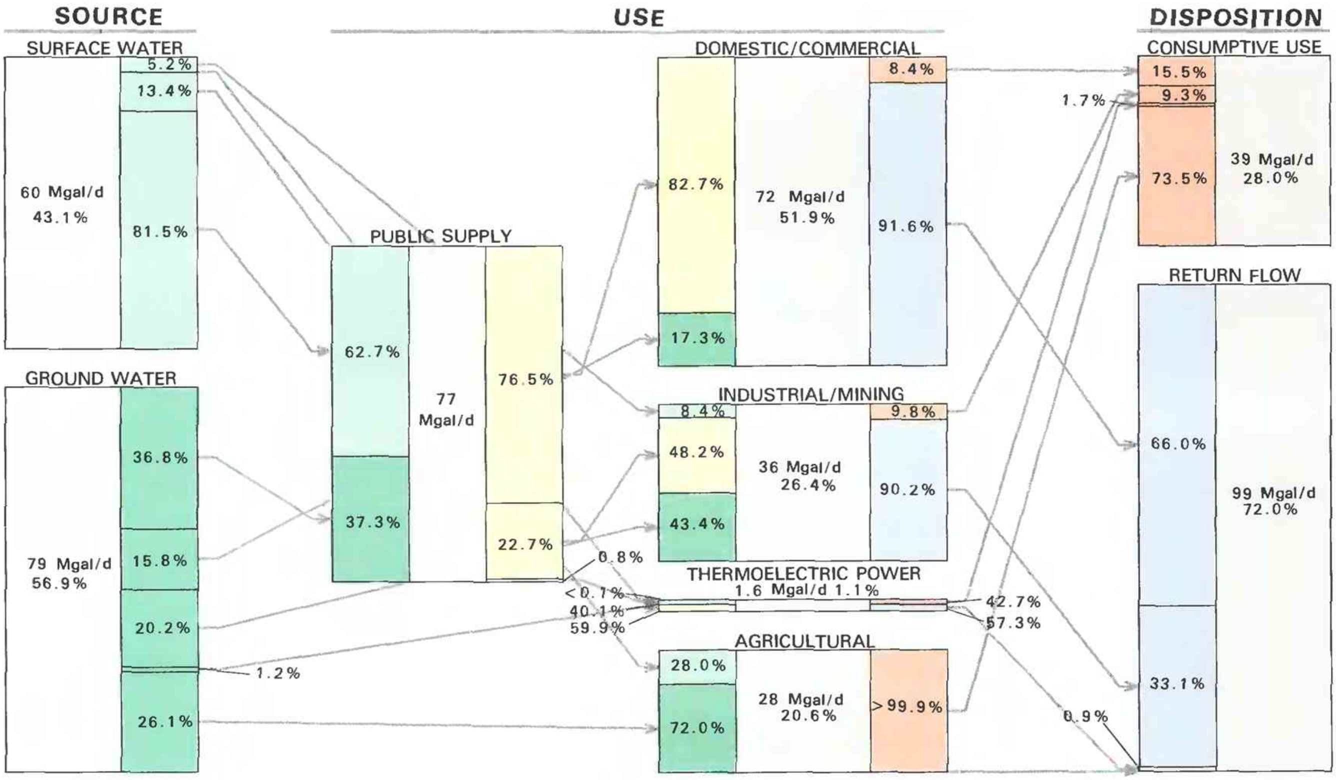


Figure 4. Source, use, and disposition of an estimated 139 Mgal/d (million gallons per day) of freshwater in Delaware, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbols: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

in the supply system. Domestic use was about 46 Mgal/d; of that quantity, 36 Mgal/d was furnished by public-supply systems that served 82 percent of the population. Self-supplied domestic use accounted for the remainder. Consumptive use of domestic water was 4.6 Mgal/d.

Commercial use in 1985 was 15 Mgal/d; of that quantity, 86 percent was provided by public suppliers, and 14 percent was self-supplied. Consumptive use of commercial water was 1.4 Mgal/d.

Industrial and Mining

Most of Delaware's heavy industry is located along the Delaware River in the northern part of the State. Self-supplied withdrawals of freshwater for industrial use decreased from 27 Mgal/d in 1980 to 19 Mgal/d in 1985. Ground water supplied 16 Mgal/d (84 percent) and surface water supplied 3.1 Mgal/d (16 percent) of these withdrawals. Deliveries of water from public suppliers to industrial and commercial users in 1980 were 8.6 Mgal/d. In 1985, the quantity delivered was 18 Mgal/d, of which virtually all was used by industry. These values indicate that, from 1980 to 1985, much of the decrease in self-supplied freshwater use by industry probably represents a shift by some firms from self-supplied to public-supplied water.

Withdrawals of self-supplied, saline surface water for industrial use remained essentially constant from 1980 to 1985. Withdrawals of this type were 390 Mgal/d in 1980 and 391 Mgal/d in 1985.

Mining in Delaware is limited almost entirely to open-pit removal of sand and gravel. The quantity of water used statewide for mining is insignificant compared to the quantities used for other purposes.

Thermoelectric Power

Thermoelectric power generation at the four major powerplants in Delaware used 1.1 percent (1.6 Mgal/d) of the freshwater withdrawn in the State in 1985 (fig. 4). This water was used principally as boiler feed for steam turbines. Powerplants on the Delaware River and on Indian River Bay (in southeastern Delaware) have access to a virtually unlimited supply of saline water, which is used for once-through cooling. The three fossil-fueled stations that utilize this method of cooling used eight times more saline water (1,120 Mgal/d) in 1985 than all the freshwater withdrawn in Delaware for all purposes. Consumptive use of water for thermoelectric power generation is almost negligible for plants using saline cooling water. However, the city of Dover plant, which does not have access to saline cooling water, consumes through cooling-tower evaporation the entire volume (0.63 Mgal/d) of freshwater it receives.

Agricultural

Agricultural use includes water withdrawn for irrigation, livestock, and other farm uses. Total agricultural water use in 1985 was 28 Mgal/d (fig. 4). Irrigation accounted for 93 percent of the total, whereas other agricultural activities accounted for the remaining 7 percent. All water used for agricultural purposes other than irrigation (1.9 Mgal/d) was ground water. Irrigation used 27 Mgal/d, of which 70 percent was ground water and 30 percent was

"Traveling-gun" irrigation system in central Kent County, west of Dover, Delaware.

surface water. Nonirrigation agricultural use has remained almost constant (about 2 Mgal/d) since 1960. Irrigation use, however, has increased considerably since the mid-1970's. Irrigated acreage in the State increased 68 percent from 1976 to 1980, and 138 percent from 1976 to 1985. Center-pivot and traveling-gun systems are the predominant methods of irrigation in Delaware. The primary crops irrigated are corn and soybeans (64 percent) and vegetables (25 percent). Much of the corn and soybean crop produced in Delaware is used as feed for poultry.

WATER MANAGEMENT

Delaware's surface- and ground-water resources are regulated by the Delaware Department of Natural Resources and Environmental Control, Division of Water Resources (DWR), under the terms of the Delaware Environmental Protection Act (Delaware Department of Natural Resources and Environmental Control, 1986a). The Water Supply Branch of the DWR issues permits for the construction of water wells and for the diversion of surface water, licenses well drillers, and maintains a data base on all water facilities in the State. In addition, the Water Supply Branch has principal responsibility for all federally based ground-water protection and management programs under the Clean Water Act of 1972 (amended 1977) and the Safe Drinking Water Act Amendments of 1986. The On-Site Wastewater Branch of the DWR issues permits for individual wastewater-treatment and disposal installations, and the Water Pollution Branch issues national pollution discharge elimination system permits and monitors wastewater flows.

The Delaware Department of Health and Social Services, Division of Public Health (DPH), regulates the quality and adequacy of public water-supply systems (Delaware Department of Natural Resources and Environmental Control, 1986b) that provide service to three or more dwellings, public and semipublic buildings, and establishments that use water to prepare food or beverages. By law, the DPH has the authority to regulate the adequacy of source water and treated water. In addition, the DPH (Delaware Department of Natural Resources and Environmental Control, 1986b) can regulate land use within 1 mile of a public-supply source to protect the quality of that source. Public-water supplies also are regulated by the Public Service Commission.

The Delaware River Basin Commission (DRBC), by agreement among the four States in the Delaware River basin, cooperates with the State of Delaware in regulating the use of surface and ground water within the State's part of the basin. All projects in the basin that will have a "substantial impact" on water resources are subject to DRBC permitting procedures. These projects include operating wells that, at a minimum, withdraw an average of 100,000 gallons per day during any month or discharge contaminants into ground water. The permitting procedure also is used to regulate land use on the recharge areas of major aquifers.

Nonregulatory agencies involved in Delaware water issues include the Delaware Geological Survey (DGS) and the Water Resources

Agency for New Castle County (WRANCC). The DGS, in addition to other responsibilities, maintains a statewide water-data network and, in cooperation with the U.S. Geological Survey, conducts investigations of the ground-water resources of the State. The WRANCC, a local agency, recently (1983) has completed a plan titled "Water 2000," which is a long-term management strategy for developing adequate water supplies in New Castle County.

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Prepared by A.L. Hodges, Jr., U.S. Geological Survey; History of Water Development section by R.D. Varrin, Water Resources Center, University of Delaware; Water Management section by P.J. Cherry, Delaware Department of Natural Resources and Environmental Control

FOR ADDITIONAL INFORMATION: Chief, Delaware Office, U.S. Geological Survey, Federal Building, Room 1201, 300 S. New Street, Dover, DE 19901

FLORIDA
Water Supply and Use

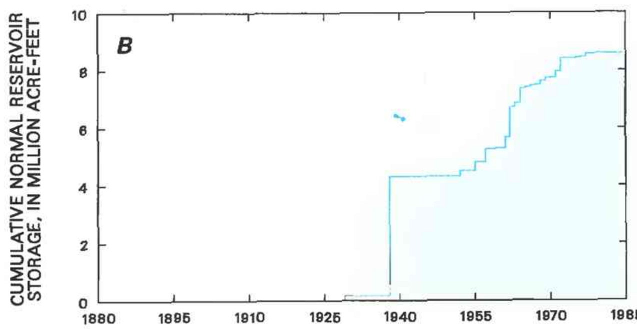
Florida, the "Sunshine State," has abundant surface-water resources that include about 1,700 streams and rivers and 7,800 freshwater lakes (Heath and Conover, 1981). The State has more available ground water, proportionally, than any other State (McGuinness, 1963). Florida is underlain virtually everywhere by aquifers capable of yielding significant quantities of freshwater to wells.

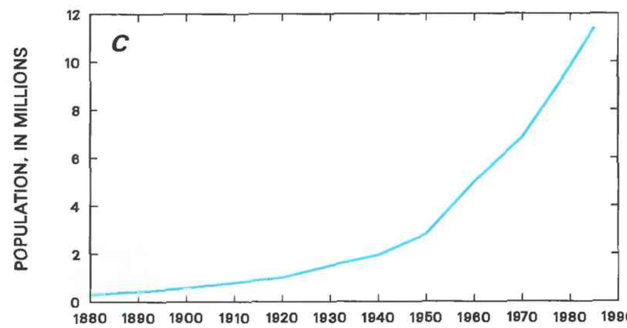
Florida, which ranks third in the Nation in precipitation, has an annual average of more than 53 inches. Annual rainfall quantities vary geographically from 64 inches in parts of northwestern Florida to 40 inches in the Florida Keys (Bridges and Foose, 1986). About 70 percent of the rainfall is returned to the atmosphere (fig. 1*A*) through evapotranspiration. The remainder is runoff to surface waters or is recharged to aquifers (Fernald and Patton, 1984).

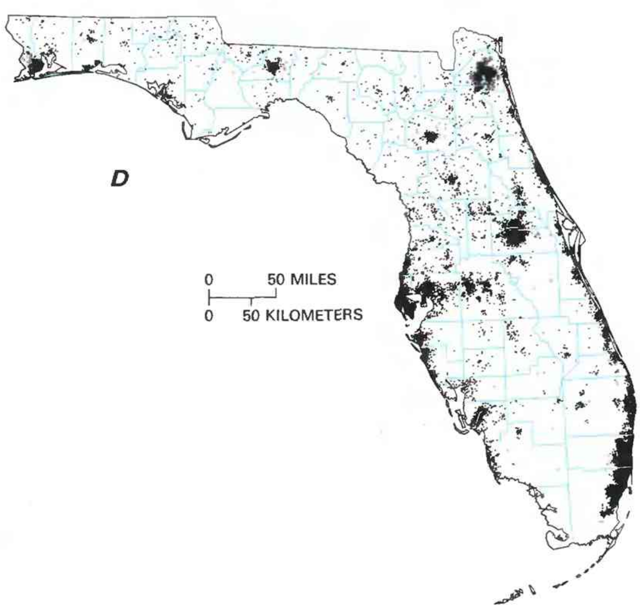
Of the total freshwater withdrawn in 1985, surface-water withdrawal was 35.5 percent, and ground-water withdrawal was 64.5 percent. Ground water is the primary source because it is readily available and is generally of good quality for most uses. The Floridan aquifer system, which underlies most of the State, provided about 62 percent of the total ground water used in 1985. Of the 11.3 million people in Florida, 47 percent live in the 13 coastal counties that border the Atlantic Ocean. These 13 counties used more than 42 percent of the total freshwater withdrawn.

In 1985, total water withdrawals in Florida were about 17,100 Mgal/d (million gallons per day). Of this quantity, 6,280 Mgal/d (37 percent) was freshwater (includes 17 Mgal/d of saline ground water that was converted to freshwater), and 10,800 Mgal/d (63 percent) was saline. Agriculture and public supply accounted for most of the total freshwater withdrawn [2,980 Mgal/d (47.5 percent) and 1,680 Mgal/d (26.8 percent), respectively]. Power generation accounted for more than 99 percent of the saline water withdrawn. An estimated 43.5 percent of freshwater withdrawals (2,730 Mgal/d) was consumed. An additional 51 Mgal/d of treated wastewater was reused for irrigation throughout the State.

Florida ranks ninth in the Nation in agricultural production and is the largest producer of citrus in the United States (Florida







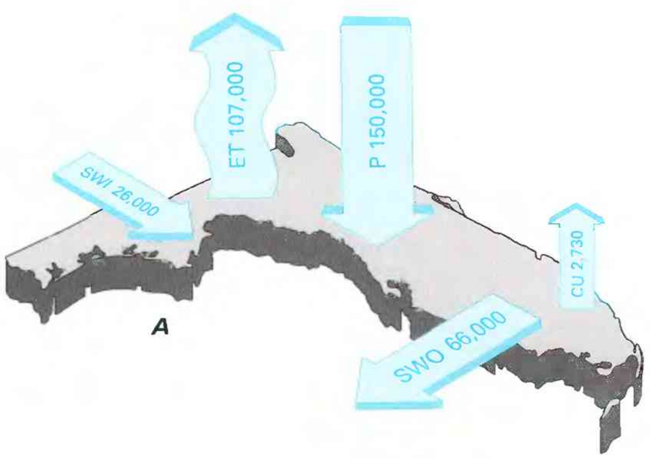


Figure 1. Water supply and population in Florida. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Fernald and Patton, 1984, p. 15. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Department of Agriculture and Consumer Services, 1986a). Irrigation withdrawal for citrus is greater than for any other crop in Florida and accounted for 34 percent of total irrigation withdrawals and 16 percent of total freshwater withdrawals for all uses.

Withdrawals for public supply increased 531 Mgal/d from 1975 to 1985 (including 17 Mgal/d of saline ground water that was converted to freshwater) and water withdrawals for agricultural irrigation increased almost 50 Mgal/d during the same period (2,930 to 2,980 Mgal/d). Population is projected to be more than 15 million by the year 2000 (Smith and Sincich, 1987). Thus, the importance of agriculture and associated land and water development in Florida will make the need to protect the hydrologic environment and to manage Florida's water resources even more important in the future.

HISTORY OF WATER DEVELOPMENT

Abundant water has been an inducement and an impediment to the development of Florida. The early history of water development in Florida was dominated by efforts to reclaim its extensive wetlands, which were nearly 50 percent of the land area before development (Hampson, 1984), for agriculture and urban growth, particularly in southern Florida.

According to Fernald and Patton (1984), channelization, which began on the Caloosahatchee River and in the upper Kissimmee River basin in 1882, started as a process of wetland drainage and land reclamation and has continued to the present. The most intensive period of drainage in the area of the Everglades and Lake Okeechobee occurred between 1905 and 1927 when six major canals and channelized rivers were connected to Lake Okeechobee. The major objective was to drain the areas just south of Lake Okeechobee and to use the thick organic soils in those areas for agriculture. Much of the later drainage work was done according to a plan prepared by the Everglades Drainage District. The District, which was established in 1913, was the first of several involved with water management in southern Florida. After several catastrophic hurricanes in the late 1920's, the Federal Government, through the U.S. Army Corps of Engineers, began a major program of flood control in Florida, including construction of the 85-mile-long Hoover Dike flanking the southern and eastern sides of Lake Okeechobee. Lake Okeechobee and the water conservation areas completed in the central Everglades by 1962 are a major part of the reservoir storage in the State (fig. *1B*).

Starting in the 1920's, many issues that relate to water, other than flood control, have become important in southern Florida. Lowered water levels caused by overdrainage intensified the adverse effects of drought; fires became common during the dry season. Near the coast, lowered ground-water levels promoted saltwater intrusion into potable water supplies, which occurred at the main well field in Miami in 1925 and 1945 (Klein and Waller, 1985).

By the late 1960's, most of the major work for the complex system of canals, levees, pumping stations, salinity-control structures, and water-conservation areas was completed in southern Florida. This system made the land more suitable for agriculture and urbanization, increased the usable water in storage, and enabled large quantities of water to be rapidly discharged through the canals to the ocean, thus decreasing the potential for flooding. Because of the severe droughts of 1961 to 1962, 1970 to 1971, and 1980 to 1982 (Waller, 1985), increasing water demands, and a new threat of saltwater intrusion, the emphasis shifted from drainage and flood control to increased management for water-supply purposes.

Following the emphasis on draining the wetlands came the major effort to develop water supplies to satisfy the needs of the greatly expanding populace (fig. *1C*) that grew from about 500,000 at the turn of the century to more than 11.3 million in 1985 (Shoemyen and others, 1986, p. 3). The distribution of population in Florida, as of 1985, is shown in figure *1D*. Domestic and public supply in the early years was obtained from shallow dug and driven wells and from the abundant lakes and rivers. Then came the trend to drill deep wells that flowed naturally. In many areas, before the advent of large-capacity pumps, flowing wells were used to irrigate crops, but the quality of water in some areas, such as in southwestern Florida, was unsatisfactory. In other areas, water for irrigation was obtained from lakes and rivers during the dry season. However, adjoining landowners objected to the additional lowering of lake levels by pumping at a time when lake levels were already low. Beginning in the 1960's, the need for dependable supplies of water for irrigation resulted in an increase in the use of ground water.

Water-quality and environmental concerns have become increasingly important in the last few decades. The issue that crystallized environmental concern in Florida was the construction of the Cross Florida Barge Canal across the northern Florida peninsula. The Barge Canal, which was the major water development issue in northern Florida, was slowed and finally deauthorized in 1986 for environmental and economic reasons. Current policies and regulatory procedures have resulted in the preservation and, in some instances, the restoration of the State's remaining wetlands. After a history of little concern for the effects of development, Florida has become most aware of the environment and its protection.

WATER USE

Although Florida has an abundant supply of freshwater, the water supply is not always available where the demand exists. The problem is aggravated in many areas where the supply is sufficient but the quality is inadequate. Six of the eight counties that use in excess of 200 Mgal/d are coastal counties (fig. *2A*). These eight counties account for one-half of Florida's population.

Because of the large population in coastal areas throughout the State and the unsuitable quality of water in some of these areas, water-supply sources commonly are located many miles inland (U.S. Geological Survey, 1984); many of these inland sources are well fields. In 1985, 162 Mgal/d of public-supply water was withdrawn from counties other than the counties of use. The six counties importing public-supply water are coastal counties. The largest importer is Pinellas County, which is supplied with more than 100 Mgal/d from adjacent Hillsborough and Pasco Counties. Other coastal counties that have large demands and limited resources also rely on inland surface-water sources. Surface water accounted for 11.0 percent (185 Mgal/d) of the total public supply in 1985; 98 percent (181 Mgal/d) of it is utilized by coastal counties.

Two alternative water-supply sources for coastal areas have become more evident between 1980 and 1985. The first alternative is obtaining potable water through the treatment of saline ground water by reverse osmosis or by dilution with freshwater. Use of this new source increased from less than 1 Mgal/d in 1980 to more than 17 Mgal/d in 1985. The second alternative is the use of treated sewage wastewater (reclaimed water) for irrigation. In 1985, about 1,122 Mgal/d of treated sewage wastewater was discharged from domestic wastewater-treatment plants, and 4.5 percent (51 Mgal/d) of this was reused for irrigation. Although data were not available for 1975 and 1980, it is believed that little or no wastewater was reused. Because intrusion of saltwater, particularly into coastal aquifers, is a major concern, these alternatives probably will continue to increase in importance.

The area of greatest fresh surface-water withdrawals is in the southern part of the State (fig. *2B*). This area is intensively irrigated for sugarcane, vegetables, and citrus and accounts for 49 percent (1,090 Mgal/d) of the State's total surface-water withdrawals. The other area of significant fresh surface-water withdrawal is Escambia County, where the withdrawal is more than 200 Mgal/d for cooling water needed for thermoelectric power generation.

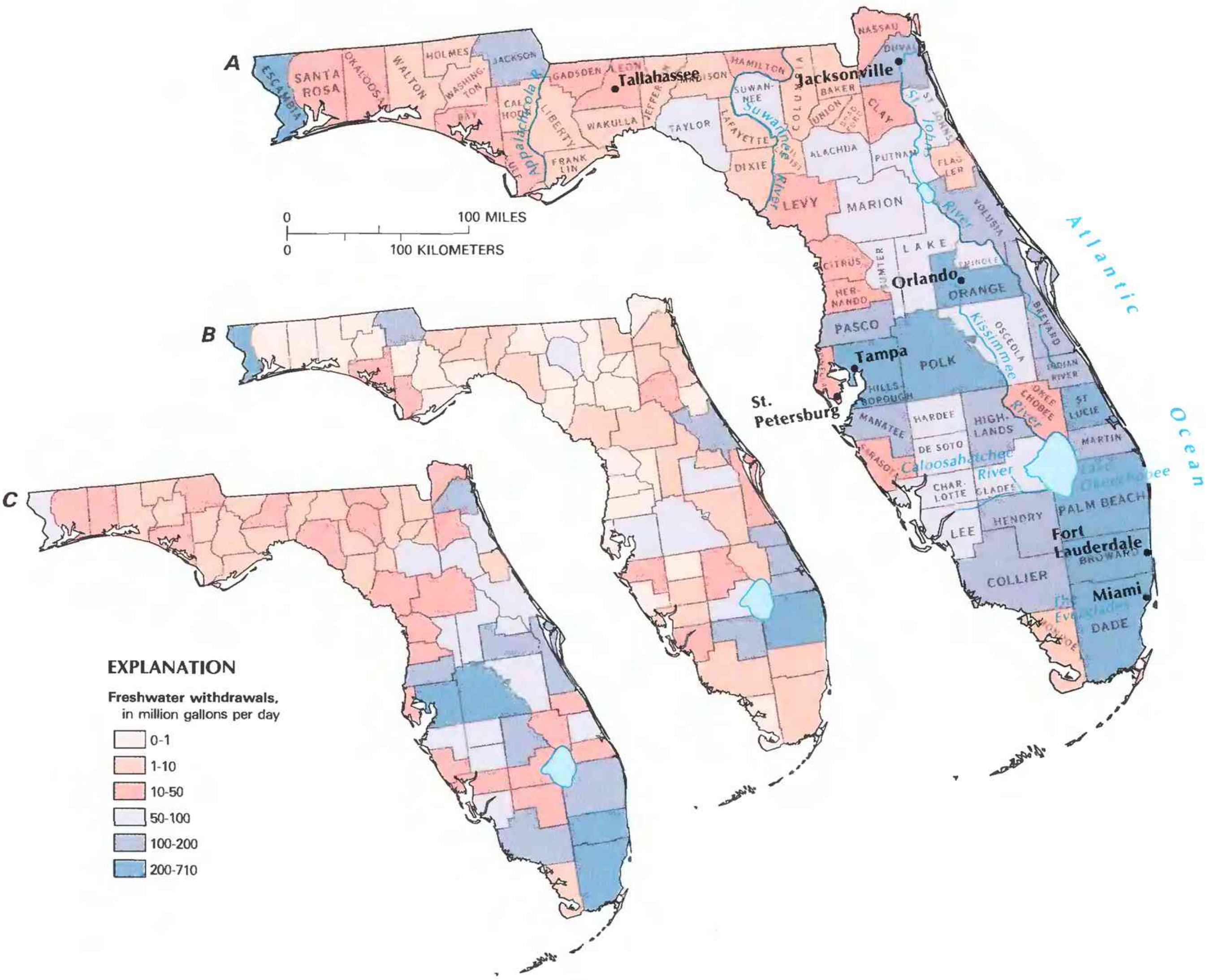


Figure 2. Freshwater withdrawals by county in Florida, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

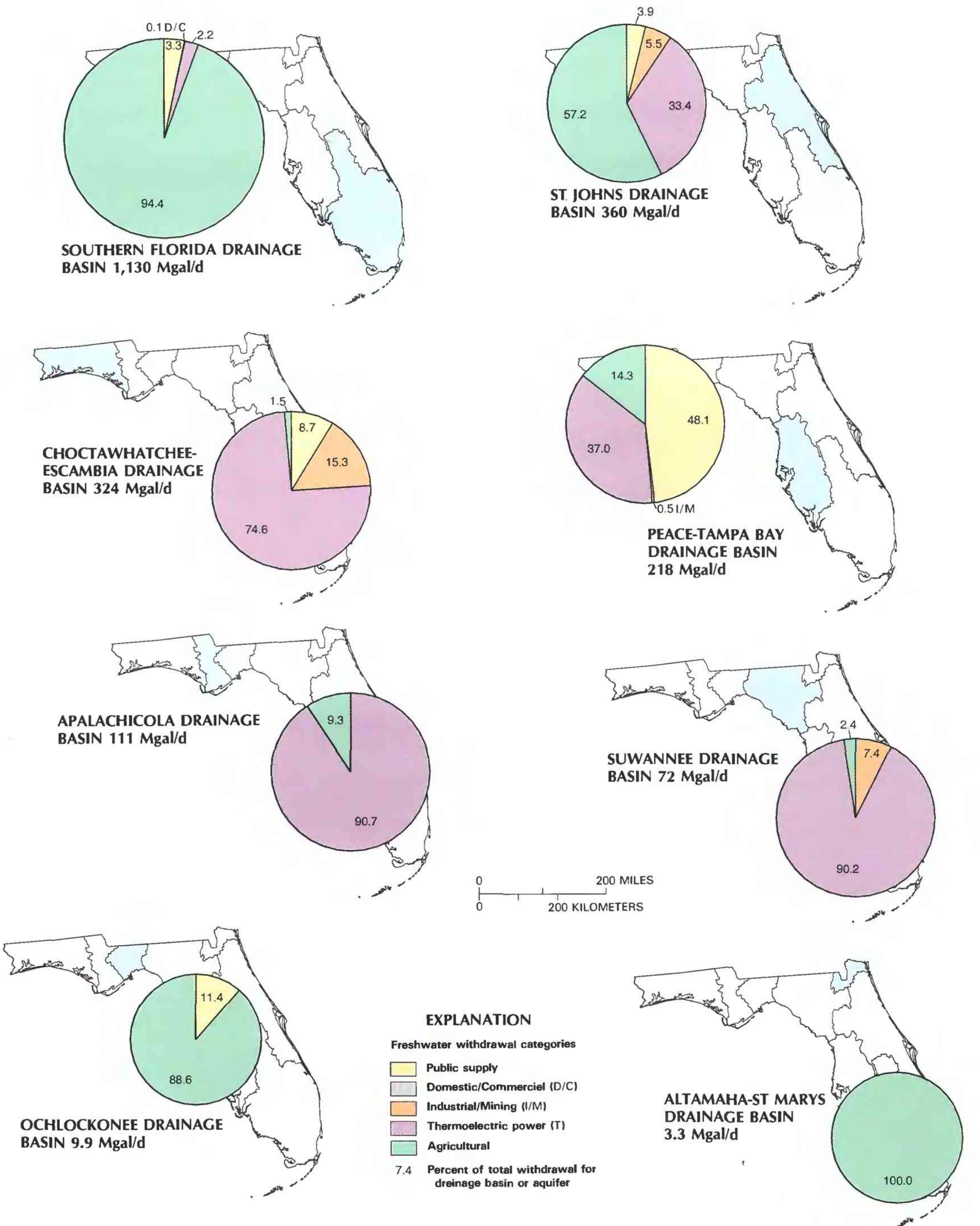
The areas of greatest fresh ground-water withdrawals are southeastern (Dade, Broward, and Palm Beach Counties) and central Florida (Hillsborough and Orange Counties) for public supply and agriculture; and Polk County for industry and agriculture (fig. 2*C*). These six counties accounted for 40 percent (1,630 Mgal/d) of the State's ground-water withdrawals in 1985.

The Southern Florida basin (fig. 3*A*), which includes the Kissimmee and the Caloosahatchee Rivers, Lake Okeechobee, and the Everglades, was the largest user of fresh surface water. This basin accounted for 51 percent of the State's surface-water withdrawals. Agricultural irrigation accounted for 94.4 percent of this basin's withdrawals. The Floridan aquifer system (fig. 3*B*), which underlies most of the State, accounted for 61 percent of the ground-water withdrawals. Agricultural irrigation accounted for nearly one-half (47.2 percent) of the withdrawals from the Floridan.

The source, use, and disposition of freshwater in Florida during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 2,230 Mgal/d was withdrawn from surface water, which represents 35.5 percent of total freshwater withdrawals. Ground-water withdrawal was 4,050 Mgal/d, which ranks Florida sixth in the Nation in ground-water withdrawals and the largest user of ground water east of the Mississippi River (Solley and others, 1988).

Withdrawals of surface water are decreasing. Overall, fresh surface-water withdrawals decreased by 1,370 Mgal/d between 1975 and 1985. More than 1,000 Mgal/d of the decrease reflects less water withdrawn for power generation because of more efficient use of water. Fresh surface-water withdrawals for irrigation decreased by more than 308 Mgal/d during this period.

In contrast to surface water, withdrawals of ground water are increasing. Fresh ground water accounted for 64.5 percent (or 4,050 Mgal/d) of Florida's total freshwater withdrawals, an increase from 51 percent of the total in 1980 and 48 percent of the total in 1975. The increase of almost 740 Mgal/d in the last 10 years about (3,310 to 4,050 Mgal/d) indicates the growing importance of Florida's aquifers. Fresh ground-water withdrawals for public supply increased 509 Mgal/d, domestic self-supply increased 58 Mgal/d, and agricultural irrigation increased 356 Mgal/d, whereas industrial



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Florida, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Franks, 1982.)

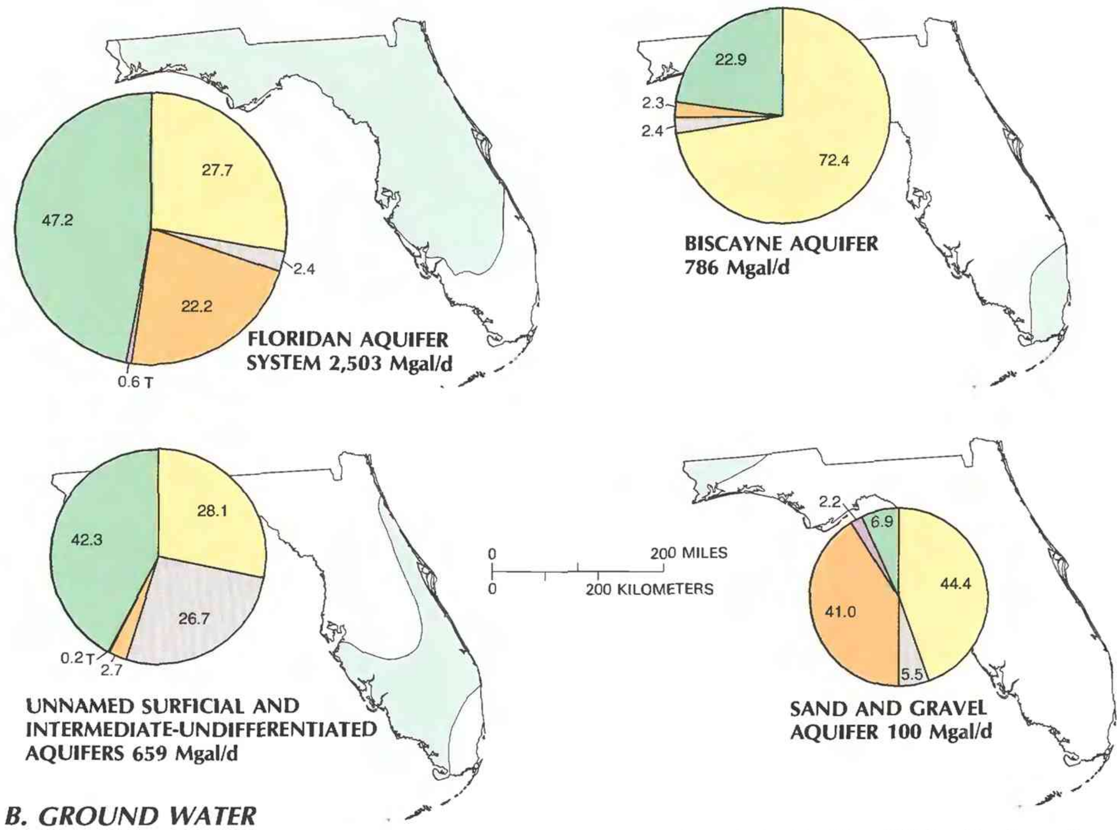


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Florida, 1985—Continued.

withdrawals decreased 147 Mgal/d and power generation decreased 41 Mgal/d.

Increases in population, tourism, and irrigated acreage have accounted for increases in withdrawals for public supply and agriculture. Florida's population increased by nearly 3 million between 1975 and 1985. The influx of millions of tourists per year (an estimated 30 million people visited Florida in 1985) is also an important factor in increasing demands for public supply. Agricultural acreage has increased by 70,000 despite the loss of more than 150,000 acres of citrus in the past 10 years (Florida Department of Agriculture and Consumer Services, 1986b).

Water withdrawals in Florida have a large seasonal variation, primarily because of variations in temperature and precipitation. Agricultural irrigation, the largest water-use category, has the greatest variation in monthly withdrawals. During 1985, irrigation demands fluctuated from 4,300 Mgal/d in April to 1,920 Mgal/d in December (fig. 5*A*). This fluctuation of more than 2,000 Mgal/d is a result of intensive crop production and extremely dry conditions during the early spring; March, April, and May account for 35 percent of the water used for irrigation but receive only 17 percent of the yearly rainfall. In contrast, July, August, and September account for 45 percent of the rainfall, but only 20 percent of the irrigation use.

The demand for public-supply water varies much less, fluctuating from 1,940 Mgal/d in May to 1,550 Mgal/d in September (fig. 5*B*). This fluctuation of almost 400 Mgal/d relates to seasonal differences in residential demand, primarily for lawn irrigation.

Industrial water demand fluctuates very little. The use is greatest in February (767 Mgal/d) because of food production, primarily the processing of citrus concentrate and vegetables.

Public Supply

Florida ranks sixth in the Nation in total surface- and ground-water public-supply withdrawals for 1985 and ranks second in the Nation, behind California, in ground-water withdrawals for public supply. Public-supply withdrawals have increased by 46 percent since 1975, and the population in Florida has increased more than 30 percent (fig. 1*C*). In 1985, a total of 633 public and private utilities supplied water to 9.7 million people, or 86 percent of the State's population, which is slightly larger than the 80-percent served by public-supply systems in 1975.

Total public-supply withdrawals for Florida in 1985 amounted to 1,680 Mgal/d, of which 89.0 percent (1,490 Mgal/d) was ground water and 11.0 percent (185 Mgal/d) was surface water (fig. 4). The Floridan aquifer system [693 Mgal/d (47 percent)] and the Biscayne aquifer [569 Mgal/d (38 percent)] supplied 85 percent of ground-water withdrawals in 1985. The Biscayne aquifer is present only in southeastern Florida, whereas the Floridan aquifer system is present in most of the State (fig. 3*B*). Total ground-water withdrawal in the State for 1985 includes 17 Mgal/d of saline water withdrawn for treatment by reverse osmosis or diluted for potable use. The Miami–Dade Water and Sewer Authority Department, which withdrew more than 292 Mgal/d from the Biscayne aquifer, was the single largest ground-water supplier in the State. Other large ground-water users are the cities of Orlando, Jacksonville, St. Petersburg, and Fort Lauderdale. The largest surface-water supplier in the State is the city of Tampa, which withdrew 54 Mgal/d in 1985.

Public-supply water is used in all major water-use categories (fig. 4) except agriculture. Domestic and commercial use, which includes indoor and outdoor use, accounted for 91.2 percent (1,530 Mgal/d) of public-supply deliveries.

Domestic and Commercial

Domestic and commercial water use in Florida totaled 1,850 Mgal/d, of which 82.9 percent (1,530 Mgal/d) was delivered from

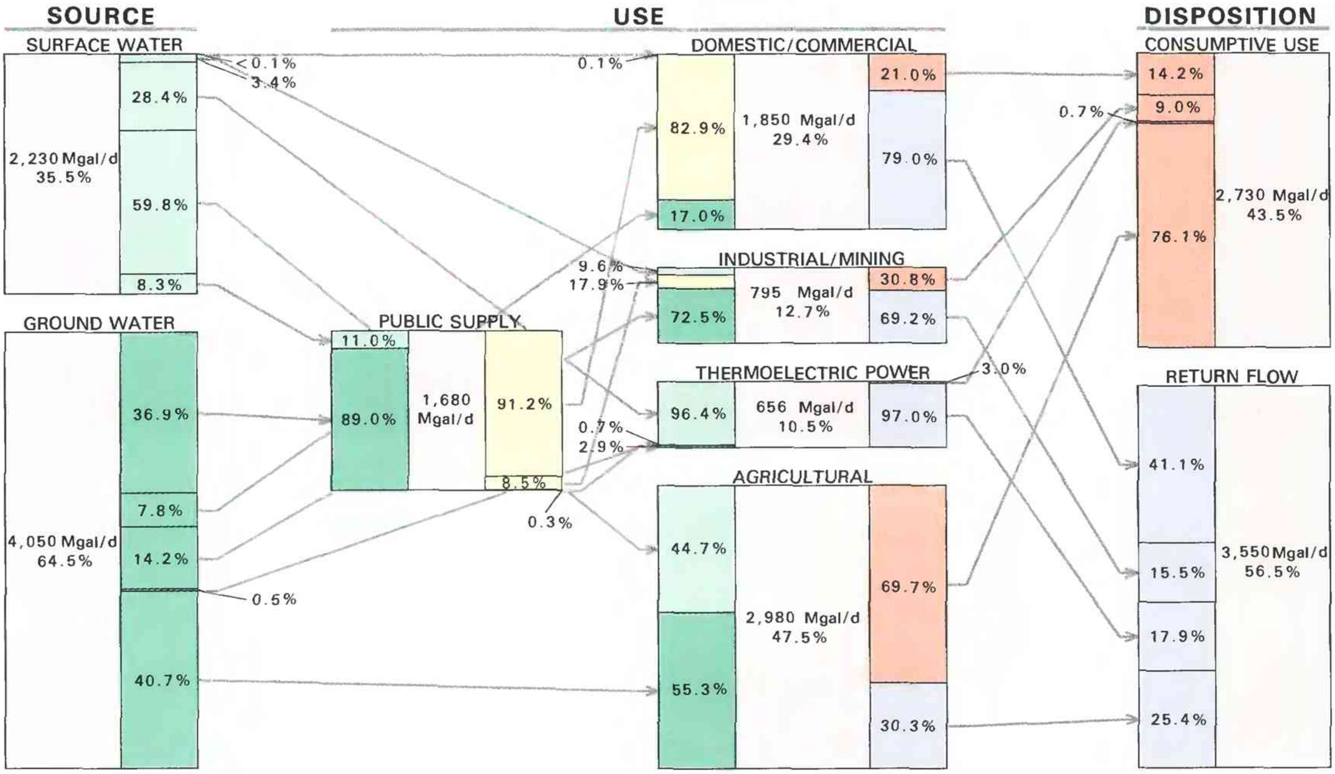


Figure 4. Source, use, and disposition of an estimated 6,280 Mgal/d (million gallons per day) of freshwater in Florida, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

public-supply systems and 17.0 percent (315 Mgal/d) was self-supplied (fig. 4). In 1985, an estimated 1.6 million Floridians were self-supplied or were served by the small utilities not inventoried. All self-supplied water is ground water and is withdrawn primarily from shallow wells.

The overall per capita use of public-supply water increased from 168 gal/d (gallons per day) in 1975 to 172 gal/d in 1985. However, for water used solely for domestic purposes, per capita use in 1985 was 123 gal/d. This use is greater than the national average of 108 gal/d and ranks Florida 17th among the 50 States.

Commercial water users include institutions, recreational facilities, military facilities, and commercial nonmanufacturing establishments. Most commercial users in Florida are served by public-supply water systems, but only 116 self-supplied users were inventoried in 1985. Commercial water use totaled 307 Mgal/d, of which 82 percent (251 Mgal/d) was delivered by public-supply water systems and 56 Mgal/d was self-supplied. More than 98 percent of the self-supplied water was ground water, and 80 percent of the ground water was from the Floridan aquifer system.

Industrial and Mining

Water withdrawn by the 223 self-supplied industries and mines inventoried in 1985 included 27 Mgal/d of saline water and 653 Mgal/d of freshwater. In addition, 142 Mgal/d of freshwater was delivered to industries or mines from public-supply systems. Total freshwater withdrawal for this category was 795 Mgal/d. Of this quantity, self-supplied surface water accounted for 9.6 percent (76 Mgal/d) and self-supplied ground water accounted for 72.5 percent (576 Mgal/d) (fig. 4). Self-supplied withdrawals have decreased during the past 10 years while deliveries from public supplies have increased. Overall decrease in use can be attributed to changes in economic conditions and conservation practices. Industrial and mining consumptive use was 30.8 percent (245 Mgal/d) of the total water withdrawals.

Mining was the largest industrial water user in 1985. Total withdrawal was 258 Mgal/d and included 148 Mgal/d for mining limestone and sand, 98 Mgal/d for mining phosphate, and 12 Mgal/d for mining other minerals. Withdrawals for mining limestone and sand, which are used primarily for roads and concrete products, have increased 60 Mgal/d during the past 10 years. Most limestone and sand is mined in Hernando, Sumter, and Lake Counties. Most phosphate is mined in the Lakeland (Polk County) area. Phosphate processing and mining withdrawals have decreased 80 Mgal/d since 1975. The pulp and paper industry, located in the densely forested areas of northern Florida, withdrew 203 Mgal/d in 1985. These withdrawals decreased slightly during the last 10 years. Mining and pulp and paper accounted for 71 percent of the self-supplied industrial freshwater withdrawals in Florida.

Thermoelectric Power

In 1985, total self-supplied withdrawals for the 50 thermoelectric powerplants inventoried equaled 11,400 Mgal/d, of which about 6 percent (656 Mgal/d) was freshwater (fig. 4). An additional 0.7 percent (4.8 Mgal/d) was withdrawn by public supply for use by thermoelectric powerplants. Most of the water withdrawn (10,700 Mgal/d) was saline. More than 99.8 percent of the total withdrawn was for cooling; the remainder was for boiler makeup and domestic uses. The consumptive water use of freshwater, which was very small, equaled 20 Mgal/d. Total water withdrawal for power generation decreased by more than 1,700 Mgal/d from 1975 to 1985, but power production increased 17 percent for the same period.

AGRICULTURAL

Agriculture was the largest user of freshwater in Florida in 1985. Total withdrawals for agricultural purposes equaled 2,980 Mgal/d, of which 44.7 percent (1,330 Mgal/d) was surface water and the remainder was ground water (fig. 4). An additional 51 Mgal/d of reclaimed sewage wastewater was used for irrigation. Irrigation of vegetable crops, field crops, fruit crops, and ornamentals and grasses accounted for the majority of total agricultural use. Nonirrigation uses, primarily for livestock and fish farming, accounted for 66 Mgal/d of agricultural use. Total consumptive use in 1985 by agriculture was 69.7 percent (2,080 Mgal/d) of total withdrawals.

The largest proportion of water withdrawn for agriculture in the State in 1985 was for citrus. Citrus accounted for 32 percent of the total acres irrigated and 34 percent of the freshwater withdrawals. The greatest concentration of citrus acreage (60 percent of the total) is in Polk, Hardee, and Highlands Counties in central Florida and in Indian River, St. Lucie, and Martin Counties along the eastern coast. About one-half of the 610,000 acres of citrus is irrigated by efficient, low-pressure, low-volume systems. Other large water users include sugarcane crops (505 Mgal/d), improved pasture (222 Mgal/d), golf courses (181 Mgal/d), and tomato crops (136 Mgal/d).

Agricultural water withdrawal has increased about 49 Mgal/d since 1975. More specifically, surface-water withdrawals have decreased 308 Mgal/d, and ground-water withdrawals have increased 356 Mgal/d. In addition to surface and ground water, reclaimed water use for irrigation increased from nearly 0 to more than 50 Mgal/d. The number of agricultural acres irrigated increased despite losses caused by freeze damage and urbanization. Nearly 90 percent of the State's agricultural acreage, excluding improved pasture, is irrigated.

About 1.9 million acres were irrigated in Florida—1.1 million by flood systems and the remainder by sprinklers or low-pressure, low-volume systems. Irrigation efficiency has been improving during the last 10 years as a result of technological advances and management practices. This greater efficiency will benefit the agricultural industry in the future as restrictions increase on withdrawals and discharges.

WATER MANAGEMENT

The Florida Water Resources Act of 1972 established authority for management of the State's water resources through five water-management districts under the general supervision of the Florida Department of Natural Resources. These districts, which encompass the entire State, 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, which was originally established in 1961, and the Suwannee River Water Management District (fig. 6). These districts are empowered to oversee water issues on a regional level. The Florida Department of Environmental Regulation was created in 1975 and assumed the powers and functions relating to water management formerly held by the Department of Natural Resources. Since 1975, the five water-management districts have functioned under the supervision of the Department of Environmental Regulation and generally have been delegated the primary responsibility for those aspects of water management relating to quantity, whereas

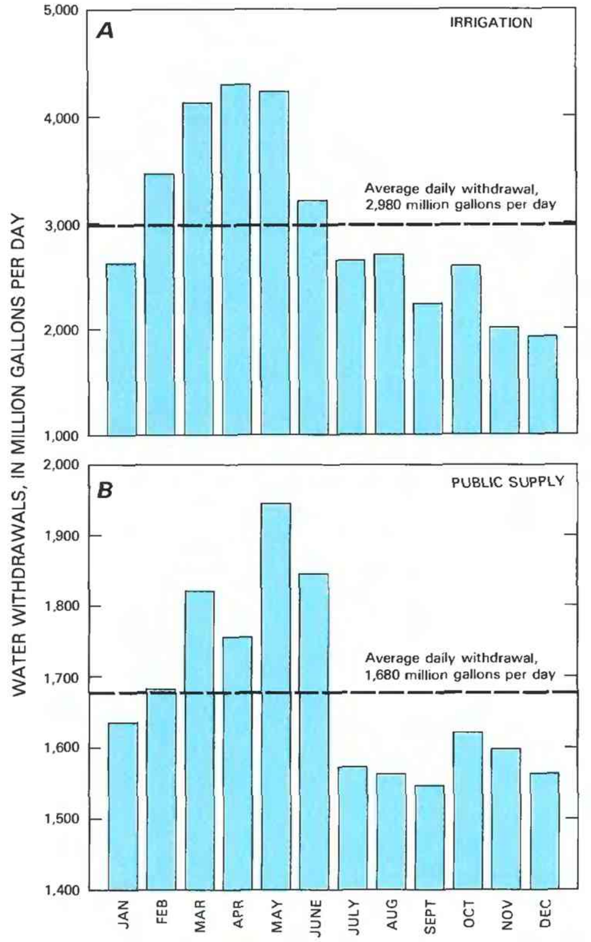


Figure 5. Selected water withdrawals for Florida, 1985. *A*, Monthly withdrawals for irrigation water use. *B*, Monthly withdrawals for public water supply.

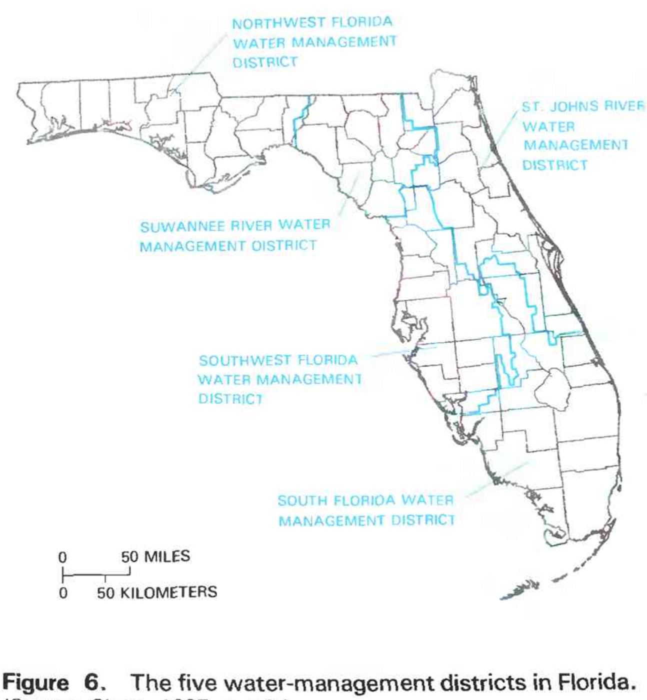


Figure 6. The five water-management districts in Florida. (Source: Glenn, 1987, p. 16.)

the Department of Environmental Regulation is concerned primarily with those aspects of water management relating to quality.

The districts regulate five types of activities—water-well construction, management and storage of surface water (including stormwater), consumptive water use, works of the district (including levees, control structures, bridges, and culverts), and wells constructed for artificial recharge. The Act of 1972 also requires that the management districts adopt plans to deal with water shortages. Permitting regulations pertaining to waste disposal or other activities that affect water quality are administered directly by the Department of Environmental Regulation. The Florida Water Quality Assurance Act of 1983 made that Department responsible for establishing a statewide ground-water-quality monitoring network and a centralized data base for the acquired information.

The Department of Environmental Regulation, the water management districts, and the U.S. Geological Survey have water-resources programs throughout the State. Through these cooperative programs, much of the hydrologic data and interpretive information needed to manage and ensure the quality and quantity of water in Florida are made available. The data for this report were collected and compiled by the U.S. Geological Survey, 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.

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Prepared by Richard L. Marella, formally with the St. Johns River Water Management District and currently with the U.S. Geological Survey; History of Water Development section by Clyde S. Conover, U.S. Geological Survey (ret.)

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 227 N. Bronough St., Suite 3015, Tallahassee, FL 32301

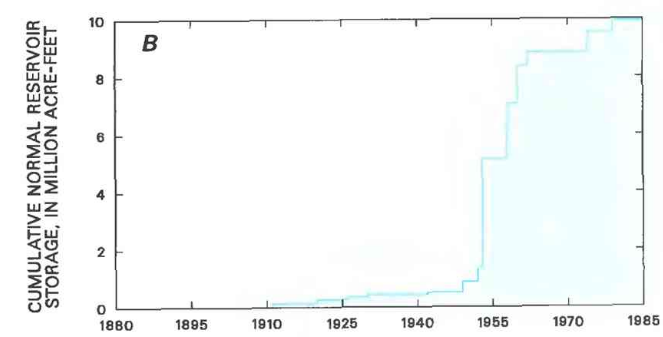
GEORGIA
Water Supply and Use

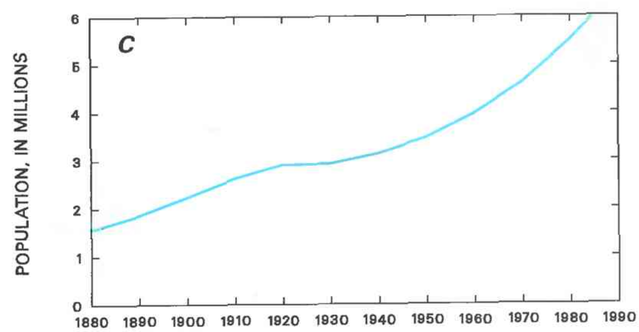
Georgia has been called a "headwaters" State because nearly all the available water originates within its borders (fig. 1*A*). It receives a statewide annual average of 50 inches of precipitation (Carter and Stiles, 1983), which ranks sixth among the contiguous 48 States in annual precipitation (National Oceanic and Atmospheric Administration, 1986). About 12 percent of this precipitation infiltrates into aquifers. In 1985, freshwater withdrawals from rivers, streams, and aquifers were 5,370 Mgal/d (million gallons per day). Of that quantity, about 16 percent was consumed, and the remainder was returned to streams, rivers, and aquifers.

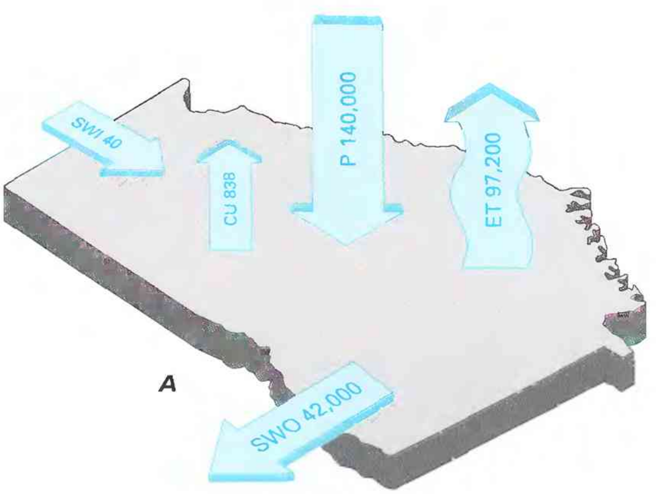
The northern one-half of the State, which is an urban and industrial region, relies primarily on surface water and has limited surface- and ground-water resources to accommodate increased use. The southern one-half of the State, which is primarily an agricultural area, depends mainly on ground water. The four major aquifers that underlie this region are capable of supplying from about 600 to 11,000 gal/min (gallons per minute) to individual wells.

Of all withdrawals, those for thermoelectric power generation were the largest. They accounted for 61.1 percent of withdrawals and 13.6 percent of consumptive use. Water withdrawn for domestic, commercial, industrial, and mining uses in 1985 was 30 percent (1,590 Mgal/d) of total freshwater withdrawals. In addition, about 9 percent of the total withdrawals was for irrigation, which accounted for about 60 percent of the total consumptive use in the State.

From 1980 to 1985, the State's population increased an estimated 9.4 percent (from 5.46 to 5.97 million), which placed Georgia 9th in population growth (U.S. Bureau of the Census, 1986). State officials have estimated that Georgia's population will increase annually by about 100,000 through the year 2000 (University of Georgia Extension Service, 1986). This projected population growth, along with the accompanying economic development, will increase the demands on supplies of freshwater. Even with Georgia's normally ample water supply, severe droughts in recent years have left







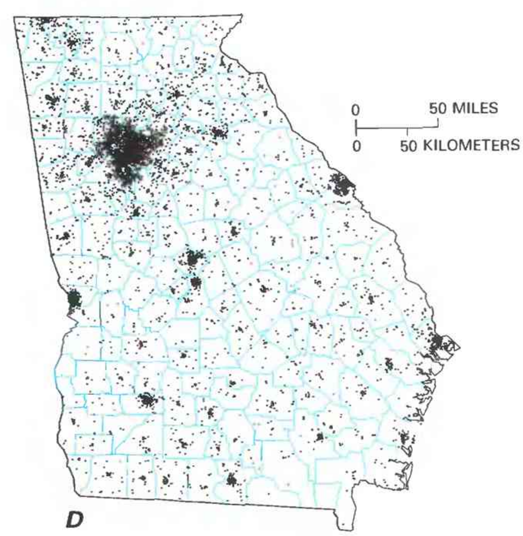


Figure 1. Water supply and population in Georgia. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Carter and Stiles, 1983. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

little assurance that sufficient water will be available in the right place and at the right time.

HISTORY OF WATER DEVELOPMENT

Water has been important in the development of Georgia, whose harbors and rivers gave early settlers ports and access to inland trade. Savannah, the State's first colony, was settled in 1733 by English colonists. Its harbor and waterways provided adequate port facilities and inland access, as well as a supply of freshwater (Granger, 1968). Early settlers diverted water from coastal rivers by systems of dikes and gates to flood fields of rice, and some of the coastal area fields were flooded and drained by tidal-powered gating systems. Navigation of the rivers, especially the Savannah, the Altamaha, and the Chattahoochee, provided natural paths for the settlement of the State. The major cities of Columbus, Macon, and Augusta are located on the Fall Line where rapids precluded further inland river travel.

North of the Fall Line, rivers helped promote industrial development by providing waterpower to operate gristmills, sawmills, and textile mills. The advent of the steamboat in the early 1800's reinforced the importance of rivers as highways of commerce. Georgia was one of the first users of steam navigation, which helped establish the rich "king cotton" trade from central Georgia (Coulter, 1960).

During the late 1800's, the State established a network of streamflow-gaging stations to determine the suitability of selected streams for power development and to assess the availability of water for mining operations, mainly gold. In the early 1900's, the first hydroelectric dams were constructed, and, by the mid-1900's, water storage had increased dramatically (fig. *1B*) to help meet the needs of the increasing population (fig. *1C*), especially in the northern part of the State (fig. *1D*). Seven major multipurpose dams were constructed by the U.S. Army Corps of Engineers to provide hydroelectric power, recreation, flood control, and navigation. Other than the power reservoirs that were built, impoundments were limited typically to farm and mill ponds because Georgia has few natural lakes.

Easy access to a water supply in the aquifers of southern Georgia spurred ground-water use. The introduction of center-pivot irrigation technology from the Great Plains into southern Georgia and the use of "traveling gun" irrigation systems allowed farmers to grow two or three crops a year. In addition, several large water-intensive industries were attracted to the abundant supplies of fresh ground water in the southern part of the State. As a result, ground-water withdrawals in Georgia doubled during the 1970's from 630 Mgal/d to more than 1,200 Mgal/d. Since 1980, ground-water withdrawals have remained relatively constant. In 1985, ground-water withdrawals totaled 1,000 Mgal/d, which is 17 percent less than during 1980.

WATER USE

Georgia has a substantial supply of water. The water budget (fig. *1A*) shows the quantities of water received as precipitation and surface-water inflows in 1985 and the quantities that were lost to evapotranspiration, consumptive use, and surface-water outflows.

Total water withdrawals, surface-water withdrawals, and ground-water withdrawals are shown by county in figure 2. Areas that have the largest withdrawals (fig. *2A*) within the State can be explained by identifying the principal categories of water use. The densely populated Atlanta area is a major center of public-supply withdrawals. Large withdrawals in central Georgia reflect the kaolin mining and processing industry and in northwestern Georgia, the carpet and textile industries. In coastal Georgia (Savannah and Brunswick areas), large withdrawals are associated with the chemical and forestry-product (pulp) industries, and, in southwestern Georgia, with irrigation. The distributions of surface- and ground-water withdrawals by county (figs. *2B,C*) reflect the dependence on surface water in the northern part of the State and the extensive development of ground water in the southern part.

Surface-water withdrawals by principal drainage basin are shown in figure *3A*. The largest withdrawals are in the Altamaha–St. Marys and the Apalachicola basins. Combined, these basins provide more than 70 percent of the surface water used in the State. The Apalachicola basin has the largest withdrawals for public supplies and is the source of water for more than one-fourth of the State's population. Most of Atlanta's water is supplied from the northern part of this basin.

Ground-water withdrawals by principal aquifer are shown in figure *3B*. Georgia's aquifers provide water for almost one-half of the total population of the State. The largest withdrawals are from the Floridan aquifer, which provides 65 percent of the ground water in the State. This aquifer is used in most of the counties in the southern one-half of Georgia.

Instream use is significant because the availability of waterpower has affected the placement of many of Georgia's industries. One instream use is hydroelectric power generation, which supplies 4.1 percent of the State's electricity. In recent years, hydropower generation was curtailed because of drought conditions and less-than-normal reservoir levels. As a result, less hydropower was generated annually from 1980 to 1985 than during the 1970's. In 1985, more than 40,000 Mgal/d was used to generate about 3,300 gigawatt-hours of electricity. The consumptive use of water in this process is mostly from evaporation, and the quantity involved is considered to be negligible. Other instream uses are harder to quantify. Georgia's rivers and streams also are used for waste assimilation, navigation, fish and wildlife habitat, and recreation.

The source, use, and disposition of freshwater in Georgia are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 4,370 Mgal/d of surface water was withdrawn in 1985, which represented 81.3 percent of the total withdrawals in the State. Of the 4,370 Mgal/d, 14.5 percent was withdrawn by public-supply systems, 0.1 percent was withdrawn by self-supplied domestic and commercial users, 6.6 percent was withdrawn by self-supplied industrial and mining facilities, 75.1 percent was withdrawn for thermoelectric power generation, and 3.8 percent was withdrawn for agricultural uses (predominantly irrigation). Other sources of water (saltwater and reclaimed sewage waste water) are not included in figure 4, but are discussed below under the appropriate categories.

The use data indicate that, in 1985, domestic and commercial use totaled 828 Mgal/d, which represented 15.4 percent of the State's total withdrawals. Of that quantity, 14.8 percent was obtained from ground-water sources, 84.7 percent was from public-supply systems, and 0.6 percent was from surface-water sources. About 17.7 percent of water for domestic and commercial use was consumed, and 82.3 percent was returned to streams and rivers where it was available for downstream use.

The disposition data indicate that, for all water withdrawn in the State, 15.6 percent (838 Mgal/d) was consumed and 84.4 percent (4,530 Mgal/d) was returned to natural sources. Domestic and commercial consumptive use accounted for 17.5 percent of total consumptive use, and domestic and commercial return flow accounted for 15.0 percent of total return flow.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In Georgia these systems deliver water for domestic and

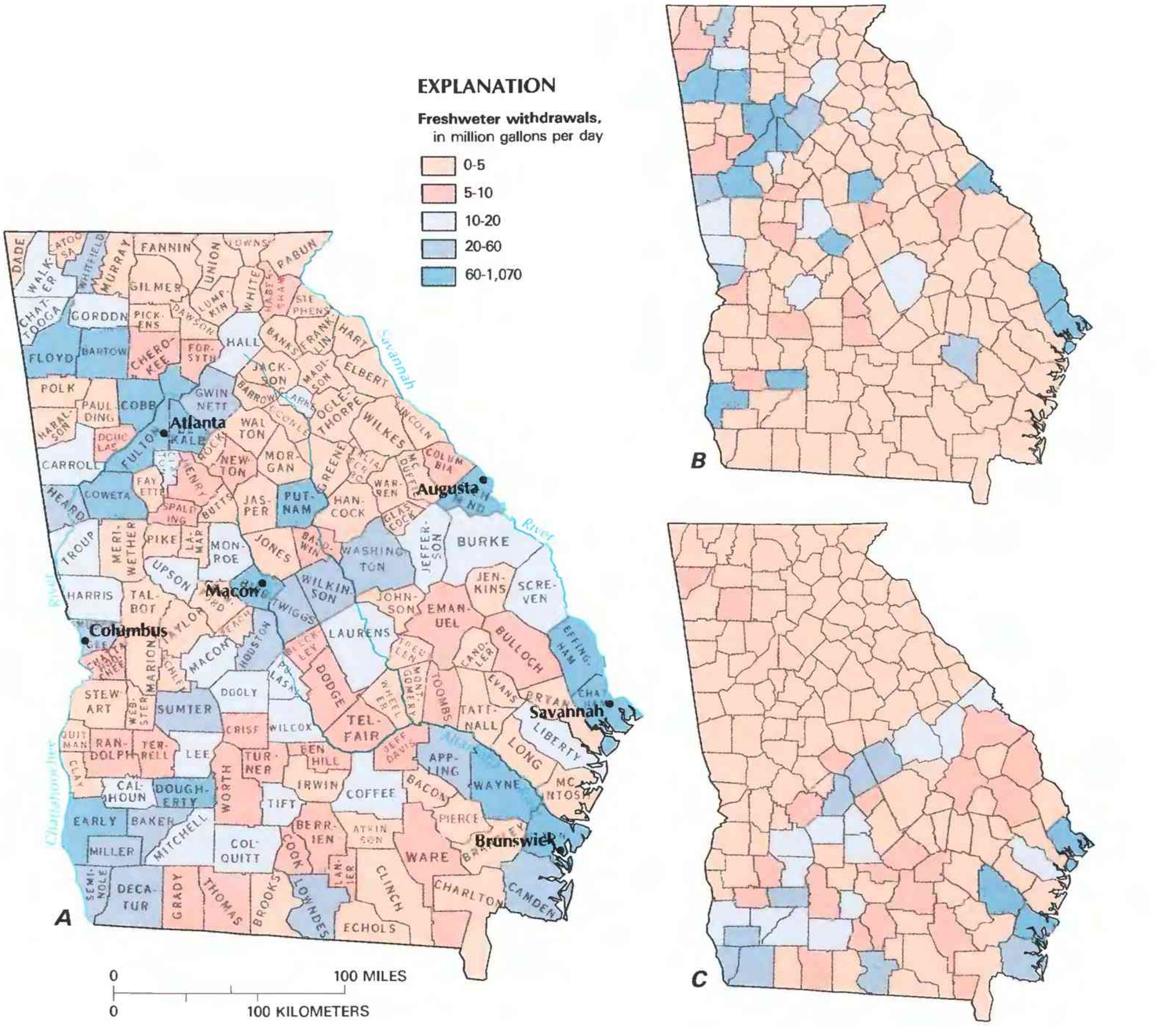
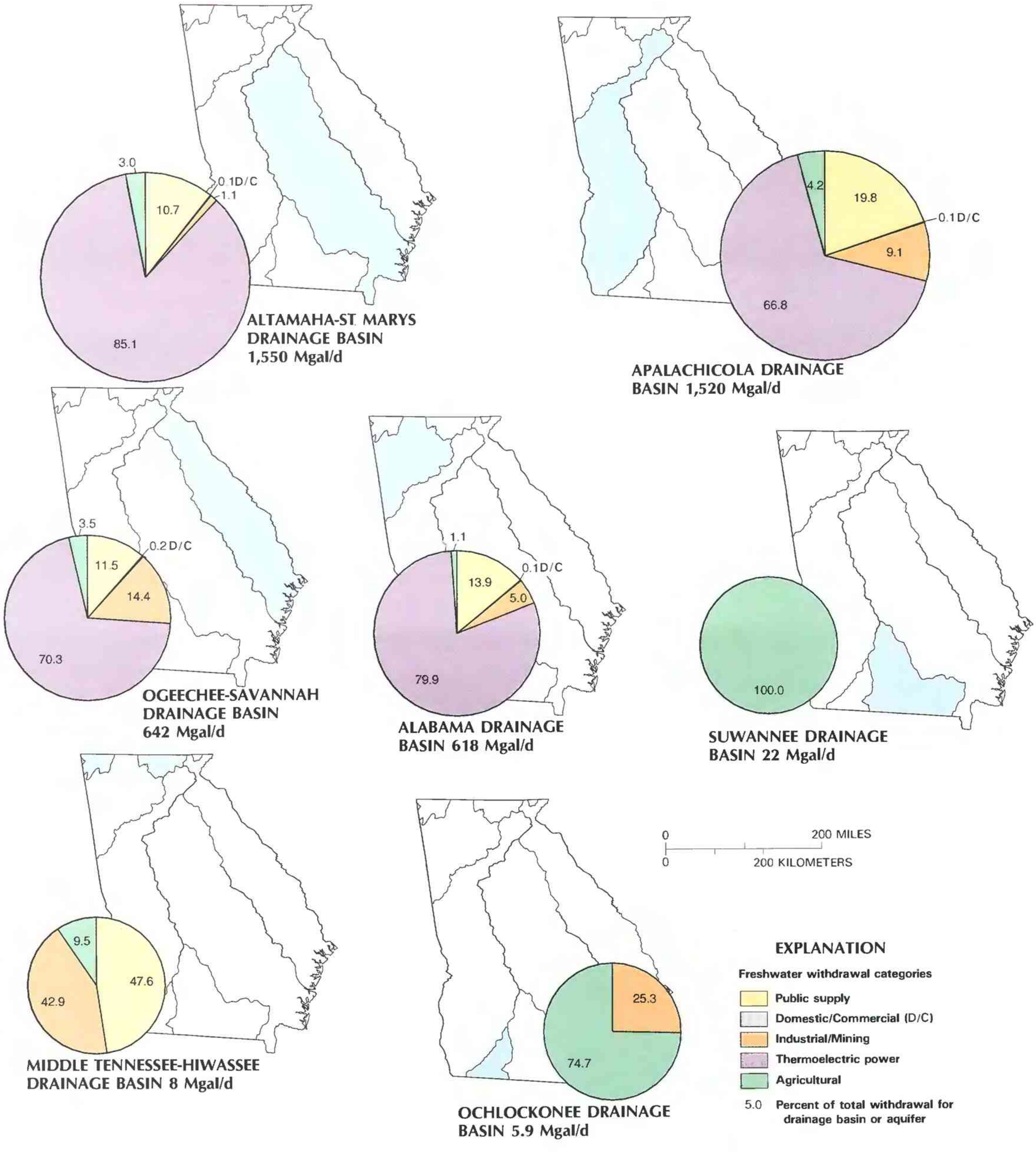


Figure 2. Freshwater withdrawals by county in Georgia, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

commercial use, industrial and mining use, and thermoelectric power generation (fig. 4). In 1985, the State was 11th in withdrawals for public supply in the United States and 11th in population (Solley and others, 1988). Withdrawals for public supply increased from 33 percent of total water withdrawals (excluding thermoelectric power) in 1980 to 39 percent in 1985. This increase was much more rapid than the population increase (fig. 5*A*). From 1950 to 1985, Georgia's population increased 73 percent (fig. 1*C*), but withdrawals for public supply increased 255 percent, which is a reflection of expanding commercial and industrial facilities and activities that depend on public-water supplies. Many cities, seeking to attract new jobs, offered to decrease the cost of water supplied to industries, saving them the time and expense of developing their own potable water supplies. Some of these cities also agreed to treat industrial wastewater as an added inducement.

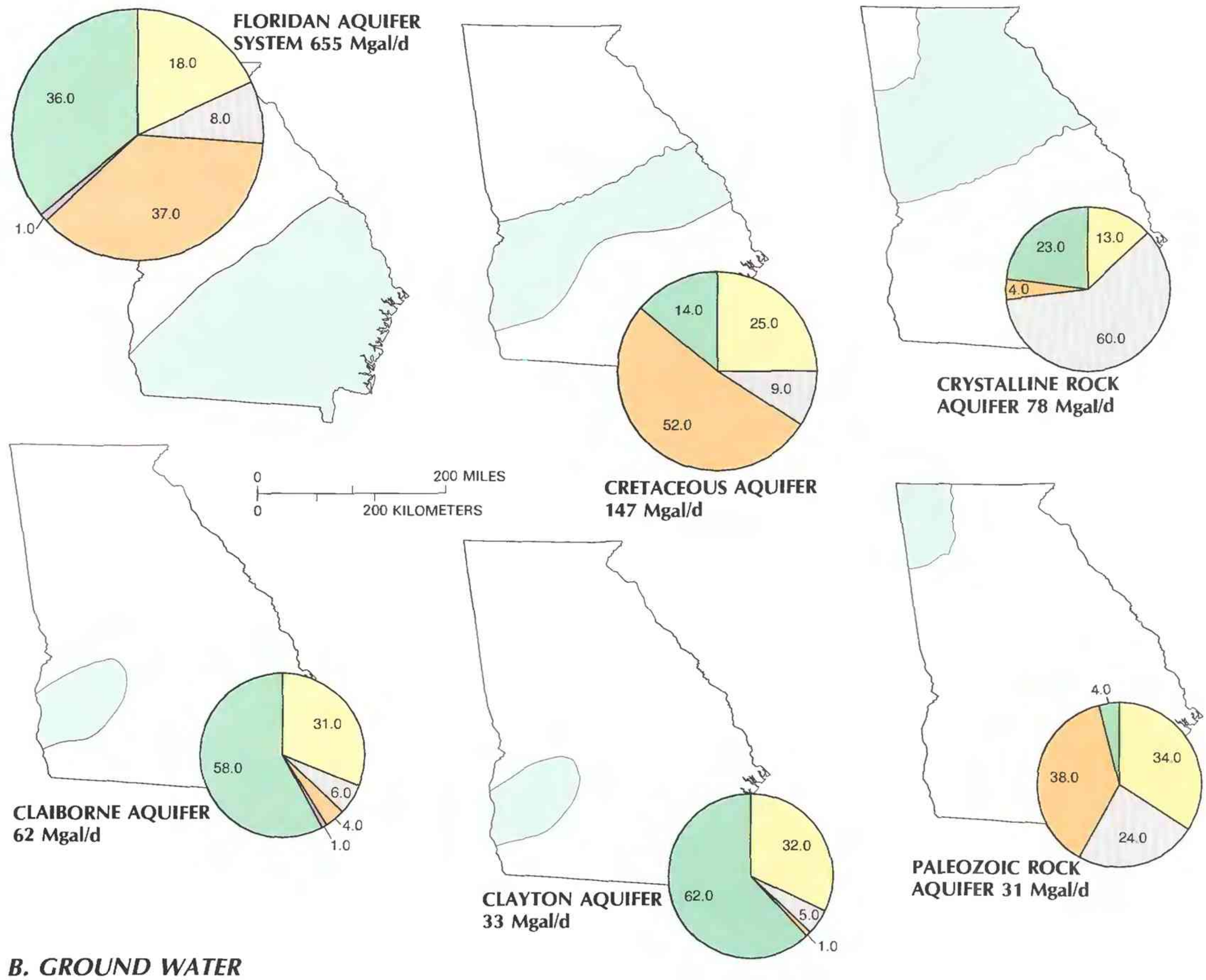
Total withdrawals for public supply in 1985 were 836 Mgal/d, of which 75.5 percent (631 Mgal/d) was surface water and 24.5 percent (205 Mgal/d) was ground water. The distribution of these withdrawals depends largely on the availability of ground water in the State. The southern one-half of Georgia (Coastal Plain) is underlain by thick layers of sand, clay, and limestone that form the most productive aquifers in the State. Three-fourths of the withdrawals in this area are from ground water. In contrast, most of the northern one-half of the State (Piedmont and Blue Ridge), where Georgia's population is greatest, is underlain by crystalline rocks that yield limited quantities of water. Thus, most large towns and cities in this region depend on surface water, which accounts for 99 percent of the water used (Barber, 1987). The northwestern corner of the State (Valley and Ridge and Appalachian Plateau) is underlain by folded sandstone, limestone, dolomite, and shale that generally yield small to moderate quantities of water to wells and springs. Surface water accounts for about 87 percent of the water used for public supply in that area.

Metropolitan Atlanta, which consists of many governmental jurisdictions, has a complex network of interconnected water systems, including public suppliers that withdraw, treat, and sell water and others that buy treated water and resell it. The unequal distribution of dependable surface-water sources in the Atlanta area has encouraged the interconnection of public-water systems. Public suppliers that have access to the more dependable sources of water have



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Georgia, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from various reports of the U.S. Geological Survey and State agencies.)



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Georgia, 1985—Continued.

expanded their water-treatment plants and sell water to public suppliers whose water sources are less dependable. The interconnection of water systems is advantageous during droughts when smaller streams and reservoirs become depleted.

Domestic and Commercial

Domestic and commercial users received water from public-supply systems and self-supplied facilities. Total use (public-supply deliveries and self-supplied withdrawals) in 1985 was 828 Mgal/d (fig. 4). Domestic use was about 644 Mgal/d, of which 545 Mgal/d was from public-supply systems that served 78 percent of the population, and 99 Mgal/d was for the 22 percent of the population that supply their own water from wells or springs. Consumptive use was 116 Mgal/d. People who purchased water for domestic use from a public-supply system used an average of 117 gal/d (gallons per day) per capita. The population served by their own water systems had a per capita use estimated at about 75 gal/d, which is substantially different from the 50- and 100-gal/d per capita use estimated in 1970 and 1980, respectively (Barber, 1987).

Commercial use in 1985 was about 171 Mgal/d, of which 28 Mgal/d was self-supplied and 142 Mgal/d was delivered by public-supply systems. Consumptive use was 31 Mgal/d. Although commercial water use is relatively small compared to domestic use, it is increasing.

Industrial and Mining

In 1985, freshwater withdrawals for industrial use totaled nearly 606 Mgal/d. Of this quantity, 323 Mgal/d was ground water, and 283 Mgal/d was fresh surface water. An additional 31 Mgal/d was withdrawn from saltwater sources. Also, 135 Mgal/d for industrial use was provided by public-supply deliveries. Georgia is the leading forestry State (University of Georgia Extension Service, 1986), and the paper industry uses more water than any of the other Georgia industries (fig. 5*B*).

Industrial withdrawals were 23 percent less during 1985 than during 1980. The decrease was distributed equally between surface and ground water. The decrease in industrial water use can be attributed, in part, to a decrease in industrial production as a result of economic conditions (Niemi and others, 1985). In addition, many industries began to scrutinize the quantity of water they used and to improve water-use efficiency. Decreased availability of water during intermittent droughts also has motivated many water-intensive industries to adopt water reuse and conservation practices. Paper

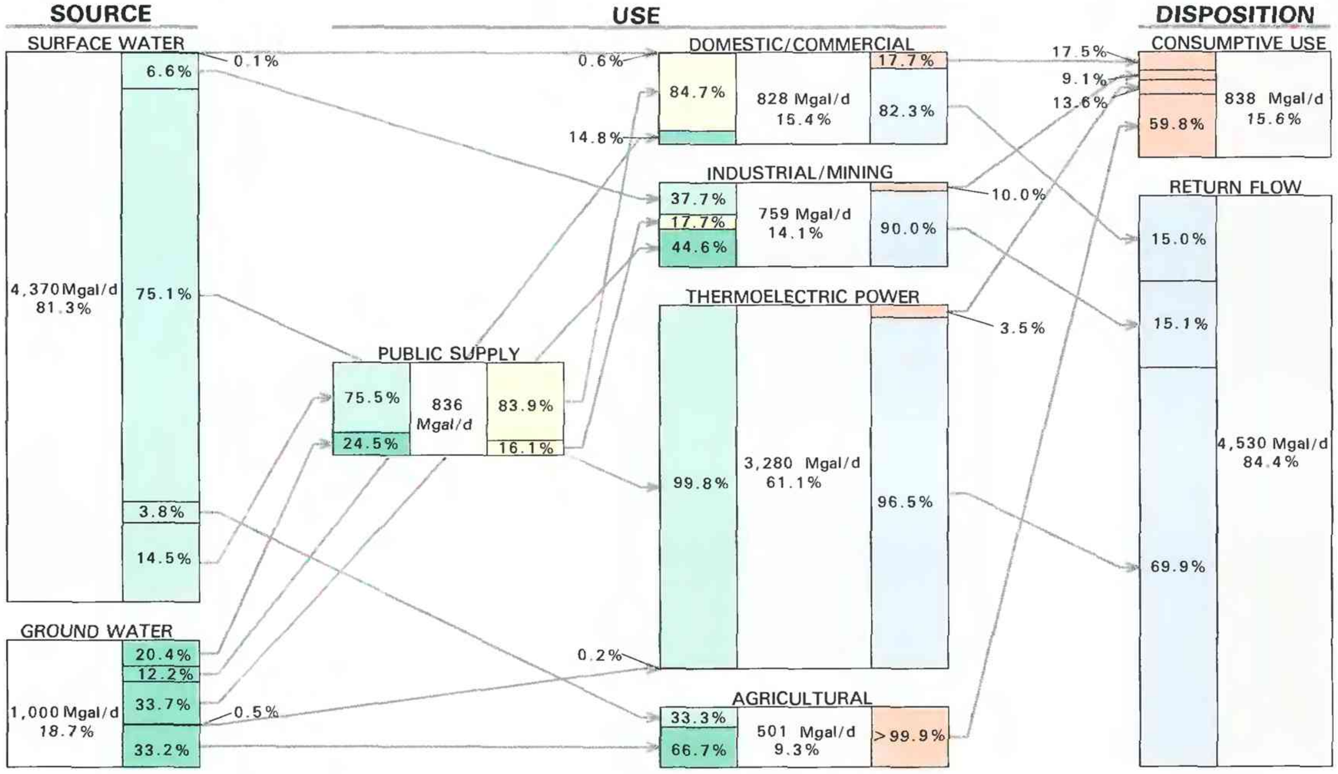


Figure 4. Source, use, and disposition of an estimated 5,370 Mgal/d (million gallons per day) of freshwater in Georgia, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

mills in the southern part of the State, for instance, have decreased their use of water by 40 to 50 percent during the last 5 years (Turlington and others, 1987).

Withdrawals for mining use were about 19 Mgal/d; ground water accounted for 84 percent of the withdrawals. Mining of kaolin, bauxite, gravel, and gold was the major water use. Nationally, Georgia ranks seventh in nonfuel mineral production and is the largest producer of kaolin (Steel and O'Connor, 1987).

THERMOELECTRIC POWER

As in many States, thermoelectric power generation is an important facet of Georgia's total water use. Georgia has 15 fossil-fuel powerplants and 2 nuclear powerplants. In 1985, these plants collectively withdrew 3,320 Mgal/d for cooling purposes. Of this quantity, fossil-fuel plants withdrew 3,220 Mgal/d of fresh surface water and 46 Mgal/d of saline surface water; nuclear plants withdrew 62 Mgal/d of fresh surface water. The plants withdrew less than 5 Mgal/d of ground water, principally to replenish water lost from boilers and for potable supplies. The withdrawal of water for cooling thermoelectric plants accounted for 61.1 percent of all water withdrawn in Georgia. However, most of the water was returned to streams and rivers, and only 3.5 percent was lost through evaporation. Consumptive use was 75 Mgal/d by fossil-fuel plants and 40 Mgal/d by nuclear plants.

AGRICULTURAL

Agricultural water use in Georgia in 1985 was dominated by irrigation. Irrigation withdrawals totaled 454 Mgal/d compared to nonirrigation agricultural withdrawals of 47 Mgal/d. Withdrawals for irrigation in Georgia increased by a factor of 12 from 1970 to 1980—from 50 Mgal/d to 580 Mgal/d (fig. 5*C*)—the fastest rate of increase in the southeastern United States (Pierce and Barber, 1984). During 1985, nearly one-third of the ground water withdrawn was for irrigation; more than 308 Mgal/d of ground water was withdrawn for irrigation, in contrast to 145 Mgal/d of surface water.

About 98 percent of the State's irrigation is in the southern part of the State where wells are extremely productive. The rapid increase in irrigation was promoted by several factors—a series of agricultural droughts, improved crop yields, and the introduction of new agricultural technologies. Large-acreage and large-water-volume systems, such as center pivots, are replacing many of the smaller irrigation systems previously used in Georgia (fig. 5*D*). During the 1980's, corn became the principal irrigated crop, surpassing the earlier leaders, tobacco and peanuts (Pierce and Barber, 1984).

Although nonirrigation agricultural use (livestock and fish farming) was only 47 Mgal/d during 1985, it was nearly double the 28 Mgal/d during 1980. This growth is primarily due to the introduc-

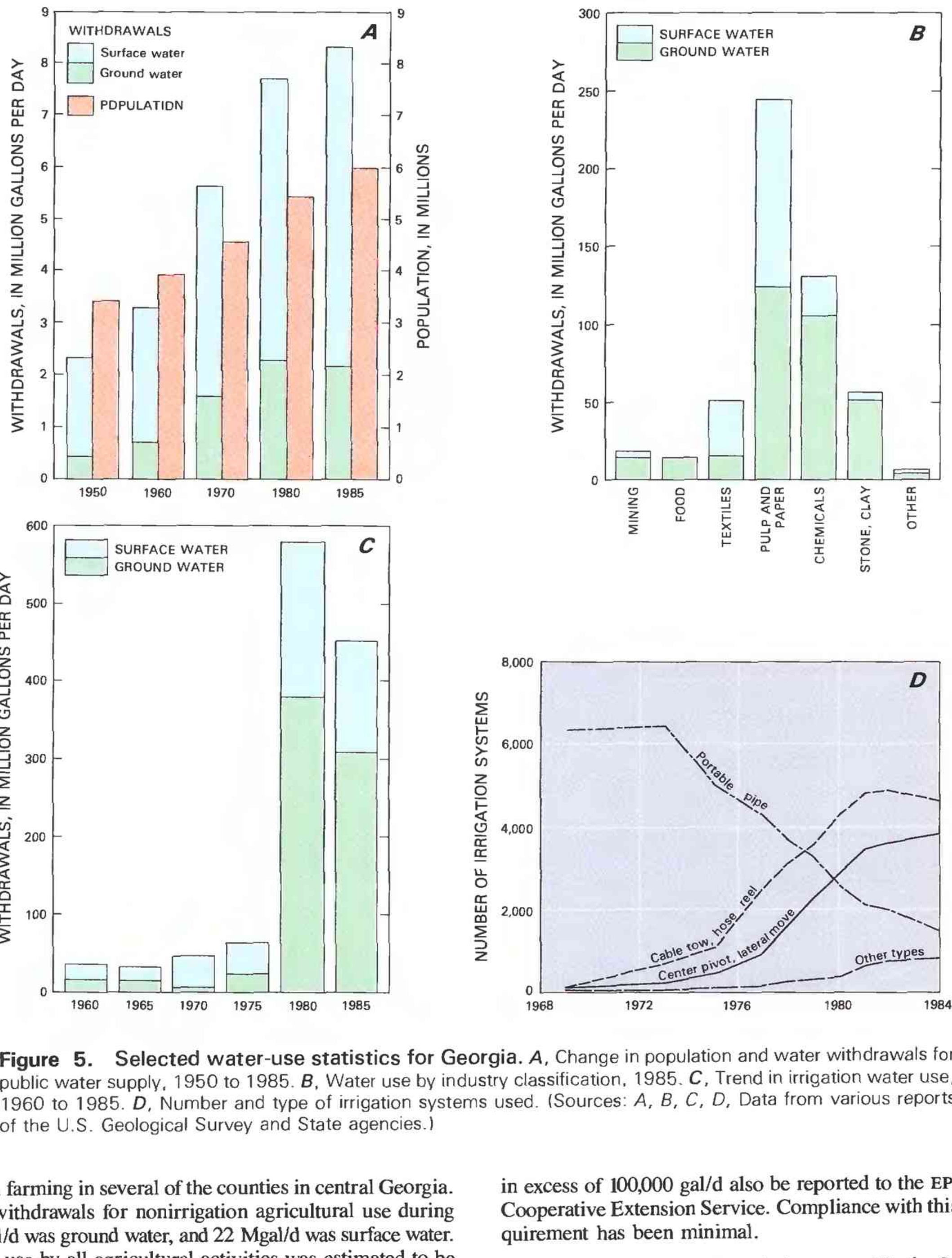


Figure 5. Selected water-use statistics for Georgia. *A*, Change in population and water withdrawals for public water supply, 1950 to 1985. *B*, Water use by industry classification, 1985. *C*, Trend in irrigation water use, 1960 to 1985. *D*, Number and type of irrigation systems used. (Sources: *A*, *B*, *C*, *D*, Data from various reports of the U.S. Geological Survey and State agencies.)

tion of catfish farming in several of the counties in central Georgia. Of the total withdrawals for nonirrigation agricultural use during 1985, 25 Mgal/d was ground water, and 22 Mgal/d was surface water. Consumptive use by all agricultural activities was estimated to be 100 percent of withdrawals.

WATER MANAGEMENT

Surface- and ground-water withdrawals are regulated by the Georgia Department of Natural Resources, Environmental Protection Division (EPD). Authority to regulate, by the issuance of permits, is provided by the 1977 Amendments to the Water Quality Control Act for Surface Water and by the 1972 Ground Water Use Act. The EPD has authority to issue permits for withdrawals of surface and ground water in excess of 100,000 gal/d. Agricultural withdrawals were exempted from the permit requirement by the Acts. Because of great increases in irrigation use in the late 1970's, the 1982 amendments to the Acts required that irrigation withdrawals in excess of 100,000 gal/d also be reported to the EPD through the Cooperative Extension Service. Compliance with this reporting requirement has been minimal.

Water demand in Georgia is managed in the following ways:

- Through the permitting process, the EPD can effectively address the locations of major water-using facilities. Applications for permits are reviewed by the EPD to determine whether the requested withdrawal will adversely affect the water source. Based on the review, the permit may be granted, the application may be amended so as to meet the needs of the applicant without causing adverse effects, or the permit may be denied. The EPD has used this process to direct major water-using facilities to areas that have adequate water to meet their needs.
- The EPD also uses an administrative approach to the permitting process, rather than a prior appropriations approach, to force conservation efforts by water users and to control demand.

• Before issuing a permit for water withdrawal, the EPD requires the permittee to have a drought-management plan. This plan, tailored to the needs of the industry or public supplier, addresses specific procedures to be initiated during a drought emergency. The 1986 drought in Georgia provided the first major test of these plans. During the drought, the EPD sent letters to permittees, primarily those that depend on small streams for water supply, directing them to implement their drought-management plans. Nonessential water uses, such as lawn watering, were limited first, and more severe restrictions were implemented as the drought persisted. This approach was effective, as shown by the cooperation of the permittees and the public.

• The EPD requires that water-saving devices for showers, toilets, and faucets be used in buildings constructed or renovated after July 1, 1980. Toilets can use no more than an average of 3.5 gallons per flush, and shower heads and faucets can allow flow of no more than an average of 3.5 gal/min at a pressure of 60 pounds per square inch.

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Prepared by R.R. Pierce, U.S. Geological Survey; Water Management section by J.E. Kundell, Vinson Institute of Government, The University of Georgia

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Suite B, 6481 Peachtree Industrial Boulevard, Doraville, GA 30360

HAWAII
Water Supply and Use

Hawaii has the most abundant rainfall of any State. Average annual rainfall for Hawaii is about 70 inches, or 22,000 Mgal/d (million gallons per day) (fig. 1A), which is the State's only source of freshwater. About 40 percent of rainfall is lost through evapotranspiration, about 30 percent is average annual runoff, and 30 percent is ground-water discharge to the ocean. As an island State, Hawaii is unique in that it does not receive additional fresh surface or ground water from other States or countries.

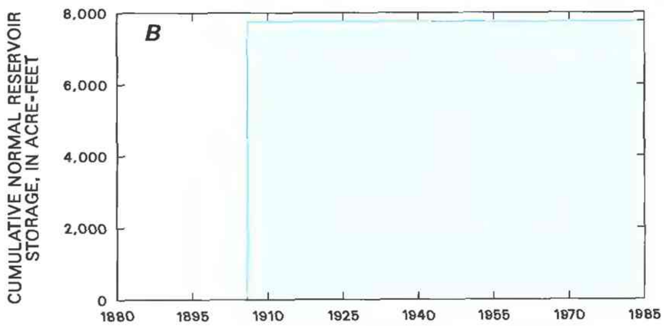
In 1985, 1,270 Mgal/d of freshwater was withdrawn from surface- and ground-water sources, which is equivalent to 1,100 gal/d (gallons per day) per capita. In 1985, about 132 Mgal/d of the total freshwater withdrawn was consumed, and 1,140 Mgal/d was returned to a natural water source.

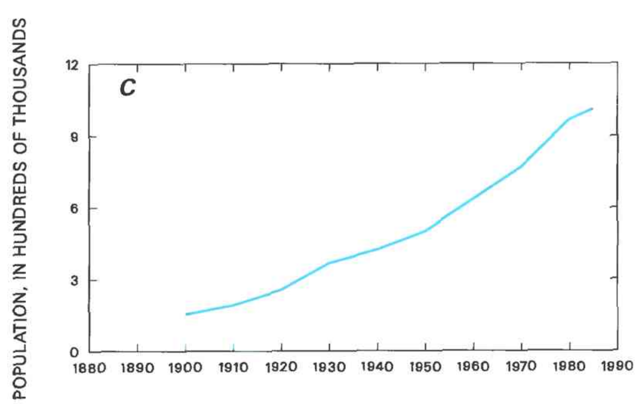
In 1985, agriculture, which was the largest water user, used 910 Mgal/d and accounted for 71.8 percent of water withdrawn and 17.4 percent of consumptive use. Domestic and commercial use was 241 Mgal/d and accounted for 19.0 percent of water withdrawn and 77.1 percent of consumptive use. The remaining 9.2 percent of water withdrawn was for industrial and mining use (27 Mgal/d) and thermoelectric power generation (90 Mgal/d). These remaining uses accounted for 5.5 percent of consumptive use.

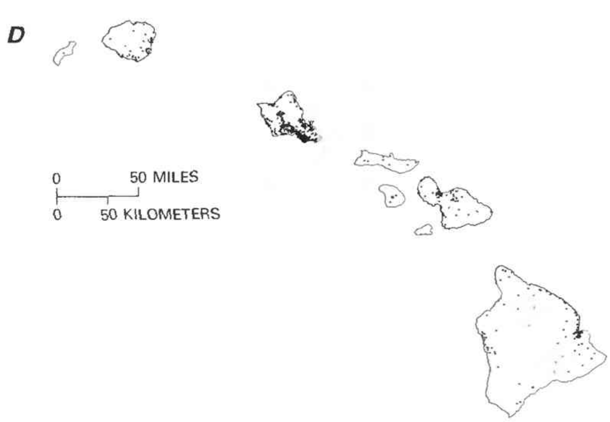
The State's resident population increased 8.5 percent from 1980 to 1985 (Hawaii Department of Planning and Economic Development, 1986). During this period, the visitor population increased 20.9 percent. The increasing resident and visitor populations are approaching the limits of the existing water supply in some areas of the State—especially in the Honolulu area, where demand already exceeds recoverable water supply. Local domestic water-supply deficits have been projected for one area on Maui and three areas on Oahu by the year 2020 (Hawaii Water Resources Regional Study, 1979).

HISTORY OF WATER DEVELOPMENT

Water supply has been a dominating feature of the evolution of the Hawaiian economy from the first settlement in about A.D. 650 to recent times. The prehistoric Hawaiians relied on water from streams, springs, and shallow excavations to irrigate their taro patches and other crops. Water use was greatly expanded in the 16th century by ingenious water-control technology as large-scale irrigated terraces (lo'i) and ditch ('auwai) systems were developed for irrigation in valleys. Water use was regulated by the Hawaiian chiefs and the land managers (konohiki), and the land was cultivated by the commoners on specified days. This same supply had to satisfy the demands of an expanding economy for a century after the opening of the archipelago to the western world by Captain James Cook in 1778.







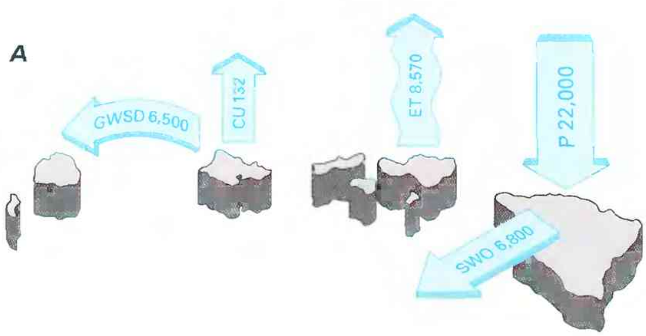


Figure 1. Water supply and population in Hawaii. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution by islands, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU**, consumptive use; **ET**, evapotranspiration; **GWSD**, ground-water storage depletion; **P**, precipitation; **SWO**, surface-water outflow. (Sources: *A*, Takasaki, 1978. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

When Cook arrived, the population of the islands is estimated to have been about 300,000; however, a century later, the population had been devastated by disease and dislocation and had diminished to about 60,000. Nevertheless, demand for water had already exceeded the easily available surface supply. Large-scale utilization of surface water, which is abundant in the rainy mountain regions, was made possible by the first gravity canal, which was constructed by western entrepreneurs in 1856 to transport the surface water to drier land for sugarcane irrigation on Kauai. The success of the Kauai canal inspired greater use of surface water on Maui for similar uses. Construction of aqueducts—the first being the Hamakua "ditch" (17 miles long, 60-Mgal/d capacity)—was completed in 1878. Reservoirs to store surface water also were constructed (fig. 1*B*).

The great impetus to the advancing economy came with the discovery of artesian ground water in the Ewa Plain of Oahu in 1879. Widespread drilling shortly thereafter proved the existence of a vast ground-water resource. The experience was quickly repeated in all the major islands. Large sugarcane plantations were organized in fertile, but arid, areas where their success depended on availability of ground water for irrigation. The concept of skimming-tunnel technology evolved and led to the construction of the first infiltration gallery in Maui in 1923. Honolulu prospered and grew after a large artesian ground-water system was discovered within the city. Honolulu soon became the uncontested urban and commercial center in the island chain.

In the early 1900's, the public had become alarmed about the long-term sufficiency of the water resources, especially in Honolulu. A severe drought in 1926 magnified this concern. In Honolulu, a Board of Water Supply was created in 1929 and given regulatory powers over water development. Basic investigations and data collection by the U.S. Geological Survey, which had started a few years earlier, were expanded.

The granting of statehood to Hawaii in 1959 set off a wave of economic activity that continues today. Expansion of the tourist industry, enhancement of the military sector, revitalization of agriculture, and the creation of light industry have been the impetus of prosperity and population growth. The adequacy of water resources continues as a public issue, once again accented by severe drought during the last several years. On Oahu, the principal aquifers have been placed under State control. After nearly a decade of legislative attempts, a State Water Code to regulate all water development became law in 1987.

Today, Hawaii has a population of more than 1 million, 77 percent of which resides on Oahu. On Oahu, water resources must be carefully allocated and managed among the principal use sectors—domestic, commercial, industrial, thermoelectric, and agricultural. The limited water supply is not, however, as apparent on the other islands, although, on Maui, the ground- and surface-water supplies are approaching the limits of development.

WATER USE

In spite of the abundance of freshwater, problems in meeting water demands are common; for example, the population seems to be increasing most rapidly where the available water supply is limited or where the demand is already stressing the available supply. Hawaii's population growth and the population distribution in 1985, are shown in figures 1*C* and 1*D*, respectively.

The island of Oahu has the greatest problems. Projections indicate that "virtually all of the existing or planned sources of domestic quality water on Oahu might be developed to their limits by the year 2000" (Hawaii Water Resources Regional Study, 1979, p. 52). Freshwater supplies are adequate to satisfy the needs for development on the other islands beyond the year 2000.

Total, surface-water, and ground-water withdrawals by county in 1985 are shown in figures 2*A*,*B*,*C*, respectively. Each of the four large counties withdrew more than 100 Mgal/d of surface and ground water during 1985 (fig. 2*A*). The fifth county, Kalawao, which is a small peninsula on the northern side of the island of Molokai, is considered to be part of Maui County for this report because of its small water use and population (fig. 2*B*). The counties of Maui and Kauai were the largest users of surface water. The City and County of Honolulu and Maui County were the largest ground-water users (fig. 2*C*).

In Maui County, the largest withdrawal of surface water (333 Mgal/d) was used mainly for agriculture (fig. 3*A*). Oahu had the smallest surface-water withdrawals—43 Mgal/d. Oahu's ground-water withdrawals, however, were the largest in the State (358 Mgal/d) and were mainly for domestic, commercial, and agricultural uses (fig. 3*B*).

The source, use, and disposition of freshwater in Hawaii are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 655 Mgal/d of ground water was withdrawn; this was 51.6 percent of the total freshwater withdrawals in Hawaii in 1985. Of that amount, 6.6 percent was directly withdrawn (self-supplied) for domestic and commercial use; 2.4 percent was self-supplied for industrial and mining use; 13.2 percent was for thermoelectric use, 51.5 percent was for agricultural use, and 26.3 percent was withdrawn by public supply. The use data indicate that domestic and commercial users accounted for 241 Mgal/d, or 19.0 percent of the State's total withdrawals. Of that amount, 81.9 percent was delivered from public-supply systems, 18.0 percent was directly withdrawn from ground-water sources, and 0.1 percent was directly withdrawn from surface-water sources. Of the water used for domestic and commercial use, 42.1 percent was consumed, and 57.9 percent was returned to the hydrologic system. The disposition data indicate that, of all water withdrawn in the State, 132 Mgal/d, or 10.4 percent, was consumed and 1,140 Mgal/d, or 89.6 percent, was returned to a natural water source. The data also indicate that domestic and commercial users accounted for 77.1 percent of the total consumptive use and 12.3 percent of the total return flow.

PUBLIC SUPPLY

Within the county governments, public water-supply systems are managed and operated by a Department of Water Supply or a Board of Water Supply (BWS). Public-supply systems withdraw, treat, and deliver water to users. Total public water-supply withdrawals in 1985 were 204 Mgal/d, of which 84.6 percent (172 Mgal/d) was from ground-water sources and 15.4 percent (31 Mgal/d) was from surface water. About 96.9 percent of the public-supply withdrawals was delivered to domestic and commercial users. The remaining 3.1 percent was delivered for industrial and mining uses.

The largest withdrawals for public water supply were on the island of Oahu, where 77 percent of the State's resident population lives. In 1985, the Honolulu BWS withdrew 130 Mgal/d of ground water to provide water to the people of Oahu. This withdrawal was 64 percent of the total public supply withdrawals in the State and 76 percent of the public supply withdrawals from ground-water sources. On the islands of Maui and Hawaii, 70 percent and 29 percent, respectively, of the total public-supply withdrawals were from surface-water sources.

The island of Oahu has an excellent natural ground-water system. A combination of large rainfall and permeable geologic structure allows the water to infiltrate easily to the aquifers; a caprock around much of the island retards ground-water flow to the ocean. In spite of this nearly ideal system, Oahu has the most serious water-supply problems in the State. The system is used intensively for

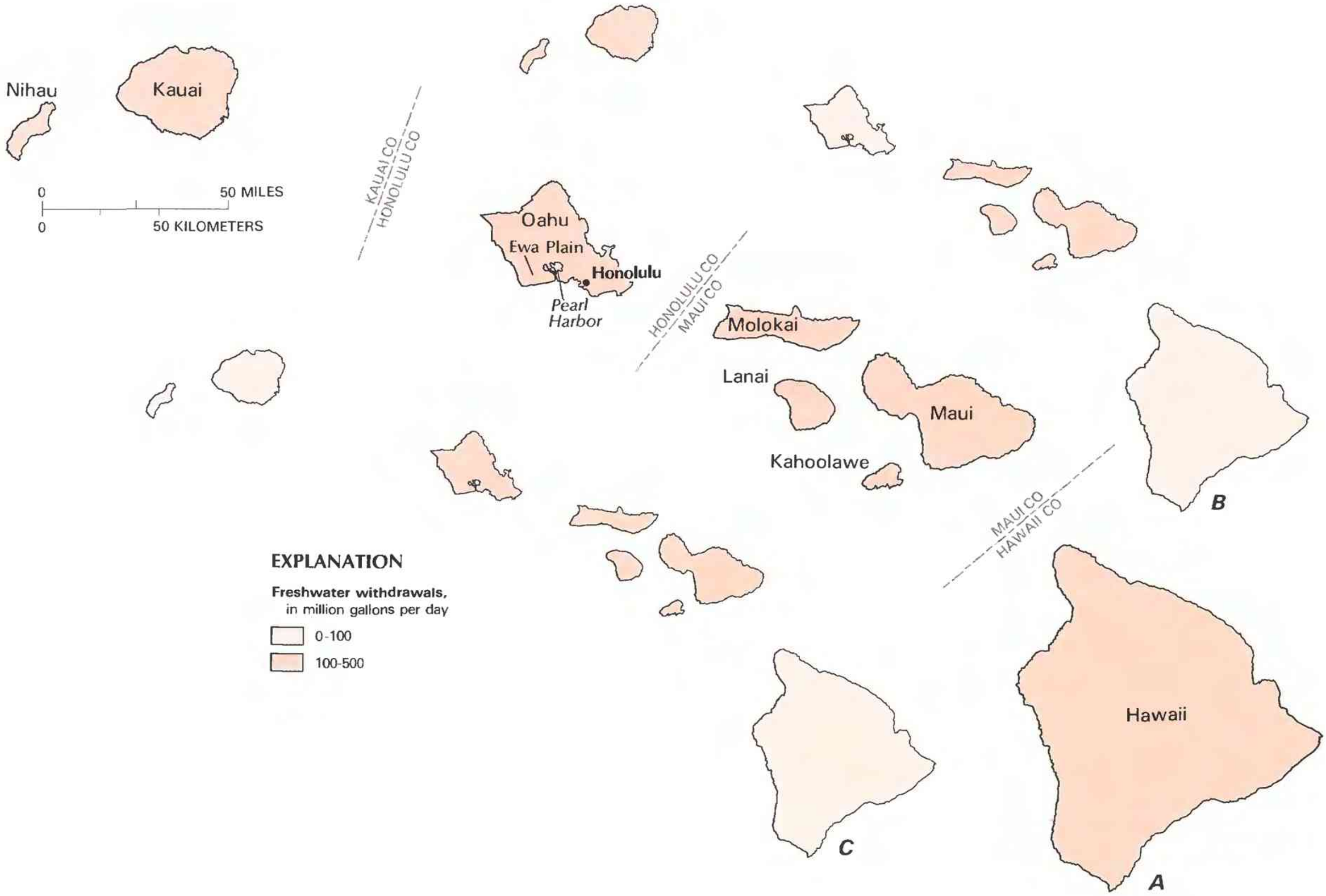


Figure 2. Freshwater withdrawals by county in Hawaii, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

agriculture and by the increasing resident population and the growing tourist industry.

To help alleviate Oahu's water-supply problems, Hawaii's Department of Land and Natural Resources (DLNR), Division of Water and Land Development (DOWALD), plans to build a desalination plant on the Ewa Plain of leeward Oahu. Construction is expected to start in 1988. The Honolulu BWS will manage and operate the plant during a 5-year study to test the feasibility of using desalted brackish ground water to supplement Oahu's limited ground-water supply. The pilot project calls for processing 1 Mgal/d. If the project is successful, the output may be expanded to 10 Mgal/d.

Domestic and Commercial

In 1985, total withdrawals and deliveries for domestic and commerical use were 241 Mgal/d, and consumptive use was 101 Mgal/d. Domestic and commercial users in Hawaii received 81.9 percent, or 198 Mgal/d, from public-supply systems (fig. 4). The other 18.0 percent was received from self-supplied facilities. Withdrawal for domestic use was 143 Mgal/d, of which 92 percent was delivered from public-supply systems that served 98 percent of the population, and 8 percent was self-supplied for 2 percent of the population (Solley and others, 1988). Consumptive use was 71 Mgal/d.

Withdrawals for commercial use in 1985 totaled 83 Mgal/d. Deliveries from public-supply systems totaled 51 Mgal/d, and 32 Mgal/d were self-supplied. Consumptive use was 31 Mgal/d. All the withdrawals for commercial use were from ground-water sources. Oahu had 88 percent of the commercial use and 96 percent of the consumptive use by commerical users.

Industrial and Mining

Industrial use is the smallest water use in Hawaii, and there is no reported mining water use. In 1985, only 27 Mgal/d, or 2.1 percent of all the freshwater withdrawals in the State, was for industrial use (fig. 4). Of the total industrial use, self-supplied systems provided 58.3 percent (16 Mgal/d) from ground water and 23.8 percent (4.8 Mgal/d) from surface water. Public-supply systems provided the remaining 17.9 percent (6.4 Mgal/d). Consumptive use totaled 6.3 Mgal/d.

Most industrial water use is for process water in the sugar mills. Where feasible, process water is recycled for irrigation. Industrial use decreased during the past two decades because many of the sugar mills were closed during that period. Industrial water demand probably will continue to decrease over the next decade because of more efficient water use by the sugar industry and a decline in the sugar industry as more mills close or become smaller.

Thermoelectric Power

Hawaii's electric companies use fossil fuel for thermoelectric power generation. No nuclear or geothermal electric plants have

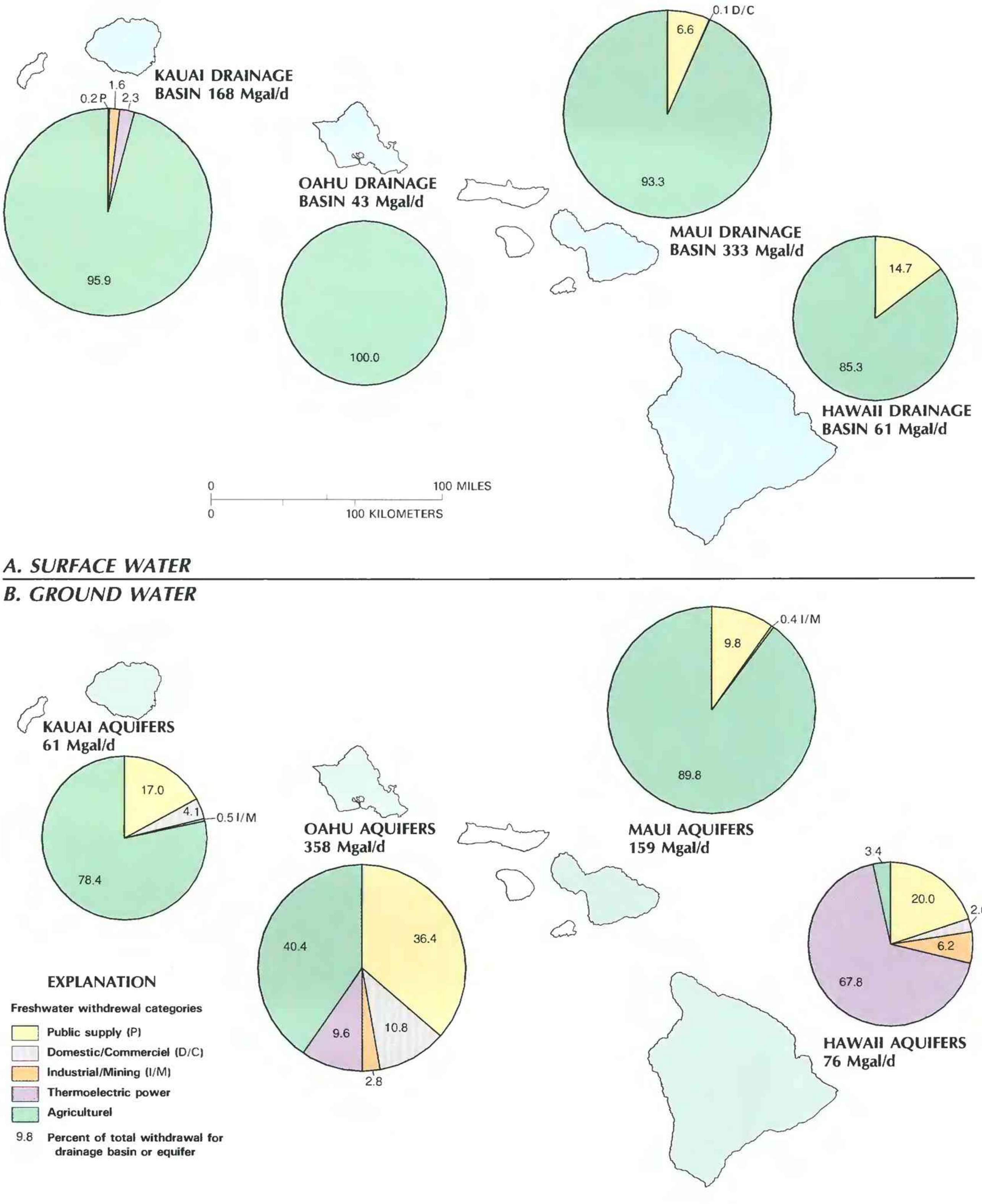


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Hawaii, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files and aquifer map from U.S. Geological Survey, 1985, p. 187.)

been used commercially in Hawaii; however, the State and private enterprise are experimenting to generate electricity from geothermal energy. Hawaii is trying to decrease its dependence on imported fossil fuel. Other local potential energy sources are hydroelectric, wind, and ocean-thermal energy.

Thermoelectric powerplants in Hawaii used 90 Mgal/d of freshwater in 1985 (fig. 4). Ground-water sources supplied 95.8 percent (86 Mgal/d) of the freshwater withdrawals, and the other 4.2 percent (3.8 Mgal/d) came from surface-water sources. Consumptive use of freshwater was 1.0 percent (0.9 Mgal/d). Thermoelectric powerplants also used 880 Mgal/d of saline surface water for cooling purposes. Thermoelectric use of freshwater amounted to only 7.1 percent of the total freshwater used in the State, but the total thermoelectric water use (fresh and saline) was 45 percent of all water withdrawals in Hawaii.

AGRICULTURAL

Agriculture is the largest water user in Hawaii. Irrigation and non-irrigation agricultural water use in 1985 totaled 910 Mgal/d, or 71.8 percent of all freshwater use. Of this amount, only 4 Mgal/d was for uses other than irrigation. Surface water supplied 63.0 percent, or 573 Mgal/d, of the water used for agriculture (fig. 4). Agricultural water use consumed 2.5 percent, and 97.5 percent was returned to flow systems.

The island of Maui used 444 Mgal/d for irrigation in 1985, which was the largest amount of water used for agriculture, and the largest amount of surface water for irrigation (309 Mgal/d) in the State. Of the four largest islands in the State, the island of Hawaii had the largest acreage under cultivation; however, it used the least amount of water for irrigation—52 Mgal/d. This is because the island of Hawaii has a large acreage of crops that use much less water than sugarcane, the State's largest agricultural crop, and the large acreage of sugarcane on Hawaii is in large-rainfall areas that require little or no irrigation.

The sugar industry was the principal pioneer and developer of Hawaii's water resources. Sugar producers drilled the first wells, dug the first water tunnels to tap the large supply of dike-impounded water, and constructed most of, if not all, the ditch systems. Because the sugar industry is the largest user of freshwater in the State, it can have the greatest effect on availability of water from existing sources.

During the past several years, the sugar companies have been switching from furrow irrigation to drip irrigation, which is more efficient. Estimates indicate that the drip method can save approximately 30 percent of irrigation water (Hawaii Water Resources Regional Study, 1979, p. 88). If some of these savings could be applied to other users, some of the water-supply problems in the State might be alleviated.

WATER MANAGEMENT

The Hawaii State Constitutional Convention of 1978 charged the State with an obligation "to protect, control, and regulate the use of Hawaii's water resources for the benefit of its people" (Hawaii Advisory Study Commission on Water Resources, 1985, p. 1). It also required the legislature to provide for a water resources agency that, as provided by law, shall set overall water conservation, quality, and use policies; define beneficial and reasonable uses; protect ground- and surface-water resources, watersheds, and natural stream environments; establish criteria for water use priorities while assuring appurtenant rights and existing correlative and riparian uses; and

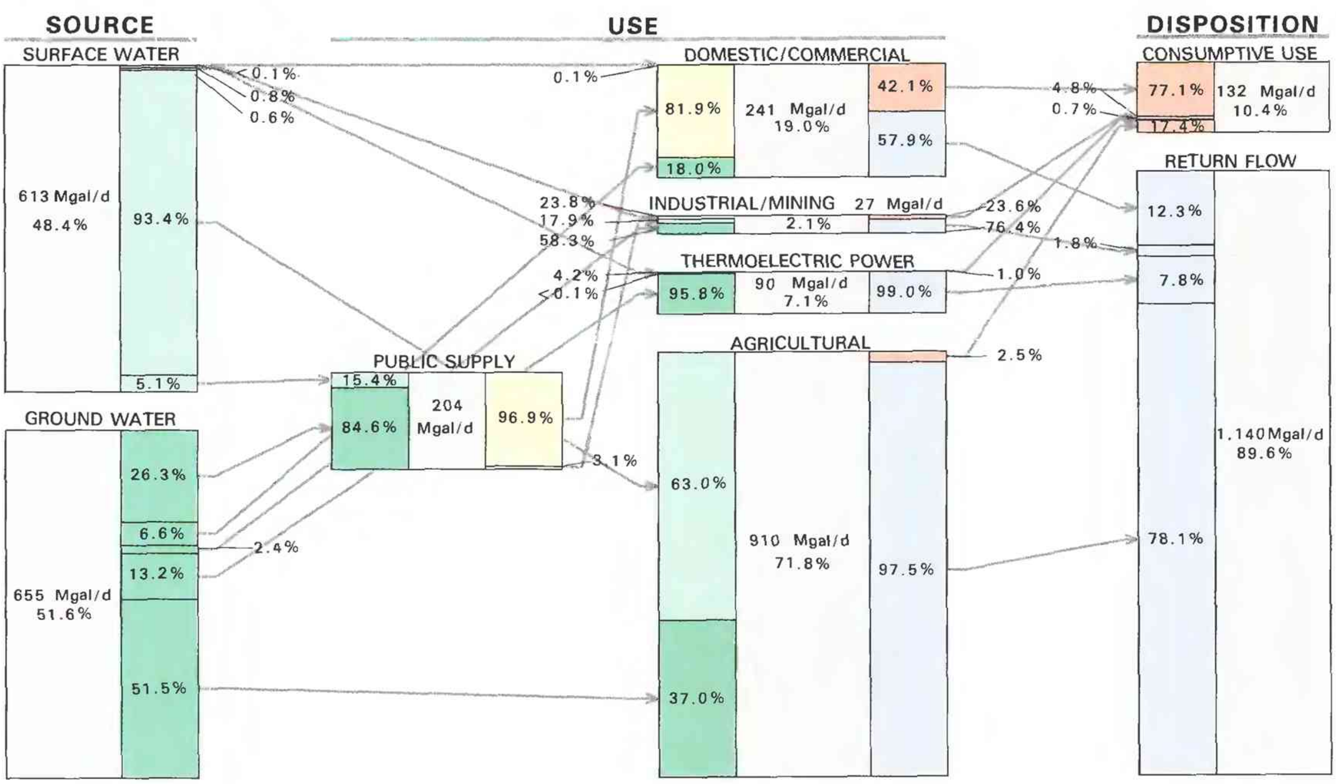


Figure 4. Source, use, and disposition of an estimated 1,270 Mgal/d (million gallons per day) of freshwater in Hawaii, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

establish procedures for regulating all uses of Hawaii's water resources (Hawaii Advisory Study Commission on Water Resources, 1985, p. 1-2).

An Act related to the administration of the State Water Code was approved by the legislature of the State of Hawaii and signed by the Governor in 1987. The Act took effect July 1, 1987, and specified that general administration of the State Water Code will rest with the Commission on Water Resources Management. The commission will consist of six members who will serve without compensation, except for expenses incurred in the performance of their duties. The chairperson of the Hawaii Board of Land and Natural Resources will be the chairperson of the Commission. The Director of the Department of Health will serve as an ex-officio voting member. The other four members will be appointed by the Governor subject to confirmation by the Senate. A Deputy for Water Resources Management will administer and implement the State Water Code under the direction of the Commission. The deputy will be appointed by the chairperson with the approval of a majority of the Commission.

Before enactment of the State Water Code, the DLNR through its DOWALD managed the water resources of the State. Chapter 177 of the Hawaii Revised Statutes, as amended, relating to Ground Water Resources of the State, and reenacted by Act 122 of the 1961 Session Laws of Hawaii, authorized the DLNR to designate ground-water control areas in the State for regulation, protection, and control, where existing or foreseeable future conditions will endanger the supply or condition of the water in such areas. Three areas on Oahu have been designated Ground-Water Control Areas (GWCA)—Pearl Harbor, Honolulu, and Waialua (fig. 5).

Under Chapter 177, the DLNR was not authorized to regulate ground-water use in nondesignated areas. With the exception of Windward Oahu, the authority to regulate the use of surface water also was absent. With the enactment of the State Water Code, the State will now be able "to protect, control, and regulate the use of Hawaii's water resources for the benefit of its people" (Hawaii Advisory Study Commission on Water Resources, 1985, p. 1).

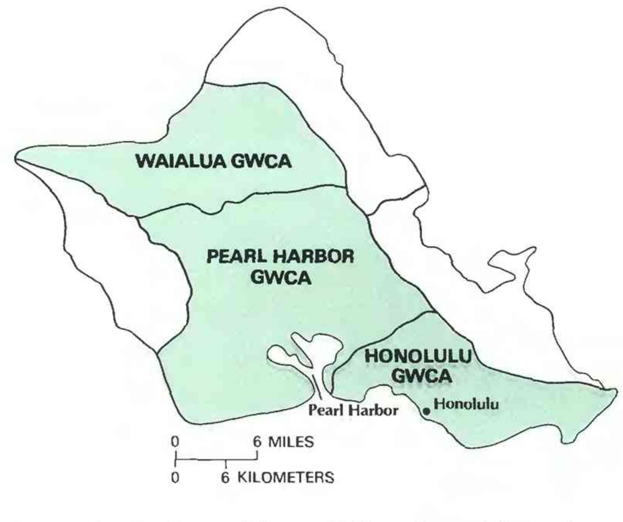


Figure 5. Designated Ground-Water Control Areas (GWCA) on the island of Oahu. (Source: State of Hawaii, Department of Land and Natural Resources.)

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Prepared by Reuben Lee and Marty G. Lum, U.S. Geological Survey; History of Water Development section by J.F. Mink and L.S. Lau, University of Hawaii, Water Resources Research Center.

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 677 Ala Moana Blvd., Suite 415, Honolulu, HI 96813

IDAHO
Water Supply and Use

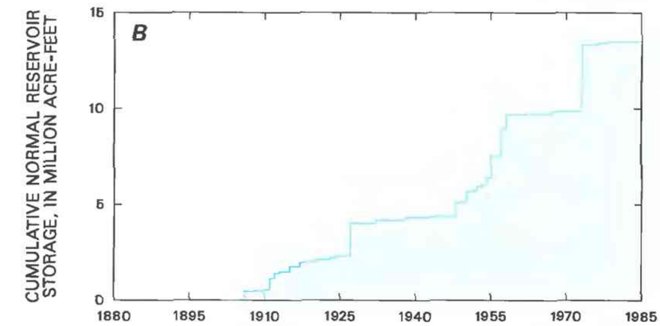
Idaho receives an average of about 22 inches per year, or 87,500 Mgal/d (million gallons per day), of statewide precipitation that falls mostly as snow in the mountains (fig. 1*A*). Fifty-two percent of the precipitation, or 45,400 Mgal/d, is lost to evapotranspiration. The remaining 48 percent is consumptively used, runs off as surface water, or recharges the ground-water systems. Surface-water inflows to the State are about 32,900 Mgal/d, and surface-water outflows are about 69,700 Mgal/d. Most of the surface water leaving Idaho flows into Washington from several rivers—the Snake, the Pend Oreille and the Spokane (Kootenai–Pend Oreille–Spokane basin), and the Clearwater (Lower Snake basin).

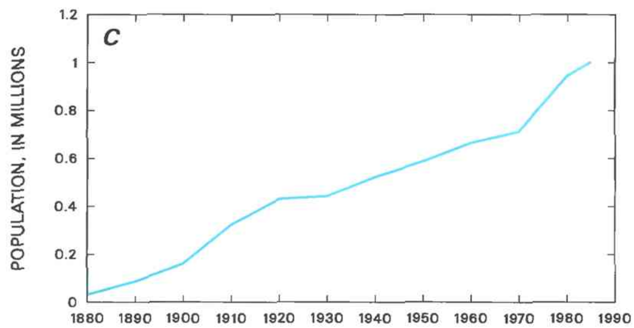
Water use in Idaho is dominated by agriculture. In the semiarid southern part of the State, most of the water is appropriated. In the humid central part, much of the land is national forest and wilderness, and water use is minimal; however, surface-water resources in the area may have potential for use elsewhere in the State. Substantial quantities of surface water flow through the State and are used to generate electricity.

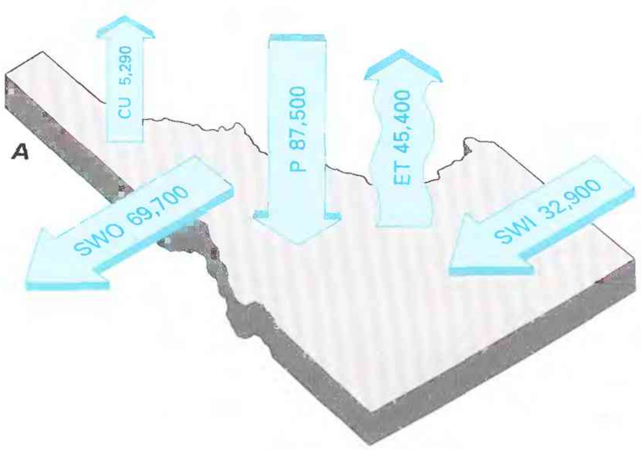
During 1985, total freshwater withdrawals for all uses were 22,300 Mgal/d, of which 5,290 Mgal/d was consumed. Surface-water withdrawals were 17,500 Mgal/d, and ground-water withdrawals were 4,800 Mgal/d. Most offstream water use is along the Snake River in southern Idaho. Agriculture is the largest offstream user of water—97.1 percent of total withdrawals and 99.8 percent of total consumptive use. Although Idaho has a small population of about 1 million (41st in the Nation), it has one of the largest amounts of irrigated cropland (4th in the Nation). Hydroelectric power generation, a nonconsumptive use, is the largest instream use of water (103,000 Mgal/d) and is concentrated along the Snake River.

In most parts of southern Idaho, surface-water resources are fully appropriated, and, in some parts, development of additional ground-water resources is restricted. Also within several areas of southern Idaho, ground-water levels have declined significantly, and withdrawals are restricted to the quantity of recharge to those areas.

The major water-use issue in the State concerns disputed water rights between operators of hydroelectric powerplants and







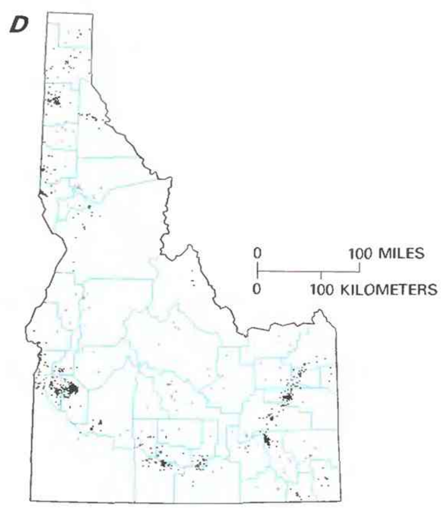


Figure 1. Water supply and population in Idaho. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey, 1986. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

agricultural users. This controversy has led to State adjudication of water rights upstream from Swan Falls Dam on the Snake River near Boise.

HISTORY OF WATER DEVELOPMENT

The first recorded use of water in Idaho was for navigation by the Lewis and Clark expedition in 1805. Fur trappers exploited mountain streams for beaver pelts during the early 1800's. Gold was discovered in a tributary to the Clearwater River in 1860 and near Boise in 1862 (Cenarrusa, 1986, p. 16). Mining near Boise and a corresponding population increase stimulated an expansion of irrigation and resulted in construction of small canal systems (Lindholm and Goodell, 1986). Since the late 1800's, water development has been related mostly to irrigation and hydroelectric power generation.

Diversions of surface water from the Boise River for irrigation began in 1843 (Caldwell and Wells, 1974, p. 31). Irrigation on the eastern Snake River Plain (a broad, arcuate plain spanning southern Idaho) began in about 1880 near Blackfoot (Lindholm and Goodell, 1986). Irrigated acreage on the plain rapidly increased to 550,000 acres by 1899 and to 2.2 million acres by 1929, as a result of congressional passage of the Desert Land Act of 1877, the Carey Act of 1894, and the Reclamation Act of 1902 (Lindholm and Goodell, 1986).

Decreed surface-water rights on the Snake River increased from 204 ft^3/s (cubic feet per second), or about 1,318 Mgal/d, in 1880 to 25,527 ft^3/s, or about 16,497 Mgal/d, in 1905 (Idaho Department of Reclamation, 1925). In 1905, streamflow that was insufficient to meet irrigation demand resulted in a dry 10-mile reach of the Snake River near Blackfoot for several days (Kjelstrom, 1986). Storage of water for irrigation began in 1906 at Milner Dam on the Snake River in south-central Idaho. Between 1905 and 1929, 31 dams were built to store water primarily for irrigation. Most large irrigation projects, all in southern Idaho, were completed by 1920.

Irrigated acreage on the Snake River Plain continued to increase, and, after 1945, development of ground-water sources was required to supplement surface-water sources (Lindholm and Goodell, 1986). Acreage irrigated using ground water increased primarily on the eastern Snake River Plain, which is underlain by fractured basalts that yield large quantities of water. By 1966, about 2.5 million acres across the Snake River Plain were irrigated using surface water, and 700,000 acres were irrigated using ground water (Lindholm and Goodell, 1986). By 1980, about 2.0 million acres were irrigated using surface water, 1.0 million acres were irrigated using ground water, and 0.1 million acres were irrigated using a combination of surface and ground water (Lindholm and Goodell, 1986). During 1980, Idaho withdrew the second largest quantity of water for irrigation in the United States (Solley and others, 1983).

Between 1950 and 1969, the construction of 18 dams throughout the State, primarily for power generation, significantly increased reservoir storage (fig. 1*B*). Dworshak Reservoir, completed in 1973 on the North Fork Clearwater River in Clearwater County, is the largest reservoir in Idaho and is used primarily for hydroelectric power generation. During 1980, Idaho and Montana were the seventh largest producers of hydroelectric energy in the Nation (Solley and others, 1983); each State produced 12,300 GWh (gigawatthours) of energy (Kjelstrom, 1986).

Idaho's economy is based on agriculture, and an abundant water supply is needed to grow and process agricultural products in a semiarid climate. Idaho's population has increased steadily (fig. 1*C*) and is concentrated near the State's water resources, particularly along the Snake River (fig. 1*D*).

WATER USE

Precipitation ranges widely throughout the State. Average annual precipitation ranges from about 10 inches on the Snake River Plain to 50 inches on the surrounding mountains (U.S. Geological Survey, 1986, p. 207). Precipitation accounts for nearly three-fourths of the water entering the State, but more than one-half of that amount is returned to the atmosphere by evapotranspiration (fig. 1*A*). Surface water accounts for about one-fourth (32,900 Mgal/d) of the water entering the State and more than one-half of the water (69,700 Mgal/d) leaving the State (fig. 1*A*). Total consumptive uses of water account for 5,290 Mgal/d (fig. 1*A*).

Withdrawals are largest on the Snake River Plain, where land and climate are suitable for agriculture. Total withdrawals (fig. 2*A*) are smallest in Benewah, Latah, and Lewis Counties in northern Idaho and are largest in Ada, Bingham, Bonneville, Canyon, Cassia, Elmore, Gooding, Jefferson, Jerome, Minidoka, Owyhee, and Twin Falls Counties in southern Idaho. Surface-water withdrawals (fig. 2*B*) are smallest in Benewah, Latah, and Lewis Counties and are largest in Bingham, Canyon, Jerome, Owyhee, and Twin Falls Counties. Ground-water withdrawals (fig. 2*C*) are smallest in Adams, Benewah, Boise, Boundary, Franklin, Gem, Idaho, Latah, Lemhi, Lewis, Nez Perce, and Shoshone Counties in northern and central Idaho and are largest in Twin Falls County.

Surface-water withdrawals by principal drainage basin unit and use are shown in figure 3*A*. Withdrawals are largest from the Upper and Middle Snake basins, which include the Snake River Plain. In Idaho, withdrawals for agriculture are larger than those for all other uses combined. Agriculture, primarily irrigation, accounts for 98.8 percent of surface-water withdrawals in the State.

Ground-water withdrawals and uses are shown in figure 3*B*. Withdrawals are largest from the eastern and western Snake River Plain aquifer systems. Agriculture accounts for 90.6 percent of total ground-water withdrawals (fig. 4). Withdrawals from aquifers not shown in figure 3*B* total 1,010 Mgal/d, of which about 75 percent is for agricultural purposes, 17 percent is for industrial and mining purposes, 5 percent is for public-supply purposes, and 3 percent is for domestic and commercial purposes.

The source, use, and disposition of 22,300 Mgal/d of water in Idaho are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 78.5 percent of total withdrawals was from surface water. Of that amount, 0.1 percent (13 Mgal/d) was withdrawn for self-supplied domestic and commercial purposes, 0.9 percent (161 Mgal/d) was for self-supplied industrial and mining purposes, less than 0.1 percent (less than 0.01 Mgal/d) was for thermoelectric power generation, and 98.8 percent (17,300 Mgal/d) was for agriculture. The use data indicate that, of 21,600 Mgal/d used for agriculture, 79.9 percent (17,300 Mgal/d) was from surface water, and 20.1 percent (4,350 Mgal/d) was from ground water. Of water used for agriculture, 24.4 percent (5,280 Mgal/d) was consumed, and 75.6 percent (16,400 Mgal/d) was returned to the hydrologic system. Finally, the disposition data indicate that of 5,290 Mgal/d consumed, domestic and commercial users consumptively used 0.1 percent (5.3 Mgal/d), industrial and mining used 0.1 percent (5.4 Mgal/d), thermoelectric power generation used less than 0.1 percent (less than 0.01 Mgal/d), and agricultural used 99.8 percent (5,280 Mgal/d).

The large quantity of water withdrawn for agriculture and returned to the system (75.6 percent, fig. 4) reflects the efficiency in delivery and application. Losses from delivery of ground water are less than those from surface water because withdrawal typically is close to the point of use. As demands for water increase, efficient use becomes increasingly important. In recent years, the amount of flood-irrigated land has decreased, and the amount of land irrigated using more efficient pivot sprinklers has increased.

As indicated in figure 4, Idaho has almost no thermoelectric power production. Although Idaho's hydroelectric power production was greater in 1980, it ranked sixth in the United States in 1985 (Solley and others, 1988). During 1985, 103,000 Mgal/d was used

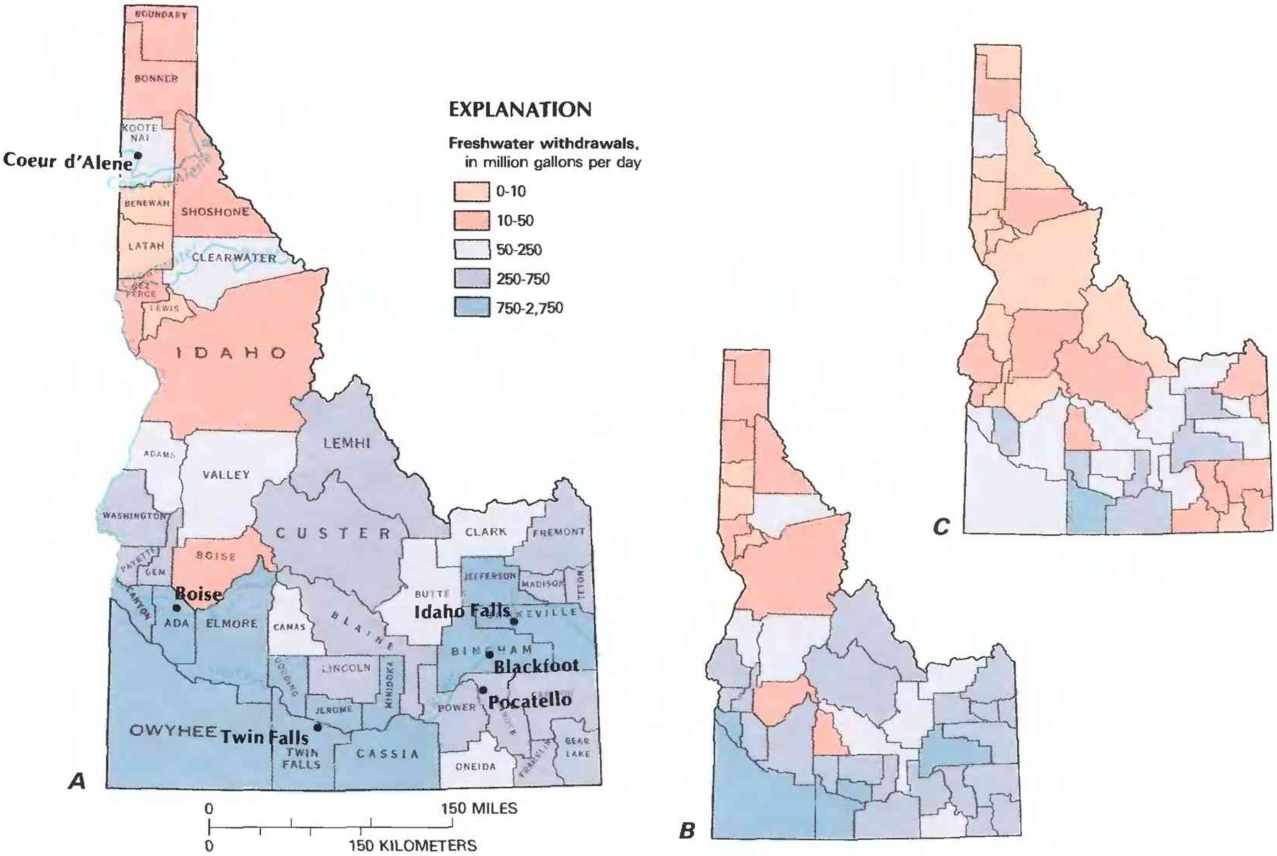


Figure 2. Freshwater withdrawals by county in Idaho, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

to produce 11,700 GWh of electricity. During 1985, at least 500 GWh of electricity was generated in the basins of the Snake, the Clearwater, the Clark Fork–Pend Oreille (Kootenai–Pend Oreille–Spokane basin), and the Boise Rivers. More than one-half the electricity produced during 1985 in Idaho was generated at dams on the Snake River. Although hydroelectric power generation is the largest instream use of water in the State, it is not considered a consumptive use and, therefore, is not shown in figure 4.

Idaho has substantial geothermal resources, primarily in the southern and central parts of the State. Geothermal water is used for irrigation, space heating, aquaculture, and recreation. The quantity of geothermal water used for irrigation and aquaculture is included in the amount of ground-water withdrawals for agriculture (figs. 2*A*,*C*,3*B*,4).

The quality of water in the State generally does not restrict its use. In areas of logging or mining, surface-water quality may be adversely affected by increased sediment transport. Mining in the South Fork Coeur d'Alene River basin in Shoshone County has caused excessive trace-metal concentrations in the Coeur d'Alene River and Coeur d'Alene Lake in Kootenai and Benewah Counties (U.S. Geological Survey, 1986, p. 208). Ground-water quality is most likely to be adversely affected on the Snake River Plain and in northern Idaho valleys, where land use activities are most intensive (U.S. Geological Survey, 1988).

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. In 1985, public-supply systems in Idaho withdrew 212 Mgal/d (fig. 4). Although this figure indicates a 32-percent increase in withdrawals since 1980, the increase, in part, may reflect different methods used to estimate withdrawals. From 1980 to 1985, the population served by these public-supply systems decreased by less than 1 percent (to 703,000) (Solley and others, 1988). Ground water accounted for 87.3 percent (185 Mgal/d) of total withdrawals for public supply during 1985 (fig. 4). Of this quantity, 96.9 percent (206 Mgal/d) was for domestic and commercial use, and 3.1 percent (6.7 Mgal/d) was for industrial and mining use. Withdrawals for public supply were less than 1 percent of total withdrawals for the State and were concentrated near large population centers (figs. 1*D*,2*A*–*C*). More than 50 percent of the public supply for the State was withdrawn in the Boise, Idaho Falls, Coeur d'Alene, Pocatello, and Twin Falls areas.

Domestic and Commercial

In 1985, total domestic and commercial water use was 311 Mgal/d, of which 66.1 percent (206 Mgal/d) was delivered by public-supply systems (fig. 4). A total of 33.8 percent (105 Mgal/d) of domestic and commercial use was self-supplied, including 13 Mgal/d from surface water and 92 Mgal/d from ground water. Self-supplied withdrawals provided 89 Mgal/d for domestic use by 301,000 residents and 16 Mgal/d for commercial use.

In 1985, consumptive use of water by domestic and commercial users was 0.1 percent (5.3 Mgal/d, or 5.3 gallons per day per capita) of total consumptive use in Idaho. Consumptive use of combined public-supply and self-supplied domestic water was 1.8 percent of withdrawals, which is smaller than the national average of 24 percent (Solley and others, 1988). The small percentage of consumptive use may be a result of self-supplied systems being used

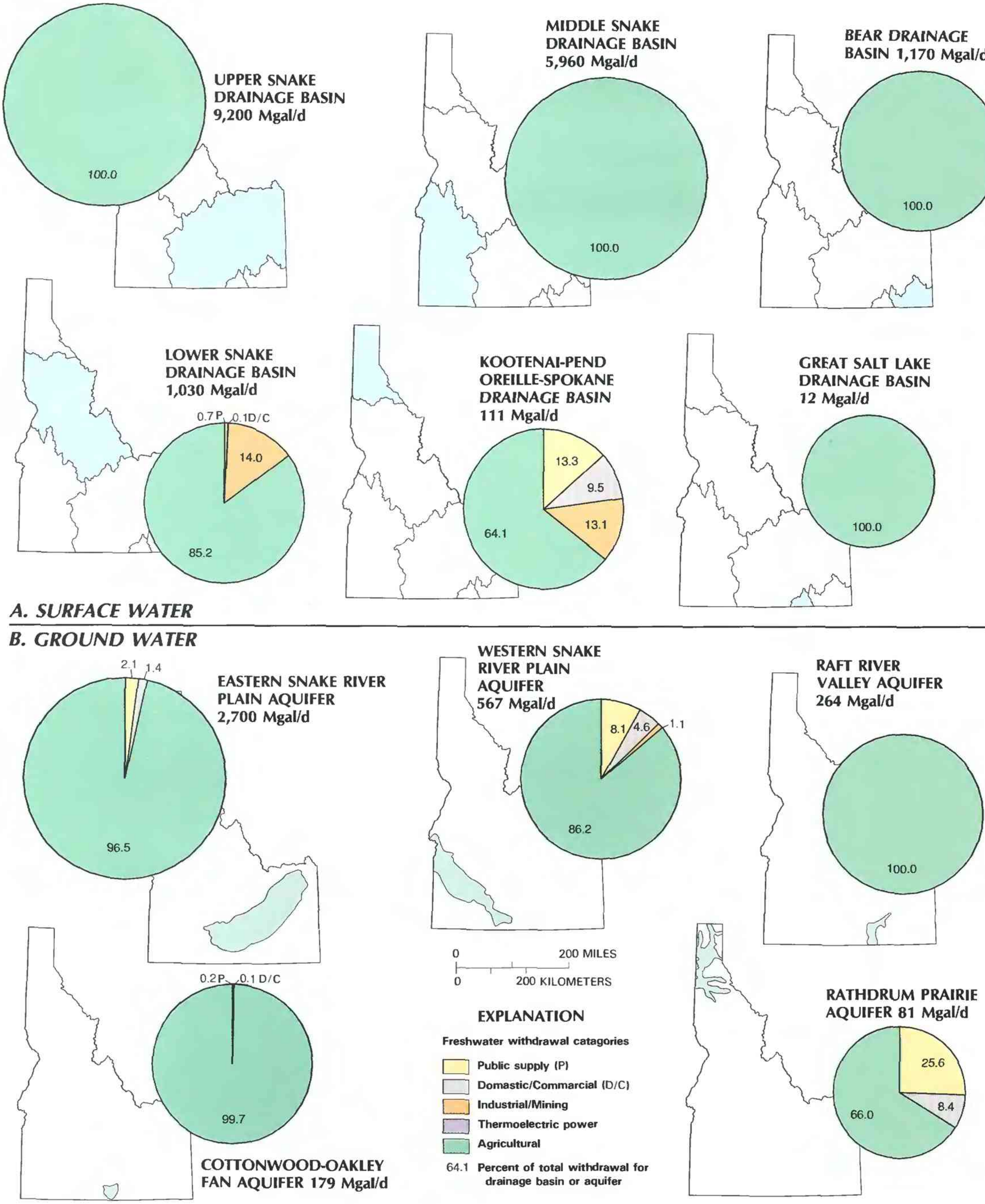


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Idaho, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Aquifer map from U.S. Geological Survey, 1985, p. 195.)

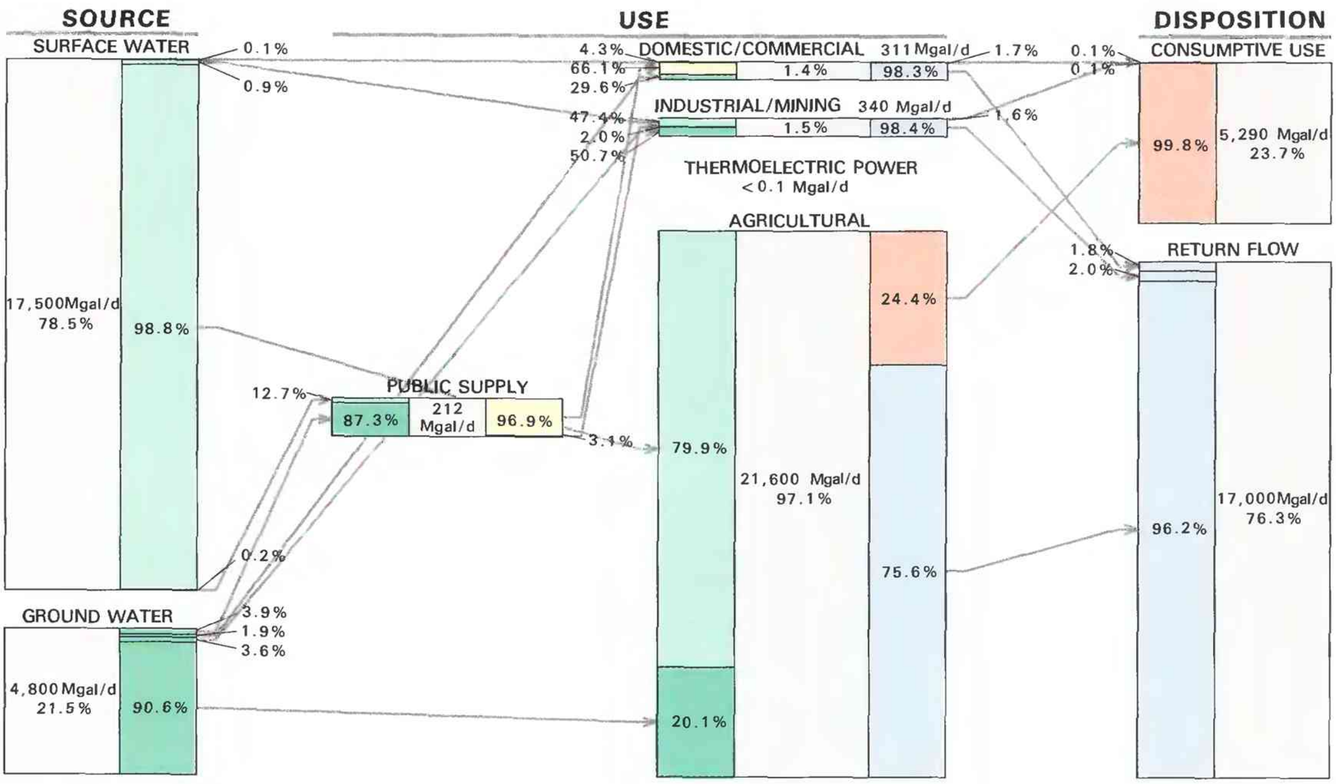


Figure 4. **Source, use, and disposition of an estimated 22,300 Mgal/d (million gallons per day) of freshwater in Idaho, 1985.** Conveyance losses in public-supply withdrawal systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

for watering lawns and livestock in areas where public supply is used for drinking water. Watering of lawns is probably the largest consumptive use of domestic water.

Industrial and Mining

In 1985, industrial and mining water use accounted for 1.5 percent (340 Mgal/d) of total withdrawals, of which 2.0 percent (6.7 Mgal/d) was delivered by public-supply systems (fig. 4). Of total industrial and mining use, 47.4 percent (161 Mgal/d) was self-supplied from surface water, primarily in northern Idaho, and 50.7 percent (172 Mgal/d) was self-supplied from ground water, primarily in southern Idaho (fig. 4).

Food processing in southern Idaho and extraction of precious metals in northern Idaho are the primary industrial and mining uses of water. Food processing and mining used 39 percent and 52 percent, respectively, of self-supplied industrial withdrawals. Pulp and paper processing in northern Idaho accounted for 7 percent of self-supplied industrial and mining withdrawals.

Consumptive use of water for industrial and mining purposes was 0.1 percent (5.4 Mgal/d) of total consumptive use in Idaho. Of the water withdrawn for industrial and mining purposes, 98.4 percent (335 Mgal/d) was returned (fig. 4).

Agricultural

Agriculture, primarily irrigation, is by far the largest use of water in Idaho (fig. 4). In 1985, withdrawals for agriculture were 97.1 percent (21,600 Mgal/d) of total withdrawals, which is more than 15 percent of agricultural withdrawals in the Nation (Solley and others, 1988). Withdrawals for nonirrigated agriculture, largely commercial fish farming in the Twin Falls area, were the largest in the Nation (1,050 Mgal/d).

Idaho was a leading national producer of several crops in 1985—first in potatoes; second in barley; third in sugarbeets, hops, and mint; fourth in onions; sixth in sweet corn (for processing) and dried beans; eighth in alfalfa hay; and tenth in wheat (Idaho Department of Agriculture, 1986, p. 6). Also, Idaho is the Nation's largest commercial producer of trout.

Areas of major surface- and ground-water withdrawals primarily reflect patterns of irrigation (figs. 2*A*–*C*,3*A*,*B*). Withdrawals are largest on the Snake River Plain in southern Idaho, where nearly all water is withdrawn for irrigation (figs. 3*A*,*B*). Almost 4.1 million acres of land in Idaho are irrigated for crop production. Sprinkler irrigation is used on 2.8 million acres, and flood irrigation is used on 1.3 million acres. About twice as much land is irrigated using surface water as ground water. Surface-water withdrawals were 17,300 Mgal/d, and ground-water withdrawals were 3,300 Mgal/d. An additional 1,050 Mgal/d of ground water was used for commercial fish farming. For every acre of land irrigated using surface water, about 7 acre-ft (acre-feet) of water is diverted. For every acre of land irrigated using ground water, less than 3 acre-ft of water is pumped. Of water withdrawn for agricultural use, 24.4 percent is consumed, and 75.6 percent is returned (fig. 4).

Much of the ground water used on the eastern Snake River Plain is from a regional basalt aquifer. Sedimentary and volcanic rock aquifers are the primary sources of water for irrigation on the western Snake River Plain and in the Cottonwood–Oakley Fan and Raft River Valley areas south of the Snake River (fig. 3*B*). Substantial water-level declines in the Cottonwood–Oakley Fan and Raft

River Valley aquifers have resulted from pumping in excess of recharge to those systems. Ground water for irrigation in northern Idaho is withdrawn primarily from the Rathdrum Prairie aquifer (fig. 3*B*), which is composed of unconsolidated silt, sand, gravel, and boulders (U.S. Geological Survey, 1985).

WATER MANAGEMENT

Idaho operates under a prior-appropriation doctrine—the earliest users of water have priority use rights. Management of water resources and protection of those resources from waste and contamination are the responsibilities of the Idaho Department of Water Resources (IDWR), the Idaho Water Resource Board, and the Idaho Department of Health and Welfare, Division of Environmental Quality.

Several other agencies, groups, and individuals have responsibilities for the administration and the management of surface water. Watermasters, under the supervision of the IDWR, are responsible for the delivery of water to users who have adjudicated water rights. Water in the Bear River basin in southeastern Idaho is apportioned according to the Bear River Compact and is administered by the Bear River Commission, which represents Idaho, Utah, and Wyoming. The U.S. Bureau of Reclamation is responsible for the management of many dams and irrigation storage facilities in Idaho. The U.S. Army Corps of Engineers is responsible for flood-control management of several Federal projects. The International Kootenai Board of Control coordinates the United States and Canadian water policies for the Kootenai River (U.S. Geological Survey, 1986).

Where declining ground-water levels become a concern to local water users, a Ground-Water Management Area (GWMA) may be established by the IDWR. The IDWR must ensure that existing water rights in these management areas are not affected adversely by new well construction. Where ground-water levels decline at a rate that threatens a reasonably safe supply for existing users, the IDWR may establish a Critical Ground-Water Area (CGWA) in which no new well permits are issued and ground-water withdrawals are decreased to levels determined by the IDWR. Currently (1988), five GWMA's and eight CGWA's, all in southern Idaho, have been designated in parts of the eastern and western Snake River Plain, Cottonwood-Oakley Fan, and Raft River valley aquifers (fig. 5, GWMA's not shown).

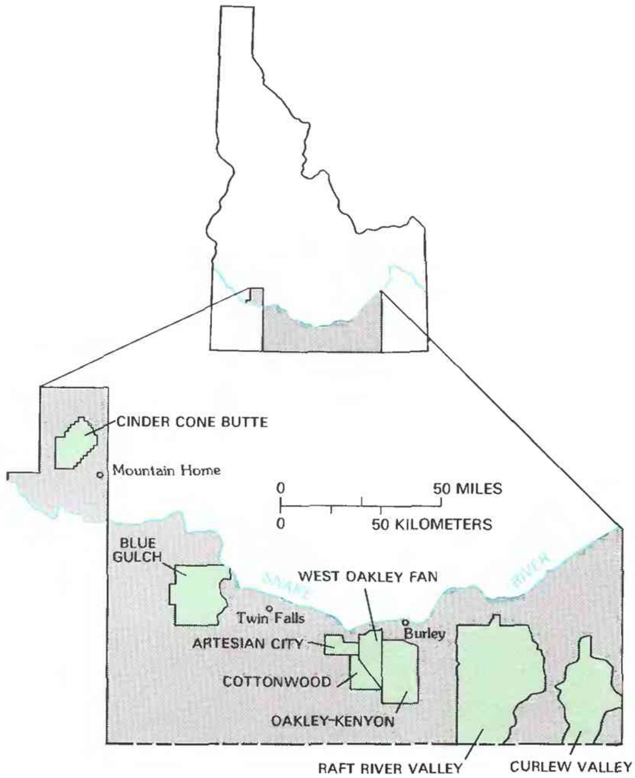


Figure 5. Location of Critical Ground-Water Areas in Idaho, 1983. (Source: Idaho Department of Water Resources, unpublished data, 1983.)

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Prepared by S.A. Frenzel.

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 230 Collins Road, Boise, ID 83702

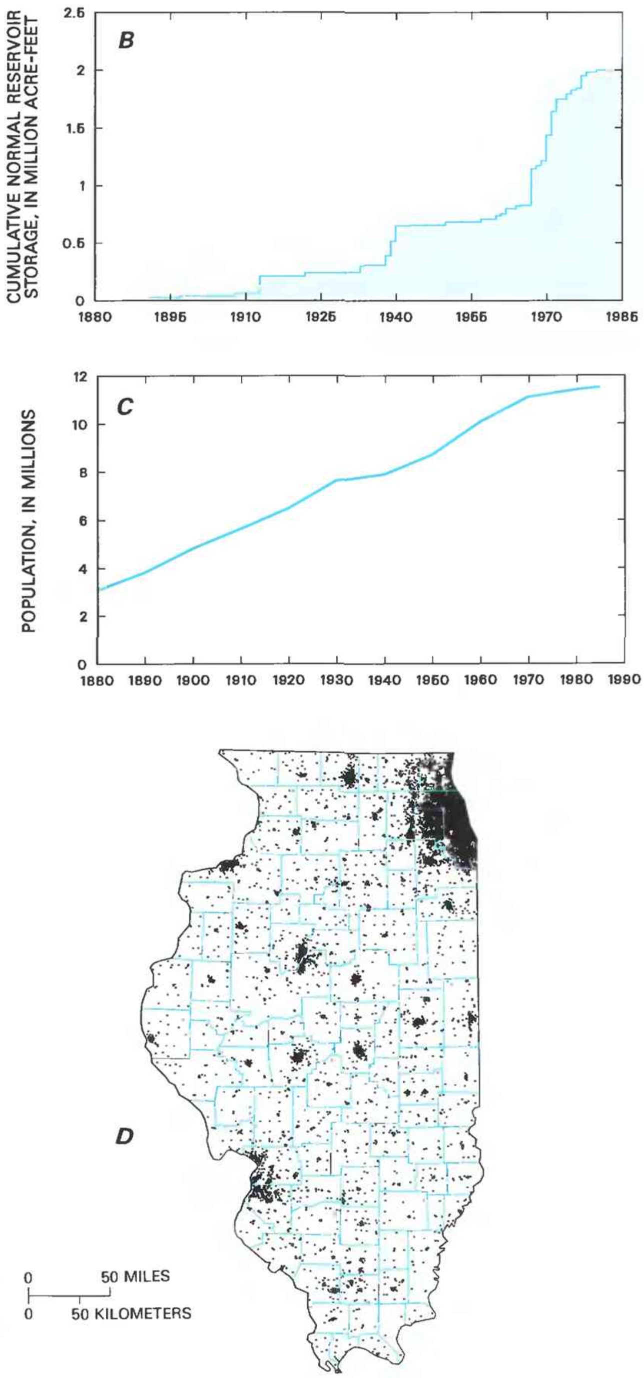
ILLINOIS
Water Supply and Use

Illinois has an abundant supply of freshwater available from surface- and ground-water sources. In 1985, long-term average precipitation was 30 inches per year, or 101,000 Mgal/d (million gallons per day), and surface-water inflow was 9,900 Mgal/d (fig. 1A). The total amount of ground water potentially available for use is 7,000 Mgal/d (Illinois Technical Advisory Committee on Water Resources, 1967, p. 74). In 1985, withdrawals from rivers, lakes, and aquifers were about 14,400 Mgal/d, and consumptive use was 686 Mgal/d. Of the total amount of water withdrawn, 93.6 percent (13,500 Mgal/d) was from surface-water sources, and 6.4 percent (930 Mgal/d) was from ground-water sources; 95.2 percent was returned to the hydrologic system for reuse.

The largest offstream water users in Illinois are thermoelectric power facilities, which withdrew 80.9 percent (11,700 Mgal/d) of total withdrawals; 1.0 percent of this water was consumed. The amount of water withdrawn for industrial and mining use was 5.9 percent (857 Mgal/d) of total withdrawals; however, industrial and mining consumptive use accounted for 41.3 percent of total consumptive use.

The largest withdrawals are in the northeastern part of Illinois. Withdrawals in the Chicago area (Lake, Cook, and Will Counties) amount to 6,070 Mgal/d and supply more than one-half of the population in Illinois. Withdrawals from Lake Michigan, the second largest freshwater lake in the world, provided 97 percent of the water used in the Chicago area. Increasing demands for Lake Michigan water were a result of declining ground-water levels, although ground water still is used in some areas because of its favorable quality.

Instream water use for hydroelectric power generation in 1985 was 23,300 Mgal/d, which surpasses all other water uses. This use is not included in any of the figures because it would mask the importance of offstream use. Intensive reuse of water in densely pop-



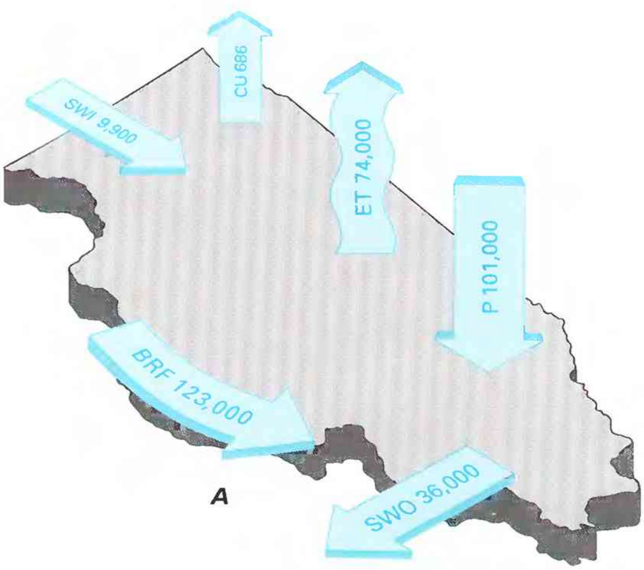


Figure 1. Water supply and population in Illinois. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Compiled from U.S. Geological Survey data; J.R. Kirk, Illinois State Water Survey, written commun., 1987; U.S. Environmental Protection Agency, 1975; Healy, 1979a; Healy, 1979a; 1979b; Healy and others, 1987; and U.S. Department of Commerce, 1951–85. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

ulated and industrialized areas has degraded the quality of many surface-water sources. Contamination of streams and lakes by sediment as a result of soil erosion is considered to be the most serious water problem in the State.

Official water-use forecasts are not available for Illinois. However, use of water for irrigation and nuclear power has increased during the past 10 years. Irrigation use has nearly doubled during that period—a trend that may lead to significant declines in ground-water levels in areas of intensive irrigation and that may affect neighboring areas that depend on ground-water supplies. Two nuclear powerplants are scheduled to begin operation in 1987; thus, the total consumptive water use is expected to increase significantly.

HISTORY OF WATER DEVELOPMENT

The surface-water resources of Illinois were important to early settlement and growth. The Ohio River was the navigation route of the first settlers at the beginning of the 19th century. In 1848, the Illinois and Michigan Canal (which is no longer being used) was completed to provide a navigable waterway from the Great Lakes to the Mississippi River. The city of Galena was established along the Mississippi River in the 1820's as the center for lead mining and, through the use of paddle-wheel steamers, contributed to the growth of navigation of the upper Mississippi River. In the 1930's, locks and dams converted the Ohio, the Mississippi, and the Illinois Rivers into modern, busy transportation arteries. Thus, navigable waterways determined the patterns of settlement and commerce.

Settlement in some areas required drainage of wetlands. Most of this drainage was accomplished after the Civil War and was essentially completed by 1920. Open ditches and, later, field tiles lowered the water table to allow the tough, but rich, prairie sod to be cultivated. Conversion of the wetlands led to the development of mechanized, large-yield crop production.

Development of water resources can range from a shallow well to a sophisticated multipurpose reservoir system. The State has many large-capacity wells. Large multipurpose reservoirs, such as Shelbyville Lake (Moultrie and Shelby Counties), Carlyle Lake (Clinton, Bond, and Fayette Counties), and Rend Lake (Franklin and Jefferson Counties) in the central and southern parts of the State, provide storage for water supply. Since construction of the first reservoir in 1891, storage has increased seventyfold (fig. 1*B*) to help meet the needs of the steadily growing population (fig. 1*C*). In 1985, Illinois' population totaled 11.5 million, which ranks fourth in the United States (U.S. Bureau of the Census, 1985a); most of the population is in the northeastern part of the State (fig. 1*D*).

In the late 1950's, impoundments were constructed for water-based recreation. More recently, recreational development usually was incorporated into the multiple purposes of large water projects. Emphasis, however, has shifted gradually to recreation associated with natural streams. Recreational activities include fishing, boating, and enjoyment of scenic rivers.

Development of water resources has been most significant in the Chicago area. Water-supply intakes have been increased in size and have been extended farther into Lake Michigan. Throughout the 1890's, increasing amounts of untreated waste were discharged into Lake Michigan and its tributaries. In 1900, the flow in the Chicago River was reversed so that wastes diluted by lake water were diverted into the Illinois River basin. Over time, methods of treating the wastewater have improved. The Metropolitan Sanitary District of Greater Chicago is constructing a tunnel and reservoir system designed to capture storm runoff in a combined sewer system that would virtually eliminate the occasional overflow into the lake during storms.

WATER USE

Water use in Illinois generally has not been restricted because surface- and ground-water supplies are abundant. The largest fresh surface-water resources are the Illinois River, which flows through central Illinois, Lake Michigan to the northeast, and the Mississippi, the Wabash, and the Ohio Rivers on the western, eastern, and southern borders, respectively. Even though supplies currently are sufficient, the Illinois Department of Transportation evaluated public-water supplies, which resulted in 20 of 99 surface-water distribution systems and 26 of 60 ground-water distribution systems being insufficient to meet demands by the year 2000 (Illinois Department of Transportation, 1982, p. 1–6; 1983, p. 4–7). In southwestern Illinois, all surface-water distribution systems are reported to be potentially deficient, although surface-water resources are adequate.

Most water withdrawals are in densely populated areas, along navigational routes, or at thermoelectric power and industrial facilities. The largest withdrawals are in the northeastern part of the State (fig. 2*A*), where the city of Chicago leads all other cities in Illinois in population and manufacturing (R.A. Tobias, Northern Illinois University, Governmental Studies Center, oral commun., 1987). Lake, Cook, and Will Counties account for 42 percent of total offstream withdrawals and 52 percent of the total population in Illinois. Withdrawals are also large along the Illinois River. For example, the city of Peoria is the third leading manufacturing area in the State and the third largest thermoelectric power user. Large withdrawals in southwestern and southern Illinois reflect the concentrated population in the East St. Louis area and the scattered thermoelectric power use. Withdrawals for thermoelectric use in the 15 largest water using counties account for 85 percent of total withdrawals.

The distribution of surface-water withdrawals by county (fig. 2*B*) is similar to total withdrawals by county (fig. 2*A*) because surface water is the source of 93.6 percent of total withdrawals. The largest surface-water withdrawals (5,900 Mgal/d) are from Lake Michigan. Since 1982, these withdrawals have increased 24 percent (Kirk and others, 1984, p. 32; 1985, p. 32). Ground-water withdrawals by county (fig. 2*C*) are largest in the northern one-third and parts of central Illinois.

Of the major river basins, the Upper Illinois and the Lower Illinois basins had the largest surface-water withdrawals (fig. 3*A*). Thermoelectric power generation accounted for most of these withdrawals. Surface-water withdrawals by public suppliers also were substantial in the Northeastern Lake Michigan–Lake Michigan region.

Surface-water quality is a major concern in Illinois. The quality of surface water is being degraded by sewage wastewater and industrial wastewater discharges in densely urbanized areas. Because of advancements in water-treatment technology, the use of surface water has not yet been limited. The Illinois Environmental Protection Agency, however, assessed the quality of many public-supply lakes and reported that nearly 50 percent did not meet State water-quality standards, mainly because of sediment contamination (Illinois Environmental Protection Agency, 1986, p. 67).

Instream uses of water, such as hydroelectric power generation, require large amounts of water. The 23,300 Mgal/d of water passing through Illinois' six hydroelectric powerplants during 1985 is nearly twice the amount withdrawn for offstream uses. The largest instream water user is a hydroelectric powerplant on the Mississippi River near Hamilton. This plant accounted for 82 percent of all hydroelectric water use in the State and used about 80 percent of the flow in the river. Hydroelectric power generation contributed 1,100 GWh (gigawatthours) of electricity, or about 1 percent of the electricity produced in Illinois. Since 1981, hydroelectric power generation has declined 10 percent because of decreases in electrical demand and increases in nuclear power generation. The quantities of water needed for other instream uses, such as navigation and recreation, are difficult to measure and were not assessed.

Of the four principal aquifers (fig. 3*B*), the sand and gravel aquifers supplied 49 percent of the total ground-water withdrawals.

These aquifers are dispersed throughout the State and generally yield water that is suitable for most uses. The deep Cambrian-Ordovician aquifer provides 54 percent of the water in the northern one-third of Illinois—mainly the Chicago and Rockford areas—and accounts for about 33 percent of the total ground-water withdrawals. Pumping from deep aquifers in the Chicago area has increased from 0.2 Mgal/d during 1864 to 199.3 Mgal/d during 1984 (Kirk and others, 1979, p. 2; 1985, p. 30). As a result of these increases, water levels have declined more than 850 feet (Kirk and others, 1982, p. 2). State authorities have been allocating Lake Michigan water to communities that compete for ground water (Illinois State Water Plan Task Force, 1983, p. 50) to allow recovery of ground-water levels. In 1985, ground-water withdrawals decreased to 174 Mgal/d as a result of these allocations. Southern Chicago suburbs that compete for ground water and are isolated from Chicago's water-supply system are allocated Lake Michigan water from public suppliers in northwestern Indiana.

The overall quality of ground water in Illinois is considered to be suitable for most uses, according to a study by the Illinois Environmental Protection Agency (1986, p. 132), which noted pollution problems in 1.5 percent of the 3,427 wells sampled. Ground-water quality in the East St. Louis area has deteriorated as a result of urbanization and industrialization (U.S. Geological Survey, 1988). Consequently, industry has decreased its use of ground water and has increased its use of Mississippi River water. This change has caused a rise in ground-water levels; however, the rise has resulted in widespread sewer-system damage and flooded basements (Voelker, 1984, p. 1–2).

The source, use, and disposition of freshwater are diagrammatically shown in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 93.6 percent (13,500 Mgal/d) of all withdrawals was from surface water. Of this total, 86.5 percent was withdrawn for thermoelectric power generation, and 9.7 percent was withdrawn for public supply. Public suppliers delivered a total of 1,530 Mgal/d to domestic and commercial users, 255 Mgal/d to industrial and mining facilities, and 0.9 Mgal/d to thermoelectric powerplants. The use data indicate that thermoelectric power accounted for 80.9 percent (11,700 Mgal/d) of all the freshwater used during 1985. Of this total, 1.0 percent (121 Mgal/d) was consumed, and the remaining 99.0 percent (11,600 Mgal/d) was returned to surface- or ground-water sources. The disposition data indicate that, of all the freshwater withdrawn, 4.8 percent (686 Mgal/d) was consumed and 95.2 percent (13,700 Mgal/d) was returned to the hydrologic system for reuse. About 16 percent of the return flow was treated by sewage-treatment facilities.

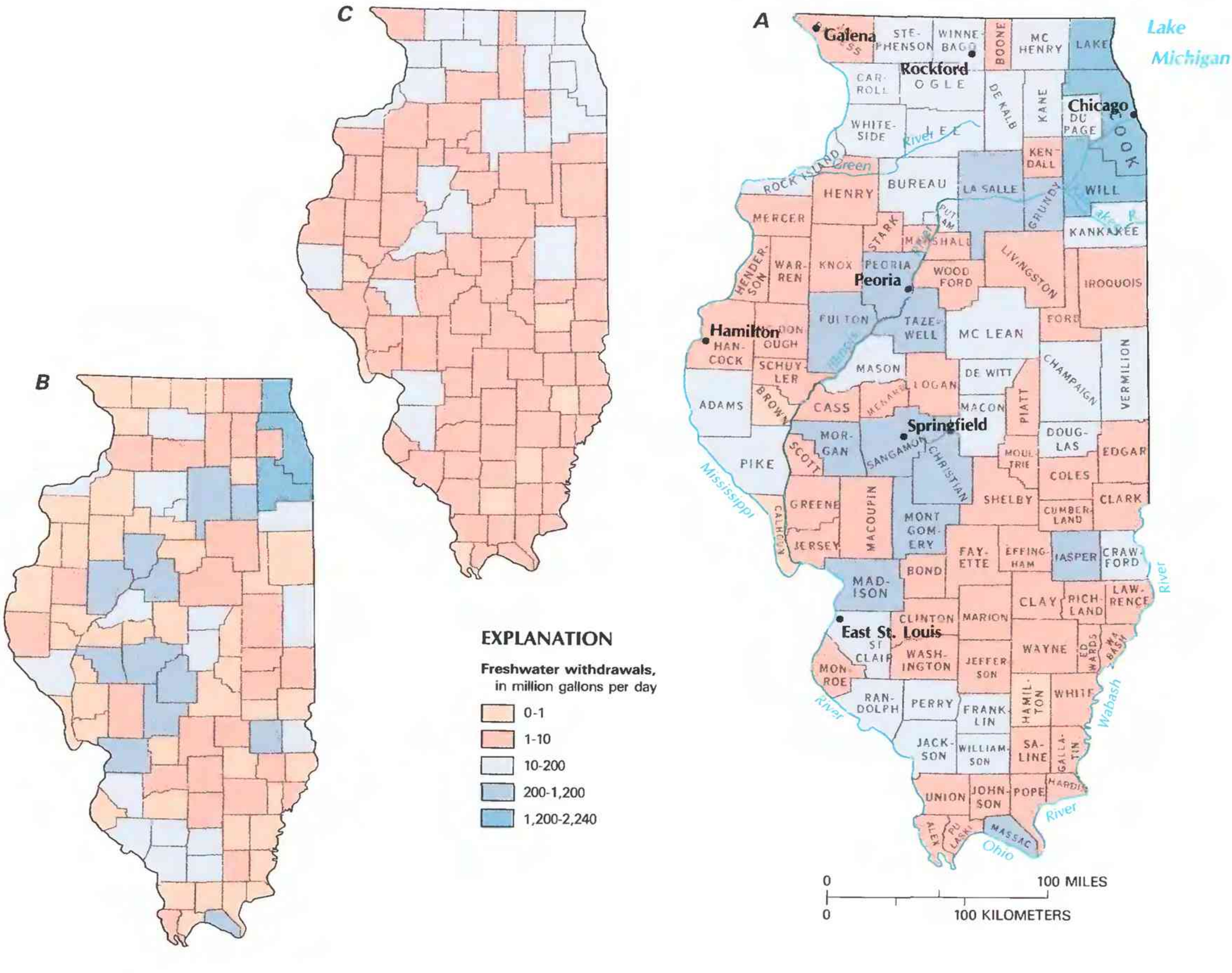
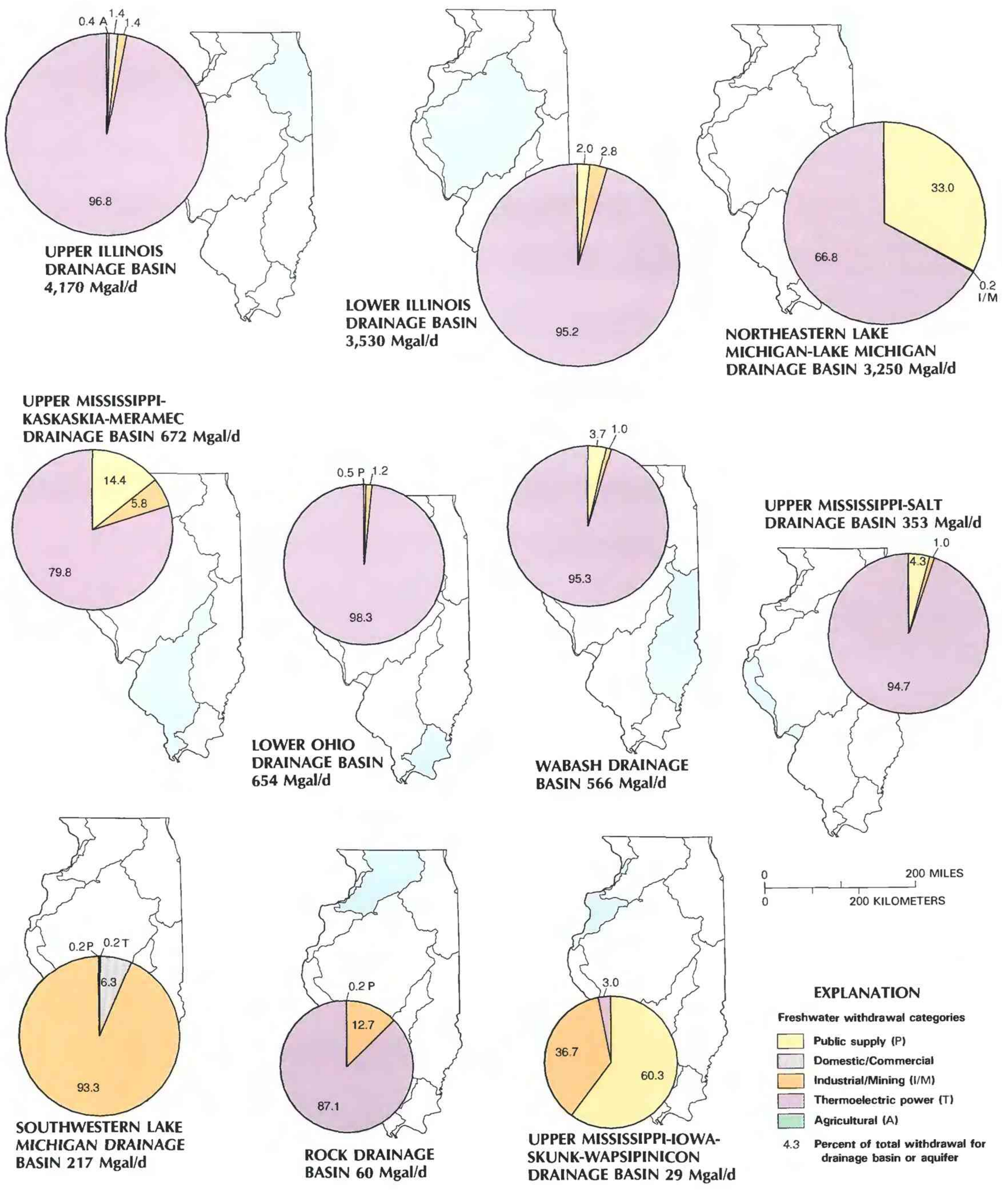


Figure 2. Freshwater withdrawals by county in Illinois, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Illinois, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Compiled by J.R. Kirk, Illinois State Water Survey, written commun., 1987; Illinois Technical Advisory Committee on Water Resources, 1967, p. 70–77).

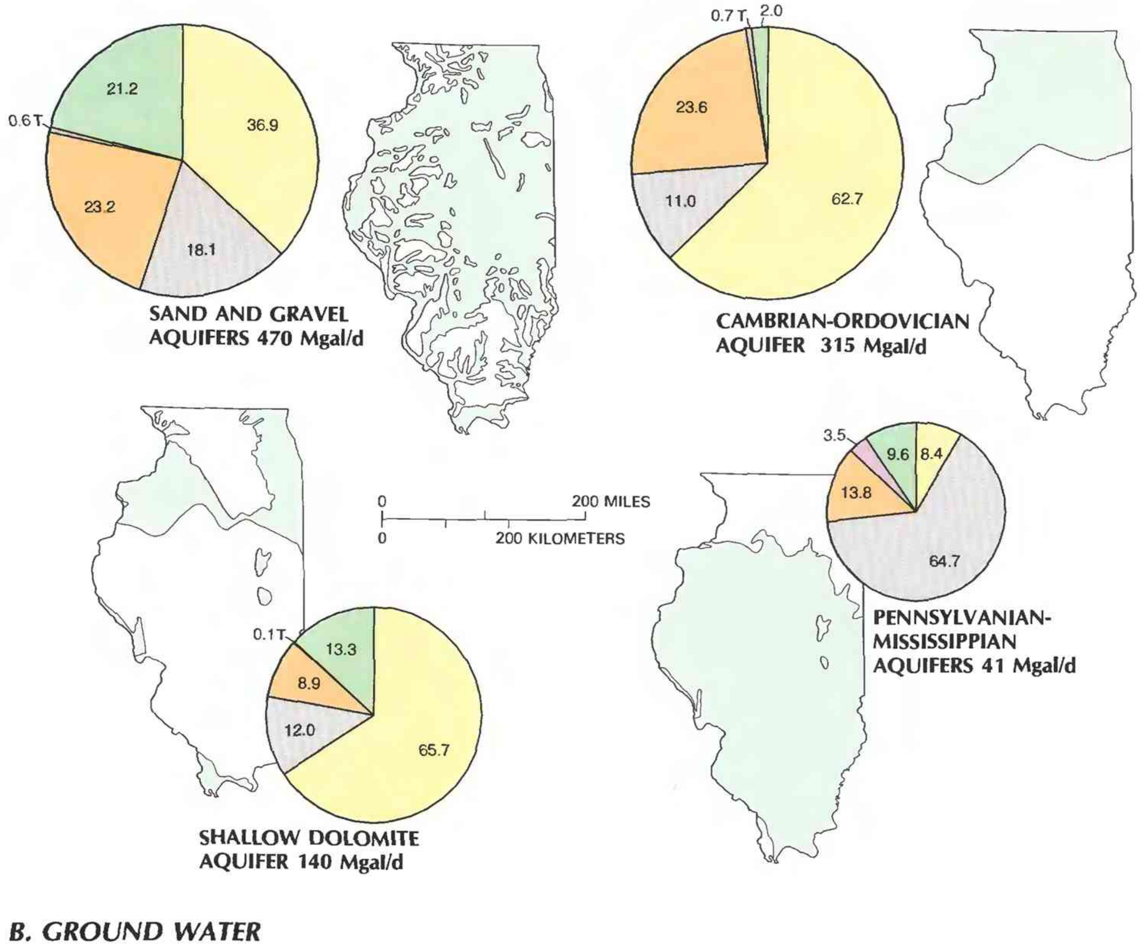


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Illinois, 1985—Continued.

PUBLIC SUPPLY

Public-supply systems deliver water for domestic, commercial, industrial, mining, and thermoelectric power uses (fig. 4). In 1985, about 1,900 systems delivered water to 9.8 million people, or 85 percent of the population. Illinois currently ranks fourth in withdrawals for public supply in the United States (Solley and others, 1988).

A total of 1,780 Mgal/d of water was delivered to users by public-supply systems. Of that amount, 73.8 percent (1,320 Mgal/d) was from surface water, and 26.2 percent (467 Mgal/d) was from ground water. In 1985, about 61 percent of the population was delivered water from surface-water sources compared to 58 percent in 1980. An increase in the population using surface water is a result of declining ground-water levels and degraded ground-water quality in densely populated areas.

Withdrawals by public suppliers in the Chicago and the East St. Louis areas are significant. The Chicago Department of Water supplied 1,040 Mgal/d from Lake Michigan to nearly one-half of the population in Illinois. Domestic and commercial use received 78 percent of this supply. Another 18 percent was delivered to industries primarily for the production of machinery, electrical equipment, and fabricated metals. The East St. Louis area has 25 public-supply systems that provided 76 Mgal/d to 439,000 people. Industries in this area are predominantly oil and ore refineries, chemical plants, and steel plants, which used 27 percent of public-supply withdrawals in East St. Louis.

Conveyance losses from public-supply systems account for 14 percent of the total water distributed (modified from American Water Works Association, 1981, p. 152–153). This amount of water equals that publicly supplied to all industries and mining operations during 1985. Conveyance losses are included in the domestic and commercial use data in figure 4.

DOMESTIC AND COMMERCIAL

In 1985, domestic water use was 980 Mgal/d, of which 850 Mgal/d was publicly supplied (87 percent) and 130 Mgal/d was self-supplied from privately owned wells that obtain water solely from ground-water sources. Public-supplied domestic use was estimated to be 86 gal/d (gallons per day) per capita, whereas self-supplied domestic use was estimated to be 74 gal/d per capita. Self-supplied domestic use ranged from 69 gal/d per capita in western Illinois to 92 gal/d per capita in northeastern Illinois (Kirk and others, 1985, p. 7). Self-supplied domestic use in northeastern Illinois generally is larger than in other parts of the State. Domestic consumptive use in Illinois was estimated to be 97 Mgal/d, which is 10 percent of the total domestic use. The majority of domestic consumptive use is evaporation from outdoor uses, such as lawn watering. Outdoor uses are small because precipitation is adequate; therefore, domestic consumptive use is small.

In 1985, commercial water use was about 578 Mgal/d, of which 107 Mgal/d was self-supplied and 471 Mgal/d was public supply. Consumptive use was 64 Mgal/d, or 11 percent of the total commercial use. Conveyance losses (205 Mgal/d) in public-supply distribution systems and some public water uses, such as fire fighting, are included in the domestic and commercial use total (1,760 Mgal/d) in figure 4.

Industrial and Mining

Freshwater withdrawals and deliveries for industrial and mining use were 5.9 percent (857 Mgal/d) of total withdrawals (fig. 4). Industries used 790 Mgal/d, and mining operations used the remaining 67 Mgal/d. Of the total industrial use, 535 Mgal/d of freshwater was self-supplied, and 255 Mgal/d was public supply. Self-supplied industries withdrew 385 Mgal/d of surface water and 150 Mgal/d of ground water, whereas mining operations withdrew 53 Mgal/d of surface water and 14 Mgal/d of ground water.

Water used for mining was mostly for oil-field operations. Oil-field operations in southern Illinois withdrew 38 Mgal/d of saltwater. In most instances, the ground water was returned directly to the producing geologic unit. The only known withdrawals of saltwater in the State are in southern Illinois. Freshwater for mining is used primarily to flush oil from oil-bearing strata.

About 47 percent of the total water used by industry and mining (321 Mgal/d of fresh and saline water) was consumed. Industrial and mining freshwater use accounted for 41.3 percent of Illinois' total consumptive use. About 95 percent of industrial withdrawals is used for cooling, which is the largest industrial consumptive use (Illinois Technical Advisory Committee on Water Resources, 1967, p. 99).

The number of industrial facilities in Illinois is larger than in any other State and reflects the importance of industrial activity to the Illinois economy (R.A. Tobias, Northern Illinois University, Governmental Studies Center, oral commun., 1987). Three-quarters of the water withdrawn for industrial use is in the Chicago, the Rockford, the Peoria, and the East St. Louis areas where primary metal, machinery, and chemical industries predominate. The primary metal industries used approximately one-half (249 Mgal/d) of the self-supplied industrial withdrawals, and the chemical industries used 23 percent (J.R. Kirk, Illinois State Water Survey, written commun., 1987).

Thermoelectric Power

In 1985, thermoelectric powerplants withdrew 80.9 percent (11,700 Mgal/d) of the total offstream withdrawals (fig. 4). Of the total thermoelectric withdrawals, fossil-fueled plants used about 68 percent, and nuclear plants used about 32 percent. Most water used by these thermoelectric powerplants is returned to rivers or lakes; about 1 percent is lost through evaporation. Consumptive use amounted to 46 Mgal/d for fossil-fueled plants and 76 Mgal/d for nuclear plants. All the water used for power generation and cooling was from surface-water sources. A small amount of ground water (less than 0.1 percent) was used for employee needs.

The State has 38 thermoelectric powerplants—33 are fossil fueled, and 5 are nuclear powered (J.R. Kirk, Illinois State Water Survey, oral commun., 1987). These plants produced 107,000 GWh of electricity, or 99 percent of the electric power produced in Illinois.

Illinois has been decreasing its dependence on fossil fuels by converting to nuclear power. Consequently, water use by nuclear powerplants is expected to increase significantly as a result of two new reactors scheduled to begin production in 1987. A nuclear powerplant in Lake County is the largest thermoelectric water user

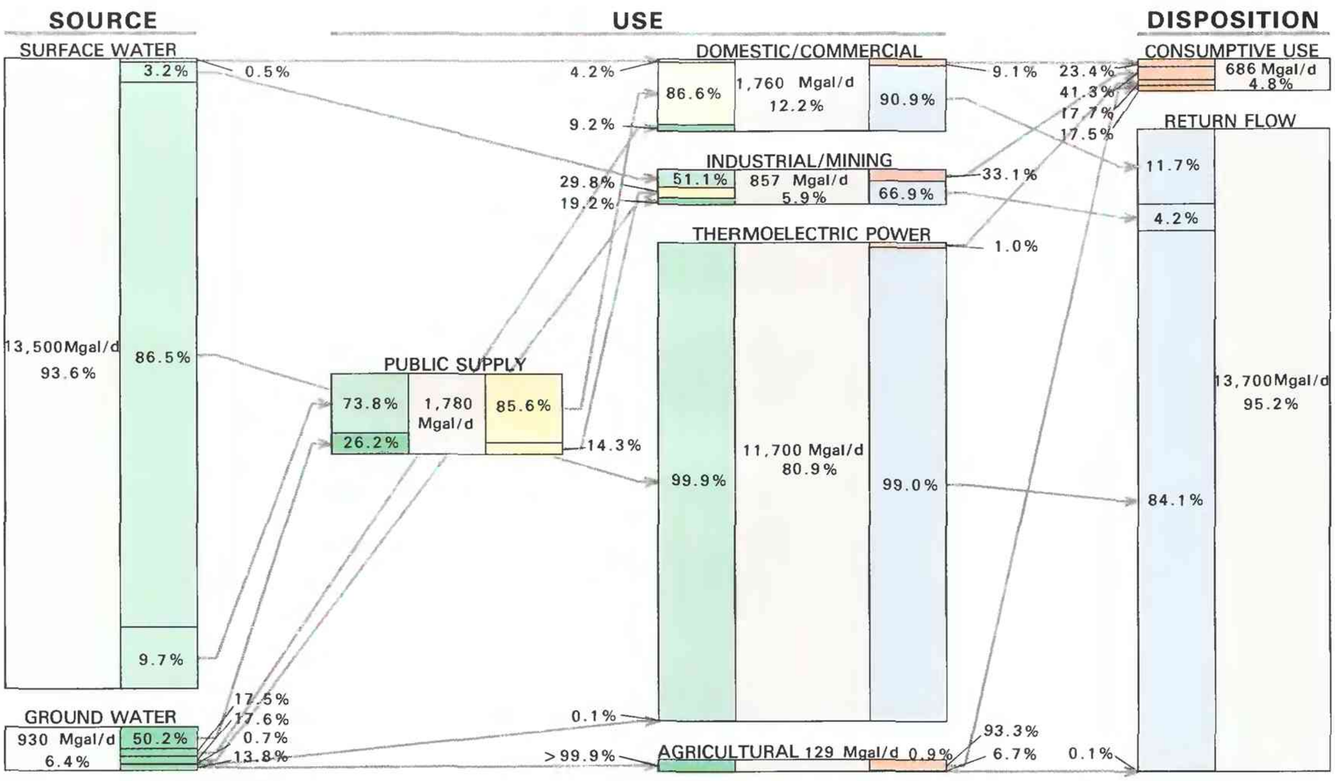


Figure 4. Source, use, and disposition of an estimated 14,400 Mgal/d (million gallons per day) of freshwater in Illinois, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

and the third largest water user in the State. Cooling-tower evaporation in Illinois' nuclear powerplants is three times as great as in the fossil-fueled powerplants; therefore, total thermoelectric consumptive use in Illinois also is expected to increase.

AGRICULTURAL

Irrigated acreage has been increasing rapidly but remains insignificant compared to Illinois' total cropland. Since 1978, irrigation withdrawals and irrigated acreage have nearly doubled. Irrigated acreage increased from about 9,000 acres in 1950 to 256,000 acres in 1984 (Kirk and others, 1985, p. 7), yet only 1 percent of the total cropland is irrigated. Crops grown on irrigated acreage include corn (73 percent), soybeans (19 percent), other vegetables (4 percent), and hay (2 percent) (Irrigation Journal, 1987, p. 20–26). Illinois currently ranks third in value of overall crop production (U.S. Bureau of the Census, 1985b).

In 1985, withdrawals for agricultural use, primarily irrigation and livestock watering, totaled 129 Mgal/d and were solely from ground water (fig. 4). As of 1987, about 1,170 irrigation wells obtain water primarily from shallow sand and gravel aquifers (Jean Bowman, Illinois State Water Survey, oral commun., 1987). Seasonal irrigation water use was 56 percent (72 Mgal/d) of the total agricultural use and is an average for the entire year; however, most land is irrigated during the summer. Sprinkler systems are used for most irrigating, and almost one-half are large-volume center-pivot systems.

Irrigation is practiced mainly in the sandy soil regions along the Illinois, the Green, and the Kankakee Rivers. Most irrigation is in Mason County, in central Illinois, which accounted for 34 percent of the total withdrawals for irrigation. Other withdrawals for irrigation were in areas where truck crops, such as melons, tomatoes, and onions, are grown. Consumptive use was estimated to be 100 percent of total withdrawals for irrigation.

Livestock watering was a small part of the total water use and is expected to remain small. In fact, withdrawals for livestock watering (57.2 Mgal/d) have decreased 16 percent since 1980 (Kirk and others, 1982, p. 13). Consumptive water use for livestock watering was estimated to be 85 percent, or 48.7 Mgal/d.

WATER MANAGEMENT

An understanding of water management in Illinois requires recognition of two major factors—water law and the decentralized nature of government. With respect to water law, Illinois is typical of the Eastern States. Surface water is governed by the doctrine of absolute ownership that grants the use of a water body to landowners adjacent to that water body. Although there is no modern test of the law, it is probable that a "reasonable use" of the water also may warrant a water right. Ground-water withdrawals are governed by the same laws. Laws for surface- and ground-water uses are modified and limited by a variety of Federal, State, and local agencies. Despite multiple jurisdictions, few conflicts have arisen, probably because of the abundance of water in the State.

Water management by the State involves all three branches of government, but the Executive Branch, headed by the Governor, is responsible for most enforcement actions. Under the direction of the Governor, programs are integrated by a Cabinet and a Subcabinet on Natural Resources and by the Bureau of the Budget. Two ad hoc committees appointed by the Governor have been important to water-resources management during the past 20 years. The first of these was the interagency Technical Advisory Committee on Water Resources that operated from 1966 to 1968. In 1967, this committee produced the report "Water for Illinois, A Plan of Action." In 1980, the second committee, a State Water Plan Task Force, was appointed to provide policy and program guidance in water-resources management to State and local agencies and to nongovernmental organizations. The Task Force produced annual progress reports and a final report titled "Illinois State Water Plan" in January 1984. Since 1984, the Task Force has produced annual reports dealing with implementation of the State water plan.

Water management is the responsibility of one-half of the State agencies engaged in aspects of water resources. The roles of agencies directly involved in water resources are summarized below.

The Illinois State Water Survey in the Illinois Department of Energy and Natural Resources is the primary State agency concerned with water research, data collection, and data requests. It shares responsibility for ground-water activities with the Illinois State Geological Survey.

The Division of Water Resources in the Illinois Department of Transportation is responsible for protective jurisdiction over public water and regulates construction in rivers, lakes, and streams. The Division allocates and regulates all water diverted from Lake Michigan for Illinois' use and also regulates the sale of water from State-owned multipurpose reservoirs.

The Illinois Environmental Protection Agency, which has a broad mandate to protect the State's environment, protects and regulates public-water supplies. It administers the Federal Clean Water Act, the Resource Conservation and Recovery Act, and the Safe Drinking Water Act. The Division of Public Water Supply within the Illinois Environmental Protection Agency is responsible for protecting the quality and the quantity of public water supplies.

An agency closely allied to the Illinois Environmental Protection Agency is the Illinois Department of Public Health, which regulates activities related to plumbing, well-pump installations, bathing beaches, and private and semiprivate water supplies, such as schools, restaurants, and hospitals.

The Illinois Department of Mines and Minerals acts to prevent pollution of freshwater supplies by oil production, gas production, or saltwater-disposal activities. Permits for drilling water wells and for plugging abandoned wells are required from this Department.

The Illinois Department of Commerce and Community Affairs is the principal State agency dealing with business and local community affairs. It administers various grant and loan programs including those for water-supply facilities. This department also has initiated a program promoting water conservation, particularly at the local level.

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FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 102 E. Main Street, 4th Floor, Urbana, IL 61801

INDIANA
Water Supply and Use

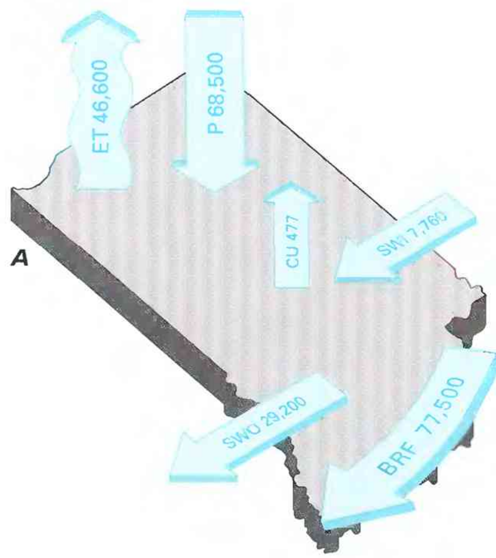
Indiana receives large quantities of water available for various uses from lakes and rivers bordering the State and from ample precipitation (fig. 1*A*). Indiana's borders are defined, in part, by Lake Michigan and the Ohio and Wabash Rivers. The largest single source of freshwater is Lake Michigan, which contains 1,300 trillion gallons of water (Great Lakes Basin Commission, 1975). Surface-water inflows, which include boundary-water withdrawals, are 7,760 Mgal/d (million gallons per day) (U.S. Geological Survey 1986b,c,d). Annual precipitation ranges from about 36 inches in the northeast part of the State to about 44 inches in the south-central part of the State and averages 39.6 inches statewide (Gann and Brown, 1989).

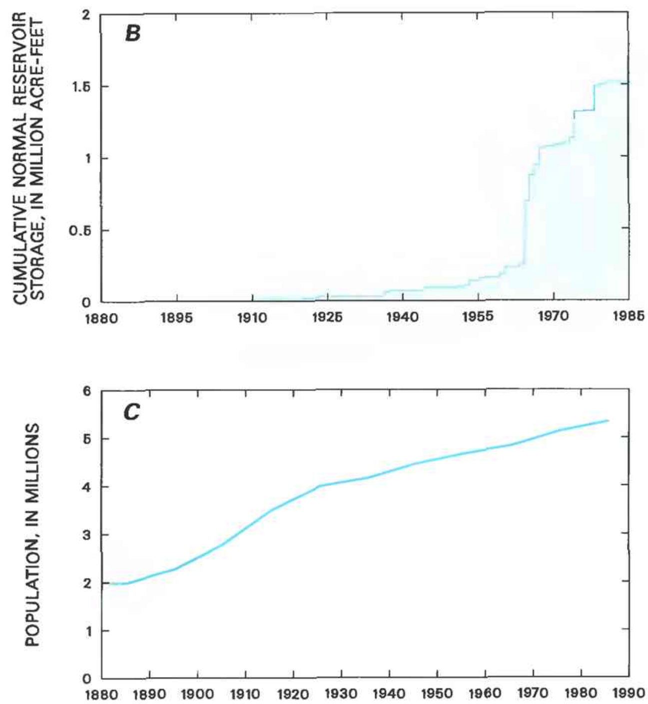
Ground-water availability differs statewide. Yields range from about 1 gal/min (gallon per minute) from wells completed in bedrock aquifers of southern Indiana to 2,000 gal/min from wells completed in outwash aquifers of central and northern Indiana (Clark, 1980).

During 1985, about 9,360 Mgal/d was withdrawn from surface- and ground-water sources to meet the needs of Indiana's citizens. This quantity placed Indiana 14th in total water withdrawals by States in 1985 (Solley and others, 1988). Of total withdrawals, 93.2 percent was from surface-water sources, and 6.8 percent was from ground-water sources.

One of the largest industrial centers in the Nation is along the southern shore of Lake Michigan. This lake provides a dependable source of water that is suitable for most uses, which is a primary reason for this dense concentration of industry. Large industrial users of water also are located along the Ohio River. These two water sources have helped to make Indiana the largest user of water for industry; total 1985 use was 2,730 Mgal/d, which was 10 percent of the total industrial water use in the United States (Solley and others, 1988). Mining is not a large user of water in Indiana.

Thermoelectric power generation is the largest user of water in Indiana, accounting for 62.0 percent of total water withdrawals. Of the 5,800 Mgal/d withdrawn for thermoelectric power genera-





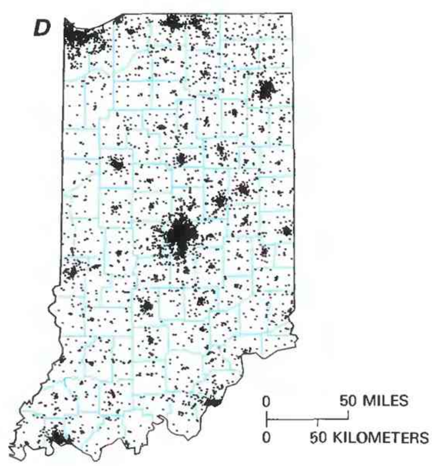


Figure 1. **Water supply and population in Indiana.** ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Gann and Brown, 1989; Indiana Department of Natural Resources, 1986; and various reports of the U.S. Geological Survey. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

tion during 1985, 1.7 percent was consumed. All 37 thermoelectric power generation plants in the State use fossil fuel.

Domestic and commercial, and agricultural are the other water use categories monitored in Indiana. About 78.3 percent (502 Mgal/d) of the water used for domestic and commercial purposes was obtained from public-supply systems and 21.7 percent (139 Mgal/d) was self-supplied. About 60 percent of the land in Indiana is used for crops and pasture (U.S. Bureau of the Census, 1984), but only 1.0 percent of the water withdrawn is used for agriculture.

Major water-management concerns are the quantity and quality of ground water. The effect of large ground-water withdrawals on nearby users is a major water use issue, which has resulted in legislation defining specific responsibilities of large-capacity users of ground water. Another concern is the potential for ground-water contamination from hazardous-waste disposal sites and the potential effect on water withdrawal, especially for public supply.

HISTORY OF WATER DEVELOPMENT

The availability of water has been important to population growth and distribution. By the time the first pioneers were starting to settle in what is now Indiana, the Indians were living in every part of the State—primarily in water-rich areas in the northern one-third of the State and along the Ohio and the Wabash Rivers.

Most of the pioneers who settled in Indiana during the late 1700's and early 1800's traveled down the Ohio River from the East. In 1810, the population was centered mainly along the major rivers of southern Indiana, the Ohio and the Wabash, and along the Whitewater River in the southeastern part of the State (Moulton, 1966). When Indiana was granted statehood in 1816, the population was spreading northward along the major streams.

During the first one-half of the 19th century, canals were an excellent means of transportation and commerce. In 1832, Indiana started construction of a great canal—the Wabash and Erie. To finance part of the construction of this canal, as well as several others, the State legislature passed the Mammoth Internal Improvements Act of 1836. Because of financial problems, the Wabash and Erie Canal was the only system to be completed (Madison, 1986). This canal originated in Ohio, flowed along the Wabash River through northern Indiana, and connected with the Ohio River at Evansville. When the last section of the canal was completed in 1853, it had a length of 468 miles, making it the longest canal in the country (Simons, 1985). The Wabash and Erie Canal was an important transportation route in moving people and agricultural products, especially in northern Indiana, where it was the primary factor in the growth of communities along its route. After the arrival of the railroads, canal transportation waned and, by the 1870's, became unimportant.

In the 1800's, development of drainage projects made great changes in the water resources of northwestern Indiana. In 1852, funding was approved to drain and use for farmland the largest wetland in the Kankakee basin, which was also one of the Nation's most famous wildlife habitats. In 1917, dredging and straightening the main stem of the Kankakee River and its tributaries began (Kankakee River Basin Task Force, 1978). This and other similar projects turned the sinuous 250-mile river into the straight 65-mile channel that it is today. During the late 1880's, industry began to develop along the shore of Lake Michigan. Because of an ample supply of water, this area (known as the Calumet region) quickly became one of the most intensively industrialized areas of the United States, which placed greater demands on the streams in the area. To improve navigation and drainage, the natural streamflow patterns in the Calumet region were changed. By 1922, the Little Calumet River, which had drained into the Great Lakes, had been diverted to drain toward the Mississippi River (Moore, 1959).

By 1837, the first reservoir in Indiana with a capacity greater than 5,000 acre-ft (acre-feet) was completed. This reservoir was built to supplement flow in the Wabash and Erie Canal. Starting in the 1950's, the construction of large reservoirs (greater than 5,000 acre-ft) increased substantially (fig. 1*B*). Between 1952 and 1980, 25 large reservoirs were built in Indiana; of these, two were on the Ohio River between Indiana and Kentucky (U.S. Geological Survey, 1986a). Many of these large reservoirs were built for reasons that reflect the increase in population from 1940 to 1970 (fig. 1*C*)—to provide a dependable supply of water to communities that had outgrown other sources, to decrease flood damage to developments in lowland areas, and to provide areas for water-related outdoor recreation, including boating, canoeing, waterskiing, swimming, ice skating, and fishing. In 1985, Indiana had 5.47 million people (fig. 1*C*), placing the State 14th in population. The distribution of the State's population is shown in figure 1*D*.

WATER USE

Precipitation accounts for 90 percent of the water entering the State (fig. 1*A*). Surface-water inflows, which include stream inflows and water withdrawn from boundary rivers and Lake Michigan, account for the other 10 percent of the water entering the State. About 61 percent of the water is lost to evapotranspiration, and 38 percent leaves as surface-water outflows. Consumptive water use accounts for less than 1 percent of the water. The 29,200 Mgal/d that leaves as surface-water outflows is more than three times the 7,760 Mgal/d that enters as surface-water inflows.

Total water withdrawals in Indiana are shown by county in figure 2*A*. The largest total withdrawals are in those counties bordering Lake Michigan and along the major rivers of Indiana—in particular, the Ohio, the Wabash, and the White Rivers.

For various reasons, part of the population lives and works where the water supply cannot meet the water demand. This condition is especially true in southern Indiana, where streamflow is variable and ground-water supplies are not dependable. Many reservoirs have been constructed to provide a sustained source of water in this area. Each of these reservoirs in southern Indiana, as elsewhere in the State, has multiple uses, such as water supply, hydropower, recreation, and flood control. Eighteen of the 35 reservoirs that have a storage capacity of at least 5,000 acre-ft (1,630 Mgal) are in the southern one-third of the State.

Surface water is the major source of water withdrawn in Indiana. The lakes, rivers, and streams of the State supply about 93.2 percent of total water withdrawals. During 1985, 8,720 Mgal/d was withdrawn from surface-water sources.

The largest withdrawals of water are for thermoelectric power generation and industry. Both of these uses occur along Lake Michigan in Lake, Porter, and LaPorte Counties. These three counties have large surface-water withdrawals and account for 35 percent of total water withdrawals. Other counties that have surface-water withdrawals greater than 100 Mgal/d (fig. 2*B*) are along the Ohio River (Dearborn, Floyd, Jefferson, and Warrick Counties), the Wabash River (Vermillion, Vigo, and Sullivan Counties), and the White River (Marion and Pike Counties). Thermoelectric power generation is the major water use in these counties.

Surface water provides for instream uses as well as the offstream uses mentioned above. The largest instream use of water in Indiana is for hydroelectric power generation. Hydroelectric powerplants are located on the Ohio River, the St. Joseph River in Elkhart County, and the Tippecanoe River in Carroll County. During 1985, these powerplants used about 9,620 Mgal/d of water in the generation of 362 GWh (gigawatthours) of electricity, which represents less than 1 percent of all power generated in the State.

Ground water accounts for about 6.8 percent of total water withdrawals in Indiana. Ground-water withdrawals are shown by county in figure 2*C*. The major withdrawals are for public supply, domestic and commercial, and industrial and mining purposes. The largest withdrawals (greater than 20 Mgal/d) are in Clark, Elkhart, Marion, St. Joseph, and Tippecanoe Counties. In Clark, Marion, and Tippecanoe Counties, glaciofluvial deposits are the principal aquifer. In Elkhart and St. Joseph Counties, the principal aquifer is glacial outwash.

Nearly all (99 percent) of the surface-water withdrawals are in four of the nine principal river basins in Indiana. The distribution of surface-water withdrawals within these four river basins is shown in figure 3*A*. In three of these basins (Middle Ohio basin, Wabash basin, and Lower Ohio basin), most withdrawals are for thermoelectric power generation. The largest withdrawals of water (66.1 percent) from Lake Michigan are for industrial users. The largest withdrawals in the remaining five principal river basins, which supply less than 1 percent (78 Mgal/d) of the State's surface-water withdrawals, are for public supply in three basins, thermoelectric power generation in one basin, and industrial and mining purposes in one basin.

Most ground-water withdrawals are from aquifers along the major rivers and from extremely productive aquifers in the northern two-thirds of the State. Four principal aquifers (fig. 3*B*) were the source for 99 percent of Indiana's ground-water withdrawals. The glaciofluvial aquifers are along the major rivers in the State; these aquifers are composed of sand and gravel, and generally are unconfined. Yields to properly constructed wells in these aquifers commonly are 100 to 500 gal/min and may exceed 1,500 gal/min (U.S. Geological Survey, 1985). Of the water withdrawn from these aquifers, 53.0 percent is for industrial and mining use.

In the northern two-thirds of Indiana, the Silurian–Devonian aquifers are overlain by Wisconsin till and glacial outwash. The Silurian–Devonian aquifers are composed of fractured limestone of irregular distribution and generally are confined. Wells completed in these aquifers commonly yield 10 to 100 gal/min; some yields exceed 600 gal/min (Clark, 1980). Aquifers within the Wisconsin till are isolated lenses of sand, gravel, and some silt and are generally confined or, at least, semiconfined. Properly constructed wells within the Wisconsin till commonly yield 10 to 100 gal/min; some yields exceed 400 gal/min. The glacial outwash aquifers are mostly sand and silt and generally are unconfined. Properly constructed wells within the glacial outwash commonly yield 100 to 500 gal/min; some yields may exceed 2,000 gal/min (Clark, 1980). Where the Silurian–Devonian aquifers are overlain by Wisconsin till, the till generally is the ground-water source for small-capacity users, and the Silurian–Devonian aquifers are the principal source for large-capacity users. The glaciofluvial and glacial outwash aquifers are capable of meeting the needs of most users. Domestic and commercial users withdraw the largest percentage of water from the Wisconsin till (40.0), whereas public suppliers withdraw the largest percentages of water from the glacial outwash (49.0) and Silurian–Devonian (45.0) aquifers. Aquifers in the remaining areas of the State supply about 1 percent (4.4 Mgal/d) of Indiana's ground water. These aquifers generally are unconfined, provide small yields, and are composed of bedrock. The primary purpose of withdrawals from these aquifers is public supply.

The offstream source, use, and disposition of freshwater in Indiana in 1985 are diagrammatically shown in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding.

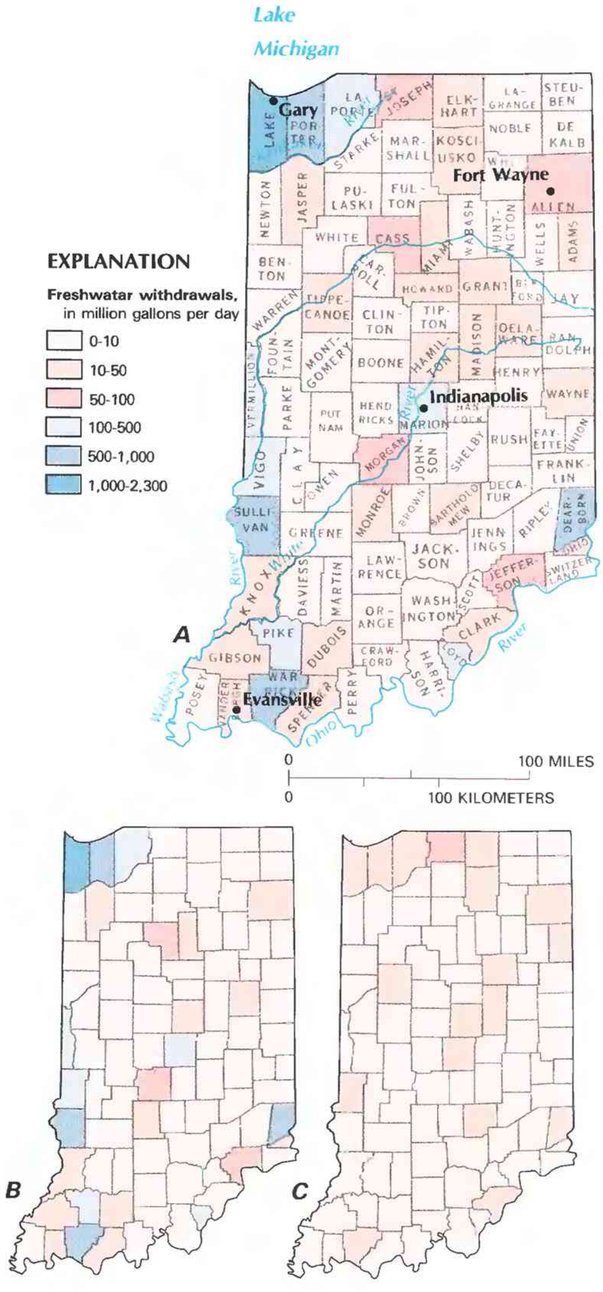


Figure 2. Freshwater withdrawals by county in Indiana, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. About two-thirds (3.67 million people) of the State's population received their water for domestic use from public-supply systems during 1985. The 687 public-supply systems also supplied water to commercial and industrial users.

As the source data in figure 4 indicate, 3.5 percent of total surface-water withdrawals and 42.7 percent of total ground-water withdrawals were for public supply during 1985. Total withdrawals for public supply were 575 Mgal/d. Of this quantity, 52.9 percent (304 Mgal/d) was from surface-water sources, and 47.1 percent (271 Mgal/d) was from ground-water sources. Domestic and commercial users received 87.4 percent (502 Mgal/d) of the water delivered by public-supply systems, which includes water lost in the distribution system. The remaining withdrawals for public supply, 12.6 percent (73 Mgal/d), were delivered to industrial and mining users.

Marion (Indianapolis), Lake (Gary), Allen (Fort Wayne), and Vanderburgh (Evansville) Counties have the largest withdrawals of surface water for public supply. The counties most dependent on ground water for public supply are St. Joseph, Tippecanoe, Elkhart, and Madison Counties.

In southern Indiana, where the surface- and ground-water resources are limited, rural public-supply systems have been developed. Typically, these systems are established by the local residents who have unreliable individual wells and cisterns. Because these systems tend to have small-capacity distribution capabilities and because the water is expensive, these rural systems usually provide water for domestic use only. Many of these systems are interconnected, which allows the water to be sold to other systems.

DOMESTIC AND COMMERCIAL

During 1985, public-supply systems and self-supplied facilities provided 642 Mgal/d to domestic and commercial users (fig. 4).

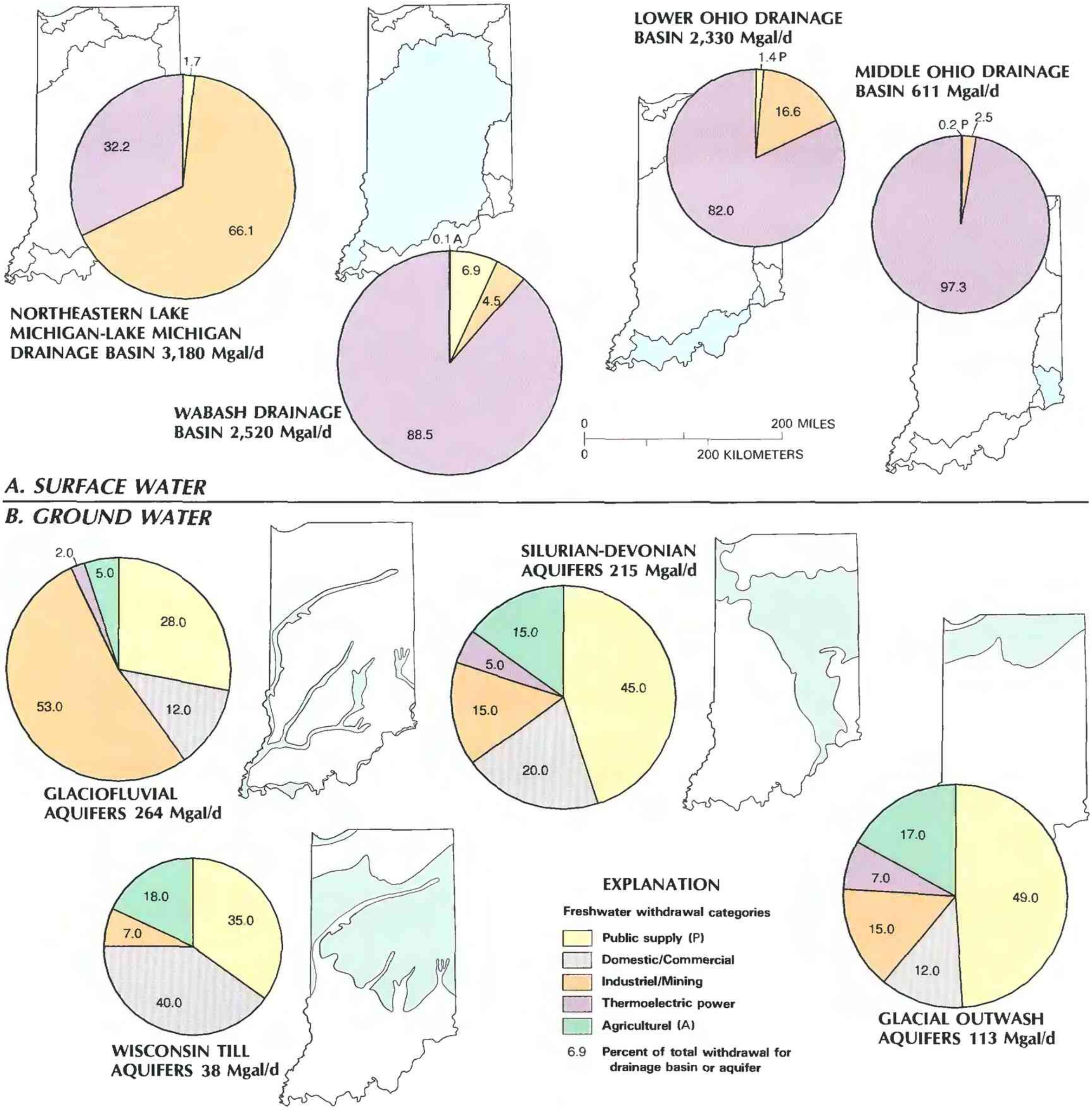


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Indiana, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Indiana Department of Natural Resources, 1986; Clark, 1980; and Geosciences Research Associates, 1982.)

This category of use accounted for 6.9 percent of total water use in Indiana. Of this total, 78.3 percent (502 Mgal/d) was from public-supply systems, 21.7 percent (139 Mgal/d) was self-supplied ground water, and less than 0.1 percent (less than 0.1 Mgal/d) was self-supplied surface water. The Silurian–Devonian aquifers and the overlying Wisconsin till and glacial outwash (fig. 3*B*) are the principal ground-water sources in central and northern Indiana.

One-third (1.8 million people) of the State's population was self-supplied and used an average of 77 gal/d (gallons per day) per capita. By contrast, the 67 percent of the population who purchased water from public-supply systems averaged 115 gal/d per capita. Commercial users received 78 Mgal/d from public-supply facilities, and 1.1 Mgal/d was self-supplied. Of the total domestic and commercial use, 9.6 percent (62 Mgal/d) was consumed and 90.4 percent (580 Mgal/d) was returned to the hydrologic system.

Industrial and Mining

Although Indiana is considered to be part of the corn belt, its industrial output is important to the economy. The most common manufacturing groups include primary metal processing, transportation equipment, electrical equipment and supplies, machinery, and fabricated metal products. The primary metal-processing category is the largest industrial water user.

Water has many industrial uses, and surface water is the primary source. Cooling and condensation constitute the largest industrial water use. Industries also use water as process water and boiler-feed water. During 1985, industrial water use (self-supplied and from public-supply systems) was 29 percent (2,730 Mgal/d) of all water withdrawn. Surface water, the largest source of self-supplied water, supplied 2,550 Mgal/d, and ground-water sources supplied 109 Mgal/d. About 80 percent of all the water used by industry was from Lake Michigan. Public-supply systems delivered 72 Mgal/d for industrial use.

The amount of water used in the extraction and processing of various minerals in Indiana is small. Most of the water withdrawn in mining is for dewatering the mined area and not for processing the material. In southwestern Indiana, coal for the State's thermoelectric powerplants is mined and processed. During 1985, an estimated 15 Mgal/d of water was used to wash coal, a process that decreases the sulfur and ash content of the coal. Petroleum is produced in east-central and southwestern Indiana by freshwater injection into the oil-bearing formation. About 1 Mgal/d is used in this process. Limestone is mined in south-central Indiana. Lawrence and Monroe Counties produce most of the building limestone quarried in the Nation. Sand and gravel is mined almost entirely from glacial drift in the northern two-thirds of the State. Much less production of sand and gravel is from the alluvium of stream valleys. During 1985, mining used a total of about 90 Mgal/d of water; about 0.3 Mgal/d of this quantity was consumed.

Thermoelectric Power

Thermoelectric power generation used 62.0 percent of all water withdrawn in Indiana, which was more than any other water use category. All thermoelectric powerplants in Indiana use either coal, fuel oil, or natural gas as their fuel source. Coal-fired, steam-generated plants were the source for about 95 percent of the electricity produced in the State. In 1985, the 37 thermoelectric power-

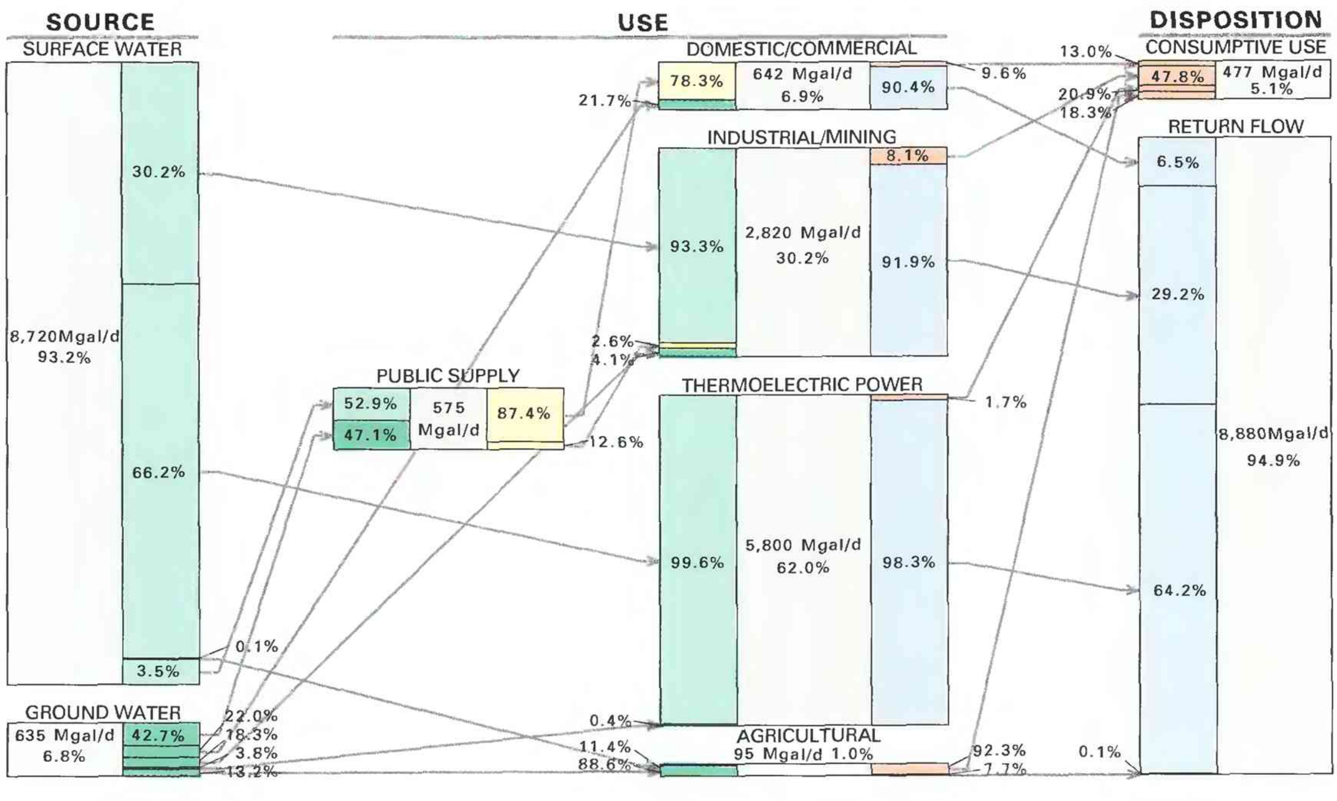


Figure 4. Source, use, and disposition of an estimated 9,360 Mgal/d (million gallons per day) of freshwater in Indiana, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Figure 5. Indiana water-management basins. (Source: Indiana Department of Natural Resources, written communication, 1983.)

generating plants in the State used a total of 5,800 Mgal/d water (fig. 4) to produce 52,900 GWh of electricity. Of this quantity, 99.6 percent (5,770 Mgal/d) was from surface-water sources and 0.4 percent (24 Mgal/d) was from ground-water sources. Most of the powerplants are located along Lake Michigan and the Ohio, the Wabash, and the White Rivers, where large supplies of water are readily available. Of the water withdrawn, 98.3 percent was returned for downstream use.

Water is used during two steps in the production of steam-generated power. Some of the water is heated to steam to spin the turbines. Most of the water withdrawn is used to cool the steam back into water. Three cooling methods (once-through, cooling towers, and cooling lakes) are used in Indiana. The once-through method is the most common.

AGRICULTURAL

Indiana consistently ranks high nationally in crop and animal production. In 1985, Indiana ranked first in grain sorghum production, third in soybean production, and fourth in corn production; it ranked second in chicken production and third in hog production (Jeff Smith, Marion County Cooperative Extension Service, oral commun., 1987).

From the late 1970's to 1985, total crop acreage under irrigation has more than doubled. Much of the irrigated acreage in 1985 was in the Kankakee basin (59,000 acres) and the St. Joseph basin (46,000 acres), especially Elkhart and Lagrange Counties (fig. 5). About 155,000 acres were irrigated in the State during 1985. Water withdrawals for irrigation averaged 47 Mgal/d on a yearly basis; however, because the typical irrigation season in Indiana is from mid-June to mid-September, the withdrawals averaged about 190 Mgal/d for this period. Traveling-gun and center-pivot systems are the most common types of irrigation in Indiana.

Water use for animal production is nearly equal to that used for irrigation. In 1985, the water used for stock watering, feed lots, dairy operations, fish farming, and other on-farm needs was estimated to be 48 Mgal/d.

WATER MANAGEMENT

Indiana began to assess the availability and the management of the State's water resources in the late 1970's. Interest in water rights and management increased in 1981 when irrigation became more widespread in northern Newton and northwestern Jasper Counties. Increased pumpage caused ground-water level declines in many of the domestic wells on properties adjacent to the irrigated areas to decline (Basch and Funkhouser, 1985). In response to this water conflict, the 1982 General Assembly enacted the Emergency Water Rights Act, which provided protection for individuals in Jasper and Newton Counties whose domestic or livestock well systems were affected by excessive declines in ground-water levels.

Proper management of the State's water resources requires that the quantity of water used and the source of that water be known. To make this information available, the 1983 General Assembly enacted the Water Resource Management Act (Indiana Code 13–2–6.1). The Water Management Branch was created within the Division of Water of the Indiana Department of Natural Resources (IDNR) to fulfill the objectives of this Act.

The Water Resource Management Act requires owners of significant water-withdrawal facilities to register their facilities with the IDNR. A significant water-withdrawal facility means "the water withdrawal facilities of a person that, in the aggregrate from all sources and by all methods, has the capability of withdrawing more than 100,000 gallons of ground water, surface water, or ground and surface water combined in 1 day." Additionally, this Act requires owners of registered facilities to file an annual report of the quantities of water withdrawn monthly by the facility. In 1985, about 2,600 facilities were registered, which accounted for 96 percent of all the water withdrawn in 1985.

The Water Resource Management Act also requires a continuing assessment of the availability of water. This assessment is being done on each of the 12 water-management basins (fig. 5) in the State. Assessment studies have been completed for the St. Joseph and the Whitewater basins; the basins now being assessed are the Kankakee, the Lake Michigan, and the Maumee. This basin assessment includes detailed studies that examine the existing water uses, available surface- and ground-water supplies, and areas of potential conflict between competing water users.

Streamflows and navigable waters are protected, in part, by legislation that requires permits for withdrawals from these waters. The criteria used to evaluate permit applications include the hydrologic characteristics of the stream or lake and the existence of prior users who may be affected by a new withdrawal.

In 1985, Indiana joined the other States and Canadian Provinces bordering the Great Lakes in signing the Great Lakes Charter. Two of the objectives of the Charter are to conserve the levels and the flows of the Great Lakes and their tributary and connecting waters, and to provide for cooperative programs and management of the water resources of the Great Lakes basin by the signatory States and Provinces. To meet these objectives, a system of water-use reporting and joint consultation is being implemented by the Great Lakes Charter Commission. Although only 10 percent of Indiana is in the Great Lakes basin (Lake Michigan, St. Joseph, and Maumee basins; fig. 5), 36 percent of the offstream water use of the State is in the Great Lakes basin.

To protect small-capacity ground-water users whose water supplies are adversely affected by the withdrawals of large-capacity ground-water users, the Emergency Water Rights Act was expanded in 1985 to include the entire State. The remedial actions that the IDNR can take to protect these small-capacity users include scheduling of water withdrawals by the offending large-capacity users, repair or replacement of the affected well, or providing an alternative supply at the expense of the offending large-capacity user(s). No statute presently protects one large-capacity water user

The ethanol plant is an example of how Indiana utilizes its many resources. Indiana is the leading State in industrial water use. (Photograph from the Indiana Department of Natural Resources.)

from the effects of another or one small-capacity water user from effects caused by another small-capacity water user.

The quality of ground water being withdrawn is an increasing concern. As of 1985, the water in 96 public-supply wells in Indiana had detectable concentrations of synthetic organic compounds (Indiana Department of Environmental Management, 1985). A State interagency work group has been formed to develop a draft ground-water protection policy to address ground-water-quality concerns. This policy will include data management, water-information exchange, priority ground waters, and ground-water monitoring.

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Prepared by E.J. Crompton, U.S. Geological Survey; Water Management section by Timothy Graves, Indiana Department of Natural Resources

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 5957 Lakeside Boulevard, Indianapolis, IN 46278

Iowa
Water Supply and Use

Iowa is unique in having two major rivers on its borders—the Missouri on the west and the Mississippi on the east. In 1985, water withdrawn from these rivers accounted for 1,020 Mgal/d (million gallons per day) of the State's 2,000 Mgal/d of surface-water inflows (fig. 1A); the remaining 980 Mgal/d entered from Minnesota streams. Iowa receives an average annual precipitation of 32 inches, which is equivalent to 85,600 Mgal/d. During 1985, total freshwater withdrawals for Iowa were 2,760 Mgal/d. Of the total withdrawals, 473 Mgal/d was consumed, and 2,290 Mgal/d was returned to the hydrologic system.

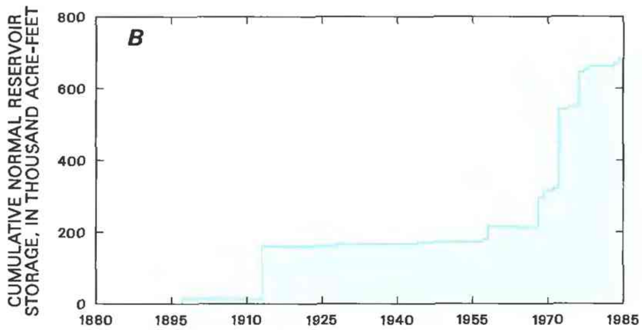
Major withdrawals in Iowa differ according to geographical area and type of use. Large withdrawals of surface water along major rivers are used for thermoelectric power generation. Ground-water withdrawals are more significant than surface-water withdrawals in the central and northern parts of the State because these areas contain most of the population and the principal use for ground water is public supply.

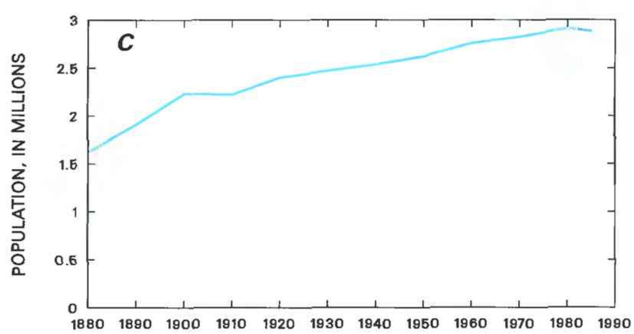
During 1985, 65.6 percent of withdrawals from surface- and ground-water sources was for thermoelectric power generation, and 3.0 percent of these withdrawals was consumed. Of the remaining withdrawals, domestic and commercial use accounted for 14.8 percent, industrial and mining use accounted for 10.9 percent, and agricultural use accounted for 8.7 percent. Of the total water consumed in Iowa, 50.5 percent was from agricultural use, 31.6 percent was from domestic and commercial use, 6.6 percent was from industrial and mining use, and 11.3 percent was from thermoelectric power generation. Surface water is the major source of water in Iowa, accounting for 75.7 percent of all withdrawals. If water for thermoelectric power generation were excluded, then ground water would be the dominant source for the remaining uses, accounting for 70 percent of withdrawals.

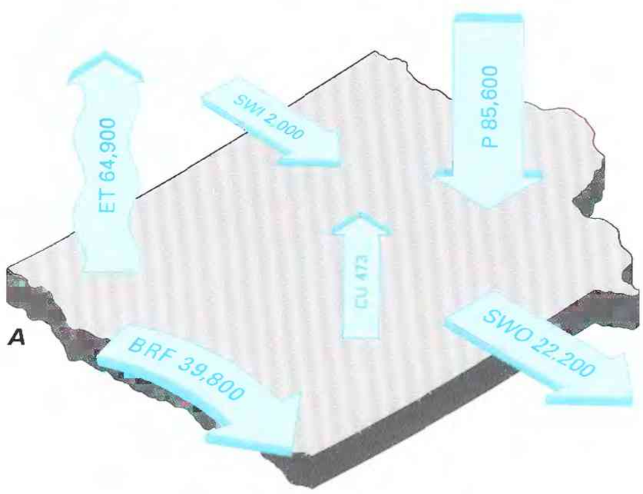
State officials have forecast water use trends for Iowa. Population in Iowa is projected to increase by 60,000 from 2.8 million in 1985 to 2.9 million in 2000, and total water withdrawals are projected to increase 19 percent from 1985 to 2005. An increase in withdrawals will be necessary to meet the needs of an increase in population and an increase in general water use.

HISTORY OF WATER DEVELOPMENT

Iowa's rivers were used by early explorers for navigational purposes. In 1673, Louis Joliet and Father Marquette were the first







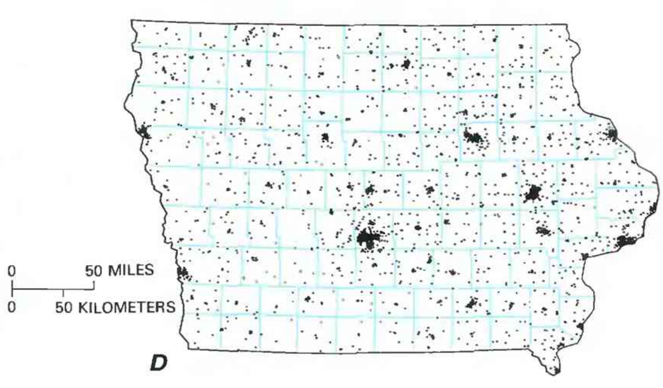


Figure 1. Water supply and population in Iowa. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Precipitation data from Iowa Agricultural Statistics, 1986; streamflow data from U.S. Geological Survey National Water Data Storage and Retrieval System; consumptive-use data from U.S. Geological Survey State Water Use Data System. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

to explore the Mississippi River. The Missouri River was explored in 1804 by the Lewis and Clark expedition. Early settlements in Iowa developed along interior and border rivers, which were used as sources of water and as trade routes. Several of these settlements became major cities.

Steamboats on the Mississippi and the Missouri Rivers demonstrated the role of rivers as transportation routes. Today, these two rivers are important for barge shipment of grain, coal, and oil. Water transportation continues to be the cheapest and most energy-efficient method for moving relatively large cargoes (Bachman and Horick, 1982).

As the rivers became more important for navigation, locks and dams were needed to maintain reliable water depths. In 1897, the first dam was built in southeastern Iowa on the Mississippi River. Dams and water storage were developed to accommodate the needs of Iowa's increasing population (fig. 1*B*). In 1985, Iowa's reservoirs had 684,300 acre-feet in cumulative water storage.

Water power was originally used for operating mills in Iowa. By 1879, there were 712 flourmills and gristmills in Iowa (Gieseke, 1970); few remain today. Hydroelectric plants, located on streams and rivers, were the first powerplants to produce electricity. Four of these plants remain in use. Fossil-fueled plants have almost completely replaced the hydroelectric plants. In 1985, thermoelectric power generation was the largest water use category in Iowa.

The population of Iowa steadily increased from about 1.6 million in 1880 to about 2.9 million in 1980, and then decreased slightly (fig. 1*C*). The total population, as well as its distribution (fig. 1*D*), affect the withdrawal and the distribution of water used for various purposes.

WATER USE

The natural water supply generally is sufficient to satisfy the demand for water in Iowa. The water budget for Iowa (fig. 1*A*) indicates the amount of water that flows to and from the State. In 1985, a total of 2,760 Mgal/d was withdrawn from surface- and ground-water sources.

The total withdrawals of freshwater by county in 1985 are shown in figure 2*A*. Large withdrawals along the State's eastern and western borders result from fossil-fueled powerplants located along the major rivers. Pottawattamie County withdrew from surface-water sources 478 Mgal/d, the largest surface-water use of any county. Large withdrawals in Polk, Black Hawk, and Linn Counties were for public supplies for Des Moines, Waterloo, and Cedar Rapids, respectively.

Surface- and ground-water withdrawals by county are shown in figures 2*B* and 2*C*, respectively. Surface-water withdrawal is greatest along the eastern and western boundaries of the State, especially from the two major rivers. Ground-water withdrawals are minimal in the southern part of the State because the ground-water supply is limited and very mineralized (fig. 2*C*).

Surface-water withdrawals by river basins and type of use are shown in figure 3*A*. The Missouri–Little Sioux and the Upper Mississippi–Iowa–Skunk–Wapsipinicon basins had the two largest

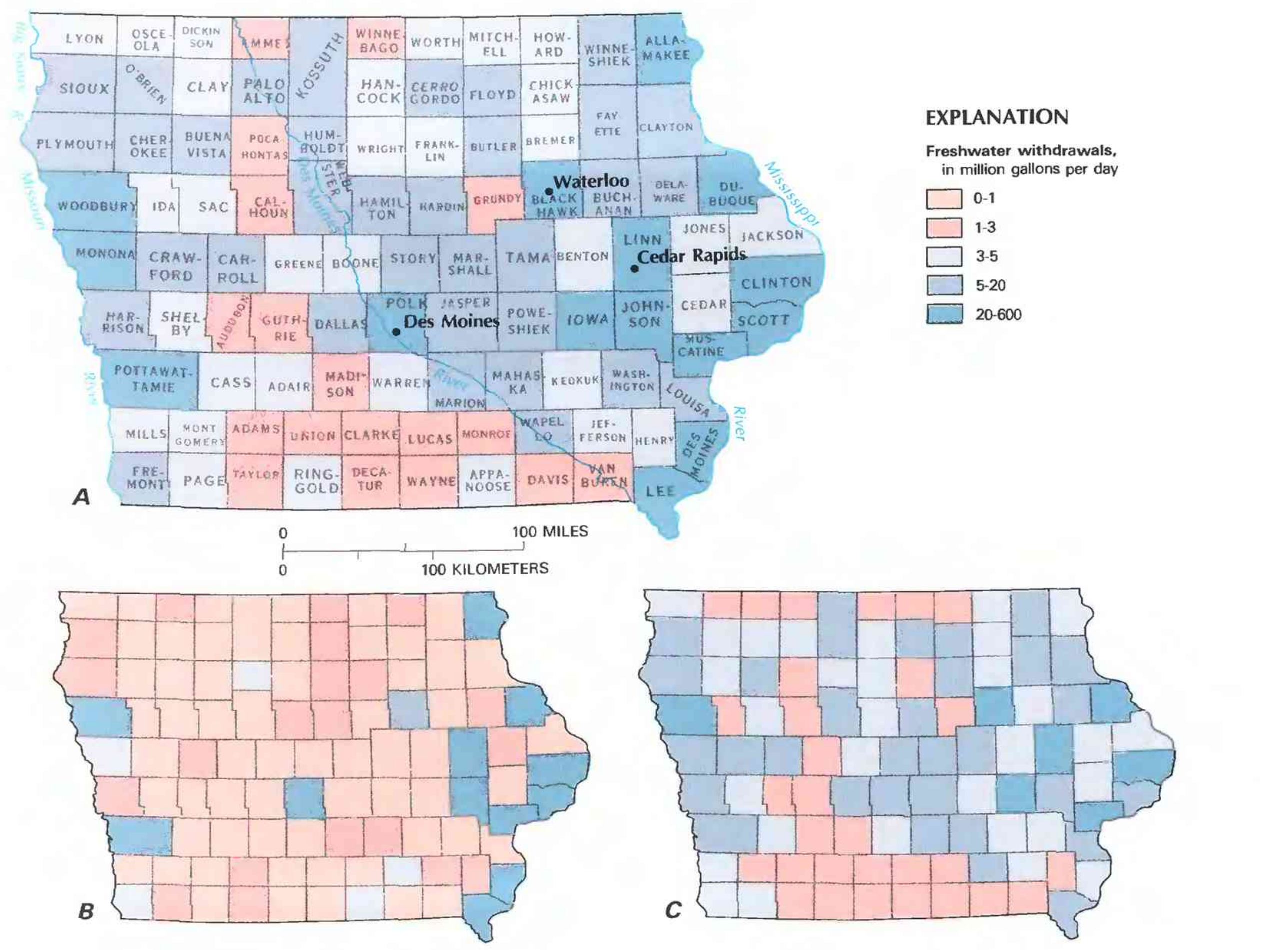


Figure 2. Freshwater withdrawals by county in Iowa, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

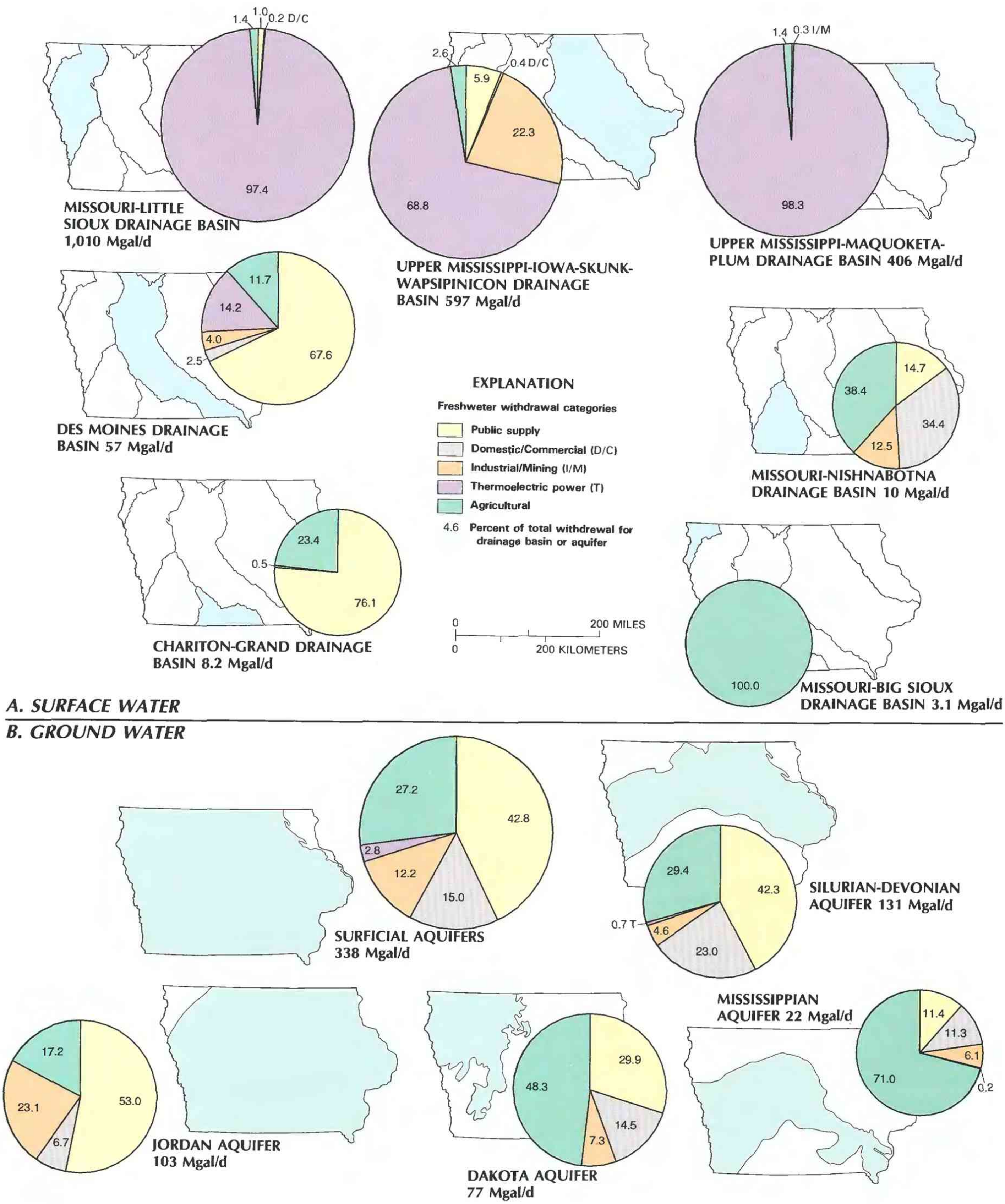


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Iowa, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

surface-water withdrawals during 1985 because of fossil-fueled powerplants operating in these basins. Of all surface-water withdrawals (2,090 Mgal/d), 48.3 percent was from the Missouri–Little Sioux basin and 28.5 percent was from the Upper Mississippi–Iowa–Skunk–Wapsipinicon basin.

The five major aquifers in Iowa and the amount of water withdrawn from each are shown in figure 3*B*. Surficial aquifers, which include alluvial, buried-channel, and glacial-drift aquifers, accounted for 50.4 percent (338 Mgal/d) of all ground-water withdrawals during 1985. The Silurian–Devonian aquifer accounted for 19.5 percent (131 Mgal/d) of all ground-water withdrawals and is used primarily in northeastern Iowa. Nearly 43 percent of the water withdrawn from surficial aquifers and the Silurian–Devonian aquifer was for public supply. The Jordan aquifer accounted for 15.3 percent (103 Mgal/d) of all ground-water withdrawals and is a primary source of ground water in the extreme northeastern corner of the State and in south-central Iowa. Public supply accounted for 53.0 percent of all withdrawals from the Jordan aquifer. The Dakota aquifer accounted for 11.5 percent (77 Mgal/d) of all ground-water withdrawals and is a primary source of ground water in northwestern Iowa. Agriculture accounted for 48.3 percent of all withdrawals from the Dakota aquifer. The Mississippian aquifer accounted for 3.3 percent (22 Mgal/d) of all ground-water withdrawals, of which 71.0 percent was for agriculture along a narrow band extending from north-central to southeastern Iowa. Of the total ground-water withdrawals from all aquifers, 38.5 percent was for public supply.

The source, use, and disposition of water in Iowa in 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 75.7 percent of total freshwater withdrawals (2,760 Mgal/d) was from surface-water sources. Of the surface-water withdrawals, 0.4 percent was for self-supplied domestic and commercial purposes, 6.6 percent was for self-supplied industry and mining, 86.1 percent was for thermoelectric power generation, 2.5 percent was for self-supplied agriculture, and 4.4 percent was for public supply. The use data indicate that 14.8 percent of total withdrawals was for domestic and commercial purposes, 10.9 percent was for industry and mining use, 65.6 percent was for thermoelectric power generation, and 8.7 percent was for agricultural use. The disposition data indicate that, of all the water withdrawn, 82.9 percent was returned to the hydrologic system and the remainder was consumed. The largest quantity of water returned to the hydrologic system was by thermoelectric power generation—76.8 percent (1,760 Mgal/d) of the total returned water. Consumptive use accounted for 36.4 percent of domestic and commercial withdrawals, 10.3 percent of industrial and mining withdrawals, 3.0 percent of thermoelectric power-generation withdrawals, and more than 99.9 percent of agricultural withdrawals.

Hydroelectric powerplants are a major instream water use. Since 1980, water use for hydroelectric power generation has decreased about 11,000 Mgal/d. Presently (1987), 4 percent of the State's electricity is produced by hydroelectric plants. During 1985, 17,200 Mgal/d was needed to generate 918 GWh (gigawatthours) of electricity. Hydroelectric powerplants have little consumptive water use. Hydroelectric-power generation is not included in figure 4.

Public Supply

Public-supply systems withdraw water, treat it, and distribute it to users. In Iowa, public-supply systems deliver water to domestic and commercial, industrial and mining, and thermoelectric power generation users (fig. 4). During 1985, Iowa ranked 28th nationally in public-supply withdrawals and 26th in population (Solley and others, 1988). Between 1955 and 1985, public-supply deliveries of water increased 148 percent, whereas population increased 7 percent (fig. 1*C*). Public-supply withdrawals have increased from 28 percent of total water withdrawn (excluding thermoelectric power generation) in 1980 to 37 percent in 1985. The increase of public-supply withdrawals is partly due to an increase in per capita domestic use—from 104 gal/d (gallons per day) during 1980 (Solley and others, 1983) to 142 gal/d during 1985. Withdrawals for public-supply also increased faster than population because of increased deliveries to industrial and commercial facilities. Total public-supply withdrawals during 1985 were 350 Mgal/d, of which 26.1 percent (91 Mgal/d) was from surface-water sources and 73.9 percent (259 Mgal/d) was from ground-water sources. The largest public-supply user is Des Moines, Iowa's State Capital, which accounted for 10 percent of the total water withdrawn in this category. In northern and central Iowa, where ground water of satisfactory and quality is abundant, 76 percent of withdrawals for public supply is from ground-water sources. In the southern one-third of the State, however, the quality of the water is different. The principal bedrock aquifer in this area, the Jordan, is more than 1,000 feet deep, and the water is extremely mineralized (Cagle and Heinitz, 1978, p. 45, 78). Hence, ground water is a source of only 55 percent of all public-supply withdrawals in this area.

Regional rural water systems are public-supply systems that are located in areas of inadequate water availability or quality. The rural water systems serve as networks that tap the best available sources of water within a region and deliver it to rural customers. The rural water systems differ in size, number of customers, sources of water, and capacity. Iowa has 23 rural water systems, most of which are in the western and the southern areas (Glanville and Williams, 1983, p. 2). Most of the water is used for domestic, agricultural, and commercial purposes.

Domestic and Commercial

Domestic and commercial water users obtain water from public-supply and self-supplied systems. Total water use during 1985 for domestic and commercial users was 410 Mgal/d, of which 74.9 percent (307 Mgal/d) was delivery from public supplies and 25.1 percent (103 Mgal/d) was from self-supplied systems (fig. 4). The amount from public supplies includes a 14-Mgal/d loss of water in the delivery system. This loss is incorporated with domestic and commercial use in figure 4.

Domestic water use was 368 Mgal/d, of which 82 percent was delivered from public suppliers. These public suppliers served 74 percent of the population of Iowa. Data submitted to the Iowa Department of Natural Resources by public suppliers indicated that domestic use averaged 142 gal/d per capita. About 18 percent of domestic water use was self-supplied. For persons who supplied their own water, 85 gal/d per capita was used to estimate this water use (Buchmiller and Karsten, 1983). Previous authors used smaller per capita quantities to estimate self-supplied domestic use. For 1970, Murray and Reeves (1972, p. 34) used 59 gal/d per capita, and, for 1980, Solley and others (1983, p. 14) used 70 gal/d per capita. Consumptive use in 1985 by publicly supplied and self-supplied domestic users was 144 Mgal/d (Solley and others, 1988).

Commercial water use was 42 Mgal/d, of which 10 percent was from public supplies (Solley and others, 1988). Consumptive use averaged 13 percent of the water withdrawn and delivered. Although commercial use is small when compared with domestic use, it is significant for counties that have large commercial users; for example, 85 percent of all surface-water withdrawals in Fremont County and 64 percent of all ground-water withdrawals in Pottawattamie County were for commercial use.

Industrial and Mining

During 1985, withdrawals for self-supplied industrial and mining use were 260 Mgal/d, and an additional 41 Mgal/d was delivered by public suppliers. Surface water accounted for 45.9 percent of the water used for industrial and mining purposes (fig. 4). In Iowa, industrial uses are mainly farm-related businesses, such as grain processing, food packaging, and farm equipment manufacture. During 1985, these industries accounted for withdrawals and deliveries of 238 Mgal/d and for a consumptive use of 13 percent (31 Mgal/d). The largest users are located in Black Hawk and Dubuque Counties, which account for 13 percent of the total industrial use. Mining activities, such as quarrying and sand-and-gravel pit operations, accounted for 21 percent (63 Mgal/d) of the total water withdrawn in this category. Of all mining withdrawals, 14 percent was in Black Hawk County.

THERMOELECTRIC POWER

Thermoelectric power generation used 65.6 percent of the total water withdrawn in Iowa (fig. 4). Thermoelectric power-generation plants include fossil-fueled and nuclear-powered powerplants located mainly along the State's border rivers. The only nuclear powerplant in Iowa is in Linn County. During 1985, thermoelectric powerplants generated 22,300 GWh of electricity, of which 2,700 GWh was from the nuclear powerplant. One percent of the 1,810 Mgal/d withdrawn for thermoelectric power generation was used at the nuclear powerplant. Of the water withdrawn for thermoelectric power generation, 99.4 percent was surface water.

The principal use of water in this category is for the production of steam and for the cooling of equipment (Buchmiller and Karsten, 1983). Very little water is lost through these processes; consumptive use during 1985 was 3.0 percent (54 Mgal/d) of withdrawals. The remaining 97.0 percent was returned to the hydrologic system (fig. 4).

AGRICULTURAL

Agriculture used 8.7 percent of the total withdrawals in Iowa during 1985 (fig. 4). Nonirrigation withdrawals were 172 Mgal/d, whereas irrigation withdrawals were 68 Mgal/d (Solley and others, 1988). Of the 239 Mgal/d withdrawn for agricultural purposes, 78.4 percent was from ground-water sources.

Iowa's agricultural withdrawals were mostly for nonirrigation purposes, such as livestock watering, during 1985. Since 1975, nonirrigation agricultural withdrawals have increased by 52 Mgal/d. Of the total withdrawals for nonirrigation agricultural purposes, 37 Mgal/d was from surface-water sources, and 135 Mgal/d was from ground-water sources. Most nonirrigation agricultural withdrawals were from the western and the eastern sections of Iowa.

Agricultural withdrawal for irrigation was 68 Mgal/d during 1985. Of this amount, 78 percent was from ground-water sources. More than 68 percent of irrigation withdrawals occurred in nine counties along the western boundary. In this part of the State, precipitation is less than the State average and there is an ample supply of ground water within 20 feet of land surface. Within the State, 178,000 acres were irrigated during 1985, of which 78 percent was irrigated by sprinklers. Irrigated acreage has increased by 121,000 since 1975 in response to more efficient irrigation methods. Consumptive use for agriculture (livestock and irrigation) was more than 99.9 percent of the withdrawals.

WATER MANAGEMENT

The Iowa Department of Natural Resources and its predecessors have managed and regulated Iowa's waters since the Iowa

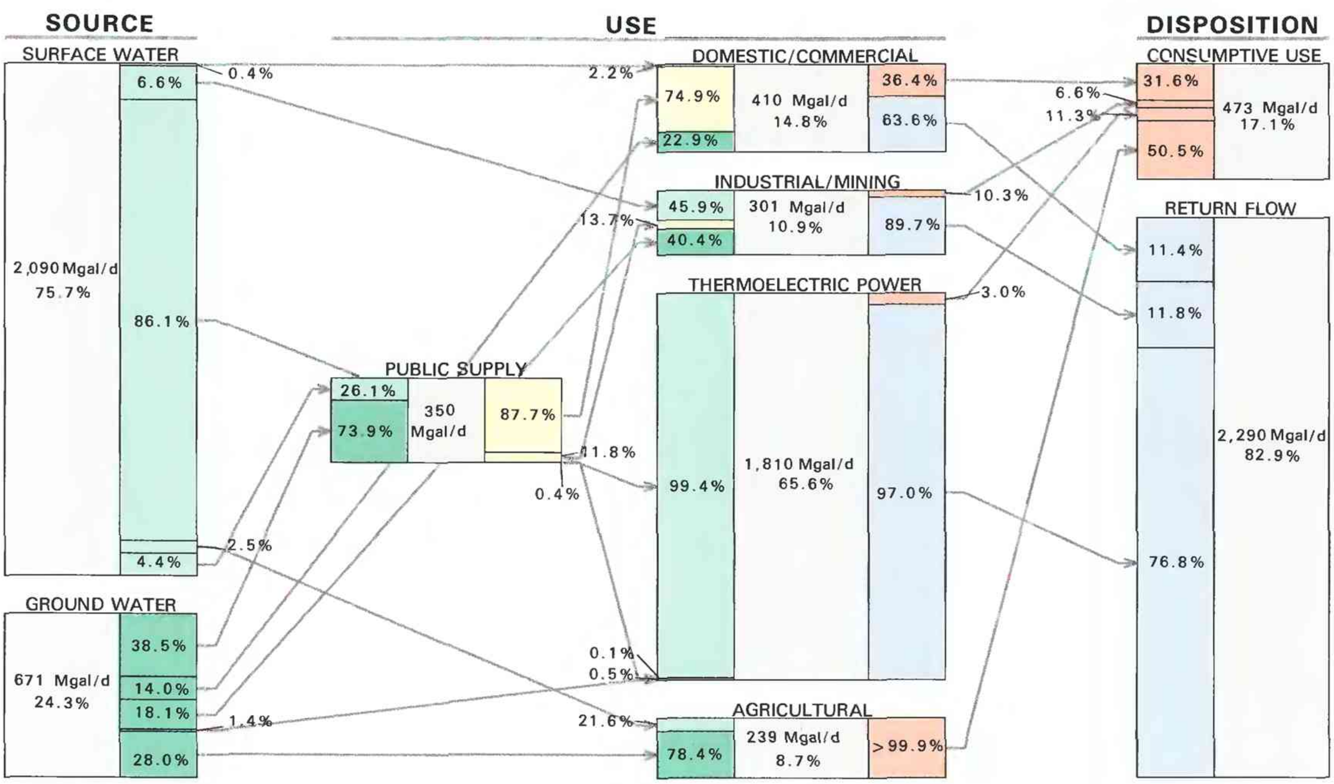


Figure 4. Source, use, and disposition of an estimated 2,760 Mgal/d (million gallons per day) of freshwater in Iowa, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Water Law was issued in 1957. This action was the result of a serious drought in 1955 and 1956 that threatened water supplies across the State. Major actions and concepts embodied in the 1957 law included the following (Iowa Water, Air and Waste Management Commission, 1985, p. 11–12):

1. Declaration that the water in Iowa is the wealth of the people of the State. Chapter 455B reads, "Water occurring in any basin or any watercourse, or other natural body of water of the State, is hereby declared to be public waters and public wealth of the people of the State of Iowa."

2. Establishment of a permit system. New users wishing to use more than 5,000 gal/d were required to obtain a permit from the Natural Resources Council.

3. Establishment of some nonregulated uses. Ordinary domestic and livestock, some municipal, industrial, and border river users were not regulated by the statute.

4. Establishment of protected streamflows. The statute provided that minimum streamflows be established to protect fish and wildlife, recreation, water quality, and other uses. Iowa was a pioneering State in this respect and recognition of these needs continues to be a distinguishing mark of the Iowa Water Law.

5. Declaration of principles and policies of beneficial use. The Council was given the mandate to protect the public interest by applying the test of beneficial use to any new request for water. This was a more rigorous requirement than the previous riparian law requiring "reasonableness" of use.

Since Iowa's Water Law was passed, several actions have been taken to improve regulation of permits in Iowa. In 1985, a plan titled "The State Water Plan" led to an amendment to the 1957 Water Law. The amendment, which became effective on July 1, 1986, stated that all water users of more than 25,000 gal/d must obtain a withdrawal permit from the Department of Natural Resources. Before July 1, 1986, municipal water users and self-supplied water users within the city limits and in existence before 1957 were not required to apply for permits if they did not increase withdrawal amounts or change the source from which they withdrew water. The amendment also required that water users withdrawing more than 25,000 gal/d from the Mississippi, the Missouri, and segments of the Big Sioux and the Des Moines Rivers that border between Lee County and the State of Missouri, be required to obtain a permit. This amendment has significantly increased the size of the permit system and has added much-needed data for water-resources planning.

Future water use trends have been estimated by State officials. Population is projected to increase by 60,000 between the years 1985 and 2000 (Iowa Development Commission, 1985, p. 77). This population increase likely will occur near existing public-supply systems. Different categories of use and predicted future trends are shown in figure 5. By the year 2005, withdrawals for public-supply systems will increase about 9 percent, domestic and commercial use will decrease water usage 13 percent, industrial use will increase by 1 percent, thermoelectric-power use will increase by 15 percent, and agricultural water use will increase by 41 percent (Iowa Water, Air and Waste Management Commission, 1985, p. 2).

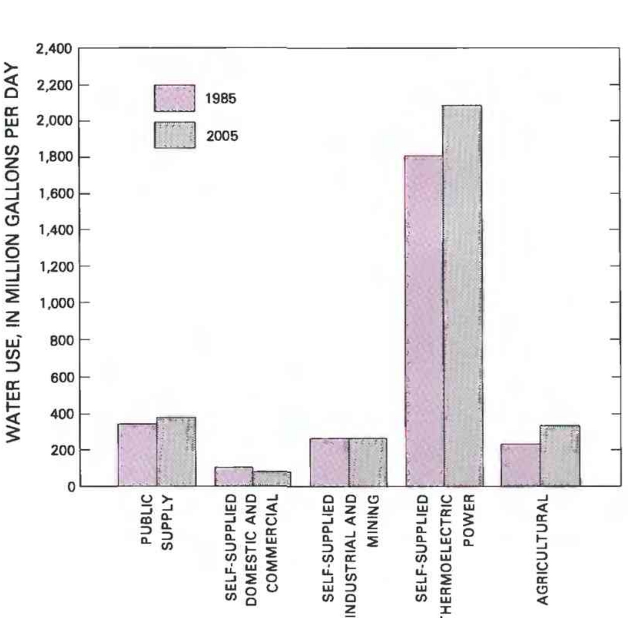


Figure 5. Estimated water use by category in 1985 and 2005. (Source: Iowa Water, Air and Waste Management Commission, 1985.)

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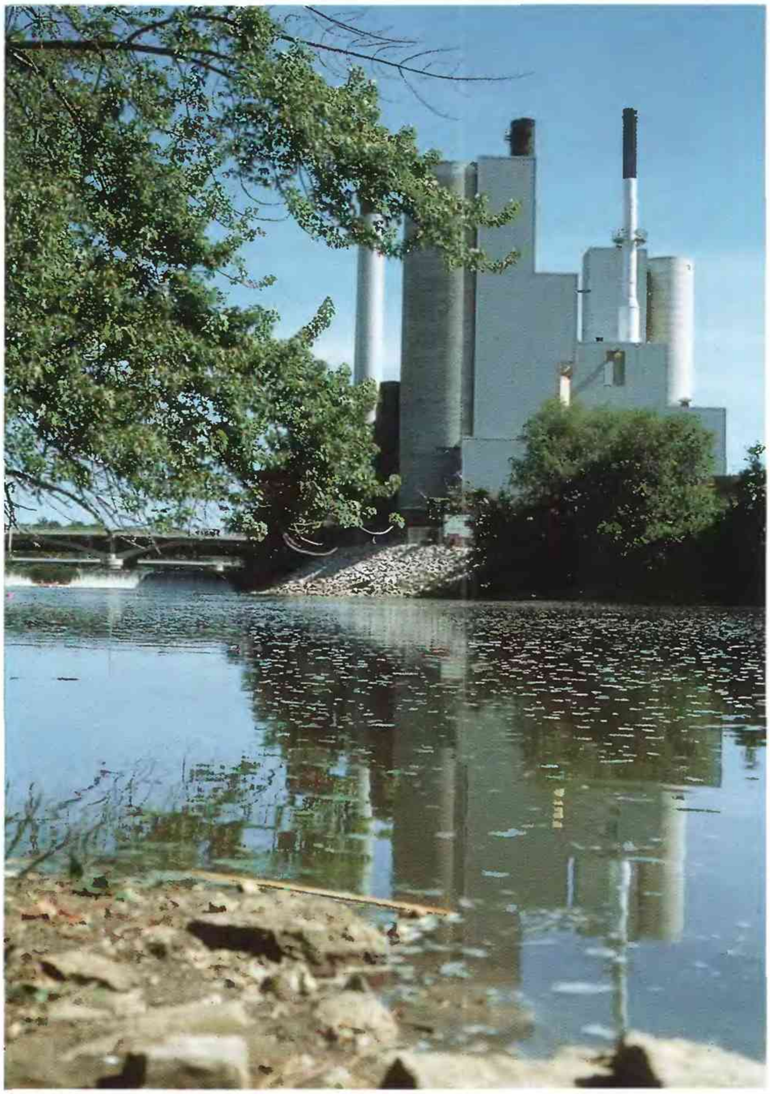


The University of Iowa powerplant used fossil fuel to produce 14.1 gigawatthours of electricity and withdrew 36 million gallons per day for cooling from the Iowa River near Iowa City in 1985. (Photograph by Joanna Thamke.)

Prepared by J.N. Thamke

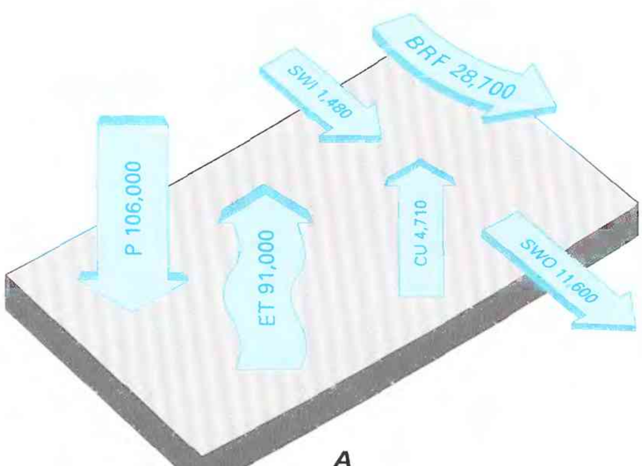
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Room 269 Federal Building, 400 South Clinton Street, Iowa City, IA 52244

KANSAS
Water Supply and Use

Most of the water available for use in Kansas enters the State as precipitation (fig. 1*A*). Statewide average annual precipitation is 27 inches, and much of the State is classified as semiarid. Of the 1,480 Mgal/d (million gallons per day) of streamflow to the State, about 90 percent is from southeastern Nebraska; the semiarid High Plains of eastern Colorado contribute little runoff to Kansas. Although the Missouri River, which has a mean discharge of nearly 28,700 Mgal/d, flows along the northeastern corner of the State, little water is diverted from this source for use in Kansas. About 10 percent of the available water recharges the State's aquifers, another 11 percent leaves the State as surface-water outflows (11,600 Mgal/d), and the remainder is consumed by human activities (4,710 Mgal/d) or by natural evapotranspiration (91,000 Mgal/d).

Western Kansas has only minor surface-water resources; however, abundant supplies of water are available from the unconsolidated aquifers in the region. The economy of the area is predominantly agricultural, and more than 70 percent of the water withdrawn in the State is used for irrigation in western Kansas. The principal urban and industrial centers are in Sedgwick County in south-central Kansas and along the Kansas River valley in the northeast. Most of the water used in Sedgwick County is obtained from ground-water sources. In northeastern Kansas, the Kansas River and its tributaries supply most of the water for industry and public supplies; most self-supplied users obtain ground water from the alluvial aquifers.

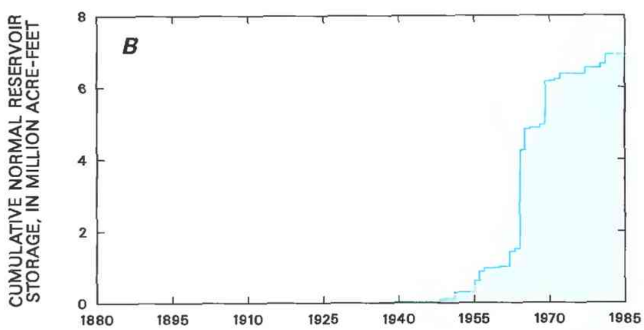
Total water withdrawn during 1985 for agricultural use (predominantly irrigation) was 4,800 Mgal/d; agriculture accounted for 95.8 percent of total consumptive use. Self-supplied withdrawals and public-supply deliveries for domestic, commercial, industrial, and mining uses were 451 Mgal/d; about 70 percent of water for these uses was obtained from public suppliers. About 416 Mgal/d, which is nearly all self-supplied from surface-water sources, was withdrawn for thermoelectric power generation.

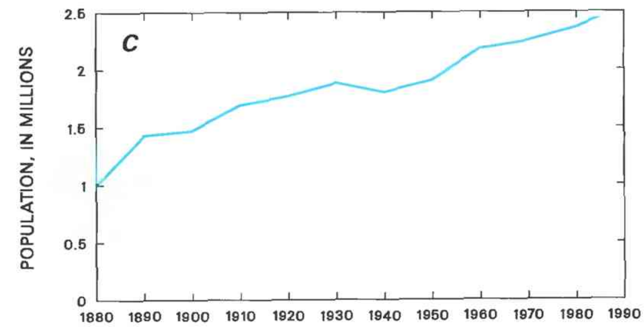


Although water supplies in Kansas are adequate for current needs, most of the water resources already have been developed. Accordingly, the State's water policy is mainly one of conservation and management rather than development.

HISTORY OF WATER DEVELOPMENT

Settlement of Kansas began in the 1850's; movement was primarily westward along the Kansas River and its tributaries. Streamflow supplied ample water for livestock and small industries,





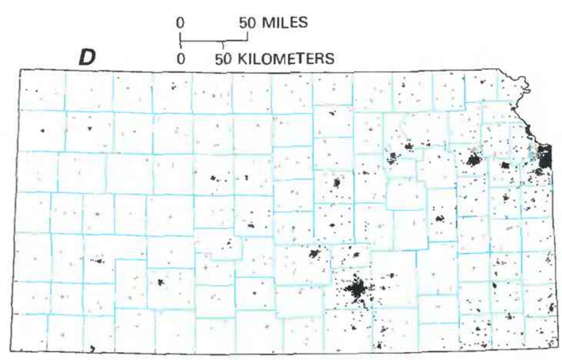


Figure 1. Water supply and population in Kansas. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Data from various reports of the National Weather Service and the U.S. Geological Survey. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

shallow wells in the alluvium satisfied household needs, and precipitation was more than adequate for agriculture. Following the Civil War, settlers moved rapidly westward and, by the 1880's, had reached the western border of the State. Conditions in the High Plains of western Kansas were different than those in the Eastern States that the settlers had left. Western Kansas is semiarid, and development of water supplies soon became a major concern.

In 1880, the Garden City Irrigation Company began construction of the first canal to divert water from the Arkansas River for irrigation. Other canals followed quickly, in the Arkansas River valley and in the valleys of other perennial streams. By 1899, the flow of the Arkansas River in western Kansas was over-appropriated, and the courts were called upon to adjudicate an equitable distribution of available water among the various canals (Kenney, 1939). The amount of water available from the Arkansas River continued to decrease, largely as a result of withdrawals for irrigation upstream in Colorado. In the early 1900's, irrigators began using centrifugal pumps to withdraw water from shallow wells drilled in the valley alluvium.

The large "upland" areas in western Kansas, however, contained no perennial streams, and ground water was not at sufficiently shallow depths to permit withdrawal by centrifugal pumps. In 1895, the Kansas Legislature passed what became known as "The Irrigation Law" (Chapter 162, Laws of 1895). This law created the Board of Irrigation Survey and Experiment, which consisted of three members appointed by the governor, and "the President of the Agricultural College and the geologist of the State University" serving as advisory members. The board was to serve for 2 years and to perform a wide variety of tests, observations, and experiments to determine the feasibility of irrigation by using ground water in the upland areas "west of the 98th Meridian" (about the western one-half of the State). In the words of the board's report to the legislature, the law contained "...ample commands, and meagre appropriations for the purpose intended" (Frost and others, 1897, p. 9).

Despite "meagre appropriations," the board constructed 15 "irrigation stations," each consisting of a well that had a windmill-powered pump and a small reservoir from which the water could be distributed. In addition, they arranged for the U.S. Geological Survey to measure the flows in the seven principal streams that cross the 98th meridian. The board also conducted a survey of existing irrigation, instituted tests of the efficiency of different forms of pumps and windmills, and attempted to map the extent of the principal aquifers in western Kansas.

The 1895 survey of existing irrigation indicated that about 11,800 acres were irrigated, mostly from wells; the average area irrigated by each installation was about 9 acres. Irrigation in western Kansas increased slowly until the 1940's, when a large increase in the demand for agricultural products, the widespread availability of natural gas and electricity for energy, and the introduction of efficient large-capacity turbine pumps made large-scale irrigation using ground water practical and profitable. Development of irrigation was spurred further by drought in the late 1950's and by the introduction of center-pivot sprinkler systems, which made irrigation much less labor intensive.

Beginning in the 1880's, the growth of towns and cities was accompanied by the development of public supplies. In the western one-half of the State, wells were drilled for public supplies, and additional wells furnished water for small self-supplied industries, as well as for the needs of several railroads.

In the more humid eastern one-half of Kansas, where streamflows were generally reliable, most public supplies were developed from surface-water sources. Many small reservoirs were built by municipalities to ensure continuity of the water supply, as well as to afford a measure of protection against floods. The first reservoir that had a storage capacity of more than 5,000 acre-ft (acre-feet) was built in 1905, but only a few reservoirs of that size or larger were completed before 1960. Fourteen reservoirs were completed during the 1960's—10 of them (which had a combined storage capacity of more than 3.5 million acre-ft) by the U.S. Army Corps of Engineers. Seven reservoirs were constructed by the U.S. Bureau of Reclamation during the 1950's and 1960's. The total 1985 storage in 37 major Kansas reservoirs is almost 7 million acre-ft (fig. 1*B*). Most of the large reservoirs in Kansas are multipurpose structures; the primary uses are flood control and water supply, and other uses include recreation and thermoelectric power generation.

Population growth and distribution are illustrated in figures 1*C* and 1*D*. Of the 1985 State population (2,450,000), more than one-half live in the urbanized eastern and south-central areas of Kansas; the western part of the State remains sparsely populated. This demographic trend, along with a general decrease in rural population and a growth in urban population during the last few decades, has contributed to a steady increase in water withdrawals for public supplies and a continuing decrease in the use of self-supplied domestic water.

WATER USE

Water supplies in Kansas are generally adequate to meet the 1985 level of demand, although streamflows in the eastern one-half of the State must be supplemented by storage during periods of less-than-average normal precipitation. Mineral concentrations in some streams during low flows are undesirably large, and reservoir releases are scheduled to dilute the water and to ensure usability. There are no major interstate transfers of water to or from Kansas. About 8 Mgal/d is diverted from the Arkansas River in Colorado for irrigation in Kansas; however, much of this water, if not diverted, would enter the State as natural flow in the river.

Freshwater withdrawals by county are shown in figure 2*A*. The counties that have the largest withdrawals generally are located in western Kansas, where agriculture is the dominant water use. Surface- and ground-water withdrawals are shown by county in figures 2*B* and 2*C*, respectively. These illustrations indicate the almost total dependence on ground water in western Kansas; only a few counties along perennial streams obtain any significant amounts of surface water. In eastern Kansas, surface water is the principal source of supply; large withdrawals of ground water are obtained primarily from the alluvium of the Kansas River valley.

Surface-water withdrawals by principal drainage basin are shown in figure 3*A*. Withdrawals in the Missouri–Nishnabotna, and the Kansas and Lower Missouri basins exceeded 200 Mgal/d in 1985. These basins had substantial withdrawals for thermoelectric power generation. The Kansas and Lower Missouri basin also had large withdrawals (88 Mgal/d) for public supply. Basins that extend into western Kansas, such as the Middle Arkansas, Smoky Hill, and Republican, are dominated by agricultural withdrawals.

Instream use of water was almost exclusively for recreation and conservation of wildlife. The topography of Kansas does not lend itself to hydroelectric power generation; a single hydroelectric plant on the Kansas River at Lawrence generated only 0.03 percent of the State's power supply during 1985 (Solley and others, 1988).

Ground-water withdrawals by principal aquifer are shown in figure 3*B*. Total withdrawals from the High Plains aquifer were 3,940 Mgal/d in 1985, which is more than six times the quantity of water withdrawn from the next-largest ground-water source (the alluvial aquifers). Of the water withdrawn from the High Plains aquifer, 97.9 percent is used for agriculture, mostly for irrigation. Withdrawals from the alluvial aquifers in 1985 were 620 Mgal/d, of which 74.8 percent is used for irrigation and 15.5 percent is used for public supply. In 1985, the Great Plains aquifer supplied 140 Mgal/d, 95.0 percent of which was used for agriculture.

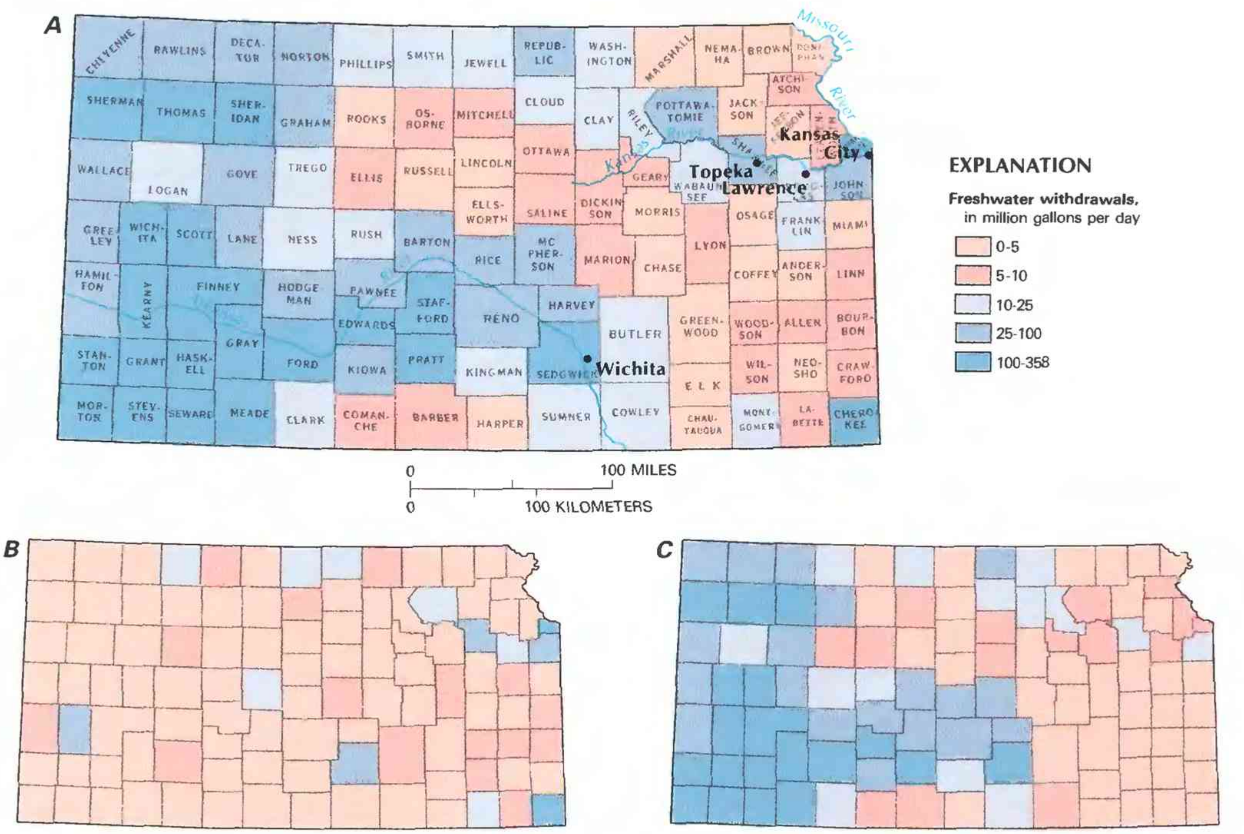


Figure 2. Freshwater withdrawals by county in Kansas, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

The source, use, and disposition of freshwater in Kansas for offstream water use in 1985 are shown diagrammatically in figure 4. The quantities of water given in the figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data in figure 4 indicate, for example, that surface water was the source of 866 Mgal/d of water, or 15.3 percent of the total freshwater withdrawals. Of that quantity, less than 0.1 percent was withdrawn directly (self-supplied) for domestic and commercial use, 2.3 percent was self-supplied for industrial and mining use, 46.5 percent was self-supplied for thermoelectric power generation, 33.0 percent was withdrawn for agriculture purposes including irrigation, and 18.2 percent was withdrawn for public supply. The use data indicate, for example, that domestic and commercial use was 316 Mgal/d, which represented 5.6 percent of the total withdrawals in the State. Of that 316 Mgal/d, less than 0.1 percent was self-supplied from surface-water sources, 86.7 percent was delivered by public-supply systems, and 13.3 percent was self-supplied from ground-water sources. Of the withdrawals and deliveries for domestic and commercial purposes, 35.4 percent was consumed use and 64.6 percent was returned to surface-water or ground-water systems. The disposition data indicate that 83.1 percent (4,710 Mgal/d) of the total withdrawals was consumed and that 16.9 percent (958 Mgal/d) was returned.

Agriculture, primarily irrigation, accounted for 84.7 percent of the water used in Kansas during 1985, and thermoelectric power generation constituted the second largest use (7.3 percent). Public-water supplies accounted for about 5.6 percent of the 1985 freshwater withdrawals. Major public-supply withdrawals were near the large population centers in Sedgwick County (Wichita) and along the lower Kansas River (Topeka and Kansas City).

Public Supply

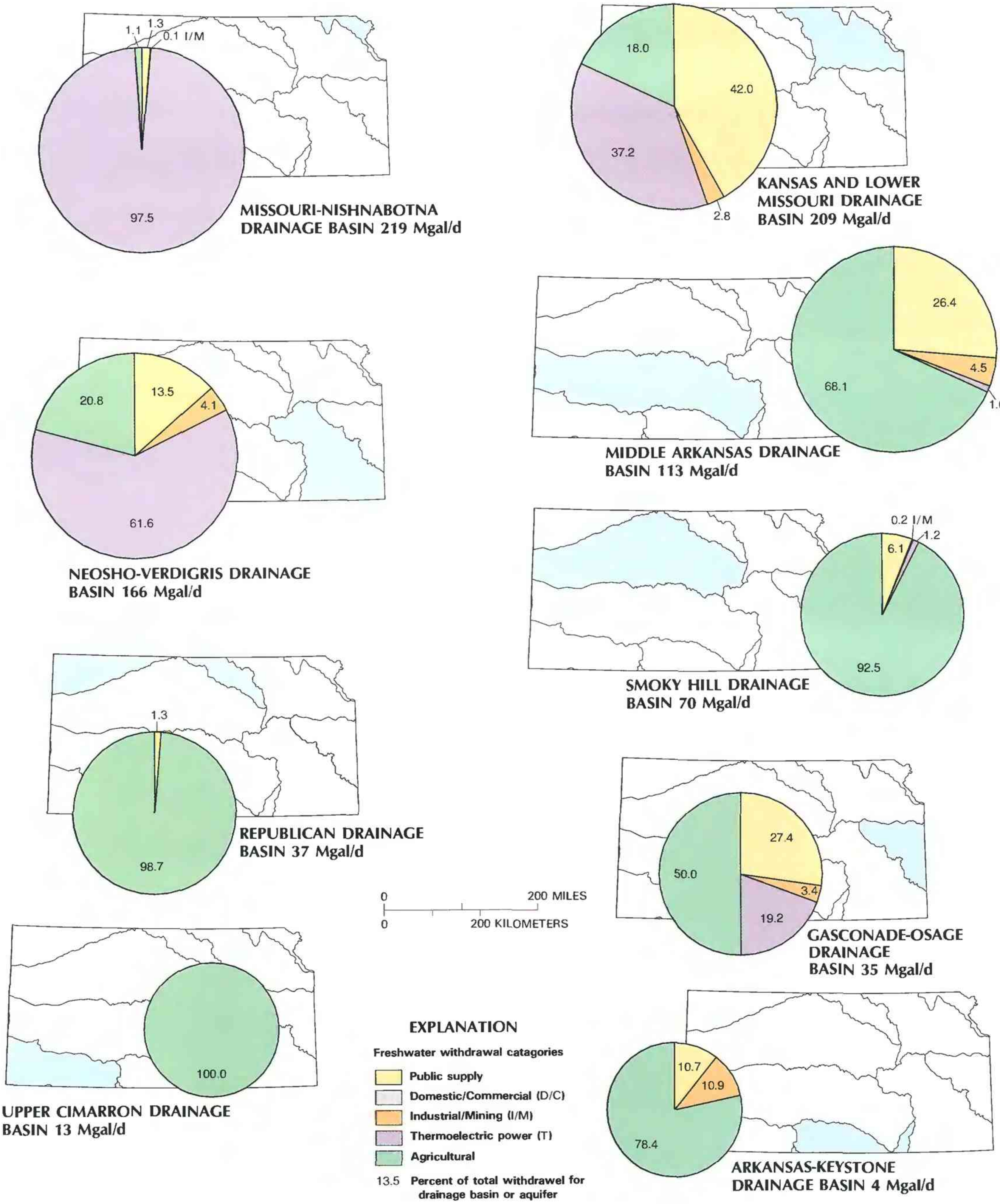
Public supply represents water withdrawn, treated, and delivered to users by public suppliers. Nearly all municipalities in Kansas have public supplies, and a large share of the rural population is served by public suppliers in the form of Rural Water Districts. About 2 million people obtain their water for domestic use from public supplies. Public suppliers also furnished 30.0 percent of the water used for industrial and mining purposes. Total withdrawals for public supplies during 1985 (316 Mgal/d) were almost equally withdrawn from ground-water and surface-water sources (fig. 4).

Domestic and Commercial

Domestic and commercial water use during 1985 was 5.6 percent (316 Mgal/d) of the total freshwater withdrawals in the State (fig. 4). However, 86.7 percent of the water used for these purposes was from public supplies. The self-supplied rural population of 453,000 people and a few dozen isolated commercial users withdrew 42 Mgal/d, which came almost entirely from ground-water sources. About 35.4 percent of the water supplied for domestic and commercial purposes was consumed.

Industrial and Mining

Of the 135 Mgal/d used by industrial and mining activities during 1985, 30.0 percent was delivered by public supplies (fig. 4). Nearly all industrial users in the smaller cities, primarily food processors, obtain water from public supplies. Water for the light-aircraft manufacturers, chemical plants, and metal-fabrication



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Kansas, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

activities in and near Wichita is self-supplied, mostly from ground-water sources. In the other major industrial area of the State, in and near Topeka and Kansas City, about one-half of the industrial water is self-supplied. Most of this self-supplied water is from surface-water sources, but a few industries have wells completed in the alluvial aquifers. The principal industrial activities in this area are food processing, metal fabrication, and chemical production. Very little mining activity occurs in Kansas; the small strip-mining operations for coal near the southeastern corner of the State obtain their water primarily from small streams in the area. Of the water withdrawn and delivered for industrial and mining use, 30.2 percent is consumed and 69.8 percent is returned directly to streams or to municipal sewage-treatment facilities.

Thermoelectric Power

About 7.3 percent (416 Mgal/d) of total withdrawals was used in 1985 for thermoelectric power generation (fig. 4). Most of the powerplants in Kansas are in the eastern one-half of the State, where 96.9 percent of the water withdrawn for power generation was self-supplied from surface-water sources. A single nuclear powerplant in Coffey County withdrew 2.1 Mgal/d (Solley and others, 1988). All other powerplants in the State burn fossil fuels. A total of 27,300 gigawatthours of electricity was generated. Consumptive use of water by thermoelectric generating plants is relatively small (10.4 percent).

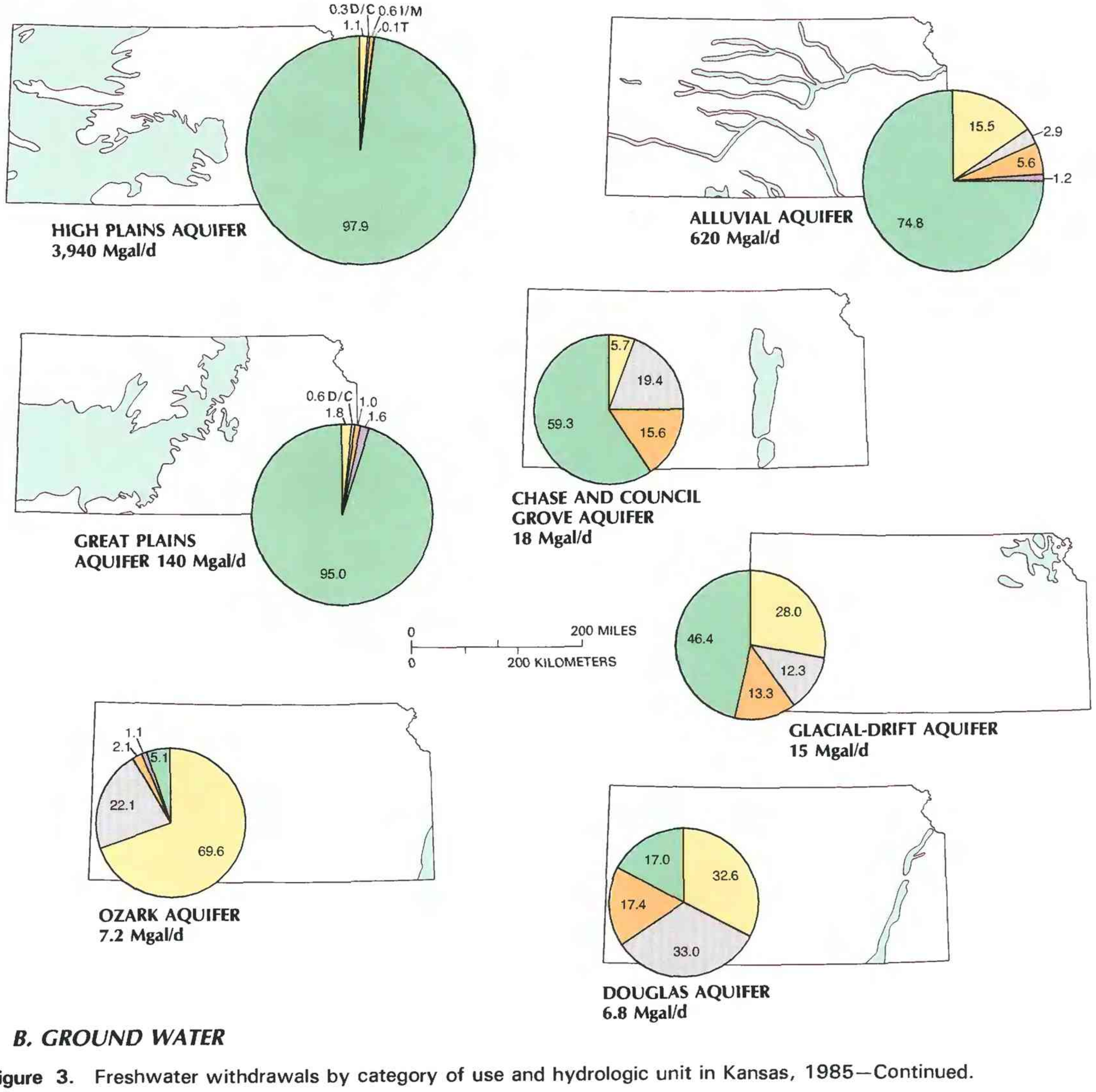


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Kansas, 1985—Continued.

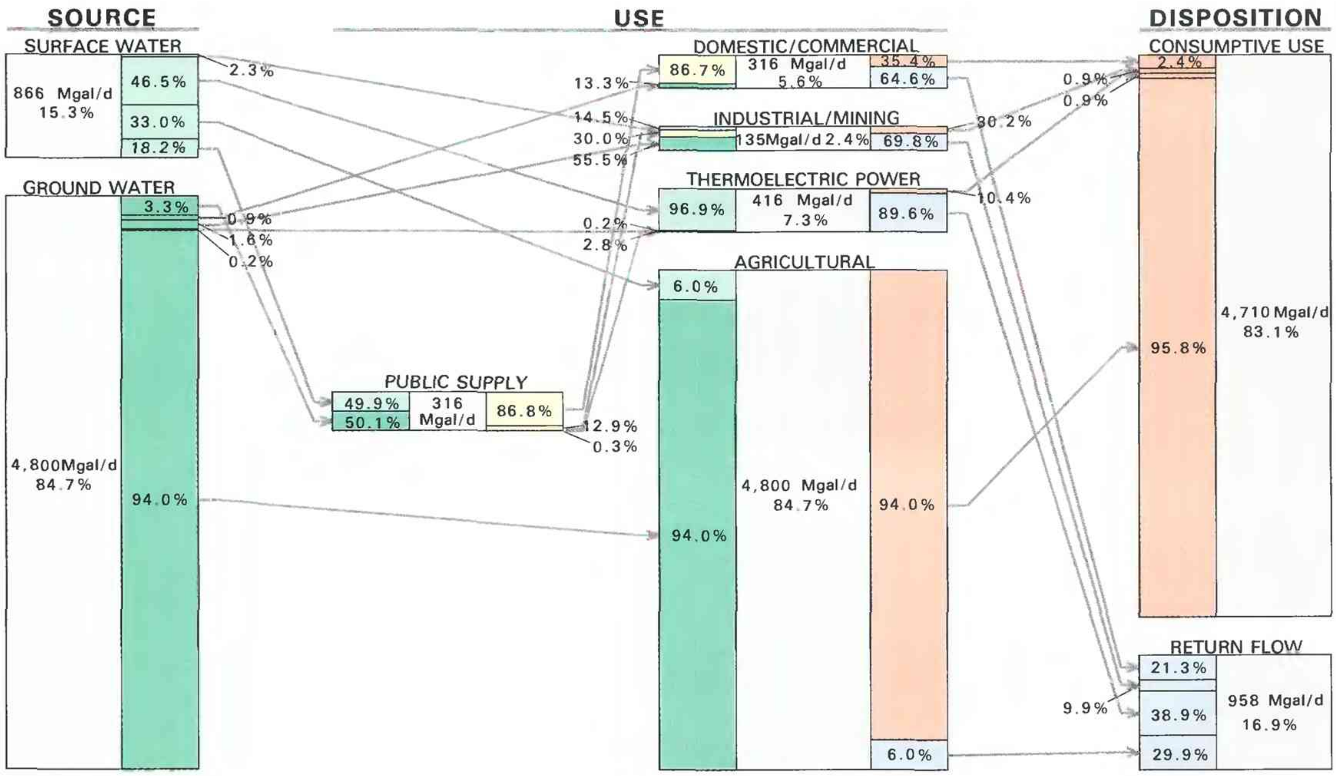


Figure 4. Source, use, and disposition of an estimated 5,670 Mgal/d (million gallons per day) of freshwater in Kansas, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

AGRICULTURAL

Almost 3 million acres were irrigated in Kansas in 1985. Most of the 4,800 Mgal/d agricultural use (fig. 4) was for irrigation of grain. Most of the water was used in the western one-half of the State—primarily from ground-water supplies. The widespread practice of sprinkler irrigation, which applies little excess water to the soil, combined with the practice of capturing runoff from flood irrigation and returning it to the soil, results in little return of irrigation water to the water table or to streams. As a result, nearly all water withdrawn for irrigation is consumed.

WATER MANAGEMENT

Kansas has several State and local agencies that have responsibilities for management of water. In addition, Federal water projects are managed by the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation. Information used by managers includes hydrologic data collected by the U.S. Geological Survey in cooperation with several Federal, State, and local agencies.

The administration of laws related to water rights, conservation, and use of water resources, including the appropriation of water, is the responsibility of the Chief Engineer, Division of Water Resources, Kansas State Board of Agriculture. The Kansas Water Appropriation Act, originally enacted in 1945 and subsequently amended several times, dedicates all waters of the State to the use of the people of the State, subject to regulation in the manner provided by the Act.

Except for domestic use, a permit to appropriate water is required for all uses of water. The date of application for a permit establishes the priority to continue the use of water during periods of shortage. An application for a permit to appropriate water may be approved if it is filed in good faith, if it is in the proper form, if the quantity and rate of use are reasonable for the intended purpose, and if use of the water will not impair existing water rights nor "prejudiciously or unreasonably affect the public interest." In addition, freshwater cannot be appropriated and used unless "poor"-quality water is not available, or it is not technologically and economically feasible to use such poor-quality water.

A right to the use of water is "perfected" by the actual use of water in accordance with the terms, conditions, and limitations of the permit. Water users also are required to submit an annual water-use report to the Division of Water Resources. The holder of a water right may change the point of diversion, the place of use, or the type of use by filing an application and receiving approval from the Division of Water Resources.

Applications for permits to appropriate water received after April 12, 1984, are considered junior to any minimum desirable streamflow requirements that have been established for the same source of supply pursuant to law. Thus far (1987), minimum desirable streamflow requirements have been established for 18 Kansas rivers and streams.

The Kansas Water Office is the water planning, policy making, and coordinating agency for the State and the marketing agency for water from State-owned storage in Federal reservoirs. The Kansas State Water Plan includes 12 river basin plans and sections on management, conservation, quality, fish, wildlife, and recreation. The planning process in Kansas is continuous, and the State Water Plan is updated annually. Before being submitted to the Governor and the legislature, the Kansas Water Plan must be approved by the

Kansas Water Authority, a policy board that has members appointed to represent various water interests and agencies. Twelve local River Basin Advisory Committees are responsible for advising the Kansas Water Authority and the Kansas Water Office on needs and courses of action within the river basins. Policy recommendations in the State Water Plan are implemented through the legislature by passing new, or amending existing, statutes and by authorizing funding for specific programs and projects.

In 1983, the Kansas Legislature enacted the Kansas Water Transfer Act. This act requires the filing of an application with the Chief Engineer by any person wishing to transfer a quantity of water in excess of 1,000 acre-ft per year a distance of 10 miles or more from the point of withdrawal to the ultimate place of use. Approval of a water transfer is an elaborate procedure requiring a formal hearing and approval by a three-member interagency panel and by the Kansas Water Authority. The panel considers the benefits to the State if the water is transferred or not, the alternative sources of water available to the applicant, the current and future needs of the area of origin, and the effects on the environment, the economy, and the public health and welfare of the proposed transfer. The applicant also must have an acceptable conservation plan.

In general, most streams and aquifers in the western part of the State are considered to be fully developed, and, because of decreased streamflows and declining ground-water levels, little or no additional water is being appropriated. In the eastern part of the State, surface water is available during periods of normal or greater-than-normal streamflow, but direct-flow water rights usually are not considered to be dependable during a drought unless they can be supplemented from storage. As a result of limitations on the availability of water in the State, Kansas has evolved from developing water for use to conserving and managing water.

In response to water-management concerns, the Kansas Legislature has allowed the organization of several types of local water districts to provide for local input into the conservation and management of water. Since the mid-1970's, five Groundwater Management Districts have been organized in the western and south-central parts of the State (fig. 5*A*). The boundaries of these Districts conform primarily to the boundaries of the High Plains aquifer (fig. 3*B*). Each district is required to develop a management program and may recommend rules and regulations to the Chief Engineer to implement policies related to the conservation and management of ground water. Examples of policies and regulations adopted within the Districts include mandatory metering, well-spacing restrictions, water-use and water-wastage restrictions, and programs related to protecting the quality of ground water.

In 1978, the Chief Engineer was given the authority to designate intensive ground-water-use control areas in the State. Control areas may be established where water levels have declined excessively, where the rate of withdrawal of ground water exceeds the rate of recharge, where preventable waste of water is occurring, where unreasonable deterioration of water quality is occurring, or where other conditions exist that require regulation in the public interest. In designating such an area, the Chief Engineer may order corrective control provisions, such as closing the area to further appropriation of water, limiting the total amount of withdrawal from the area, decreasing the permissible amount of withdrawal of ground water, or any other controls necessary to protect the public interest.

Currently (1987), six intensive ground-water-use control areas have been designated, (fig. 5*B*). Control areas have been designated by the Chief Engineer for water-quantity and water-quality problems.

In 1986, the Kansas Legislature enacted the Water Assurance Program Act. This act allows public water suppliers and industrial water users located downstream from a Federal reservoir to organize a Water Assurance District. A District may contract with the State for the use of State-controlled storage in the reservoir so that water may be released during periods of low flow, ensuring that its water needs are met. This program is intended to help manage the storage and use of water in several major river basins in the eastern part of the State. Public suppliers and industrial users also may enter into contracts with the State to purchase water directly from storage under the State Water Marketing Program administered by the Kansas Water Office. The price of water is based on the cost to capitalize the State's investment and pay for administration of the program. A surcharge of 2.5 cents per 1,000 gallons is added for future water development. Protection of releases of water for the Water Assurance Districts or the Marketing Program from unlawful diversion is the responsibility of the Division of Water Resources.

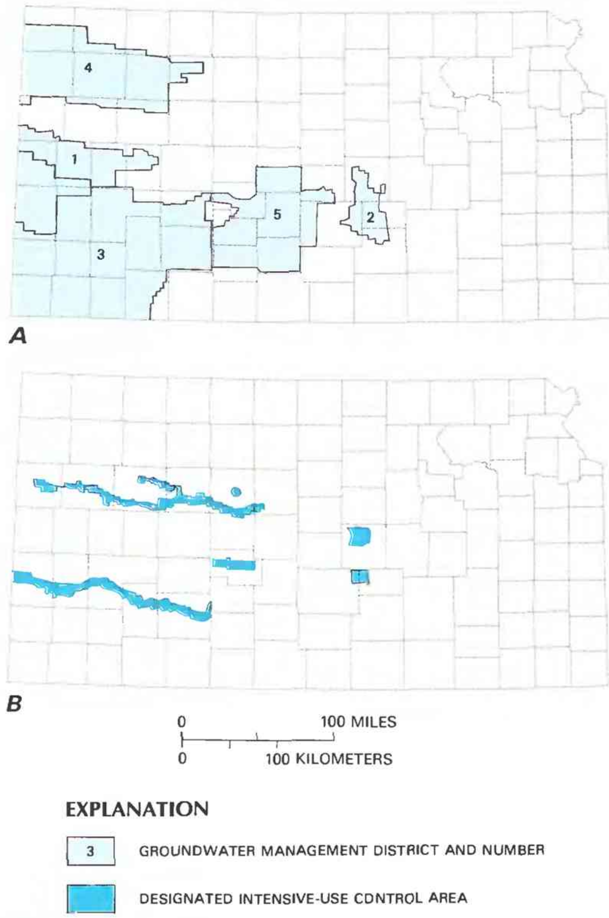


Figure 5. Groundwater Management Districts and control areas of ground-water withdrawal in Kansas, 1985. *A*, Groundwater Management Districts. *B*, Control areas of intensive ground-water use. (Source: Division of Water Resources, Kansas State Board of Agriculture files.)

In 1986, the State implemented legislation that requires conservation plans to be prepared by water users in certain situations. Members of Water Assurance Districts and water-transfer applicants must prepare a conservation plan, and water users seeking to purchase water through the Water Marketing Program may be required to develop and implement such a plan in accordance with State-approved guidelines. In addition, the Chief Engineer may require conservation plans from anyone filing an application for a permit to appropriate water after July 1, 1986.

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Prepared by C.H. Baker, Jr., and J.F. Kenny, U.S. Geological Survey; Water Management section by D.L. Pope, Division of Water Resources, Kansas State Board of Agriculture

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 4821 Quail Crest Place, Campus West, Lawrence, KS 66049

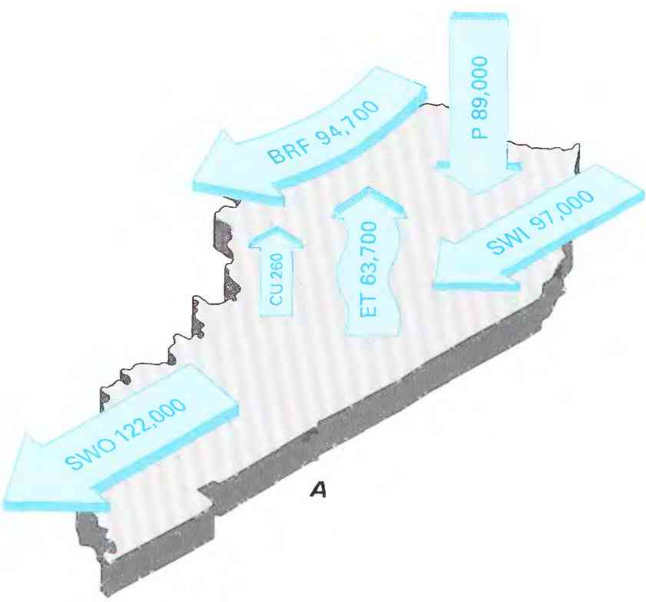
KENTUCKY
Water Supply and Use

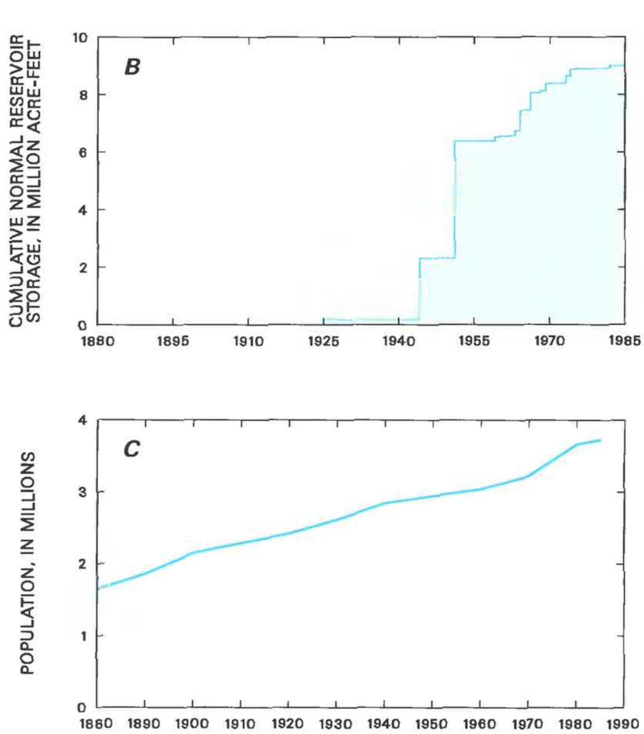
Kentucky has a large quantity of water that is suitable for most uses. Much of this water is available from boundary-river flow of the Ohio River and surface-water inflows of the Cumberland and the Tennessee Rivers (fig. 1A). These streams represent more than twice the average total water produced by precipitation in Kentucky.

Average annual precipitation in Kentucky is about 47 inches (Conner, 1982, p. 30), which is distributed unequally geographically and seasonally. Geographically, average annual precipitation ranges from about 40 inches in the north to about 52 inches in the extreme south-central and southeastern parts of the State (Conner and Ashby, 1979, p. 1). Seasonally, precipitation generally is deficient during late summer and fall when demand for water is greatest.

The Ohio River supplies more than one-half of all surface water withdrawn in the State, and the alluvial aquifer along the river furnishes about 60 percent, or 125 Mgal/d (million gallons per day), of all ground water withdrawn in Kentucky. Most of the State depends on surface-water supplies because of the small yields from aquifers. During periods of little precipitation, stream discharge may be insufficient to meet the demand in some of the densely populated areas. Lexington, the second largest city in the State, uses the Kentucky River as its main source of water. A concern is that the flow of the Kentucky River may not meet water-supply demands during times of drought. The U.S. Army Corps of Engineers (1978, p. 61) estimated that the level of the Kentucky River would fall below the primary intake for Lexington if a severe drought, such as the one in 1930, were repeated. To compound the problem, water-quality degradation due to insufficient dilution during droughts is possible in the Kentucky River and in many other streams that are used for water supply.

Total surface-water and ground-water withdrawals in Kentucky were 4,200 Mgal/d during 1985. Surface water accounted for 95.1 percent of all withdrawals. Thermoelectric power generation accounted for 81.1 percent of all water withdrawn and for 47.5 percent of all consumptive use. Withdrawals for public supplies were 9.6 percent (404 Mgal/d) of total withdrawals. Self-supplied domestic, commercial, industrial, and mining withdrawals of water were 7.9 percent (330 Mgal/d) of total withdrawals. Agriculture





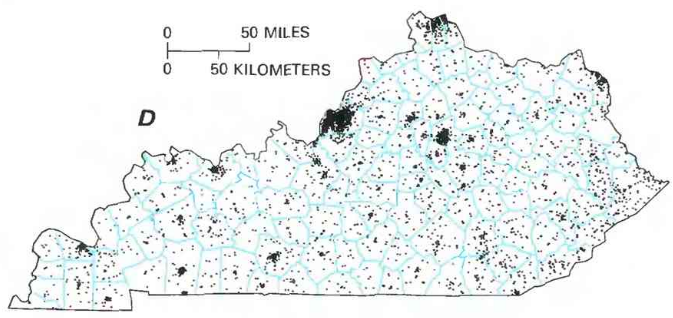


Figure 1. Water supply and population in Kentucky. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey files. *B,* U.S. Army Corps of Engineers, 1981b. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

withdrew 1.4 percent (58 Mgal/d) of total withdrawals, almost all of which was consumed.

HISTORY OF WATER DEVELOPMENT

The rapid development of Kentucky during the early 1800's was due, in part, to its boundary and interior rivers. Although many settlers came to the area by way of rugged overland trails, the Ohio River served as an important transportation artery for goods that were impossible to move along mountain trails. The Ohio River channel was sufficiently wide and deep to permit passage of flatboats and keelboats. The only major obstacle was a line of shallow waterfalls or rapids at Louisville, which resulted in settlement there (Bartlett, 1984, p. 62).

From 1830 until 1951, reservoir storage in Kentucky increased to 6.3 million acre-feet (fig. 1*B*) to help meet the water demands of the increasing population (fig. 1*C*). Before 1830, impoundments were limited to farm ponds because no natural lakes of substantial size existed in Kentucky.

Expanded use of the Ohio River for transportation, public and industrial water supplies, power generation, and recreation is reflected by the population distribution of the State. One-third of the State's population lives in cities and counties within a few miles of the river (fig. 1*D*). From 1885 to 1920, 12 lock-and-dam systems were constructed on the Ohio River, and many of these currently are being replaced by 19 high-lift structures that can accommodate larger commercial boats. Commercial traffic on the Ohio River amounts to about one-third of the total inland waterway freight tonnage of the Nation (Baer, 1986, p. 13). Water from the Ohio River is used by some of the larger cities, such as Louisville and Paducah, for industrial complexes, such as the Calvert City area, and for several powerplants that use water either for hydropower or for cooling. Water sports use associated with the Ohio River and its tributaries have continued to expand. More than 750 public and private facilities for recreational boating are located along the Ohio River and its tributaries (Baer, 1986, p. 13), and, during 1984, about 83 million people used those facilities.

Many of the larger interior streams in Kentucky also were developed for water supplies and transportation. This development led to a concentration of population and towns along the rivers. During the early 1900's, the Kentucky, the Green, the Barren (principally Warren County), the Cumberland, and the Tennessee Rivers were used for the transportation of goods, such as bearskins, beaver fur, corn, livestock, tobacco, hemp, and liquor. During the 1830's, five lock-and-dam systems were constructed on the Kentucky River, four were constructed on the Green River, and one was constructed on the Barren River (Clark, 1960, p. 179). Many of the larger interior cities, such as Lexington and Frankfort, developed water supplies from the interior streams and used the streams to transport goods. The growth of these cities, to a large extent, depended on the availability of water.

Ground water was essential for the early settlement of parts of Kentucky. Towns and farms, not located near streams, used ground water. The availability of ground water made settlement possible in many areas where a dependable surface-water supply was unavailable.

WATER USE

Water that enters and leaves Kentucky is shown schematically in figure 1*A*. About 97,000 Mgal/d enters the State as surface-water inflows and 89,000 Mgal/d as precipitation. An additional 94,700 Mgal/d is flow in boundary rivers. Most of the losses are from surface-water outflows (122,000 Mgal/d) and evapotranspiration (63,700 Mgal/d). About 260 Mgal/d is lost through consumptive use.

The distribution of fresh surface- and ground-water withdrawals differs within the State. Total water withdrawals by county are shown in figure 2*A*. Major withdrawals coincide with the population centers of Louisville, Lexington, Owensboro, and Paducah. Additionally, large withdrawals in Pulaski and Muhlenberg Counties supply water for cooling at the thermoelectric powerplants. Withdrawals of surface water and ground water are shown by county in figures 2*B* and 2*C*, respectively. The magnitude of surface- and ground-water withdrawals for the counties along the Ohio River reflects the importance of this river and alluvial aquifer to the development of the water resources of the State.

Withdrawals of surface water by principal drainage basin are shown in figure 3*A*. Of the surface water withdrawn, 57 percent is from the Lower Ohio basin. The alluvial aquifer along the Ohio River is the most intensively used aquifer (fig. 3*B*).

The source, use, and disposition of freshwater are diagrammatically presented in figure 4. The quantities of water given in the figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that the 3,990 Mgal/d of surface water withdrawn represents 95.1 percent of the total surface- and ground-water withdrawals in Kentucky. Of that quantity, about 0.4 percent (16 Mgal/d) is withdrawn directly (self-supplied) for domestic and commercial use; 4.9 percent (197 Mgal/d) is withdrawn for self-supplied industrial and mining use; 84.4 percent (3,370 Mgal/d) is withdrawn for thermoelectric power generation; 1.4 percent (55 Mgal/d) is withdrawn for agriculture; and 8.9 percent (356 Mgal/d) is withdrawn for public supplies. The use data indicate domestic and commercial use as 7.2 percent (301 Mgal/d) of the total withdrawals for the State. Of that 301 Mgal/d, 5.2 percent (16 Mgal/d) was from a surface-water source, 79.0 percent (238 Mgal/d) was delivered by public supplies, and 15.9 percent (48 Mgal/d) was from a ground-water source. Of the domestic and commercial water withdrawn and delivered, 20.3 percent (61 Mgal/d) was consumed and was not available for reuse, and 79.7 percent (240 Mgal/d) was returned to the hydrologic system for reuse. The disposition data indicate that for all the water withdrawn in the State, 6.2 percent (260 Mgal/d) was consumed use and 93.8 percent (3,940 Mgal/d) was returned for future use.

During 1985, about 91,000 Mgal/d of water was used instream by hydroelectric powerplants in the State. About 2,940 GWh (gigawatthours) of electricity was produced, which represented about 5 percent of the total amount of power generated in Kentucky. The consumptive use of water in this process is mostly from evaporation, and the amount is negligible. Thermoelectric powerplants produced 60,100 GWh of electricity; these powerplants withdrew 3,410 Mgal/d for cooling water, and consumptive use was 124 Mgal/d (fig. 4).

PUBLIC SUPPLY

Public-supply systems withdrew about 404 Mgal/d of water during 1985 (fig. 4), which is a 15-percent increase from 1980. The 404 Mgal/d includes an estimated 10-percent delivery to public uses, such as fire fighting, and losses in the distribution system. Public-supply systems delivered 58.8 percent (238 Mgal/d) of water to domestic and commercial users and 41.2 percent (167 Mgal/d) to industrial and mining users. No water was contributed to thermoelectric use from public supplies.

Of the total public-supply withdrawals during 1985, 356 Mgal/d was surface water, and 49 Mgal/d was ground water. Surface- and ground-water withdrawal patterns differ geographically within the State. Areas of largest surface-water withdrawals for public supplies are along the Ohio River. More than 99 percent of the withdrawals in the Kentucky–Licking basin for public supplies are from surface-water sources. Most of the ground water used for public supplies is from the alluvial aquifer underlying the flood plain of the Ohio River. In extreme western Kentucky, aquifers yield dependable quantities of water for public supplies.

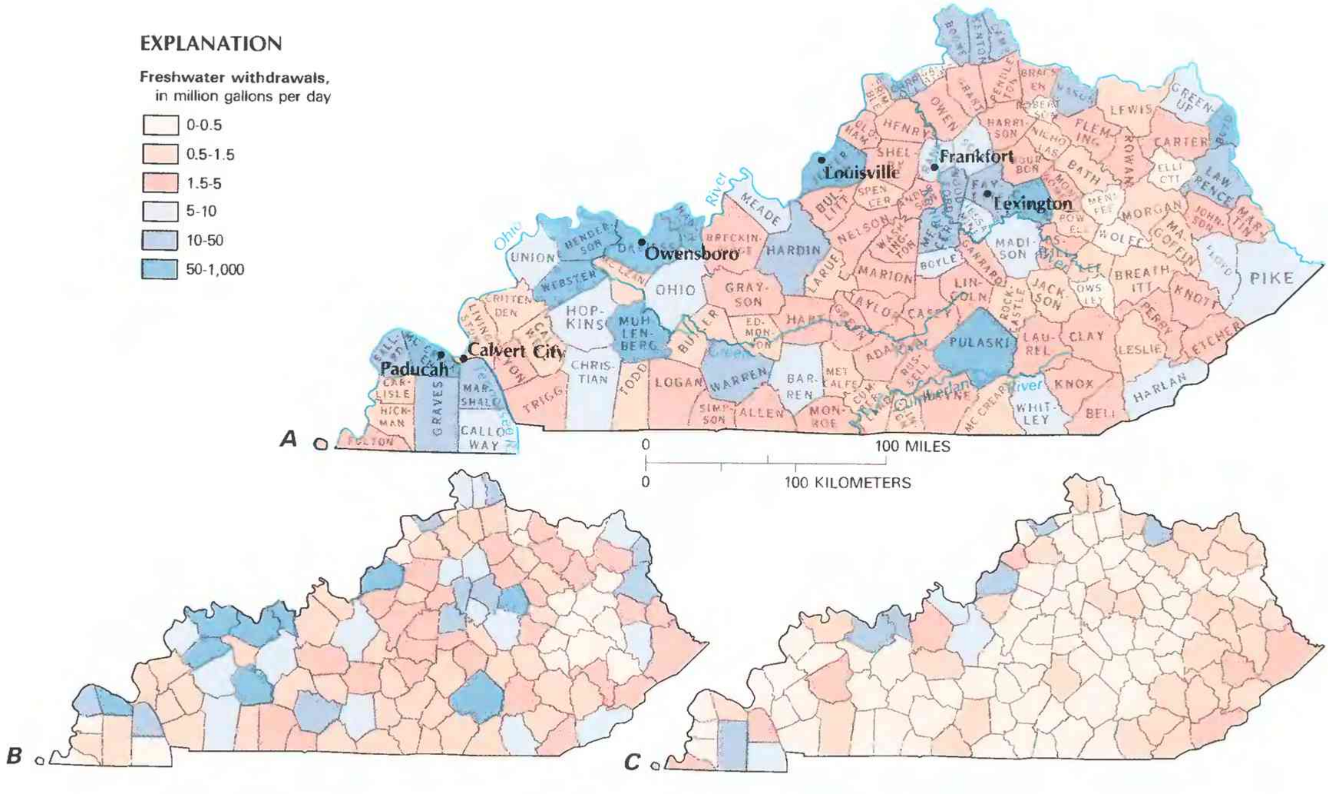


Figure 2. Freshwater withdrawals by county in Kentucky, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Two counties account for 38 percent of all water withdrawn for public supplies. Jefferson County (Louisville) withdraws 29 percent (119 Mgal/d) of the total water withdrawn for public supplies in Kentucky. Fayette County (Lexington) withdraws 9 percent of the total for public supplies (almost 36 Mgal/d).

Domestic and Commercial

Water for domestic and commercial use is furnished by public- and self-supplied systems. Combined withdrawals and deliveries during 1985 were 301 Mgal/d (fig. 4). Withdrawals and deliveries for domestic use, excluding distribution losses, totaled 226 Mgal/d during 1985. Public suppliers delivered 179 Mgal/d to domestic users during 1985. The remaining 47 Mgal/d was self-supplied from surface- and ground-water sources; about 10 percent was from surface-water sources, and about 90 percent was from ground-water sources. Delivery from the expanded public water-distribution systems increased from serving 67 percent of the population in 1980 to 74 percent in 1985. Domestic use from public supplies was estimated to be 64 gal/d (gallons per day) per capita during 1985; for domestic users of self-supplied systems, use was estimated to be 50 gal/d per capita.

Commercial use was about 34 Mgal/d in 1985. Of this quantity, 18 Mgal/d was furnished by public supplies, and 16 Mgal/d was provided by self-supplied withdrawals.

Industrial and Mining

Water withdrawn and delivered during 1985 for industrial and mining purposes was 433 Mgal/d (fig. 4). Public supplies furnished 38.5 percent (167 Mgal/d) and self-supplied systems provided 175 Mgal/d of surface water and 66 Mgal/d of ground water for industrial use. Self-supplied systems withdrew 22 Mgal/d from surface-water sources and 3 Mgal/d from ground-water sources for mining activities. Consumptive use was 4.1 percent (18 Mgal/d) for all industrial and mining use.

Most of the major water-using industries are along the Ohio River. Many industries also are located in the western part of the Kentucky–Licking basin near Lexington. The extreme western part of the State has plentiful ground-water sources and attracts industries that use large quantities of water. The largest quantities of water are used to manufacture or produce food, textile, pulp and paper, chemical, metal, and distillery products.

Thermoelectric Power

Water withdrawn for thermoelectric power generation accounted for 81.1 percent of the total offstream withdrawals during 1985 (fig. 4). Twenty-two fossil-fueled powerplants produced 60,100 GWh of electricity and withdrew 3,410 Mgal/d for cooling. Of the water withdrawn for cooling, 3.6 percent was lost through evaporation (consumptive use), so all but 124 Mgal/d was return flow to the streams for reuse. The 124 Mgal/d was 47.5 percent of the total consumptive use. Surface water was the source for about 99 percent of the water required for thermoelectric power generation. Only one plant, which is in Mason County, withdraws ground water.

Agricultural

About 58 Mgal/d during 1985 was withdrawn for agricultural purposes. Although this represents the smallest quantity of water for the use categories shown in figure 4, nearly all water withdrawn was consumed. Agriculture represents the largest percentage of consumptive use compared to the amount withdrawn for the categories represented.

Water withdrawn for livestock production during 1985 was about 50 Mgal/d; livestock watering is the major agricultural water use. Surface-water sources, such as streams and ponds, supplied

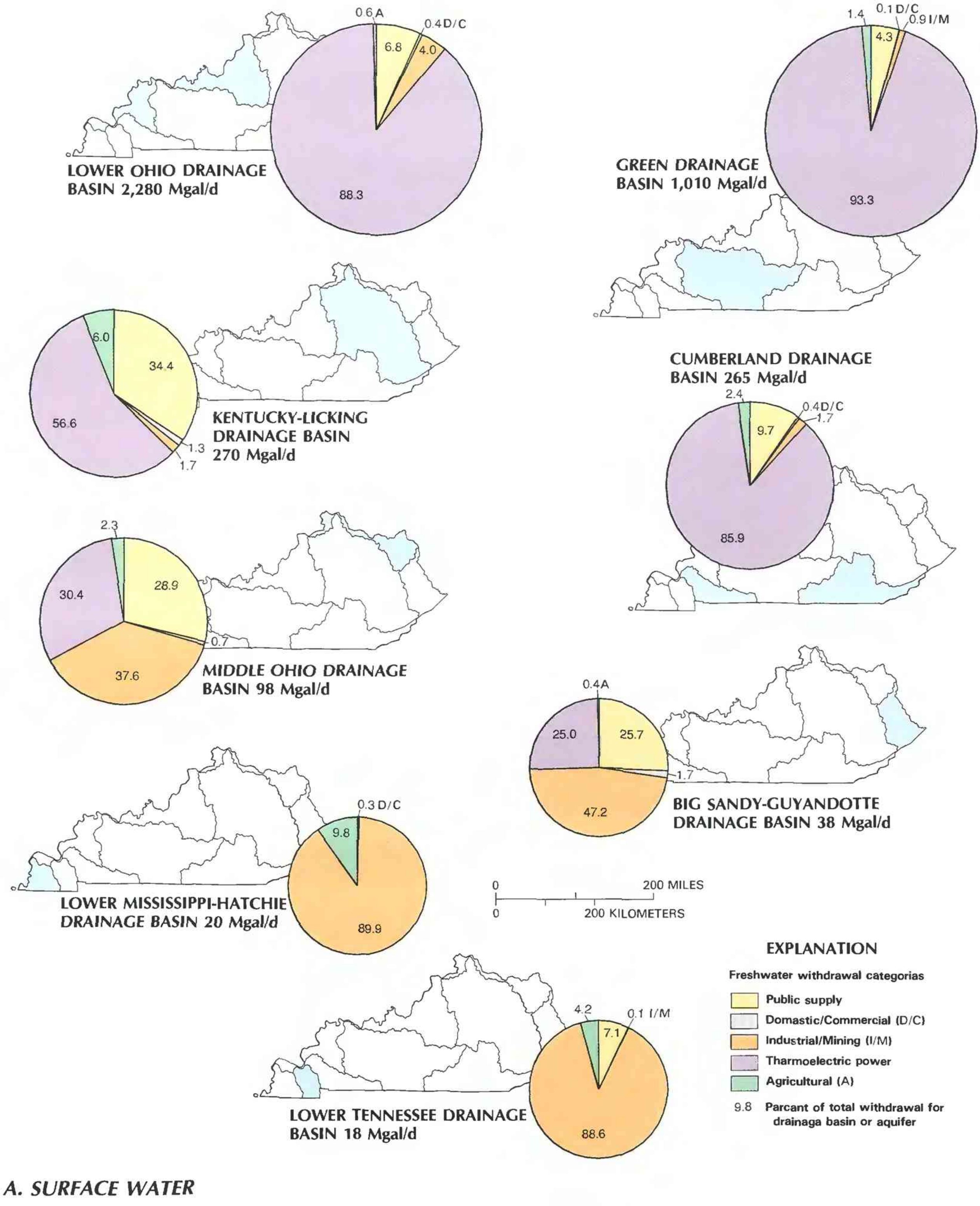


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Kentucky, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files.)

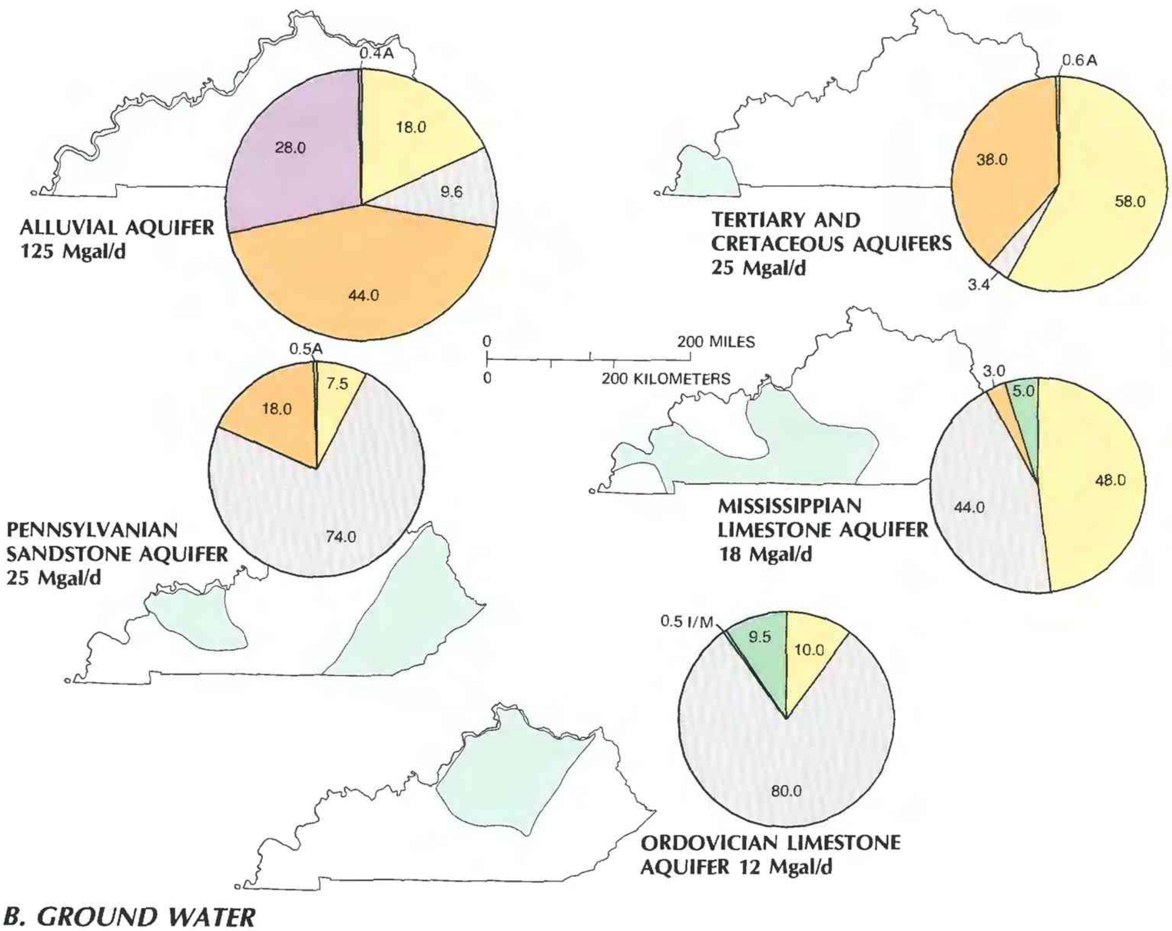


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Kentucky, 1985—Continued.

95.2 percent (55 Mgal/d) of the water. Water withdrawn for irrigation (8 Mgal/d) increased by 51 percent from 1980 to 1985. Historically, water for irrigation has been insignificant compared to overall water use. Tobacco farms throughout the State presently (1987) are the major users of irrigation systems. The current agricultural trend in Kentucky, however, is toward "truck farming," which requires supplemental irrigation to produce good-quality crops. This trend is especially prominent in the central and extreme western parts of the State (J.R. Davis, U.S. Department of Agriculture, oral commun., 1987). Because more irrigation is required for this type of farming, rapid increases in the water used for irrigation are expected within the next few years.

WATER MANAGEMENT

Water management in Kentucky is complicated by a mixture of statutory and common-law rights. Despite some fundamental problems, the superimposing of statutory rights on older common-law rules has served to make water available to more users.

In 1954, the Kentucky Legislature officially adopted the Reasonable Use rule (KY Acts, Ch. 247, Sec. 2). This rule provided that water use by a riparian owner for domestic purposes had priority over other uses. The Reasonable Use rule was repealed in 1966 (KY Acts, Ch. 23, Sec. 39) and replaced by KRS (Kentucky Revised Statute) 151, a broadly based water-resources statute, administered by the Kentucky Natural Resources and Environmental Protection Cabinet (KNREPC). Withdrawal, transfer, and diversion of all public water (except for certain exempted uses) are regulated by a permit process.

Each permit must be specific in terms of quantity, time, place, and rate of withdrawal. Permits have no expiration date. Domestic and agricultural uses are exempted by statute (KRS 151.140), as are steam-generating plants. Water used for underground injection for the production of oil or gas also is exempted. Users withdrawing 10,000 gal/d or less are classified as an additional user group not subject to permitting. All permitted water users must keep records of all withdrawals, transfers, and diversions and must report to the KNREPC.

In response to an increasing need for critical review of the water-allocation process, the Division of Water of the KNREPC has formed an independent advisory group called the Water Allocation Task Force. This group is preparing to recommend improvement in Kentucky's water-use program to the 1988 General Assembly. The Water Allocation Task Force is represented by all major user groups (agriculture, commerce, industry, utilities, oil, gas, coal), as well as relevant public agencies and the Kentucky Legislature. The Task Force is addressing short-term improvements to the water-permit process by which the State allocates existing water resources. They also are developing long-term plans and funding capabilities that will augment supplies, thereby decreasing the need for stricter controls on allocation of the resource.

The State water-use program is operated primarily by the Water Quantity Management Section of the Division of Water's Water Resources Branch of the KNREPC. This program promotes appropriate management and use of water supplies and offers technical assistance to local and regional water managers and community officials. This program promotes conservation education for all com-

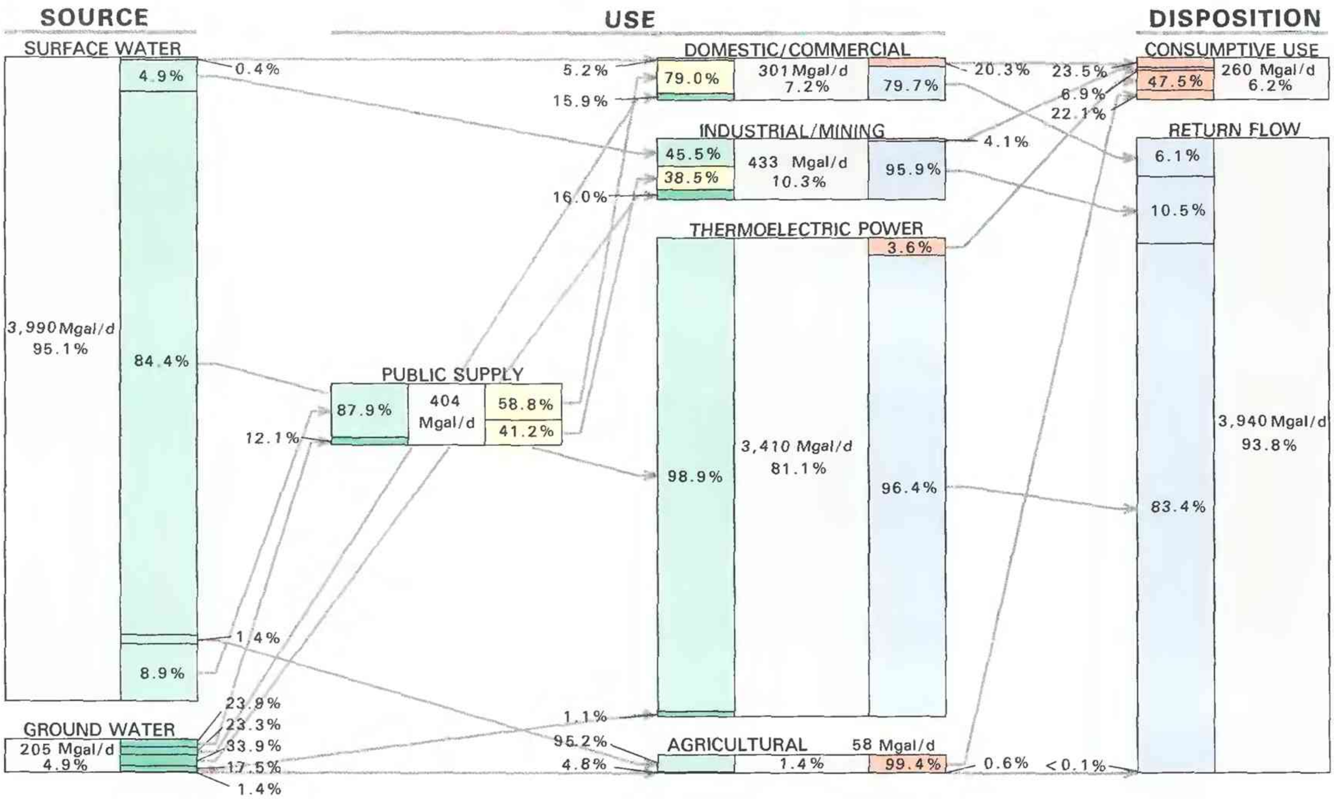


Figure 4. Source, use, and disposition of an estimated 4,200 Mgal/d (million gallons per day) of freshwater in Kentucky, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (*Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.*)

Louisville Water Company Crescent Hill Reservoir, Louisville, Kentucky. Water use is primarily for domestic, commercial, and industrial activities. (*Photograph by Jennifer M. Marsh.*)

munities and is especially encouraged for communities whose demand approaches or exceeds available supply. A "Water Shortage Response Plan" (Kentucky Natural Resources and Environmental Protection Cabinet, 1986) offers specific, step-by-step guidelines for assessing water-supply availability, determining the need to conserve, and managing water use at the local level.

Through the Federal-State Cooperative Program, the U.S. Geological Survey cooperates with the KNREPC as part of the National Water-Use Information Program. With this cooperative effort, accurate and timely water-use data are being collected and analyzed for water-resources planning and management.

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Prepared by Clyde J. Sholar, U.S. Geological Survey; History of Water Development section by Ralph R. Huffsey, Kentucky Water Resources Research Institute; Water Management section by V. David Lee, Kentucky Natural Resources and Environmental Protection Cabinet, Division of Water

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 2301 Bradley Avenue, Louisville, KY 40217

LOUISIANA
Water Supply and Use

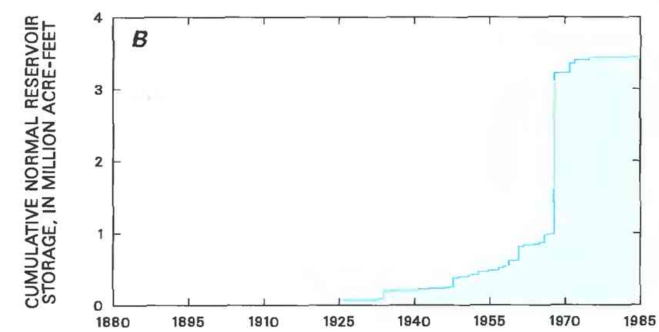
Louisiana has abundant water resources. Several large rivers either flow through or form part of the borders of the State. Humid subtropical climates prevail, and extended droughts are uncommon (U.S. Geological Survey, 1984). The average annual precipitation is 56 inches or 127,000 Mgal/d (million gallons per day) (fig. 1*A*). Of this quantity, 64 percent (82,000 Mgal/d) is lost in evapotranspiration.

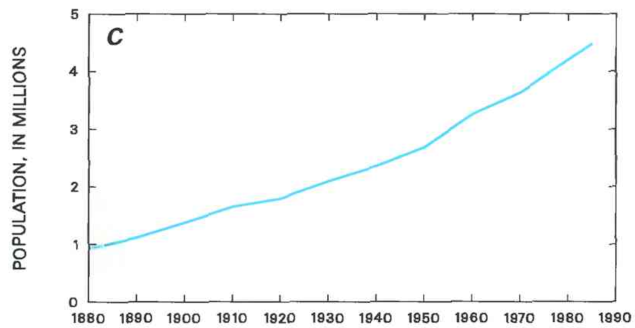
From 1980 to 1985, the population in Louisiana increased from 4.20 million to 4.48 million. Areas most likely to be affected by additional growth are Lake Charles, Monroe, Shreveport, and cities along the Mississippi River corridor from Baton Rouge to the Gulf of Mexico. The growth potential of these areas is indicative of continued industrial development.

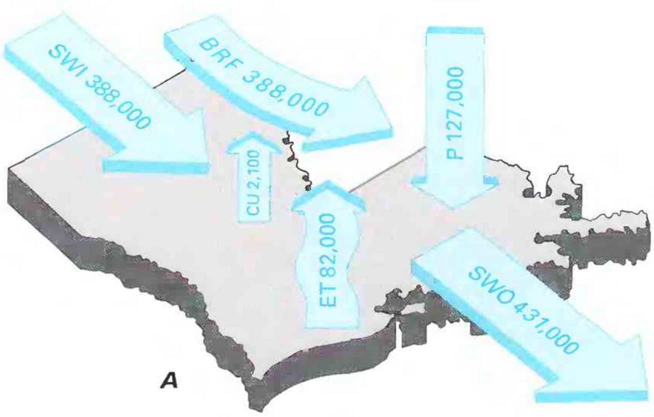
The southeastern part of the State, which includes large urban and industrial areas, depends on both surface- and ground-water supplies. Thermoelectric power generation throughout the State relies mainly on surface water. In the southwestern part of Louisiana, ground water provides the necessary water for public supply, industry, and agriculture (primarily rice irrigation).

Available surface supplies in Louisiana are generally of good quality for most uses. However, human activities can, in local areas, adversely affect the surface-water quality, principally by industrial-waste discharge, nonpoint-source runoff, and insufficient assimilation of domestic waste. Also, saltwater intrusion can be a problem in coastal sections of streams during low flow. Ground water also is available in most areas in a quantity and a quality suitable for the major-use categories (U.S. Geological Survey, 1985). Naturally occurring minerals may adversely effect ground-water use in local areas. Water-quality constraints on use of ground water are attributed to hardness, iron, sodium, chloride, and pH.

In 1985, about 10,400 Mgal/d of water was withdrawn from surface- and ground-water sources. Of the total withdrawals, 8,470 Mgal/d was fresh surface water, 1,430 Mgal/d was fresh ground water, and 500 Mgal/d was saline surface water. Of the freshwater withdrawals, 2,100 Mgal/d was consumed, and 7,880 Mgal/d was returned to natural surface- or ground-water sources. Much of the water supply and use information described herein is collected







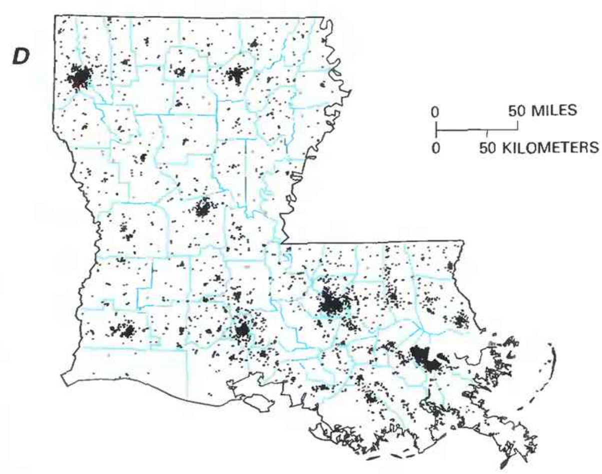


Figure 1. Water supply and population in Louisiana. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey reports and files. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

through a cooperative program with the Louisiana Department of Transportation and Development, (DOTD).

HISTORY OF WATER DEVELOPMENT

The extensive network of tributaries of the Lower Mississippi, Red–Sulphur, and Lower Red–Ouachita basins provided the earliest thoroughfares and means of livelihood for the Louisiana territory. The first European explorers found the marshes, swamps, and bottom-land flood plains to be the most productive areas for hunting, gathering, fishing, and agriculture. The first permanent European settlement was established in 1714 at Natchitoches on the Red River in west-central Louisiana. Soon after, in 1718, New Orleans was founded; the settlers were aware that the site was prone to overbank flooding from the Mississippi River and would require levee construction and channel dredging to remain habitable.

The population steadily increased in Louisiana during the 18th century as settlers established themselves along the waterways and began to farm the fertile flood-plain soils. Domestic freshwater supplies from rainfall, streams, and ground water were collected and stored at each homestead, a practice that continued in some rural areas until recently, when public supplies finally became available. From the 1720's to the 1860's, large plantations grew indigo, tobacco, sugarcane, and cotton for export. Little irrigation was practiced on these early bottom-land plantations, although rice commonly was planted along the lower edge of the backslope of natural levees to take advantage of spring floodwaters. The cotton industry began to expand around 1810 because of steamboat transportation, which enabled crops to be shipped faster and more cost effectively.

During the past 100 years, the nature of water development in Louisiana has changed significantly. The increased use of the railroad in the late 1800's led to a decrease in the widespread use of steamboats for transportation and shifted the emphasis of river transportation to commercial towboats and barges. In 1888, the first pumping operation for irrigating rice fields began, and rice cultivation expanded to upland prairies. Since 1925, 39 major surface-water reservoirs have been constructed for water supply, recreation, and power generation in areas of large relief in the northern and western parts of the State. Toledo Bend Reservoir, the largest of these, was completed in 1969 on the Sabine River (Sabine and De Soto Parishes); its operation is administered jointly by Texas and Louisiana. Cumulative normal storage of large reservoirs in the State is shown in figure 1*B*.

Lumbering was introduced in 1890, and timber was harvested extensively from the swamps by means of rafts and pullboats. The peak in lumbering was over by 1925, and attention was focused on the expanding petroleum industry. A steady increase in population (fig. 1*C*) accompanied the development of oil and gas. Population began to shift from rural areas to the State's principal urban-industrial centers (fig. 1*D*). Rice, soybeans, and milo became major farm crops. Aquifer development for domestic, industrial, and agricultural uses began in the early 20th century. Saltwater intrusion gradually became a local constraint because of intensive use of ground water in southern Louisiana. At present (1987), however, saltwater intrusion generally is not a problem. In some areas, aquaculture (the growing of catfish and crawfish for commercial purposes) has become a major activity.

The construction of levees, canals, floodways, and diversion structures along the Mississippi River has contributed to the development of the State. The first artificial levee system was completed in New Orleans in 1727, and, by 1844, a continuous levee existed from below New Orleans to Baton Rouge. Protection of the west bank of the river continued upstream to the mouth of the Arkansas River in Arkansas. Severe floods constantly damaged the levees. In 1879, the Mississippi River Commission was established to coordinate the construction, improvement, and maintenance of the system. After the disastrous flood of 1927, authorization was given for the development of a flood-control plan involving the entire lower Mississippi River basin and the Atchafalaya River basin (the eastern part of the Louisiana Coastal basin). Under this plan, the U.S. Army Corps of Engineers constructed the Bonnet Carré Spillway in St. Charles Parish in 1936, the Morganza Floodway near Morganza in Pointe Coupee Parish in 1954, and the Old River Control Structure at the northern tip of Pointe Coupee Parish in 1962; these projects were in addition to many auxiliary floodways, canals, diversion structures, and levees. An auxiliary Old River Control Structure was completed and dedicated in the spring 1987.

Navigation needs also have stimulated ongoing water-development projects by the U.S. Army Corps of Engineers, most notably, the Gulf Intracoastal Waterway in the southern edge of the State, and the Red River Waterway (Red–Sulphur basin) in the northwest. The Sabine River Diversion Canal became operational in 1981. The 25-mile-long canal, which diverts water from the Sabine River west of Lake Charles, was constructed to provide water for industrial and agricultural uses in the Lake Charles area.

WATER USE

Louisiana has an ample supply of freshwater to meet present and probable future needs. The water budget (fig. 1*A*) shows the quantities of water that enter and leave the State. Incoming components consist of surface-water inflow and precipitation, and outgoing components consist of surface-water outflows, evapotranspiration, and consumptive use.

Total freshwater withdrawals by parish are shown in figure 2*A*. The major areas of total withdrawals reflect the major categories of water use within the State. The area south of Lake Pontchartrain near New Orleans reflects the large concentration of population and the commercial and the industrial activities. Large withdrawals southwest and north of Baton Rouge reflect the petrochemical industry. Industry and irrigation of rice and other crops in the southwestern part of the State make substantial demands on the water supply. The distribution of surface- and ground-water withdrawals by parish (figs. 2*B*,*C*) reflects the availability of large quantities of surface and ground water in southern Louisiana. Surface-water withdrawals in northwestern Louisiana (fig. 2*B*) also are large because of the concentrated population in the Shreveport area. In the extreme southeastern part of the State, ground-water development has been slight.

The largest surface-water withdrawal, 4,640 Mgal/d, is from the lower Mississippi basin (fig. 3*A*) and is mainly for thermoelectric power generation. In the Louisiana coastal basin, the largest surface-water withdrawals are for agriculture. Ground-water withdrawals are dominant in southwestern and southeastern Louisiana, where agriculture accounts for 73.8 percent of water withdrawals from the Pleistocene aquifer (fig. 3*B*).

The quality of surface water in Louisiana is generally sufficient for most uses. Surface water is used for public supply for New Orleans, Jefferson Parish, and Shreveport. Impaired quality, and the resultant limitations on use of the water, is of concern locally. Increased fecal coliform bacteria counts have been observed in the Tangipahoa River (Lower Mississippi–Lake Maurepas basin); the Mississippi River; the Atchafalaya, Vermilion, and Mermentau Rivers (Louisiana Coastal basin); and the Red River. Toxic and hazardous substances are a concern in the Mississippi and Calcasieu Rivers. Water-quality problems in the Vermilion River are related to municipal and industrial discharges, agricultural nonpoint-source discharges, and saltwater intrusion. Turbidity from agricultural runoff is a concern in the Mermentau River. Water-quality problems in the Red River result from disposal of municipal wastes and agricultural and urban runoff. In some streams, inadequate dissolved-oxygen concentrations also have been reported.

Ground water in Louisiana generally is of good quality for most uses. Ground water is the source for 85 percent of all public-

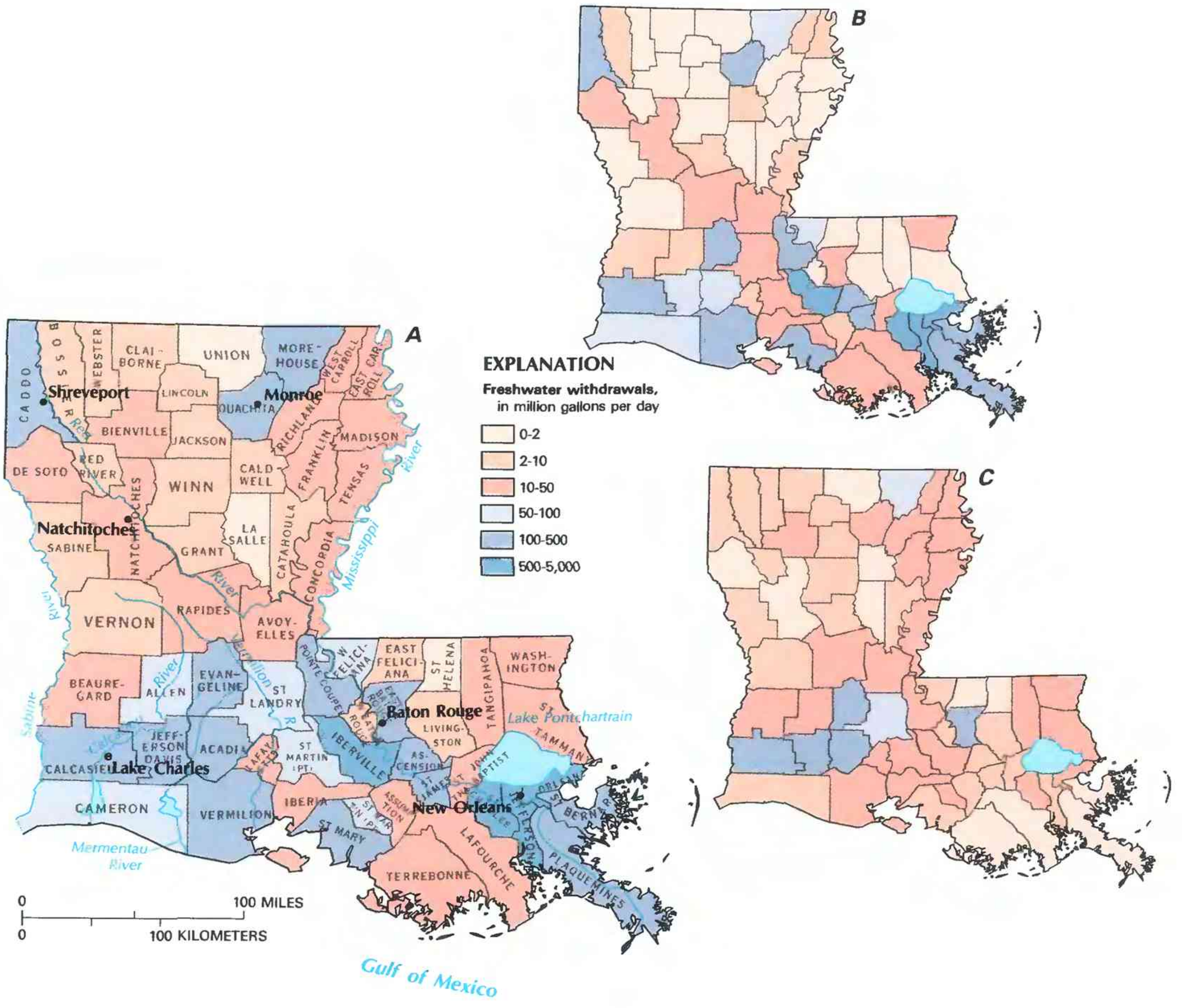


Figure 2. **Freshwater withdrawals by parish in Louisiana, 1985.** *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: *A, B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

supply systems and for virtually all domestic rural users (U.S. Geological Survey, 1985). Localized concerns about ground-water quality include pH, hardness, chloride, sodium, and iron concentrations. Water from the alluvial aquifer generally is not suitable for public supply unless it is treated for hardness and removal of iron. In the Carrizo-Wilcox aquifer, 50 percent of the iron concentrations are between 50 and 650 μg/L (micrograms per liter). The medium iron concentration is about 150 μg/L. In the Cockfield and Sparta aquifers, 50 percent of the iron concentrations are between 80 and 900 μg/L and the median concentration is 300 μg/L. Locally, water from the Pliocene–Miocene aquifers may have iron concentrations that exceed 300 μg/L. Ninety-five percent of the concentrations are less than 800 μg/L. In the Pleistocene aquifers, less than 5 percent of the iron concentrations exceed 2,000 μg/L (U.S. Geological Survey, 1988). In local areas, the occurrence of saltwater in aquifers also is a concern.

The source, use, and disposition of freshwater are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 8,470 Mgal/d of surface water and 1,430 Mgal/d of ground water were withdrawn in 1985. Total water withdrawals decreased by 16 percent between 1980 and 1985. Surface-water withdrawals decreased 16 percent and ground-water withdrawals 19 percent between 1980 and 1985. The use data indicate that in 1985 total domestic and commercial use was 674 Mgal/d, which represents 6.8 percent of the State's total use. Of that 6.8 percent, 93.1 percent (627 Mgal/d) was from a public supplier (surface and ground water) and 6.9 percent (46 Mgal/d) was self-supplied from ground water (rural domestic wells). The disposition data indicate that, for all water withdrawn in the State, 21.2 percent (2,100 Mgal/d) was consumed, and 78.8 percent (7,800 Mgal/d) was returned to the hydrologic system.

Instream use of water is significant in Louisiana. The only hydroelectric powerplant is at Toledo Bend Reservoir on the Sabine River (Sabine Parish); it uses water from Louisiana and Texas. Water from the Sabine River is impounded and released to turn turbines at the powerhouse in Burkeville, Tex. Flow through the powerhouse in 1985 was 2,770 Mgal/d. One-half of this quantity (about 1,380 Mgal/d) was used instream for Louisiana hydroelectric power generation. When the Waterford III Powerplant upstream from New Orleans became operational in 1983, the Mississippi River provided the largest quantity of water for power generation in Louisiana; in 1985, this quantity was 2,410 Mgal/d (Lurry, 1987). Only offstream water use is identified in figure 4.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In Louisiana, these systems furnish 99.8 percent of their supply for domestic and commercial use and 0.2 percent for industrial and mining use (fig. 4). In 1985, Louisiana was ranked 14th for withdrawals for public-supply systems, although it was 18th in population in the United States (Solley and others, 1988). Total water withdrawals for public supply in 1985 were 628 Mgal/d (fig. 4). From 1980 to 1985, total water withdrawals for public supply increased by about 26 Mgal/d (4 percent), surface-water withdrawals by public suppliers increased by 15 Mgal/d (4 percent), and ground-water withdrawals by public suppliers increased by 11 Mgal/d (4 percent) (Lurry, 1987).

Of the 628 Mgal/d of public-supply withdrawals, 56.0 percent (352 Mgal/d) was surface water and 44.0 percent (276 Mgal/d) was ground water. Orleans Parish, in which the city of New Orleans is located, used the most surface water for public supply—135 Mgal/d from the Mississippi River. East Baton Rouge Parish, in which the city of Baton Rouge is located, used the most ground water for public supply—57 Mgal/d. The source of this water is aquifers ranging in age from Pleistocene to Miocene.

DOMESTIC AND COMMERCIAL

Domestic and commercial water users received water from public-supply systems and self-supplied facilities. Combined use in 1985 was 674 Mgal/d (fig. 4). Domestic use in 1985 was about 665 Mgal/d, of which 619 Mgal/d was from public-supply systems that served 87 percent of the population, and 46 Mgal/d was from the 13 percent of the State's population that supply their own water from rural domestic wells. Domestic and commercial consumptive use was 124 Mgal/d. An average of 161 gal/d (gallons per day) per capita was used by consumers who purchased their water from a public-supply system.

Commercial water use in Louisiana in 1985 was about 8 Mgal/d. Of that quantity, 97 percent was provided by public-supply systems. Consumptive use was less than 2 Mgal/d.

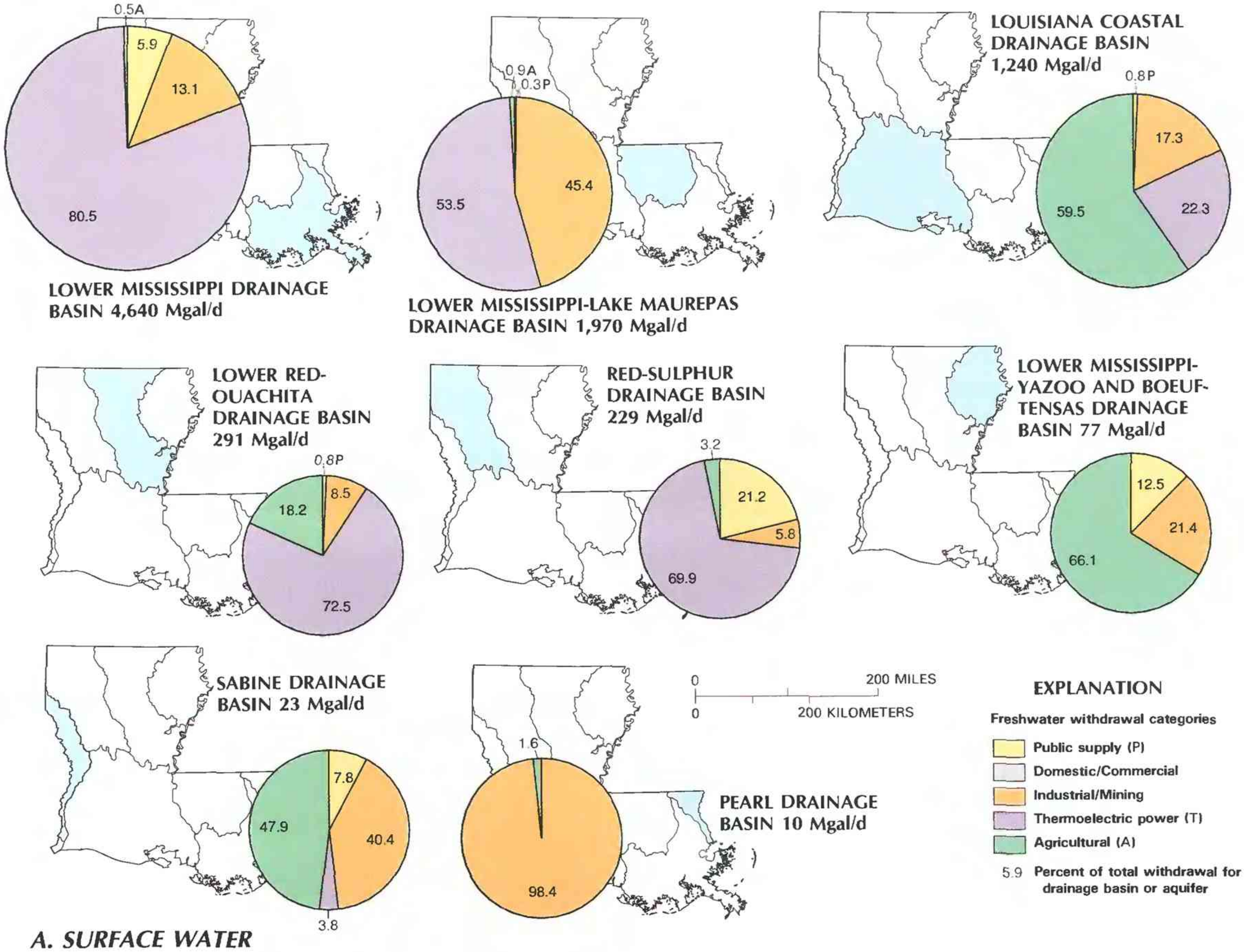


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Louisiana, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey National Water Data Storage Retrieval System.)

INDUSTRIAL AND MINING

During 1985, industrial and mining use was 2,070 Mgal/d (fig. 4). Of that quantity, 86.4 percent (1,790 Mgal/d) was self-supplied from surface-water sources, 13.5 percent (281 Mgal/d) was self-supplied from ground-water sources, and 0.1 percent (1.4 Mgal/d) was delivered by public suppliers. About 9.2 percent (190 Mgal/d) of the water used for industrial and mining purposes was consumed.

Total industrial use decreased by 43 percent (1,590 Mgal/d) from 1980 to 1985 (Lurry, 1987). During 1980, surface water withdrawn by industry and mining was 3,280 Mgal/d, compared to 1,790 Mgal/d during 1985, and ground-water withdrawn by industry and mining was 392 Mgal/d, compared to 281 Mgal/d during 1985. Major industries in Louisiana are oil and gas production, petrochemicals, and wood and paper. The decrease in industrial water use is attributed to the depressed market for oil and gas production and petrochemicals, as well as conservation and recycling of processed water by major industries.

THERMOELECTRIC POWER

Total freshwater use for thermoelectric power generation in 1985 was 55.2 percent (5,470 Mgal/d) of the total freshwater used in the State (fig. 4). Water use for power generation increased by 2 percent from 1980 to 1985 (Lurry, 1987). Surface water for power generation was 5,800 Mgal/d during 1980 and 5,930 Mgal/d during 1985, which is an increase of 2 percent (these figures include saline surface water). Of the fresh surface water used for power generation, fossil-fueled plants used about 4,350 Mgal/d, and nuclear powerplants used about 1,080 Mgal/d (Solley and others, 1988). Ground-water use for power generation was 47 Mgal/d in 1980 and 36 Mgal/d in 1985, which is a decrease of 23 percent. Of the 36 Mgal/d of ground water used for power generation, 99 percent was for fossil-fueled plants. Louisiana has 18 fossil-fueled plants and 2 nuclear powerplants. Total consumptive use for power generation was 205 Mgal/d in 1985. Fossil-fueled plants accounted for 188 Mgal/d of consumptive use, and nuclear powerplants accounted for 17 Mgal/d of consumptive use.

AGRICULTURAL

Agricultural water use (irrigation, livestock, and aquaculture) in Louisiana in 1985 was 1,690 Mgal/d (fig. 4). Withdrawals for irrigation were about 1,484 Mgal/d, and withdrawals for nonirrigation were 203 Mgal/d. Rice irrigation in southwestern Louisiana, which is the principal agricultural water user, utilizes virtually all irrigation withdrawals. Withdrawals for rice irrigation in 1980 were 2,075 Mgal/d. Thus, withdrawals decreased 28 percent from 1980 to 1985.

Nonirrigation agricultural water use was 11 Mgal/d for livestock and 192 Mgal/d for aquaculture. Withdrawals for livestock decreased from 15 Mgal/d in 1980 to 11 Mgal/d in 1985. Of the 11 Mgal/d used for nonirrigation agriculture, all was consumed.

Surface water provided 53.4 percent (902 Mgal/d) of the water used for agricultural purposes, and ground water provided 46.6 percent (788 Mgal/d). Consumptive use was 1,580 Mgal/d, and conveyance losses were 146 Mgal/d.

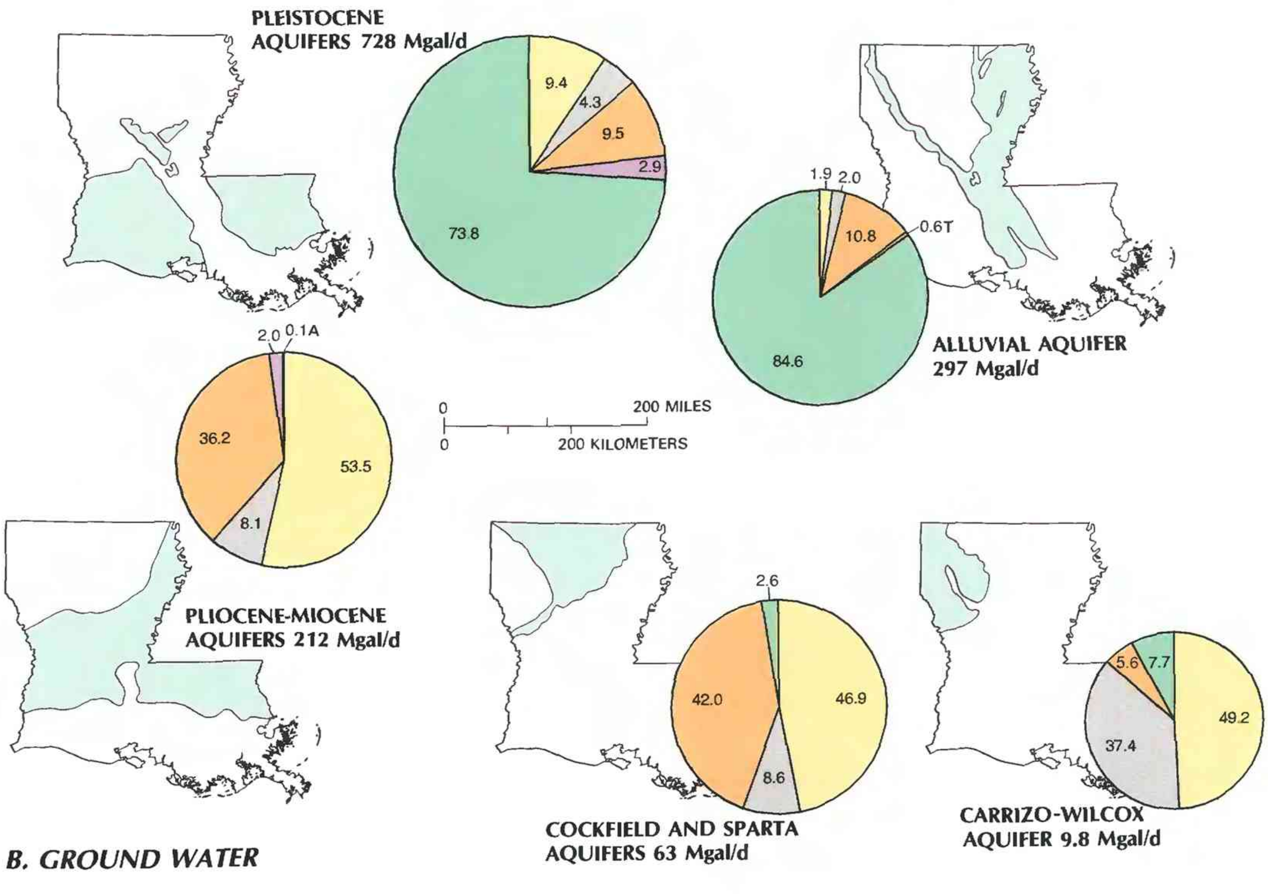


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Louisiana, 1985—Continued.

WATER MANAGEMENT

Several State agencies have management-related responsibilities for surface- and ground-water resources in Louisiana. Although no one agency has absolute responsibility for managing the water resources of the State, the DOTD traditionally has been the lead agency in these activities.

The Louisiana Water-Resources Study Commission, which was established in 1964 to assess the State's water policies and the roles of the different agencies, concluded its mission and submitted its final report to the legislature in 1984. The riparian doctrine is used with regard to surface-water rights. Various State statutes define the rights of landowners, nonriparians, and the State to withdraw and use surface waters. No statewide permits or regulations pertain to surface-water use.

With respect to ground water, the DOTD issues licenses and regulates water-well drillers, administers programs related to the construction and registration of water wells and boreholes, and regulates the plugging and the sealing of abandoned wells and holes. Additionally, the DOTD maintains an extensive computerized water-resources data base, which is available to the general public upon request. The Louisiana Department of Health and Human Resources sets standards and monitors public-supply sources. The Department of Environmental Quality has broad responsibilities for protecting surface and ground water through regulation of waste-disposal activities. The Louisiana Department of Natural Resources, Office of Conservation, is involved with the protection of ground water related to oil and gas development and lignite mining and regulates the drilling and the use of injection wells by the industry. The Capital Area Groundwater Conservation Commission (in Baton Rouge) has authority to regulate ground-water use in its five-parish area (East and West Baton Rouge, Pointe Coupee, and East and West Feliciana). The Commission requires the reporting of water use. Under the DOTD's free-flowing well program, owners or lessees of free-flowing water wells that produce more than 25,000 gal/d are required to install control devices on those wells to conserve ground water.

In 1983, the Louisiana Water-Resources Program was established in the DOTD under Act 625. This Act provides for a statewide program of planning, development, and management of the water resources. Some elements of this Act include developing a water-data information base, managing the State's water resources, providing water-related technical assistance, establishing water-resource priorities, and cooperating with the Federal Government in planning and developing the State's water resources. The DOTD also is involved with drainage, flood control, and navigation problems.

The Sabine River Authority was created between Texas and Louisiana to regulate the withdrawal of water from the Sabine River. The Red River Compact, which was ratified by Texas, Oklahoma, Arkansas, and Louisiana in 1978, provides for an equitable apportionment of streamflow among these States.

The U.S. Army Corps of Engineers is involved in water management in Louisiana. The Corps has ongoing projects on several of the larger rivers, such as the Red River. On the Red River, the Corps has developed a navigation plan that includes the construction of five locks and dams. When this project is completed, the Red River will be navigable north to Shreveport.

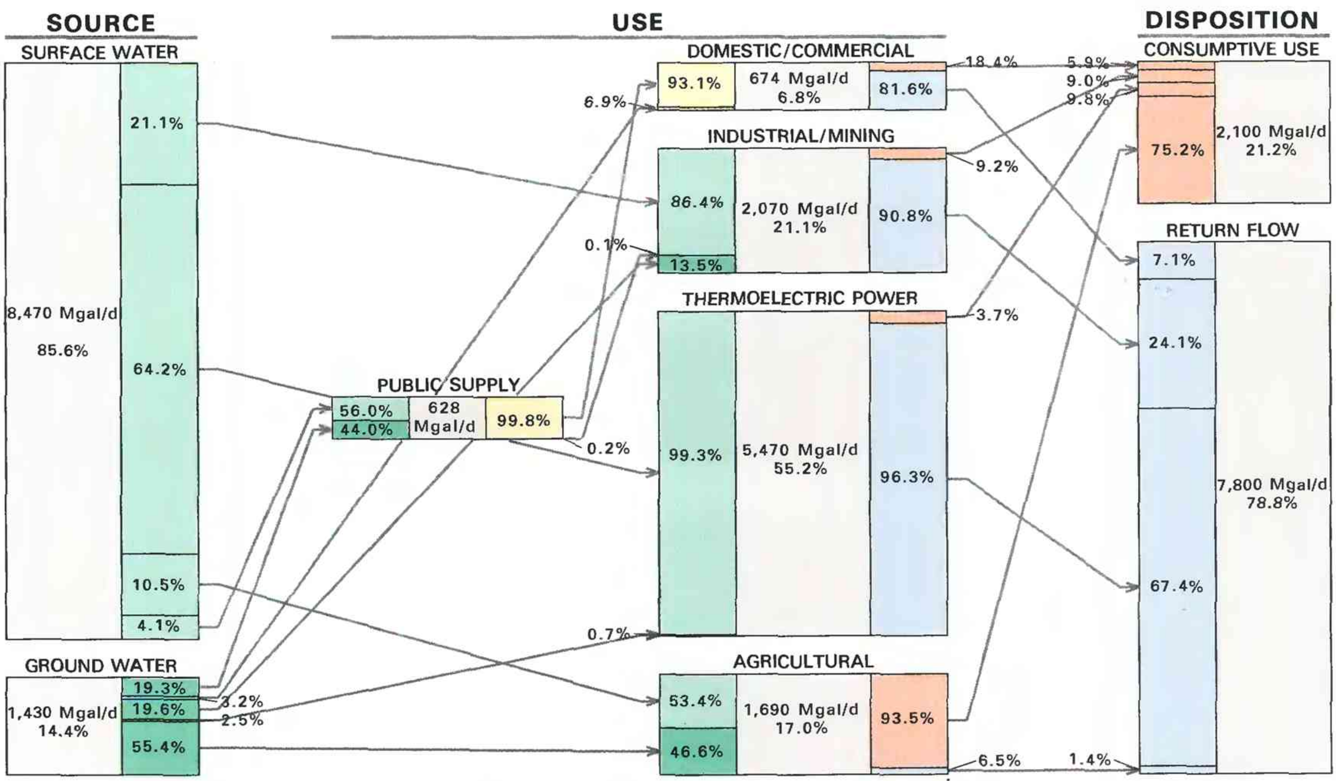


Figure 4. Source, use, and disposition of an estimated 9,900 Mgal/d (million gallons per day) of freshwater in Louisiana, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

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The Calcasieu River saltwater barrier, which is located about 2 miles upstream from Lake Charles, Louisiana. The barrier is designed to impede the movement of saltwater upstream into the freshwater swamps. (Photograph by Dennis K. Demcheck.)

Prepared by D.L. Lurry and K.J. Covay, U.S. Geological Survey; K.K Hirschboeck, Department of Geography and Anthropology, Louisiana State University; and Z. Bolourchi, Louisiana Department of Transportation and Development

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, P.O. Box 66492, Baton Rouge, LA 70896

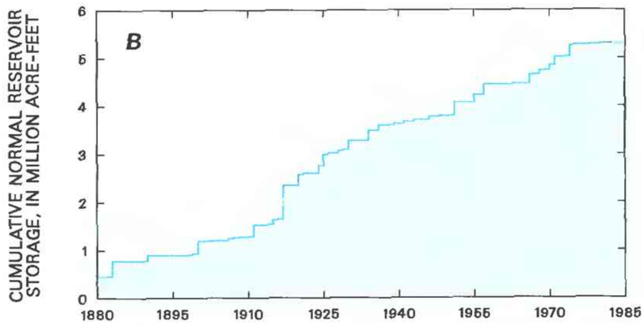
Maine
Water Supply and Use

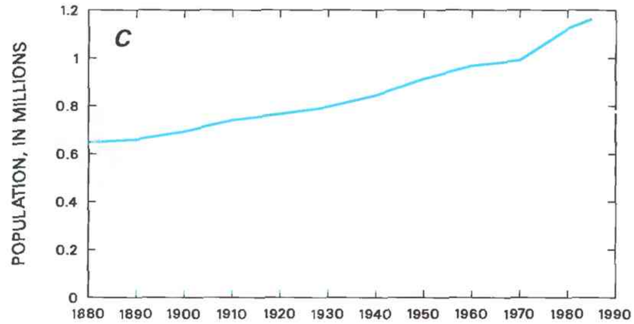
Maine has abundant surface-water resources and limited ground-water resources. The State has more than 2,900 lakes and ponds and more than 70 streams that have a length of 20 or more miles (Attwood, 1946). In 1985, 92.3 percent of the freshwater used offstream was withdrawn from surface-water sources. Ground water is withdrawn from two major aquifer types—unconsolidated glaciofluvial deposits and fractured bedrock composed of sedimentary, igneous, and metamorphic rocks. The glaciofluvial deposits are the most favorable for development of large water-supply wells; however, these deposits are limited in size and distribution. Although ground water accounts for only 7.7 percent of water withdrawn statewide, it serves as the source of domestic water for about one-half of Maine's population. The quality of surface water and ground water generally is suitable for most uses.

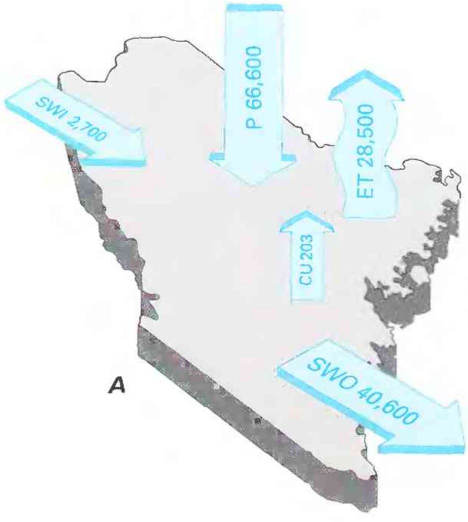
The water budget shows that about 66,600 Mgal/d (million gallons per day), or 96 percent, of the water entering the State is derived from precipitation (fig. 1*A*). The two largest components of water leaving the State are evapotranspiration (28,500 Mgal/d) and surface-water outflows (40,600 Mgal/d). During 1985, 849 Mgal/d was withdrawn for various uses, and 203 Mgal/d was consumed; the remainder was returned to the hydrologic system.

The greatest demand for water is in southwestern and coastal Maine and along Interstate Highway 95, which traverses the southern coast to Portland, then to Augusta, Bangor, and north through Penobscot and Aroostook Counties. Industrial and mining use accounts for 65.9 percent of the estimated offstream water use, followed by domestic and commercial use at 18.2 percent, thermoelectric power use at 12.2 percent, and agricultural use at 3.7 percent. The largest water users are the pulp and paper companies.

In southwestern coastal Maine, water-supply shortages are beginning as a result of a steadily increasing year-round population and the increasing demands of a large summer tourist population.







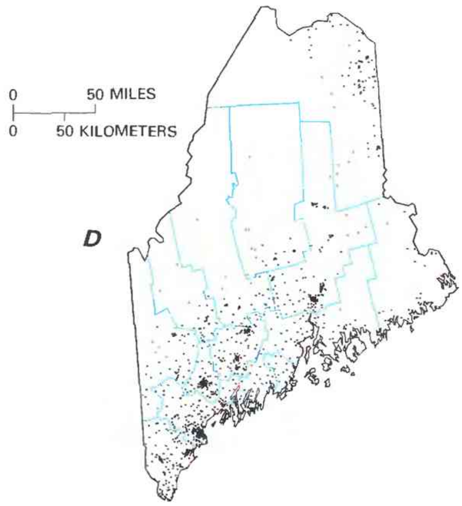


Figure 1. Water supply and population in Maine. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Knox and Nordenson, 1955. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Cumberland and York Counties are experiencing rapid growth and rapid increases in the demand for water. Maine's population is estimated to have increased about 3 percent from 1980 to 1985, when it was about 1.16 million. Additional population increases, along with accompanying economic development, will increase demand for water in the same areas where the adequacy of water supply is becoming a problem. Water-supply shortages are predicted for 57 percent of the towns in coastal Maine by the year 1990 (Caswell and Ludwig, 1978). Water-management agencies will need to protect the quality and the quantity of existing and potential supplies and to develop regional solutions to the long-term water-supply issues.

Information on water use for Maine is in an initial stage of development. Much of the information collected for this report, and for previous water-use reports, is based on estimates of water-use amounts. As the water-use issue in the State becomes more important, implementation of a formal program for the continuous collection and analysis of water-use data will receive greater priority.

HISTORY OF WATER DEVELOPMENT

The rivers, lakes, and streams of Maine were important to the early settlement and colonization of the State. The first permanent settlement in Maine was at Georgetown (Sagadahoc County) in 1607 (Attwood, 1946). About 40 settlements had been established in southern and coastal areas by the end of the 1600's. Each river along the coast of Maine provided a transportation route that allowed colonists on the coast to move inland during the 1700's. As settlers moved upstream to trade and farm, they constructed dams at natural waterfalls and rapids to harness water power for the operation of gristmills and sawmills. Timber harvesting along streams was a major industry; it depended on large streamflows in the spring for the transportation of logs to mills and shipping ports downstream. In the early 1800's, small dams were constructed at natural lakes and at suitable locations along rivers and streams to impound spring runoff. The dams increased the amount of water available to transport logs, which extended the log-transporting season. Because the economic development of the State depended on hydropower and dams, early legislation, such as the Maine Mill Act, favored the rights of dam owners over those of other potential users. As turbines replaced water wheels, larger dams were constructed on the rivers. These dams terminated anadromous fish runs on the Kennebecand the Androscoggin Rivers in the mid-1800's. Anadromous fish hatch in freshwater, mature in saltwater, and return to spawn in freshwater.

The "Telos War," one of the most famous conflicts over water use in Maine, occurred in the 1840's in Aroostook County. Loggers in the Penobscot basin built a dam at the outlet of Chamberlain Lake (Piscataquis County) and constructed a canal between Telos and Webster Lakes that diverted the flow from a 249-square-mile drainage area in the St. John basin to the Penobscot basin. St. John loggers attempted to destroy the dam; however, the Penobscot loggers successfully maintained the dam. The flow from this area is considered to be a permanent contributor to the drainage of the Penobscot River.

In the late 1800's and early 1900's, the construction of large industrial plants and mills on Maine's rivers marked the beginning of the use of major rivers for large-scale industrial projects. In addition, some uses of the river were impaired by increasing industrial waste discharges that degraded the water quality. Industries that depended on surface-water use included pulpmills and papermills, woolen mills, tanneries, shoe factories, and facilities that processed agricultural products. During the same time, electric utilities began construction of hydroelectric projects that would provide the first electric power to Maine's largely rural population.

To retain spring runoff from precipitation and snowmelt and to increase the efficiency of regulation of river flow for hydroelectric power generation, large storage reservoirs were constructed at the headwaters of most of the major river basins. These reservoirs retained large quantities of water in April and May and provided a greater sustained flow through the summer. This regulation benefited other users by maintaining stable water levels during the summer for recreation and by providing increased base flows, which increased stream waste-assimilation capacity during the low-flow season. The last major dam to be constructed in Maine was on the Kennebec River in the 1950's. Additional small dams on headwater and tributary streams and increased storage capacity at existing dams increased water storage to more than 5 million acre-feet by the early 1970's (fig. 1*B*). By this time, most of the sites that had significant hydropower potential had been developed, and competition for the use of Maine's surface-water resources began to increase.

In the last 10 years, interest has been renewed in developing additional hydropower capacity at existing sites, at abandoned sites, and at sites that have output potential. This increase in hydropower development was the result of the oil embargo of the 1970's, the demands of the increasing population in southwestern Maine and along the Interstate Highway 95 corridor (figs. 1*C*,*D*), and the increased value of electric power produced by means other than use of imported fossil fuels. Since 1979, about 100 applications have been processed that request approval to construct and operate projects capable of producing about 250 megawatts of new or increased hydroelectric capacity.

WATER USE

The climate of Maine provides a substantial supply of water to the State. Annual precipitation ranges from about 34 inches in the northeast to 55 inches in the northwest and north-central mountains and averages about 42 inches statewide (Knox and Nordenson, 1955). The State's water budget (fig. 1*A*) shows the estimated proportions of water entering and leaving the State.

The distribution of total freshwater withdrawals by county is shown in figure 2*A*. The two counties that have the largest withdrawals are Cumberland and Penobscot. Cumberland County (Portland) has the largest population of any county in Maine and also has large industrial water users that required total supplies of about 374 Mgal/d in 1985. Penobscot County had withdrawals of about 157 Mgal/d; the pulp and paper industry is a large water user.

Surface- and ground-water withdrawals by county are shown in figures 2*B* and 2*C*, respectively. Surface water is the largest source of water used in the State, accounting for about 92.3 percent. Cumberland and Penobscot Counties had the largest surface-water withdrawals. Ground water constituted 7.7 percent of the total freshwater withdrawals, and is the source of domestic water for about one-half of Maine's population. In 1985, about 43 Mgal/d was withdrawn from ground-water sources to supply 545,000 people. Maine's large rural population depends almost entirely on dug or drilled wells as sources of domestic water. Cumberland and York Counties account for about 44 percent of all ground-water withdrawals.

Surface-water withdrawals from the six major drainage basins in Maine ranged from 29 Mgal/d in the Kennebec basin to 373 Mgal/d in the Saco basin (fig. 3*A*). Of the water withdrawn in the Kennebec basin in 1985, 45.1 percent was used for industrial and mining purposes, and 34.6 percent was used for public supply. In the Saco basin, 73.4 percent of the water withdrawn was used by thermoelectric powerplants, and 10.0 percent was used for public supply.

Ground-water withdrawals by aquifer (fig. 3*B*) were estimated from sparse data of ground-water supply and use in Maine. Data for the four principal aquifers indicate that withdrawals were largest from glaciofluvial deposits (43 Mgal/d) and crystalline bedrock (17 Mgal/d).

The source, use, and disposition of freshwater in Maine are shown diagrammatically in figure 4. The quantities of water given in the figure and elsewhere in this report may not add to the totals

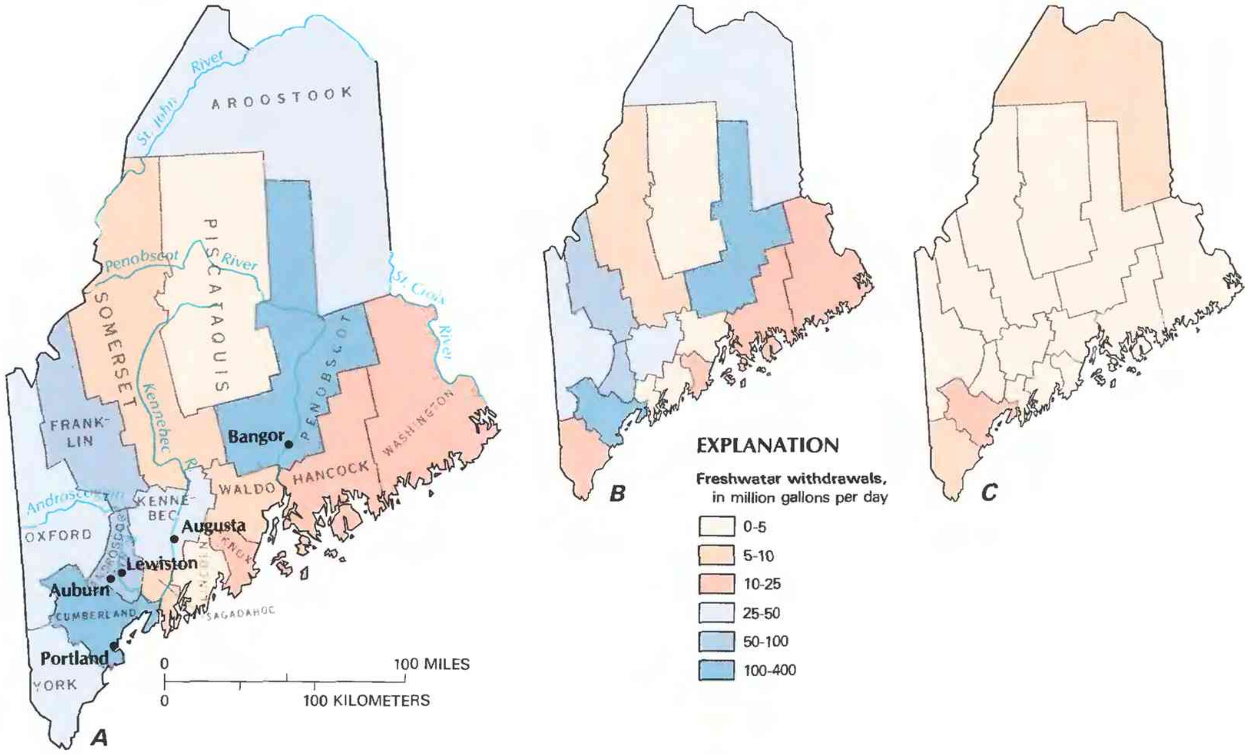


Figure 2. Freshwater withdrawals by county in Maine, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

indicated because of independent rounding. The source data indicate that the 783 Mgal/d of surface water withdrawn in 1985 was 92.3 percent of the total surface- and ground-water withdrawals in Maine. Of that amount, 3.6 percent is directly withdrawn (self-supplied) for domestic and commercial use; 68.9 percent is self-supplied by industrial and mining facilities; 13.2 percent is withdrawn for thermoelectric power generation; 3.6 percent is withdrawn for agriculture; and 10.8 percent is withdrawn by public-supply systems. The use data indicate that domestic and commercial use was 155 Mgal/d, which represented 18.2 percent of the State's total use. Of that 18.2 percent, 18.1 percent was obtained from a surface-water source, 62.9 percent was from a public-supply system, and 18.9 percent was from ground-water sources. During domestic and commercial use, 59.9 percent of the water was consumed, and 40.1 percent was returned to a natural water source where it became available for additional use. The disposition data indicate that, for all water withdrawn in the State, 23.9 percent (203 Mgal/d) was consumed and 76.1 percent (645 Mgal/d) was returned to the hydrologic system. Domestic and commercial consumptive use was 45.7 percent of all freshwater consumptive use in the State during 1985 and represented 9.6 percent of all return flow.

Instream use (not included in fig. 4) also is significant because water-generated power has been an important part of Maine's history, and water availability has affected the placement of many industries. Consequently, the largest instream use of water is hydroelectric power generation. The consumptive use of water in hydroelectric power generation is mostly from evaporation, and the amount involved is negligible.

PUBLIC SUPPLY

Public-supply systems withdraw water, treat it, and distribute it to users. About 72 percent of Maine's population relies on public supplies. The demand for public-supply water is greatest in Cumberland County (Portland), which accounts for about 22 percent of the State's total population served by public supplies (fig. 5). Penobscot (Bangor), Kennebec (Augusta), York, and Androscoggin Counties combined account for an additional 50 percent of the population served by public supplies. The remaining 28 percent of the State's population served by public supplies is distributed among the other 11 counties. About 108 Mgal/d is collectively withdrawn in the 16 counties of Maine for public supply (fig. 6); about 77.9 percent is surface water, and 22.1 percent is ground water (fig. 4).

Of the 849 Mgal/d of freshwater withdrawn for offstream use in the State, about 13 percent (108 Mgal/d) is withdrawn by public supplies. Although this is a small amount of the total water withdrawn, it has the potential for increasing rapidly. In areas of southern Maine, growth is rapid, and the need for additional water supplies is becoming critical. From 1980 to 1985, the population of York and Cumberland Counties in southwestern Maine increased 9.6 and 4.9 percent, respectively.

The statewide demand for public supplies increased about 3 percent from 1980 to 1985. The increase is attributed to the general population increase and the extension of service areas by public suppliers. The demand for potable ground-water supplies in the southern part of the State is expected to continue to increase concurrent with development. New sources of water need to be identified.

DOMESTIC AND COMMERCIAL

A total of 155 Mgal/d was used for domestic and commercial purposes in the State in 1985 (fig. 4); of this quantity, 62.9 percent was delivered by public suppliers, and the remainder was self-supplied about equally from surface- and ground-water sources. About 84.2 percent of the withdrawals for domestic use was from

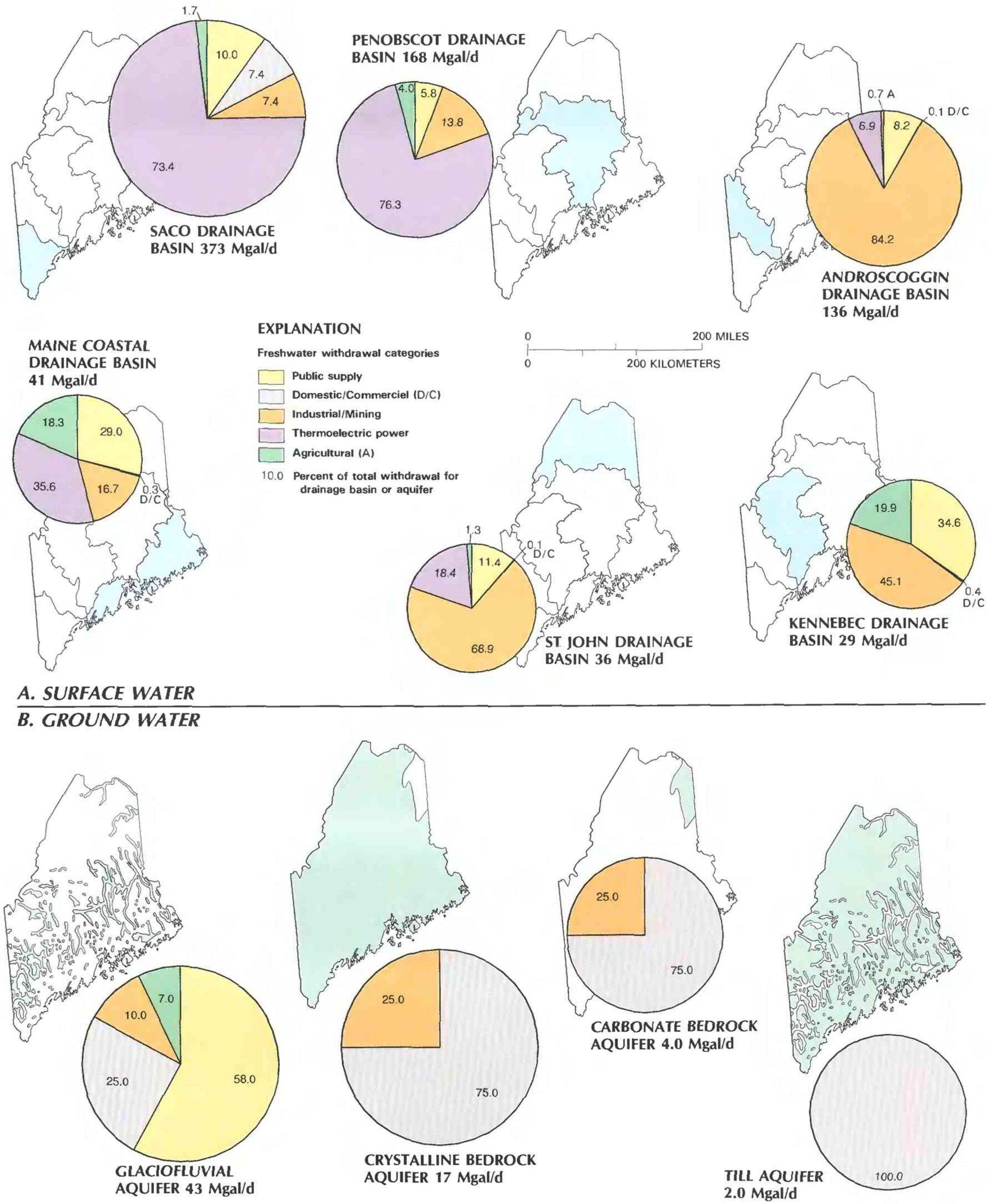


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Maine, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files.)

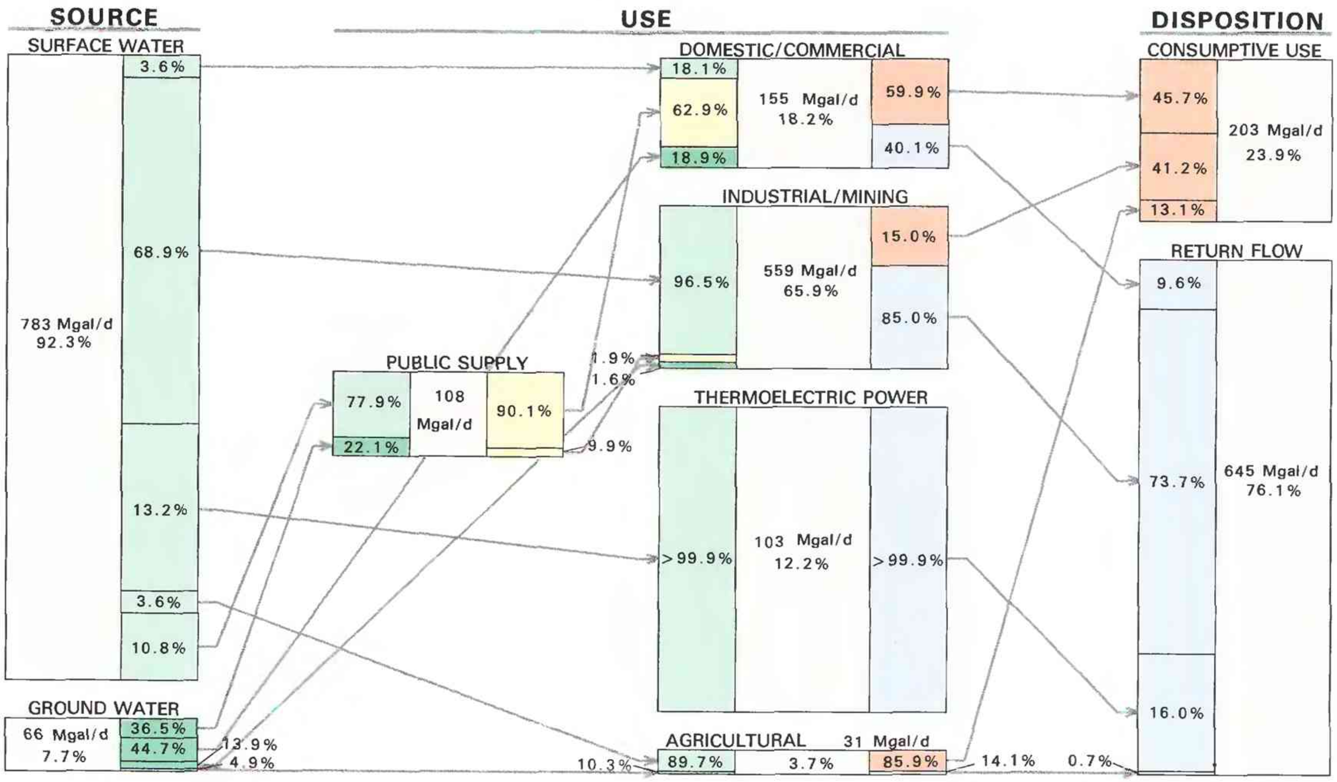


Figure 4. Source, use, and disposition of an estimated 849 Mgal/d (million gallons per day) of freshwater in Maine, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

public supplies. About 59.9 percent (93 Mgal/d) of water withdrawn and delivered for domestic and commercial purposes was consumed —80 Mgal/d by domestic and 13 Mgal/d by commercial.

Industrial and Mining

In 1985, industrial and mining freshwater use was 559 Mgal/d, which was 65.9 percent of Maine's total water use (fig. 4). About 96.5 percent (539 Mgal/d) was self-supplied from surface-water sources. Industrial water use was 555 Mgal/d, of which the pulp and paper industry used 30.8 percent (171 Mgal/d). Consumptive use for all industries was 84 Mgal/d. Industrial use of saline water (not shown in fig. 4) was 30 Mgal/d.

The mining industry in Maine is small. Total freshwater use by mining in 1985 was 4.0 Mgal/d; of this, 0.8 Mgal/d was from ground water.

Thermoelectric Power

Maine has 16 thermoelectric powerplants; 15 are fossil fueled, and 1 is nuclear. Freshwater use for thermoelectric plants totaled 12.2 percent (103 Mgal/d) of statewide water use (fig. 4). Surface water is the major source of water for the fossil-fueled plants. Surface-water withdrawals for thermoelectric use was about 12.2 percent (103 Mgal/d) of the total surface-water withdrawals. Consumptive use by the power companies is reported as zero for fossil-fueled and nuclear powerplants.

The nuclear powerplant used about 621 Mgal/d of saline water (not included in fig. 4) for cooling purposes during 1985. This saline water is withdrawn from an estuary, used for cooling, and returned to the estuary.

Several biomass electric plants are scheduled to begin power generation in 1989. Some of these plants will use large volumes of ground water for cooling.

Agricultural

Water withdrawn for agriculture is for irrigation and nonirrigation purposes. Water for irrigation use accounted for about 0.2 percent of total water use in Maine in 1985. Irrigated acreage decreased 41 percent from 1980 (10,750 acres) to 1985 (6,340 acres). Consumptive use by agriculture, mostly by evapotranspiration, was 27 Mgal/d in 1985, which was 13.1 percent of total consumptive use (fig. 4).

WATER MANAGEMENT

Surface-water use in Maine is managed by public and private agencies. Flows of most major rivers are regulated by private companies and electric utilities that use the river for hydroelectric power generation or for process water. Streamflow and water-quality requirements for these companies usually are established by the Federal Energy Regulatory Commission or by State regulatory agencies through licensing procedures.

The water-quality classification of the State's rivers and lakes, and their protection, are the responsibility of the Maine Department of Environmental Protection (MDEP). The MDEP licenses waste discharges to surface-water bodies and monitors the licensees and receiving waters to ensure standards of water quality.

Use of surface water for public supply is regulated by the Maine Department of Human Services (MDHS). The MDHS reviews water-supply development plans, establishes water-supply quality

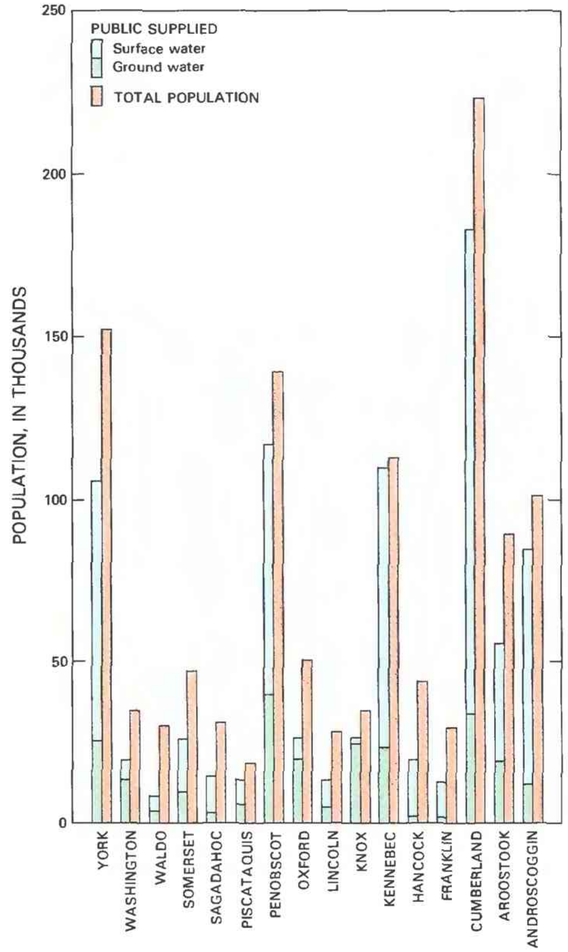


Figure 5. Population served by public-supplies by county and total population in Maine, 1985. (Sources: Compiled by U.S. Geological Survey from Maine Department of Human Services and Maine Public Utilities Commission data.)

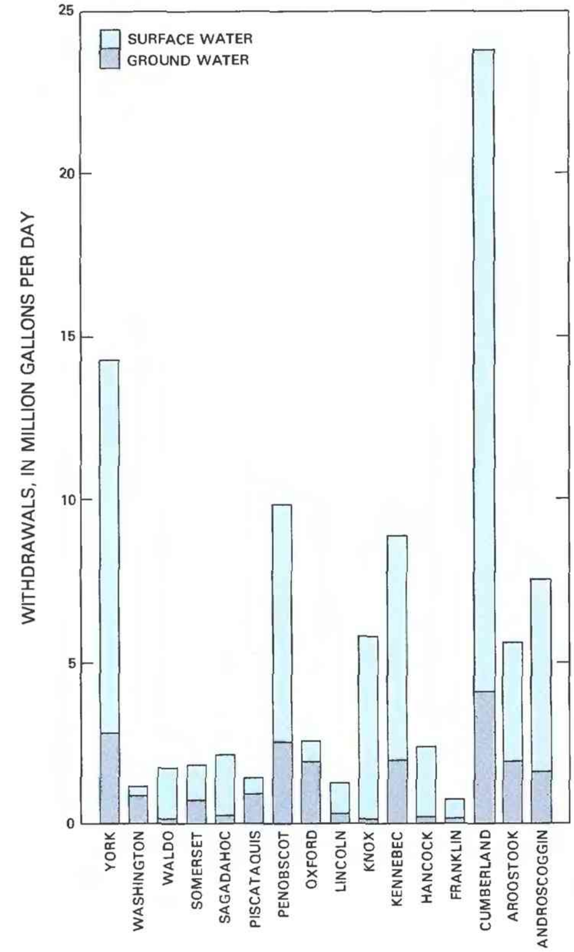


Figure 6. Freshwater withdrawals for public supply by county in Maine, 1985. (Sources: Compiled by U.S. Geological Survey from Maine Department of Human Services and Maine Public Utilities Commission data.)

standards, and monitors the quality of water delivered to consumers to ensure compliance with the standards.

The Maine Department of Inland Fisheries and Wildlife (MDIFW) and the Department of Marine Resources (DMR) manage and protect the aquatic life in streams. The MDIFW reviews all applications that involve alteration of streambeds and streamflows in streams above head of tide. The DMR reviews all developments in tidal streams and upland streams that contain anadromous fish populations.

Several State agencies have statutory responsibilities for ground-water protection and management. The Department of Conservation (DOC), through the Maine Geological Survey, is responsible for coordinating ground-water research, mapping ground-water availability, and performing research into permit-related ground-water problems. The DOC's Land Use Regulation Commission regulates activities that affect ground water in the unorganized territories, where population is sparse.

The MDHS is responsible for reviewing and approving new public-supply sources, monitoring the quality of existing sources, performing research on ground-water-transmitted diseases, and performing water-quality analyses of private water supplies.

The Department of Environmental Protection, through its Bureaus of Water, Land, and Oil and Hazardous Materials, is responsible for reviewing and licensing activities that affect ground water. This Department also is responsible for research into the effects of gasoline leaks, road salt, pesticides, and other contaminants on ground-water quality and for ground-water-quality assessments, emergency response, and cleanup.

Maine's comprehensive surface-water-management program has been evolving since the 1800's. The State's ground-water program is now being formulated by the Ground-Water Committee of the State's Land and Water Resources Council. The great importance of water resources to the economy of Maine ensures that surface- and ground-water management will continue to receive priority from Federal, State, regional, and local officials. The U.S. Geological Survey and organizations of the State of Maine have had cooperative agreements for the systematic collection of streamflow records since 1909, and for water-quality and ground-water records since 1957.

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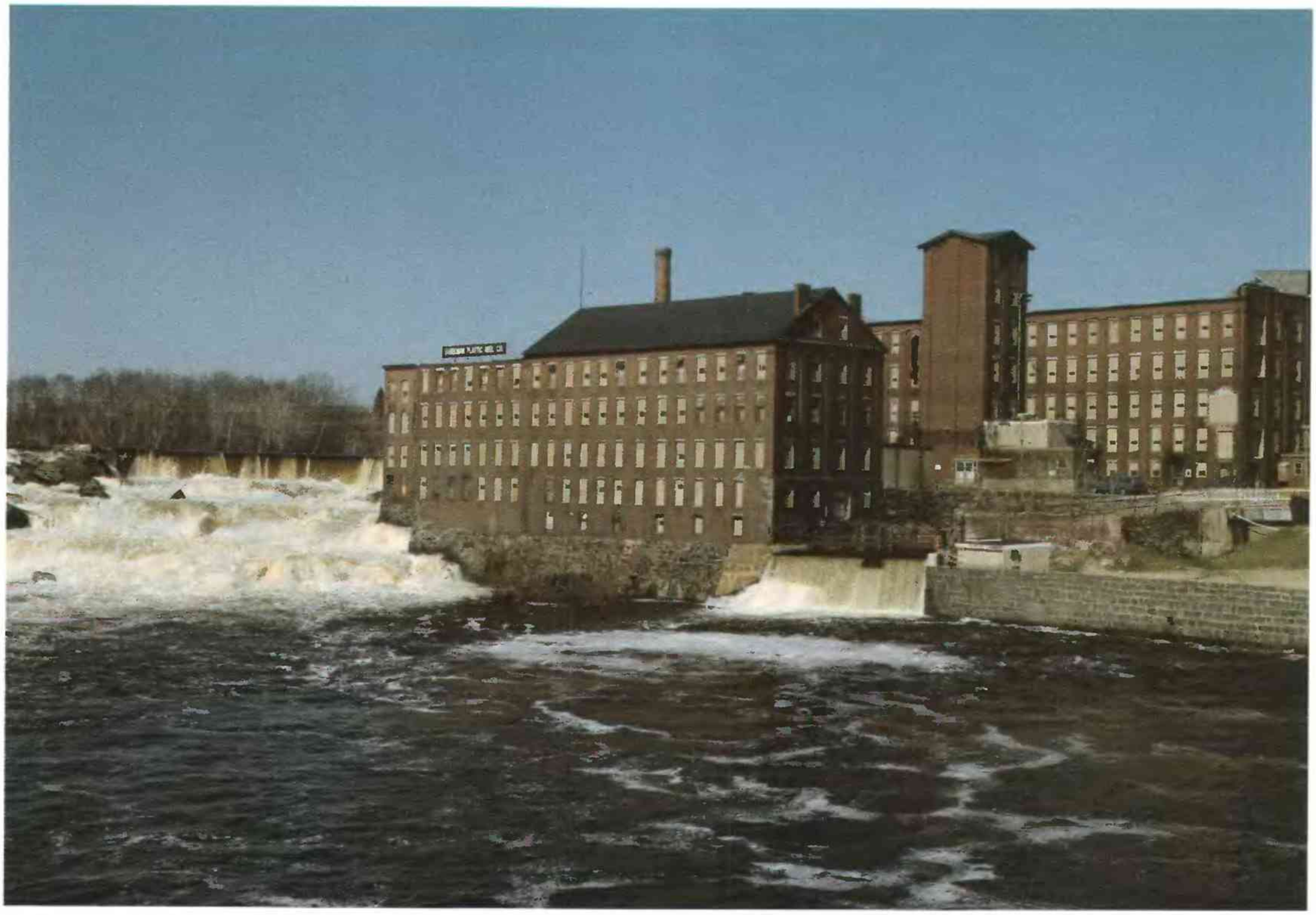

Textile mill on the Androscoggin River in Lewiston–Auburn, Maine. Water power was the major source of energy for these mills at the turn of the century. (Photograph from Maine Geological Survey.)

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Prepared by W.J. Nichols, Jr., and D.J. Cowing

FOR ADDITIONAL INFORMATION: Office Chief, U.S. Geological Survey, 26 Ganneston Drive, Augusta, ME 04330

Maryland and the District of Columbia
Water Supply and Use

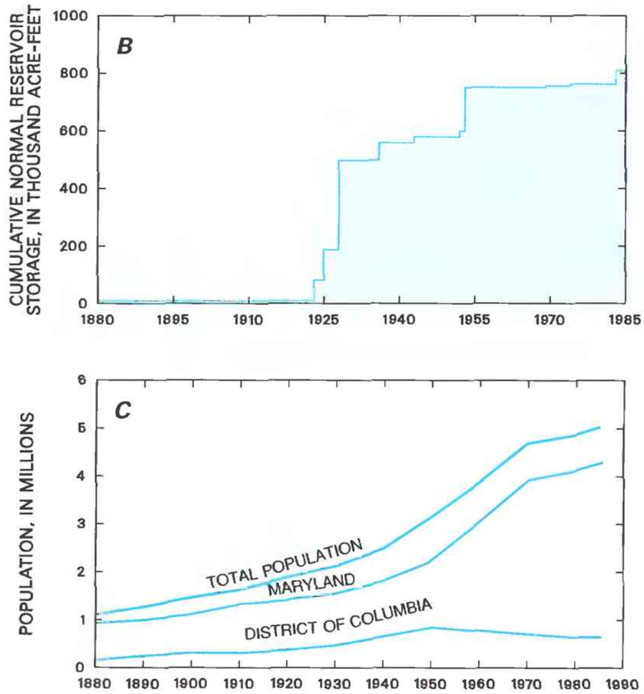
Maryland and the District of Columbia have abundant surface- and ground-water resources. These two areas receive an average of 55,000 Mgal/d (million gallons per day) of water as precipitation and streamflow from adjacent States. An estimated 130,000 billion gallons of water is in storage in aquifers underlying the area (Walker, 1970, p. 9). The water budget for Maryland and the District of Columbia, shown in figure 1A, indicates the amount of water entering and leaving the area. Average precipitation is about 42 inches per year, or 25,000 Mgal/d. In general, precipitation is greater in the eastern and extreme western parts of Maryland than in the central part. Water lost by evapotranspiration is about 28 inches per year, or 17,000 Mgal/d (Walker, 1970, p. 17). Cumulative normal storage of water in reservoirs in Maryland in 1985 was about 800,000 acre-ft (acre-feet) (fig. 1B).

During 1985, about 6,710 Mgal/d of fresh and saline water was withdrawn from surface- and ground-water sources in Maryland. The major water uses were public supply, domestic and commercial, industrial and mining, thermoelectric power generation, and agricultural. About 157 Mgal/d of the total water withdrawn in Maryland is consumed and not available for immediate reuse. Most of the State's water remains available for reuse; for example, one Maryland industry uses municipal sewage wastewater effluent for cooling water. Eighty-one percent (5,420 Mgal/d) of the total fresh and saline withdrawals during 1985 was for thermoelectric power generation; of this amount, 93 percent was from saline surface-water sources, and a negligible amount was consumed.

Total freshwater withdrawals during 1985 were 1,410 Mgal/d for Maryland, of which 218 Mgal/d was transferred for public supply use to the District of Columbia. An additional 130 Mgal/d was withdrawn in the District of Columbia for thermoelectric power generation. The largest withdrawals were for public supply (55 percent of the total freshwater withdrawn in Maryland). Surface water comprised 84.5 percent of total freshwater withdrawn in Maryland and was the source of water for the District of Columbia. Ground water was only 15.5 percent of total freshwater withdrawn in Maryland; however, aquifers in Maryland provided water for nearly 1.4 million people (about 32 percent of the State's population).

From 1980 to 1985, the population in Maryland increased an estimated 4 percent—from 4.22 million to 4.39 million (fig. 1C). In the District of Columbia, the population decreased 2 percent during the same period—from 0.638 million to 0.626 million. State officials have estimated that Maryland's population will increase by about 32,000 per year through the year 2000 (Maryland Department of State Planning, 1986). This projected population increase, plus the accompanying economic development, will increase demands on the State's freshwater supplies.

Important surface-water issues are the degradation of water quality in rivers and streams from acid mine drainage, agricultural



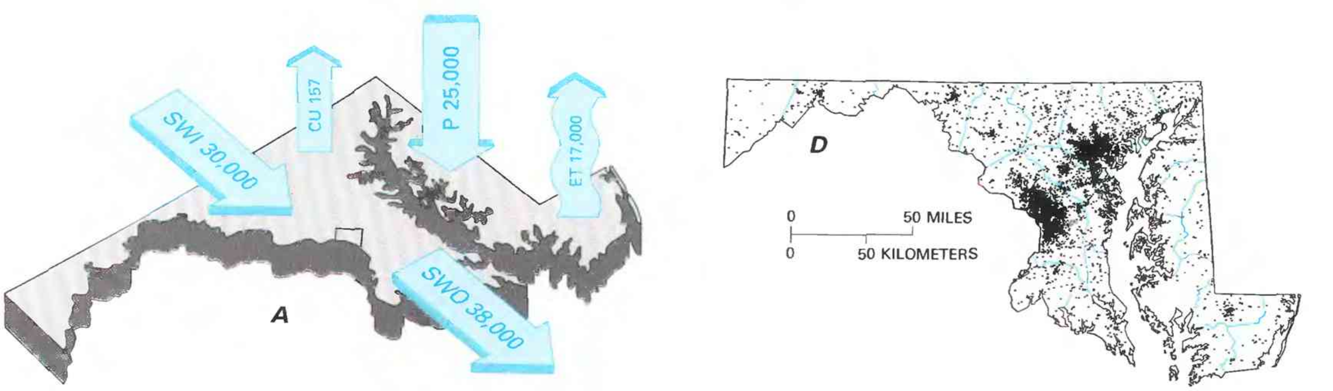


Figure 1. Water supply and population in Maryland and the District of Columbia. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Walker, 1970; Moyer, 1986. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

runoff, and improper disposal of municipal and industrial wastes. Major concerns about ground water that is used for public supply are the capability of aquifers to meet increasing demand, existing and potential saltwater intrusion into wells along coastal areas, and current and potential contamination from land-use activities. Water-use forecasts have been developed for some areas by the Maryland Water Resources Administration. The purpose of these forecasts is to improve water-supply-resource development, management, and conservation, as well as to provide a general process of forecasting water use that may be applied to other areas in the State.

HISTORY OF WATER DEVELOPMENT

Water has been important in the development of Maryland and the District of Columbia. Rivers, bays, and harbors gave early settlers ports and access to inland trade. In the Upper Chesapeake basin, the earliest colonists established settlements in shoreline areas of the Chesapeake Bay and relied on natural resources for sustenance. Domestic water needs were supplied by shallow dug wells. Surface-water sources were plentiful but, in some instances, were not potable because of salinity in tidal areas or degradation from sewage or sediment. Shore settlements and farming in the 1600's created two environmental problems that have persisted through the centuries—contamination of drinking water by human and animal wastes and silting of harbors (Maryland Office of Environmental Programs, 1984, p. 6). As early as 1800, siltation caused some ports in southern Maryland to become unusable. During the 18th century, pioneers settled in central Maryland and expanded urban development in shoreline communities. Baltimore became the "undisputed mercantile center of the Chesapeake Bay by 1785" (Mitchell and Muller, 1979, p. 14).

The 19th century brought rapid changes in the demands on Maryland's natural resources, including water. Agriculture remained the leading economic activity, but erosion, widespread soil exhaustion, and lessened crop yields were the result of continuance of old farming methods and, in some instances, population overcrowding (Van Ness, 1974, p. 156–160). The 19th-century industrial development greatly affected western Maryland and the Baltimore area. Most water, obtained from shallow dug wells and springs, was used in printing processes, weaving and spinning factories, mills and iron works (at waterpower sites on streams around Baltimore), ship building, food processing, and distilling. Widespread drilling of wells for water supply did not begin until about 1853; after that, the demand for ground water increased rapidly. By 1860, about 100 artesian wells had been drilled in Maryland, nearly all in or near Baltimore; most of these wells were used for industrial purposes (Bennett and Meyer, 1952, p. 11).

At the beginning of the 20th century, Maryland still was primarily agricultural. In 1918, the State had four cities of more than 10,000 inhabitants; the largest, Baltimore, had a population of about 560,000. By 1985, Baltimore's population had increased to nearly 760,000. Population growth in Maryland and the District of Columbia from 1880 to 1985 is shown in figure 1*C*, and population distribution in 1985 is shown in figure 1*D*.

During Baltimore's early development, ground water was used for domestic supply and fire protection. By 1865, however, many of the wells were abandoned, mainly because of well failure or contamination. The city then turned to surface water for public supply, constructing dams on streams in the city to create reservoirs. The demand for public supply increased greatly in 1918, when nearly 50 square miles of land surrounding Baltimore was annexed. More dams and reservoirs were built, including two in Baltimore County (Loch Raven, completed in 1923; Prettyboy, completed in 1936) and one in Baltimore and Carroll Counties (Liberty, completed in 1953), to meet public-supply demand (City of Baltimore Department of Public Works, 1970, p. 3–12). Cumulative normal storage of all reservoirs in Maryland in 1985 was about 800,000 acre-ft (fig. 1*B*). In the 1960's, construction of a water line from the Susquehanna River to Baltimore's filtration plants provided an additional source of water for the city during severe drought.

Use of water for irrigation has increased significantly in Maryland. In 1949, about 30 farms totaling 697 acres were irrigated. By 1985, farmland totaling 57,400 acres was irrigated. In the 1950's, most irrigation was in the central and western counties. However, improved transportation networks, less expensive land, and longer growing seasons, in addition to the pressure for urban development in the central and the western counties, caused a major shift in vegetable growing and irrigation to the counties east of the Chesapeake Bay, where about 90 percent of irrigation now occurs (Brodie and others, 1984, p. 2).

The history of water-resource development in the Potomac basin includes many congressional authorizations for studies and projects that began in the 1800's. Before the 1950's, the studies focused on problems of navigation, flood control, and hydroelectric power. Rapid population and economic growth that followed World War II emphasized the need for water management in the basin to support this growth (U.S. Army Corps of Engineers, 1983a, p. 3).

The largest water use in the Potomac basin is in the District of Columbia metropolitan area. Water development in the District of Columbia began with the use of shallow dug wells and springs that supplied the earliest water needs of the city. By the mid-1800's, however, these sources were no longer adequate for the growing population (51,000 in 1850). The Potomac River was selected as the water-supply source for the city, and, in 1853, the U.S. Army Corps of Engineers began construction of a dam and reservoir on the river upstream from Great Falls in Montgomery County (Johnston, 1964, p. 46). The resulting public-supply system was completed in 1863 and became known as the Washington Aqueduct. In later years, additional dams and reservoirs were constructed on the Potomac and its tributaries to meet the growing water needs of the Washington metropolitan area, the most recent being Bloomington on the North Branch in Garrett County (completed in 1983) and Seneca on Seneca Creek in Montgomery County (completed in 1984).

Use of ground water for public supply in the District of Columbia continued until about 1907, when the use of shallow wells and springs for public supply was prohibited because of water-quality problems (Johnston, 1964, p. 47). Some privately owned wells remained in use. Although ground water is still available in the District of Columbia, quantities are not sufficient to supplement surface-water sources.

WATER USE

Maryland has an abundant supply of water; however, the geographic distribution of freshwater withdrawals from surface- and ground-water sources differs across the State. Total withdrawals, surface-water withdrawals, and ground-water withdrawals by county in Maryland and the District of Columbia are shown in figures 2*A*, 2*B*, and 2*C*, respectively.

The largest freshwater withdrawals in Maryland are mainly in the areas of greatest population density (see figs. 1*D* and 2*A*). However, some areas of large withdrawals reflect particular types of water use within the State; for instance, most of the water used for irrigation is withdrawn in the less-populated counties of the Eastern Shore (area east of Chesapeake Bay).

The selection of the source of water supply (surface or ground water) is guided primarily by availability or accessibility of the resource. The areas west of the Fall Line (approximately a line from Washington to Baltimore to northeastern Cecil County) are underlain by relatively unproductive crystalline rock and consolidated sedimentary strata. There, demands for large quantities of water are most readily met by abundant fresh surface-water sources (figs. 3*A*). Conversely, east of the Fall Line, unconsolidated deposits, which consist mostly of sand and gravel, commonly provide large quantities

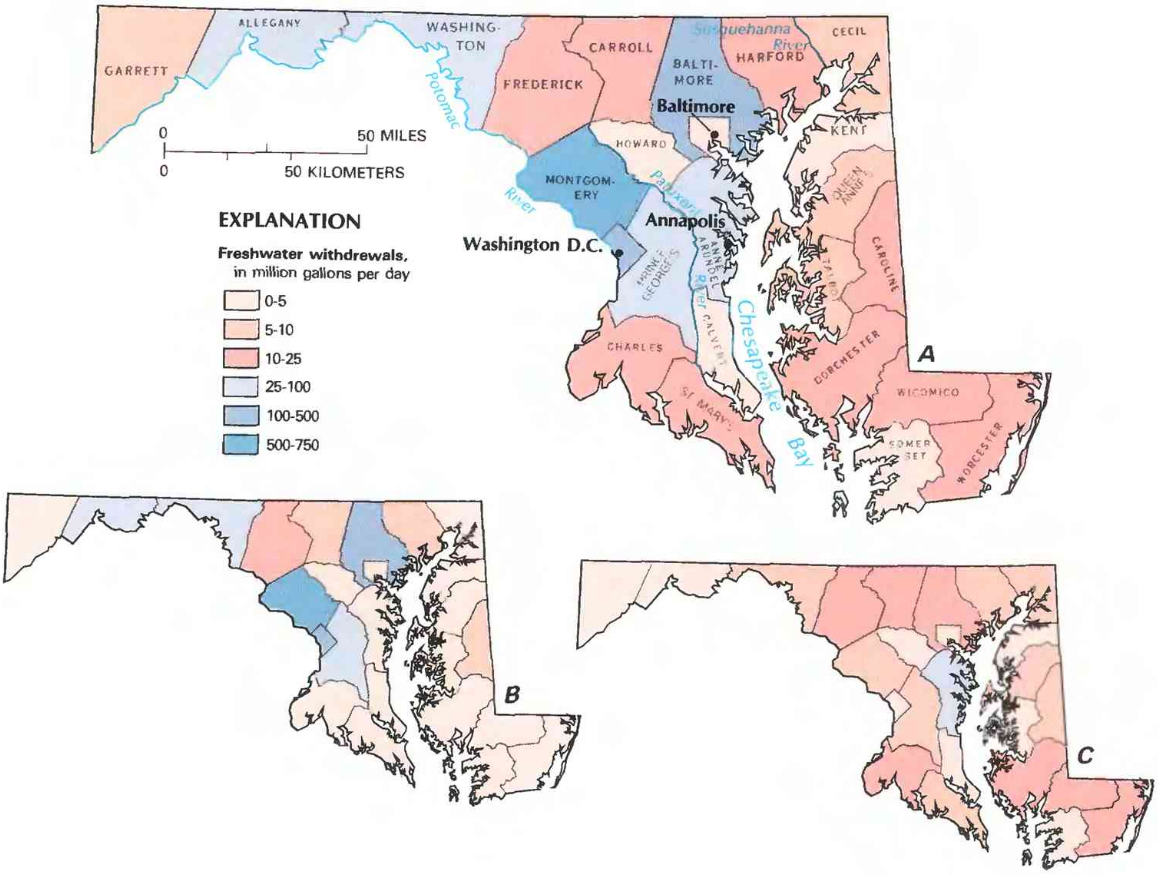


Figure 2. Freshwater withdrawals by county in Maryland and the District of Columbia, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

of ground water to meet the needs of most users (fig. 3*B*). The Eastern Shore depends almost entirely on ground water for freshwater supply. Surface water is less suitable than ground water in that area because of insufficient topographic relief to build large reservoirs, salinity from tidal effects, and degradation of surface-water quality from nutrient and pesticide runoff in agricultural areas.

The largest river basins in Maryland are the Potomac and the Upper Chesapeake (fig. 3*A*). The primary surface-water users in the Potomac basin include public suppliers, industries, and thermoelectric power facilities. The largest user of surface water in the basin is the District of Columbia. Nearly 348 Mgal/d was withdrawn from the Potomac River during 1985 for water supply and for power generation; this is an increase of 7 Mgal/d over withdrawals during 1980 and accounts for about 56 percent of the water withdrawn from the basin.

In the Upper Chesapeake basin, which comprises the major part of the area east of the Fall Line in Maryland, ground water is the predominant source of supply. Baltimore, which is the largest industrial area in the State, is in this basin. Of the 405 Mgal/d of fresh and saline water used by industries during 1985, more than 70 percent was withdrawn for industries in and near the city of Baltimore. Water use for irrigation also is greatest in the Upper Chesapeake basin. Of the 34 Mgal/d used for irrigation in the State, 94 percent (32 Mgal/d) was withdrawn in the basin.

Instream water use also is significant in Maryland. Navigation, marine commerce, and commercial and sport fishing, as well as water recreation activities, are associated with the Chesapeake Bay and many of the State's rivers and streams. The largest measurable instream use of water is hydroelectric power generation, which accounts for 6 percent of the total energy generated by all powerplants (including fossil-fuel and nuclear powerplants) in the State. Twelve hydroelectric powerplants in Maryland are producing or are licensed to produce hydroelectric energy (Weisberg, 1985, p. 1); the largest of these is on the Susquehanna River in Harford County (fig. 2*A*). During 1985, about 16,680 Mgal/d of the river's water was used at this facility to generate 1,484 gigawatthours of electricity for southeastern Pennsylvania. Although large volumes of water were diverted to produce electricity, the amount of consumptive use was negligible. Some water is evaporated during the generation process and from the reservoirs associated with hydroelectric power generation.

The source, use, and disposition of freshwater in Maryland and the District of Columbia in 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that, of the 1,320 Mgal/d of surface water withdrawn in Maryland and the District of Columbia, 53.1 percent (702 Mgal/d) was withdrawn by public-supply systems. About 32 percent of this water was exported to water suppliers in neighboring States and in the District of Columbia. Less than 1 percent of total fresh surface-water withdrawals was for commercial purposes (all self-supplied domestic withdrawals were assumed to be from ground-water sources only). Of the 771 Mgal/d of water withdrawn by public suppliers, 91.0 percent was from surface water, and 9.0 percent was from ground water. Public-supply systems delivered 92.8 percent (716 Mgal/d) of the water to domestic and commercial users and 7.2 percent (55 Mgal/d) to industries and mining operations. No public-supply water was delivered to ther-

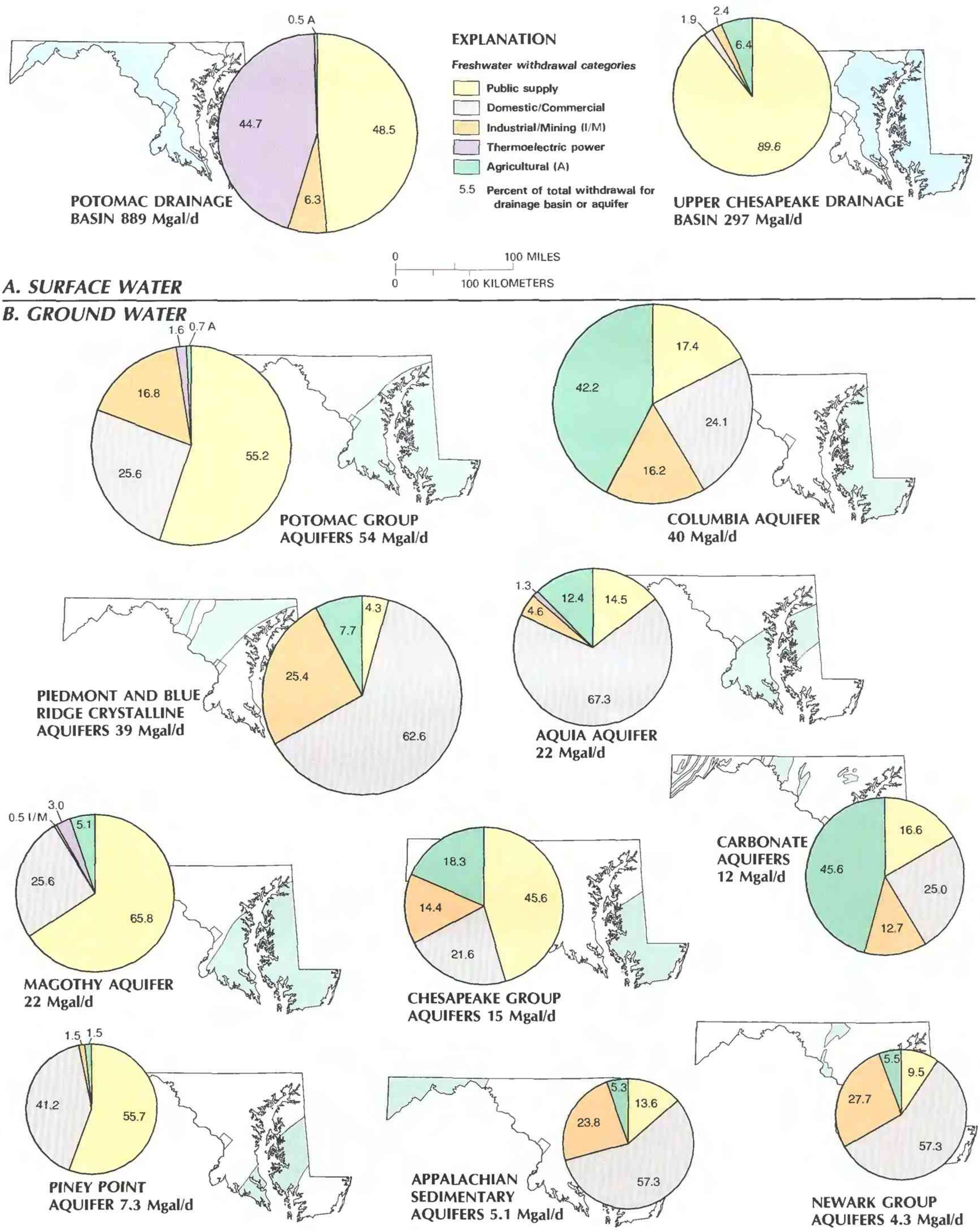


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Maryland and the District of Columbia, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data compiled from Maryland Water Resources Administration and U.S. Geological Survey files.)

moelectric powerplants. The largest withdrawals of fresh surface water by self-supplied users were for thermoelectric power generation. Other sources of water (saline surface water and reclaimed sewage wastewater) are not included in figure 4 but are discussed under the appropriate use categories.

The source data in figure 4 indicate that the 219 Mgal/d of ground water withdrawn in Maryland during 1985 was 14.2 percent of the total water withdrawals. Of the quantity, 31.9 percent was withdrawn by public-supply systems, 37.3 percent was withdrawn directly for self-supplied domestic and commercial use, 15.0 percent was withdrawn by industries and mining operations from individually owned wells, less than 1 percent was withdrawn for thermoelectric power generation, and 15.0 percent was withdrawn for agricultural activities, including irrigation.

The use data in figure 4 indicate that most freshwater used (52.2 percent, or 804 Mgal/d) was for domestic and commercial purposes, including transferred water and conveyance losses. Of this 52.2 percent, less than 1 percent was self-supplied from surface-water sources, 10.2 percent was self-supplied from ground-water sources, and 89.0 percent was delivered by public-supply systems. Agricultural activities withdrew the least amount of water—3.7 percent (57 Mgal/d) of the total withdrawals.

The disposition data indicate that 10.4 percent (157 Mgal/d) of all freshwater withdrawn during 1985 was consumed or was no longer readily available for reuse, the data also indicate that 89.6 percent (1,380 Mgal/d) was returned to natural water sources.

Thermoelectric power generation in the District of Columbia used 130 Mgal/d from the Potomac River. Water for domestic and commercial needs in the District of Columbia (218 Mgal/d) is withdrawn in Maryland and transferred to the District of Columbia by way of the Washington Aqueduct; of this water, 22 Mgal/d was consumed, and the remainder was returned.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In 1985, public water suppliers, which included municipalities, county-operated systems, and private water suppliers, furnished freshwater to nearly 3.6 million residents of Maryland (about 81 percent of the total population). Public-supply use increased from 45 percent of total freshwater withdrawals during 1980 to 55 percent during 1985. The increase in withdrawals corresponds to the population increase (from about 4.2 million in 1980 to 4.4 million in 1985) in the State, the expansion of public-supply services, and increased withdrawals by commercial and industrial facilities served by public water suppliers.

Total public-supply withdrawals during 1985 were about 771 Mgal/d, 702 Mgal/d from surface water and 70 Mgal/d from ground water (fig. 4). Most of the public-supply systems in central and western Maryland rely on surface water. The largest user of surface water for public supply is Baltimore, whose main water supply is from reservoirs on the Patapsco and Gunpowder Rivers in Baltimore County. During 1985, about 256 Mgal/d of water was withdrawn for use by the city, as well as by surrounding areas of Baltimore, Howard, Anne Arundel, and Carroll Counties. Another large user of surface water for public supply is the Washington Suburban Sanitary Commission, which withdrew 154 Mgal/d in 1985 from the Potomac and Patuxent Rivers and delivered water to most of Prince Georges and Montgomery Counties and to part of Howard County.

Several municipalities in Virginia and West Virginia withdraw water from the Potomac River in Maryland. The largest distribution system—the Washington Aqueduct—delivers water to the District of Columbia. During 1985, 218 Mgal/d of water was withdrawn from the Potomac River for public supply in the District;

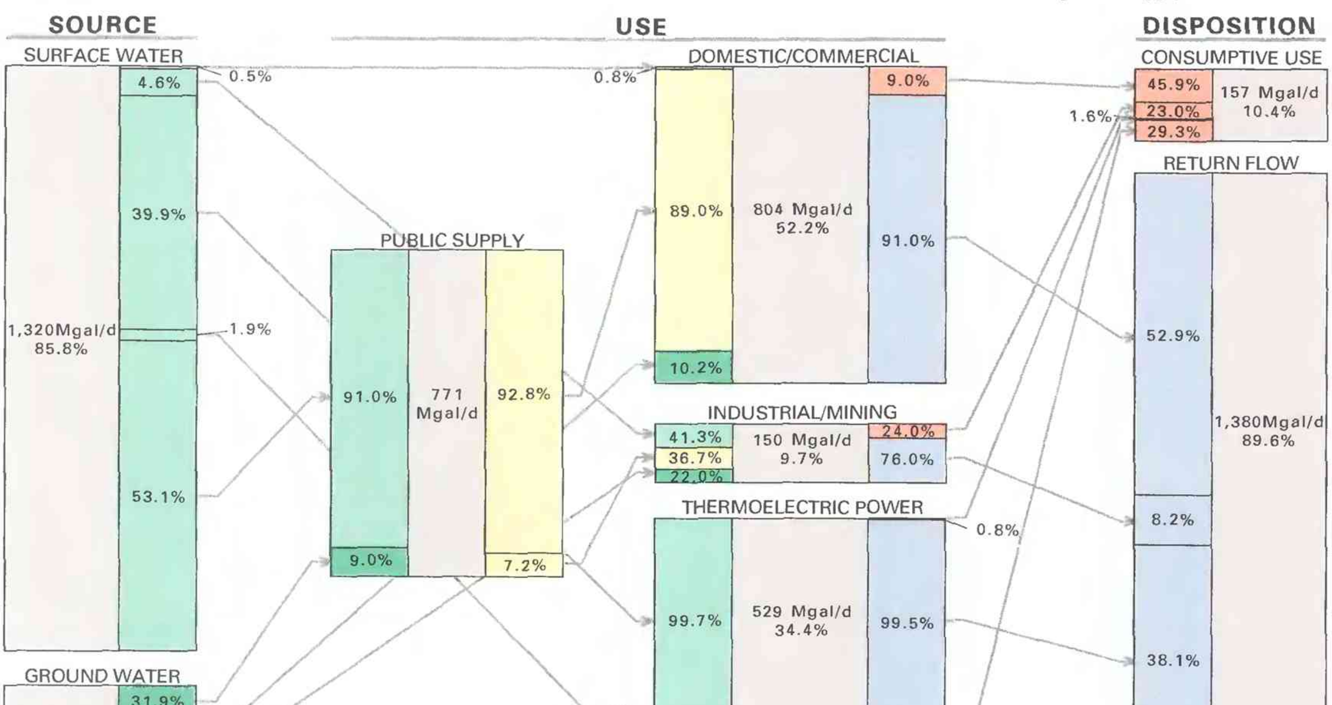


Figure 4. **Source, use, and disposition of an estimated 1,540 Mgal/d (million gallons per day) of freshwater in Maryland and the District of Columbia, 1985.** Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

this withdrawal constituted a 4-percent increase from the withdrawal in 1980.

Two municipalities in Maryland obtain all or part of their water supply from bordering States. The city of Cumberland in Allegany County receives water from Pennsylvania; Delmar, located on the stateline of Maryland and Delaware, has wells in both States that are used for public supply.

Most public water suppliers that rely on ground-water sources are east of the Fall Line; the largest withdrawals (nearly 30 Mgal/d in 1985) are in Anne Arundel County. Most of these withdrawals are centered in the northern, more densely populated area bordering Baltimore. In the counties east of Chesapeake Bay, public-supply systems rely on ground water and, with one exception, constitute the largest water use in each county.

East of the Fall Line, fresh ground water generally is available in sufficient quantity for use by public-supply systems. In some areas, however, intensive withdrawals have led to declines in water levels in the source aquifer. For example, in Charles County, the Waldorf area has evolved from a quiet, rural area (before 1960) to a rapidly developing residential area within commuting distance of the District of Columbia. Early water requirements were easily satisfied by shallow dug wells. Meeting the water demands of the growing population and commercial development required increasingly larger quantities of water than could be provided by wells in shallow aquifers. To meet these demands, the Charles County Department of Public Works drilled wells into the deeper Magothy aquifer. As the demand for water continued to increase, additional wells were drilled into the Magothy. Because of increasing concern about the capacity of the Magothy aquifer to supply sufficient quantities of water in the Waldorf area, new public-supply wells, which are screened in aquifers below the Magothy aquifer, were put into production in 1985, and use of the Magothy aquifer was decreased.

Domestic and Commercial

Domestic and commercial water users receive water from public-supply systems and from private wells. During 1985, the combined use was 804 Mgal/d in Maryland and the District of Columbia; this amount includes 294 Mgal/d of transferred water and conveyance losses. Domestic water use was about 428 Mgal/d, of which 365 Mgal/d was received from public-supply systems. About 19 percent of the population in Maryland withdrew 63 Mgal/d from individually owned wells; this amount is an increase of 22 percent over the amount withdrawn during 1980. Per capita domestic use of self-supplied water was estimated to be 75 gal/d (gallons per day). Domestic consumptive use is estimated to be 43 Mgal/d, or 10 percent of the total water used for domestic purposes during 1985.

In Maryland, commercial use, which also includes educational institutions and military installations, was about 82 Mgal/d during 1985, of which 57 Mgal/d was provided by public water-supply systems and 25 Mgal/d was self-supplied. Consumptive use of water for commercial purposes was about 8 Mgal/d. The Washington Aqueduct withdrew about 174 Mgal/d of water in Maryland during 1985 and transferred it to the District of Columbia for domestic use. In addition, 22 Mgal/d was supplied for commercial use and 22 Mgal/d went to other public uses and conveyance losses.

Industrial and Mining

Heavy and light industries are important to the economy of Maryland. Heavy industries include steel mills, shipyards, petroleum refineries, chemical plants, and truck-assembly lines. Light industries include food processing, publishing, clothing manufacturing (Di Lisio, 1983, p. 115), mining (including quarrying), and commercial fishing.

In 1985, 425 Mgal/d of water was withdrawn or delivered by public-supply systems for industries and mining, of which 150 Mgal/d was from freshwater sources and 275 Mgal/d was from saline-water sources. In addition, nearly 81 Mgal/d of reclaimed sewage water was used in the manufacture of steel. Self-supplied industrial and mining water withdrawals amounted to 371 Mgal/d, which was about 43 percent less than during 1980. This decrease may be associated with a general decline in manufacturing in the State. Most of the recent economic growth has been in the nonmanufacturing sector, including service-oriented and commercial operations (Di Lisio, 1983, p. 119). The largest self-supplied industrial uses of water are for steel production and shipbuilding. More than 270 Mgal/d of surface water and nearly 3 Mgal/d of ground water were withdrawn for these purposes. The District of Columbia does not use large quantities of water for industrial purposes.

Mineral resources mined in Maryland are used for building materials and fuels. The leading commodities are bituminous coal, stone, sand, and gravel (Di Lisio, 1983, p. 95–112). Limestone is quarried mainly in the central area of the State; sand and gravel are excavated east of the Fall Line. Bituminous coal is the most valuable mineral extracted and is produced only in Garrett and Allegany Counties. Water is used in mining operations primarily for dewatering and mineral washing. In 1985, 21 Mgal/d was withdrawn for mining use, of which 9 Mgal/d was from surface water, and 12 Mgal/d was from ground water.

Thermoelectric Power

Surface water is used in the generation of electricity in 14 thermoelectric powerplants in the State. In addition, some ground water is used in several of the plants east of the Fall Line. Thirteen powerplants use fossil fuels, and one uses nuclear power.

During 1985, these powerplants withdrew about 5,420 Mgal/d of fresh and saline water, primarily for cooling purposes; this withdrawal is a decrease of about 1,100 Mgal/d from withdrawals of 1980. The decrease in water use coincides with energy-consumption trends in Maryland and parallels nationwide patterns. Energy usage by all major consuming sectors increased steadily from 1960 to 1973, but that trend ended in the mid-1970's. Total energy consumption during 1985 (828.1 trillion British Thermal Units) was about 17 percent less than in 1973 (999.4 trillion British Thermal Units); most of the decrease was in Maryland's industrial sector (Maryland Power Plant Research Program, 1986, p. 1–8).

Of the 5,420 Mgal/d withdrawn during 1985, fossil-fuel powerplants used about 397 Mgal/d of fresh surface water and nearly 2,600 Mgal/d of saline surface water, compared to about 1.8 Mgal/d of ground water. The nuclear powerplant withdrew about 2,430 Mgal/d of saline surface water compared to 0.3 Mgal/d of ground water. Water used for cooling accounts for about 80 percent of all thermoelectric power withdrawals in Maryland. Most of this water is returned to surface-water sources; less than 10 percent is lost through evaporation.

The District of Columbia has two fossil-fuel thermoelectric powerplants. About 130 Mgal/d of fresh surface water was withdrawn during 1985 to generate electricity from these plants.

Agricultural

Farms in counties east of the Chesapeake Bay are noted for poultry, vegetable, grain, and cattle production. The largest proportion of land used for agriculture (75 percent) is in Kent County. The four counties of the lower Eastern Shore (Dorchester, Wicomico, Somerset, and Worcester) account for about 34 percent of total agricultural receipts in the State, primarily because this area is one of the Nation's leading producers of broiler chickens (Di Lisio, 1983, p. 80). Southern Maryland (west of Chesapeake Bay and south of Baltimore) is the principal tobacco-growing area in the State. Although tobacco acreage has decreased during the past few decades, partly because of expanding residential development, it remains an economically important crop. Central Maryland is an area of grain and livestock production and dairy farming. In western Maryland, farming is restricted by mountainous terrain, thin soils in some areas, and shorter growing seasons. Major agricultural activities in western Maryland include fish farming (aquaculture), fruit orchards, and some livestock production (Di Lisio, 1983, p. 65–80).

In 1985, 57 Mgal/d of water was withdrawn for agricultural activities, of which 23 Mgal/d was used primarily for livestock watering and aquaculture and 34 Mgal/d was used for irrigating crops. Of the total water withdrawn for irrigation, nearly 15 Mgal/d was supplied by surface water compared to 20 Mgal/d from ground water. Caroline County contains 28 percent of the irrigated acreage in the State and withdraws 9 Mgal/d of water for irrigation, Dorchester County, 26 percent and 5 Mgal/d; Queen Annes County, 15 percent and 5 Mgal/d; and Wicomico County, 9 percent and 3 Mgal/d. Principal irrigated crops include corn, grains, melons, soybeans, tomatoes, and tobacco. On the basis of historical trends and the sporadic nature of precipitation during the growing season, irrigated acreage is expected to continue to increase. This will further increase demand on the State's water resources.

About 10 Mgal/d of the total withdrawals during 1985 for nonirrigated agricultural use was from surface-water sources, and 13 Mgal/d was from ground-water sources. Consumptive use for all agricultural activities was 80.0 percent of withdrawal.

WATER MANAGEMENT

In Maryland, surface- and ground-water withdrawals are managed and regulated by the Maryland Department of Natural Resources (DNR). The Natural Resources Article 8, Sections 203, 801, and 802, of the Annotated Code of Maryland directs the DNR to plan and supervise the development and the conservation of the State's water resources and to regulate withdrawals of water through issuance of appropriation and use permits. Responsibility for implementing the water-appropriation law is vested in DNR's Water Resources Administration (WRA). The WRA establishes the management policy for the State's water resources by the following procedures:

- Analysis of the potential effect of individual appropriation requests on the water resource and on other users of the resource.
- Use of quantitative computer models of aquifers and subbasins to analyze the potential effect of a proposed withdrawal and to establish a level of use considered reasonable in view of an applicant's basic right to withdraw water as part of land ownership.
- Analysis of regional effects of collective water appropriation in view of an area's future water supply and demand. This analysis includes identification of water-supply problems, review of alternative methods of expanding supplies, and establishment of a program for future water-supply management and conservation. These water-use forecasts help to improve water-supply development and management in particular areas and to provide a general process of forecasting water use that may be applied to other areas in the State. Such forecasts have been published for Charles and St. Marys Counties (Maryland Water Resources Administration, 1983a,b).

Water-supply management policy and plans are implemented through the process of requiring a water appropriation and use permit for any withdrawal of surface or ground water in the State. Only self-supplied domestic uses are exempt from the appropriation permit requirements. The permit designates the average quantity of water to be withdrawn and requires biannual water-use reports for withdrawals of 10,000 gal/d or more. A water-use data system has been established and is maintained by the WRA on the basis of water-use reports submitted to the agency. The WRA also is responsible for water-conservation activities, water-supply reservoir planning and development, coordination of water-supply planning activities with neighboring States and regional basin commissions, and mitigation of consumptive water losses through structural and nonstructural techniques, such as augmentation reservoirs and improvement of pumping-plant operations.

In the District of Columbia, the following agencies are responsible for managing the water resources:

- The U.S. Army Corps of Engineers is responsible for developing and maintaining the water-supply source for the District. As part of this responsibility, plans to ensure adequate water supply for the District were initiated by the Corps of Engineers in 1942. Recent studies projected water shortages during future drought years unless actions are taken to decrease water demands, to provide new supply sources, and to improve management of existing water-supply systems (U.S. Army Corps of Engineers, 1983a, p. 1). As a result of these studies, positive actions have been initiated to ensure a dependable water supply for the District of Columbia metropolitan area for the next 50 years. These actions include completion of two dams and reservoirs (Bloomington and Seneca) and development by the Interstate Commission on the Potomac River Basin of a water use reservoir-management plan for the Potomac basin that predicts and schedules releases from various reservoirs to maximize the available water resources.
- The District of Columbia Department of Public Works, through its Water and Sewer Utility Administration, is responsible for delivering and metering water supplies to users and for repairing the distribution system.
- The District of Columbia Department of Consumer and Regulatory Affairs regulates permits for withdrawals and for disposal of wastewater, monitors water quality, and responds to chemical spills that might adversely affect water supplies.

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Prepared by J.C. Wheeler

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 208 Carroll Building, 8600 LaSalle Road, Towson, MD 21204

MASSACHUSETTS
Water Supply and Use

Freshwater is plentiful in Massachusetts. Average annual precipitation, which is 45 inches, or 17,000 Mgal/d (million gallons per day), is fairly evenly distributed across the Commonwealth and throughout the year. About 71 percent of the precipitation is returned to the atmosphere by evapotranspiration (fig. 1A), and the remainder enters the surface- or ground-water system.

Each year, about 8,000 Mgal/d of water enters Massachusetts from adjacent States as streamflow, and about 15,000 Mgal/d leaves as streamflow and as discharge into the ocean through sewers and storm drains. Ground water, which is recharged mainly by precipitation, gradually discharges to streams and the ocean; about 180 Mgal/d is withdrawn through wells. Estimated ground-water discharge to the ocean along the coast of Massachusetts totals about 500 Mgal/d.

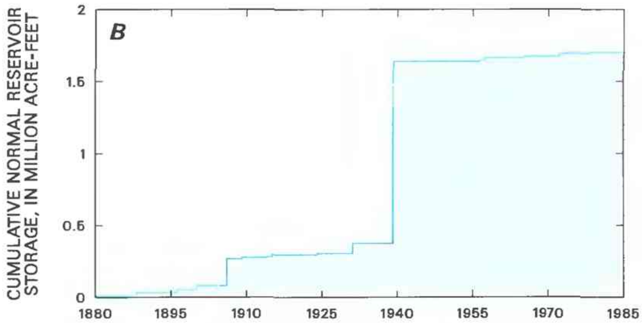
In 1985, about 6,260 Mgal/d of freshwater was withdrawn from rivers, streams, lakes, and aquifers in Massachusetts. Most was returned to the surface- or ground-water system for reuse, and the rest (316 Mgal/d; fig. 1A) was consumed. Of the total fresh surface and ground water withdrawn in 1985, 81.1 percent was withdrawn to generate thermoelectric power; most of this water (95.0 percent) was returned to surface water where it could be reused. Surface water is the main source of water for public supply, industry, and thermoelectric power in all major urban areas of the State. Surface-water supplies have been augmented by the construction of 22 reservoirs, most of which have been built since 1880 (fig. 1B). Ground water is the main source of supply for private-property owners outside of public-supply areas. It also is the main source for public-supply systems in many parts of the State where demand is less than 10 Mgal/d and where sand and gravel aquifers are locally available. On Cape Cod and the islands, ground water is the main source of supply because it is more readily available and less expensive to develop than surface water.

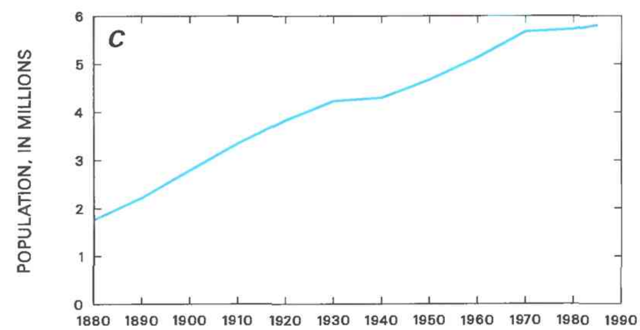
Agriculture in Massachusetts accounts for 0.3 percent of all water used. The major cash crop is cranberries, which require large amounts of water for irrigation. An estimated two-thirds of the Nation's cranberries are produced in southeastern Massachusetts.

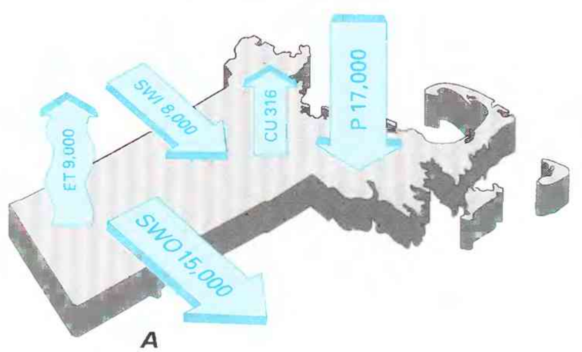
In 1970, the population of Massachusetts was almost 5.7 million (fig. 1C), and about 75 percent of the people lived in the eastern part of the State (fig. 1D). The population increased 3 percent between 1970 and 1985; most growth occurred in counties to the north and south of Boston. New sources of water are needed in communities that have experienced the largest gains in population or those that have problems related to quality of surface or ground-water supplies. Some older water-storage and water-delivery systems need improvements.

HISTORY OF WATER DEVELOPMENT

Availability of water has been important throughout the history of Massachusetts. Native Americans settled near rivers and used







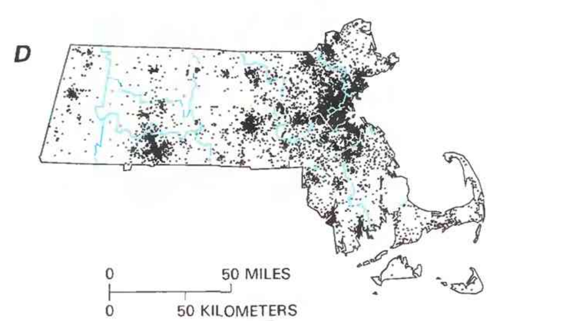


Figure 1. Water supply and population in Massachusetts. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

these waterways for transportation and access to the ocean and as a source of food. Colonists from Europe first settled near natural harbors along the Atlantic coast and, later, on the banks of navigable rivers. The first settlers found that the New England soil was poorly suited for farming and, instead, found wealth in fishing and timber harvesting. Whaling reached its peak on Nantucket Island in 1726 (Hart, 1927, v. 2, p. 386–417; v. 3, p. 526–546).

During the 18th and 19th centuries, the ample surface-water supplies and fast-moving rivers provided power to mills and hastened industrial development in the State. Shipyards were active along the coast, and many industries, such as textile, tanning, and paper, flourished along major rivers. Other industries less dependent on water, such as shoe, rubber, brick, printing, furniture, metal products, and machinery, were important to the Commonwealth's economy (Bearse, 1971, p. 78–79; Massachusetts Historical Commission, 1982a, p. 187–231; 1982b, p. 209–245; 1984, p. 236–285; 1985, p. 271–355; 1987, p. 225–306).

Boston used local springs and shallow artesian wells as sources of water in the early 17th century (Kaye, 1976, p. 14), but as Boston's urban area increased, the need was created for an improved water-supply system. In 1796, water was brought to the city from Jamaica Pond (Suffolk County) through 40 miles of wooden pipes (Kaye, 1976, p. 16). In the middle to late 1800's, the city received water from Lake Cochituate (Middlesex County) and from reservoirs on the north and south branches of the Sudbury River (Middlesex County,) about 25 miles west of Boston. In 1895, the Metropolitan Water Board began work on the Wachusett Reservoir (Worcester County), which that would increase its water-supply capacity (Metropolitan District Commission, 1983). The Metropolitan District Commission was created in 1919 to consolidate responsibility for metropolitan water supply, sewage disposal, and park management. Soon after, construction began on the Quabbin Reservoir, 65 miles west of Boston in Worcester, Franklin, and Hampshire Counties. Before it was completed in 1939, four towns had been inundated, and six town boundaries had to be relocated (Metropolitan District Commission, 1983). Management of the water-supply system for the Boston metropolitan area was transferred to the Massachusetts Water Resources Authority (MWRA) in 1986.

All cities and towns in the State outside of the Boston metropolitan area that have more than 50,000 people obtain most of their water from surface-water sources. Although some of this water comes from rivers and from natural lakes and ponds, most is supplied from reservoirs. In 1987, the State had 22 major reservoirs, 13 of which were built for water supply. The first reservoir in Massachusetts to have a capacity greater than 5,000 acre-ft (acre-feet) was built in 1845, and the last was built in 1985. The largest increase in cumulative water storage occurred in 1939, when the Quabbin Reservoir was put into operation (fig. 1*B*).

Although the greatest source of water supply in Massachusetts is surface water, especially from the Connecticut River in the western part of the State and from the Merrimack River in the northeastern part of the State, ground water is becoming increasingly important. Many cities and towns are seeking ways to increase water supplies within their boundaries and to protect the recharge areas of aquifers. In 1987, about one-third of the population used ground water from public and private sources. Ground-water withdrawals are increasing most rapidly on Cape Cod, where all towns but one use ground water and where the population has grown rapidly during the past two decades.

WATER USE

Although Massachusetts has substantial supplies of surface and ground water, the distribution of water across the State does not correspond with the demand. Urbanization of the eastern one-half of the State, where water is needed most, hinders the development of new surface-water reservoirs. Total, surface-water, and ground-water withdrawals in each county are shown in figures 2*A*, 2*B*, and 2*C*, respectively. More surface water than ground water is withdrawn in Massachusetts, except in the southeastern part and in Essex and Hampshire Counties, where withdrawals of both types of water are equal.

The greater Boston area uses about one-half of all the surface water withdrawn in the State, and most of this comes from the MWRA water system. The eastern counties of Middlesex, Suffolk, Norfolk, and Bristol generally use more surface water than do most of the central and western counties (fig. 2*B*).

Surface-water withdrawals from principal drainage basins showing percentage of use by categories are shown in figure 3*A*. Thermoelectric powerplants are major users of surface water in Massachusetts, especially in the Massachusetts-Rhode Island Coastal (7,420 Mgal/d of fresh and saline water), the Merrimack (632 Mgal/d of freshwater), and in the Connecticut River (398 Mgal/d of freshwater) basins. Surface and, to a lesser extent, ground water are important for industrial, commercial, and public supplies across the State. A relatively small amount of surface and ground water is used for agriculture (figs. 3*A*,*B*).

Instream use of water also is significant in Massachusetts and has affected the location of many of the State's industries. Instream uses include navigation, hydroelectric power generation, waste assimilation, recreation, and aquatic habitat. Currently (1988), the largest instream use of water is hydroelectric power generation, which supplies about 5 percent of the State's electricity. In 1985, 98,100 Mgal/d of water was used by hydroelectric powerplants to generate 1,990 GWh (gigawatthours) of electricity. Evaporative losses during this process are considered to be insignificant.

The source, use, and disposition of freshwater in Massachusetts during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 95.0 percent, or 5,940 Mgal/d, of the total water withdrawn in Massachusetts in 1985 was surface water. About 9.9 percent of this surface water was withdrawn by public suppliers, 2.9 percent was directly withdrawn (self-supplied) for domestic and commercial use, 1.7 percent was self-supplied for industrial and mining use, 85.3 percent was withdrawn by thermoelectric powerplants, and 0.2 percent was withdrawn for agriculture.

The use data indicate that about 15.5 percent, or 967 Mgal/d, of the State's total water use was for domestic and commercial purposes. About 71.8 percent of this water was delivered by public supplies, 17.7 percent was self-supplied from surface-water sources, and about 10.6 percent was self-supplied from ground-water sources. In the course of using this water, 19.6 percent was consumed, and 80.4 percent was returned to surface- or ground-water sources.

The disposition data indicate that 5.0 percent of the State's total withdrawals was consumed and that 95.0 percent was returned to surface- or ground-water sources for reuse. Consumptive use refers to water that has been evaporated, transpired, incorporated into products and crops, assimilated by humans or livestock, or otherwise no longer available.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. About 767 Mgal/d of water was withdrawn in 1985 by public-water systems (fig. 4). Almost one-fourth of that total, 181 Mgal/d, was ground water, and the rest was surface water.

From 1980 to 1985, statewide withdrawals of surface water for public supply decreased about 25 Mgal/d and withdrawals of ground water for public supply decreased about 13 Mgal/d, largely as the result of aggressive leak-detection and conservation programs. During the same period, withdrawals from private domestic wells

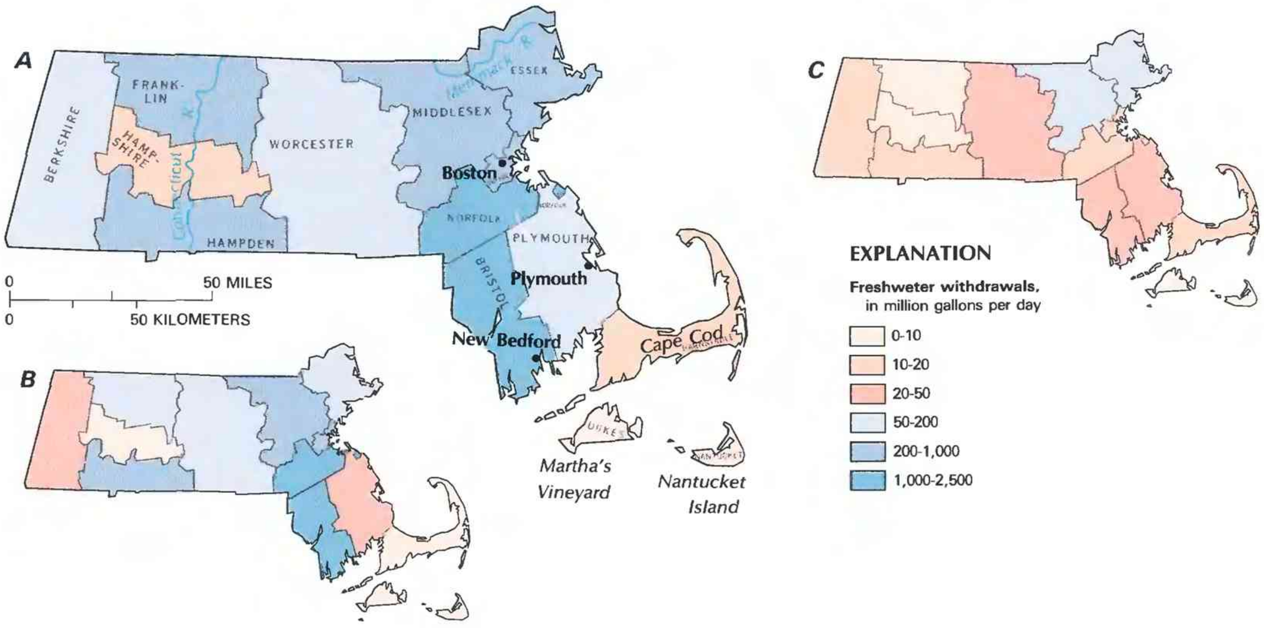


Figure 2. Freshwater withdrawals by county in Massachusetts, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

increased by 3 Mgal/d. The Merrimack basin, including the Concord and the Shawsheen River basins, in northeastern Massachusetts had the largest population increase of any part of the State—24 percent from 1980 to 1985. Withdrawals of surface water for public supply increased about 21 percent, and withdrawals of ground water for public supply decreased about 19 percent. Cape Cod, another rapidly growing area of the State, experienced a 12-percent increase in population, a 5-percent increase in withdrawals of surface water for public supply, and a 5-percent increase in withdrawals of ground water for public supply. However, the increase in ground-water withdrawals does not include the many new private wells that have been installed on Cape Cod (B.J. Rosinoff, Cape Cod Planning and Economic Development Commission, oral commun., 1987).

The proportion of ground- to surface-water withdrawals for public supplies differs across the State. The southeastern part of Massachusetts, including Plymouth, Cape Cod, and the offcoast islands, is underlain by the coastal plain aquifer, which consists of thick permeable sand and gravel deposits of glacial origin. These deposits yield water readily and are used extensively for public and agricultural supplies. In most other areas of the State, permeable sand and gravel deposits mainly along stream valleys are hydraulically connected to streams and other surface-water bodies, but the deposits are discontinuous and the underlying bedrock commonly yields only small quantities of water. Consequently, most large towns and cities use surface water for public supply.

The Quabbin Reservoir is the principal source of public supply to most cities and towns within 15 miles of Boston. This reservoir, which has a surface area of 39 square miles and a capacity of about 1,265,000 acre-ft (412 billion gallons), may be the world's largest reservoir built expressly for public water supply (Knowlton and Coogan, 1974, p. 216). However, in recent years, the quantity of water delivered to the Boston area has exceeded the supply system's rated capacity of 300 Mgal/d. The MWRA is investigating ways to augment and conserve supplies, including water conservation and leak detection, preservation and development of water sources, and greater self-reliance by communities receiving all or part of their water from the MWRA (Massachusetts Water Resources Authority, 1987, p. 8).

Domestic and Commercial

In Massachusetts, water used in households (domestic use) and in commercial enterprises, such as hospitals, hotels, and computer firms, is obtained from both public and private water-supply systems. In 1985, these uses totaled about 967 Mgal/d (fig. 4).

Public systems provided about 92 percent of the 450 Mgal/d of water for domestic use. Although most water used domestically was returned after treatment to rivers and streams or to the ground through septic systems, about 17 percent was consumed. Water delivered from public systems for domestic purposes is used at an average rate of 78 gal/d (gallons per day) per capita (Solley and others, 1988).

Commercial uses were about 514 Mgal/d, about one-half of which was provided by public systems. About 22 percent of the total was consumed use.

Industrial and Mining

In 1985, about 200 Mgal/d of freshwater (fig. 4) and about 22 Mgal/d of saline water were withdrawn for industry. Withdrawals that were self-supplied totaled 26 Mgal/d of ground water, 103 Mgal/d of fresh surface water, and 22 Mgal/d of saline surface water. Public water systems delivered about 69 Mgal/d. About 20 percent of the total quantity of water (fresh and saline) used by industry (44 Mgal/d) was consumed.

The quantity of water used by industry in Massachusetts in 1985 was only about one-fourth of that used in 1970 (Murray and Reeves, 1972, p. 24; Solley and others, 1988). Between 1970 and 1985, manufacturing industries such as textile, shoe, paper, and shipbuilding declined in size, while the number of service, computer, electronics, and research industries, which generally use less water, increased. Part of the industrial decline was due to the high cost of treating process water from paper and other industries (Anthony Maevsky, U.S. Geological Survey, written commun., 1987).

Mining operations withdrew about 2.0 Mgal/d of ground water in 1985 and are not reported to have used any surface water. Although most mining in Massachusetts today is for sand and gravel, in past centuries clay, building stones [especially granite, sandstone (brownstone), and slate], and bog iron were important commodities (Massachusetts Historical Commission, 1982a, p. 207–209; 1982b, p. 218–220; 1984, p. 248–250; 1985, p. 338–339; 1987, p. 303–304).

Thermoelectric Power

In Massachusetts, almost all withdrawals of saline surface water and 85.3 percent of the self-supplied fresh surface-water withdrawals are used to cool condensers in thermoelectric plants. The State has 44 thermoelectric powerplants; 42 use fossil fuel, and 2 use nuclear fuel. In 1985, these plants used about 8,450 Mgal/d of fresh and saline water for cooling and generated about 35,800 GWh of electricity (Solley and others, 1988). Fossil-fueled plants withdrew 4,880 Mgal/d of fresh and 2,890 Mgal/d of saline surface water. Nuclear plants withdrew 191 Mgal/d of fresh and 487 Mgal/d of saline surface water. The powerplants received a comparatively small amount of water (4.2 Mgal/d) from public systems.

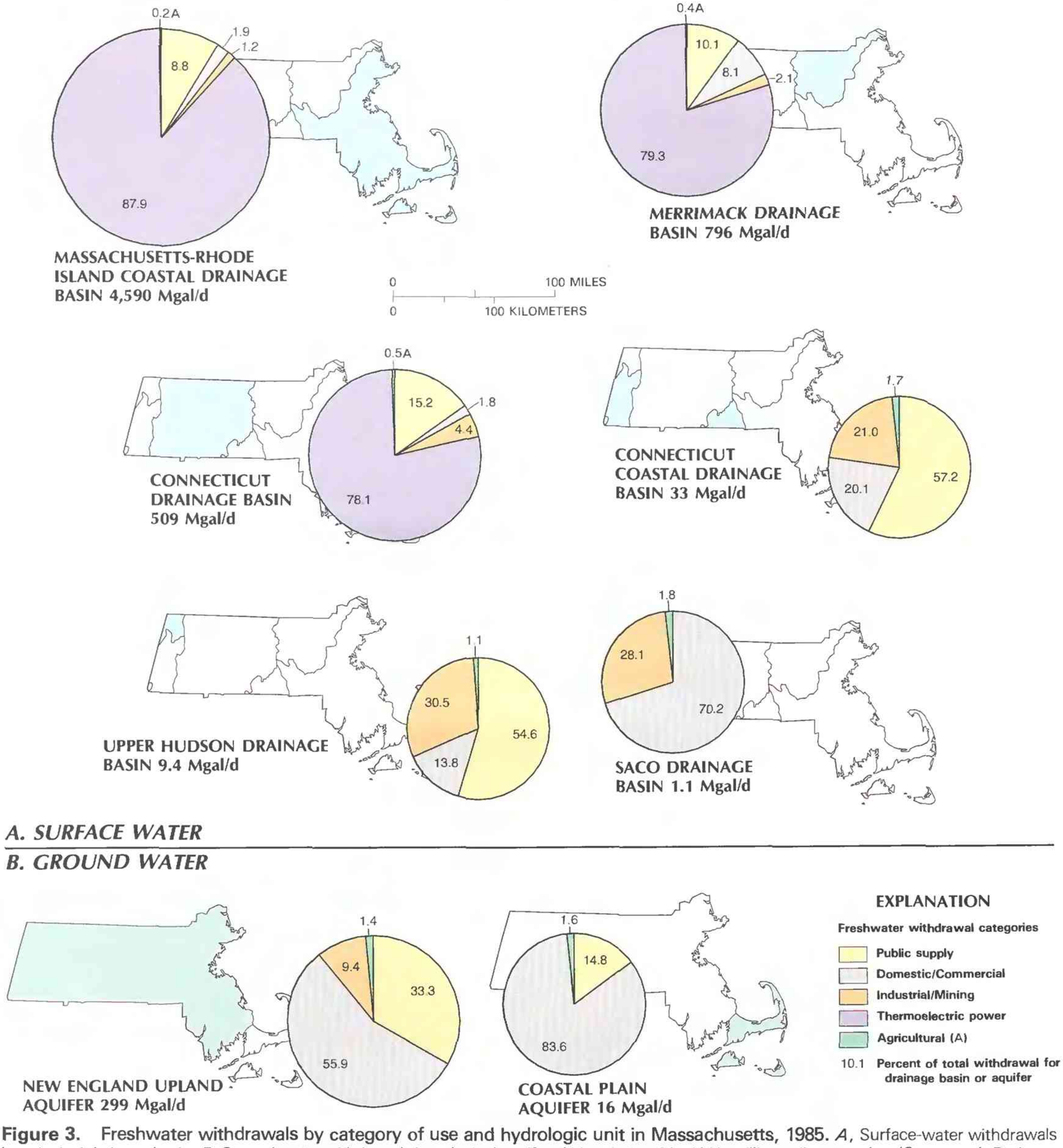


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Massachusetts, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Aquifer map from U.S. Geological Survey, 1985, p. 251.)

AGRICULTURAL

Agriculture in Massachusetts withdrew three times more surface water than ground water and accounted for 0.3 percent of all water during 1985 (fig. 4). Most water withdrawn for agricultural purposes is used to irrigate crops and golf courses. All irrigation is done by spraying, except in southeastern Massachusetts where about 1,800 acres of cranberries are flooded annually. In 1985, about 16 Mgal/d of water was withdrawn for irrigation, and 1.3 Mgal/d was withdrawn for other agricultural purposes, such as feeding livestock. Most water used in agriculture is considered to be consumed, although some undoubtedly recharges the ground-water system.

From 1970 to 1985, withdrawals of water in Massachusetts for irrigation decreased almost fourfold, from 58 to 16.3 gal/d, and withdrawals of water for other agricultural uses decreased from 2.1 to 1.3 Mgal/d (Murray and Reeves, 1972, p. 22; Solley and others, 1988). These decreases mainly reflect the decline of tobacco as an important crop and the loss of farmland to commercial, industrial, and residential development.

WATER MANAGEMENT

In Massachusetts, cities and towns have the primary responsibility to regulate land use and to manage water resources, whether or not the water resources are within their boundaries. However, communities must follow guidelines specified in State laws.

Policies pertaining to water-resources planning and management are made primarily by the Massachusetts Water Resources Commission (MWRC) within the Executive Office of Environmental Affairs (MEOEA) and by MWRA. The MWRC also sets criteria and priorities for cooperative programs between Federal and State governmental agencies that relate to water issues. The MWRC includes representatives from five departments in MEOEA and from the Executive Office of Communities and Development, as well as six representatives of the public. Most of the water-resources planning and management functions are divided between two MEOEA departments—the Department of Environmental Management (MDEM) and the Department of Environmental Quality Engineering (MDEQE).

Water-resources responsibilities of the MDEM are met by the Division of Water Resources. These responsibilities include data collection and analysis, flood control, and water-resources planning and development. The Division also licenses well drillers and maintains files of well-completion reports. The Division has cooperative programs with the U.S. Geological Survey and other Federal agencies to collect data on water resources (for example, streamflows, water levels, water chemistry, water use) and to assess ground-water resources. As part of this effort, the U.S. Geological Survey maintains a network of 72 continuous streamflow-gaging stations in cooperation with various State and Federal agencies.

The MDEQE has several divisions that are responsible for water quality—Water Supply, Water Pollution Control, Environmental Monitoring, Hazardous Waste, Solid Waste, and Wetlands and Waterways Regulation. They are described briefly as follows:

• The Division of Water Supply issues well permits for public supplies, collects information on ground-water quality, and allocates funds to communities for water treatment and for acquisition of land to protect aquifers.

• The Division of Water Pollution Control is responsible for improving water quality and preventing water pollution. This function is partly accomplished by the issuance of surface-water and ground-water discharge permits. The Division also administers the

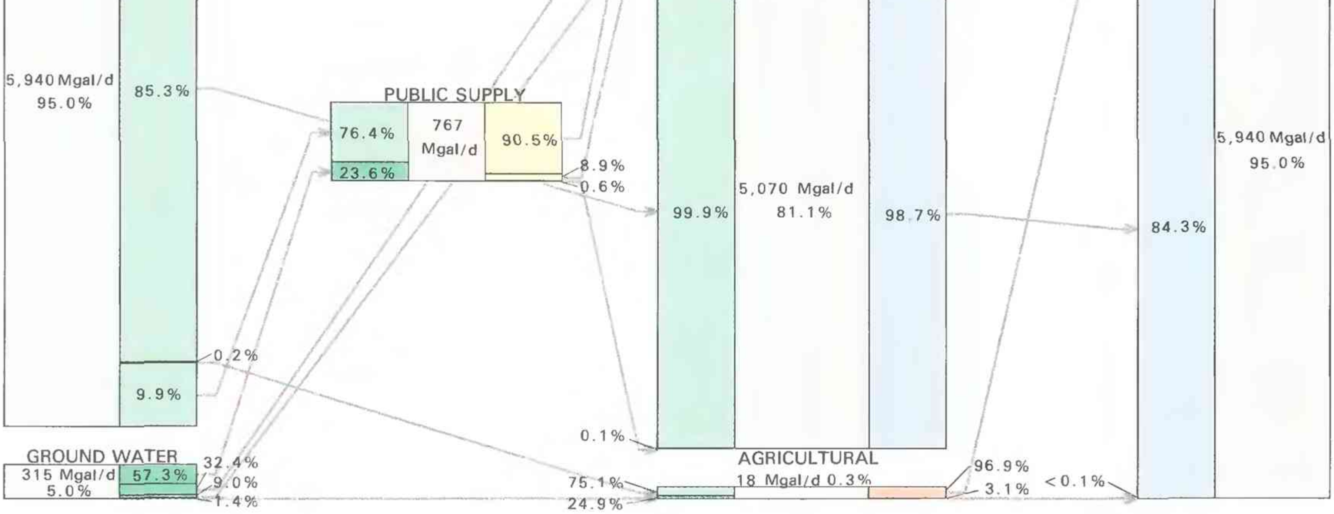


Figure 4. Source, use, and disposition of an estimated 6,260 Mgal/d (million gallons per day) of freshwater in Massachusetts, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

MDEQE's water-resources inventory and water-quality research programs in cooperation with universities and the U.S. Geological Survey.

• The Division of Environmental Monitoring is the analytical laboratory for the MDEQE. It regularly collects and analyzes samples of raw and treated public drinking water and is responsible for the analysis of samples of ground water that may be contaminated.

• The Division of Hazardous Waste responds to spills and other emergencies involving oil and hazardous materials, investigates illegal disposal activities, and supervises the cleanup of hazardous waste sites. It also approves programs to monitor ground-water movement and quality, supervises hydrogeologic studies, and evaluates proposals to clean contaminated water.

• The Division of Solid Waste is responsible for overseeing the operation of landfills and other solid-waste facilities and for ensuring that environmental safeguards are used to protect surface water and ground water from leachate contamination. The division also helps communities to develop long-term solid-waste-disposal plans.

• The Division of Wetlands and Waterways Regulation works with local conservation commissions to administer the Wetlands Protection Act, which regulates activities in or near wetlands.

Several recent State and Federal acts affect the management of water resources of Massachusetts. In 1983, the Massachusetts State legislature passed the Interbasin Transfer Act (Chapter 658) authorizing the MWRC to approve or disapprove any significant transfer of surface or ground water, including wastewater, outside of a river basin. Before an interbasin transfer is approved, the MWRC assures that all reasonable efforts have been made to identify and develop water sources in the receiving area of a transfer, that all practical measures have been taken to conserve water in the receiving area, and that reasonable streamflows will be maintained in the river from which water is diverted. In addition, environmental studies are required.

In 1985, the Massachusetts Legislature passed the Water Management Act (Chapter 21G). That Act requires registration and permitting of all water withdrawals greater than 100,000 gal/d and gives the MDEQE additional authority to respond to water emergencies.

At the Federal level, the U.S. Congress passed several amendments to the Federal Safe Drinking Water Act in June 1986. These require the U.S. Environmental Protection Agency to develop drinking-water standards for 83 contaminants and to define treatment techniques for each of these and others whose contaminant levels are less well known. Other provisions include mandatory filtration of most surface water, disinfection of all drinking water, and the development of State programs for wellhead protection and demonstration projects for sole-source aquifers. Massachusetts is actively developing plans to protect areas around wells that supply public drinking water, as required by the wellhead-protection program. The sole-source-aquifer program is designed to protect critical aquifer areas from degradation. In Massachusetts, the aquifer on Cape Cod and the islands of Nantucket and Martha's Vineyard have been designated as sole-source aquifers.

Several amendments to the Federal Water Pollution Control Act that were passed by Congress in January 1987 pertain to the management of water resources in Massachusetts. Among other provisions, the Act includes grant programs to help States control sources of pollution to lakes and to restore their quality, to control pollution from nonpoint sources to navigable water, and to control the discharge of pollutants in municipal and industrial discharges. Buzzard's Bay, which lies between Cape Cod and New Bedford, is listed among estuaries that will be given priority consideration in a new protection program. In addition, the Act grants funds to the MWRA to study the environmental quality of Boston Harbor, to develop a program to improve the quality of its water, to build a new wastewater treatment plant for areas served by the MWRA, and to improve the existing wastewater facility on Deer Island in Boston Harbor.

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Prepared by Alison C. Simcox, Gene W. Parker, and Monica J. Webster

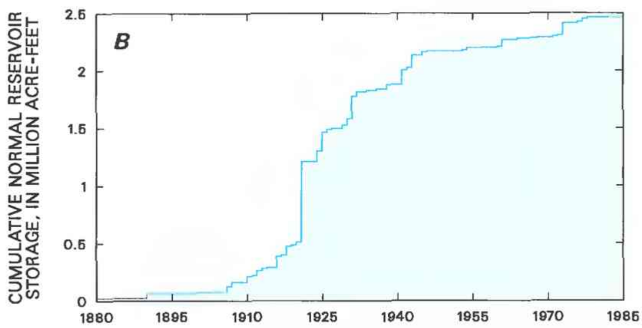
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 10 Causeway Street, Boston, MA 02114–1384

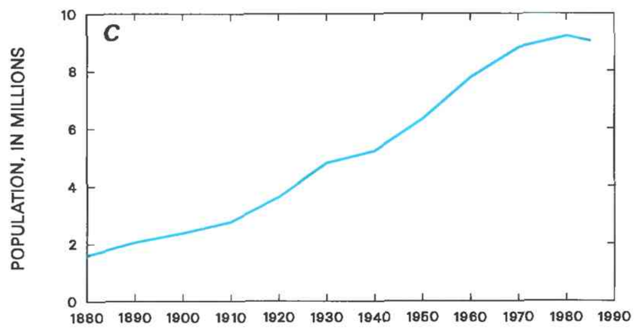
MICHIGAN
Water Supply and Use

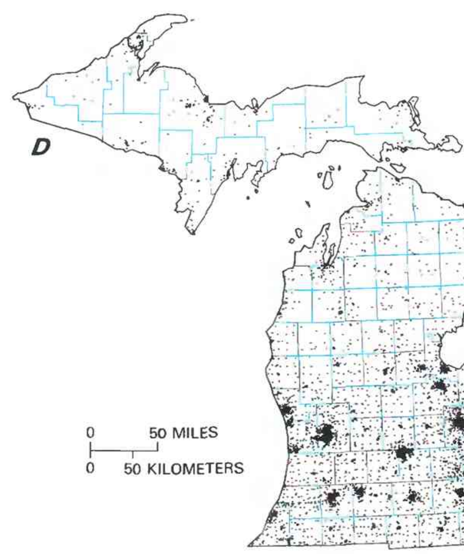
Michigan, the "Great Lakes" State, has often been called a "Water Wonderland" because of its 3,251 miles of Great Lakes shoreline, 36,350 miles of inland streams, and more than 35,000 mapped lakes and ponds. The four Great Lakes bordering Michigan (Superior, Michigan, Huron, and Erie) contain 5,080 cubic miles of water and are the State's greatest freshwater resource. Michigan is ranked 35th among the States in annual precipitation (Miller and others, 1963), with an average annual precipitation of 32 inches, or 86,000 Mgal/d (million gallons per day) (fig. 1*A*). About 26 percent of this precipitation infiltrates into the State's aquifers (N.G. Grannemann, U.S. Geological Survey, oral commun., 1987). Surface-water inflows total 3,200 Mgal/d compared to surface-water outflows of 36,500 Mgal/d, mainly in the St. Joseph River, which crosses and recrosses the Michigan–Indiana State line, and in streams tributary to the Great Lakes. Flow of ground water directly to the Great Lakes is estimated to be 20,200 Mgal/d. In 1985, 11,400 Mgal/d of freshwater was withdrawn from Michigan's lakes, rivers, streams, and aquifers; this amounted to 1,270 gal/d (gallons per day) per capita (Solley and others, 1988).

In 1985, self-supplied water withdrawals and public supply deliveries for domestic, commercial, industrial, and mining uses totaled 2,790 Mgal/d. Of total ground- and surface-water withdrawals, 73.5 percent (8,390 Mgal/d) was for thermoelectric power generation, which accounted for 18.3 percent of all consumptive water use. Agriculture, including irrigation, accounted for 2.1 percent of all withdrawals and 39.3 percent of total consumptive use.

The southeastern one-quarter of the State, which is an urban and industrial region, relies primarily on surface water. This area is adjacent to extremely large surface-water resources that can accommodate future increases in water use. The southern and central parts of the State are primarily agricultural areas and depend on ground- and surface-water resources. Two principal aquifers—the Marshall and the Saginaw—provide water for this region. Wells completed in these aquifers are capable of producing from 100 to 1,000 gal/min (gallons per minute). The northern and central parts







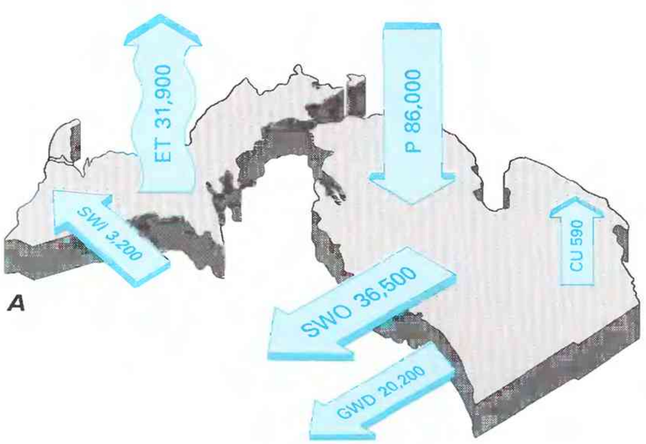


Figure 1. **Water supply and population in Michigan.** *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **GWD,** ground-water discharge to the Great Lakes; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Nurnberger, 1982. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

of the Lower Peninsula are rural and agricultural regions that rely on water from glacial aquifers. These aquifers yield from 1 to 2,000 gal/min to properly constructed wells. Small-yield wells completed in bedrock are the primary source of water in the rural Upper Peninsula. Although water supplies from freshwater sources are abundant, supplies are not always available in sufficient quantities throughout this area.

From 1980 to 1985, the population decreased from 9.26 to 9.06 million. However, State officials have estimated that Michigan's population will increase by about 25,000 per year through the year 2000 (Michigan Department of Management and Budget, 1985). This projected population increase, primarily in the large metropolitan centers of southeastern Michigan, along with accompanying economic development, undoubtedly will increase the demand for water.

HISTORY OF WATER DEVELOPMENT

The history of Michigan has been dependent on the location and availability of its water resources. In the late 1600's, Jolliet and others explored Michigan's lakes and rivers for a water route to China. Although a route was not found, these explorations identified the bounty of Michigan's resources.

The first settlements were located at strategic points between the Great Lakes. Three important early settlements were Sault Ste. Marie (Chippewa County), St. Ignace (Mackinec County), and Detroit. Whoever controlled these settlements also controlled navigation in the narrow waterways between the Great Lakes. This was especially true at Sault Ste. Marie, which is between Lake Superior and Lake Huron, where travel required portage around the falls on the St. Marys River.

In the early 1800's, timber from the northern one-half of the Lower Peninsula was harvested and floated downstream to lumbermills along Lakes Michigan and Huron. From these mills, wood products were transported to markets along the Great Lakes. However, this economic boom was minor, compared to that started by copper mining in the Upper Peninsula in the 1840's.

As copper and iron mines were developed along the southern shore of Lake Superior, construction of a canal around the falls between Lakes Superior and Huron was imperative. Construction of the Soo Canal in 1855 (Sommers, 1977) permitted economic transport of these ores to mills along the lower Great Lakes. In the 1880's and 1890's, Michigan was the Nation's leading producer of timber, copper, and iron ore. During the 1950's and 1960's, the tonnage passing through the Soo Canal was among the greatest of any canal in the world.

In 1867, Michigan's first storage reservoir of greater than 5,000 acre-ft (acre-feet) was constructed for lumber milling near Traverse City (Grand Traverse County). Fifty years later, normal reservoir storage had increased fiftyfold and, by 1921, had more than doubled again. In 1985, total reservoir storage at 87 sites was nearly 2.5 million acre-ft (fig. 1*B*). These reservoirs have multiple uses, such as power generation, recreation, fish propagation, and irrigation.

In the early 1900's, Detroit became the center of the Nation's automobile industry. One of the factors that allowed this industry to flourish was the availability of large quantities of freshwater for manufacturing processes and for transportation of goods and materials. In 1985, the automobile and related industries were still the largest users of self-supplied water in the Detroit area (Macomb, Oakland, and Wayne Counties).

The population of Michigan increased steadily from the early 1900's to about 1970 (fig. 1*C*). From 1970 to 1980, the population increase slowed, and, from 1980 to 1985, population decreased 2.1 percent.

Since the 1960's, the economy of Michigan has focused on growing and processing agricultural products. Agriculture is an important consumer of water. In the eastern "Thumb" area of Michigan (Huron, Sanilac, and Tuscola Counties), sugar is processed from the irrigated sugar-beet fields. Along the Kalamazoo River, as elsewhere in the State, the pulp and paper industry processes many of the State's various tree species. Along the eastern shore of Lake Michigan, orchards and vineyards are significant land uses, and associated processing plants are among the leading employers.

Easy access to shallow glacial aquifers and deeper bedrock aquifers encouraged industrial and municipal development in the central part of Michigan. Development of ground-water supplies was rapid in the cities of Lansing, Jackson, Battle Creek, Kalamazoo, and Cadillac. In recent years, some wells in these cities have been abandoned because of contamination. However, supplies have continued to be developed, and ground-water withdrawals have increased by 66 Mgal/d since 1980.

WATER USE

The State has substantial supplies of water. Because of the four Great Lakes that border it, Michigan has access to nearly 20 percent of all the fresh surface water in the world. The water budget (fig. 1*A*) gives an overview of the amounts of water that move into and out of the State.

Water withdrawals have distinct patterns. Withdrawal of water in the Detroit metropolitan area reflects not only population density (fig. 1*D*), but also considerable power generation and auto manufacturing (figs. 2*A*,*B*). Large volumes of water are withdrawn in Marquette County for ore processing. Withdrawals in south-central Michigan (Kalamazoo and Ingham Counties) and in southwestern Michigan (Muskegon, Kent, and Berrien Counties) are dominated by manufacturing and nuclear power generation, respectively. Irrigation in southwestern Michigan and the "Thumb" is a significant demand on the State's water supply. The distribution of surface- and ground-water withdrawals (figs. 2*B*,*C*) reflects the availability of freshwater throughout the State and the predominance of surface-water use. In parts of the State—for example, in the Saginaw River valley (Southwestern Lake Huron–Lake Huron basin) from Saginaw to Bay City—deteriorating ground-water quality has caused a shift toward surface water as a source of supply.

The St. Clair–Detroit and the Northeastern Lake Michigan–Lake Michigan basins support the largest withdrawals in the State (fig. 3*A*). The St. Clair–Detroit basin supplies water to large industries and to 50 percent of the State's population. The Northeastern Lake Michigan–Lake Michigan basin supplies water for power generation. In central and northern Michigan, ground-water withdrawals dominate water uses other than power generation, yet these uses are less than 5 percent of total water use in the State. The Saginaw Formation is the principal aquifer for the city of Lansing, and the Marshall Formation is the principal aquifer for the city of Battle Creek (fig. 3*B*). Other cities, like Kalamazoo and Cadillac, depend on the glacial aquifer for their water supplies. Each of these principal aquifers—Saginaw Formation, Marshall Formation, and glacial—produces more water than all other aquifers combined.

The source, use, and disposition of freshwater are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data in figure 4 indicate that the 10,800 Mgal/d of surface water withdrawn is 94.8 percent of the total ground- and surface-water withdrawals in Michigan. Of that quantity, 0.2 percent is directly withdrawn (self-supplied) for domestic and commercial use, 11.6 percent is self-supplied by industrial and mining facilities, 77.5 percent is withdrawn for thermoelectric power generation, 1.2 percent is withdrawn by agriculture, and 9.5 percent is withdrawn by public-supply systems. Other withdrawals of water (saline water and reclaimed sewage wastewater) are not included in figure 4 but are discussed below under the appropriate categories. The use data indicate, for example, that domestic and commercial use totaled 1,160 Mgal/d, which represented 10.2 percent of the State's total withdrawals. Of that 1,160 Mgal/d, 86.4 percent was delivered by public-supply systems, 2.3 percent was self-supplied from surface-water sources, and 11.3 percent was self-supplied from ground-water sources. The disposition data indicate that, of all water withdrawn, 5.2 percent (590 Mgal/d) was consumed, or no longer readily available for reuse, and 94.8 percent (10,800 Mgal/d) was returned to a surface-water source where the water became available for downstream use.

Michigan has significant instream (nonwithdrawal) uses of water, the largest of which are navigation and recreation. The four Great Lakes bordering the State, as well as their connecting channels, are used extensively for commercial shipping. These lakes and the abundant inland lakes provide attractive opportunities for recreational boating, water skiing, swimming, and fishing. Although navigation and recreation are important uses of water statewide, the amount of water used for these purposes is difficult to estimate.

The largest instream use of water for which estimates are available is hydroelectric power generation. In 1985, more than 600 GWh (gigawatthours) of electricity was generated by 13,400 Mgal/d of surface water. That electricity production represented a decrease of 79 percent since 1980 and was less than 1 percent of the electricity used in the State. This decrease has resulted from lessened efficiency of aging hydroelectric facilities and cheaper oil prices. Consumptive use of water from this process is negligible. Because water use for hydropower is an instream use, it is not shown in figure 4.

Public Supply

Public-supply systems in Michigan withdraw water, treat it, and distribute it to users (fig. 4). In 1985, the State was 27th in public-

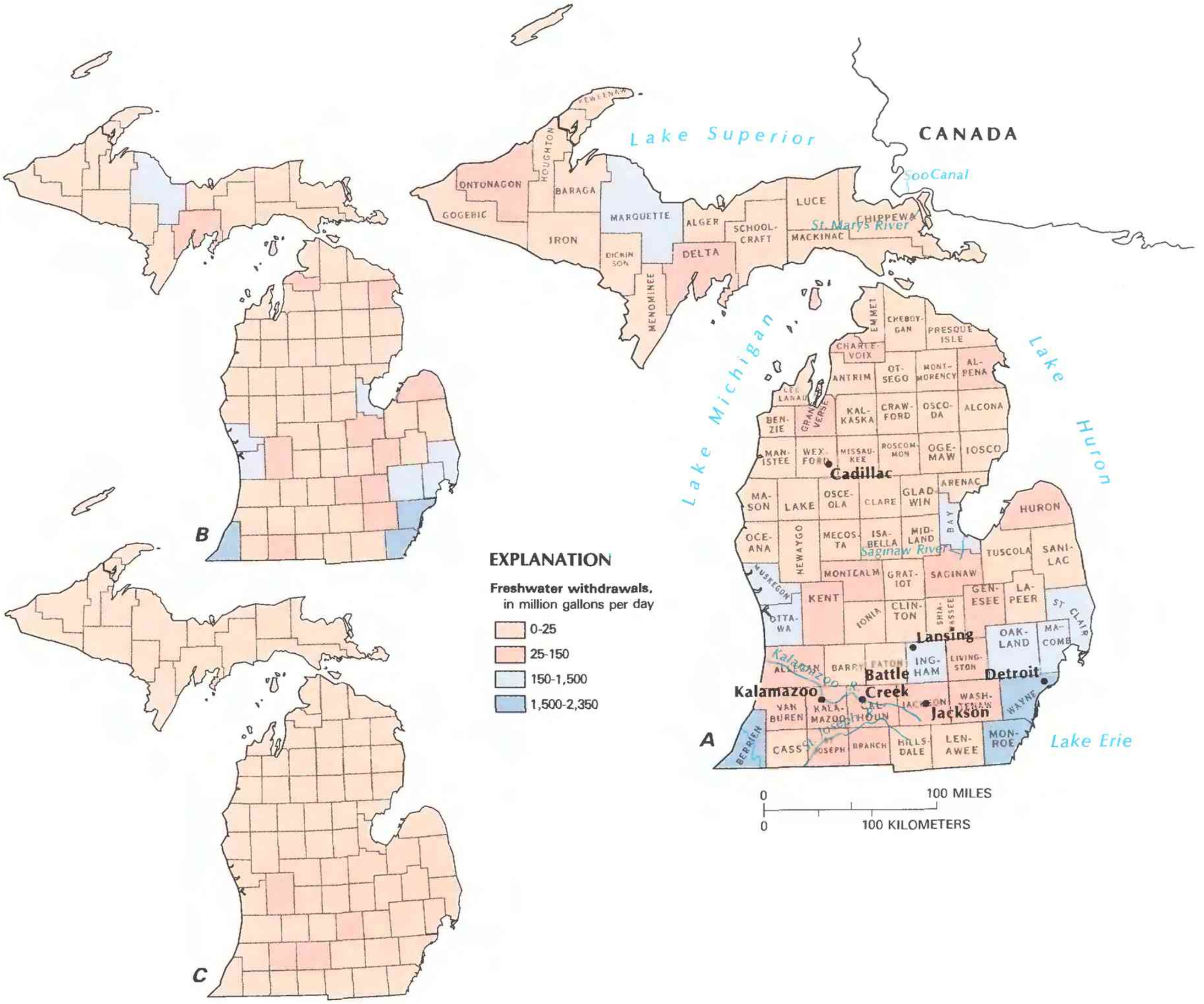


Figure 2. Freshwater withdrawals by county in Michigan, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

supply withdrawal, although it was 8th in population in the United States. From 1980 to 1985, public-supply deliveries of water decreased almost 4 percent—from 1,300 to 1,250 Mgal/d. This decrease reflects a population decrease of 2 percent during this period; however, the population that used public-water supplies increased by 780,000 during this same period. This apparent disparity is explained by water-conservation efforts, loss of industry that is supplied by public systems, and smaller per capita use. Many cities now offer to supply water to and treat discharge from new industrial and commercial facilities to encourage development within city limits.

Total withdrawals by public supply in 1985 were 1,250 Mgal/d, of which almost 82.2 percent (1,030 Mgal/d) was surface water and 17.8 percent (222 Mgal/d) was ground water. The distribution of

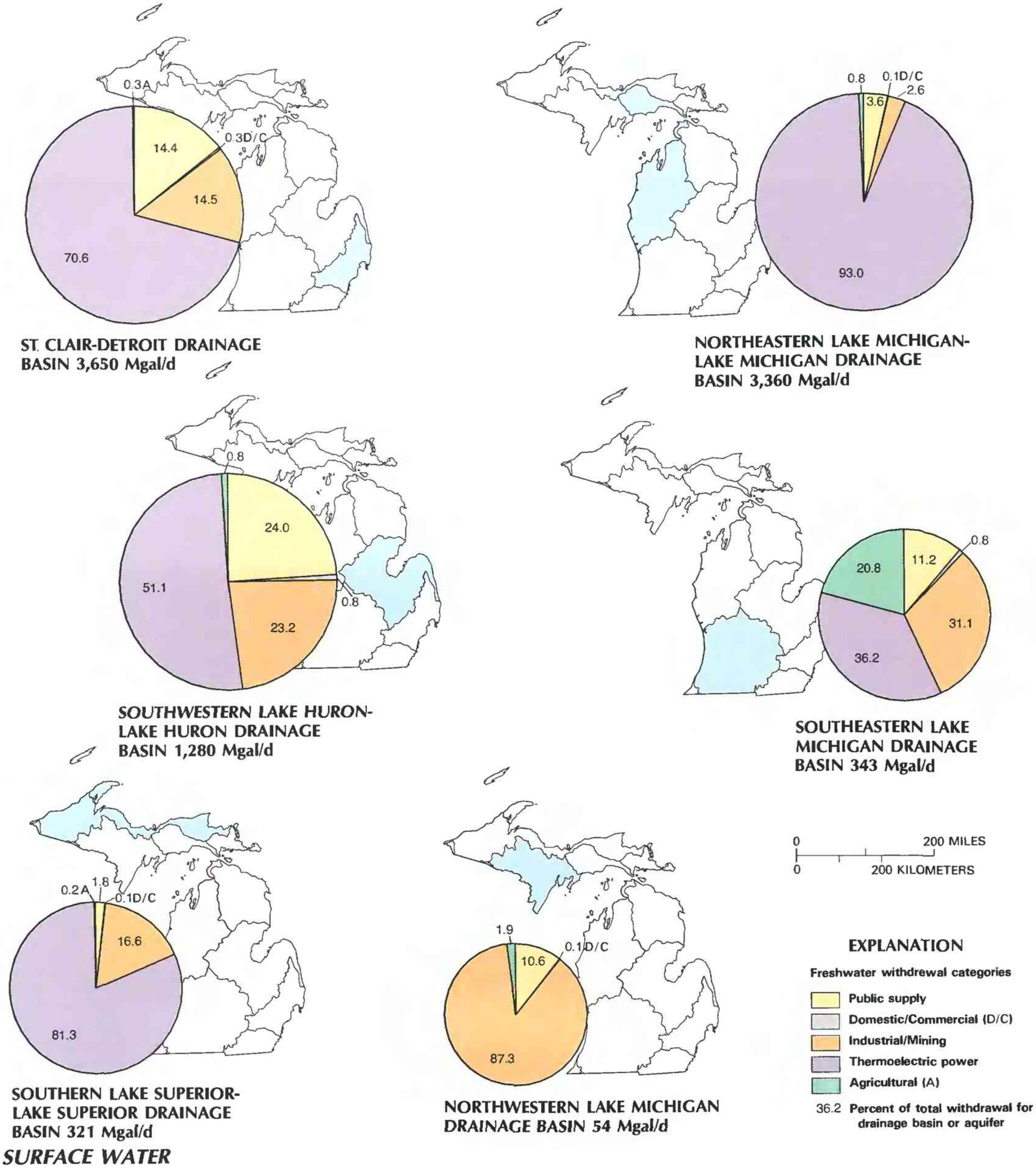


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Michigan, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from Bedell, 1982, p. 19–43.)

surface- and ground-water use differs across the State. The southeastern area is underlain by thick layers of clay and shale and includes some of the least productive aquifers in the State (fig. 3*B*). Nearly all the withdrawals for public supply are from surface-water sources in this part of the State. In contrast, most of the northern and central areas of the State are underlain by glacial deposits and sandstones, which locally yield large quantities of water and regionally provide dependable quantities of water for public supply. The eastern Upper Peninsula contains sedimentary rocks overlain by glacial deposits. The western Upper Peninsula is underlain mostly by igneous and metamorphic rocks and small areas of sandstone. In some parts, glacial deposits are good aquifers, but, in much of the area, they are thin and discontinuous. Well yields differ throughout the Upper Peninsula. However, ground water provides nearly 37 percent of the public supply in the Upper Peninsula and provides 17 percent in the Lower Peninsula (fig. 3*B*).

Metropolitan Detroit has many water-distribution agencies, including public-water suppliers that withdraw, treat, and sell water, and others that buy this treated water and resell it through distribution systems that span six counties. The potential for deterioration of water quality in the southeastern part of the State has encouraged the interconnection of public-supply systems. Public suppliers that have access to the more dependable sources of water—for example, the Great Lakes connecting channels—are able to expand their water-

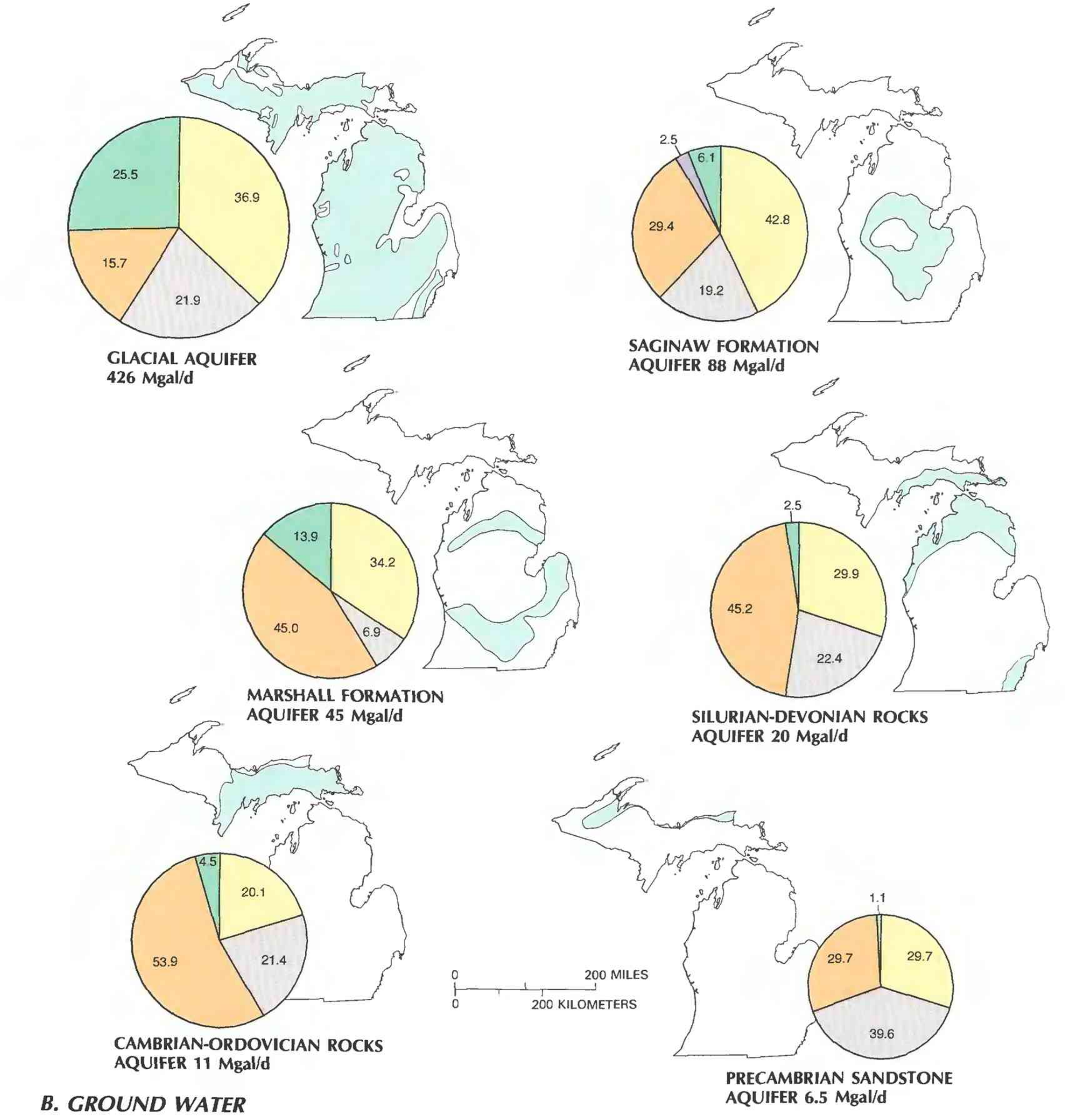


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Michigan, 1985—Continued.

treatment plants and to sell water to other public suppliers whose water sources are insufficient. The interconnection of water systems is advantageous during droughts when small streams and reservoirs are depleted (Fulcher and others, 1986).

DOMESTIC AND COMMERCIAL

Domestic and commercial water users obtain water from public-supply systems and from self-supplied facilities. Combined total use in 1985 was 1,160 Mgal/d (fig. 4). Domestic use in 1985 was nearly 789 Mgal/d. About 666 Mgal/d was from public-supply systems, which served 82 percent of the population, and 123 Mgal/d was from self-supplied systems (wells and springs), which served the remaining 18 percent of the population. Domestic consumptive use was 98 Mgal/d. A 1978 survey of public-supply facilities (Bedell, 1982) showed that an average of 75 gal/d was used by people who purchase water from a public-supply system. Other studies for the Michigan Department of Public Health have determined that per capita use from self-supplied sources is about the same.

Commercial use in 1985 was 373 Mgal/d, of which 34 Mgal/d was provided by self-supplied systems and 339 Mgal/d was provided by public-supply systems. Consumptive use was 25 Mgal/d. Although relatively small compared to domestic use, commercial use has increased 15 percent since 1980, compared to a growth rate of 6 percent in domestic use.

INDUSTRIAL AND MINING

In 1985, freshwater used for industrial and mining purposes amounted to 1,630 Mgal/d (fig. 4). In addition, 4.5 Mgal/d of saline ground water was used. Self-supplied systems provided more than 8 Mgal/d of ground water and 52 Mgal/d of surface water for mining activities. These systems also provided 121 Mgal/d of fresh ground water, 1,200 Mgal/d of fresh surface water, and 3.7 Mgal/d of saline ground water for industrial uses. Public-supply systems provided 247 Mgal/d for industry. Consumptive use for all industries was 7.7 percent (126 Mgal/d).

Nonmining industrial water use is dominated by the auto and steel industries; Michigan is one of the leading auto-producing States in the Nation. Nonmining industrial water use is by far the largest industrial user of water in the State—96 percent of all water used for industrial and mining purposes. Most of the saline ground-water withdrawals (3.7 Mgal/d for nonmining industrial use) are for the production of bromides, which has been dramatically curtailed during the past 5 years. The remaining saline-water withdrawals (0.8 Mgal/d for mining use) are the byproduct of oil and gas production and are used for dust control on unpaved rural roads. Intermittent drought conditions have encouraged many water-intensive industries to increase their efforts at water reuse and conservation. Any decrease in industrial water use also can be attributed, in part, to a decrease in production because of economic conditions.

THERMOELECTRIC POWER

Water withdrawn for thermoelectric power generation dominates Michigan's total water use. The State has 91 thermoelectric powerplants, of which 88 use fossil fuel and 3 use nuclear fuel. In 1985, these plants withdrew 8,390 Mgal/d for cooling purposes

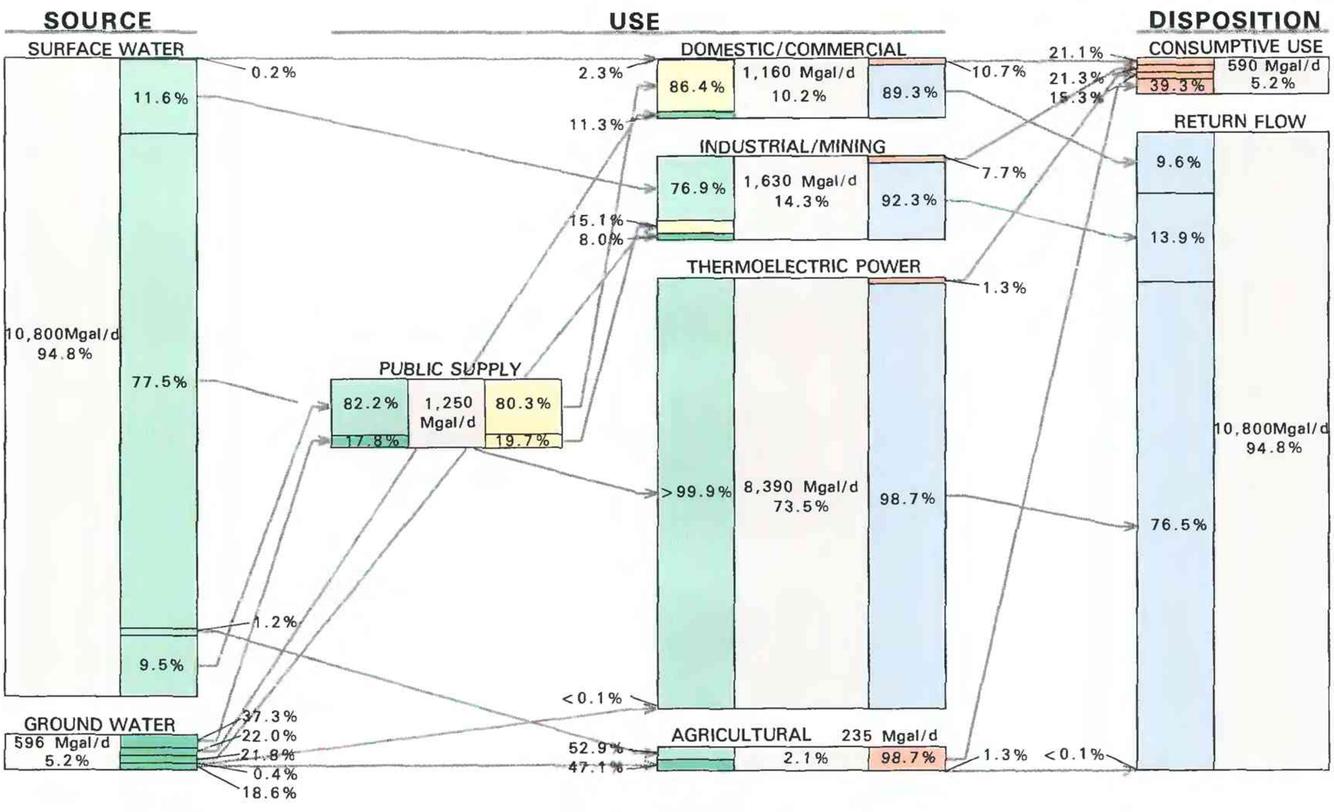


Figure 4. Source, use, and disposition of an estimated 11,400 Mgal/d (million gallons per day) of freshwater in Michigan, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbols: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

(fig. 4). Of this volume, fossil-fuel plants withdrew more than 6,220 Mgal/d of surface water and 2.3 Mgal/d of ground water to generate almost 73,800 GWh of electricity. Nuclear plants withdrew 2,170 Mgal/d of surface water to generate about 16,400 GWh of electricity. Ground water is used principally to replenish water lost from "closed" cooling systems and for human use. Withdrawal of water for thermoelectric powerplants accounts for 73.5 percent of all freshwater withdrawals in Michigan. Of total water withdrawn for this purpose, 98.7 percent of the water is returned to Michigan's streams, and 1.3 percent of the water is consumed or is lost through evaporation. Newer powerplants have more efficient cooling towers that increase the percentage of water evaporated.

AGRICULTURAL

Withdrawals for agriculture in Michigan in 1985 were dominated by irrigation (210 Mgal/d); nonirrigation withdrawals totaled 25 Mgal/d; total agricultural use was 235 Mgal/d (fig. 4). Irrigation water use in Michigan remained comparatively constant from 1970 to 1985. Most of the State's irrigation is in the southern counties, where wells completed in glacial aquifers typically yield from 500 to 2,000 gal/min. Productive soils and availability of water have produced a thriving agricultural industry in this area.

Center-pivot irrigation, which initially was developed in the Midwest, is the predominant method of sprinkler irrigation. During the late 1970's and early 1980's, corn surpassed other crops as the leading irrigated crop in the State. The rapid increase in the volume of water used for irrigation in Michigan during the 1960's through the early 1980's was promoted by several factors: improved crop yields, new agricultural practices, and improved irrigation technology suited to the specific crops grown in Michigan, which are mainly navy beans and orchard crops.

The use of reclaimed sewage wastewater for irrigation decreased by more than one-third, or 9.5 Mgal/d, from 1980 to 1985. In the mid-1970's, technology was developed that allowed the application of treated liquid wastes to fertilize crops. Initial rates of application were excessive and damaging to crops, and this, coupled with instability in crop prices and market conditions, led to a decrease in the application of reclaimed sewage wastewater for irrigation purposes. Until crop prices stabilize or begin to rise, the future of irrigation using such wastewater in Michigan will remain doubtful. Reclaimed sewage wastewater is not shown in figure 4.

WATER MANAGEMENT

Legal aspects of water use in Michigan are guided by the riparian doctrine; therefore, limited administrative procedures govern water rights. The Michigan Department of Natural Resources has primary responsibility for water-resources management; additional water-related programs are under the control of the State's Departments of Agriculture, Commerce, Public Health, and Transportation. A number of boards and commissions also formulate water-resources policies, set State standards, and oversee water-management efforts in the State.

Surface- and ground-water withdrawals are not regulated by the State; however, several statutes regulate water-related activities. These statutes include the Michigan Environmental Protection Act, the Water Resources Commission Act, the Flood Control Act, the Inland Lakes and Streams Act, the Shorelands Protection and Management Act, and the Wetland Protection Act. Together, these statutes provide a basis for protecting and managing water and related land resources in the State.

With the exception of water for public supply, water-use reporting is not mandatory in Michigan. Water-use data are collected statewide through voluntary surveys administered in 5- to 10-year intervals through ongoing State regulatory programs and by the U.S. Bureau of the Census. These data are compiled as part of the U.S. Geological Survey-State cooperative Water-Use Information Program. Data-collection efforts are focused primarily on the four major water-use categories of public supply, industry, thermoelectric power generation, and irrigation.

Two important initiatives relating to water use and water-resources management in Michigan are the Great Lakes Charter and the Great Lakes and Water Resources Planning Commission. The Great Lakes Charter was adopted in 1985 by eight Great Lakes States and two Canadian Provinces to strengthen regional water-management efforts. The Charter calls for the development of a regional water-use data-management system to document significant water withdrawals and diversions from the Great Lakes. Various actions are recommended to improve water management throughout the Great Lakes system.

The Great Lakes and Water Resources Planning Commission (1987c) has prepared Michigan's first State water-management plan. The plan includes recommendations for new legislation requiring mandatory water-use reporting for industry, power generation, and agriculture. In addition, a nonmandatory process is recommended for management of water resources in critical watersheds in the State, including regulation of minimum instream flows to protect instream water uses while providing water for lawful water withdrawals. This plan was adopted formally in September 1987.

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Prepared by M.J. Sweat, U.S. Geological Survey; Water Management section by R.L. Van Til, Great Lakes and Water Resources Planning Commission, Michigan Department of Natural Resources

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 6520 Mercantile Way, Suite 5, Lansing, MI 48911

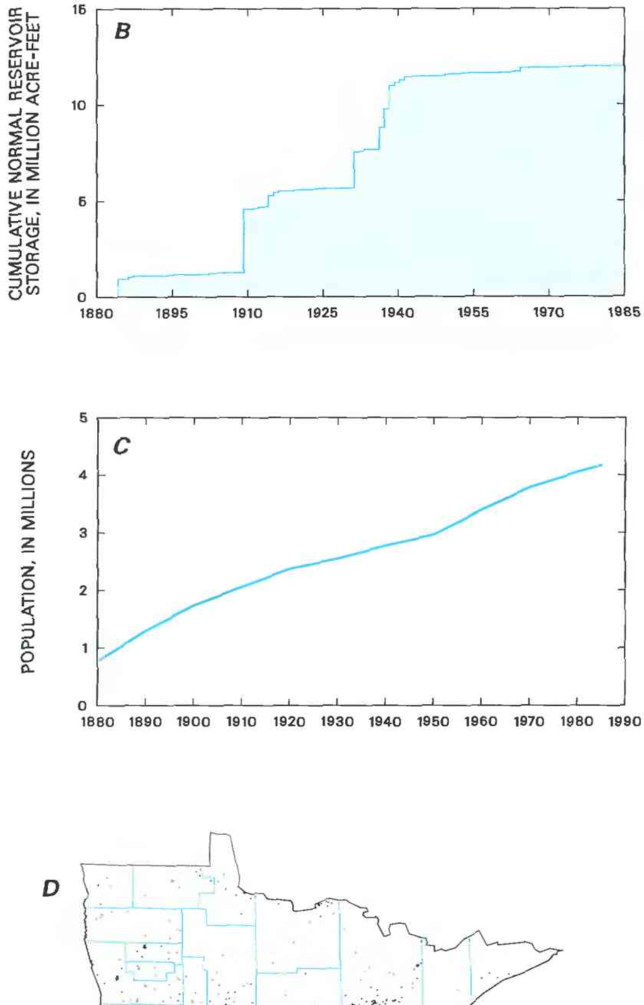
MINNESOTA
Water Supply and Use

Minnesota, "The Land of 10,000 Lakes," has abundant freshwater resources. Drained by the Red River of the North, the northwestern part of the State provides water that eventually enters or drains into the Arctic Ocean, whereas the northeastern part provides water for the Atlantic Ocean by way of the Great Lakes and the St. Lawrence River. Most of Minnesota, however, is drained by the Mississippi River, which begins in the State's north-central region and flows to the Gulf of Mexico (Hess, 1987). Minnesota receives an annual average precipitation of about 26 inches (Gibson and Seymour, 1987), which is equivalent to 104,000 Mgal/d (million gallons per day) statewide (fig. 1*A*). Of that precipitation, about 15 percent infiltrates into the State's aquifers (M.E. Schoenberg, U.S. Geological Survey, written commun., 1987).

In 1985, about 2,840 Mgal/d of freshwater was withdrawn from Minnesota's rivers, streams, and aquifers; of that amount, 768 Mgal/d was consumed, and 2,070 Mgal/d was returned to a natural water source. The northeastern one-half of the State, which is dominated by forestry, tourism, paper production, and mining, relies primarily on surface water because ground-water resources are limited. In contrast, the southwestern one-half of the State, which is primarily an agricultural area, depends mainly on ground water. Self-supplied withdrawals and public-supply deliveries for domestic, commercial, industrial, and mining uses amounted to about 1,090 Mgal/d in 1985. Thermoelectric power generation accounted for 52 percent (1,480 Mgal/d) of total surface- and ground-water withdrawals and 18.2 percent (140 Mgal/d) of all consumptive water use in the State. Irrigation accounted for 19.0 percent (131 Mgal/d) of all water withdrawn and 24.7 percent (190 Mgal/d) of all consumptive use.

HISTORY OF WATER DEVELOPMENT

Rivers and lakes were the original pathways into the former wilderness now called Minnesota. The American Indians first traced



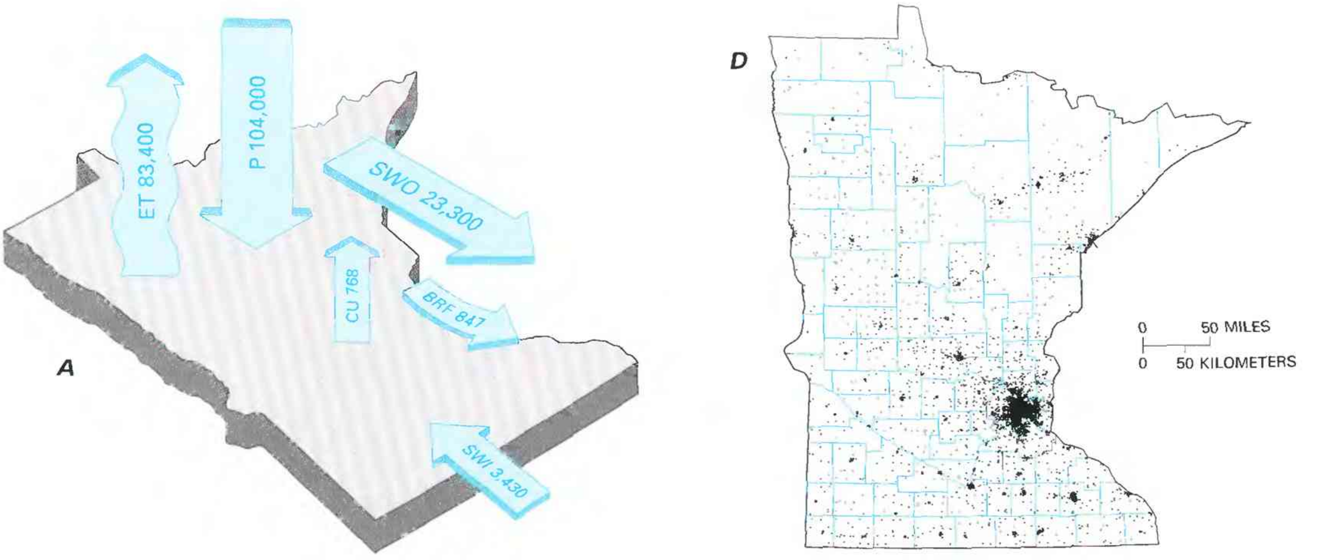


Figure 1. Water supply and population in Minnesota. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, L.C. Trotta and K.T. Gunard, U.S. Geological Survey, written commun., 1987. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

the routes, wearing smooth the portages between water bodies. During the 1670's, French explorers and the voyageurs, robust men employed by the fur companies to transport goods and men by canoe, traveled many of these same routes. The first steamboat, "The Virginia," reached Fort Snelling (Hennepin County) in 1823 (Szarkowski, 1958, p. 29). During the 1830's, steamboats began to replace the paddlers, and, within a few decades, the free-spirited voyageurs vanished. With the dawning of the age of the railroad, river navigation was all but forgotten. However, with Federal subsidies, traffic on the Mississippi River increased again. Today, barges carry large tonnages of coal, oil, and grains up and down the river (Szarkowski, 1958, p. 39).

Minnesota commonly has been a leader in harnessing the power of its rivers for various purposes. The first waterpower-driven sawmills were constructed in 1839; these mills marked the birth of the State's lumber-processing industry (Larson, 1979). In 1848, Franklin Steel built a dam at the site of St. Anthony Falls (Hennepin County), which is the only major waterfall on the Mississippi, to power a sawmill (Northern States Power Company, 1984, p. 14). By 1850, 153 sawmills were operating statewide. In 1905, the number of sawmills peaked at more than 300, but, by 1940, the major pine forests were gone (Szarkowski, 1958, p. 75). At first, flour mills also were driven by waterpower. In 1821, the first such mill was constructed at St. Anthony Falls by soldiers from Fort Snelling, and, by 1860, there were 85 mills in Minnesota (Larson, 1979). However, advancing technology brought an end to the era of waterpower-driven mills.

In 1882, the Minnesota Brush Electric Company first used turbines to change the direct mechanical energy of falling water at St. Anthony Falls into electrical energy. In 1885, when the direct-current electric motor began to be used to convert electrical power back to mechanical power, hydroelectric power replaced waterpower for sawmills and flour mills. Mills then could be built wherever electrical wires could be strung. By 1915, many of the almost 500 flour mills in the State were driven by hydroelectric power; Minneapolis was known as the world's milling center (Larson, 1979).

Hydroelectric-power plants increased in number so that, by the 1920's, they generated one-third of the Nation's electricity. Their number continued to increase through the 1930's but leveled off until the 1960's, when cheaper fossil-fueled plants started to replace them.

Early commerce and the resultant commercial water use depended on transportation, and the coming of the railroads signaled the beginning of modern water development in Minnesota. The increase in railroad construction after the Civil War made St. Paul the transportation center of the upper Midwest and the gateway to the Northwest. In 1888, 150 trains arrived and departed every day from St. Paul's Union Depot (Kunz, 1987, p. 3). Ice was cut from the river in winter to cool produce shipped by rail in the summer. The locomotives themselves used substantial amounts of ground water until 1955, when they converted from steam to diesel power. Minnesota-founded commercial giants like Sears (1886), Greyhound (1915), Gamble's (1920), Northwest Airlines (1926), and Super Valu (1926) used ground water as the coolant for air conditioning (Larson, 1979). The air-conditioning surge that began in 1935 in the Twin Cities (Speer and others, 1940, p. 32) outstripped heavy industry as a user of ground water by 1976 (Horn, 1983, p. 15).

By 1890, so many settlers had arrived that most of the former wilderness was deeded (Polley, 1978, p. 179). By the turn of the century, more Norwegians lived in Minnesota than in Norway (Szarkowski, 1958, p. 76). By this time, thousands of wells had been drilled to supply the State's growing rural population. The next great increase in domestic use began about 1940 with the advent of modern water-using appliances.

Duluth, in northeastern Minnesota, developed a public water supply in 1869, withdrawing about 6,000 gal/d (gallons per day) from Lake Superior. Public supplies continued to be developed along rivers, lakes, railroads, and highways. A water supply was one of the first public utilities developed by municipalities because of the need for a fire-protection system to keep insurance rates reasonable. In 1906, after repeated epidemics of typhoid fever, the Minnesota State Board of Health condemned many surface-water supplies and recommended use of ground water as an alternative source (Woodward, 1985, p. 15–16). Withdrawals increased from about 40 Mgal/d in 1905 (Hall and others, 1911, p. 123) to about 145 Mgal/d in 1950 (MacKichan, 1951), still mostly from surface-water sources. However, because subsequent population growth was outside the established surface-water supply areas (Horn, 1983, p. 12), ground-water withdrawals (229 Mgal/d) became predominant over surface-water withdrawals (210 Mgal/d) in 1980.

The first industrial use of water in Minnesota was for the production of paints by Native Americans (Martin, 1932, p. 105; Winchell, 1888, p. 398). Heavy industry got a late start in Minnesota, compared to the Northeastern States, but grew quickly. By 1880, Minnesota manufacturers employed 20,000 workers; 75 years later, the number was more than 10 times as great (Szarkowski, 1958, p. 237). Industrial water use at the turn of the century was mainly in processing of agricultural products; use of water by this industry increased until the 1950's and has declined only slightly since (Young and Woods, 1987). In the mid-1960's, wood products, farm machinery, and skilled industries reached a peak of water use. Since then, decreases in use have resulted mainly from improved efficiency of use, increased recycling to meet discharge-quality standards, and a regional decline in some industries that used large amounts of water. Most of the decreases have been in the use of surface water (Gersmehl and others, 1986, p. 12).

In Minnesota, the use of water in mining has been important since iron-ore mining started in the 1880's. Minnesota once possessed the world's largest concentration of high-grade iron ore. Following the depletion of the high-grade ore, new methods were developed to mine low-grade ore (taconite). As a result, Minnesota still accounts for more than one-half of the Nation's iron-ore production (Hess, 1987). Large quantities of water were pumped in 1985 for dewatering the iron mines and the many sand and gravel pits throughout the State.

Large-scale agricultural use of water began in Minnesota in the mid-1800's when the settlers began to clear the land for farms. In the early 1900's, more powerful tractors allowed farmers to plant and harvest more crops. Until grasshoppers descended on the prairies in 1873 and forced diversification, wheat was preeminent among Minnesota crops (Szarkowski, 1958, p. 233–235). From 1920 to 1970, there was a shift toward more livestock and livestock products (Borchert and Yeager, 1969, p. 76–77); as a result, water use was increased in every county.

Records indicate that irrigation began in Minnesota in the early 1920's. Expansion of irrigation systems was curtailed during World War II, but resumed when materials were again available for the construction of new wells (Allred, 1976, p. 5). In 1961, the State issued permits for a total of 5,902 million gallons (mostly surface water) to be applied to about 20,000 acres (Minnesota Conservation Department, 1962, p. 11). Irrigation expanded gradually until the middle 1970's, when a combination of severe drought, expensive grain prices, and tax incentives prompted many farmers to obtain irrigation permits for on-farm wells (Gersmehl and others, 1986, p. 16). As a result, withdrawals for irrigation doubled from 1975 to 1977 in some parts of the State (Lindholm, 1980, p. 2).

In 1909 and from 1931 to 1937, total reservoir storage capacity in Minnesota was greatly increased (fig. *1B*). Total storage capacity has been relatively constant since about 1940.

From 1980 to 1985, the population of Minnesota increased about 3 percent, from 4.06 million to 4.19 million (fig. *1C*). About one-half of the people (fig. *1D*) live in the seven-county metropolitan area surrounding Minneapolis and St. Paul (Twin Cities), which is the largest metropolitan area in the upper Midwest (Hess, 1987).

WATER USE

Minnesota has abundant supplies of water. The proportions of water that flow to and from the State are shown by the water budget (fig. 1*A*). About 12 percent of Minnesota's surface-water outflow is to Lake Superior.

The distribution of total, surface-water and ground-water withdrawals differs across the State (fig. 2). Large surface-water withdrawals in the Minneapolis–St. Paul area (fig. 2*B*) reflect the density of population and industry, whereas withdrawals in northeastern Minnesota (St. Louis and Itasca Counties) reflect the predominance of large iron-ore mining and ore-processing industries. Although smaller in comparison, forest product industries in northern Minnesota and chemical and food-processing industries in southern Minnesota also use significant quantities of surface water. Water withdrawals for irrigation from wells completed in sandy, unconsolidated aquifers across the State constitute a significant demand on the State's water supply (fig. 2*C*).

The largest surface-water withdrawals are in the Western Lake Superior and Mississippi Headwaters basins (fig. 3*A*) but for different reasons. The Western Lake Superior basin supports an iron mining and shipping trade, whereas the Mississippi Headwaters basin supports a sizable population and a large concentration of industry and thermoelectric powerplants. Ground water is withdrawn throughout the State; most ground water is withdrawn for public supply (fig. 3*B*).

Instream water use historically has been large because the availability of waterpower has affected the placement of many of Minnesota's industries. Because 99 percent of Minnesota waterways are used for fishing and swimming (Peissig, 1986, p. 807), the largest instream use of water is for fish habitat and recreation. This use nearly equals total streamflow (fig. 1*A*). In 1985, the second largest instream use of water was for hydroelectric power generation, which supplied 3 percent of the State's electricity. In recent years, electric power companies have renovated several old hydroelectric facilities

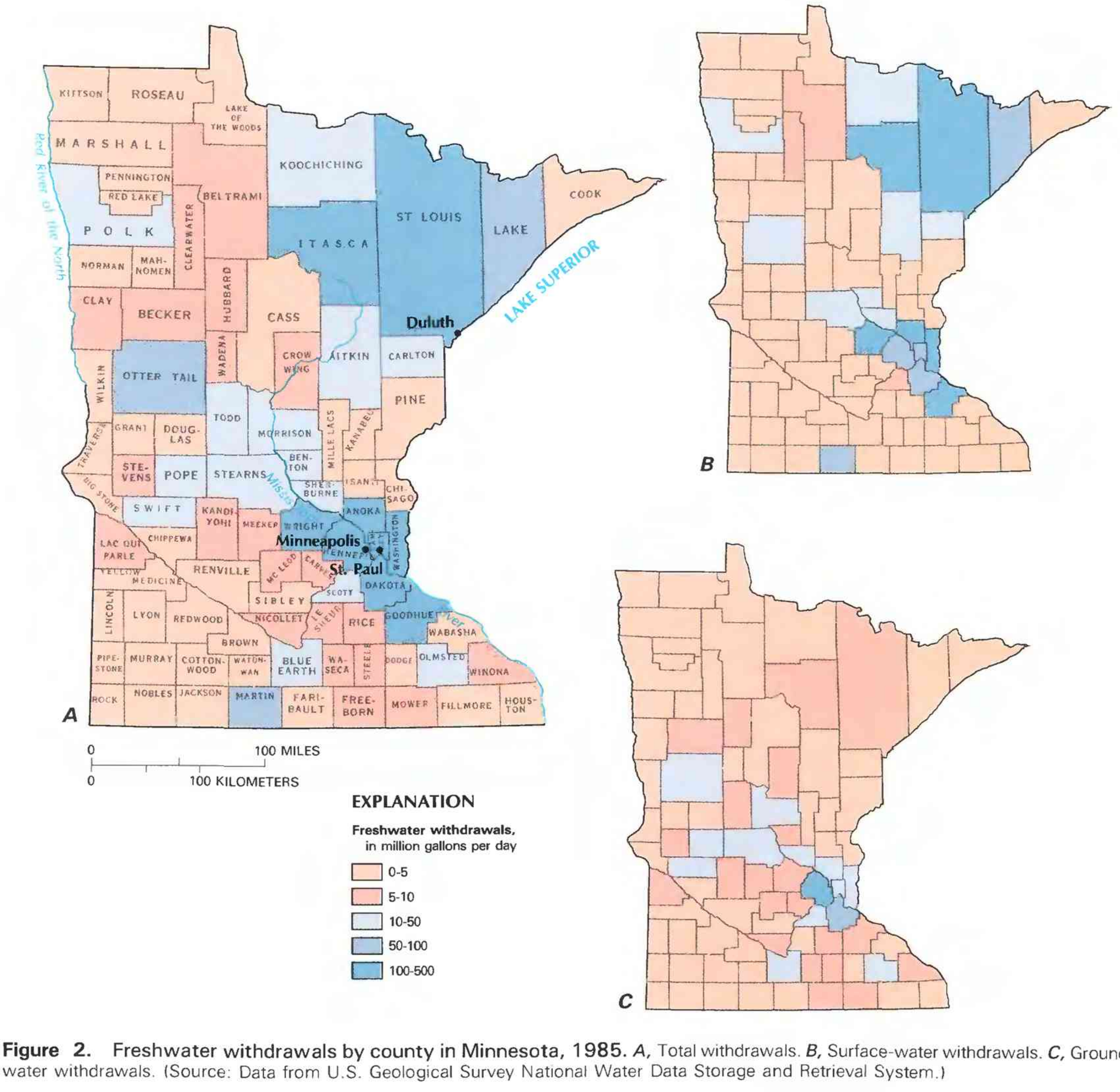


Figure 2. Freshwater withdrawals by county in Minnesota, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

(Beaupre, 1983). In 1985, about 22,700 Mgal/d was used to generate 1,050 gigawatthours of electricity; the consumptive use of water in this process is mostly from evaporation and the amount involved is negligible.

The source, use, and disposition of offstream freshwater in Minnesota in 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The withdrawal data indicate that 75.8 percent (2,150 Mgal/d) of total withdrawals was from surface water and 24.2 percent (685 Mgal/d) was from ground water. The withdrawal data also indicate the percentage of withdrawals by the various categories; for example, 9.7 percent (208 Mgal/d) of the surface water withdrawn in 1985 and 38.7 percent (265 Mgal/d) of the ground water were diverted to public supply systems. Other sources of water, such as sewage wastewater, are not included in figure 4 but are discussed under the appropriate categories. The use data indicate the quantity of water used and the percentage of use supplied from surface- and ground-

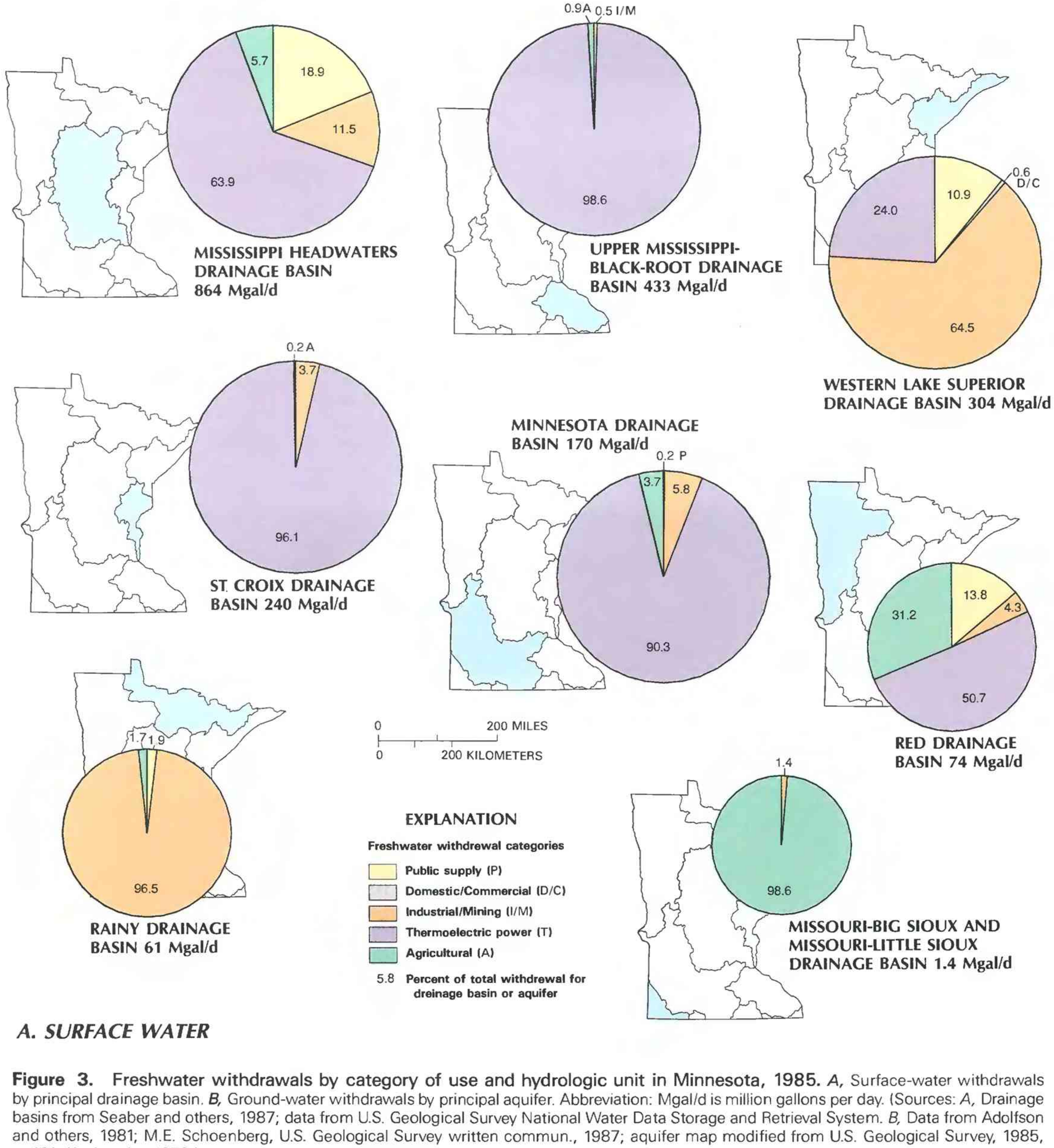


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Minnesota, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from Adolfson and others, 1981; M.E. Schoenberg, U.S. Geological Survey written commun., 1987; aquifer map modified from U.S. Geological Survey, 1985, p. 181; Kanivetsky, 1978.)

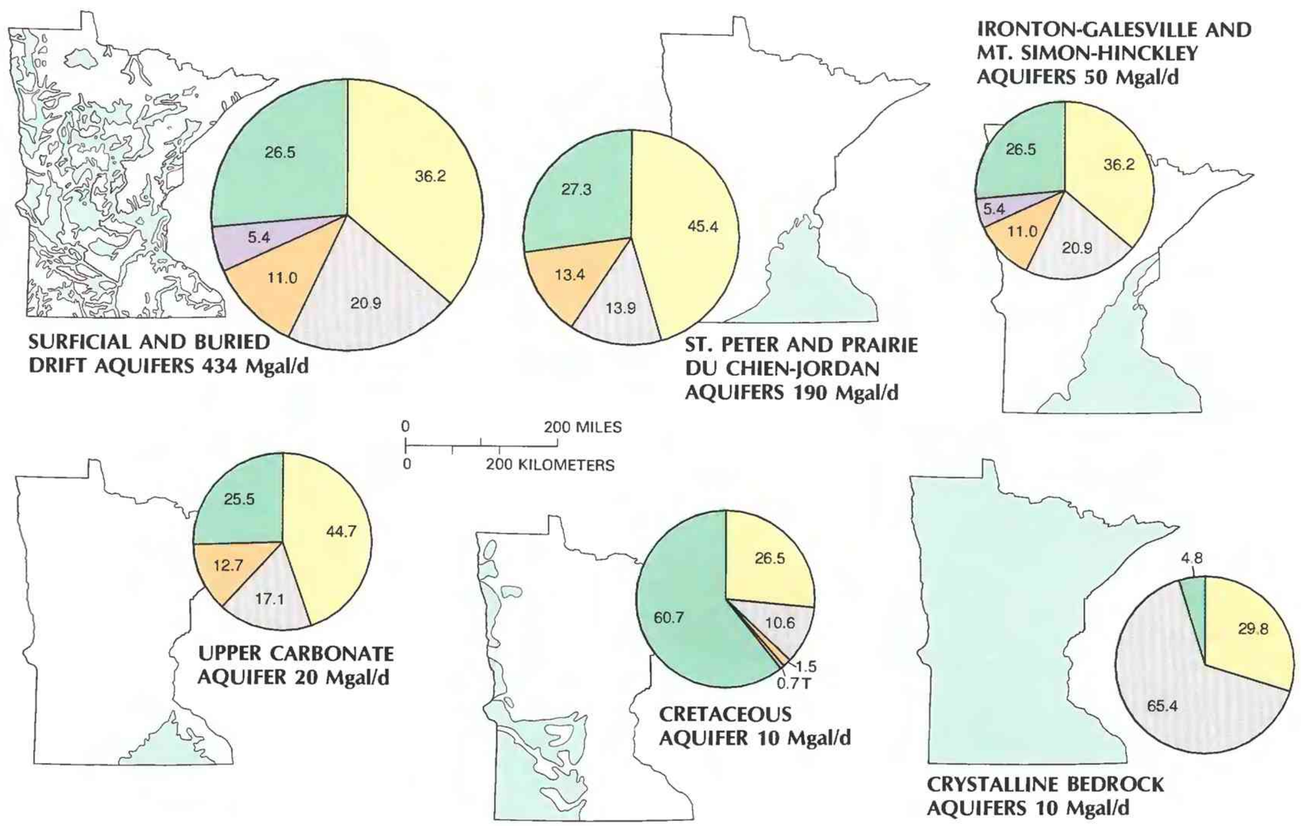
water sources and public-supply systems. For example, water withdrawn and delivered for domestic and commercial use totaled 583 Mgal/d, of which 0.3 percent (1.8 Mgal/d) was obtained from self-supplied surface-water sources, 26.7 percent (156 Mgal/d) was from self-supplied ground-water sources, and 73.0 percent (425 Mgal/d) was delivered by public-supply systems. The use data also indicate that 31.3 percent (183 Mgal/d) of the water withdrawn and delivered for domestic and commercial use was consumed and was no longer readily available for reuse, and 68.7 percent (400 Mgal/d) was returned to a natural water source where it became available once again for use downstream. The disposition data indicate that, of all water withdrawn in the State, 27.1 percent (768 Mgal/d) was consumed and 72.9 percent (2,070 Mgal/d) was returned. Domestic and commercial use accounted for 23.8 percent (183 Mgal/d) of the consumptive use and 19.4 percent (400 Mgal/d) of the return flow.

Public Supply

Public supply is a conveyance mechanism to indicate water withdrawn and delivered by public water systems. Public-supply systems in Minnesota furnish water for domestic and commercial, industrial and mining, and thermoelectric power purposes (fig. 4). In 1985, Minnesota was 25th in withdrawals by public water supply, although it ranked as the 21st most populous State. Withdrawals by public water supply increased from 30 percent of total water withdrawn (excluding that for thermoelectric power generation) in 1980 to 35 percent in 1985 (Solley and others, 1983, p. 47). This increase outpaced Minnesota's 3-percent increase in population during the same period (fig. 1*C*). This trend may reflect population migration to the cities or the expansion of commercial and industrial facilities and other activities that depend on public water supplies. Many municipalities, seeking to attract new jobs, furnished public water supplies to industries and, as an added inducement, agreed to treat industrial wastewater. Regardless of the purpose for which it was furnished, all these withdrawals for public supply not consumed eventually become wastewater discharge. In Minnesota, 97 percent of these discharges are treated before they are returned to the environment (Minnesota Pollution Control Agency, 1985, fig. 3).

Total withdrawals by public-supply systems in 1985 were 473 Mgal/d, of which 43.9 percent (208 Mgal/d) was surface water and 56.1 percent (265 Mgal/d) was ground water. The water source used depends, to a large extent, on the nature of the underlying geology. The southeastern part of the State, where population is most dense, is underlain by thick layers of limestone and sandstone that include the most productive aquifers in the State. Two-thirds of the withdrawals for public supply in this part of the State is from ground-water sources. In contrast, most of the northeastern part of the State is underlain by crystalline rocks that yield limited quantities of ground water. For this reason, most large towns and cities in this region depend on surface water. In western Minnesota, where yields to wells completed in bedrock aquifers are small, water from sand and gravel deposits in unconsolidated glacial drift accounts for most public-supply withdrawal.

The Twin Cities metropolitan area has a complex network of interconnected water systems. Minneapolis and surrounding cities withdraw water from the Mississippi River at a point upstream in Anoka County. St. Paul and surrounding cities also withdraw water from the Mississippi River but combine it with water from the Vadnais Lake chain in Ramsey County and with ground water withdrawn in Anoka County. The interconnection of water systems is advantageous during droughts when streams and reservoirs can be severely depleted.



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Minnesota, 1985—Continued.

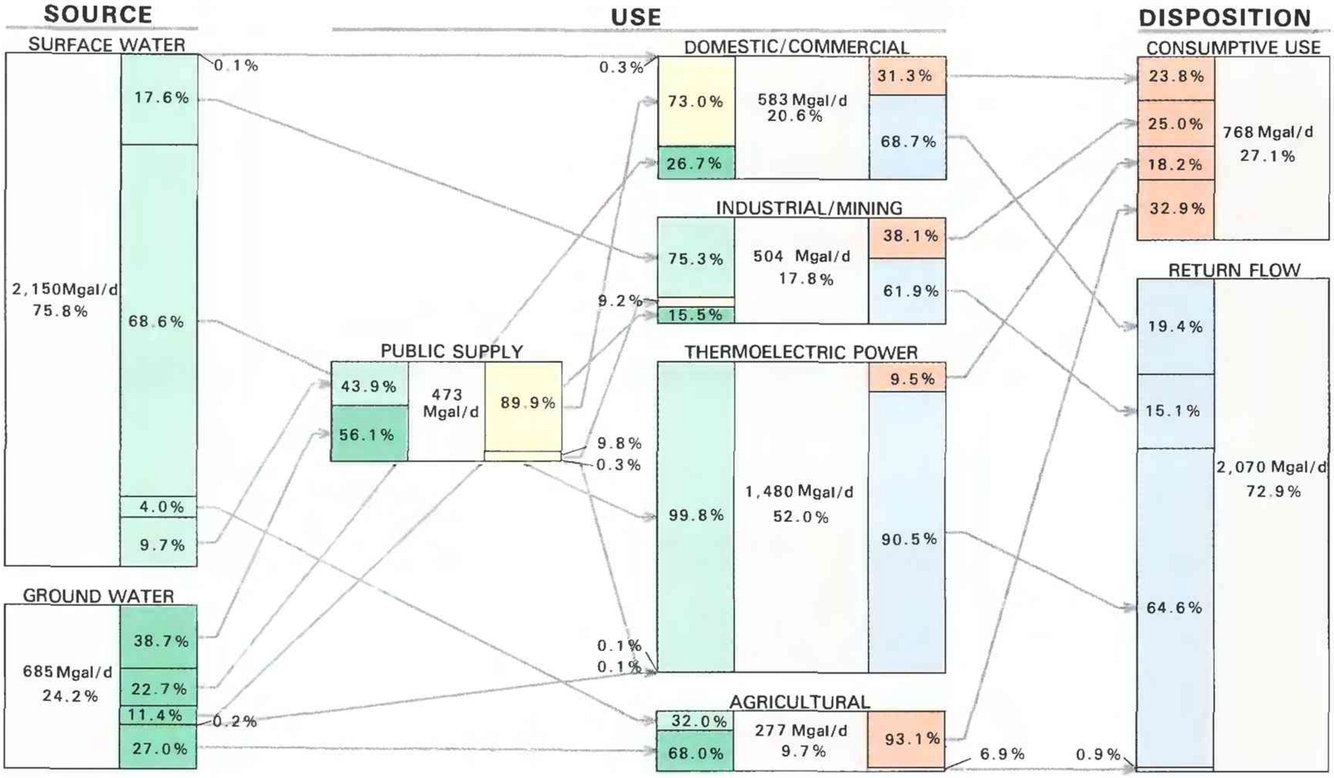


Figure 4. **Source, use, and disposition of an estimated 2,840 Mgal/d (million gallons per day) of freshwater in Minnesota, 1985.** Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Domestic and Commercial

Domestic and commercial water users received water from public-supply deliveries and from self-supplied withdrawals. Combined total of deliveries and withdrawals in 1985 were 583 Mgal/d (fig. 4). Withdrawals and deliveries for domestic use in 1985 were about 532 Mgal/d. Of that total, 401 Mgal/d was from public-supply systems, which served 64 percent of the population, and 131 Mgal/d was self-supplied by the remaining 36 percent of the population. Consumptive use was 172 Mgal/d. Public-supply water facility records indicate that deliveries to all users average 175 gal/d for each person served. For the self-supplied population, the average per capita use for domestic purposes was about 88 gal/d (Horn, 1986).

Commercial use of water in 1985 was about 49 Mgal/d, of which 23 Mgal/d was delivered by public supplies and 26 Mgal/d was self-supplied. Consumptive use was 11 Mgal/d. Commercial water use is small when compared to domestic use. One reason may be that many self-supplied systems are too small to be covered by the permitting system, and no estimates of this additional use have been made.

Industrial and Mining

In 1985, water withdrawn and delivered for industrial and mining use amounted to 504 Mgal/d (fig. 4). Self-supplied systems related to mining activities provided 271 Mgal/d of surface water (a national maximum) and 1.7 Mgal/d of ground water. Self-supplied systems also provided 108 Mgal/d of surface water and 76 Mgal/d of ground water for all other industrial uses. Consumptive use for all industries and mining was 38.1 percent (192 Mgal/d) of withdrawals and deliveries.

The industries that have the largest water use in Minnesota are metal, paper, pulp, and chemical processing. Industrial water use has decreased 23 percent since 1980 (Solley and others, 1983, p. 47), following a trend that began in the 1960's.

Thermoelectric Power

As in many States, water use associated with thermoelectric power generation is an important facet of Minnesota's total water use. The State has 34 thermoelectric powerplants, of which 32 use fossil fuel and 2 use nuclear fuel. In 1985, these plants withdrew 1,480 Mgal/d for cooling purposes (fig. 4). Of this volume, fossil-fueled plants withdrew 712 Mgal/d of surface water and 1.2 Mgal/d of ground water. Nuclear powerplants withdrew 762 Mgal/d of surface water and no ground water. Consumptive use was 125 Mgal/d by fossil-fueled plants and 15 Mgal/d by nuclear powerplants. The withdrawal of water for cooling in thermoelectric powerplants accounts for 52 percent of all water withdrawn in Minnesota. However, most of the water is returned to Minnesota's streams; 9.5 percent of the water used for cooling is lost through evaporation and is considered to be consumed.

Agricultural

Use of water for agriculture in Minnesota in 1985 was dominated by irrigation; for example, irrigation withdrawals totaled 214 Mgal/d, whereas nonirrigation withdrawals totaled 63 Mgal/d. Water withdrawn for irrigation increased tenfold from 20 Mgal/d in 1970 to 214 Mgal/d in 1985 (fig. 4), the third fastest rate of increase among the Northeastern States (Murray and Reeves, 1972, p. 22). Since 1980, surface-water withdrawals for irrigation have increased 333 percent, from 18 to 78 Mgal/d, in contrast to a slight decrease in ground-water withdrawals, from 139 to 131 Mgal/d (Solley and others, 1983, p. 47). In 1985, 5 Mgal/d of wastewater from canneries and sewage plants was used for irrigation. The increase in surface-water irrigation is caused by an increase in the production of wild rice, mainly in Aitkin, Beltrami, Cass, Clearwater, and Polk Counties (fig. 2*B*), which contain 90 percent of the world's wild-rice paddies. Flood-irrigation methods made Minnesota the world's largest producer of wild rice in the early 1980's (Claude E. Titus, Minnesota Wild Rice Promotion Council, written commun., 1983).

Most ground water withdrawn for irrigation is from surficial outwash sand and gravel aquifers. The average irrigation well is 126 feet deep and yields 892 gallons per minute (U.S. Bureau of the Census, 1986, p. 16, 17). The irrigation wells provide water to center-pivot sprinklers that are used almost exclusively to apply water to crops. In 1985, the leading crops (in acres) irrigated by ground water were corn (158,400), soybeans (40,800), and potatoes (19,100).

Expectations are that irrigation use probably will increase through the 1980's. However, the rate of increase may decline because of competition with California in wild-rice production and the placement of corn acreage in the Conservation Reserve Program of the U.S. Department of Agriculture.

In 1985, nonirrigation agricultural water use, including water for livestock and other farm purposes, was 63 Mgal/d, which is a slight decrease from 68 Mgal/d in 1980 (Solley and others, 1983, p. 47). This trend may reflect the economic slowdown affecting Midwestern farmers and the decrease in number of farms. Of the total withdrawals in 1985 for nonirrigated agricultural use, 53 Mgal/d was from ground water, and 10 Mgal/d was from surface water. Consumptive use for all agricultural activities, except wild-rice irrigation, was nearly 100 percent.

WATER MANAGEMENT

In Minnesota, allocation of water through a permit system began in 1937, when the State first required permits for water withdrawals outside municipal limits. The motivation for water-appropriation permits came from a severe drought in the Midwestern States in the 1930's. At the same time, a public water permit program was started to regulate modifications to surface-water bodies in the State. By 1955, all water appropriators that had permits were required to file annual water-use reports with the Minnesota Department of Natural Resources (MDNR). By 1966, all large users, whether or not they had permits, were required to report pumpage. In 1973, the legislature eliminated all the previous exemptions from permit requirements except the one for domestic supplies for less than 25 people. Permits and annual pumpage reports were required from all self-supplied water users who withdrew either 10,000 gal/d or 1 million gallons per year. As a result, the number of permit applications received by the MDNR increased by 90 percent from 1974 to 1975.

Permit applications doubled again from 1975 to 1977 as irrigation increased because of drought. From July 1, 1976, to June 30, 1977, 92 percent of applications were for irrigation permits. Increased concern for protecting the State's water resources prompted legislation in 1977 requiring additional information from permit applicants and the protection of low streamflows and lake levels. The State legislature recognized that the water-resource information needed by the MDNR to implement safeguards against overdevelopment of the resource and similar information collected by several other State agencies had to be readily accessible. In 1976, computerization of water-resource information began to manage the greater volume of data more efficiently.

A cooperative water-use project between the MDNR and the U.S. Geological Survey began in October 1978. The project gave the MDNR an opportunity to evaluate and expand the newly developed State water use data system. A systems unit was established by MDNR in January 1979 to centralize computer data processing and to manage the project. The Survey temporarily assumed project leadership in April 1981. With further assistance from the Land Management Information Center of the Minnesota State Planning Agency, a water use data base was developed, and the system was transferred to the Survey's minicomputer in 1987.

The Survey's National Water-Use Information Program encouraged collection of data on discharge, return flows, power generation, and other data related to water use in addition to water withdrawals. These data were acquired from agencies that already were collecting the data, such as the Minnesota Pollution Control Agency and the Minnesota Energy Agency (Horn, 1986, p. 2–8).

Other aspects of water management and policy are planned and coordinated by the Environmental Quality Board and the Governor's Subcabinet Committee on Energy-Environment-Resources (U.S. Geological Survey, 1986, p. 293). Local watershed districts in Minnesota plan for overall development, describe water problems, and propose solutions. In 1985, the State legislature enacted the Comprehensive Local Water Management Act (Minnesota State 110B), which encourages every county outside the Twin Cities metropolitan area to develop a comprehensive water plan (Minnesota State 110B.04 Subds. 1 and 2) and to address surface- and ground-water problems within each county (Garvey and others, 1986, p. 24–26).

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Prepared by L.C. Trotta

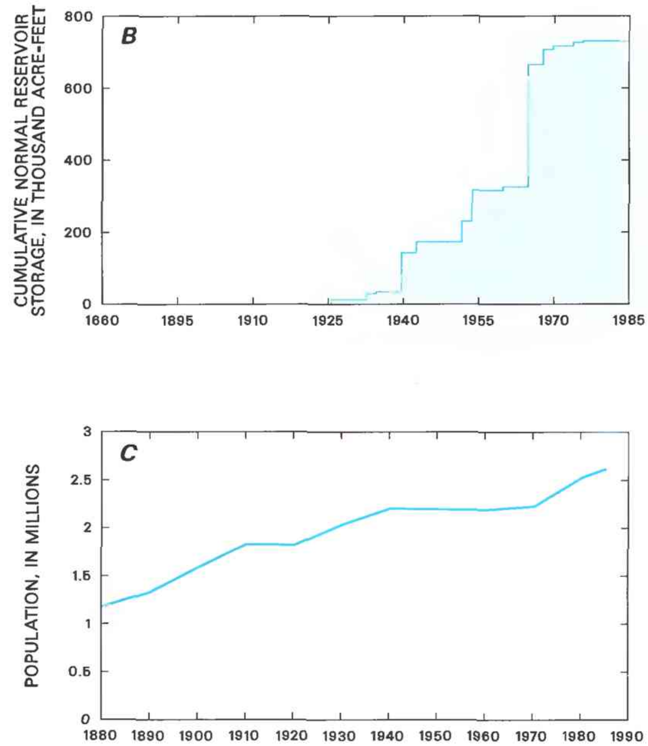
FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Room 702, Post Office Building, St. Paul, MN 55101

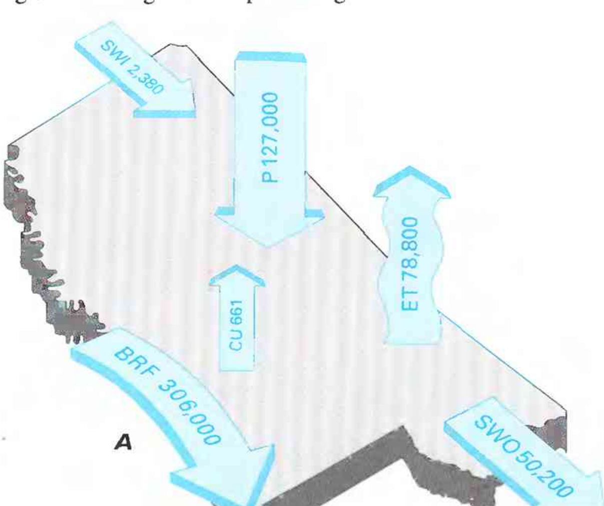
Mississippi
Water Supply and Use

Mississippi has large quantities of fresh surface or ground water (fig. 1*A*) that are available in nearly all parts of the State. Precipitation provides an average of 127,000 Mgal/d (million gallons per day), or about 56 inches annually (National Oceanic and Atmospheric Administration, 1985). During 1985, freshwater withdrawals from surface and ground water in the State were 2,320 Mgal/d. Of this quantity, 28.6 percent (661 Mgal/d) was consumed, and 71.4 percent (1,650 Mgal/d) was returned to the hydrologic system. Some of the most productive and cultivated farm land in the country is located in a 7,000-square-mile area in the northwestern part of the State commonly called the "Delta" The Delta corresponds to the area shown as the Mississippi River alluvial aquifer in figure 3*B*. During 1985, 54.9 percent (1,270 Mgal/d) of all freshwater withdrawals in the State was for agricultural use, and about 98 percent of this quantity was used in the Delta. About 800 Mgal/d of the agricultural withdrawals was used for rice irrigation, and more than 300 Mgal/d of ground water was used for catfish farming.

Total water withdrawals for domestic, commercial, industrial, and mining uses were 561 Mgal/d. About 15 percent of this water was consumed, and 85 percent was returned to streams or other surface-water sources. Freshwater use for thermoelectric power generation was 481 Mgal/d. Of this quantity, 19.9 percent was consumed, although the range for return flows extended from virtually 0 to 100 percent.

Increased population and the accompanying economic growth and greater water demand are expected to increase the demand for freshwater supplies in Mississippi. The population increased about 18 percent from 1960 to 1985—from about 2.2 million to more than 2.6 million. The population is expected to increase by 32,000 per year through the year 2000 (J.R. Williamson, Mississippi Research and Development Center, oral commun., 1987). The Mississippi Legislature recognized the potential growth and increased demands





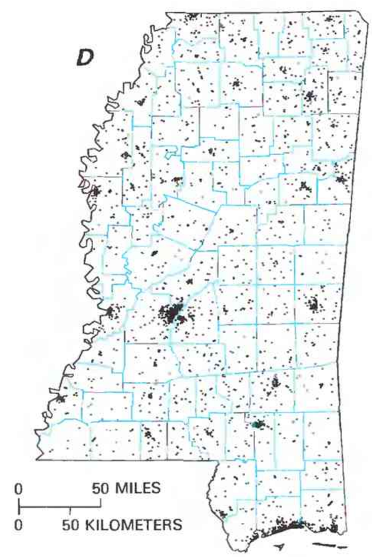


Figure 1. Water supply and population in Mississippi. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System; National Oceanic and Atmospheric Administration, 1985. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

on the freshwater supplies of the State. In 1985, the legislature passed laws that are based on a policy of conservation of water resources to protect and plan for Mississippi's present and future water needs.

HISTORY OF WATER DEVELOPMENT

Water has been important to the settlement and development of Mississippi. Indian villages were located near streams that provided water for drinking and washing (Bettersworth, 1959). Rivers were used by explorers and settlers as pathways to discover and develop new territory and as a source of water for towns and trading posts. The earliest settlements within the State were established by the French at Biloxi on the gulf coast and Natchez on the Mississippi River. Rivers, such as the Mississippi and the Tombigbee, provided natural arteries for development. The Natchez Trace, a road through the interior of the State, became important in the early 1800's because of flatboat traffic on the Mississippi River. These boats could not be moved against the current and so were scrapped at Natchez or New Orleans, La., leaving the boatmen to return upstream to Tennessee on foot along the Natchez Trace. The route, which followed Indian trails from Natchez to Nashville, Tenn., opened the interior of the State to settlement. Settlers from Alabama followed the Tombigbee River into Mississippi and then used the river to transport goods to the Gulf of Mexico. The city of Columbus began as a trading post on the Tombigbee River.

The arrival of the steamboat on the Mississippi River in 1811 contributed to economic and population growth during the mid-19th century. Easy access to markets, as well as an abundance of inexpensive land, helped the growth of the "Cotton Kingdom" in northern and central Mississippi where much of the land was planted in cotton. By 1860, the State's population was almost six times the 1830 population, and, by 1880, the State had more than 1 million residents. However, by the late 1800's, erosion had decreased the fertility of the soil, and farmers looked to the Delta region of northwestern Mississippi for more land (Federal Writer's Project, 1949).

Flooding of the Delta, which occurred almost annually, had restricted development of its very fertile land until the late 19th century, when systems of levees were constructed to decrease flooding from the Mississippi and other rivers that cross the region. These levees and systems of drainage canals, which were constructed by private, local, and State interests, allowed the Delta to be cleared and farmed. However, in 1927, a disastrous flood breached the levees and inundated the Delta for 4 months (Bettersworth, 1959). Congress then authorized the U.S. Army Corps of Engineers to coordinate flood-control activities along the Mississippi River (Mississippi River Commission, 1940), and a new levee system and four major reservoirs were constructed to control flooding in the Lower Mississippi–Hatchie and Lower Mississippi–Yazoo basins; the additions significantly affected normal reservoir storage in the State (fig. 1*B*).

The growth of industry in Mississippi after World War II, coupled with increasing population (fig. 1*C*) and the resulting shift of population from rural to urban areas (fig. 1*D*), prompted attention to water supply. The population shift to urban areas was largest in Jackson and cities along the gulf coast. A supply that was sufficient for rural and agricultural use typically was inadequate for urban and industrial use. Completed in 1965, the Ross Barnett Reservoir, which is located near Jackson on the Pearl River, is a source of public-water supply for the city of Jackson and a regional recreation facility. This lake more than doubled the normal storage capacity of Mississippi's reservoirs (fig. 1*B*).

Early improvements in navigation included harbor dredging in gulf coast ports, construction of cut-off channels at bends, and channel dredging in the Mississippi River. A more recent project is the Tennessee–Tombigbee Waterway in northeastern Mississippi, which was completed in 1985. The Waterway provides a shorter transportation route from the Tennessee River to the Gulf of Mexico by way of the Tombigbee River rather than the Mississippi River.

WATER USE

Large quantities of water are available from many rivers and streams in Mississippi. Surface-water inflow is 2,380 Mgal/d and surface-water outflow is 50,200 Mgal/d. In addition, the Mississippi River, which forms most of the western boundary of the State, has an average daily discharge of 306,000 Mgal/d (474,000 cubic feet per second) at Memphis; this discharge is six times greater than the combined discharge of all rivers draining the State.

The distribution of total freshwater withdrawals in Mississippi by county is shown in figure 2*A*. The large withdrawals in various parts of the State reflect the major uses. In the northwestern part of the State agriculture is the primary water user, whereas in the northeastern and north-central counties most water use is by industries. The southern one-half includes Jackson, the most populous city in the State, and other major cities along the Mississippi gulf coast; this area has greater domestic, commercial, industrial, mining, and thermoelectric power uses than any other area of the State.

The distribution of surface- and ground-water withdrawals by county is shown in figures 2*B* and 2*C*. Almost all large quantities of surface water were withdrawn and used in the Delta; these quantities range from 30 to 400 Mgal/d (fig. 2*B*). Hinds and Jackson Counties were the only counties outside the Delta to have surface-water withdrawals that exceeded 30 Mgal/d. Ground-water withdrawals by county (fig. 2*C*) ranged from less than 1 to 300 Mgal/d; four counties in the Delta had withdrawals that exceeded 100 Mgal/d. Surface-water withdrawals by major drainage basins and distribution of those withdrawals among the user categories are shown in figure 3*A*. Withdrawals from the Lower Mississippi–Hatchie and Lower Mississippi–Yazoo basins were almost 10 times the next largest basin. Most (69.4 percent) of the withdrawals in this basin was used for thermoelectric power generation, but the largest consumptive user was agriculture.

Ground-water withdrawals from the Mississippi River alluvial aquifer in the Delta (fig. 3*B*) were used mostly for agriculture—aquaculture and rice irrigation. Lowndes and Monroe Counties on the Mississippi–Alabama border had ground-water withdrawals from the Cretaceous aquifer system (fig. 3*B*) that exceeded 15 Mgal/d. The water was withdrawn for public supply and industry. In the southeastern part of the State, the counties of Jones, Forrest, Harrison, and Jackson had ground-water withdrawals larger than 15 Mgal/d from the Miocene and Oligocene aquifer system. The main water withdrawals were for public supply, industry, and thermoelectric power generation.

Principal instream water uses in Mississippi include recreation, waterborne transportation, and wildlife habitat. The quality of surface and ground water throughout the State is suitable for most purposes. There are no hydroelectric powerplants in the State.

The source, use, and disposition of freshwater in Mississippi are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that the 736 Mgal/d of surface water provided 31.8 percent of total surface- and ground-water withdrawals in Mississippi. Of that amount, 13.2 percent was self-supplied for industrial and mining purposes, 58.4 percent was self-supplied for thermoelectric power generation, 23.5 percent was self-supplied for agriculture, and 5.0 percent was withdrawn for public water-supply systems. Other sources of water (saline and reclaimed sewage water) are not included in figure 4 but are discussed under appropriate categories. The use data indicate that the domestic and commercial category used 302 Mgal/d, which represented 13.1 percent of the State's total withdrawals. Of the 302 Mgal/d, 93.3 percent was delivered from

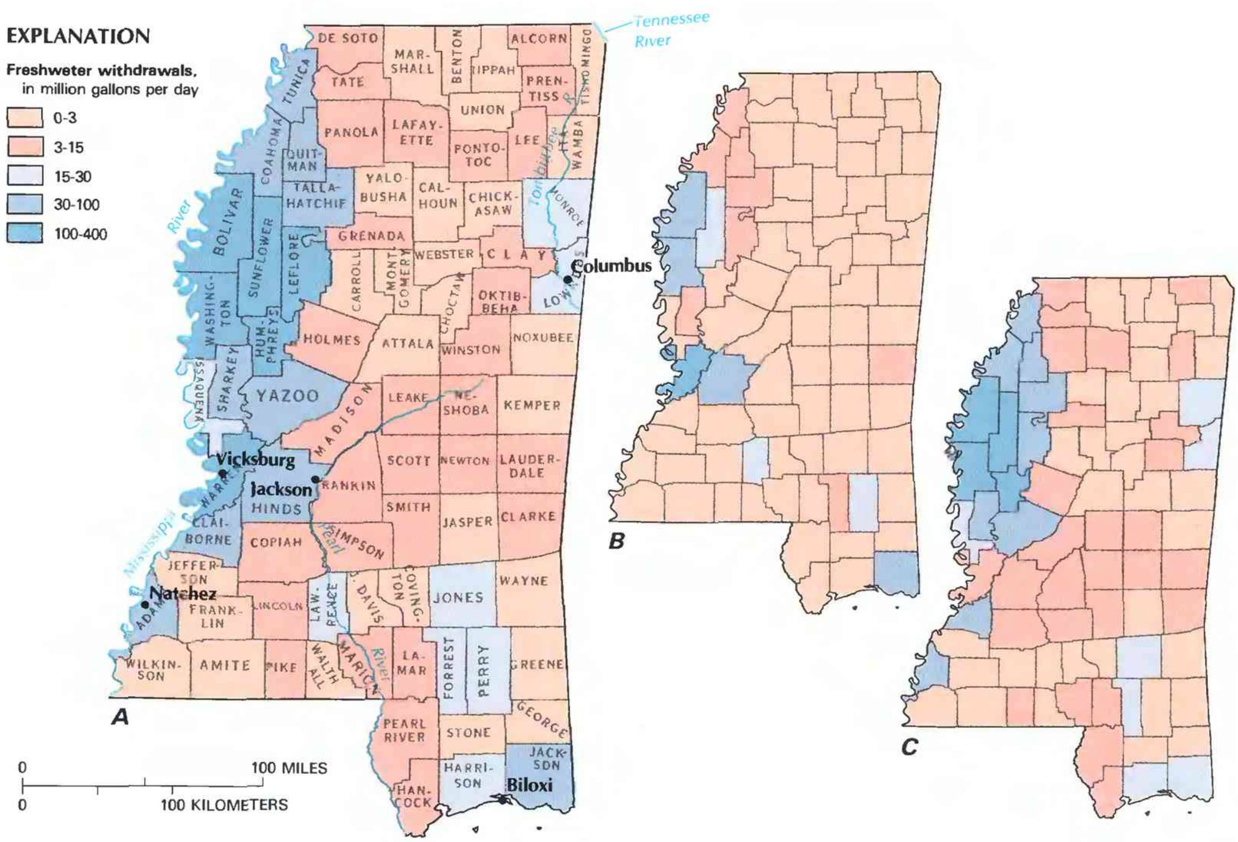


Figure 2. Freshwater withdrawals by county in Mississippi, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

public-supply systems, and 6.7 percent was self-supplied from ground-water sources. The disposition data indicate that 14.7 percent of water used for domestic and commercial purposes was consumed and no longer readily available for reuse, and that 85.3 percent was returned to water sources where it became available for additional use. Of the total quantities of water withdrawn in the State, 28.6 percent (661 Mgal/d) was consumed and 71.4 percent (1,650 Mgal/d) was returned to surface- and ground-water sources.

PUBLIC SUPPLY

The public-supply systems in Mississippi withdraw, treat, and distribute water to users (fig. 4). Of the State's 1,400 public suppliers, three use a combination of surface and ground water, and the others use only ground water. About 11.7 percent of the water for public supply is withdrawn from surface water, and 88.3 percent is from ground water. The availability of ground water in much of the State and the cheaper cost of treatment as compared to surface water account for the dominance of ground-water systems.

The most populous areas of the State also have the largest public-supply withdrawals. Jackson, the capital of Mississippi, had a population of 385,000 in the Metropolitan Statistical Area in 1985 (U.S. Bureau of the Census, 1986), which is about 15 percent of the State's population. Public water suppliers in Jackson obtained water from the Pearl River (31 Mgal/d) and the Eocene aquifer system (2.9 Mgal/d). A second population center is the Mississippi gulf coast, particularly Harrison and Jackson Counties, which had a total population of 269,000 (10 percent of the State). Public water supplies were withdrawn from ground water in these counties, principally from the Miocene and Oligocene aquifer system.

DOMESTIC AND COMMERCIAL

Mississippi is among the most rural of the States in the United States (Hoffman, 1987); nevertheless, 86 percent of the people in Mississippi are supplied with domestic water by public-supply systems. An increasing number of people who live outside of urban areas are served by rural water systems, which provide improved service, maintenance, and assurance of a reliable supply of potable water.

People who obtain their water from a public-supply system use an estimated 73 gal/d (gallons per day) per capita. People who have self-supplied water systems (usually a domestic well) use an estimated 45 gal/d per capita because they tend to have fewer appliances that require water. About 20 percent of water used for domestic purposes was consumed.

Commercial water use is small; about 4.1 Mgal/d is self-supplied, and 47 Mgal/d is supplied by public-supply systems. About 16 percent of water used by commercial entities was consumed.

INDUSTRIAL AND MINING

Industrial and mining water use was 259 Mgal/d during 1985 (fig. 4). Of this total, 37.5 percent (97 Mgal/d) was self-supplied from surface-water sources, and 51.7 percent (134 Mgal/d) was from ground-water sources. The remaining 10.8 percent (28 Mgal/d) was delivered to industries by public-supply systems.

Industries that have self-supplied systems (excluding mining operations) used 227 Mgal/d of freshwater; 96 Mgal/d was from surface water, and 131 Mgal/d was ground water. Industries also used 5.7 Mgal/d of saline water, which is not included in figure 4. Pro-

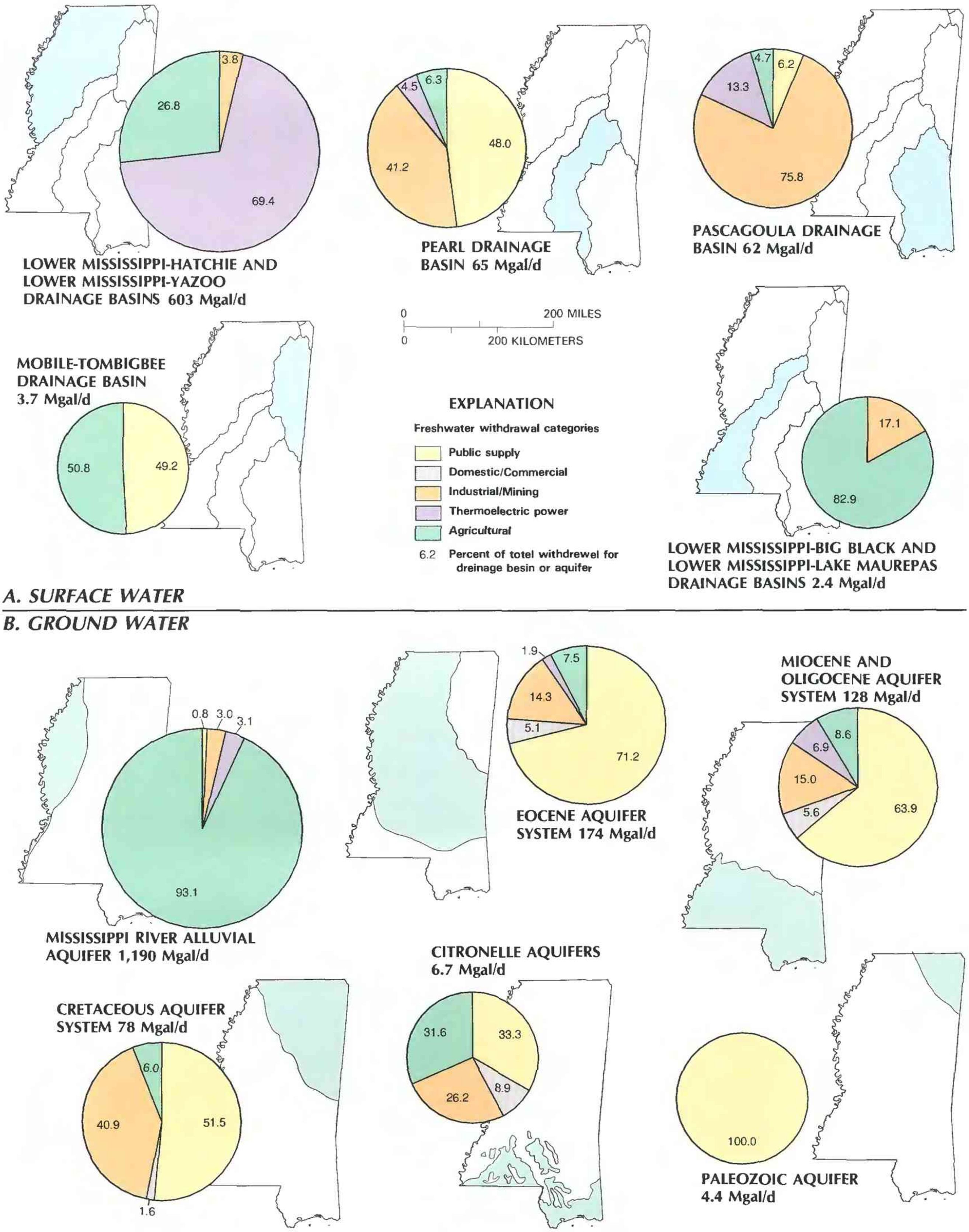


Figure 3. Freshwater withdrawals by hydrologic unit and category of use in Mississippi, 1985. *A, Surface-water withdrawals by principal drainage basin. B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Aquifer map from U.S. Geological Survey, 1985, p. 271; data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

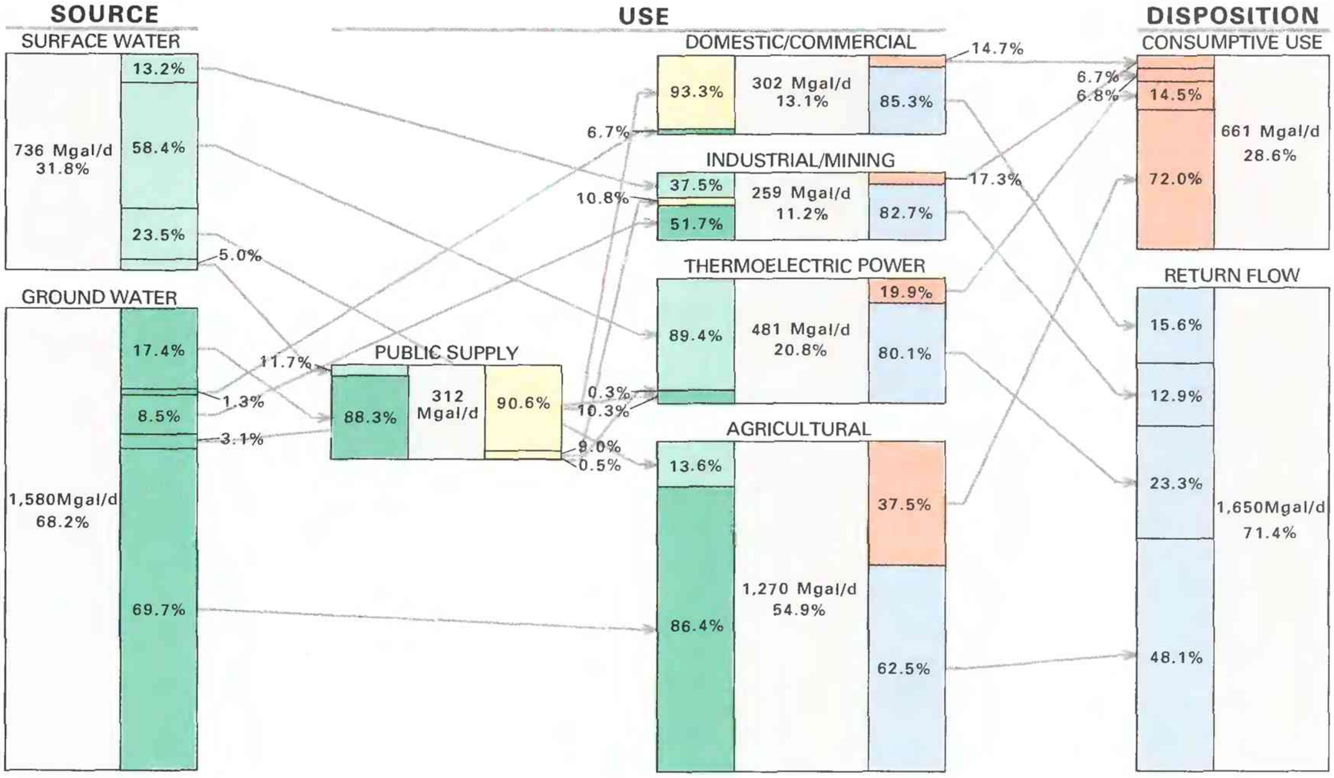


Figure 4. Source, use, and disposition of an estimated 2,320 Mgal/d (million gallons per day) of freshwater in Mississippi, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

duction of pulp, paper, agricultural chemicals and fertilizers, and petroleum refining are the major water-using industries in Mississippi. About 17 percent (44 Mgal/d) of the water used by industries was consumed.

Because of production decreases, industrial water use decreased between 1980 and 1985. In addition, many industries have implemented water-conservation measures. In the past, large quantities of water commonly were pumped through a cooling system and discharged. By 1987, many industries in the State had installed cooling towers and use other water-conservation methods.

Mining water use was 3.7 Mgal/d in 1985—16 percent from surface water and 84 percent from ground water. Mining in Mississippi is mostly for the production of clay, agricultural lime, sand, and gravel. The methods employed in these operations are strip mining and dredging of river and lake bottoms. The demand for water is small because it is used mainly for washing the products and is recirculated from pond to pond. Consumptive use was about 23 percent.

Thermoelectric Power

Large thermoelectric power generating plants are commonly located near major streams. These plants use surface water for cooling and ground water for boiler water and domestic purposes. During 1985, about 481 Mgal/d of freshwater was used for thermoelectric power generation (fig. 4). An additional 191 Mgal/d of saline water also was used. About 89.4 percent of the freshwater withdrawn for thermoelectric power generation was surface water. Freshwater withdrawals for thermoelectric power decreased from about 1,030 Mgal/d during 1980 to 481 Mgal/d during 1985. This decrease was due, in part, to additional power purchases from out-of-State facilities and an accompanying decrease in power production in Mississippi. Some of the decrease in water use probably can be attributed to improvements in plant design and better management of the water supply.

Of the electric generating plants in Mississippi, 12 use fossil fuel, and 1 uses nuclear fuel. About 30,200 gigawatthours of electricity was produced in the operation of these plants in 1985. The State's one nuclear powerplant began operation in the summer of 1985. This plant, located in Claiborne County, uses ground water for cooling. The water is withdrawn by three collector wells that have a series of horizontal pipes extending under the Mississippi River, about 110 feet beneath the riverbed. This plant withdrew 33.6 Mgal/d during 6 months of operation in 1985.

Agricultural

Agriculture is the largest user of water in Mississippi—54.9 percent of the total freshwater withdrawals (fig. 4). Agricultural use is divided into two categories—irrigation and nonirrigation. Irrigation use includes water for pastures and row and field crops. In 1985, about 258,000 acres of the State were irrigated by sprinklers, and another 484,000 acres were irrigated by flooding. The water use for irrigation was 886 Mgal/d—18 percent from surface water and 82 percent from ground water. The conveyance losses were 10 percent of the total withdrawal, and consumptive use was 44 percent.

For many years, cotton and soybeans were the primary crops grown in Mississippi. They are still the major crops grown using sprinkler irrigation. However, during the past 12 years, rice acreage has expanded rapidly, particularly in the Delta. Periodic water-use studies of rice cultivation in the Delta indicate that water use for rice irrigation increased from about 28 Mgal/d in 1950 to more than 200 Mgal/d in 1960. Withdrawals exceeded 200 Mgal/d through 1975 (fig. 5A), even though rice acreage was restricted during this time.

After 1975, when restrictions were lifted, rice acreage increased. During 1981, rice acreage reached a maximum of 335,000 acres; the corresponding total water use was about 1,050 Mgal/d (fig. 5*B*). After 1981, decreasing prices for rice on the world market caused a decrease in crop acreage. During 1985, 800 Mgal/d of water was used to irrigate 190,000 acres of rice. Of this amount, 143 Mgal/d was from surface-water sources, and 657 Mgal/d was from ground-water sources.

Nonirrigation agricultural water use was 385 Mgal/d. This water was used for livestock watering, aquaculture (mostly catfish farming), and other farm purposes. Aquaculture accounted for about 89 percent, or 343 Mgal/d, of the water used for nonirrigation agriculture. During 1985, new catfish ponds occupied a cumulative 8,800 acres, which brought the State total to about 72,000 acres for about 400 commercial catfish farms. The greatest expansion was in the Delta, which now has more than 96 percent of the commercial catfish ponds in the State. Humphreys County, which has about 36 percent of the State's catfish-farm acreage, led the State in catfish production.

In the Delta, ground water is the only source used to maintain pond levels for catfish ponds because it is readily available, it is free from pollutants, and it has an average temperature of about 65 degrees Fahrenheit. In other areas of the State, aquaculture withdrawals were 15 percent surface water and 85 percent ground water. Aquaculture's rapid expansion since 1980, especially in the Delta, has not been matched by increases in water use (fig. 5*C*). Water-conservation measures, such as paddle-wheel aerators and improved pond liners, have kept water use at about 330 Mgal/d since 1981.

WATER MANAGEMENT

The laws that control management of Mississippi's water resources changed significantly in 1985. Since that time, a comprehensive water-management system has been evolving. Before 1985, surface-water permits for any beneficial use were issued under a 1956 law that was based on riparian rights and the principle of prior appropriation. Ground water was not regulated until 1976, but, even then, the law exempted withdrawals for agricultural purposes and for oil and gas production. Ground-water use permits could not be issued except in areas declared to be "capacity use areas," where water problems had already been encountered.

In 1985, the Mississippi Legislature passed legislation that restructured water management in the State. It declared surface and ground water to be a "basic resource" of Mississippi; therefore, most withdrawals are subject to regulation. Any person who withdraws water in the State is required to obtain a permit unless the water is used only for domestic purposes or is withdrawn from a well less than 6 inches in diameter at the surface. The new law also stresses water conservation and development of the maximum beneficial use of the State's water.

The Mississippi Bureau of Land and Water Resources (BLWR), Department of Natural Resources, is the primary regulatory agency for water use. Under the 1985 legislation, all entities who were withdrawing water as of April 1, 1985, were given 3 years to file a "notice of claim" to be able to continue that use, subject to certain hydrologic limitations. All new users will be evaluated by the same criteria. The quantity of water that is available for allocation from a surface-water source is the amount in excess of the stream's minimum flow. The minimum flow (the smallest average flow expected over a 7-day period every 10 years) is determined by the BLWR. For a ground-water source, the withdrawals must not exceed the rate of recharge to that aquifer.

If necessary, public suppliers can be permitted to withdraw more water from a source than these hydrologic limits would allow. During 1987, the BLWR continued the process of evaluating notices

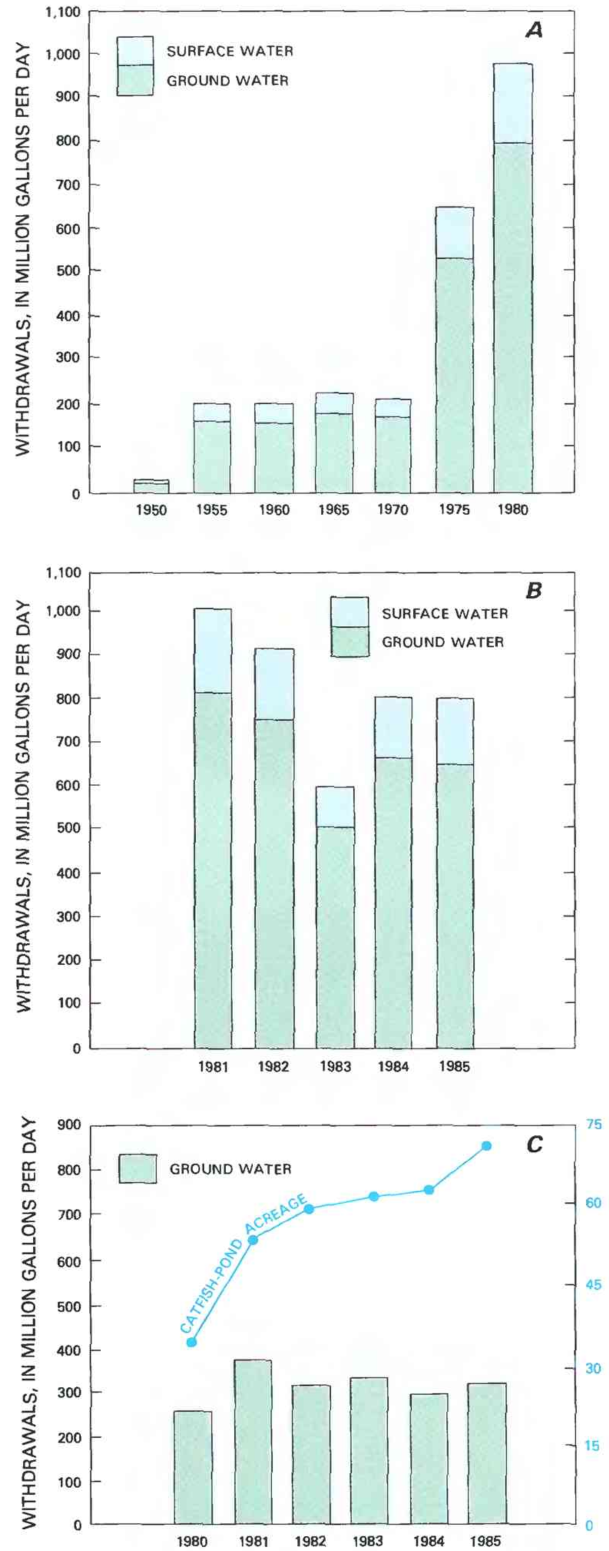
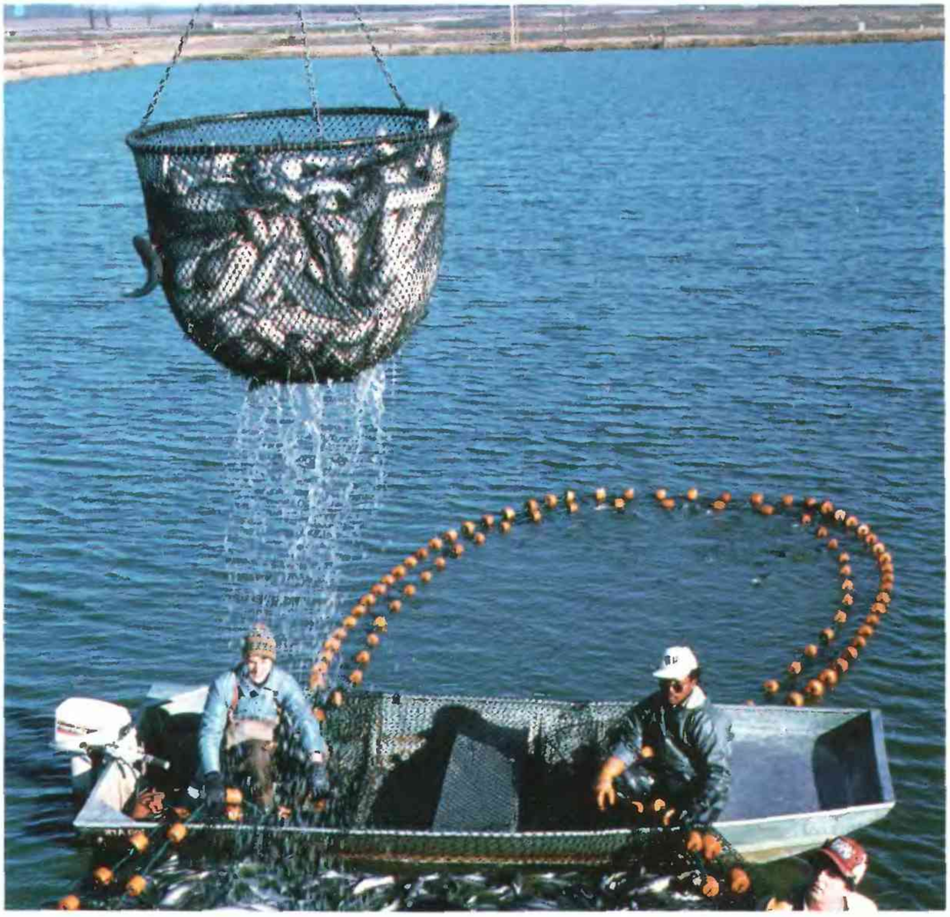


Figure 5. Water use for rice irrigation and aquaculture, Delta region of Mississippi. ***A,*** Water withdrawals for rice irrigation, 1950 to 1980. ***B,*** Water withdrawals for rice irrigation, 1981 to 1985. ***C,*** Water withdrawals for aquaculture and catfish-pond acreage, 1980 to 1985. (Sources: *A, B,* Callahan, 1985. *C,* Withdrawal data from U.S. Geological Survey National Water Data Storage and Retrieval System; pond-acreage data from Mississippi Cooperative Extension Service, written commun., Thomas L. Wellborn Jr., 1986).



Harvesting catfish in the Delta region of Mississippi. In 1985, Mississippi used 343 million gallons per day of water for aquaculture and accounted for 60 percent of the catfish-pond acreage in the United States. (Photograph by Craig Tucker, Delta Branch Experiment Station,Mississippi State University.)

of claim as well as permit applications. After the permits are issued, the BLWR may require periodic water use reports from permit holders that use more than 20,000 gal/d.

The permitting process is also the beginning of two other activities mandated by the 1985 law—the creation of a central water-management data base and the development of a State water-management plan. Information that is submitted as part of permit applications will be incorporated into the water-management data base and may be used as input for river basin or aquifer studies. The BLWR already has initiated studies in parts of Mississippi that have water-supply problems. Eventually, these water-resources studies will be used to formulate an overall water-management plan for the State that will address what supplies of water are available and how they should be used for the State's present and future water needs.

The 1985 legislation also provided for the creation of water-management districts in areas where more local control is desirable. A water-management district can be created under criteria provided in State law, and the authority for issuing and monitoring water use permits, conducting water-resources studies, and planning for future water needs can be delegated to the district by the BLWR. A water-management district for the Delta was under study during 1988.

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Prepared by J.A. Callahan and Nancy L. Barber, U.S. Geological Survey; History of Water Development section by Charles D. Lowery, Department of History, Mississippi State University

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Suite 710, 100 W. Capitol Street, Jackson, MS 39269

Missouri
Water Supply and Use

Missouri has substantial water resources (fig. 1*A*). Two of the largest rivers in the United States, the Missouri and the Mississippi, border or flow across the State. The average annual rainfall is 39 inches (U.S. Weather Bureau, 1969) and ranges from 36 to 48 inches from northwest to southeast. The average quantity of water received from precipitation is about 129,000 Mgal/d (million gallons per day). During 1985 about 6,110 Mgal/d of freshwater was withdrawn from streams and aquifers in Missouri—89.5 percent from surface-water sources and 10.5 percent from ground-water sources. This is equivalent to about 1,210 gal/d (gallons per day) per capita. About 5,610 Mgal/d was returned to natural water sources for possible future use, and 504 Mgal/d was consumed.

North of the Missouri River and in western Missouri, ground water commonly is saline (Fuller and others, 1967, p. 295), so that surface water is the preferred water source in these areas. In southern Missouri, the ground water is fresh and is used extensively for public and domestic supplies. In extreme southeastern Missouri, which is an intensively farmed area, ground water is used extensively for irrigation.

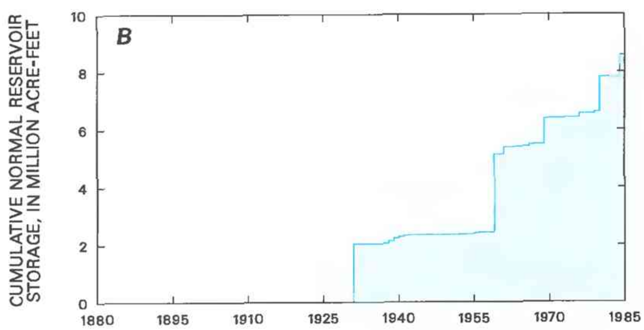
Missouri, the 15th most populous State, had a population of 5.03 million in 1985, which is a 2.9-percent increase from 1980. Much of the population is clustered along the Missouri and the Mississippi Rivers. Public-supply systems serving these areas rely mostly on surface water.

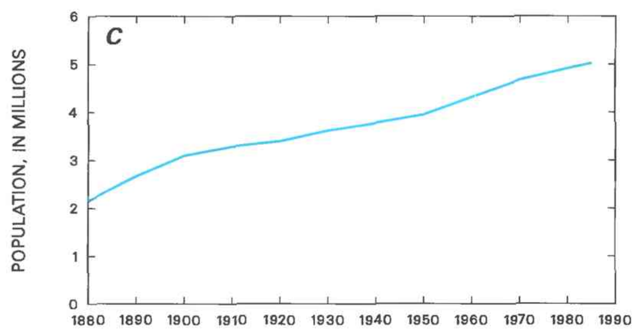
The most significant sources of ground water are the Mississippi Alluvial Plain aquifer of southeastern Missouri, the Ozark aquifer of southern Missouri, and the major river valley aquifer of central and eastern Missouri. Ground water supplies fewer persons but a larger number of towns than does surface water. Most self-supplied domestic withdrawals and some industrial withdrawals are from ground-water sources.

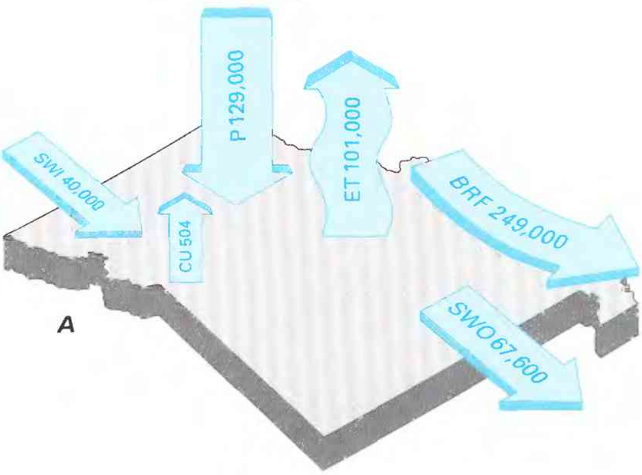
Public-supply systems furnished 10.6 percent of the total water used during 1985. The remainder (89.4 percent) was self-supplied water. Public supplies were utilized by domestic and commercial, industrial, and thermoelectric power users. Of the total withdrawals during 1985, about 80.7 percent was used for thermoelectric power production, about 9.5 percent for domestic and commercial use, 5.7 percent for agricultural use, and 4.1 percent for industrial and mining use.

HISTORY OF WATER DEVELOPMENT

Water had a significant role in the development of Missouri. Early settlements in Missouri developed along the Missouri and the Mississippi Rivers. The first permanent settlement was Ste.







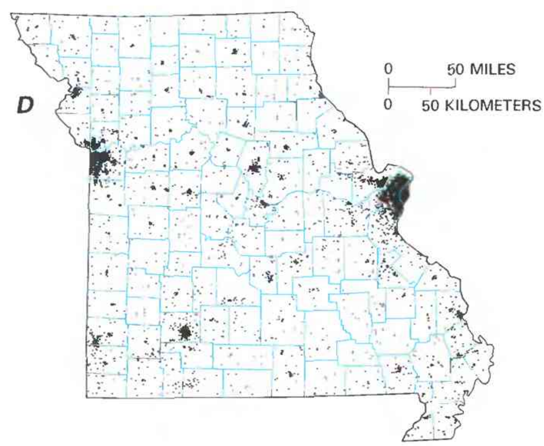


Figure 1. Water supply and population in Missouri. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Solley and others, 1988; Data from U.S. Weather Bureau, 1969. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Genevieve, established in 1735 along the Mississippi River. Smaller streams and springs were invaluable for the water power necessary to operate gristmills. Also, economic development in Missouri between 1820 and 1860 was dependent on river navigation as the primary form of transportation. All 10 of the largest population centers in Missouri in 1860 were along or near the Missouri or the Mississippi River (Meyer, 1963, p. 242).

After the Civil War, the railroad replaced the river as the primary mode of transportation; however, water continued to be significant in the economic development of Missouri. The railway industry depended on Missouri's rivers to transport railroad ties. The ties were floated down many rivers to southern Missouri, where they were loaded onto railroad cars. Throughout the last one-half of the 19th century, Kansas City and St. Louis increased in population as well as in industrial activity (Meyer, 1963, p. 446).

Major agricultural development occurred along the larger rivers as flood plains were used for row-crop production. Corn was the chief crop during the post-Civil War years, and cotton became a commercial crop in southeastern Missouri during the late 1800's and early 1900's. In 1905, the Missouri Legislature authorized drainage of swampland in the Mississippi River Alluvial Plain in the southeastern corner of the State. The Little River Drainage District was established to oversee building of bridges and levees in this area. The Little River was diverted through canals to the Mississippi River, and levees were created along the Mississippi River and other streams to retain floodwaters. This drainage program produced the State's most fertile agricultural area (Meyer, 1963, p. 456).

Until the last three or four decades, irrigation was not common. During the 1970's, the use of center-pivot irrigation systems substantially increased because these systems require little labor, can be used on irregular terrain, and can apply water uniformly (Pfost, 1984). In the Mississippi River Alluvial Plain, improved land-grading techniques have increased the efficiency of flood irrigation (D.L. Pfost, University of Missouri, oral commun., 1987).

In 1913, the first large dam in Missouri was constructed in southwestern Taney County; it created Lake Taneycomo and has provided 19,700 acre-ft (acre-feet) of water storage for hydroelectric power, recreation, and flood control. Bagnell Dam on the Osage River in Miller and Camden Counties, which was completed in 1931, created the Lake of the Ozarks. This lake has become the center of a large recreational development that generates substantial income and a large number of jobs. By 1984, Missouri's 37 large dams had a cumulative water storage of 8.6 million acre-ft (fig. 1*B*).

The steady increase in the population from 1880 through 1985 (fig. 1*C*), has resulted in increased demands on the water resources. The principal population centers are the Kansas City and the St. Louis metropolitan areas, where about 50 percent of the population of the State resides (fig. 1*D*). The estimated State population for the year 2000 is 5.4 million (Ryan Burson, State Demographer, written commun., 1987), an 8-percent increase from the 1985 population.

WATER USE

Surface water is plentiful throughout the State, but the distribution is not uniform, especially during droughts when many sources of surface water become insufficient to meet the demand (Skelton, 1976). Much of the population is situated near the large rivers, which are a reliable source of water. Aquifers containing abundant water are present throughout the State. However, in northern and western Missouri, ground water commonly is too saline (dissolved-solids concentrations range from 500 to 40,000 milligrams per liter) for domestic or agricultural use (Fuller and others, 1967, p. 295). Aquifers along the large rivers, in the Mississippi River Alluvial Plain, and in the Missouri Ozark Plateau in the southern one-half of the State are used extensively for water withdrawals (Emmett, 1985, p. 282). The proportion of surface- to ground-water withdrawals has been about constant for the last 35 years—85 to 90 percent surface water and 10 to 15 percent ground water.

Counties that had the largest total withdrawals in 1985 (fig. 2*A*) were those that had large population centers (fig. 1*D*), intensive agricultural activity, large mining operations, or thermoelectric powerplants. Large quantities of water for agricultural use were withdrawn in Butler, New Madrid, Scott, and Stoddard Counties in the Mississippi River Alluvial Plain and in Barton County in southwestern Missouri. Counties that had large withdrawals for mining were Iron and Reynolds, where most withdrawals were from dewatering active and inactive lead mines. Large withdrawals for thermoelectric plants occurred in Boone, Clay, Franklin, Greene, Jackson, Jefferson, New Madrid, Osage, Platte, and St. Charles Counties and in the city of St. Louis.

The largest surface-water withdrawals by county (fig. 2*B*) coincide with the densely populated areas and sites of thermoelectric powerplants. Large ground-water withdrawals by county (fig. 2*C*) coincide with areas of dense population, intensive agricultural activity, and mining operations.

Of the nine major drainage basins in Missouri, the largest surface-water withdrawals were in the Lower Missouri, the Upper Mississippi–Kaskaskia–Meramec, and the Lower Mississippi–St. Francis basins (fig. 3*A*). These three basins accounted for 62 percent of all the surface-water withdrawals in the State and for 87 percent of the thermoelectric power production.

Ground-water withdrawals (fig. 3*B*) were largest from the Mississippi Alluvial Plain aquifer of southeastern Missouri, where irrigation is the primary use; from the Ozark aquifer of southern Missouri, a weathered carbonate-rock aquifer, and from the major river valleys aquifer in the central and eastern parts of the State, where the primary uses are for public supply, domestic, and industrial purposes. These three aquifers supplied 80 percent of the total ground-water withdrawals in Missouri during 1985.

The source, use, and disposition of 6,110 Mgal/d of freshwater during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that, during 1985, surface-water withdrawals were 5,470 Mgal/d, or 89.5 percent of the total, and ground-water withdrawals accounted for about 640 Mgal/d, or 10.5 percent of the total. Public-supply withdrawals were 73.5 percent surface water and 26.5 percent ground water. About 79.4 percent of the water withdrawn for public supply was used for domestic and commercial purposes, and about 20.6 percent was used for industrial and mining purposes. As indicated by the use data, water for domestic and commercial use was 12.1 percent self-supplied ground water and 87.9 percent deliveries from public supply. More than 99 percent of the water for thermoelectric power production was self-supplied surface water. Water for agriculture was 15.3 percent self-supplied surface water and 84.7 percent self-supplied ground water. As indicated by the disposition data, 52.0 percent of all consumptive use was accounted for by agriculture. Estimated withdrawals and returns for most use categories are shown in figure 5.

Hydroelectric powerplants are instream users that do not consume appreciable quantities of water. They produce relatively inexpensive electricity and, therefore, are favored by electric power companies and consumers. Six hydroelectric powerplants used 20,200 Mgal/d of water and produced 3,930 GWh (gigawatthours) of electricity during 1985. Because of Federal regulations, most electricity produced by hydropower in Missouri was sold for use in the State.

Treated sewage wastewater discharges totaled 885 Mgal/d. Little, if any, of this potentially useful water supply was reused before being returned to the surface-water system.

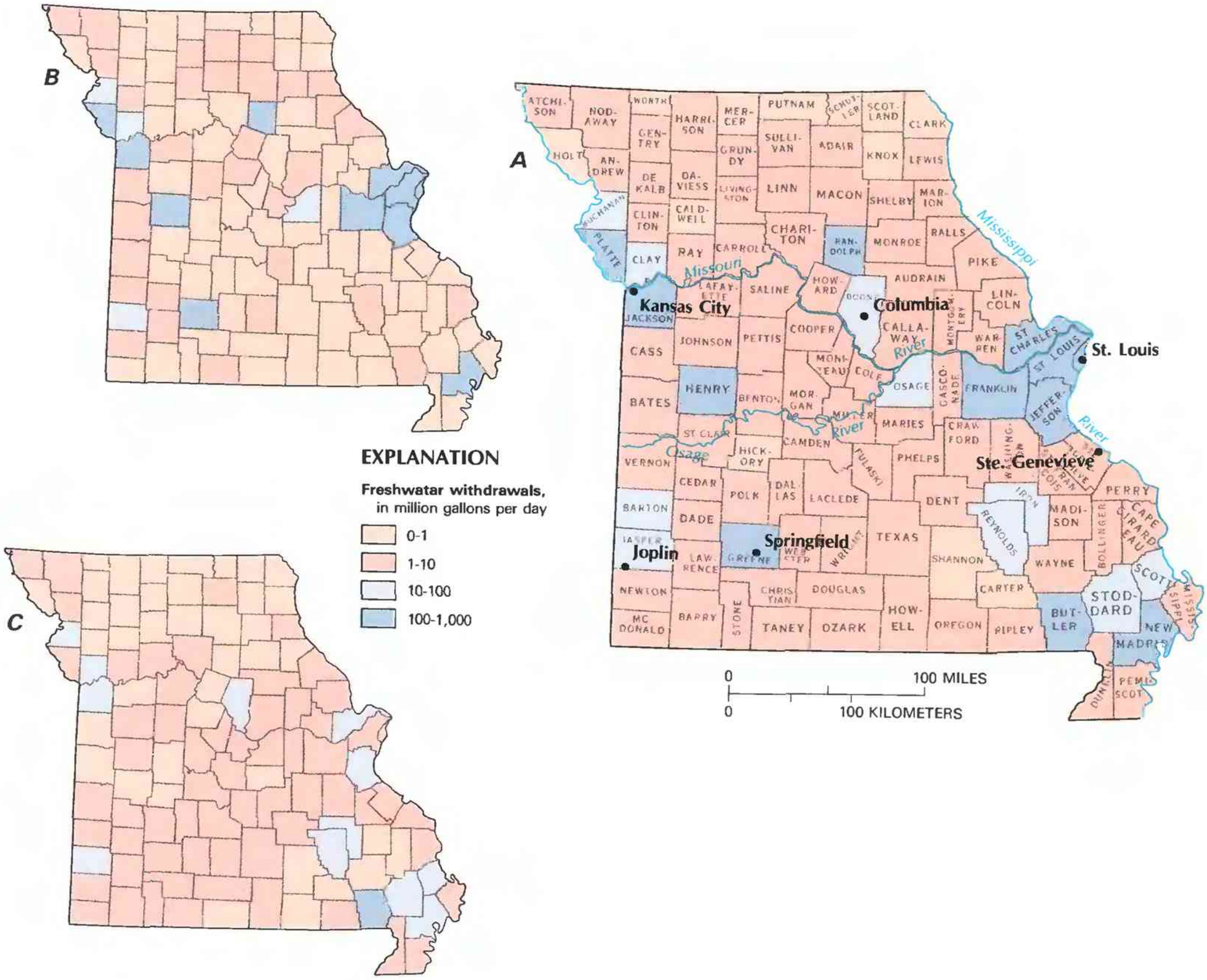


Figure 2. Freshwater withdrawals by county in Missouri, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Public Supply

Public-supply systems withdraw, treat, and deliver water to users. Most of the domestic and commercial water and more than one-half of the industrial water came from public supplies (fig. 4). Public supplies were not a significant source of water for agriculture or thermoelectric power production. Small public-supply systems withdrew only a few hundred gallons per day, whereas large systems withdrew as much as 152 Mgal/d (Missouri Public Drinking Water Program, 1985; B.H. Mazur, Missouri Public Drinking Water Program, written commun., 1986). Withdrawals for public supply decreased 12 percent from 733 Mgal/d during 1980 to 645 Mgal/d during 1985, while the population increased by 2.9 percent.

Domestic and Commercial

Domestic and commercial water use was 583 Mgal/d during 1985, which was about 9.5 percent of the total use. Domestic use was 505 Mgal/d (including 97 Mgal/d for municipal use and conveyance loss), of which 451 Mgal/d was delivered from public suppliers and 54 Mgal/d was self-supplied. Domestic consumptive use was 114 Mgal/d. Public-supply systems served 82 percent of the population. Public- and self-supplied domestic use was 100 gal/d per capita. Excluding municipal use and conveyance loss, per capita use was 81 gal/d.

Commercial use during 1985 was about 78 Mgal/d, and consumptive use was about 5 Mgal/d. Public-supply systems provided 78 percent of the water for commercial use, and self-supply facilities provided the remaining 22 percent.

Industrial and Mining

Industrial and mining use was 249 Mgal/d during 1985. About 53.4 percent of the water was from public-supply systems. Dewatering of active and inactive lead mines accounted for 24 Mgal/d, or about 10 percent, of the water used in this category. Consumptive use for industry and mining was about 33 Mgal/d. During 1985, about 409,000 tons of lead were mined from seven mines—90 percent of the lead production in the United States (Ohl and others, 1986).

Industrial use during 1985 was about 221 Mgal/d, of which about 23 percent was self-supplied surface water, 17 percent was ground water, and 60 percent was water from public supply. Food-processing plants were one of the major industrial water users. Consumptive use was 30 Mgal/d, which was about 14 percent of withdrawals.

Mining withdrawal during 1985 was about 28 Mgal/d,of which about 12 percent was self-supplied surface water, and 88 percent was self-supplied ground water. In addition, about 0.3 Mgal/d of saline ground water was withdrawn from oil wells. Little, if any, public-supplied water was used in mining. Consumptive use of water was estimated to be 2.8 Mgal/d, which is about 10 percent of the total withdrawals for mining.

Thermoelectric Power

Thermoelectric power generation results in the largest off-stream use of water—about 80.7 percent of the total withdrawals for 1985. During 1985, 1 nuclear-fueled thermoelectric powerplant and 25 fossil-fueled thermoelectric powerplants withdrew 4,930 Mgal/d of water, consumed 89 Mgal/d of water, and produced 48,500 GWh of electricity. The powerplants generally are near the population centers. More than 99 percent of the water used for thermoelectric power production was surface water, and about 98 percent was returned to the streams. The powerplants generally are near the population centers. More than 95 percent of the power produced in Missouri is used in the State.

Missouri's large water-cooled powerplants have the capacity to affect fish and other aquatic organisms adversely and to raise the temperature of the stream or impoundment. In many instances, the water sources are large relative to the volumes withdrawn and returned. However, fishkills have been recorded during cold weather when fish tend to congregate in the warm pools. When power production is decreased suddenly, the temperature of the receiving water rapidly decreases and fish may die from thermal shock (J.C. Ford, Missouri Department of Environmental Quality, oral commun., 1987).

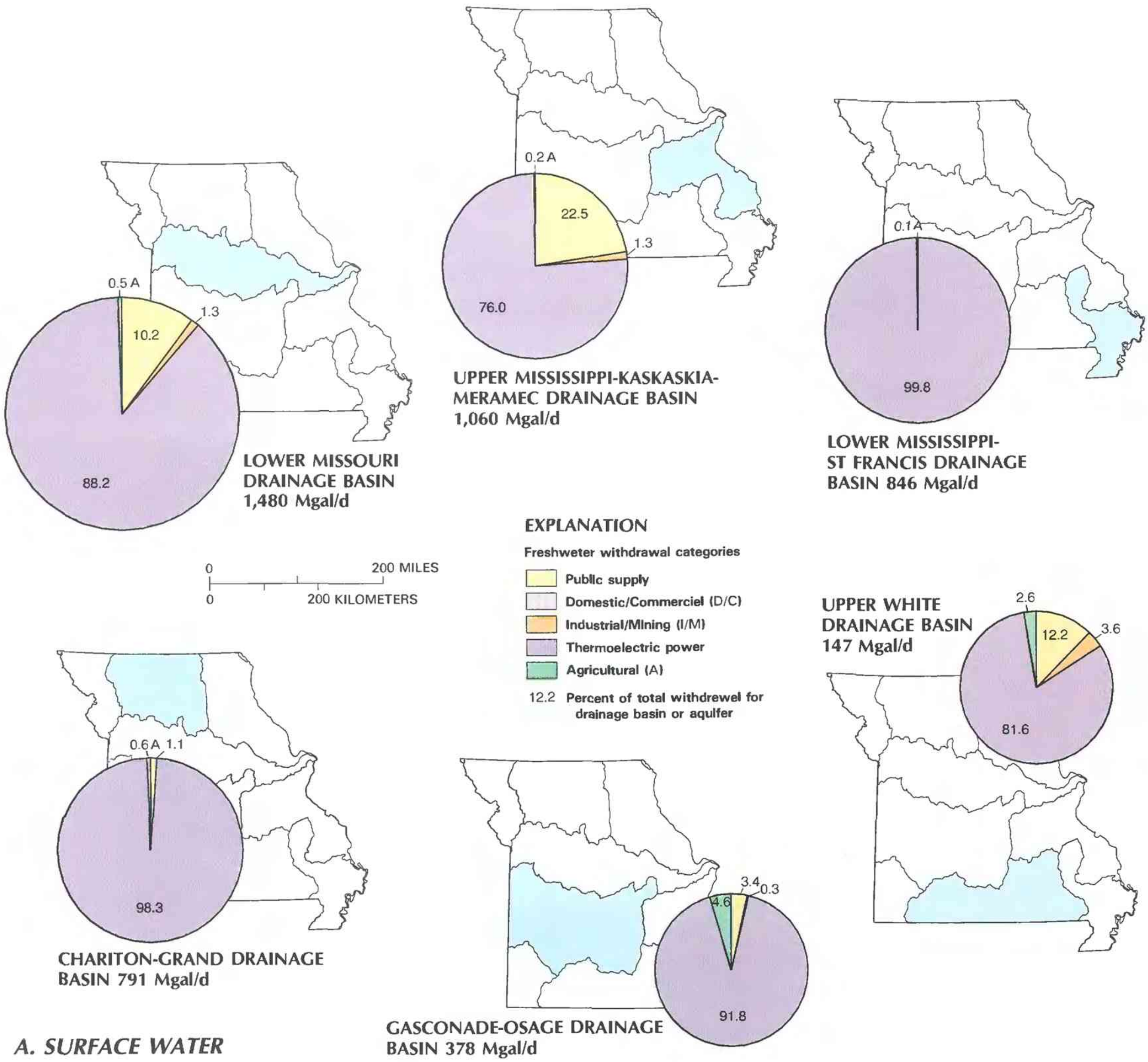


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Missouri, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from Mesko and Berkas, 1988; Imes, 1985.)

AGRICULTURAL

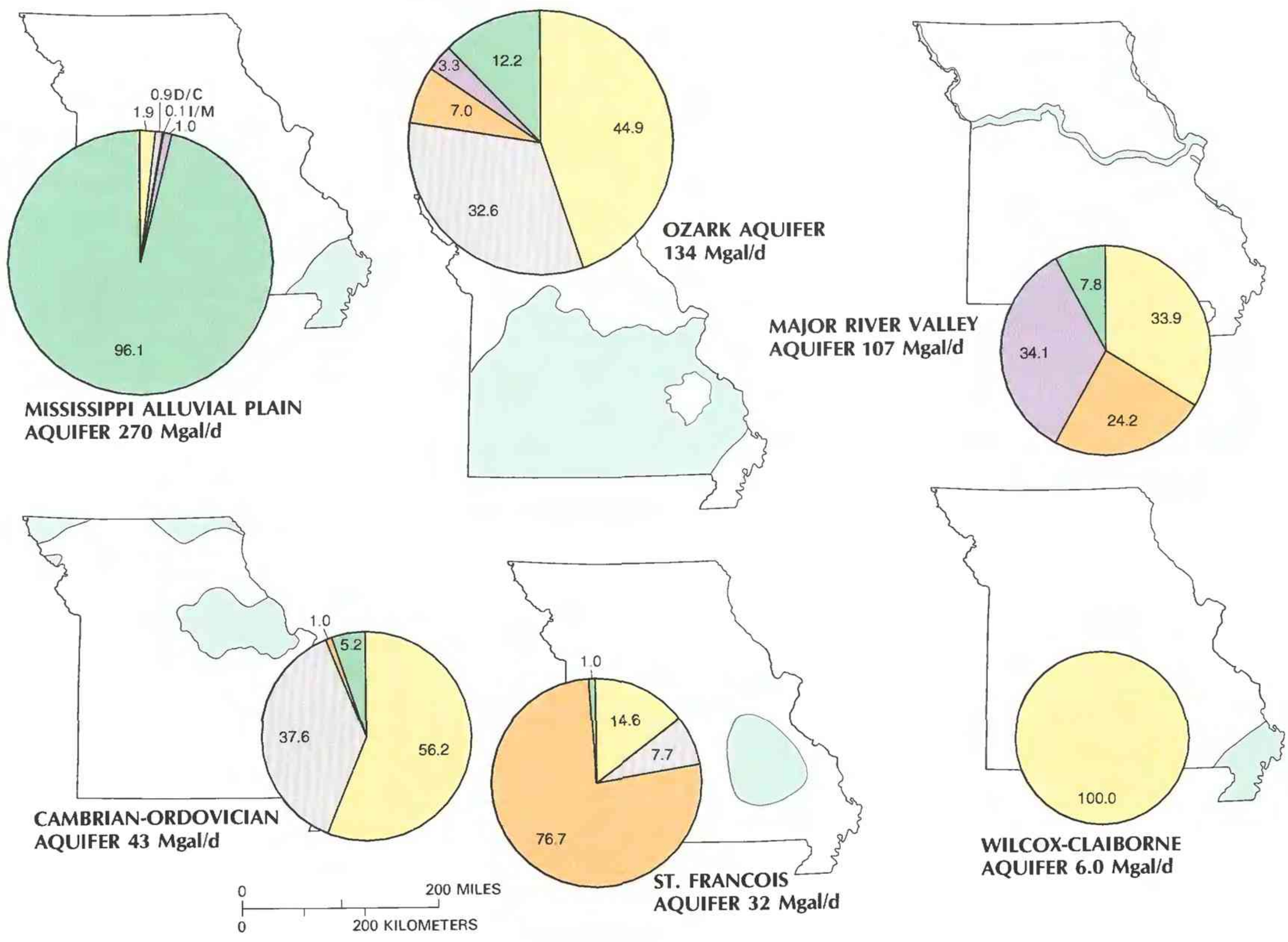
The largest agricultural use of water is for irrigation. Significant nonirrigation uses are watering livestock and aquaculture. During 1985, irrigation withdrawals were about 306 Mgal/d, and nonirrigation withdrawals were 41 Mgal/d. Agricultural consumptive use was 262 Mgal/d, or 52.0 percent of the total consumptive use.

About 45.9 percent of all ground water withdrawn was used for agriculture, and 93 percent of irrigation water was provided by ground water. Much of this was withdrawn from the Mississippi Alluvial Plain aquifer, which yields as much as 3,000 gallons per minute to wells (Luckey, 1985, p. 14). During 1985, about 172,000 acres were irrigated by spraying, and 326,000 acres were irrigated by flooding. Water use for irrigation increased 135 percent from 1980 to 1985, while irrigated acreage increased about 35 percent (Irrigation Journal, 1986, p. 25). Primary crops were soybeans, sorghum, corn, wheat, cotton, rice, and alfalfa. Irrigation has become more common in recent years, largely because of the advances in irrigation technology and the increases in crop yields; 10-year average (1977–86) increases in crop yields because of irrigation have been 38 percent for soybeans and 47 percent for corn (Herman Workman, University of Missouri, written commun., 1987).

WATER MANAGEMENT

The Missouri Department of Natural Resources, Division of Geology and Land Survey, is the principal agency responsible for regulating surface- and ground-water withdrawals. Water use is monitored through the 1983 Major Water User Program (Revised Statutes of Missouri, chapter 256.400). A major water user is defined as anyone who has a water source capable of producing and the equipment necessary to withdraw or divert 100,000 gal/d. Major users are required to report the location of the water source, the quantity of water withdrawn or diverted annually, and the purpose for which the water was used to the Division of Geology and Land Survey. Categories of use, as defined by the 1983 Major Water User Program, include domestic, fish and wildlife, industrial, irrigation, municipal, recreational, and electric power. The water use report also requires users to list locations of surface-water withdrawal sites and locations and specifications of wells.

The Division of Geology and Land Survey also regulates and issues permits to water-well drillers through the 1985 Water Well Driller's Law (Revised Statutes of Missouri, chapter 256.600). Under this law, all well drillers and pump installers must be permitted by the Division, and all completed wells must be inspected and certi-



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Missouri, 1985—Continued.

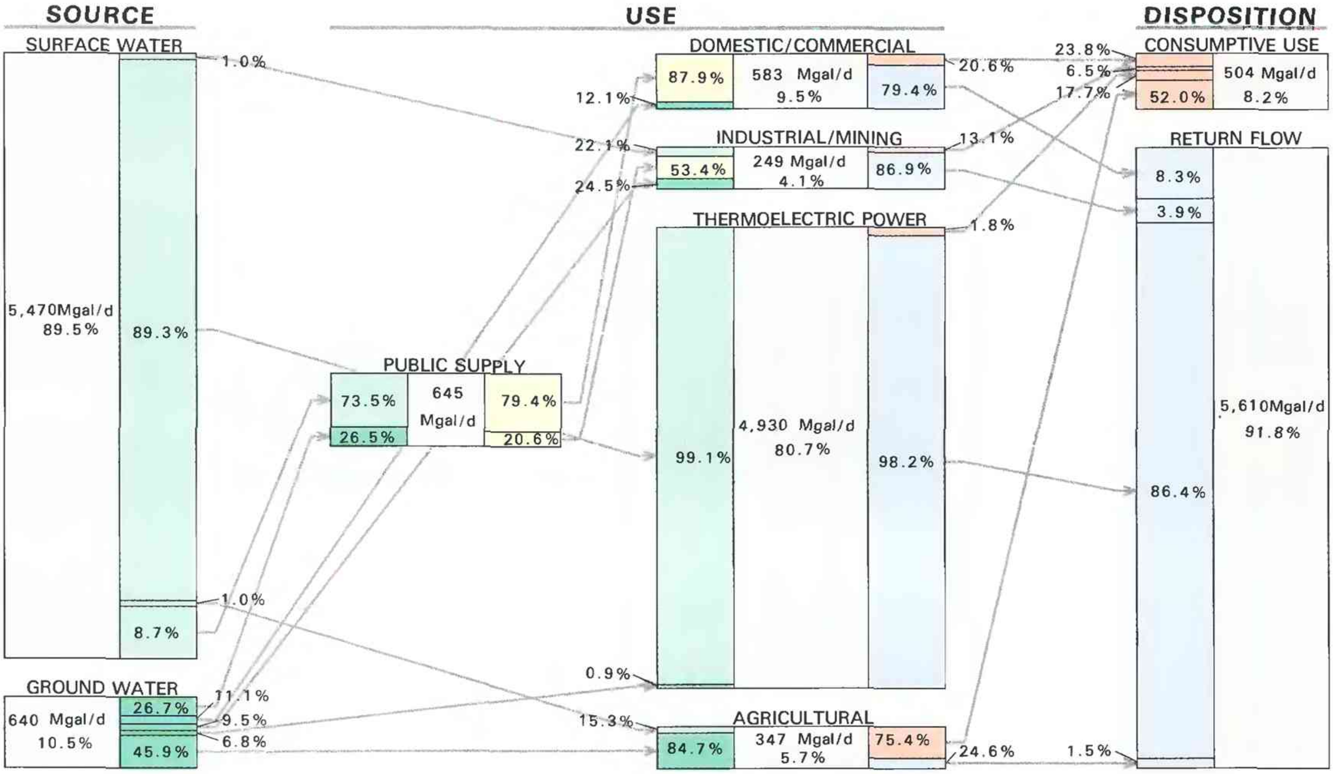


Figure 4. Source, use, and disposition of an estimated 6,110 Mgal/d (million gallons per day) of freshwater in Missouri, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

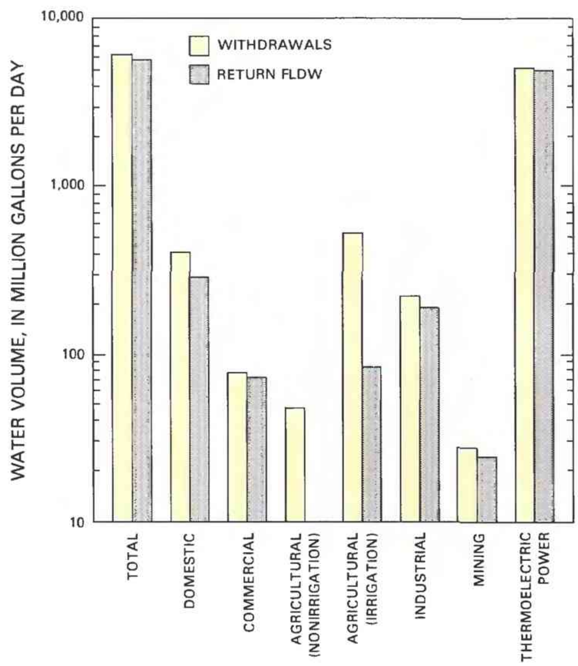


Figure 5. Freshwater withdrawals and return flow in Missouri, 1985. (Source: Data from the U.S. Geological Survey National Water Data Storage and Retrieval System.)

fied. This law regulates well standards to prevent contamination of ground water. The Division also advises prospective well owners about the size and the specifications necessary for a well to meet their objectives.

Other than major use and water-well drilling, water use is not regulated in Missouri. Water can be used for any purpose to the extent that the diversion of water is beneficial. This is consistent with the riparian doctrine of water rights.

The Department of Natural Resources periodically publishes reports related to water management. The State Water Atlas (Missouri Division of Geology and Land Survey, 1986), which was originally published in 1982, was revised in 1986. It contains data regarding surface water, ground water, and water use. In 1985, the Division of Geology and Land Survey published the Missouri Regional Watershed Assessment (Barnett and others, 1985), which evaluated water-quality and water-supply concerns by basin.

In 1984, voters of Missouri passed a one-eighth cent sales tax for soil and water conservation. These funds provide assistance to farmers for improving the efficiency of water use and for decreasing soil erosion.

The issue of water allocation between States is a concern for Missouri, which has no water compacts or treaties with other States (Waite and Skelton, 1986, p. 307). Negotiations have been conducted with representatives of Arkansas and Kansas to develop interstate water compacts regulating flow of the streams that cross State boundaries. Allocation of Missouri River water is complicated by differences in water law between the States of Missouri and Iowa, which follow a riparian doctrine, and the upstream Western States, which follow the prior-appropriation doctrine.

Hydroelectric power generation plant at Table Rock Dam, near Branson, Missouri. The plant is to the right of the spillway. In the foreground is the Shepard of the Hills State Fish Hatchery. (Photograph by Wayne R. Berkas.)

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Prepared by Dennis C. Hall, U.S. Geological Survey; History of Water Development and Water Management sections by Sarah H. Steelman, Missouri Division of Geology and Land Survey.

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 1400 Independence Road, Mail Stop 200, Rolla, MO 65401.

MONTANA
Water Supply and Use

Because Montana is transected by the northern Rocky Mountains, it receives an extremely variable, though generally sufficient, supply of precipitation. The annual precipitation ranges from about 6 inches in the driest valleys to about 100 inches in the northernmost Rocky Mountains; the average annual precipitation for the State is 15 inches. In addition to the precipitation, about 13,800 Mgal/d (million gallons per day) of water flows into Montana from other States and Canada (fig. 1*A*). Most of this inflow is from Canada into the northwestern corner of Montana.

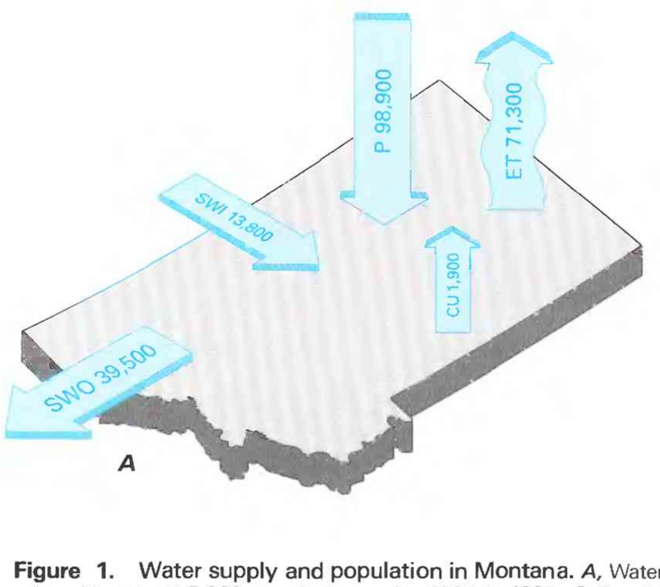
From the available supply, about 8,650 Mgal/d of freshwater was withdrawn for use in 1985. Of the water withdrawn, 97.7 percent was from surface-water sources, and 2.3 percent was from ground-water sources. Agricultural use, which was the largest category of water use, accounted for 96.5 percent of all water withdrawals. Irrigation was particularly significant in the Missouri River drainage, where five of the seven counties that have the largest withdrawals for irrigation are located. Ground water was an important source for public supply because wells provide 39.2 percent of withdrawals for public supply. Ground water also is important to industrial and mining use, and accounts for about 48.7 percent of use for that category. About 15 percent of the total ground-water use in 1985 was in Missoula County in western Montana. Of total freshwater withdrawals, 78.0 percent was returned to surface- and ground-water sources, and 22.0 percent was consumed.

The greatest water-use concern in Montana in 1985 was the statewide drought. Agriculture was severely affected; nonirrigated crops were damaged by a lack of precipitation during the early part of the growing season, and irrigated crops were affected by a shortage of irrigation water, especially in the Missouri River drainage.

Montana's population increased from about 787,000 in 1980 to about 823,000 in 1985, an increase of 4.6 percent. State officials believe that this moderate growth will continue in the near future and estimate that the population in the year 2000 will be between 850,000 and 900,000 (Phillip Brooks, Montana Department of Commerce, oral commun., 1987). This modest increase in population and its attendant increase in economic development probably will not affect Montana water use as much as the natural fluctuations in water available for irrigation.

HISTORY OF WATER DEVELOPMENT

From the time of the earliest explorers, who used the network of Montana rivers for transportation, to modern farmers and



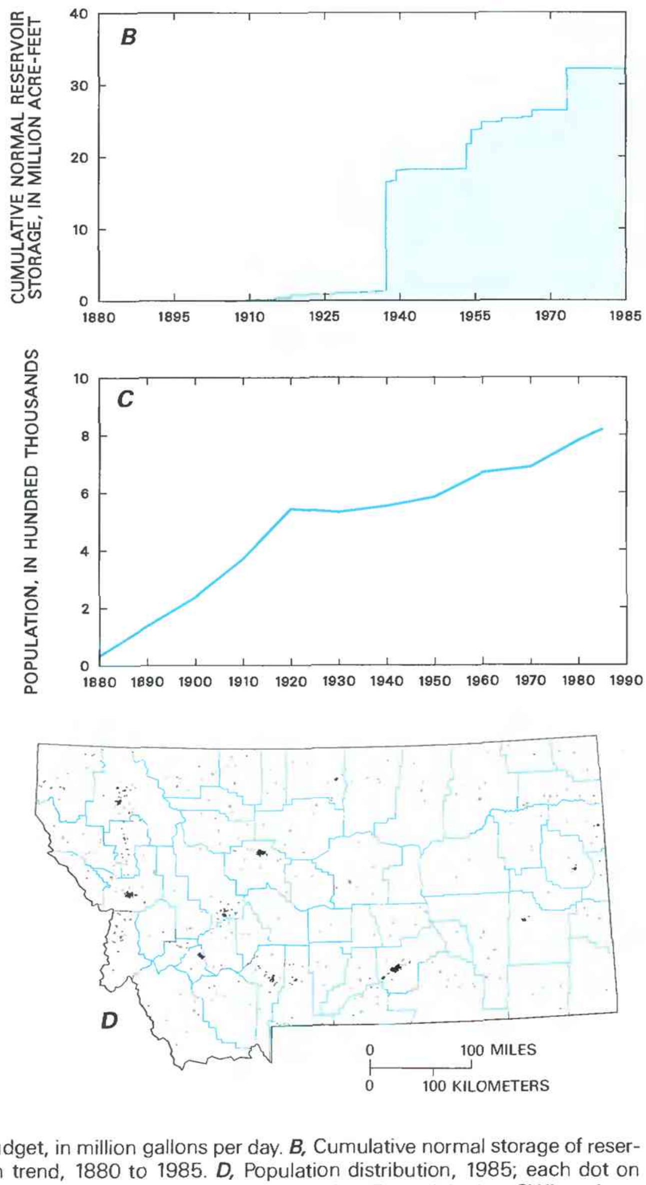


Figure 1. Water supply and population in Montana. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey and National Oceanic and Atmospheric Administration files. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

ranchers, who depend largely on irrigation, water has been a significant factor in the State's development. A "boom" in Montana's growth and economy occurred in the late 1800's when abundant lodes of gold, silver, and copper were discovered in the western mountains. The earliest water development was in response to placer gold discoveries as small streams were dammed and diverted to provide water for sluicing operations. In the early 1900's, the first large-scale dams were constructed in the upper Missouri River drainage to provide power for the expanding mining and ore-processing operations in Silver Bow, Deer Lodge, and Cascade Counties.

Soon after the earliest mining activities, the rapidly expanding railroad network reached Montana, and farmers and ranchers from the Eastern States moved into previously undeveloped areas. Because many of these areas lacked sufficient water to support agriculture, homesteaders petitioned Congress for aid in obtaining irrigation projects. Congress responded by passing the Carey Land Act in 1894, which granted 1 million acres to each Western State that would develop the land. In Montana, several irrigation projects were constructed as a direct result of the Carey Land Act.

By the mid-1930's, Montana's economy was reeling from the effects of the nationwide depression and severe drought conditions. The State Water Conservation Board was created to ease the effects of drought through the construction of water diversion and storage projects. From its inception in 1935 to its reorganization into the Montana Water Resources Board in 1968, the State Water Conservation Board was responsible for the development of about 180 small water projects (Montana Department of Natural Resources and Conservation, 1985).

Total water storage in Montana increased substantially in 1937, when the first and largest Federal multipurpose project (Fort Peck Lake, which is mainly in Valley and Garfield Counties) began storing water (fig. 1*B*). Significant increases in total water storage occurred from 1937 to 1973 as five additional Federal multipurpose projects became operational. Water use for hydroelectric-power generation has increased substantially as a result of the large Federal projects, whereas increased use for other purposes within the State has been moderate.

Population growth in Montana has not been greatly affected by the construction of water projects (fig. 1*C*). Since the end of World War II, population growth has been moderate and fairly steady, largely as a result of the slow but steady expansion of the State economy. The western one-half of the State is more densely populated than the eastern one-half (fig. 1*D*). Although the largest city, Billings, is in the eastern part of Montana, the next four largest communities are located in the western part.

WATER USE

Because of Montana's location astride the Continental Divide of the northern Rocky Mountains, the State generally receives a sufficient annual supply of water. The water budget for Montana (fig. 1*A*) indicates that surface-water outflow is substantially more than surface-water inflow. The distribution of total freshwater, surface-water, and ground-water withdrawals by county is shown in figures 2*A*, 2*B*, and 2*C*, respectively.

The areas of largest withdrawals (fig. 2*A*) are those of largest irrigation use. Almost all water withdrawn for irrigation is from surface sources, although ground-water withdrawals for irrigation are increasing in northeastern Montana, where recently discovered unconsolidated aquifers are productive. Because surface water is the predominant water source in most of Montana, the distribution of surface-water withdrawals (fig. 2*B*) closely matches the distribution of total withdrawals (fig. 2*A*). Within the major river basins, total withdrawals and irrigation withdrawals are largest in the Missouri River drainage (the Saskatchewan, Missouri Headwaters, Missouri–Marias, Missouri–Musselshell, Milk, and Missouri–Poplar basins of fig. 3*A*). Of the seven counties that have the greatest irrigation withdrawals, five (Beaverhead, Madison, Gallatin, Broadwater, and Teton) are in that drainage. In the Yellowstone River drainage, Carbon and Yellowstone Counties have the largest irrigation withdrawals; industrial and public water supply withdrawals in Yellowstone County are among the largest in Montana. The Yellowstone River drainage corresponds to the Upper Yellowstone, Bighorn, Powder–Tongue, Lower Yellowstone, and Missouri–Little Missouri basins of figure 3*A*.

Although ground-water withdrawals are only 2.3 percent of the total water withdrawals, ground water is an important source of agricultural and domestic water in many areas of the State. In addition, ground water in Missoula County is a major source of supply for industry and public supply. Most of the ground water used throughout the State (fig. 3*B*) is from western and eastern Cenozoic aquifers that consist of alluvial, glacial, and basin-fill deposits of gravel, sand, silt, and clay.

The source, use, and disposition of freshwater in Montana are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 97.7 percent (8,450 Mgal/d) of the total withdrawals was from surface-water sources in 1985. Likewise, 2.3 percent (203 Mgal/d) of the total withdrawals was from ground-water sources. The source data also indicate the percentage of water withdrawn that was used for the various uses; for example, 1.1 percent (96 Mgal/d) of the surface water withdrawn in 1985 was for public supply. Similarly, 97.7 percent (8,260 Mgal/d) of the surface water withdrawn was for agriculture.

The use data indicate how much water was used and the percentage of use provided from surface water, ground water, and public suppliers; for example, domestic and commercial uses totaled 173 Mgal/d in 1985, of which 8.9 percent (15 Mgal/d) was self-supplied from ground-water sources, 90.6 percent (157 Mgal/d) was delivered by public supply, and 0.5 percent was self-supplied from surface-water sources. The 173 Mgal/d used for domestic and commercial purposes constituted 2.0 percent of the total water use in 1985. Agriculture, which was the largest category, accounted for 96.5 percent (8,350 Mgal/d) of the total water use.

The disposition data indicate how much water was consumed and how much was returned to the hydrologic system. About 22.0 percent (1,900 Mgal/d) of the water withdrawn in 1985 was consumed, whereas 78.0 percent (6,750 Mgal/d) was returned to surface- and ground-water systems.

Nonwithdrawal or instream water use also is important in Montana. The largest instream use is hydroelectric power generation, which used 65,500 Mgal/d in 1985 to generate 10,200 gigawatt-hours of electricity. The quantity of water that passed through hydroelectric turbines in 1985 represents nearly 60.0 percent of the total surface-water supply in the State. Most of the larger hydroelectric dams are located on the larger rivers in the State, and the water passing through the turbines is reused at downstream sites.

Although hydroelectric power generation is commonly considered to be a nonconsumptive water use, the large reservoirs required to impound the water are subject to large evaporation loss. During 1985, the estimated evaporation loss from constructed reservoirs was 3,000 Mgal/d, which greatly exceeded all other consumptive uses (fig. 5).

Although difficult to quantify, instream use for fish and wildlife, water quality, channel maintenance, and recreation also is important in Montana. An administrative process for reserving flow for instream needs has been developed, and instream flow reservations have been established for the Yellowstone River drainage. The instream flow reservation process also is presently underway for the Clark Fork (Kootenai–Pend Oreille–Spokane basin of fig. 3*A*) and the Missouri River drainages.

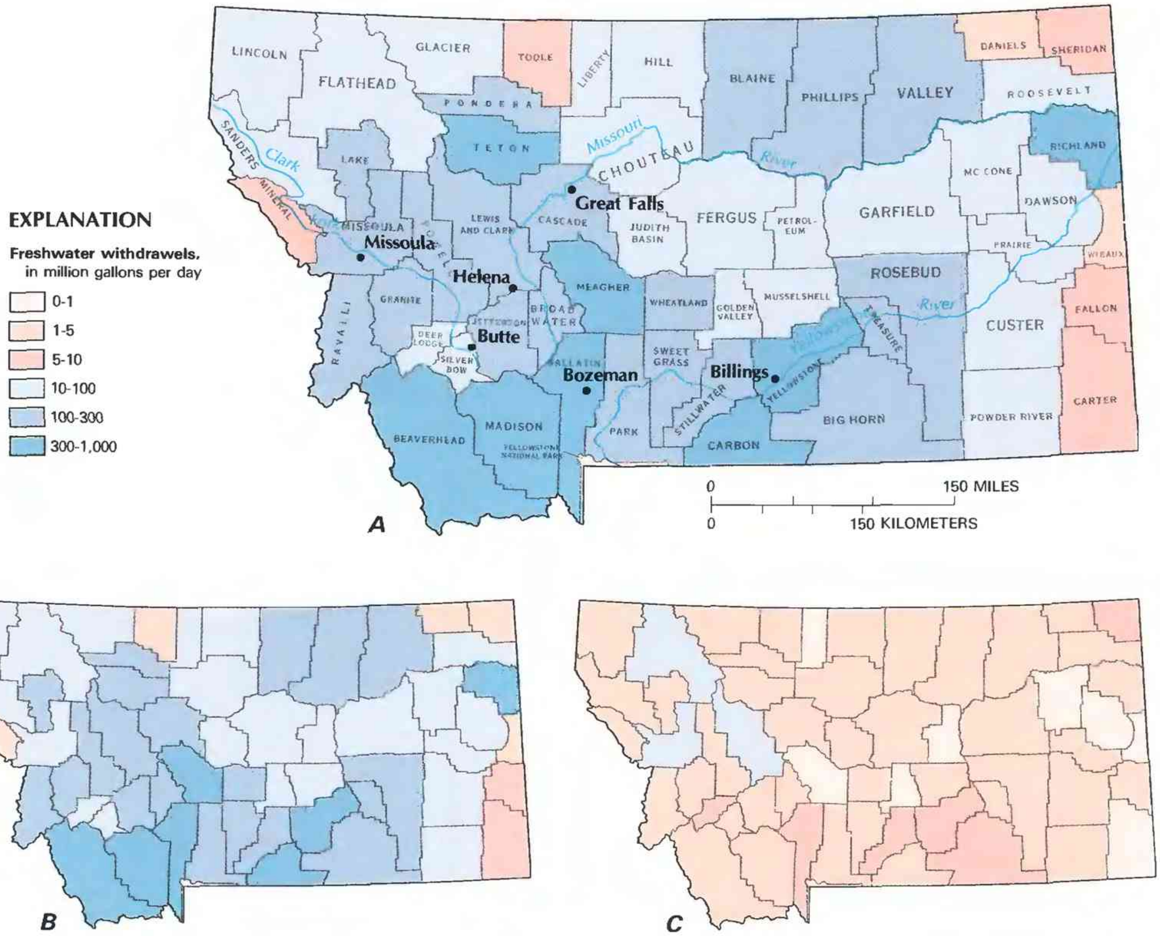


Figure 2. **Freshwater withdrawals by county in Montana, 1985.** *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. Virtually all water supplied by public-supply systems in Montana is for domestic and commercial uses. About 75 percent of the population receives water for domestic use from public-supply systems. In 1985, the total water withdrawn by public suppliers was about 158 Mgal/d, which is 1.8 percent of the total State withdrawals. Most large communities in Montana are near streams of good-quality water (acceptable for human consumption and most uses); for example, Billings, Bozeman, Butte, Great Falls, and Helena depend solely on surface water for public supply. Missoula, Montana's third largest community, uses only ground water for public supply because of contamination of its surface-water source by *Giardia lamblia*, an intestinal parasite. Statewide, withdrawals by public suppliers included about 96 Mgal/d from surface-water sources and about 62 Mgal/d from ground-water sources.

In 1985, withdrawals for public supply were 10.5 percent larger than in 1980. The difference is attributed to increased lawn and garden watering because of the drought in 1985 and to the estimated 4.6 percent population increase from 1980 to 1985. Future increase in public-supply use is expected to be slight. Increases due to population growth and the development of new water systems are likely to be offset by a decrease in domestic use that is a result of increasing costs of maintaining and renovating old supply systems.

DOMESTIC AND COMMERCIAL

Domestic and commercial water users receive water from public-supply systems and self-supplied facilities. The combined use in 1985 was 173 Mgal/d, including delivery-system losses of about 38 Mgal/d. About 3.2 percent (60 Mgal/d) of the 135 Mgal/d delivered was consumed.

Domestic water use was about 106 Mgal/d (discounting delivery losses), of which about 90 Mgal/d was received from public-supply systems. Per capita use of water provided by public-supply systems was 147 gallons per day. Water restrictions were placed on some communities in 1985 because of the drought; such activities as washing cars and watering lawns generally were allowed only on alternate days.

Self-supplied domestic water is obtained mainly from wells, although springs serve as a source in a few areas. In a few rural parts of eastern Montana, potable water must be hauled from outside sources because the local sources are unusable.

Domestic water use accounted for about 1.2 percent of the State's total withdrawals in 1985. Domestic water use is about the same as in 1980 and is likely to remain about the same in the future because of a modest projected population increase.

Commercial water use in 1985 totaled about 29 Mgal/d, nearly all of which was delivered from public-supply systems. Commercial water use was 0.3 percent of Montana's total withdrawals. As

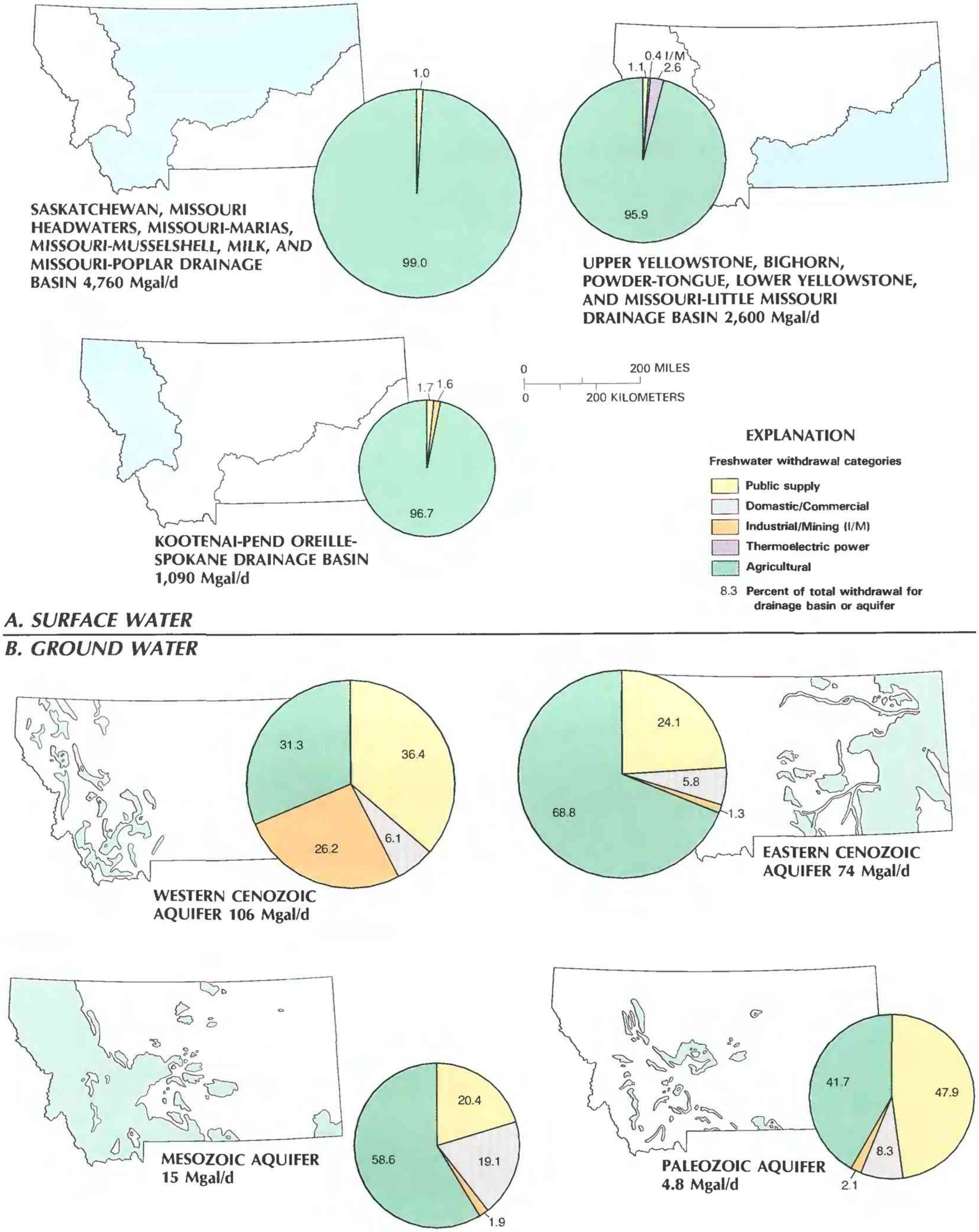


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Montana, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files; aquifer maps from U.S. Geological Survey, 1985, p. 287.

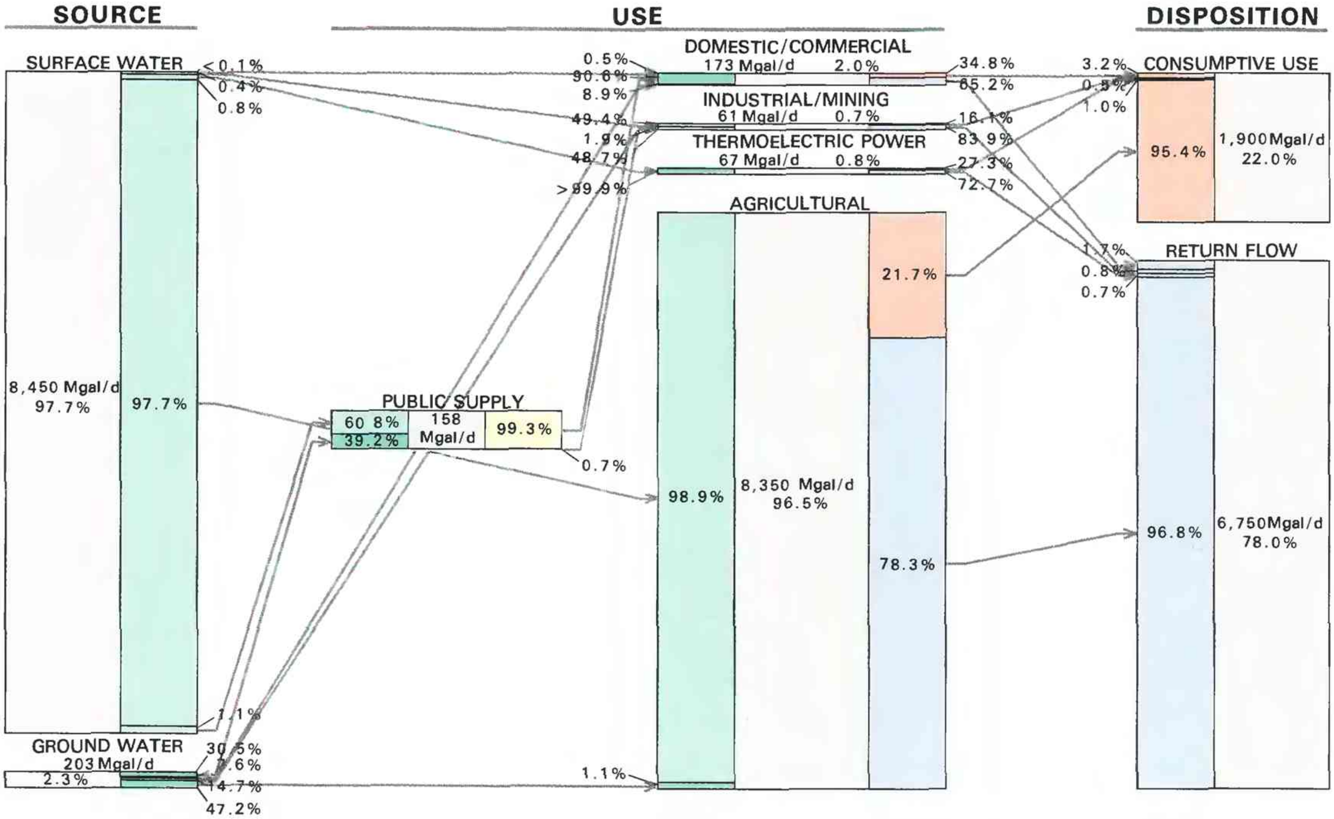


Figure 4. Source, use, and disposition of an estimated 8,650 Mgal/d (million gallons per day) of freshwater in Montana, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

in the case of domestic water use, commercial water use demand is expected to remain about the same in the near future. Increased demand resulting from moderate population growth is expected to be offset by decreases in use because of conservation measures and increasing cost of public supplies.

Industrial and Mining

In 1985, water withdrawals for industrial uses were 57 Mgal/d and for mining uses were 4.2 Mgal/d. All but 1.9 percent of the water used by industry and mining is self-supplied and is obtained about equally from surface- and ground-water sources. Consumptive use for industry and mining was 16.1 percent (9.8 Mgal/d) of withdrawals.

The largest withdrawals for industry were in western Montana, where most of the water was used for manufacturing of wood products, which includes pulp and paper production. Although most wood-product plants use surface water, the largest plant in the State relies exclusively on ground water. The petroleum- and sugar-refining industries also used significant quantities of water, most of which was surface water. Almost all petroleum and sugar refining is in eastern Montana, mostly in and near Billings.

Mining activities that used water in 1985 included a large silver and copper mine in northwestern Montana, several gold mines in southwestern Montana, several large coal mines in southeastern Montana, and many scattered small operations that mine various minerals. The large copper mines in Butte, which had been a mainstay of Montana's economy for many years, were not operating in 1985 and used little water.

Water withdrawals by industry and mining in Montana represent 0.7 percent of the total withdrawals. Industrial water use is not expected to change significantly in the future because increased conservation is expected to offset any increases due to new or expanded industrial operations. Water use for mining may increase substantially in the future if the presently inactive mines in Butte reopen. Even so, industrial and mining water use is not expected to increase substantially as a percentage of total use.

Thermoelectric Power

In 1985, Montana had seven fossil-fueled thermoelectric power generation facilities in operation; six of the plants are coal-fired facilities in the coal-rich southeastern part of the State, and one is a small lumber waste-fired plant in the densely timbered northwestern corner of the State. In 1985, the seven plants withdrew 67 Mgal/d from surface-water sources (fig. 4). Virtually all water used by the thermoelectric plants was for cooling. Six of the facilities use once-through cooling, where consumptive use is negligible. The largest plant, however, continually recycles cooling water so that all water withdrawn is eventually consumed. Overall, consumptive use was 27.3 percent of the total water withdrawn for thermoelectric power generation.

Withdrawals for thermoelectric power generation in Montana in 1985 represented 0.8 percent of total withdrawals. This percent-

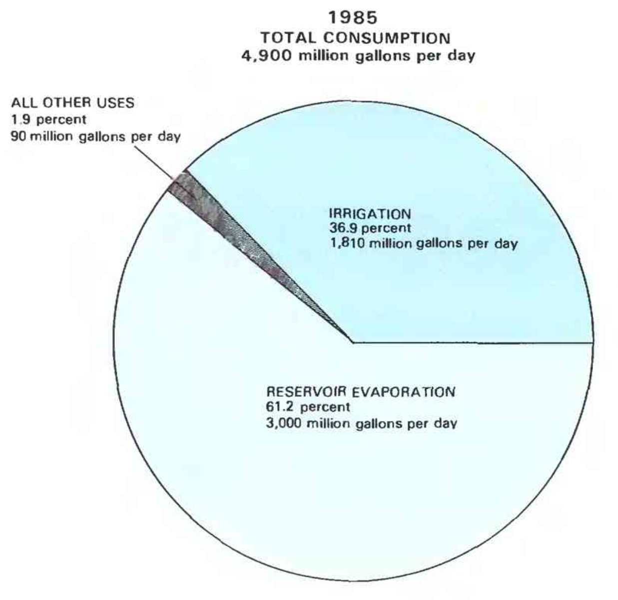


Figure 5. Instream and offstream consumptive use in Montana, 1985. (Sources: Reservoir evaporation data from Montana Department of Natural Resources and Conservation, 1986. All other consumptive use data from Solley and others, 1988.)

age is about the same as in 1980 and is not expected to change significantly in the near future.

AGRICULTURAL

Withdrawals for agriculture in Montana account for 96.5 percent of all withdrawals. Irrigation water withdrawals dominate not only agricultural withdrawals, but all combined categories of offstream use. Total withdrawals for agriculture in 1985 were 8,350 Mgal/d, of which 8,300 Mgal/d was used for irrigation.

In 1985, Montana had a water-short year in most places. Mountain snow, the source of most irrigation water, had less-than-average water content at most reporting sites in April. Rainfall also was less than average from May to July, when normally about one-half of the yearly precipitation is received. June was reported to be the driest ever recorded in some areas (U.S. Geological Survey, 1986b). The net result was a decrease in irrigated acreage in some areas and crop losses in others because the limited water supply could not overcome the large deficit caused by the drought. Areas most affected by the water shortages were all within the Missouri River drainage. The statewide weather pattern changed near the end of August, bringing abundant rainfall to most of Montana. Ironically, the late rains generally hindered harvesting of the crops that survived the drought.

Largely because of shortages in water supply resulting from the drought, the total withdrawals for irrigation in 1985 (8,300 Mgal/d) were about 5,130 Mgal/d less than the estimated withdrawals in 1980 (Montana Department of Natural Resources and Conservation, 1986). In 1985, irrigated acreage was about 2.3 million acres compared with an estimated 2.9 million acres irrigated in 1980. Ground-water withdrawals for irrigation in 1985 were about 1.1 percent of the total agricultural withdrawals, which is about the same percentage reported in 1980. Of the 2.3 million acres under irrigation in 1985, about 1.6 million acres (70.0 percent) were flood irrigated, and the rest were sprinkler irrigated. Because flood irrigation is less efficient than sprinkler irrigation, irrigation conveyance losses are large and amount to about 51.4 percent of the total irrigation withdrawals. Improving irrigation efficiency would result in more water being immediately available for withdrawal but would also decrease return flows. In many basins, the late-season return flows constitute an important source of irrigation supply at a critical stage of crop growth.

In Montana, the major irrigated crop is alfalfa, which is used for winter feeding of livestock. Other irrigated crops include wheat, barley, oats, other small grains, sugar beets, corn, and cherries. Additional surface-water irrigation development seems unlikely in the near future because of the high cost and the generally uncertain economic outlook for farming. Some additional ground-water sources may be developed, but increasing energy costs may preclude large increases in ground-water irrigation. In the future, total withdrawals for irrigation are expected to be larger than withdrawals for irrigation in 1985, but significant long-term change appears to be unlikely.

In 1985, agricultural withdrawals for livestock and other farm uses amounted to 50 Mgal/d. About 68.8 percent of this quantity was from surface-water sources and about 31.2 percent was from ground-water sources. In 1985, reported withdrawals for nonirrigation uses (50 Mgal/d) were greater than reported withdrawals in 1980 (28 Mgal/d) (Solley and others, 1983) primarily because of more comprehensive data on livestock water needs for 1985 than for 1980. Nonirrigation agricultural water use may increase in the future if the livestock market improves.

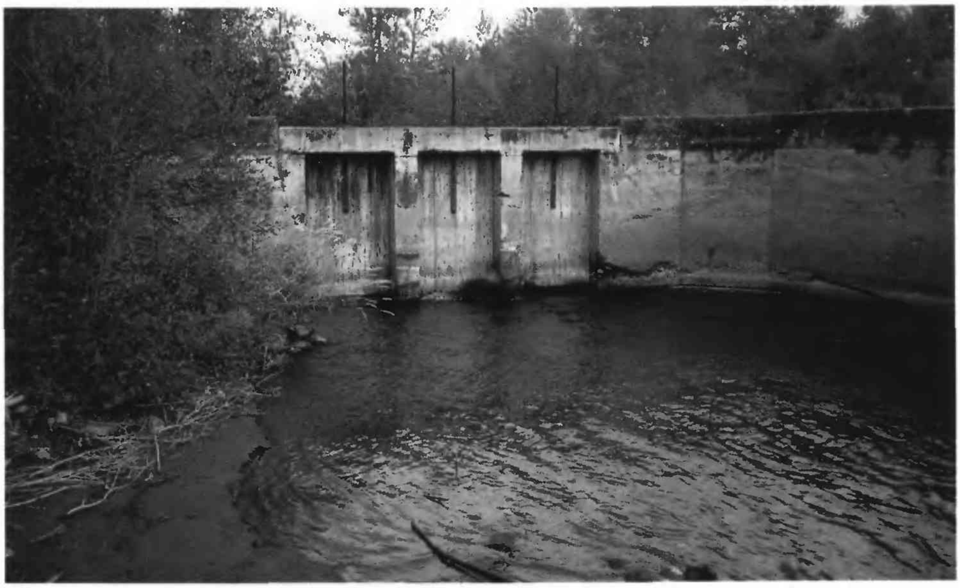
Although Montana is generally considered to be water sufficient, the drought of 1985 and its effect on the agricultural economy are reminders that adequate supplies of water are not always available at the right time and place. Consideration of these vagaries of nature is important in planning for future water use.

WATER MANAGEMENT

Several State agencies share responsibilites for management of Montana's water resources. The Montana Department of Natural Resources and Conservation (DNRC) has overall responsibility for water-resources planning and also is charged with administering the 1973 Montana Water Use Act, which is a water-rights permitting program based on the doctrine of prior appropriation. The Water Use Act requires that surface- and ground-water development after July 1, 1973, be subject to the issuance of a permit by the DNRC. Although ground-water withdrawals are expressly included in the Water Use Act, wells that have anticipated withdrawal rates less than 100 gallons per minute are exempted from the permit requirements. A permit allowing the proposed development is issued provided that the following criteria are met:

1. The amount of water requested is unappropriated and available at the times the applicant proposes to use it,
2. The proposed means of diversion or construction are adequate,
3. The proposed use of water is beneficial, and
4. The proposed use will not unreasonably interfere with other planned uses or developments for which a permit has been issued or for which water has been reserved.

Before 1973, water withdrawals were not subject to a permit system, and a right to use water could be established by simply putting the water to use. Because no legal filings or recordings were required, it became impossible to discern priority dates and whether claimed rights were legitimate. Consequently, in 1979, the Montana Legislature enacted a measure to adjudicate all water rights before 1973. Any person claiming a water right had to present a claim to the DNRC by June 30, 1983. A copy of the claim was then filed with one of four specially created water courts that examine all claims within a particular basin and issue a preliminary decree. Following an opportunity for objections and appeals by all affected parties, the water court judge then issues a final decree establishing adjudicated water rights in the basin. By the end of 1986, preliminary or final decrees had been issued for 40 of the 85 basins in Montana (James Kindle, Montana Department of Natural Resources and Conservation, oral commun., 1987).



Surface-water diversion structure on the Gallatin River, Gallatin County, Montana. Structure is typical of older diversions in many locations in Montana. (Photograph by D.R. Johnson.)

Because of uncertainty about the status of Indian and Federal water rights under State law, the Montana Legislature established a Reserved Water Rights Compact Commission to negotiate water rights compacts with the various Indian tribes and Federal agencies. To date, one compact allocating waters within the Fort Peck Indian Reservation in the Missouri River drainage has been approved by the tribe and the Montana Legislature.

International treaties between the United States and Canada that affect Montana streams include the Boundary Waters Treaty of 1909 and the Columbia River Treaty of 1964. As of 1987, one interstate compact governing the Yellowstone River basin among Montana, North Dakota, and Wyoming was in effect.

Other State agencies that have regulatory responsibilities affecting the use of water include the Montana Department of Health and Environmental Sciences, which is responsible for regulating the quality of lakes, streams, and ground-water resources; the Montana Department of Fish, Wildlife and Parks, which reviews proposed water-resources projects to ensure that fish and wildlife resources are not damaged; and the Department of State Lands, which is responsible for the use of water on various State-owned lands and administers various mining-reclamation acts that indirectly affect water use. The Montana University System Water Resources Research Center is the center of academic oriented water research in Montana and coordinates and directs specialized research, sometimes at the request of water-management and regulatory agencies. In addition, the Montana Bureau of Mines and Geology conducts applied research studies of ground-water resources, and the University of Montana Biological Station at Flathead Lake (Flathead and Lake Counties) conducts water-quality research studies.

All foregoing agencies actively cooperate with the U.S. Geological Survey to collect and interpret ground- and surface-water data and to conduct hydrologic investigations throughout the State. The DNRC also has a specific cooperative program with the U.S. Geological Survey to collect, interpret, and disseminate water-use data for all major water use categories. Because accurate and current information on water use is fundamental to sound water-resources management, the cooperative water use program will have a significant role in the development of water resources in Montana.

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Prepared by Charles Parrett and D.R. Johnson

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 428 Federal Building, 301 South Park, Drawer 10076, Helena, MT 59626

NEBRASKA
Water Supply and Use

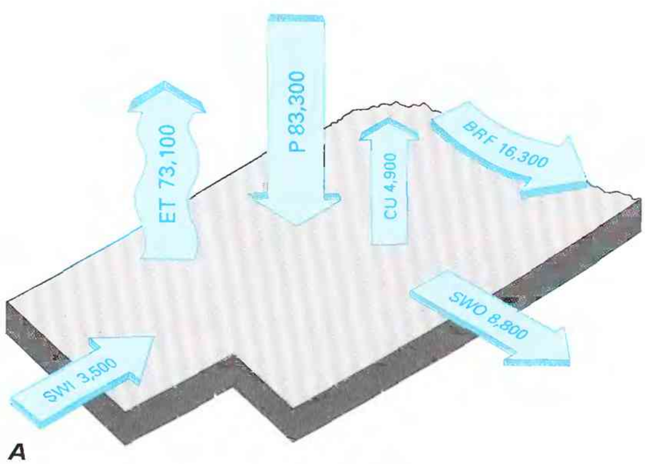
Nebraska was once described as being part of the "Great American Desert" (Dick, 1975, p. 6). Settlers, however, were able to use the fertile soils and the water from precipitation and irrigation to develop Nebraska into a leading agricultural State. Precipitation provides about 83,300 Mgal/d (million gallons per day) but ranges greatly, from about 15 inches in the panhandle in western Nebraska to about 30 inches in southeastern Nebraska. Surface- and ground-water resources furnish ample water supplies for most parts of the State (fig. 1*A*). The Platte, the Republican, and the Niobrara River flow eastward across much of the State. Large river systems such as the Loup, the Big Blue, and the Elkhorn originate within Nebraska. Water also is available from the Missouri River, which borders the State on the northeastern and eastern sides.

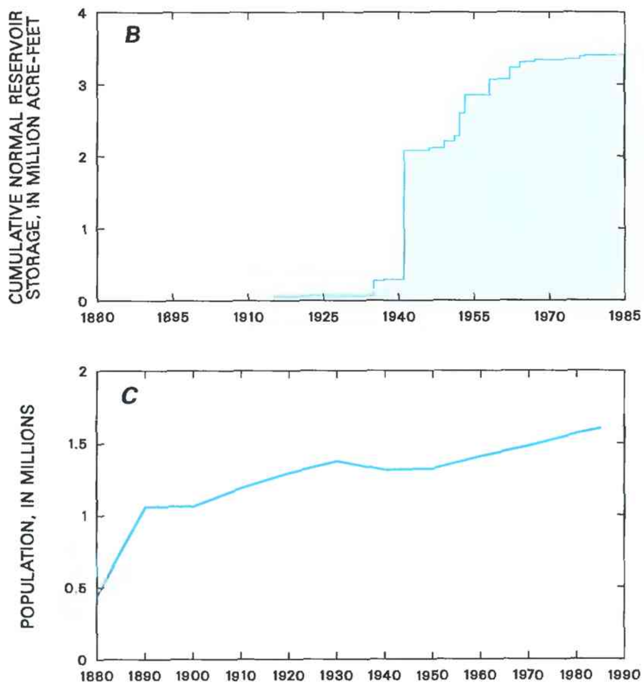
Most of Nebraska is underlain by the High Plains aquifer, which supplies 92 percent of all ground water used. Most of this water is withdrawn for irrigation (Steele, 1988). The available fresh ground water in storage in Nebraska could supply the total offstream water use for the entire United States for about 4 years (Bentall and Shaffer, 1979).

In Nebraska, 44.3 percent of all offstream use of water is supplied by surface water; the remaining 55.7 percent is supplied by ground water. Most of the offstream use of water is for agricultural purposes, which accounts for 47.3 percent (2,100 Mgal/d) of the surface-water withdrawals and 94.6 percent (5,290 Mgal/d) of the ground-water withdrawals. In 1985, there were 7.48 million acres of irrigated land. Surface water from canal and pump diversions and ground water from more than 71,000 irrigation wells furnished most irrigation water (Ellis and Pederson, 1986). Omaha, the largest city in Nebraska, withdrew about one-half of its public-water supply from the Missouri River. All but four communities used ground water for public supply.

Water for domestic and commercial use is supplied from private and public sources. Domestic use is estimated to be 87 gal/d (gallons per day) per capita from private supply and 112 gal/d per capita from public supply. Industry and mining represent a small part of offstream water use. Sugar-beet processing is the major industrial user. The major mining use is for operation of gravel pits and limestone quarries. Water is used offstream to generate thermoelectric power at 21 fossil-fueled and 2 nuclear powerplants. Most of the water withdrawn for thermoelectric cooling is supplied by surface water; this category represents 22.0 percent of all offstream uses.

Although most supplies of surface and ground water are abundant, declining ground-water levels in southwestern Nebraska and the leaching of agricultural chemicals and nitrates to the shallow aquifers are causing concern. In some of these areas, State and local





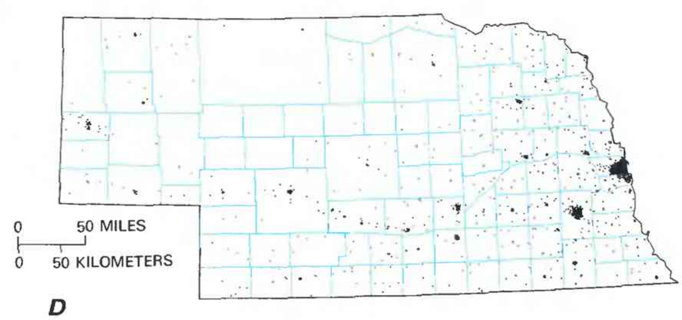


Figure 1. Water supply and population in Nebraska. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Compiled by U.S. Geological Survey from National Oceanic and Atmospheric Administration data. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

agencies have established restrictions in the form of ground-water control areas to manage available water resources for future use.

HISTORY OF WATER DEVELOPMENT

During the early 1800's, the stream and river valleys of Nebraska became pathways to the west for explorers, traders, and fur trappers. During 1819–20, Major Stephen Long, who led an Army expedition, described the plains area between the Missouri River and the Rocky Mountains as almost wholly unfit for cultivation, and of course uninhabitable by a people depending upon agriculture for their subsistence." (Dick, 1975, p. 6). Most of the plains area was considered to be Indian country, and non-Indians without Government license were not allowed to settle on Indian lands. The creation of the Nebraska Territory in 1854 changed this policy, and, by 1856, the non-Indian population was more than 10,000 (Olson, 1966).

Two events affected the settlement of Nebraska—the enactment of the Homestead Act in 1862 and the construction of the transcontinental railroad across Nebraska in 1866–67. On January 1, 1863, the Nation's first entry under the Homestead Act was made by Daniel Freeman for 160 acres in Gage County, Nebraska. During the next 32 years, 68,862 individuals received patents for more than 9.6 million acres in Nebraska. The railroad provided a means for new settlers to move westward and made it easier for them to market their crops and livestock.

Most early settlements were along streams, where water was available for domestic and livestock use and to operate grain mills. During the 1800's, most surface-water irrigation was in the arid western part of the State. The first recorded irrigation was during the early 1860's in Lincoln County (Fine, 1956). The Bickel and the Owasco Canals in Kimball County had the earliest water right (December 31, 1876) for use of surface water for irrigation (Nebraska Department of Water Resources, 1986). The first uniform and inclusive water-rights laws were enacted in 1895. In the late 1800's and early 1900's, many low-head hydroelectric powerplants were built throughout Nebraska. Some of these plants used stream appropriations from earlier water-powered grain mills.

Most of the early irrigation depended on surface-water diversions during the growing season. The first major use of off-season storage was in 1910 with the completion of the Pathfinder Reservoir on the North Platte River in south-central Wyoming. Some of the spring runoff stored in the reservoir was released for irrigation in the North Platte River valley in western Nebraska.

In 1933, the State legislature passed a bill authorizing the formation of public power and irrigation districts. The Central Nebraska Public Power and Irrigation District completed Kingsley Dam in 1941, which created Lake McConaughy (fig. *1B*). Kingsley Dam, just north of Ogallala, stores water diverted from the North Platte River for the irrigation of more than 200,000 acres in south-central Nebraska. Since 1946, most development of surface water for irrigation has been through pumping and storage and diversion systems built by the U.S. Bureau of Reclamation in the Republican, the Niobrara, and the Loup River basins.

Development of ground-water resources for irrigation in Nebraska has paralleled the development of well-drilling methods, pumping equipment, and distribution systems for applying the water. Before 1900, windmills were commonly used to pump water from shallow hand-dug wells (Barbour, 1899). During the early 1900's, improved drilling methods and the use of gasoline-powered pumps made it possible to obtain ground water from deeper wells for irrigation along stream valleys (Slichter and Wolff, 1906). During the late 1940's, many irrigation wells were drilled in the upland areas of Box Butte County, in the panhandle, and in the upper part of the Big Blue River basin. The major impetus for development of ground water for irrigation, however, was the drought of the mid-1950's. By 1957, there were more than 23,000 irrigation wells, which was more than a 150-percent increase over the number in 1952. The development of center-pivot irrigation systems made irrigation with ground water possible in areas where topography or soils were not favorable for gravity-irrigation systems.

Total population increased (fig. *1C*) at the same time as the increase in irrigation development and irrigated acreage. However, much of the population moved from rural to urban areas (fig. *1D*), and operations shifted from small to large farms. The result was a change in water use from self-supplied domestic and livestock use to public-supplied domestic use. Power generation and irrigation water use also increased.

WATER USE

Overall, the State has an ample supply of water available from surface- and ground-water resources. The water budget (fig. *1A*) shows large inflows of surface water from other States and from the Missouri River on the eastern border. Inflow of 3,500 Mgal/d reflects the 1985 stream and canal inflow plus the withdrawals from the Missouri River for public supply and thermoelectric cooling. Precipitation provides 83,300 Mgal/d. Surface-water outflows are about 2.5 times the surface-water inflows. Outflow of 8,800 Mgal/d includes stream and canal outflow and return flow to the Missouri River.

Major areas of water withdrawals are distributed across the State (fig. *2A*). Total withdrawals are largest in Lincoln, Scotts Bluff, and Douglas Counties. Total withdrawals, are smallest in Grant, Hooker, and Pawnee Counties. Major surface-water withdrawals (fig. *2B*) occur in Washington, Cass, and Nemaha Counties for thermoelectric power generation along the Missouri River and in the Platte River valley for irrigation. The withdrawals of surface water for irrigation are largest in the North Platte River in western Nebraska (fig. *3A*). Agricultural use in this basin accounted for 99.0 percent of all withdrawals. The Lower Missouri–Little Sioux basin, where 96.0 percent of the water is withdrawn for thermoelectric cooling, is the area of second-largest withdrawals.

Recoverable supplies of ground water suitable for domestic and agricultural use have been estimated to be 1,880 million acre-feet (Bentall and Shaffer, 1979). Ground-water withdrawals (fig. *2C*) reflect large irrigation use in Holt County in north-central Nebraska and in many counties in the southwestern part of the State.

The High Plains aquifer underlies approximately 84 percent of Nebraska (fig. *3B*) and provides 94.7 percent of all ground-water withdrawals for agriculture and 92 percent of ground-water withdrawals for all uses in the State. The aquifer has a greater average thickness and larger areal extent in Nebraska than in other High Plains States (South Dakota, Wyoming, Colorado, Kansas, Oklahoma, Texas, and New Mexico). The saturated thickness exceeds 1,000 feet in some areas of the Sand Hills in north-central Nebraska (Weeks and Gutentag, 1981). In eastern Nebraska, the Valley alluvial, the Paleovalley alluvial, the Niobrara, and the Dakota aquifers are major sources of ground water. Withdrawals for agricultural use account for 67 percent of the water produced from these aquifers, and withdrawals for public supplies are 24.8 percent of total use. Public supplies for Omaha and Lincoln are obtained from the valley alluvial aquifers associated with the Platte River. The Dakota aquifer is used mainly by farmers in the northern and eastern parts of the State for agricultural purposes and for public supply.

Major water concerns in Nebraska are associated with water use and environmental issues. A major surface-water issue is the effect of irrigation development on flows in the Platte River and the subsequent effect on habitat for the endangered whooping crane and other wildlife species. A major ground-water concern is the increasing contamination from nonpoint-source agricultural activities.

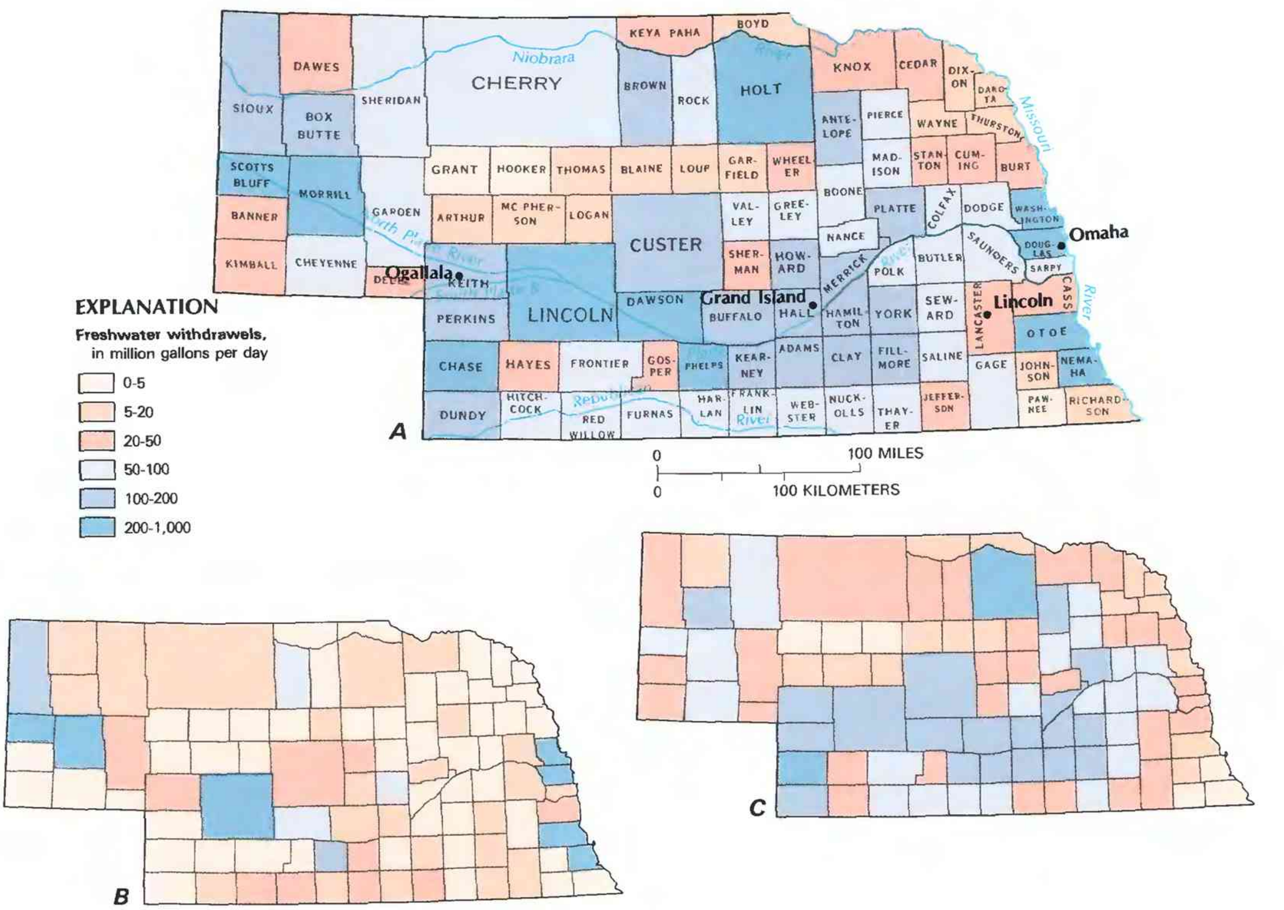


Figure 2. Freshwater withdrawals by county in Nebraska, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

The source, use, and disposition of surface and ground water during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The diagram indicates that surface water provided 44.3 percent (4,450 Mgal/d) of the water withdrawn in the State; 47.3 percent (2,110 Mgal/d) was withdrawn for agricultural purposes. Ground water provided the remaining 55.7 percent (5,590 Mgal/d); 94.6 percent (5,290 Mgal/d) of this water was withdrawn for agriculture. Of the water used by agriculture, 28.5 percent (2,110 Mgal/d) was surface water, and 71.5 percent (5,280 Mgal/d) was ground water. Agriculture accounted for 97.2 percent (4,770 Mgal/d) of the total water consumed.

The only major instream water use is for the production of hydroelectric power. This instream use is not included in figure 4. Hydroelectric power systems used 7,080 Mgal/d of water to generate 683 gigawatthours of electricity, which is 14 percent of all electrical power generated for the State. Hydroelectric power is generated by pass-through turbine systems, which consume little or no water.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. Public supply is used by more than 450 communities in Nebraska. In 1985, withdrawals for public supply totaled 248 Mgal/d, of which 15.9 percent (39 Mgal/d) was from surface water and 84.1 percent (209 Mgal/d) was from ground water. Use of water for public supply generally remained constant from 1980 to 1985 (increased of 0.5 percent) which compares with an increase in population of 2.2 percent (Steele, 1988).

In several areas, communities have reported increased concentrations of nitrates in water from city wells. The Federal maximum contaminant level for drinking water—10 mg/L of nitrate-nitrogen (U.S. Environmental Protection Agency, 1986)—has been exceeded in the public supplies of some of these communities. As a result, the suppliers have been forced to abandon wells, drill deeper wells, relocate well fields, and, in some instances, provide bottled water to customers.

Domestic and Commercial

Domestic and commercial use was 2.2 percent of withdrawals (224 Mgal/d) during 1985 (fig. 4). Domestic use totaled 173 Mgal/d, of which 149 Mgal/d was provided by public suppliers and 24 Mgal/d was self-supplied. The per capita use of water for public supply was 112 gal/d, and the per capita use of self-supplied water was 87 gal/d. The overall average per capita decrease in domestic water use from 191 gal/d in 1980 to 108 gal/d in 1985 can be attributed partly to a change in reporting methods and partly to reductions in such uses as lawn and garden watering due to greater than average precipitation in 1985 (Steele 1988.)

Commerical use of water in 1985 totaled 51 Mgal/d, of which almost all was delivered by public-supply systems. Ground water was the exclusive source of water for self-supplied commercial use.

Industrial and Mining

In 1985, industrial and mining use totaled 2.2 percent of withdrawals (216 Mgal/d). About 97 Mgal/d of industrial water was

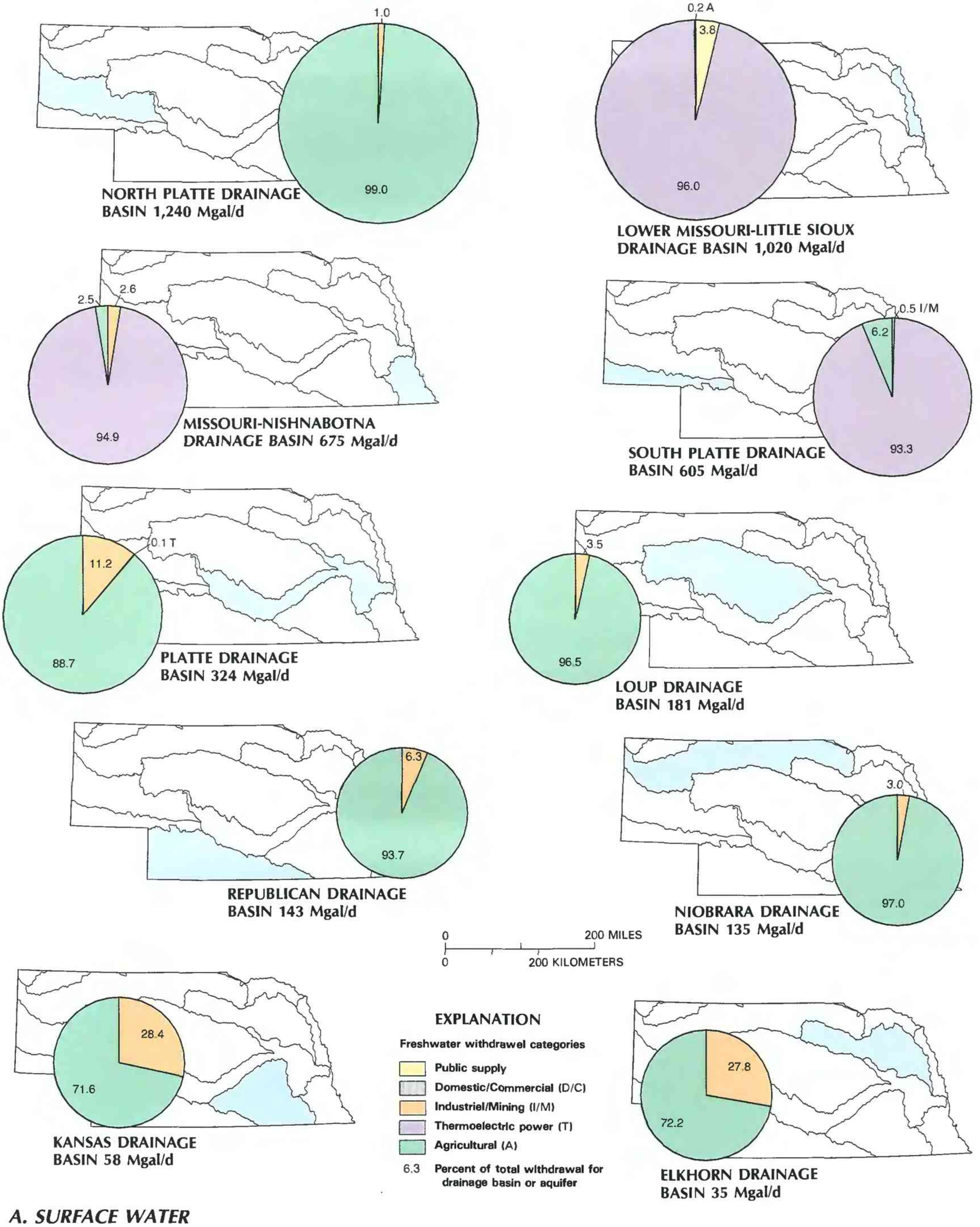


Figure 3. **Freshwater withdrawals by category of use and hydrologic unit in Nebraska, 1985.** *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

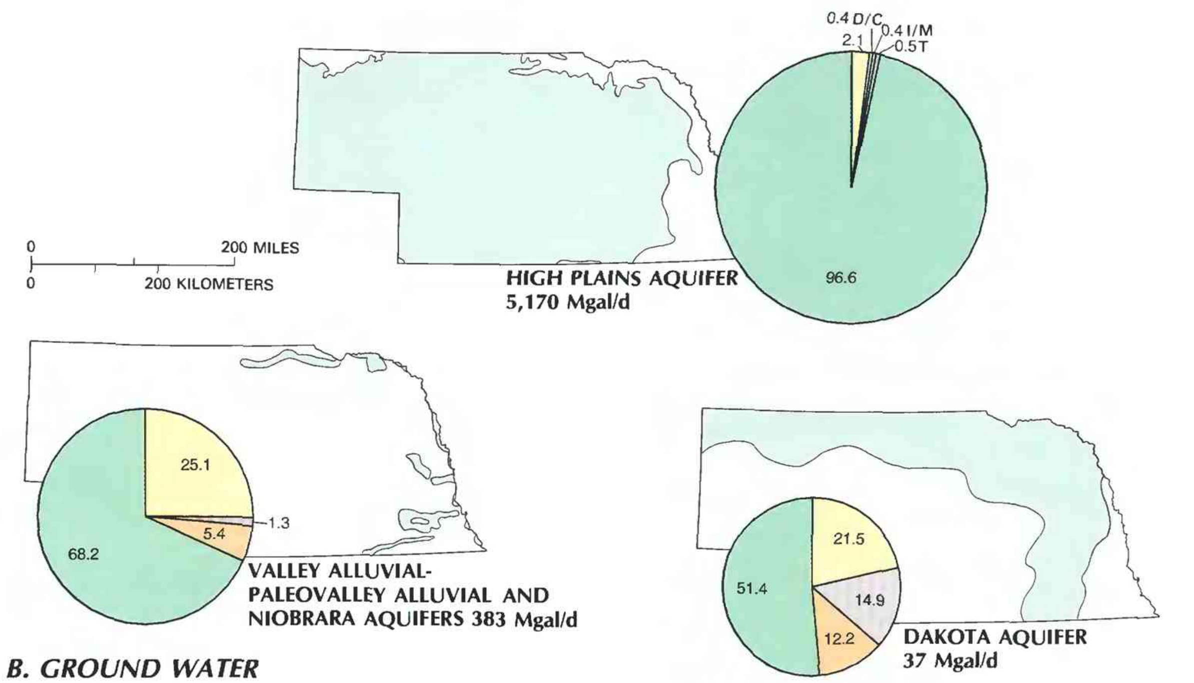


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Nebraska, 1985—Continued.

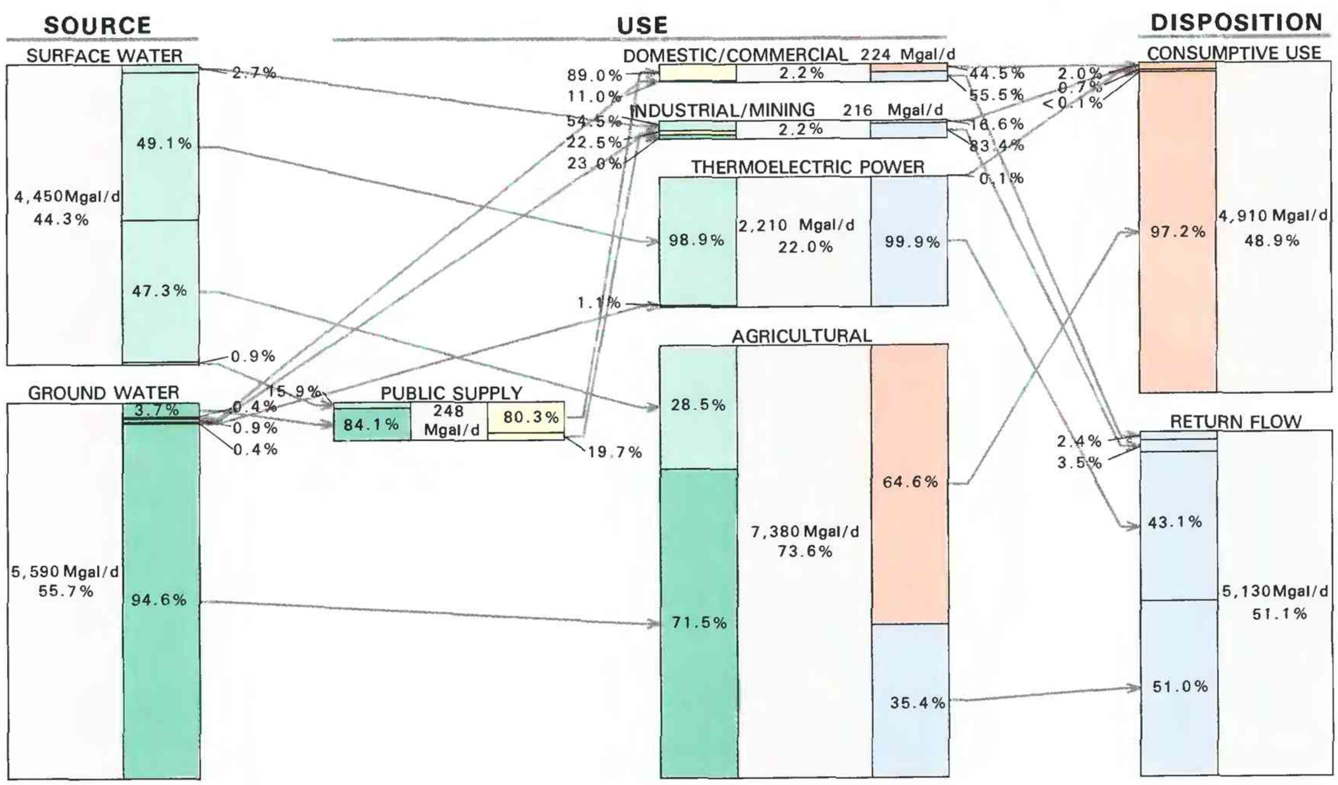


Figure 4. Source, use, and disposition of an estimated 10,000 Mgal/d (million gallons per day) of freshwater in Nebraska, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

self-supplied, and the remaining 3 percent was public supply. Self-supplied industrial use accounted for 48 Mgal/d; 7.2 Mgal/d was from surface water, and 41 Mgal/d was from ground water. Public supply provided the remaining 19.7 percent (49 Mgal/d) of water for industrial uses.

Major industrial uses of water occur at various locations across the State in a variety of industries. In the panhandle, sugar-beet processing is a significant water user; in many urban and rural locations, the meatpacking industry uses large amounts of water in the processing of cattle, hogs, and turkeys. Soymeal processing also uses large quantities of water.

In 1985, estimated withdrawals for mining operations were 119 Mgal/d. Of that amount, 93 percent (111 Mgal/d) was self-supplied by surface water, mainly for quarrying and gravel-washing operations at more than 220 sites. Three operational pits provided clay for brick and tile plants in Omaha, Lincoln, and Endicott (Cathy Brown, Mine Safety and Health, written commun., 1986). Ground water provided 7 percent (8.6 Mgal/d) of the total mining water use, which was mainly for secondary oil recovery.

Thermoelectric Power

Several public utility districts rely on a mixture of power-generating facilities to meet the needs of urban and rural customers. Many larger cities, such as Omaha, Lincoln, Grand Island, Hastings, and Fremont, supply their own electric power by using municipal generating systems. Nebraska has 21 fossil-fueled and 2 nuclear powerplants. The nuclear plants are on the Missouri River—one near Omaha and the other near Brownville. These generating facilities used a combined total of 2,210 Mgal/d, of which 98.9 percent (2,190 Mgal/d) was self-supplied from surface-water sources; and 1.1 percent (20 Mgal/d) was self-supplied from wells.

The fossil-fueled facilities used 1,420 Mgal/d supplied from both surface- and ground-water resources. Consumptive use was 1.8 Mgal/d. The two nuclear plants withdrew 794 Mgal/d of water from the Missouri River for pass-through cooling and reported no consumptive use. The withdrawal of water for thermoelectric cooling represented 22.0 percent of the total offstream freshwater use.

Agricultural

Irrigation is the largest water use in Nebraska. Agricultural use, which includes irrigation, accounted for 73.6 percent (7,380 Mgal/d) of all offstream use in 1985. Irrigation withdrawals were 7,270 Mgal/d. In 1985, about 7.48 million acres were irrigated, which ranks the State second only to California in the number of acres irrigated, (Nebraska Department of Agriculture, 1985). All other agricultural withdrawals totaled 120 Mgal/d.

Water for agricultural uses was supplied from surface- and ground-water sources. Water was either withdrawn directly from the surface-water source or conveyed through a network of canals. The canals, for the most part, are along the Platte, the Republican, and the Loup Rivers. Data provided by H.L. Becker (Nebraska Department of Water Resources, oral commun., 1987) indicate that more than 7,800 permits for surface water have been issued in the State. The largest canal system is operated by the Central Nebraska Public Power and Irrigation District (fig. 5). The District stores water for diversion in Lake McConaughy near Ogallala, and uses several storage reservoirs and hundreds of miles of canals and laterals to provide water for areas of cropland in south-central Nebraska. Other major canal systems include the Frenchman-Cambridge and the Bostwick Irrigation Districts in the Republican River basin, the Mirage Flats and the Ainsworth Irrigation Districts in the Niobrara River basin, and the Farwell and the North Loup Irrigation Districts in the Loup River basin.

Ground water accounted for 71.5 percent (5,280 Mgal/d) of the total agricultural withdrawals. Significant growth in agricultural irrigation can be attributed to an increase in the number of wells (fig. 6) completed in the High Plains aquifer). The thickness of this aquifer differs across the State; the maximum thickness is greater than 1,000 feet in some areas of the Sand Hills. Of the 23 counties that have more than 1,000 registered irrigation wells, 6 have more than 2,500 wells. Merrick County in central Nebraska, has more than 3,700 irrigation wells, which is a density of more than 8 wells per square mile (Ellis and Pederson, 1986). From 1980 to 1985, the acreage irrigated increased 6 percent, but total water withdrawals decreased 22 percent (Steele, 1988). The amount and timing of

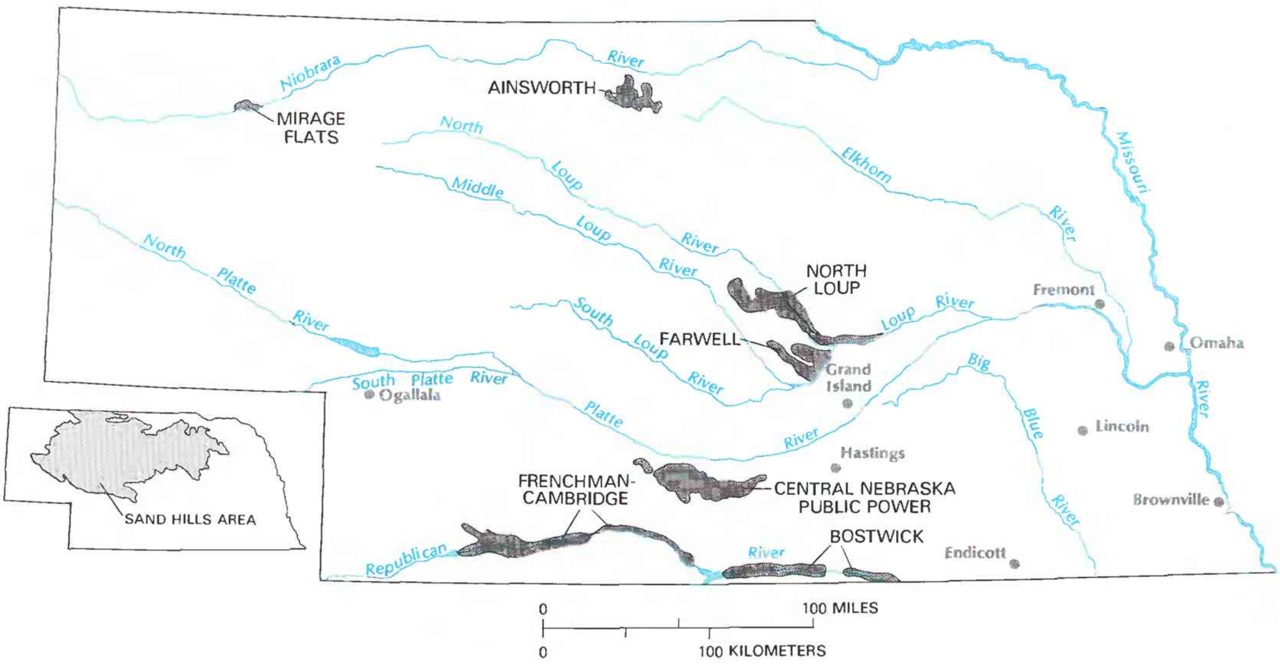


Figure 5. Irrigation districts of Nebraska.

precipitation in many areas of the State and increased pumping costs contributed to decreased irrigation demand in 1985. Continued education in techniques for conserving moisture, such as irrigation scheduling and tillage and an awareness of declining water tables, has made many irrigators more efficient in farming methods and more conservative in the use of water.

Gravity systems are used on 55 percent of irrigated lands, and sprinkler systems are used on the remaining 45 percent. Sprinkler systems are about 35 percent more efficient than gravity systems. The number of acres served by sprinker irrigation increased from 2.4 million in 1980 to 3.3 million in 1985 (Steele, 1988).

Conveyance losses can be large in deliveries from surface-water sources in canals and laterals; losses are smaller in deliveries from ground-water sources. In 1985, average conveyance losses for agricultural irrigation were estimated to be 35 percent of withdrawals.

Nonirrigation agricultural use accounts for only 1.6 percent of all agricultural use; however, it is important in the economy of the State through the support of a large livestock industry. In 1985, Nebraska ranked second nationally in the number of cattle and calves and fifth in the number of hogs and pigs. The Sand Hills area supports a large cattle industry; Cherry County has the largest water withdrawals—more than 5.0 Mgal/d.

WATER MANAGEMENT

The management of water as a resource has been an important issue in Nebraska since the late 19th century. Surface-water rights first were disputed in the panhandle in the 1880's. Two procedures evolved for determining the use of surface water—riparian and prior appropriation rights. Both types of rights still exist in Nebraska; however, the riparian right is relied on only occasionally. Riparian right allows some landowners who have land abutting a stream to use water from the stream for a beneficial purpose on, and only on, the abutting land. The prior appropriation right, which was first adopted in 1895, is a system of priority in the diversion of water and is based on the earliest use of water. When shortages occur, water users that have the later priority dates must leave sufficient water for water users that have earlier priorities.

A system of preferences also exists but is subordinate to the "first in time, first in right" priority system. Domestic use has preference over all other uses, and agriculture has preference over manufacturing and power uses. However, a junior preferred user is not entitled to the water being used by a senior, but inferior, user, unless the inferior user is compensated for all damages. For example, an agricultural user that has a 1960 priority date cannot take water from a hydroelectric powerplant that has a 1945 water right without paying for the lost power revenues.

State statutes empower the Nebraska Department of Water Resources to oversee the issuance and administration of surface-water rights. The Department also has some jurisdiction over ground water, including the required registration of all wells except those used solely for domestic purposes.

The Nebraska Natural Resources Commission is responsible for State water planning. The Commission works with 24 Natural Resources Districts, which are political subdivisions that have taxing authority and manage soil and water resources on a local level. As a result of the Ground Water Management and Protection Act, the Districts have the authority to establish ground-water control and management areas. Management alternatives provided by the Act include well spacing, rotation of pumping, allocation of water, and moratoriums on drilling. The Act also requires the best management practices to protect water quality.

Two "control" areas were established in 1977, one in the Upper Republican Natural Resources District in southwestern Nebraska and the other in the Upper Big Blue Natural Resources District in east-central Nebraska.A third area was established in 1979 in the Little Blue Natural Resources District, also in east-central Nebraska. All three areas have experienced declines in ground-water levels from average predevelopment levels. The first "management" areas were established in 1987. In the Central Platte Natural Resources District, the management areas provide mechanisms for regulating both the volume of withdrawals and the leaching of agricultural chemicals.

Before the legislation that mandated Natural Resources Districts, State laws permitted the creation of ground-water conservation districts. These districts have the authority to levy taxes and to manage ground water. Five of these districts still exist in Clay, Fillmore, Hamilton, Seward, and York Counties.

The Nebraska Department of Environmental Control is responsible for the protection and improvement of water quality in the State and administers point- and nonpoint-source pollution-control programs for surface and ground water. The Nebraska Department of Health administers the Federal Safe Drinking Water Act, conducts a Public Water System Program to provide safe water through public systems, and serves as advisor for individuals to ensure safe water from private domestic systems.

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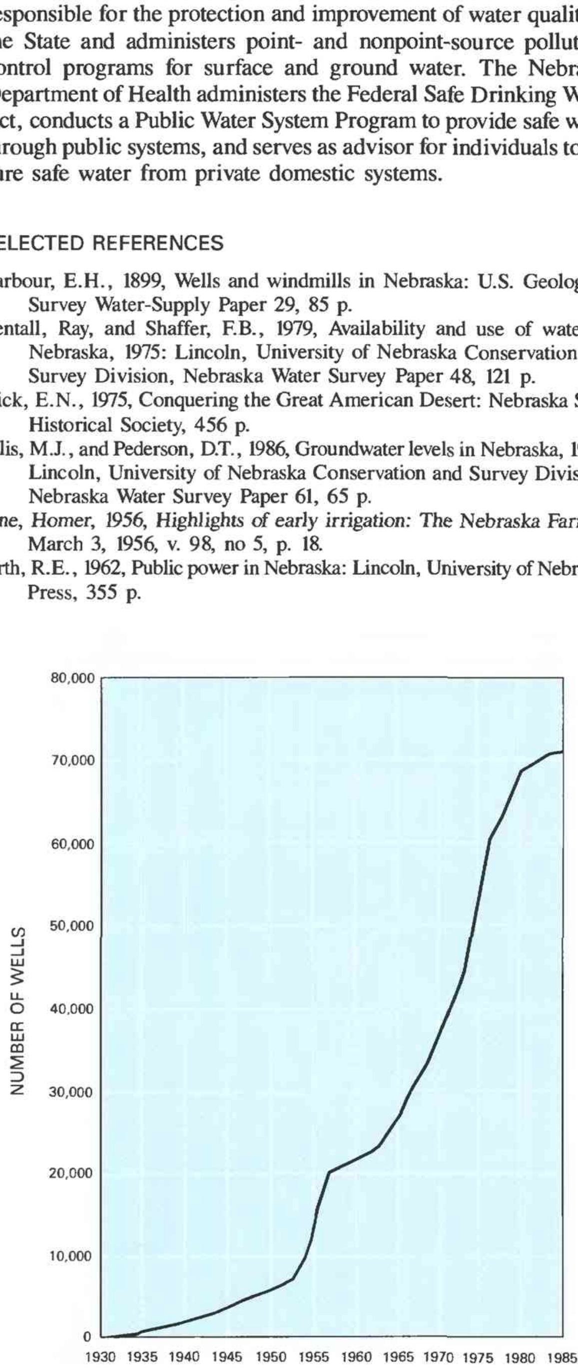

Figure 6. Registered irrigation wells. (Source: Data from Nebraska Department of Water Resources.)

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Prepared by P.A. Bartz, W.M. Kastner, and M.J. Ellis

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 406 Federal Bldg., 100 Centennial Mall North, Lincoln, NE 68508

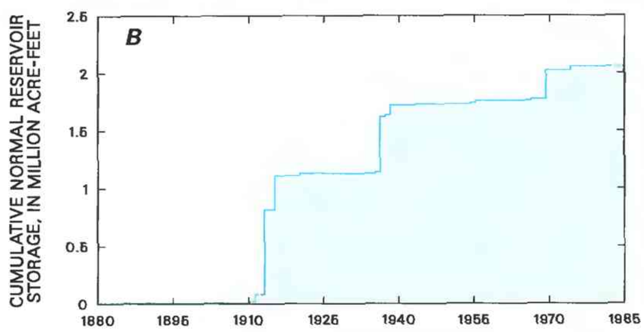
NEVADA
Water Supply and Use

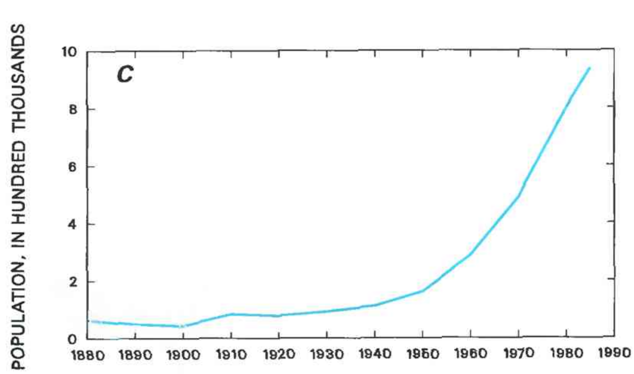
Nevada is the most arid State in the Nation (Geraghty and others, 1973, pl. 3). More than 97 percent of Nevada's water supply is received as precipitation, which is an annual average of about 9 inches over the 110,500 square-mile State. A water budget (fig. 1*A*) indicates that 94 percent, or about 46,800 Mgal/d (million gallons per day), of the total water supply is returned to the atmosphere as evaporation from water bodies and soils or as transpiration from native plants. The remaining water loss (2,830 Mgal/d) is accounted for by consumptive use (1,890 Mgal/d) and surface-water outflow (940 Mgal/d) to adjacent States.

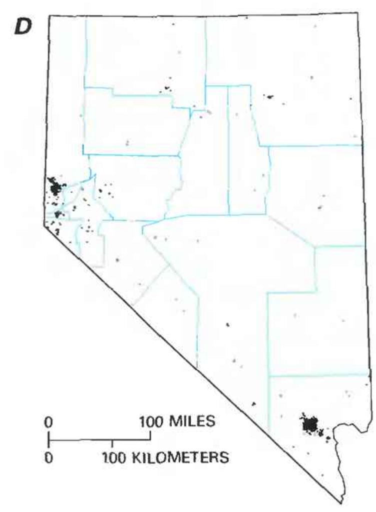
Total water withdrawal in 1985 was 3,740 Mgal/d, of which 90.3 percent was for agriculture, less than 8 percent for public supplies, and about 2 percent for all other uses combined. Agricultural uses accounted for 91.6 percent of the consumptive use. Surface water constituted 75.8 percent of the supply in 1985.

In 1980, Nevada had the ninth smallest population and the fourth smallest population density among the 50 United States (U.S. Bureau of the Census, 1983, p. 1–17 and 1–20), and yet it ranked first in population growth from 1960 to 1970 (71.3 percent) and from 1970 to 1980 (63.8 percent) (U.S. Bureau of the Census, 1983, p. 1–62). Nevada's rapid population growth has stressed the available water supplies and changed the types and locations of water use. Population distribution parallels water availability, with 59 percent of the population living in the Las Vegas area in the southeastern part of the State (near the Colorado River), 29 percent living in the Reno–Sparks–Carson City area in the northwest (adjacent to the Truckee and Carson Rivers), and the remaining 12 percent sparsely distributed in predominantly arid interior valleys.

By the year 2000, water supplies for several of Nevada's major population centers may not meet expected demands during drought conditions. The State Engineer's Office, water districts, and city and county planning agencies are developing water-resource plans, conducting or planning conservation education programs, and studying alternative sources of water.







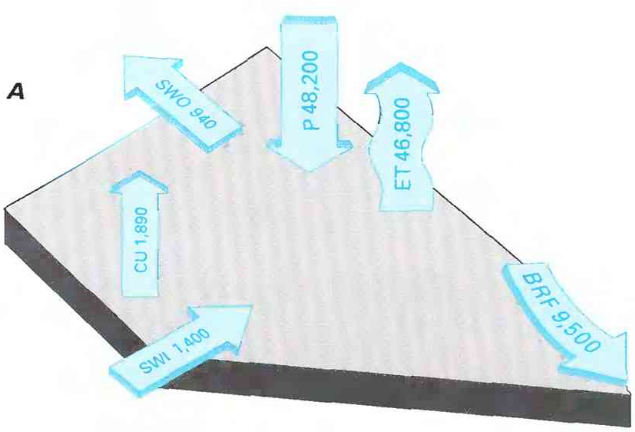


Figure 1. Water supply and population in Nevada. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Nevada Division of Water Planning, 1980; Colorado River Commission, written commun., 1987; Theodore Smith, Peabody Coal Company, oral commun., 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

HISTORY OF WATER DEVELOPMENT

Development of Nevada's limited water resources began during the mining boom of the late 1840's with the construction of diversion structures and ditches to supply water to ore-processing mills along the Carson River. Irrigation of river-bottom lands adjacent to the mill ditches was the next step in water development. During the 1850's and 1860's, most water development was in support of mining, although limited farming served emigrants traveling the Overland Trail and the Old Spanish Trail (McNeely and Woerner, 1974, p. 2–3). Water development in southern Nevada began in 1855 with diversion of Las Vegas Wash to irrigate 75 acres at the present site of Las Vegas (Scott and others, 1971, p. 1–2). The first major industrial and public-supply development was a reservoir and a 31-mile pipeline to transport water to the mining town of Candelaria (Mineral County) in the late 1860's. In 1873, a dam, a series of flumes, and a pipeline were constructed to transfer water from the Sierra Nevada to Virginia City. The mining industry has followed boom-and-bust cycles. Where communities, such as Virginia City, remained after the decline of mining, upgraded versions of the original water systems are still used for public supplies; in other areas, such as Candelaria, only ghost towns remain as monuments to human ingenuity in developing water supplies in the Nation's most arid State.

With the decline in mining from 1860 to 1870, many former miners settled on bottom lands along the few perennial streams in the State. By 1905, farmland available to new settlers was farther from the main streams and the cost of irrigation development was prohibitive for individual farmers. This situation led to the formation of companies to build and operate community canals and distribution systems (Smales and Harrill, 1971, p. 5).

The Newlands Project was the first publicly financed effort resulting from the Reclamation Act of 1902. Upon completion of the project in 1915, diverted Truckee River and Carson River flows were used to irrigate 90,000 acres in the Carson Desert near Fallon (Smales and Harrill, 1971, p. 5).

Major surface-water supplies in Nevada were fully allocated by about 1940; therefore, development of normal reservoir storage (fig. *1B*) has not increased as rapidly as the population has increased (fig. 1*C*). Normal reservoir storage larger than 5,000 acre-ft (acre-feet) shown in figure *1B* includes storage in lakes, where the maximum lake-surface altitude has been artificially raised by a dam; storage in several reservoirs in the Truckee River basin in California; and Colorado River water allocated by Nevada.

About 50 percent (1.02 million acre-ft) of the 2.06 million acre-ft of normal reservoir storage shown in figure *1B* is partly or wholly located in California at Lake Tahoe, Independence Lake, Boca Reservoir, Donner Lake, and Stampede Reservoir (fig. 5). Nevada's annual allocation of water from the lower Colorado River is 300,000 acre-ft (Decree of the Supreme Court of the United States in Arizona vs. California dated March 9, 1964). The 300,000 acre-ft is displayed in figure *1B* rather than as a percentage of normal storage in Lake Mead and Lake Mohave, because no existing storage space in reservoirs along the lower Colorado River is allocated to individual States (Joseph Jones, U.S. Bureau of Reclamation, oral commun., 1987). The present allocation of water from the Truckee River system and from the lower Colorado River is the result of many legal rulings and interstate compacts; therefore, rather than attempt to show changes in normal storage allocated to Nevada through time, current allocations are displayed in figure *1B* beginning in the years the dams were completed.

The number of people filing Homestead and Desert Land Entry applications increased rapidly during the late 1940's. The water situation became critical, and little additional supply was developed during this time. The U.S. Bureau of Land Management declared a moratorium on Desert Land Entry applications in Nevada in the mid-1960's to slow the development on new lands (Smales and Harrill, 1971, p. 5–6). The Ninth Circuit Court of Appeals removed the moratorium in 1977; however, application processing has since been suspended pending further legal decisions (Peter G. Morros, Division of Water Resources, written commun., 1988).

Nevada's population is concentrated in the Las Vegas and the Reno–Sparks–Carson City metropolitan areas (fig. *1D*). As population and total water use have increased in Nevada, ground-water resources, which had been used intermittently to supplement surface-water supplies, have become primary sources of water, and Nevada's use of its Colorado River allocation has rapidly increased.

WATER USE

Availability of water, which reflects the variable climate in the State, always has been a controlling factor in the settlement of Nevada. During the last 15 years, the State population has almost doubled from 489,000 in 1970 (U.S. Bureau of the Census, 1983, p. 1–82) to more than 967,000 in 1985 (Bureau of Business and Economic Research, University of Nevada, Reno, written commun., 1987) . However, because a large part of water use has been for agriculture, the total estimated withdrawals only increased from 3,300 Mgal/d (Murray and Reeves, 1972, p. 28) to 3,740 Mgal/d during this same period. In contrast, water-use estimates since 1950 indicate that withdrawals for public supply have increased in proportion to the rapid population growth.

The dominance of agricultural use of water is highlighted by comparing population distribution (fig. *1D*) with total freshwater withdrawal (fig. *2A*). Elko, Humboldt, Lyon, and Churchill Counties account for 7 percent of the State's population, contain more than 60 percent of total irrigated acreage, and withdraw the largest quantities of water (a combined 59 percent). Clark and Washoe Counties have 82 percent of the population and contain less than 6 percent of total irrigated acreage, but rank fifth and sixth, respectively, in total freshwater withdrawals (sum, 13 percent).

Surface-water withdrawals account for 75.8 percent and ground-water withdrawals account for the remaining 24.2 percent of freshwater withdrawals. The general pattern of larger withdrawals in the northern part of the State, decreasing southward (figs. *2B* and *2C*), reflects climate, surface-water resources, and depths to ground water beneath the valley floors. Primary surface-water sources are the Humboldt River within the Black Rock Desert–Humboldt basin (39 percent of the total surface-water withdrawals); the Truckee, Carson, and Walker Rivers within the Central Lahontan basin (35 percent); and the Colorado River within the Lower Colorado–Lake Mead basin (8 percent) (fig. *3A*). Although the Central Nevada Desert basins is the largest basin in the State, it is arid as the name implies and has limited surface-water resources (6 percent of the total surface-water withdrawals) (fig. *3A*).

Withdrawal of water from the Colorado River has increased 670 percent in 20 years, from 22,716 acre-ft/yr (acre-feet per year) in 1965 (U.S. Bureau of Reclamation, 1967) to 175,711 acre-ft/yr in 1985 (U.S. Bureau of Reclamation, 1987). Use of the Colorado River will continue to increase as demand in southern Nevada increases. Nevada is allocated a maximum consumptive use (withdrawals minus return credits) of 300,000 acre-ft/yr, which was set by the decree of the Supreme Court of the United States in Arizona vs. California dated March 9, 1964. Nevada is projected to use all its firm water (water available during low-flow years) from the Colorado River by the year 2030 (Jerry Edwards, Colorado River Commission, oral commun., 1987).

About 90 percent of ground-water withdrawals is from basin-fill aquifers (fig. *3B*). Most of the water from carbonate-rock aquifers is obtained from springs. Although the carbonate-rock aquifers are being studied extensively as a possible supplemental source of water for southern Nevada, little ground water has been pumped from these aquifers. Volcanic-rock aquifers are locally important for the city of Fallon and the Nevada Test Site (primarily in Nye County), but are not used extensively elsewhere.

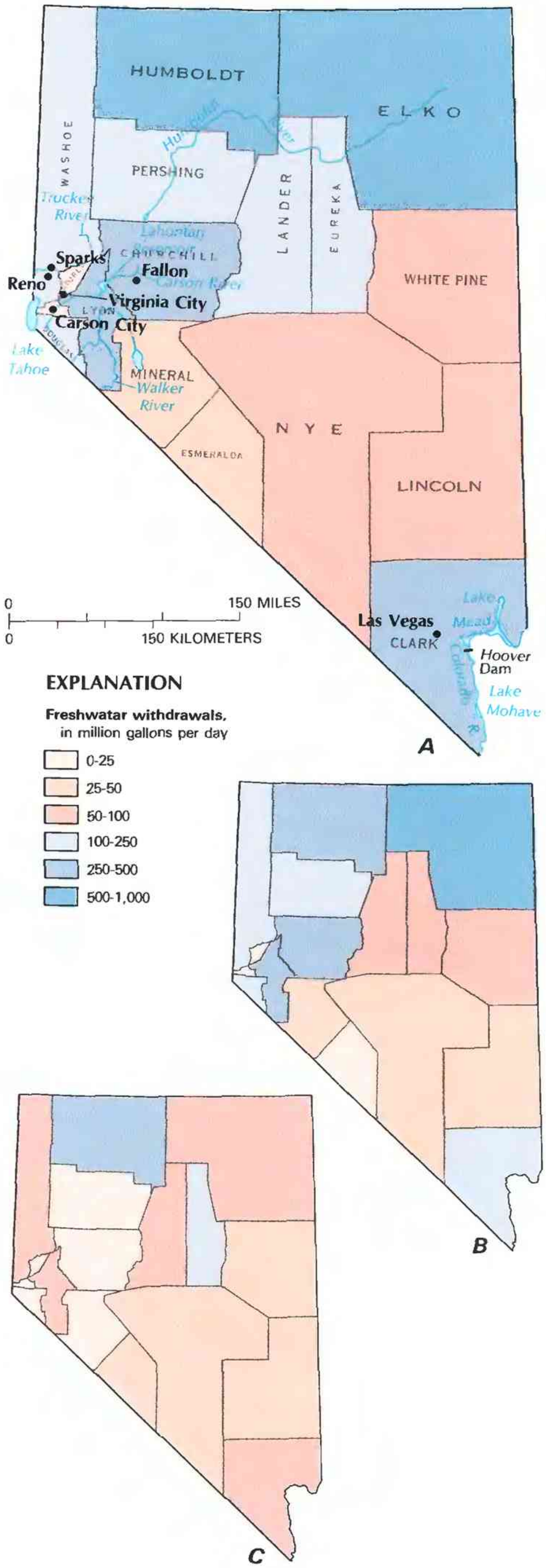


Figure 2. Freshwater withdrawals by county in Nevada, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Instream water use in Nevada is for hydroelectric-power generation, fish and wildlife habitat, and recreation; however, estimates of instream water use were made only for power generation. Estimates for hydroelectric power generation are not shown in figure 4. Ten hydroelectric powerplants used 8,900 Mgal/d of surface water to produce 4,350 GWh (gigawatthours) of power in 1985. These values include about 53 percent of the water used and the power generated at Hoover Dam (fig. 5); the remaining 47 percent is included in Arizona water-use values. The Nevada part of Hoover Dam water use (8,260 Mgal/d) accounts for 93 percent of instream use of water in the State. Four small hydroelectric powerplants are on the Truckee River and two are on the Carson River in west-central Nevada; five of these six plants were operated in 1985 and used about 630 Mgal/d to produce 43 GWh. Consumptive use of instream water for hydroelectric-power generation is negligible compared to the total amount of water that passes through the turbines.

With the exception of surface-water inflows (1,400 Mgal/d, fig. 1*A*), the only interstate transfer of water into the State is into Clark County by the Black Mesa pipeline. About 1.5 Mgal/d of ground water is pumped from the Black Mesa area in Arizona and is used to transport coal slurry about 300 miles to a powerplant near Laughlin (Clark County) where the water is used for cooling. Other than surface-water outflows (940 Mgal/d, fig. 1*A*), the only interstate transfer of freshwater from Nevada is less than 0.2 Mgal/d of ground water pumped 32 miles from the Central Nevada Desert Basins to Wendover, Utah, where it is used for public supply. Treated effluent from three sewage-treatment facilities in California and Nevada is transferred from the Lake Tahoe basin to Douglas County for irrigation (Brown and others, 1986, p. 9).

Major intrastate transfers include: (1) Water from the Colorado River to southern Nevada for public and industrial supply, (2) water from the Truckee River to Spanish Springs Valley (fig. 6) north of the Reno–Sparks area and to Lahontan Reservoir for irrigation, (3) water from the distribution system servicing the Reno–Sparks area to small public-supply companies servicing valleys to the north, and (4) surface water from the Lake Tahoe and Washoe Valley hydrographic basins (fig. 6) to Carson City and Virginia City for public supply (Scott and others, 1971, p. 80).

Salinity is the primary water-quality constraint on the use of water. Playas distributed on valley floors throughout the State are areas where dissolved-solid concentrations in ground water are most likely to exceed 1,000 milligrams per liter (Nowlin, 1986, pl. 1). Also, the use of water in Nevada may be limited in areas of human-induced contamination (U.S. Geological Survey, 1988, p. 355).

Source, use, and disposition of freshwater for public-supply, domestic and commercial, industrial and mining, thermoelectric-power, and agricultural purposes are shown diagrammatically in figure 4. The quantities of water given in figure 4, and elsewhere in this report, may not add to the totals indicated because of independent rounding. The source data indicate that 2,830 Mgal/d of surface water was withdrawn in 1985, which was 75.8 percent of total freshwater withdrawals in Nevada. Of this 2,830 Mgal/d, 92.5 percent was withdrawn for agriculture, and 6.8 percent was for public supplies. Self-supplied domestic and commercial use, self-supplied industrial and mining use, and self-supplied thermoelectric use each account for 0.4 percent or less of the fresh surface water withdrawn. The use data indicate that 90.3 percent of water used in Nevada was for agriculture. Of the 3,370 Mgal/d used for agriculture, 77.6 percent was surface water, and 51.4 percent of the water used was consumed.

More than 11 Mgal/d of reclaimed sewage effluent was used during 1985 to irrigate golf courses, pastures, and crops, and as cooling water at powerplants. The use of reclaimed effluent is concentrated primarily in Clark, Douglas, and Elko Counties, and in Carson City.

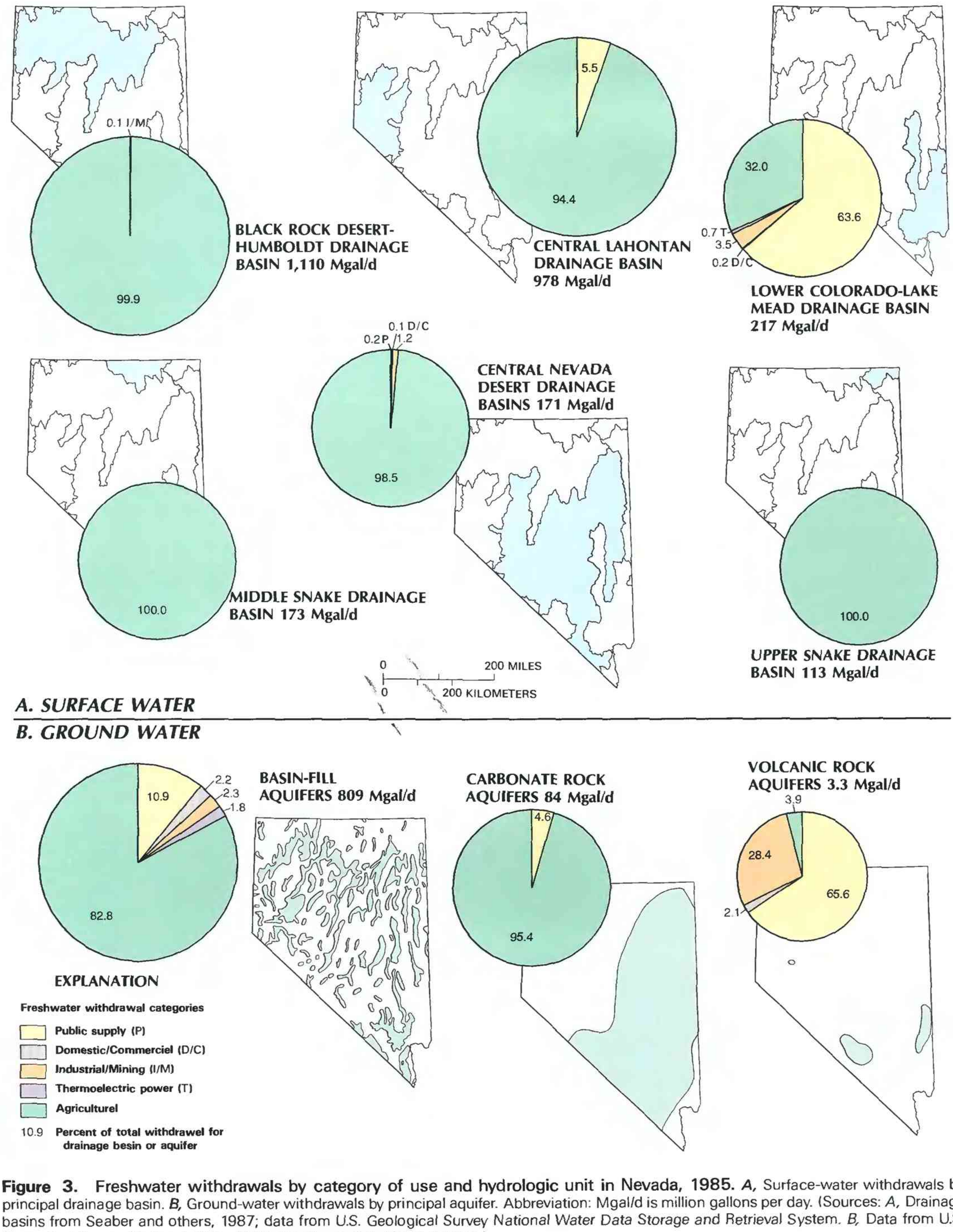


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Nevada, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. Withdrawals for public supply in 1985 were 288 Mgal/d, of which 193 Mgal/d (67.2 percent) was surface water and 94 Mgal/d (32.8 percent) was ground water (fig. 4). Public-supply companies withdrew less than 8 percent of all freshwater withdrawn in Nevada. More than 90 percent of Nevada's population is served by public-water supplies. The growth rate of the supply provided by public-supply systems (52 percent from 1965 to 1975, 69 percent from 1975 to 1985) has been slightly larger than the growth rate of population (30 percent from 1965 to 1975, 59 percent from 1975 to 1985) (Murray, 1968, p. 16, 47; Murray and Reeves, 1977, p. 20, 30; Solley and others, 1988 p. 17, 63). This difference is primarily due to an increase in the proportion of the population served by public-supply systems, an expanded commercial use of water, and a gradually increasing per capita use.

Of the more than 300 water-supply systems, each of which serves at least 25 people, 39 systems use surface water for part of or all their supply. However, 66 percent of those who rely on public water supplies receive surface water; this has increased from 39 percent in 1960 (MacKichan and Kammerer, 1961, p. 13). Therefore, although most suppliers rely on ground water for their supplies, those withdrawals are small compared to surface-water withdrawals. The two primary sources of surface water for public supply are the Colorado River for the Las Vegas area, and the Truckee River system for the Lake Tahoe and Reno–Sparks areas.

Domestic and Commercial

Total self-supplied withdrawals and public-supplied deliveries for domestic and commercial use in 1985 were 298 Mgal/d (fig. 4). Withdrawals and deliveries for domestic use were 201 Mgal/d, of which 189 Mgal/d was delivered by public suppliers. About 95 percent of the 12 Mgal/d of self-supplied domestic use was ground water. Commercial use represented 61 Mgal/d, of which an estimated 54 Mgal/d was from public suppliers. Water lost during conveyance or used directly from transmission lines, such as for fire fighting, is included in the domestic and commercial water-use category in figure 4. About 38.3 percent (114 Mgal/d) of domestic and commercial use was consumed. Domestic use of water delivered by public suppliers averaged 215 gal/d (gallons per day) per capita; domestic use of self-supplied water averaged 141 gal/d per capita. These per-capita use rates are among the largest in the Nation (Solley and others, 1988, p. 17).

Industrial and Mining

About 1 percent (38 Mgal/d) of 1985 freshwater withdrawals was used for industrial and mining purposes; of that, 21 Mgal/d was consumed. Industrial use of water totaled 16 Mgal/d, of which 48 percent was self-supplied surface water (primarily from the Colorado River), 38 percent was delivered by public-supply systems, and an estimated 14 percent was self-supplied ground water. Mining use of freshwater totaled 22 Mgal/d, of which 13 percent was surface water and 87 percent was ground water. In addition, less than 3 Mgal/d of saline ground water was used for mining in 1985. Nevada led the Nation in the production of gold and barite in 1985 and was the sole producer of magnesite and mercury (Nevada Division of Mine Inspection, 1986, p. i).

Thermoelectric Power

Nevada has 11 thermoelectric powerplants, of which 7 are fossil fueled and 4 are geothermal. Water for power generation

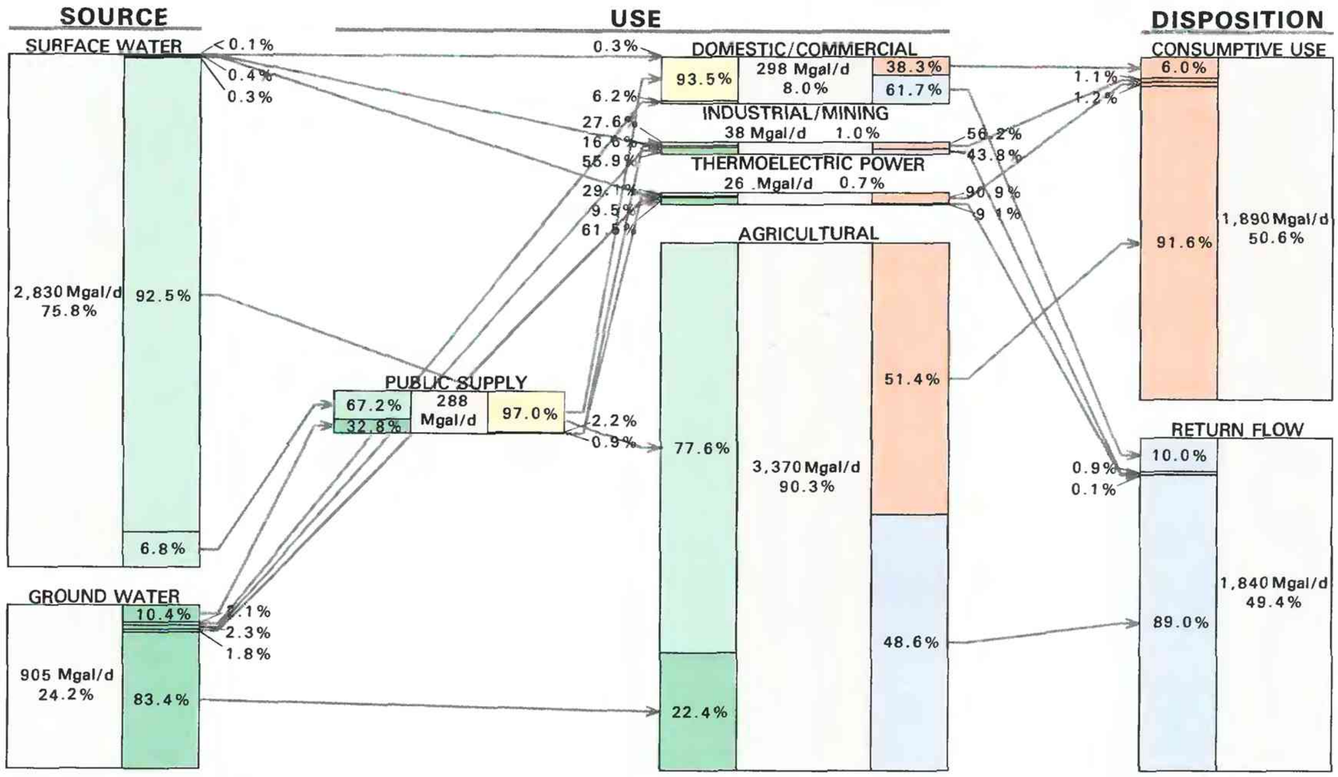


Figure 4. Source, use, and disposition of an estimated 3,740 Mgal/d (million gallons per day) of freshwater in Nevada, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

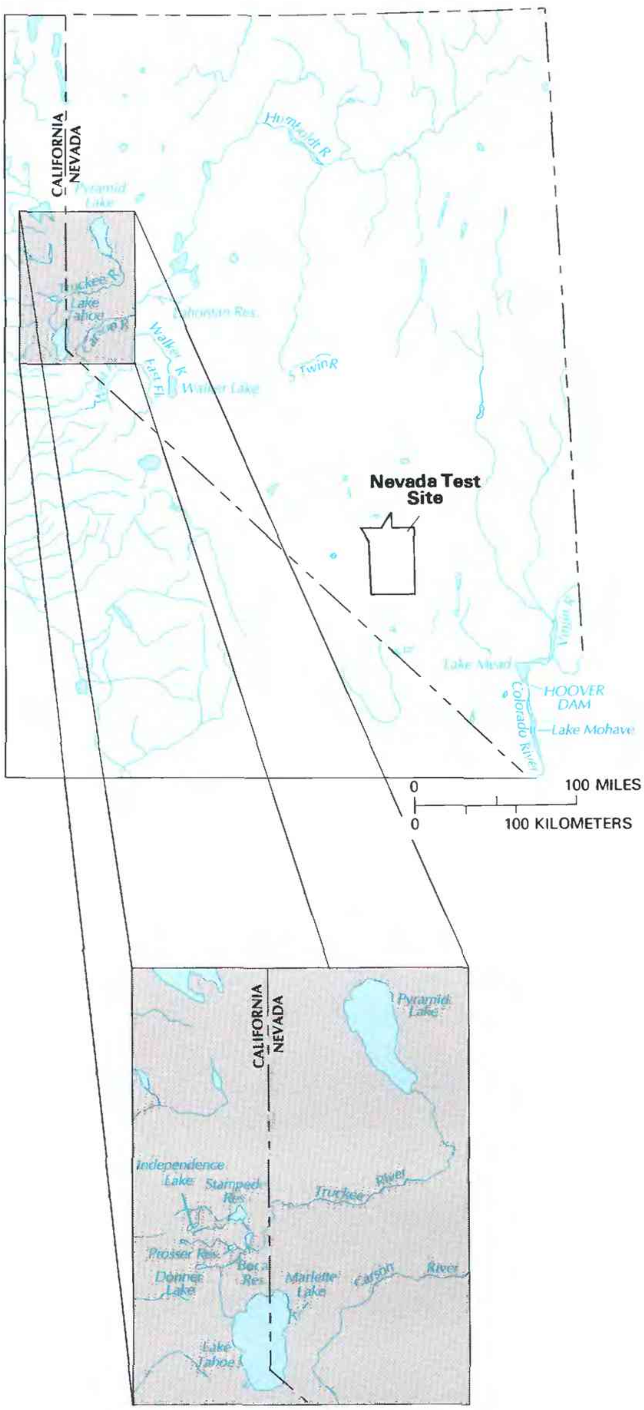


Figure 5. Principal lakes and reservoirs providing water-supply storage for Nevada.

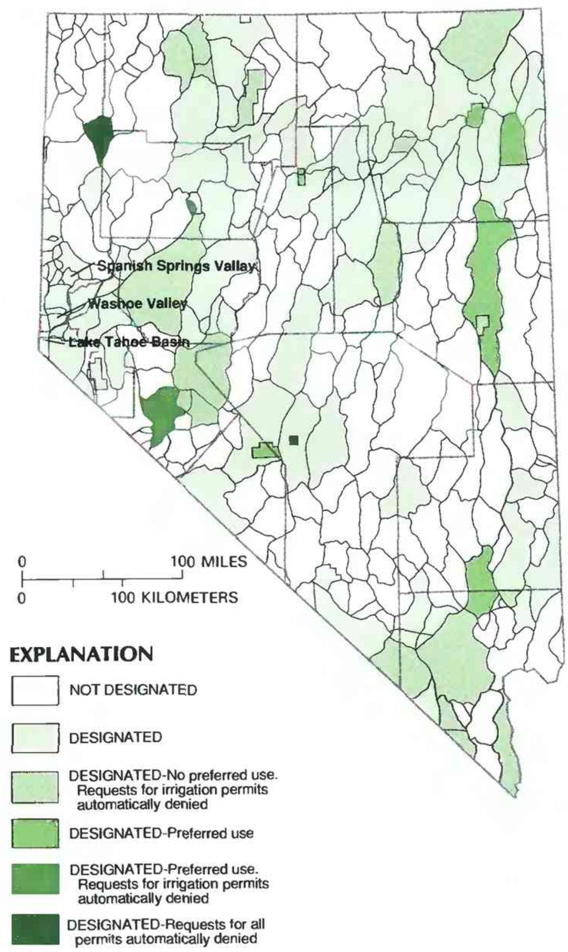


Figure 6. Designated ground-water basins of Nevada as of 1986. (Source: Nevada Division of Water Resources files, 1987.)

represents 0.3 percent of total surface-water withdrawals and 1.8 percent of total ground-water withdrawals in Nevada (fig. 4). Water use for thermoelectric powerplants in 1985 was as follows: surface water accounted for 29.1 percent (7.5 Mgal/d), ground water 61.5 percent (16 Mgal/d), and public supply 9.5 percent (2.4 Mgal/d) (fig. 4). About 0.3 Mgal/d of the public-supplied water was treated sewage effluent. Estimated water use for thermoelectric powerplants decreased from 95 Mgal/d in 1975 (Murray and Reeves, 1977, p. 28) to 26 Mgal/d in 1985 because a relatively small fossil-fueled plant switched from once-through cooling to closed-loop cooling. However, consumptive-use estimates increased by 2 Mgal/d—to 24 Mgal/d in 1985 (fig. 4). Eighty-four percent of the 26 Mgal/d withdrawn and 95 percent of the 12,400 GWh generated in 1985 were at three fossil-fueled plants.

Although geothermal powerplants produced less than 1 percent of the power generated in 1985, their importance is expected to increase in the future. Three of the four geothermal plants began production in December 1985, and several potential geothermal sites are being developed.

AGRICULTURAL

Irrigation dominates all other categories of water use in Nevada (fig. 4). More than 90 percent (2,600 Mgal/d) of all surface water withdrawn in 1985 was for irrigation. Surface-water withdrawals for irrigation have been relatively unchanged for the last 15 years. Of all ground-water withdrawals, 83 percent (750 Mgal/d) was for irrigation—more than a 140-percent increase since 1975 (Murray and Reeves, 1977, p. 24). Use of treated sewage effluent for irrigation was 11 Mgal/d in 1985. Statewide, sewage effluent accounts for less than 0.5 percent of the water withdrawn for irrigation. Locally, however, it may be the dominant source of irrigation water, particularly for many golf courses in southern and west-central Nevada.

Estimates of irrigated acreage for 1985 are 2 percent less than that for 1975, but estimates of total water withdrawn for irrigation are 8 percent more (Murray and Reeves, 1977, p. 24), because larger consumptive-use rates were used in the 1985 calculations (U.S. Soil Conservation Service, 1985, p. NV683-19 to NV683-45). Most land removed from agricultural production during 1975-85 was the result of expanding urban and suburban areas in southern and west-central Nevada. Irrigated acreage in less populated areas is still increasing.

High daytime summer temperatures and little relative humidity cause water-application rates to be large compared to those for most States. The average amount of water withdrawn annually for irrigation is 4.5 acre-ft per acre, which includes conveyance losses. Conveyance losses are decreasing slowly with increased use of sprinkler systems, which were used on about 19 percent of irrigated land during 1985. The percentage of crops irrigated by sprinklers is expected to continue to increase as the nonagricultural demand for water and the need for water conservation increase.

All crops grown in Nevada are irrigated; therefore, the distribution of agricultural water use is controlled primarily by the location of the few perennial streams and large springs and by the availability of relatively shallow ground water. Of all surface-water irrigation, 78 percent occurs in the Black Rock Desert–Humboldt and the Central Lahontan basins. Of all ground-water irrigation, 78 percent occurs in the Black Rock Desert–Humboldt basin and the Central Nevada Desert basin.

Hay crops, including alfalfa and grass, represent more than one-half the crops produced in the State. The application rates for these perennial crops are larger than for most crops because two to four cuttings are grown each year. About 90 percent of irrigated land is used for hay crops or pasture. Other crops include potatoes, winter and spring wheat, barley, onions, garlic, alfalfa seed, and assorted vegetables.

Agricultural water not used for irrigation includes 12 Mgal/d for livestock and 14 Mgal/d for 12 fish-rearing stations and hatcheries. Consumptive use for these two categories was 6 Mgal/d, almost all of which was accounted for directly by livestock or evaporated from water bodies.

WATER MANAGEMENT

Because Nevada is the most arid State and competition for water is intense, its water resources are strictly regulated and controlled. The Office of the State Engineer, under the Nevada Department of Conservation and Natural Resources, is responsible for managing the State's surface-water and ground-water resources. Nevada State Water Law is based on the prior-appropriation doctrine, commonly referred to as "first in time—first in right," and the concept that beneficial use is the measure of a right for the water (Nevada Division of Water Resources, 1974, p. 8). The State Engineer administers ground-water resources using the concept of perennial yield; that is, ground-water withdrawal from a basin does not exceed ground-water recharge.

The basic foundation of Nevada's water law was initiated with the Act of 1903. This legislation created the State Engineer's Office and provided a statutory mechanism for adjudicating existing rights—those rights involving use of water before that date. Major change to the water law occurred with the passage of the Act of 1913, which provided a statutory appropriation process, recognized public ownership of waters above or beneath the surface of the ground, defined beneficial use more clearly, established eminent domain and abandonment of water rights, significantly changed the process for determining vested water rights, and provided for reservoir permits (Rice, 1974, p. 3-4).

The Act of 1939, the most comprehensive ground-water law in the western United States at that time, provides a mechanism for designating ground-water basins that the State Engineer determines are in need of additional administration. Designation usually occurs when ground-water withdrawals and applications approach the perennial yield of the basin or when pending competitive applications to appropriate water exceed the perennial yield of the basin. The State Engineer is empowered to designate preferred uses of the limited resource within any designated ground-water basin. Nevada's 232 ground-water basins, of which 98 were designated as of 1986, are shown in figure 6.

No formal State drought-management plan has been published; however, conservation measures implemented by individual communities during a drought may include: (1) rationing water for nonessential uses such as lawn watering and car washing, with penalties for violators, and (2) voluntary water conservation. Other conservation measures employed in Nevada include educational programs to encourage water conservation, reuse of treated sewage effluent for powerplant cooling and irrigation, and conversion from flood irrigation to sprinkler and drip systems. Proposed conservation measures include rescinding a legislative mandate against installing water meters in the Reno–Sparks area, restricting water usage for cosmetic purposes that increase evaporative losses, and developing a system for monitoring the amount of surface and ground water used for irrigation.

In the early 1970's, the Las Vegas area, with its increasing rate of water use and population growth, was expected to experience serious water shortages by the year 2000. Alternatives studied by Montgomery Engineers of Nevada (1971, p. i) to help managers forestall the impending water shortage included increasing the price of water by as much as 100 percent, importing water from other States, redistributing population, and limiting population growth.

As of 1986, allocation of the Colorado River of 300,000 acre-ft/yr to Nevada, "...along with 50,000 acre-feet of available ground-water, will provide a dependable water supply to southern Nevada well past the turn of the century," according to J.L. Stonehocker (Colorado River Commission, written commun., 1986). This does not imply, however, that water-conservation measures be postponed in southern Nevada.

Undeveloped sources of water are limited, and the importation of water may not be politically or economically feasible; therefore, effective water-use management will remain a priority in the State. Methods to better conserve and use existing and potential water supplies are continually being developed to meet future needs.

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Prepared by Elizabeth A. Frick and R.L. Carman

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Federal Building, Room 224, 705 North Plaza Street, Carson City, NV 89701

New Hampshire
Water Supply and Use

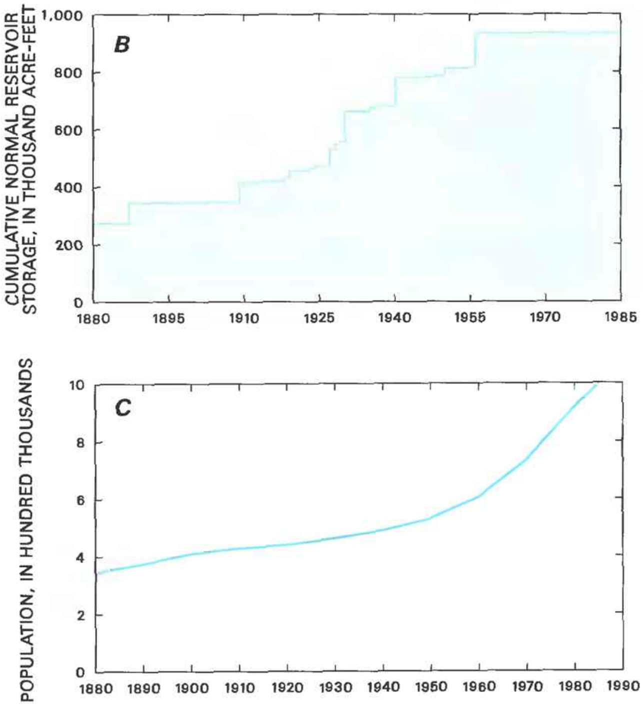
New Hampshire has many lakes, ponds, streams, and rivers in a setting of highlands and rolling lowlands. Average annual precipitation is about 42 inches, or about 18,500 Mgal/d (million gallons per day) (fig. 1*A*). Precipitation ranges from about 34 inches in the Connecticut River valley to about 89 inches in the White Mountains in the east-central part of the State (National Oceanic and Atmospheric Administration, 1982). Average annual runoff ranges from 18 inches in coastal areas and in parts of the Connecticut River valley to about 42 inches in the White Mountains. Surface-water inflows from other States and Canada are estimated to be 5,330 Mgal/d. Total inflow to New Hampshire (precipitation plus surface-water inflows) is about 23,800 Mgal/d. Surface-water outflows are about 15,500 Mgal/d. Evapotranspiration is estimated to be 8,260 Mgal/d. Consumptive use is generally small—76 Mgal/d.

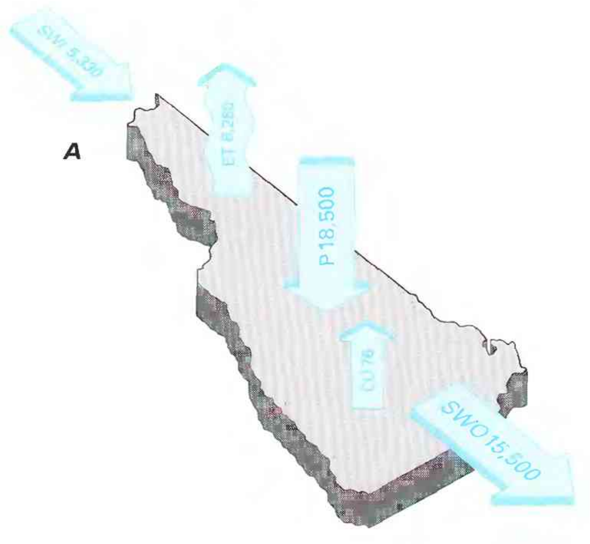
Instream water use was about 14,500 Mgal/d, and offstream water use (fresh and saline) was 894 Mgal/d in 1985. Almost all instream water use was for generation of hydroelectric power, whereas offstream water use was for thermoelectic power cooling and for domestic and commercial, industrial and mining, and agricultural uses. Wastewater return flow was about 252 Mgal/d during 1985 (Solley and others, 1988).

Population in New Hampshire increased at a slow, steady rate of less than 1 percent per year until the 1950's and then gradually increased to about 2 percent per year in 1970. The population growth rate was 2 percent per year from 1970 to 1985. As of 1987, 52 percent of the population resides in the southeastern part of the State in Hillsborough and Rockingham Counties.

Merrimack County, third largest in population, uses the greatest amount of freshwater. Of all offstream freshwater use in the State, 80 percent is in Merrimack, Rockingham, and Hillsborough Counties. If saline water is included, then offstream use is largest in Rockingham County.

Surface water is the source of most freshwater withdrawals. Fresh surface-water withdrawals range from about 39 Mgal/d in the Connecticut basin to about 329 Mgal/d in the Merrimack basin. Of all surface freshwater withdrawals in the State, 55 percent is from the Merrimack basin.





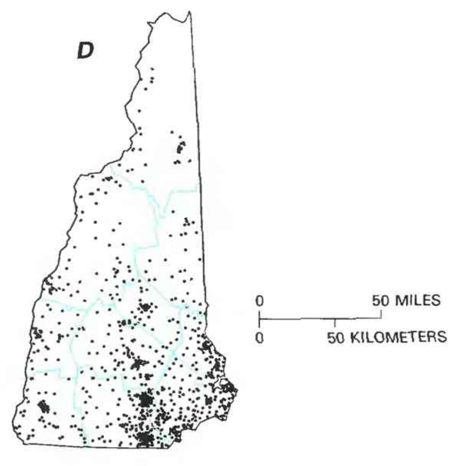


Figure 1. Water supply and population in New Hampshire. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from Rand McNally and Company, 1976; Knox and Nordenson, 1955; Gebert and others, 1985; U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Total ground-water withdrawals of freshwater are about 84 Mgal/d, ranging from about 1.3 Mgal/d in Coos County to almost 17 Mgal/d in Merrimack County. Almost 70 percent of this total is withdrawn in Merrimack, Hillsborough, Rockingham, and Sullivan Counties. In 1985, about 40.1 percent of the total ground-water withdrawals was for industrial and mining use, 25.8 percent was for domestic and commercial use, and 33.4 percent was withdrawn for public supply. The current rate of population growth (and corresponding increase in demand for commercial and industrial services), along with discoveries of surface- and ground-water contamination and the limited sources of water supply, are presenting the State with new challenges.

The population in the southern part of the Merrimack River valley and along the coast has been increasing steadily since the middle of the 20th century. The statewide trend in population from 1880 to 1985 is shown in figure 1C. In 1985, 70 percent of the population resided in the four southeastern counties of New Hampshire—Hillsborough, Merrimack, Rockingham, and Strafford (fig. 1D). Water use is rapidly increasing in these counties, and water shortages and contamination problems also are occurring at an increasing rate. The State has initiated several programs to address the problems; one such program is a detailed inventory of water use to provide information and statistics on how the water resources are being used.

HISTORY OF WATER DEVELPMENT

New Hampshire's many rivers and streams were natural transportation routes for the Indians and the European explorers and traders. The settlers and farmers who followed built settlements and established farms at or near falls, rapids, or crossings that were barriers to navigation or overland travel and, therefore, were logical places for trading and commerce (U.S. Geological Survey, 1986, p. 330). As the population increased, farming spread to surrounding areas, and mills were built along streams and rivers to process farm products and to provide waterpower. Most water was used for water supply, transportation, and waterwheel power. Ground-water use was mostly limited to a few dug wells where springs or streams were not readily available.

While new settlements were being developed in outlying areas, the older settlements were improving the operation of mills by building dams and diversion channels. Canals, locks, and dams were built to bypass difficult river reaches. Outlets of natural lakes and low-lying areas were dammed to create, regulate, or increase storage. Cumulative normal reservoir storage from 1880 to 1985 is shown in figure 1B.

Improvements in overland transportation during the 1800's resulted in a major decrease in the use of rivers and streams for travel and transport of goods. As communities increased in size, many dug wells, streams, and springs that had been the main sources of water supply became inadequate or contaminated, particularly during dry periods or major fires. In 1852, a group of citizens in Nashua chartered the first public-supply system; water delivery started in 1855 (Calderwood, 1974, p. 214). The water source was a small stream whose drainage area could be locally controlled to prevent or limit potential contamination. Manchester established a public-supply system in 1874 by impounding a small local stream (Calderwood, 1974, p. 214).

Hydroelectric powerplants began to replace mechanical waterpower in the late 19th century. At first, these plants used existing dams and structures, but, as the technology evolved, larger dams and specialized hydroelectric generating facilities were constructed. The new hydroelectric facilities enabled users to be in population centers that were considerable distances from the power sources.

Drilled wells were introduced in the region during the late 1800's but were not common until electricity and electrical pumps became available. As of 1987, drilled wells are the major means of obtaining ground water for new public-supply systems and domestic self-supplied systems. Ground-water withdrawals now provide 31.6 percent of the water used by public-supply systems. Surface-water withdrawals, which are still a significant source of water for public-supply systems, provide the other 68.4 percent.

Until recently, most wastewater was returned directly to streams where it was diluted and naturally improved to some degree. With time, however, wastewater discharges led to severe contamination in many of the major rivers across the State. During the last 20 to 30 years, the construction of wastewater-treatment plants has substantially improved surface-water quality.

WATER USE

Historically, water supply in New Hampshire has been more than sufficient to satisfy demands. The total water budget for the State (fig. 1A) shows the amount of water that is potentially available. The distribution of water use across the State reflects differences in population and industry. Total surface-water and ground-water withdrawals by county are shown in figures 2A, 2B, and 2C, respectively. Freshwater withdrawals—surface water by principal drainage basin and ground water by principle aquifer—are shown in figures 3A and 3B, respectively.

The areas of large withdrawals (fig. 2A) reflect the concentration of population and industry within the State. Merrimack, Rockingham, and Hillsborough Counties, which are the most populous in the State, withdraw the most water. The large amount of surface-water withdrawal in Coos County (fig. 2B) is related to paper industry demands rather than population demands. The distribution of ground-water withdrawals by county (fig. 2C) reflects the distribution of population within the State (fig. 1C).

The predominant use of surface water in the southern part of the State is for thermoelectric power generation (fig. 3A), whereas industrial and mining use accounts for most of the surface water withdrawn in the northern part of the State. Some water uses are so small they could not be represented in figure 3A. Most large-yield wells used for public and industrial supply are completed in stratified-drift aquifers (fig. 3B), whereas individual domestic household wells generally are completed in crystalline-bedrock or till aquifers.

The source, use, and dispositon of freshwater in New Hampshire are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that, in 1985, fresh surface-water withdrawals were 87.8 percent (603 Mgal/d) of the total withdrawals in New Hampshire. Of that quantity, about 55.7 percent (336 Mgal/d) was withdrawn for thermoelectric power generation, 34.0 percent (205 Mgal/d) was self-supplied by industrial and mining facilities, 10.1 percent (61 Mgal/d) was withdrawn for public-supply systems, and 0.2 percent (1.2 Mgal/d) was withdrawn for agricultural use. Saline-water use is not shown in figure 4, but is included in the discussion of thermoelectric power. About 81.7 percent (72 Mgal/d) of public-supplied water was delivered for domestic and commercial use, whereas 18.3 percent (16 Mgal/d) was delivered for industrial and mining use. The use data indicate that 23.0 percent (22 Mgal/d) of all water used for domestic or commercial use was withdrawn directly from ground-water sources, whereas 77.0 percent (77 Mgal/d) was delivered by public suppliers. For all water used in the State, the disposition data indicate that about 11.0 percent (76 Mgal/d) was consumed use and that 89.0 (611 Mgal/d) percent was returned to the hydrologic system. The largest consumptive use of water, about 67.1 percent of total water consumed, was for industry and mining.

Hydroelectric power generation is the principal instream water use. An estimated 14,500 Mgal/d, or 16,200 acre-feet per year, was needed to generate the 1,470 gigawatthours of electricity produced by hydroelectric powerplants during 1985.

PUBLIC SUPPLY

About 637,000 people or two-thirds of the State's population, are served by public-supply systems (New Hampshire Water Supply and Pollution Control Commission, 1985). The total population, withdrawals, and uses include some seasonal residents and their water use. The number of persons receiving public-supply water in each county, the population of each county, and the total surface- and ground-water withdrawals in each county are shown in figures 5*A* and 5*B*. In 1985, total withdrawals for public supply were 89 Mgal/d. Of this quantity, about 71 percent was delivered for domestic use at an average per capita rate of 99 gal/d (gallons per day); the remainder was used for commercial and industrial purposes.

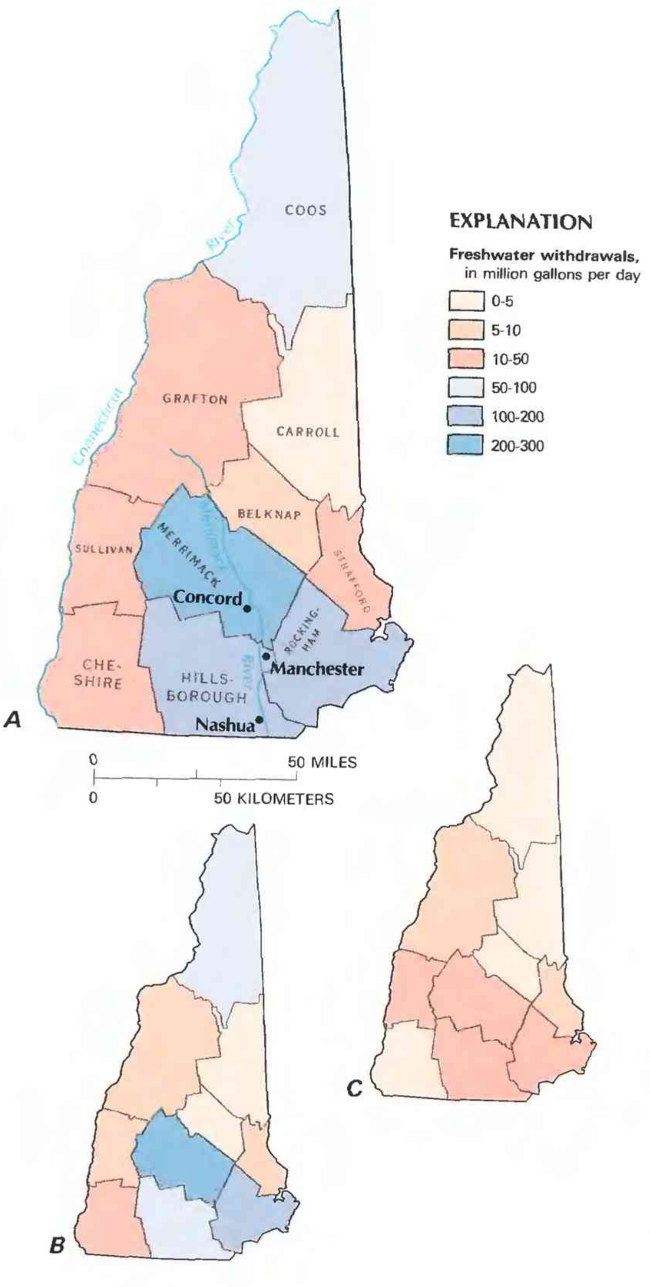


Figure 2. Freshwater withdrawals by county in New Hampshire, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Water is delivered by public-supply systems to two of the four categories of offstream water use shown in figure 4. Withdrawals of water by public systems decreased from 28 percent of total water withdrawals (excluding those for thermoelectric power generation) in 1980 (Solley and others, 1983, p. 38) to 25 percent in 1985. A comparison of 1980 and 1985 withdrawals by public supplies indicates that ground-water withdrawals decreased about 35 percent and that surface-water withdrawals increased about 32 percent.

Surface water provides 68.4 percent of the total water withdrawn for public supply (fig. 4) and serves about 67 percent of the population that uses public systems. Impoundments on small streams and lakes are the major sources of surface water; however, surface water also is obtained from some large streams and rivers. Hillsborough County withdraws about 42 percent (25 Mgal/d) of the surface water used for public supply and serves about 43 percent of the statewide population that receives surface water from public supply. This county includes two major cities—Manchester and Nashua—that depend mostly on surface water (fig. 5*B*). Withdrawals in the Merrimack River basin, which includes most of Hillsborough County, comprise more than 60 percent of the State's total surface-water withdrawals for public supply. Public-supply systems in Carroll County use the smallest amount of surface water in the State—1.6 percent for public supply.

In New Hampshire, most wells that provide at least 0.1 Mgal/d of ground water to public systems are completed in the stratified-drift aquifers (U.S. Geological Survey, 1985, p. 307). Ground water for small public-supply systems is withdrawn from either stratified-drift or crystalline-bedrock and till aquifers. Three counties—Belknap, Coos, and Sullivan—have ample supplies of surface water and account for 6 percent (less than 2 Mgal/d) of the ground water withdrawn for public supplies. Rockingham and Hillsborough Counties account for 40 percent (11 Mgal/d) of the ground water withdrawn by public-supply systems (fig. 5*B*). About 73 percent of the population served by public supplies from ground-water sources live in Rockingham, Hillsborough, Strafford, and Merrimack Counties (fig. 5*A*).

DOMESTIC AND COMMERCIAL

Domestic and commercial water users received water from public-supply and self-supplied systems. In 1985, combined total use was 94 Mgal/d (fig. 4) of which 77.0 percent (72 Mgal/d) was provided by public suppliers. Domestic use in 1985 was about 85 Mgal/d, of which 63 Mgal/d was from public-supply systems that serve about 64 percent of the population, and 22 Mgal/d was from self-supplied systems that served 36 percent of the population. From 1980 to 1985, domestic self-supplied ground-water withdrawals increased 138 percent, and the population served increased 110 percent (Solley and others, 1983, p. 14). About 20.0 percent (17 Mgal/d) of the total withdrawals and deliveries for this category was consumed. In 1985, commercial use was about 9 Mgal/d and was entirely from public-supply systems. Consumptive use was 20 percent (1.8 Mgal/d) of the total supply.

INDUSTRIAL AND MINING

Industry is a major offstream water user in the State. However, the amount of water used was not reported until 1985, when the State started a program to determine the quantity of this water use. Water use for mining is small—less than 1 percent (1.2 Mgal/d) of the total freshwater offstream use. In 1985, most of the water use for mining was for washing at sand and gravel operations. Industrial and mining use is estimated to be 37.2 percent (255 Mgal/d) of the total freshwater withdrawn (fig. 4). The public-supply deliveries, which were estimated to be the quantity remaining after domestic and commercial uses were accounted for, represents 6.4 percent of all water used by industry. Self-supplied surface water was estimated from surface-water-discharge permits. These discharges were estimated from maximum reported flows and probably are larger than the actual use by industry. Self-supplied ground water was estimated to be the difference between the total quantity of water withdrawn by industry and the quantity that originated as surface water.

In 1980, about one-half of the total self-supplied industrial withdrawals were in Merrimack County, where a metal casting company in Tilton uses large quantities of surface water for washing and cooling. About one-fourth of all self-supplied withdrawals was used by the paper industry in Coos County. Carroll and Belknap Counties have the smallest industrial use totals—0.1 and 0.6 percent, respectively. Industries that use self-supplied systems and that discharge water to septic systems on their properties are not included in the totals. A comparison of 1980 and 1985 data indicates that ground-water withdrawals for industrial use increased 162 percent and that surface-water withdrawals increased 4 percent.

THERMOELECTRIC POWER

About 542 Mgal/d of water (saline and fresh) is withdrawn to generate thermoelectric power in New Hampshire. Of this total, about 70 percent was used in Rockingham County, 20 percent in Merrimack County, and 8 percent in Hillsborough County. Almost all this water was withdrawn by fossil-fueled powerplants for cooling; about 38 percent of the water (207 Mgal/d) was saline water, and 62 percent (336 Mgal/d) was freshwater. Comparison of 1980 and 1985 data indicates an increase of 353 percent in fresh surface-water withdrawals and a decrease of 67 percent in saline surface-water withdrawals. At the Vermont Yankee Nuclear Plant, 1 percent is used for cooling. Although this plant is in Windham County, Vt., it withdraws water from the Connecticut River in New Hampshire.

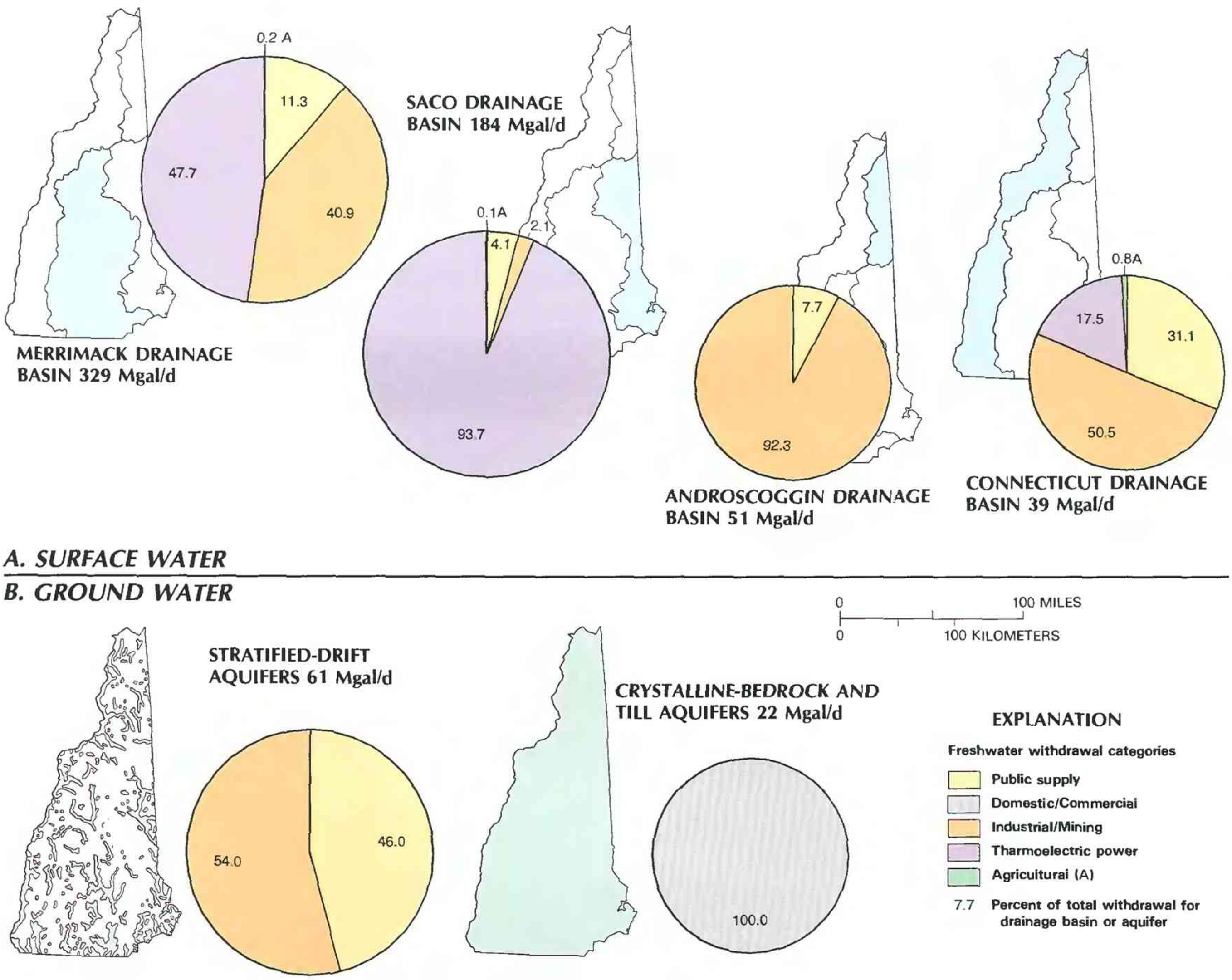


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in New Hampshire, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from various reports of the U.S. Geological Survey and State agencies; aquifer map from U.S. Geological Survey, 1985, p. 305.)

AGRICULTURAL

Major agricultural activities in New Hampshire include dryland farming of such products as corn, potatoes, and hay and the raising of livestock and poultry. About 1 percent of the acreage used for crops is irrigated, mostly by spraying (U.S. Bureau of the Census, 1983, p. 1). Livestock and poultry farming, which accounts for about 75 percent of annual farm revenues, uses about 68 percent of the water withdrawn for agriculture (U.S. Bureau of the Census, 1983, p. 2). About 45.3 percent of the water withdrawn for agricultural purposes was consumed. Grafton, Hillsborough, and Merrimack Counties are the largest agricultural water users—22, 19, and 14 percent, respectively. Belknap County withdraws the least amount (3 percent) of the water used for agriculture. Comparison of 1980 and 1985 nonirrigation agricultural water use indicates an increase of 136 percent in ground-water withdrawals, an increase of 27 percent in surface-water withdrawals, and a decrease of 68 percent in consumptive use. Irrigation surface-water withdrawals decreased 64 percent, whereas irrigated acreage decreased 27 percent.

WATER MANAGEMENT

Withdrawals of surface water in New Hampshire for public supply are closely monitored to assure that the supply is adequate for the demand. Discharges of wastewater are regulated to protect the water quality of streams. In 1983, the State legislature recognized the need to consolidate existing data and to collect more data on the quantity, quality, and use of the State's water resources. Chapters 361 and 402 of the Laws of 1983 recognized the interaction between surface and ground water and stated that they must be conserved, protected, and managed for the public good. This legislation also authorized the collection of data on water use through registration and reporting by large-volume users. The Water Management Bureau within the Water Resources Division of the Department of Environmental Services was charged with developing and implementing the registration and reporting program.

Only managers of activities that use more than 20,000 gal/d are required to register and report the quarterly water use. These activities include, but are not limited to, public supply, wastewater-treatment plants, industries, businesses, agriculture, hydropower, and snowmaking. Registration establishes the ownership and location of a facility, including the sources and destinations of the water and the purposes for which it is used. Flow through the facility must be accurately metered. Several acceptable methods of measurement are allowed, depending on the type of water use and nature of the facility.

Monthly water use totals are reported to the Water Management Bureau on a quarterly basis. The Bureau uses a computerized data base to store and retrieve water use data. The data base is an important element in the water-budget approach that is now used in New Hampshire to assess the availability of water in all drainage basins of the State.

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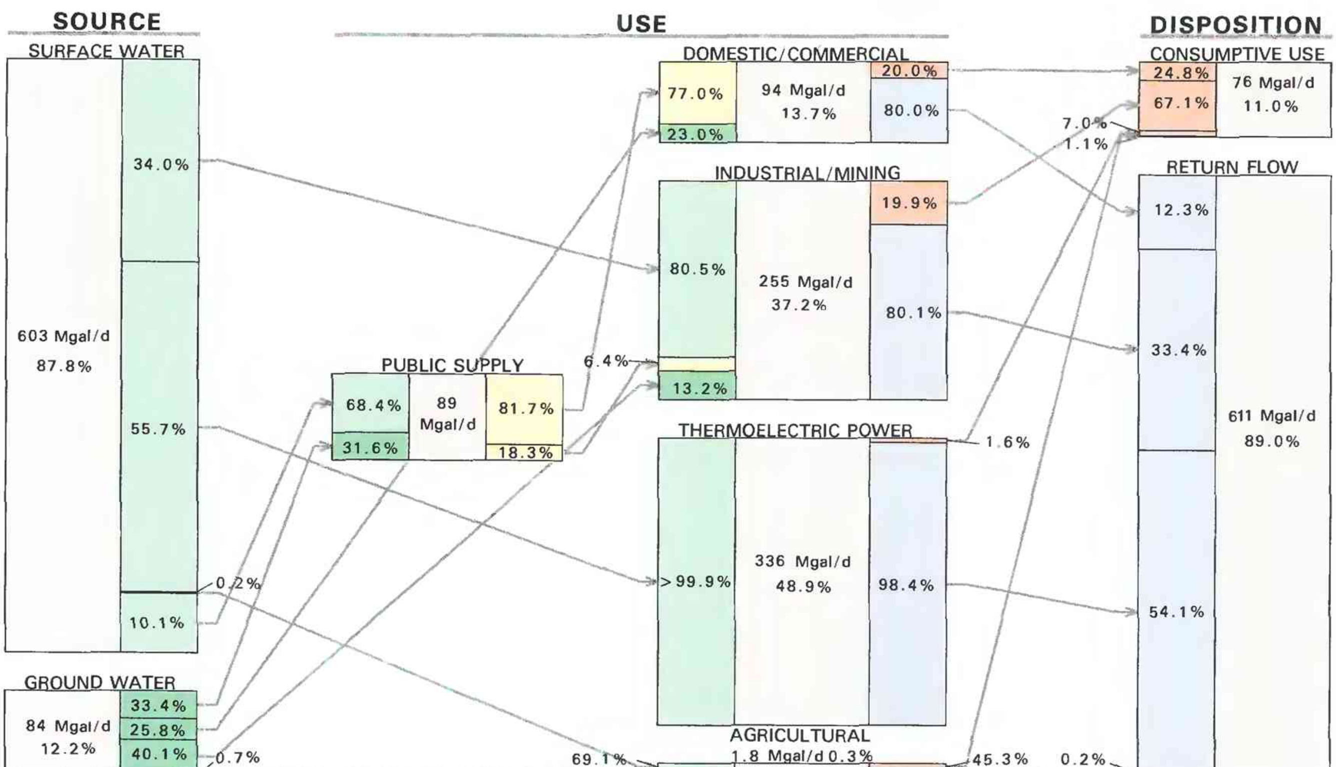
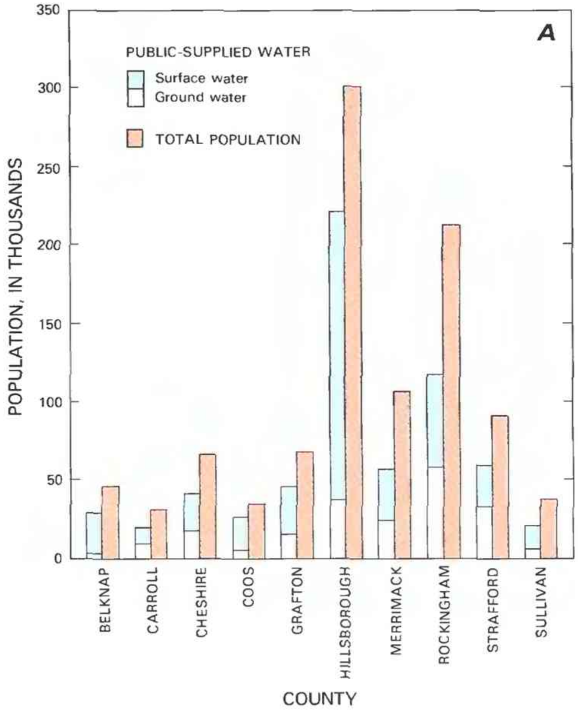


Figure 4. Source, use, and disposition of an estimated 687 Mgal/d (million gallons per day) of freshwater in New Hampshire, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)



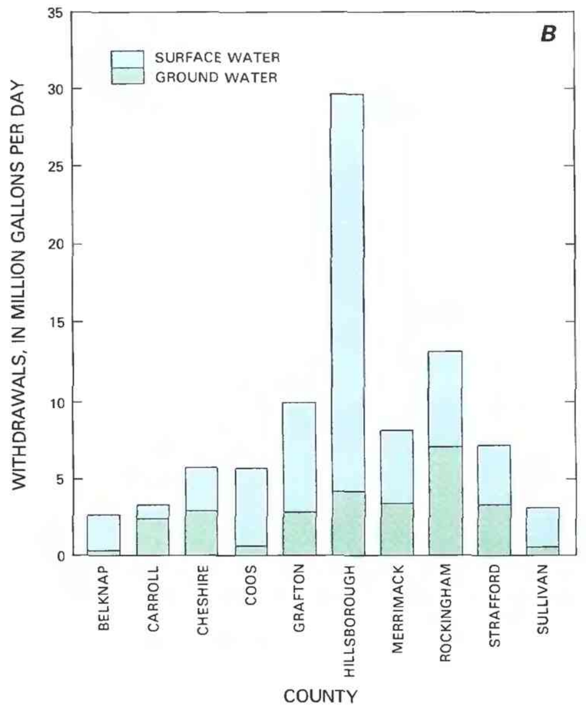


Figure 5. Public supply for New Hampshire. *A*, Population served by public-supplied freshwater withdrawals and total population by county. *B*, Public-supplied freshwater withdrawals by county. (Source: New Hampshire Water Supply and Pollution Control Commission, 1985.)

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Prepared by New Hampshire-Vermont Office, U. S. Geological Survey; Water Management section by Ken Sterns, Water Management Bureau, New Hampshire Department of Environmental Services

FOR ADDITIONAL INFORMATION: Chief, New Hampshire-Vermont Office, U.S. Geological Survey, RFD 12, 525 Clinton Street, Bow, NH 03304

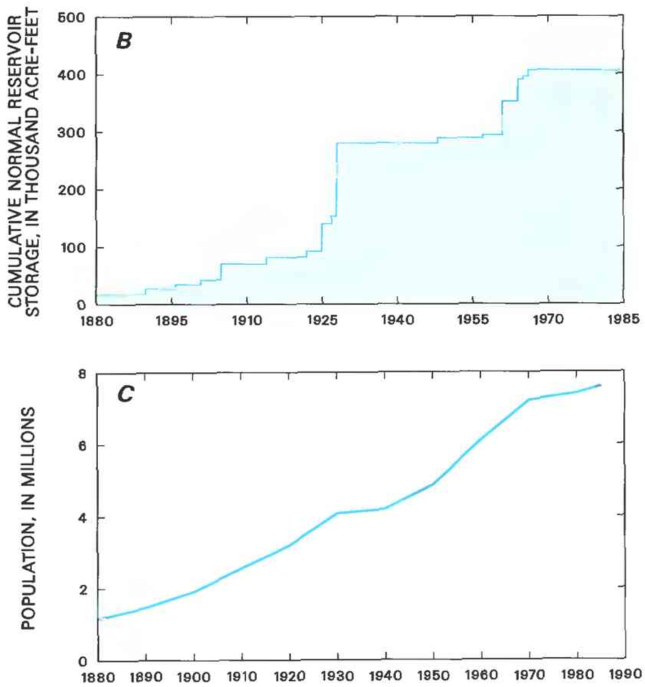
NEW JERSEY
Water Supply and Use

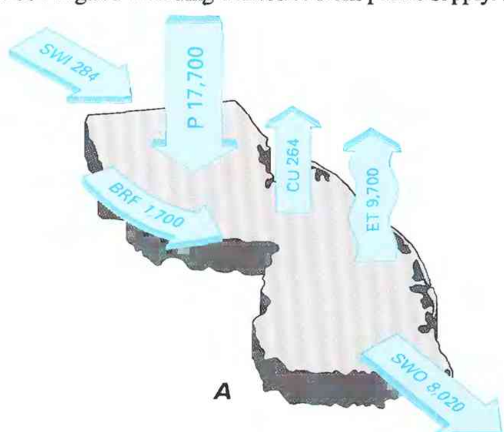
The primary source of water in New Jersey, the Garden State, is its ample precipitation, which averages about 45 inches annually, or 17,700 Mgal/d (million gallons per day). New Jersey also receives about 150 Mgal/d from rivers and streams that flow across the New Jersey–New York border under normal flow conditions (fig. 1*A*). The State generally receives an additional 134 Mgal/d withdrawn from the Delaware River, which is New Jersey's western boundary. The State lost about 8,020 Mgal/d from river and stream outflows and 264 Mgal/d from consumptive use. About 9,700 Mgal/d was lost to evapotranspiration.

In 1985, New Jersey faced an unprecedented second drought less than 3 years after the drought emergency that occurred between 1980 and 1982. Beginning in April 1985, mandatory restrictions on water use were implemented in 230 northeastern municipalities and in the New Jersey part of the Delaware basin. Voluntary restrictions were implemented elsewhere. The restrictions limited domestic water use to 50 gal/d (gallons per day) per person in dwellings that had one to four families per water meter and limited nondomestic users to 75 percent of normal water use. Nondomestic users included industrial and commercial users and domestic users in dwellings that had more than four families per water meter (New Jersey Department of Environmental Protection, 1987). For this reason, water-use amounts reported in 1985 represent suppressed withdrawals. In late September, Hurricane Gloria brought rainfalls that augmented water supplies. By mid-October, mandatory water-use restrictions were lifted, and the drought emergency was officially terminated in March 1986.

During 1985, about 2,230 Mgal/d of freshwater—an average of about 295 gal/d per capita—was withdrawn in New Jersey for many uses, including domestic and commercial, industrial processes and cooling, mining, power production, and crop irrigation. Of the 2,230 Mgal/d, about 73.0 percent (1,630 Mgal/d) was withdrawn from surface water, and 27.0 percent (600 Mgal/d) was from ground water. Public suppliers withdrew about 961 Mgal/d, or 43 percent of the total freshwater withdrawals. Domestic and commercial use was about 804 Mgal/d including deliveries from public supply. Industrial and mining companies used about 575 Mgal/d, including deliveries from public supply. Thermoelectric powerplants used about 725 Mgal/d, primarily from surface water. Agriculture used about 129 Mgal/d.

New Jersey is divided into two distinct geographic regions separated by the Fall Line (fig. 2*A*). North of the Fall Line (an area of about 3,321 square miles) the State lies in three physiographic provinces, each of which is underlain by different aquifer systems. Fractured siltstones and sandstones of the Newark Supergroup





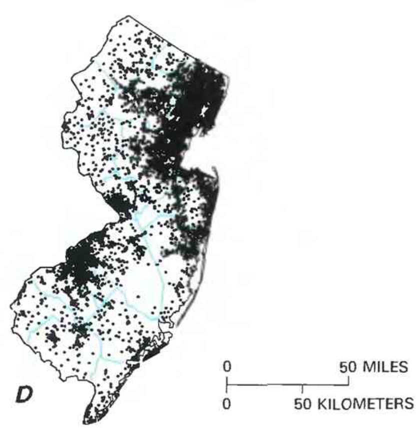


Figure 1. Water supply and population in New Jersey. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

underlie the Piedmont province, fractured crystalline rocks underlie the Highlands province, and Paleozoic sedimentary rocks form the aquifers of the Valley and Ridge province (U.S. Geological Survey, 1985). Significant thicknesses of unconsolidated glacial sediments overlie the fractured rock aquifers north of the Wisconsin terminal moraine. For the purposes of this report, withdrawals from aquifers in the Newark Supergroup, Valley and Ridge sedimentary aquifers, and Highlands crystalline aquifers are not differentiated with respect to withdrawals from glacial sediments or nonglacial fractured rock.

About 875 Mgal/d of freshwater was withdrawn north of the Fall Line in 1985. Of that amount, about 674 Mgal/d, or 77 percent, was from surface water, and about 201 Mgal/d, or 23 percent, was from ground water. The primary source of surface water in this region is the Delaware River, which provides as much as 175 Mgal/d under normal operating conditions. However, in 1985, withdrawals from the Delaware were decreased to about 66 Mgal/d while the Delaware and Raritan Canal was being refurbished. The Raritan, the Passaic, the Wallkill (Sussex County), the Hackensack, and other rivers provide the balance of the surface-water withdrawals. North of the Fall Line, the Wanaque (Passaic County), the Round Valley (Hunterdon County), the Spruce Run (Hunterdon County), and the Boonton (Morris County) Reservoirs are the largest surface-water storage facilities.

South of the Fall Line lies the Coastal Plain, an area of about 4,200 square miles. The Coastal Plain is underlain mainly by stratified, unconsolidated marine sediments of Cretaceous age. These sediments consist of sand, gravel, silt, and clay that thicken seaward from a featheredge at the Fall Line to more than 6,500 feet in southern Cape May County (Gill and Farlekas, 1976). Permeable beds of coarse materials form five major aquifer systems in the Coastal Plain. In order of decreasing magnitude of withdrawal, they are the Potomac–Raritan–Magothy aquifer system, the Kirkwood–Cohansey aquifer system, the Atlantic City 800-foot sand, the Englishtown aquifer system, and the Wenonah–Mount Laurel aquifer.

About 1,355 Mgal/d of freshwater was withdrawn in the Coastal Plain in 1985. Of this amount, about 958 Mgal/d (71 percent) was surface water, and about 397 Mgal/d (29 percent) was ground water. Important surface-water sources in southern New Jersey include the Manasquan (Monmouth County), the Toms (Ocean County), the Mullica (Atlantic County), the Salem (Salem County), the Cohansey (Cumberland County), and the Great Egg Harbor (Atlantic County) Rivers.

HISTORY OF WATER DEVELOPMENT

Beginning about 1660, early settlers of New Jersey established their homes along the easily navigable Hudson and Delaware Rivers and their tributaries where fertile land could be found near sheltered harbors. Sites along streams and rivers, where flow was sufficient to allow waterpower development, became very important to continued growth and settlement as industry developed. New Jersey became an early leader in 19th-century industrial growth because of the availability of waterpower and the State's proximity to the major ocean ports of New York and Philadelphia. The census of 1870 reported 11,108 waterpowered flourmills and gristmills in operation. These mills generated almost 26,000 horsepower. A study conducted in 1890–91 listed 12,880 flourmills and gristmills and 4,085 other types of mills that generated 30,870 horsepower (Vermeule, 1894, p. 8).

From the beginning of settlement, these rivers and streams plus wells were relied on for drinking water. What was perhaps one of the first wells for a freshwater supply in the United States was drilled in the city of New Brunswick by Levi Disbrow sometime before 1823 (Johnson, 1966).

During the 1840's, Jersey City, Newark, and Paterson (Passaic County), each a prosperous and growing center of population and industry, began to develop improved sources of freshwater. After the Civil War, noting the increasing pollution of the water sources and the growing concern about epidemics of water-borne typhoid fever, these cities began looking to other sources for fresh drinking water. Most northeastern New Jersey cities were using water transported from upland or filtered sources by 1905 (North Jersey District Water Supply Commission, 1945).

The State of New Jersey has been involved in water-supply management since 1791, when it granted all the water of the Passaic River watershed to the "Society for the Establishment of Useful Manufacturers" founded by Alexander Hamilton (Kroeck, 1974). Two grants that were significant for development of industrial water use in the early 1800's and that affected later generations were for the building of the Delaware and Raritan Canal and the Morris Canal (Kroeck, 1974).

The Delaware and Raritan Canal Company constructed a canal 60 miles long from Raven Rock (Hunterdon County) on the Delaware River to New Brunswick near the mouth of the Raritan River. The canal was opened in 1834, and, in 1867, it was acquired by the United New Jersey Railroad and Canal Company. The canal continued to be operated as a navigable route for commercial traffic until competition by railroads caused barge shipping to become uneconomical. Barge traffic declined until it was discontinued in 1933. Ownership of the canal was transferred to the State of New Jersey in 1934 (Kroeck, 1974). The canal is now operated as an important interbasin water-transport system.

The Morris Canal and Banking Company built the Morris Canal, which extended from the Delaware River at Phillipsburg (Warren County) to the Hudson River at Jersey City. To supply water for several reaches of the canal, the capacities of Lake Hopatcong (Morris County) and Greenwood Lake (Passaic County) were increased. Today, these lakes are important emergency sources of fresh surface water for northeastern New Jersey during times of drought (Kroeck, 1974).

Because of the increasing statewide demand for surface water, many improvements have been made in the water-supply systems. These improvements include the development of increased interconnections between public-supply systems and the refurbishment of the Delaware and Raritan Canal in 1985 to increase interbasin transfers of surface water. During the past 60 years, reservoir storage has increased fivefold to its present level of more than 404,000 acre-feet (fig. *1B*). In response to the problems in critical water-supply areas and elsewhere, increased storage capacity in the reservoir system is planned, including the construction of the new Manasquan Reservoir in Monmouth County. A study is being initiated to assess the need for the Confluence and the Six Mile Run Reservoirs in the Raritan basin (part of the Lower Hudson–Long Island basin).

Although New Jersey enjoys an annual average precipitation of about 45 inches, an increasing population (fig. *1C*) has led to serious water-storage problems during drought. These problems can be traced to the historical tendency to rely on the "home-rule principle" (Kroeck, 1978), under which the cities and the townships of New Jersey exercised control over their water supplies. For this reason, the State has traditionally limited its role in water-supply management. In the 1960's, a devastating drought focused attention on the seriousness of New Jersey's water-supply problems and increased popular support for necessary legislation. Authority for managing the State's water resources became centralized in 1970 when the New Jersey Department of Environmental Protection was created. Legislation during the 1970's and 1980's has further strengthened the ability of the State to manage this vital resource.

WATER USE

Increasing population (fig. *1C*) and population distribution (fig. *1D*) affect the distribution of water use in New Jersey. In 1985, the State was ninth in population in the United States (about 7.5

million residents) and first in population density (more than 1,000 people per square mile)(U.S. Bureau of the Census, 1987). Especially dense populations in the northeastern counties of Bergen, Passaic, Essex, Hudson, and Union have resulted from the development of business, industry, and transportation in this area.

Mercer County had the largest total freshwater withdrawals (627 Mgal/d) of all the counties in 1985 (fig. 2*A*). The largest part of these withdrawals (563 Mgal/d) was for thermoelectric power production. The largest surface-water withdrawals were in Mercer County (614 Mgal/d), followed by Passaic County (179 Mgal/d), Burlington County (150 Mgal/d), Somerset County (105 Mgal/d), and Hunterdon County (105 Mgal/d) (fig. 2*B*). Camden County had the most ground-water withdrawals in 1985 (82 Mgal/d), of which almost 72 Mgal/d was for public supply (fig. 2*C*). Middlesex County was second in ground-water withdrawals (55 Mgal/d). Most of the intensive freshwater-use industries are located along the Delaware River and in the Delaware and Coastal basin (fig. 3*A*). Although aquifers in the Newark Supergroup yield significant amounts of freshwater, ground-water supplies are insufficient to meet the needs of the public. Therefore, public-supply systems in northeastern New Jersey have always relied primarily on surface water (fig. 3*A*).

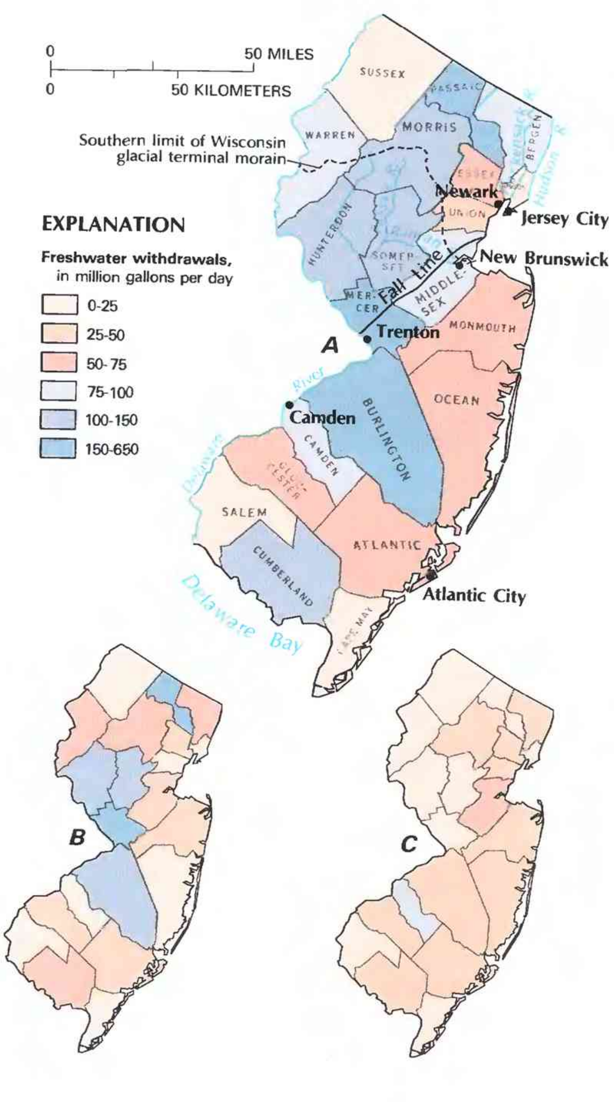


Figure 2. Freshwater withdrawals by county in New Jersey, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

South of the Fall Line, water supplies, with the exception of water for agricultural use, were obtained primarily from ground water in 1985. The most intensively pumped aquifer system, the Potomac–Raritan–Magothy, reportedly supplied about 235 Mgal/d in 1985 (fig. 3*B*). The Kirkwood-Cohansey aquifer system, the Atlantic City 800-foot sand, the Wenonah-Mount Laurel aquifer, and the Englishtown aquifer system provided a total of about 163 Mgal/d in 1985.

Large withdrawals from the Potomac-Raritan-Magothy aquifer system have caused saltwater intrusion in the aquifer in the Middlesex County area. The possibility exists for a similar situation to occur in the Camden metropolitan area. This problem, along with concern about ground-water quality, is forcing suppliers to find additional surface-water supplies to meet the increasing demand.

The source, use, and disposition of freshwater in New Jersey in 1985 are shown diagrammatically in figure 4. Because of independent rounding, the quantities of water given in this figure and elsewhere in this report may not add to the totals indicated. The source data indicate that surface water provided 73.0 percent (1,630 Mgal/d) of total water withdrawn in the State and that 44.2 percent was withdrawn for thermoelectric power generation. Ground water provided the remaining 27.0 percent (600 Mgal/d), of which 68.8 percent was withdrawn by public suppliers. The use data indicate that 36.0 percent (804 Mgal/d) of total self-supplied withdrawals and public-supplied deliveries were for domestic and commercial purposes. Of that water, 91.9 percent was delivered by public suppliers. The disposition data indicate that about 88.2 percent of the water used was returned to the hydrologic system for additional use, and about 11.8 percent was consumed.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. More than 630 public-supply systems in New Jersey (Whipple, 1987) provide water for domestic, commercial, industrial, and power production use (fig. 4). In 1985, the State was ninth in public-supply withdrawals (Solley and others, 1988), and about 89 percent of the population of New Jersey was served by public suppliers.

Withdrawals for public supply in 1985 totaled about 961 Mgal/d, or about 43 percent of all freshwater withdrawals. Of this total, 57.0 percent was surface water and about 43.0 percent was ground water (fig. 4). Because of the diverse geology and the resulting available sources of water, there are large differences in freshwater withdrawals for public supply and in deliveries throughout the State.

In northern New Jersey, about 77 percent of withdrawals by public-supply systems (more than 466 Mgal/d) was obtained from surface-water sources, principally from the Hackensack, the Passaic, the Raritan, and the Delaware Rivers. About 23 percent of freshwater withdrawals for public supply north of the Fall Line was obtained from aquifers in the Newark Supergroup (111 Mgal/d), the Highlands crystalline aquifer (29 Mgal/d), and the Valley and Ridge sedimentary aquifers (0.2 Mgal/d) (fig. 3*B*). In the five northeastern counties (Bergen, Passaic, Essex, Hudson, and Union), which include 43 percent of the total population of the State, public-supply systems provided nearly 430 Mgal/d of freshwater to users (fig. 5). This amount is about 45 percent of all public-supply deliveries in the State.

In contrast, public suppliers of the Coastal Plain obtain about 77 percent of their withdrawals from ground-water sources. The marine sediments that comprise the Coastal Plain aquifers yield large quantities of freshwater. In 1985, about 81 Mgal/d, or about 23 percent of withdrawals for public supply were from surface-water sources in the Coastal Plain. Of that amount, more than 28 Mgal/d was withdrawn in Monmouth County (fig. 5*C*). Of the 273 Mgal/d reportedly withdrawn by public suppliers from Coastal Plain aquifers in 1985, 181 Mgal/d (more than 66 percent) was from the Potomac–Raritan–Magothy aquifer system. Of that amount, more than 70 Mgal/d was withdrawn in Camden County (fig. 5*D*).

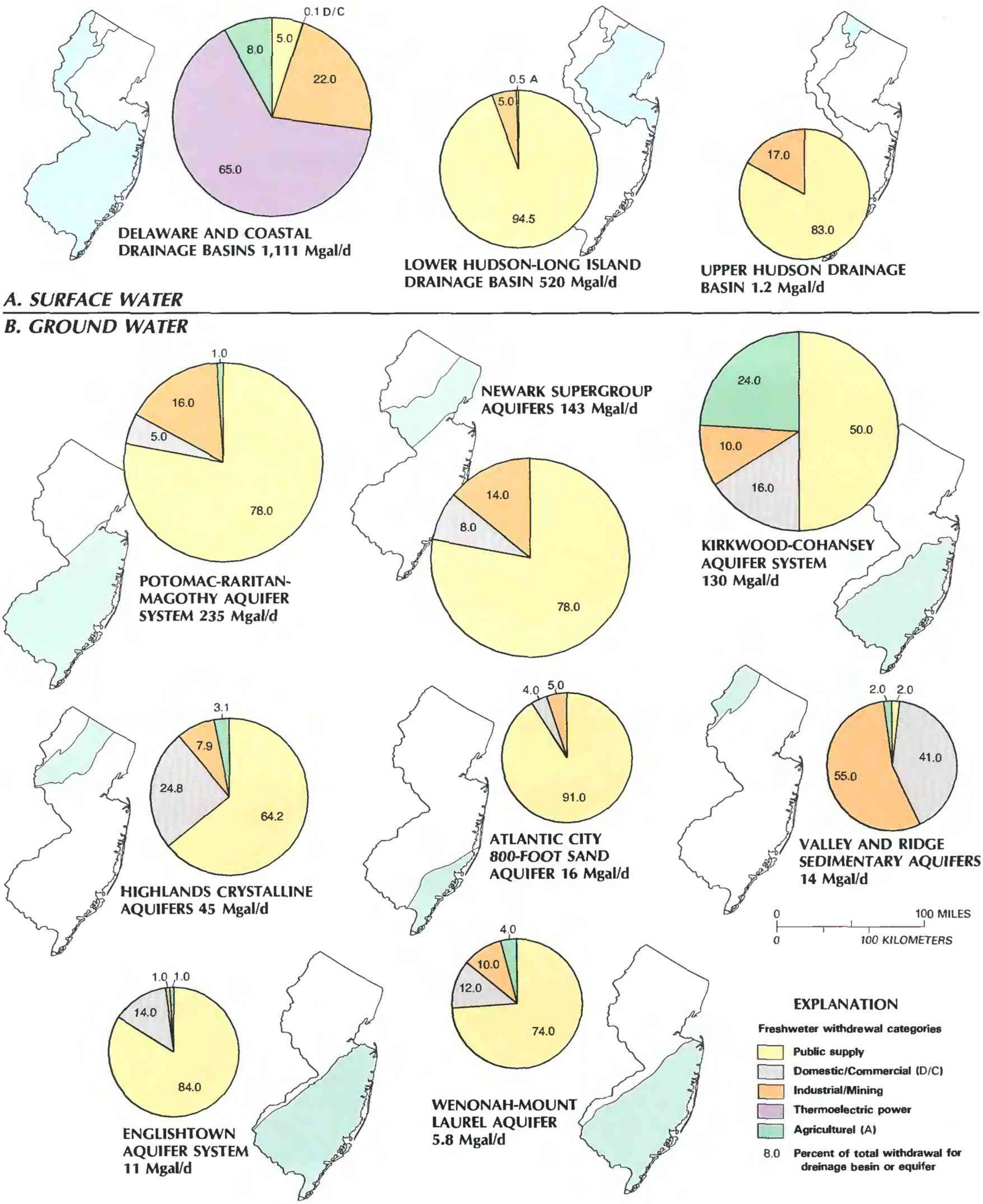


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in New Jersey, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* River basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System; Zapecza, 1984.)

DOMESTIC AND COMMERCIAL

Domestic and commercial users obtain water from public suppliers and self-supplied facilities. Combined use in 1985 was 804 Mgal/d, or about 36.0 percent of all freshwater withdrawals and deliveries (fig. 4). Of this amount, 167 Mgal/d, or about 19 percent, represents water imported into the various counties by way of intercounty transfers by public-supply systems. Self-supplied domestic and commercial users relied almost exclusively on ground water to meet their freshwater requirements.

Domestic water delivered by public-supply and self-supplied withdrawals was estimated by multiplying 1985 U.S. Bureau of the Census population estimates by an average 75 gal/d per capita. Domestic water use in 1985 was 567 Mgal/d. Of this amount, about 512 Mgal/d was provided by public-supply systems, and about 55 Mgal/d was withdrawn by self-supplied users. These self-supplied domestic withdrawals amounted to about 2.5 percent of total offstream water use in New Jersey in 1985. Consumptive use for domestic withdrawals and deliveries was 92 Mgal/d.

Commercial water use totaled about 237 Mgal/d in 1985. About 9 Mgal/d was withdrawn by self-supplied users; of this amount, only 0.1 Mgal/d was from surface water. An estimated 228 Mgal/d was delivered to commercial users from public-supply systems. Consumptive use was 9 Mgal/d.

INDUSTRIAL AND MINING

Total industrial and mining freshwater use was about 575 Mgal/d (fig. 4), which was about 25.7 percent of all water used in New Jersey in 1985. This amount includes about 493 Mgal/d for industrial use and 82 Mgal/d for mining use.

Industrial freshwater withdrawals in New Jersey in 1985 included about 77 Mgal/d of ground water and 195 Mgal/d of surface water (all self supplied). Public-supply deliveries were 221 Mgal/d. Self-supplied industrial withdrawals represented about 12 percent of the total water use for 1985. Additionally, about 801 Mgal/d of saline water was used by industry in 1985 to support production lines and for cooling. Consumptive use 39 Mgal/d of freshwater and 16 Mgal/d of saline water.

Industrial water use is dominated by six major manufacturing industries, which, combined, account for 88 percent of the total water used by all manufacturing industries in New Jersey. They are (in order of magnitude of water use) chemicals and allied products, petroleum and coal products, paper and allied products, food and kindred products, primary metals, and textile mill products, as designated by the New Jersey Department of Environmental Protection (1980, p. 114). Most companies in four of these sectors—chemicals, paper, primary metals, and textile products—are located in northeastern New Jersey. Companies in the petroleum and coal products sector are located in Middlesex, Mercer, and Gloucester Counties. The food industry, which is distributed throughout all but Ocean and Sussex Counties, has its greatest concentrations in five northeastern counties.

Mining withdrawals accounted for more than 3 percent of the total water use in 1985. Mining withdrawals were about 82 Mgal/d, of which 73 Mgal/d, or about 89 percent, was surface water and 9 Mgal/d was ground water. Most mining withdrawals in 1985 were by many sand and gravel companies in New Jersey.

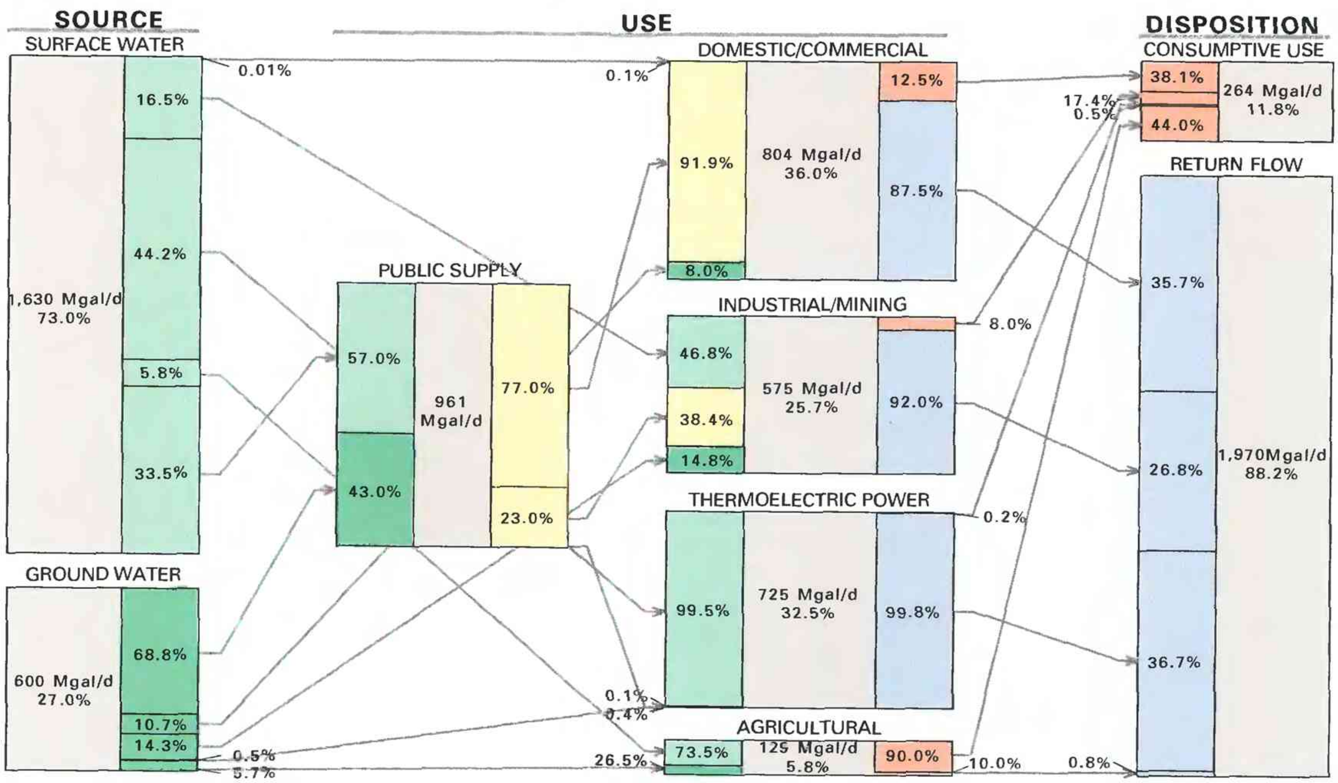


Figure 4. Source, use, and disposition of an estimated 2,230 Mgal/d (million gallons per day) of freshwater in New Jersey, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

THERMOELECTRIC POWER

In 1985, freshwater use for thermoelectric power generation, which was second only to domestic and commercial water uses in New Jersey, totaled 725 Mgal/d, or about 32.5 percent of all freshwater use. Of the State's 14 fossil-fueled generating facilities, 3 withdrew about 722 Mgal/d of fresh surface water, or about 99 percent of thermoelectric withdrawals, and 9, as well as two nuclear-power-generating facilities, relied on saline surface-water diversions for their cooling operations and used a combined total of about 3,820 Mgal/d in 1985. Thermoelectric plants also used small amounts of fresh ground water (3.4 Mgal/d) primarily for ancillary plant operations and human consumption. One fossil-fueled facility in New Jersey is unique in that it obtains ground water from a local public supplier and uses it for steam generation and to replenish water evaporated in its cooling tower; this plant used about 0.60 Mgal/d in 1985. Total thermoelectric power generation in New Jersey in 1985 was 34,000 gigawatthours.

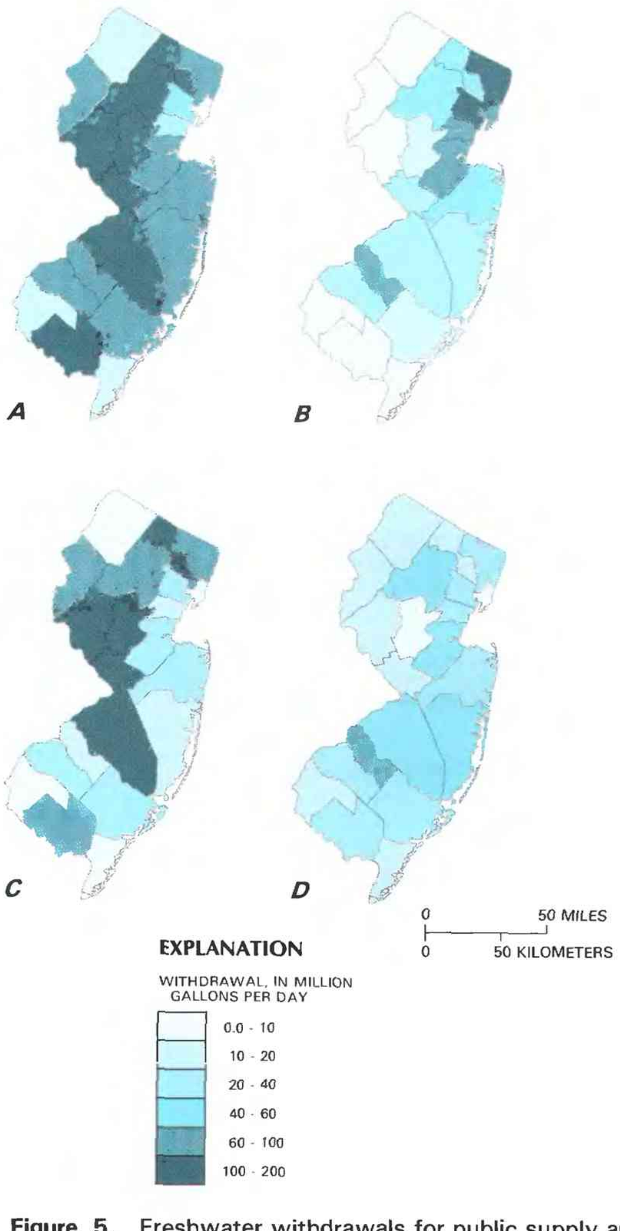


Figure 5. Freshwater withdrawals for public supply and deliveries by county in New Jersey, 1985. *A*, Total withdrawals. *B*, Total deliveries. *C*, Surface-water withdrawals. *D*, Ground-water withdrawals. (Source: *A*, *B*, *C*, *D*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Instream water use in New Jersey for hydroelectric power generation is small. In 1985, two hydroelectric generation facilities were online, one in Passaic County and the other in Warren County. Combined, they used about 77 Mgal/d. Three hydroelectric facilities either are in the planning stage or have been brought online since 1985.

AGRICULTURAL

Total agricultural withdrawals in New Jersey in 1985 were about 129 Mgal/d, or about 5.8 percent of total offstream use. Of that amount, about 3.1 Mgal/d was withdrawn for such nonirrigation uses as livestock watering.

In the State, more surface water than ground water is withdrawn for irrigation. Total surface-water withdrawals in 1985 for irrigation of all crops was reported to be about 92 Mgal/d, whereas fresh ground-water withdrawals totaled almost 34 Mgal/d. More than one-half the surface-water withdrawals, about 50 Mgal/d, was used by farmers to flood about 3,000 acres of cranberries for irrigation and plant protection. Surface-water withdrawals for all other crops were about 42 Mgal/d.

In 1985, New Jersey had more than 500,000 acres under cultivation for all crop types. Of this amount, about 89,000 acres (excluding cranberry acreage) were irrigated for various crops, as reported by the Cooperative Extension Service, Cook College, Rutgers University. The majority of acreage under irrigation was located in Atlantic, Burlington, Cumberland, Gloucester, and Salem Counties, which are all on the fertile Coastal Plain. Combined, these counties accounted for about 80 percent of all irrigated acreage, most of which was planted with vegetable and fruit crops. About 62,360 acres were harvested for fresh market and food processing in 1985 (New Jersey Department of Agriculture, 1986).

WATER MANAGEMENT

The State of New Jersey Water Supply Management Act of 1981 is perhaps the most comprehensive State water-supply management legislation to date. The Act repealed most preexisting water-supply statutes, expanded the State's powers concerning water-supply management, and clarified the State's role and responsibilities in water management. The Act delegates powers, functions, and duties to the New Jersey Department of Environmental Protection and outlines general water-system management authority. This authority has been interpreted as relating to interconnections, safe system yield, water conservation, provision for system storage, infrastructure management, and State powers over diversion and use of water from depleted aquifers (Whipple, 1987). Also, the Water Supply Bond Act of 1981 (Public Law 1981) was passed to provide funds for planning, designing, acquiring, and constructing water-supply facilities. A referendum, which was passed in 1983, also allows the bond funds to be used for ground-water studies (U.S. Geological Survey, 1985).

New Jersey has taken a comprehensive resource-management approach to water-supply protection. Most State laws dealing with water management require certain facilities or users to self-monitor quantities withdrawn and water quality for State review. Under New Jersey Law 1947, as strengthened by the 1981 Water Supply Management Act, the New Jersey Department of Environmental Protection has instituted an Allocation Permit process that requires all those who divert ground and surface water of 100,000 gal/d or greater to obtain an allocation permit and to report monthly withdrawals each quarter. Further, all irrigators must have their wells certified regardless of pumping capacity. New Jersey also has required that all well drillers working within the State be licensed.

In addition to permit processes, administrators of this legislation have decided to concentrate efforts on "critical water-supply management areas" rather than to impose what may be deemed to be excessive controls over public suppliers in a State that has traditions of strong home rule (Whipple, 1987). Two such areas in the State (fig. 6), which have been designated critical water-supply management areas, have related problems with respect to depletion of aquifers caused by prolonged overpumping.

Critical Water-Supply Management Area No. 1, which is comprised of eastern Middlesex County and the northeastern sections of Monmouth and Ocean Counties (fig. 6), was designated in 1985. In this area, overpumping of the Old Bridge aquifer, a unit of the Potomac–Raritan–Magothy aquifer system, has allowed saline-water intrusion into the aquifer, which has resulted in a decrease in the availability of fresh ground water from this source. Feasibility studies are underway to explore alternative sources of water supply to mitigate the decreases in ground-water withdrawals needed to limit saline-water encroachment (Whipple, 1987).

In 1986, the Metropolitan Camden area was designated Critical Water-Supply Management Area No. 2 (fig. 6) because of the possibility of saltwater contamination in the overpumped Potomac–Raritan–Magothy aquifer system. In this area, overpumping of the aquifer system has reversed the normal flow of water from the aquifer to the river; the river now recharges the aquifer. In the event of a severe drought, decreased streamflow in the Delaware River could allow the saltwater front in the Delaware Bay to advance upstream to the Camden area, thereby allowing the intrusion of saltwater into the aquifer.

In the Atlantic City area (Atlantic County), depletion of the Atlantic City 800-foot sand is also a problem. The possibility of this area being designated a critical water-supply management area is being investigated (Whipple, 1987).

A 1954 Supreme Court decree set maximum diversions from the Delaware River basin at an average of 800 Mgal/d for New York and 100 Mgal/d for New Jersey and mandated flow at Montague (Sussex County) to be maintained at a minimum of 1,700 cubic feet per second to limit movement of saltwater upstream in the river. This same decree designated the Chief Hydraulic Engineer (now Chief Hydrologist) of the U.S. Geological Survey, or a designee, as River Master for the Delaware River basin. The River Master's prime responsibility is the administration of the terms of the decree, conservation of the waters in the watershed, and annually reporting to the United States Supreme Court and to the Governors of the States of Delaware, New Jersey, New York, and Pennsylvania on conditions within the basin (Supreme Court of the United States, 1954).

The Delaware River Basin Commission was formed in 1961 upon adoption of the Interstate–Federal Delaware River Basin Compact. Comprised of representatives of the Federal Government, and the States of Delaware, New Jersey, New York, and Pennsylvania, the commission is empowered to regulate water resources and control development of other natural resources in the basin (American Water Works Association, 1985).

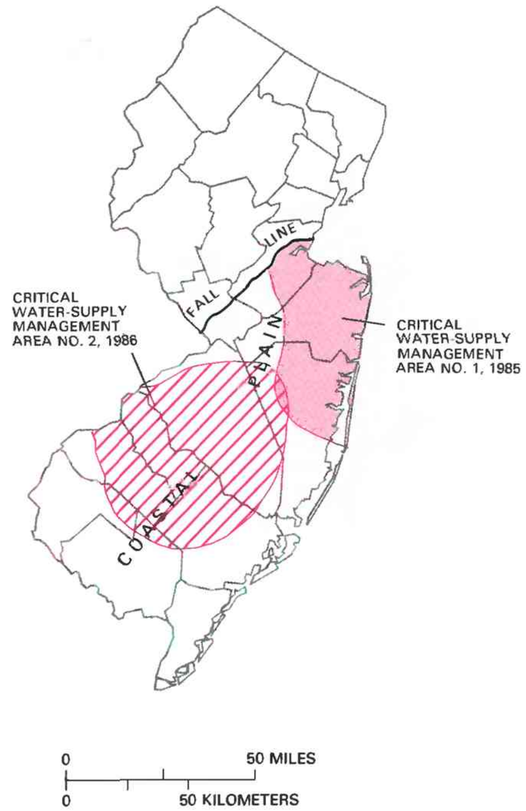


Figure 6. Critical water-supply management areas in New Jersey, 1985. (Source: New Jersey Department of Environmental Protection, 1987.)

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Prepared by C.L. Qualls and M.A. Horn

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 810 Bear Tavern Road, Suite 206, West Trenton, NJ 08628

NEW MEXICO
Water Supply and Use

New Mexico has a semiarid climate, with an average annual precipitation of 13 inches. Water supplies can be abundant at times in some locations, but, overall, water is scarce. The physiography ranges from plains to mountains; the altitude ranges from 3,000 to 13,000 feet above sea level. The precipitation varies with the terrain. More than 90 percent of New Mexico's precipitation and surface-water inflow from adjacent States returns to the atmosphere through evapotranspiration (fig. 1*A*).

In 1985, New Mexico residents withdrew about 3,290 Mgal/d (million gallons per day) of freshwater from aquifers and watercourses; consumptive water use was about 1,530 Mgal/d (excluding reservoir evaporation). The New Mexico State Engineer reported that reservoir evaporation was about 423,000 acre-ft (acre-feet), or 378 Mgal/d, in 1985 (Wilson, 1986). Unless otherwise noted, the data in the figures and text do not include reservoir evaporation as a withdrawal or consumptive use.

Agriculture (including irrigation) is the largest water use in the State. Irrigation is the most prevalent in the Rio Grande, the San Juan, and the Pecos River valleys and in the High Plains of eastern New Mexico. Unfavorable economic conditions made it difficult for farmers to irrigate as much acreage in 1985 as they had in previous years.

The population of New Mexico increased almost 9 percent from 1,302,894 in 1980 to 1,417,790 in 1985 (Wilson, 1986). Water withdrawals for domestic and commercial uses have increased along with the population, especially in the larger cities of Albuquerque, Las Cruces, and Santa Fe.

As in other Western States, New Mexico's economy has suffered from the depressed fossil-fuel and mineral-resource industries. Consequently, mining and industry used considerably less water during 1985 than in the past.

HISTORY OF WATER DEVELOPMENT

New Mexico has a long and rich history of water-resource development that predates the landing of the pilgrims at Plymouth Rock. The earliest community use of water was for the cultivation of crops by the Pueblo Indians, who built irrigation canals to transport water to their fields during prehistoric times (Harris, 1984).

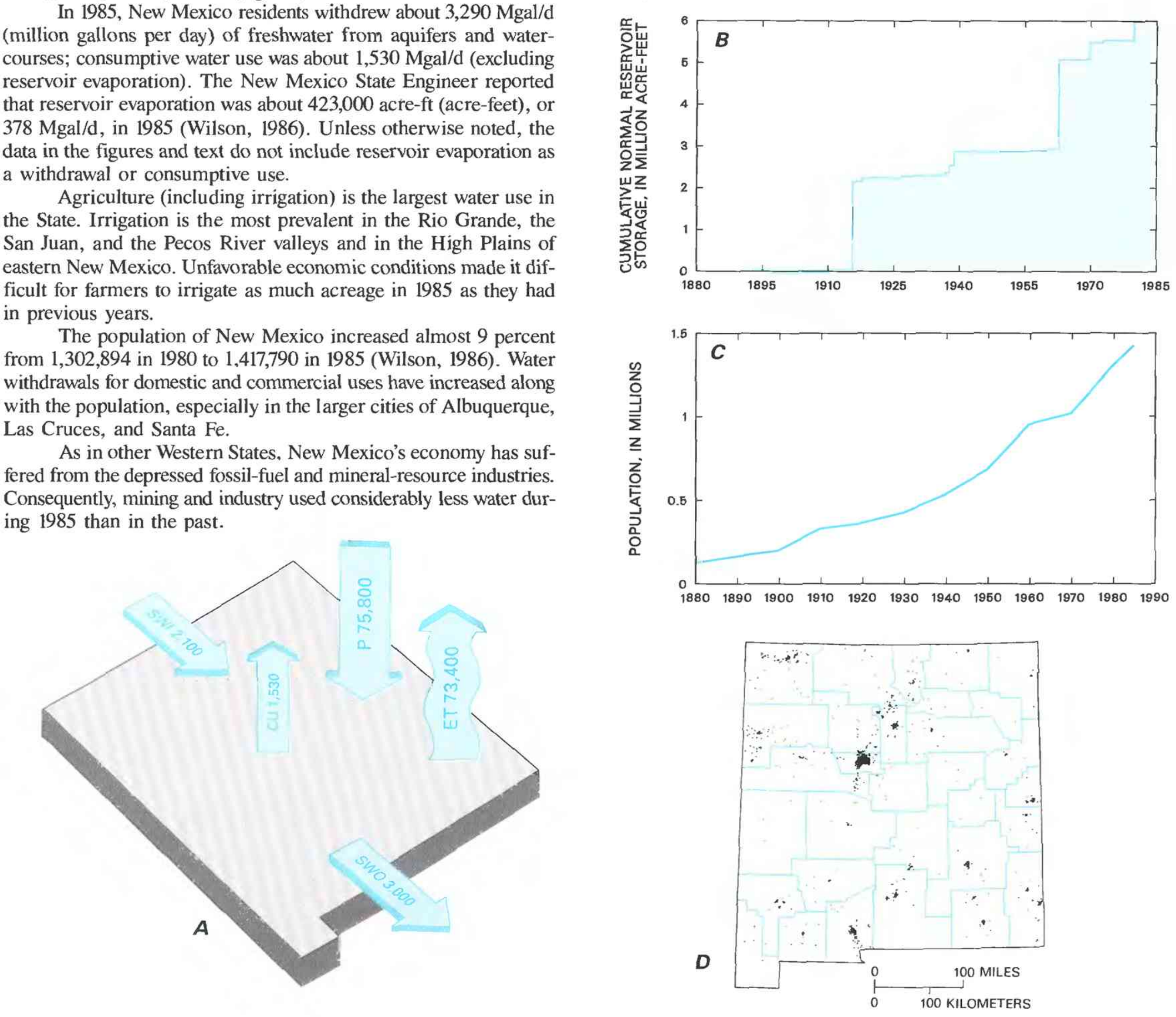

Figure 1. Water supply and population in New Mexico. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* U.S. Bureau of Reclamation, 1976; Wilson, 1986. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

The availability of water affected the pattern of settlement and development of semiarid New Mexico. The Rio Grande valley, which has abundant streams and fertile grasslands, provided natural routes for Spanish explorers (Francisco de Coronado in 1540; Don Juan de Onate in 1598) and settlers traveling north from Old Mexico. In 1610, the Spanish established headquarters at La Villa Real de la Santa Fe de San Francisco de Assisi (now Santa Fe), the oldest seat of government in the United States (U.S. Bureau of Reclamation, 1976).

The small rural communities of colonial New Mexico were patterned after the Indian pueblos. Spanish farmers built and maintained community ditches, called acequias, as a communal enterprise (New Mexico State Engineer Office, 1967, p. 147). The acequia system has been in continuous use since the 17th century in many northern New Mexico communities. Today's State water law has its roots in Spanish laws, customs, and methods of water-use administration.

Spanish colonization in the 1700's and 1800's in the Rio Grande valley brought expansion in population and irrigated agriculture. Growth and development were primarily within the fertile valleys of the major streams. The United States declared war on Mexico on May 10, 1846, and took possession of New Mexico in the same year. The Treaty of Guadalupe Hidalgo, in 1848, officially transferred the territory to the United States. By 1890, water shortages had occurred along the lower Rio Grande. To ease the shortages and to meet treaty obligations with Mexico, the U.S. Bureau of Reclamation built Elephant Butte Dam in Sierra County. The dam was completed in 1916 and today stores water used to irrigate about 160,000 acres in New Mexico and Texas. Major reservoirs constructed on streams and rivers throughout the State are used to regulate and conserve water supplies. The cumulative total conservation storage capacity of reservoirs that have capacities greater than 5,000 acre-ft in the State was more than 5.9 million acre-ft in 1985 (fig. *1B*). The major cities of Santa Fe, Albuquerque, and Las Cruces in the Rio Grande valley constitute 32 percent of the State's population (Wilson, 1986). The population growth from 1880 to 1985 and the distribution of 1985 population are shown in figures *1C* and *1D*, respectively.

In 1888, a site at Embudo on the Rio Grande in northern New Mexico was chosen as the training center for the first hydrographers of the Irrigation Survey, a new bureau that had just been added to the U.S. Geological Survey under John Wesley Powell (Frazier and Heckler, 1972). The first recording streamflow-gaging station was established at this site in 1889 to train hydrographers and to evaluate streamflow for irrigation supply. This station is still in operation today.

Ground-water development in the State began with the discovery of artesian ground water near Roswell in the Pecos River basin in 1891; within 35 years, more than 1,400 artesian wells were operating in the area (New Mexico State Engineer Office, 1967). In 1985, ground water was the primary source of water for 60 percent of the State's irrigated cropland (Lansford and others, 1986). Another 13 percent of the irrigated cropland acreage was irrigated from surface- and ground-water supplies.

New Mexico's average annual precipitation of 13 inches makes irrigation a critical component of the State's agricultural economy. From 1940 to 1985, irrigated cropland in New Mexico nearly tripled. Today, more than one-half of the State's cropland is irrigated (Lansford and others, 1986). Irrigation has made the production of pecans, chiles, and onions especially profitable in southern New Mexico.

The State's early economy was largely dependent upon farming and ranching. Oil, discovered in the 1920's, brought additional economic prosperity to northwestern and southeastern New Mexico. However, the defense and the technological industries that developed during World War II soon eclipsed agriculture as the economic base in the Albuquerque region.

Several major projects represent more recent milestones in New Mexico's water development. The San Juan–Chama Project, authorized in 1962, diverts water from the San Juan River basin in southern Colorado and transports it through 26 miles of underground pipeline beneath the Continental Divide into Heron Reservoir (Rio Arriba County) in the Rio Grande basin of northern New Mexico. The water is used for municipal, domestic, agricultural, industrial, fish and wildlife, and recreational purposes (Cannon, 1969). The Navajo Indian Irrigation Project also was authorized in 1962. In 1976, water from the San Juan River was delivered to irrigate the first 9,200 acres of the 110,000-acre project in San Juan County in northwestern New Mexico. Between 1976 and 1985, an additional 37,400 acres was developed (Lansford and others, 1986). The huge irrigation project is creating agricultural land from former rangeland.

WATER USE

New Mexico's surface-water supply varies greatly with time and location. The average annual precipitation ranges from 8 inches in the arid desert regions to 30 inches in the mountains (New Mexico State Engineer Office, 1967). Spring snowmelt and intense summer rainstorms create large volumes of surface-water runoff. The construction of reservoirs since 1893 (fig. *1B*) has helped to regulate the surface-water supply. The reservoirs provide flood and sediment control, recreation, water for hydroelectric use, and storage of water for irrigation use.

New Mexico relies on ground water to meet many of its water-use needs because of the scarcity and the variability of surface water. Ground water was the source for 45.9 percent of the State's total withdrawals in 1985. The State has an abundance of ground water in storage, but it is not distributed uniformly. Additionally, some ground water is difficult to extract, and excessive salinity limits its use. In the southeastern counties of Curry, Roosevelt, Lea, Chaves, and Eddy, ground-water levels have been declining as a result of extensive withdrawals for irrigation.

Total, surface-water, and ground-water withdrawals by county in 1985 are shown in figures *2A*, *2B*, and *2C*, respectively. San Juan County, in northwestern New Mexico, had the largest total and surface-water withdrawals of New Mexico's 33 counties. Of the water withdrawn, 99 percent was surface water, which was used for irrigation, mining, power production, and domestic purposes. Doña Ana County had the second-largest withdrawals. Most of these withdrawals were for irrigation, power production, mining, and domestic and commercial purposes. Chaves County ranked third in total withdrawals and first in ground-water withdrawals. In general, the areas in the State that withdraw the most water are the areas of extensive irrigation.

About one-third of New Mexico's residents live in Bernalillo County, where the State's largest city, Albuquerque, is located. However, Bernalillo County ranks seventh in total withdrawals by county, which demonstrates the difference in magnitude of withdrawals for irrigation and for domestic purposes.

Surface-water withdrawals for agriculture during 1985 were dominant in all the principal river basins (fig. *3A*). The largest agricultural withdrawals (mainly for irrigation) were in the Rio Grande–Elephant Butte, the San Juan, the Rio Grande–Mimbres, and the Upper Pecos basins. In the San Juan basin, thermoelectric power use accounted for 11.3 percent of the surface-water withdrawals. The three powerplants in the San Juan basin withdrew virtually all the surface water used for power production in the State. In all but two of the principal basins, some surface water was withdrawn for industrial and mining use. About 12.4 percent of all the water withdrawn for public-supply systems (for domestic, commercial, industrial, and mining purposes) was surface water (Solley and others, 1988).

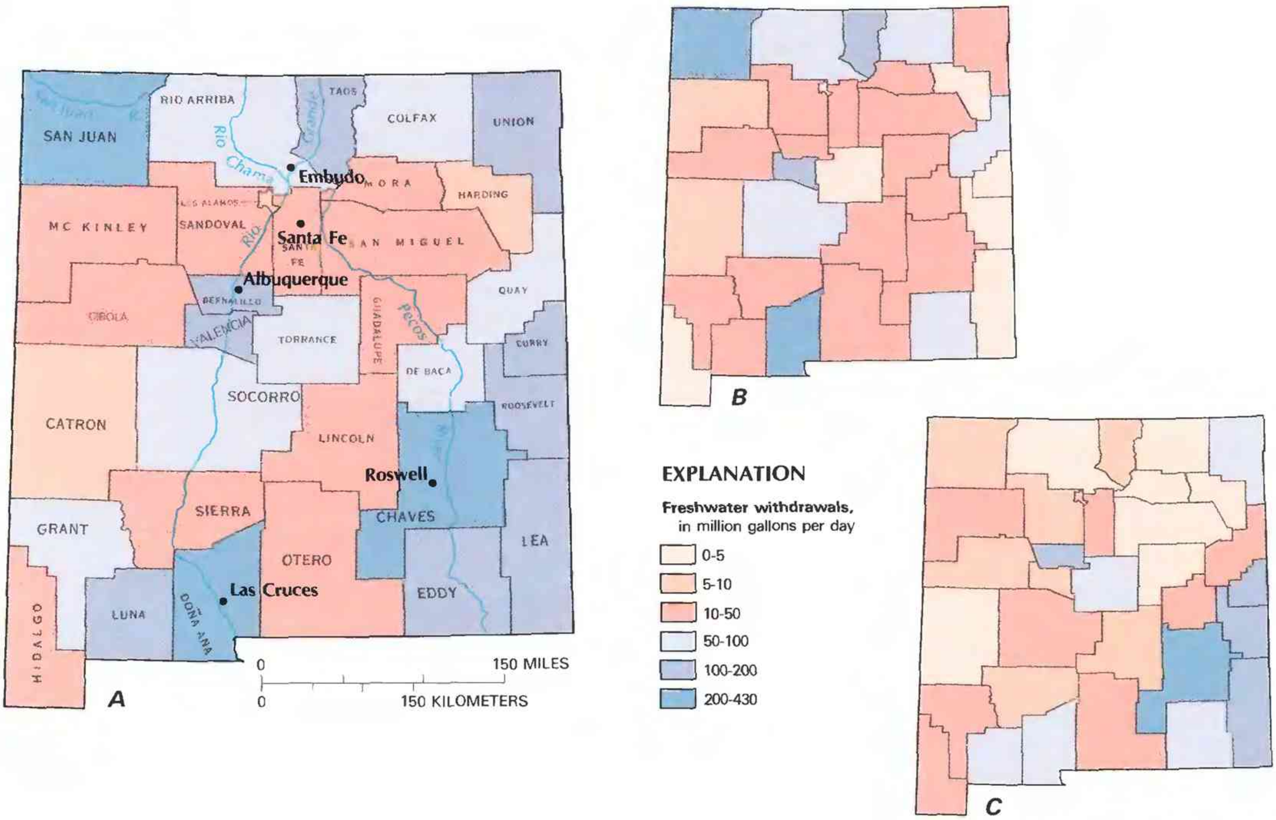

Figure 2. Freshwater withdrawals by county in New Mexico, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Ground-water withdrawals during 1985 (fig. 3*B*) served all categories of use. The largest quantity of ground water was withdrawn in the southeastern part of the State and was used mainly for irrigation. Ground water was the source for all self-supplied domestic and commercial use and for 87.6 percent of the publicly supplied water. Industry, mining, and thermoelectric powerplants in southern and eastern New Mexico also used ground water, which was largely from the basin-fill aquifers.

The source, use, and disposition of freshwater in New Mexico are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 95.0 percent (1,690 Mgal/d) of the surface water and 78.5 percent (1,180 Mgal/d) of the ground water were withdrawn in the State by agricultural users. The use data indicate that 58.8 percent of the water withdrawn for agriculture was surface water and 41.2 percent was ground water. Of the total agricultural withdrawals, 46.1 percent (1,320 Mgal/d) was consumed, and 53.9 percent (1,550 Mgal/d) was returned to the hydrologic system. The disposition data indicate that agricultural use accounted for 86.2 percent (1,320 Mgal/d) of all the water consumed and 88.5 percent (1,550 Mgal/d) of all the return flow.

Reservoir evaporation is an additional category of use shown only in figure 5*A*. It represented 19.5 percent of the State's total consumptive use in 1985, (Wilson, 1986). Fish and wildlife and recreation are additional categories of use for which the New Mexico State Engineer collects data. These two categories were combined in figure 5*A*.

Hydroelectric power generation is the main instream water use in the State. The hydroelectric powerplant at Elephant Butte Dam (Sierra County) on the Rio Grande is the largest in the State and has a generating capacity of 24,300 kW (kilowatts). The plant was built in 1916 and is owned by the U.S. Bureau of Reclamation. Four smaller hydroelectric systems were operated in 1985. These smaller systems have capacities of 200 kW or less (New Mexico Energy and Minerals Department, 1986). Hydroelectric powerplants are under construction at El Vado Dam and Abiquiu Dam (both in Rio Arriba County) on the Rio Chama and at Navajo Dam (San Juan County) on the San Juan River.

Public Supply

New Mexico's public-supply systems withdraw and deliver water to domestic, commercial, and industrial users. Almost all (98.8 percent) of the water delivered by public-water suppliers was for domestic and commerical use (fig. 4). Of the supply delivered by public-water systems in 1985, 87.6 percent was ground water.

About 80 percent of the ground-water withdrawals for public-supply systems came from wells completed in basin-fill aquifers (fig. 3*B*) that underlie the large population centers of Albuquerque, Las Cruces, and Santa Fe. The basin-fill aquifers consist of sand, gravel, silt, and clay. Normal well yields range from 100 to 500 gallons per minute and well depths commonly are between 100 and 500 feet below land surface (U.S. Geological Survey, 1985). Metropolitan Albuquerque (population of 442,000) and Las Cruces (population of 48,700) rely solely on ground water to supply their domestic and commercial needs (Wilson, 1986). Santa Fe, the State capital, uses surface and ground water for its domestic and commercial needs.

Domestic and Commercial

Most domestic and commercial users received water from public-supply systems during 1985. Water use for domestic and com-

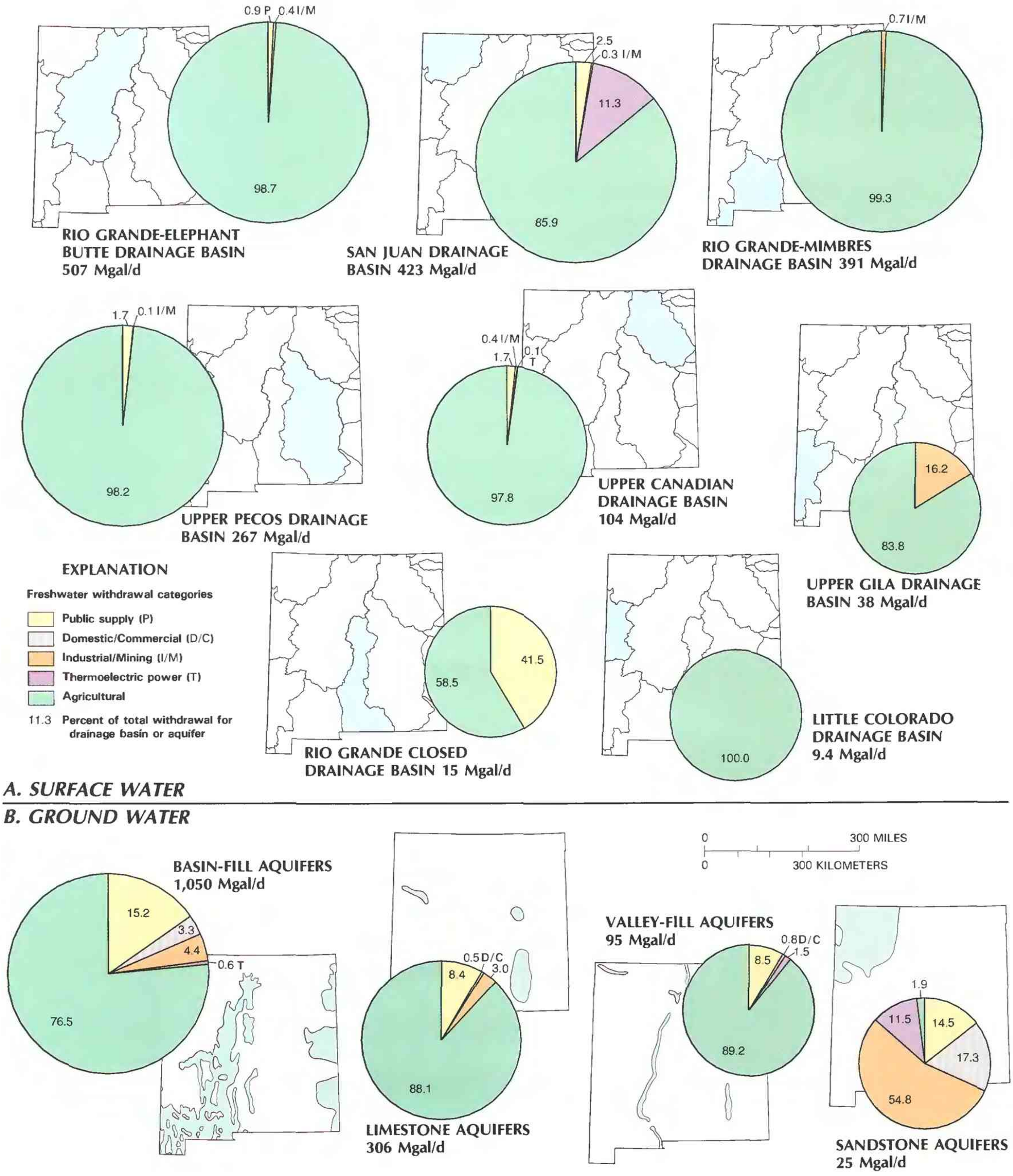

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in New Mexico, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Compiled by the U.S. Geological Survey on the basis of data from Wilson, 1986; U.S. Geological Survey, 1985.)

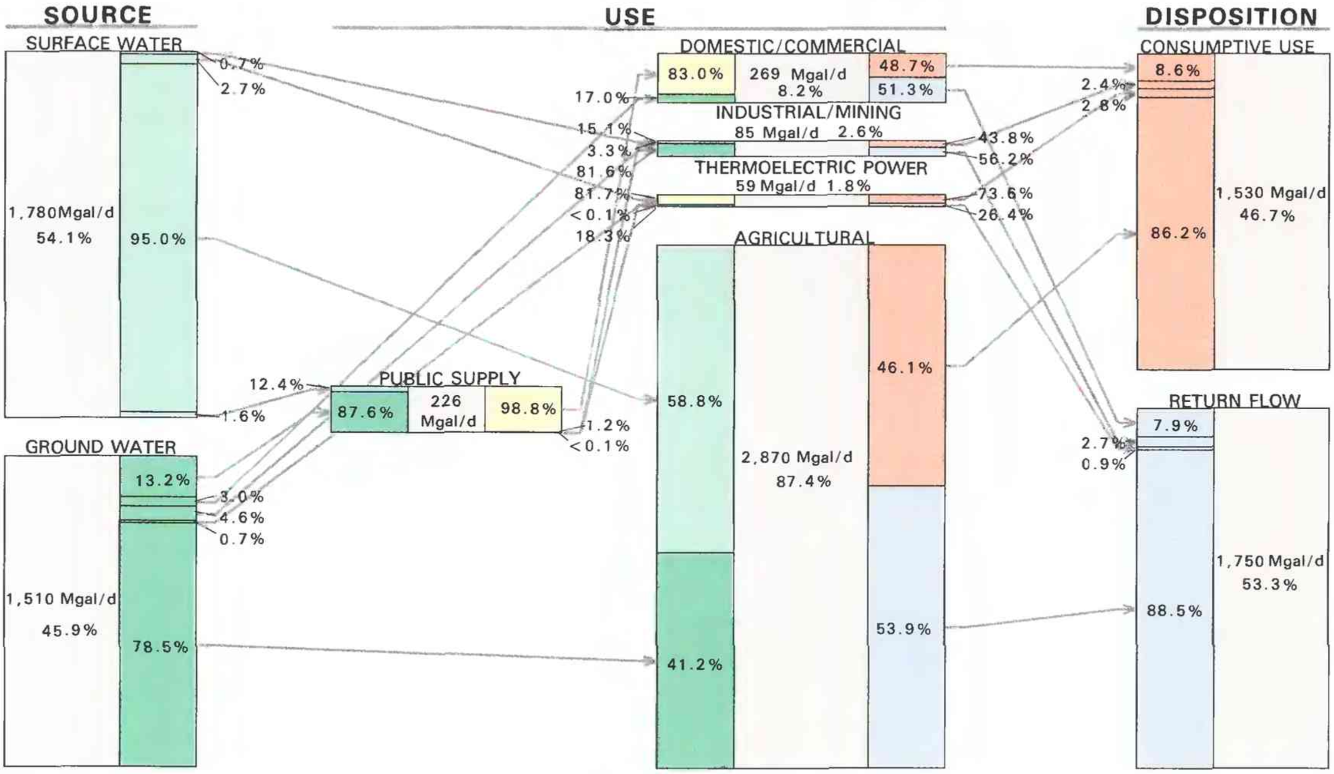

Figure 4. Source, use, and disposition of an estimated 3,290 Mgal/d (million gallons per day) of freshwater in New Mexico, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

mercial purposes totaled 269 Mgal/d in 1985 (fig. 4). Public water suppliers delivered 83.0 percent (223 Mgal/d), and self-supplied users withdrew 17.0 percent (46 Mgal/d) of the water for domestic and commercial use.

The average per capita use was 178 gal/d (gallons per day) for publicly supplied domestic users compared to 93 gal/d for self-supplied users. All self-supplied water for domestic use in 1985 was ground water. Similarly, 89 percent of the water delivered by public-water suppliers for domestic use was ground water. Total domestic consumptive use was 106 Mgal/d.

Water delivered for commercial purposes by public-supply systems amounted to 42 Mgal/d in 1985 (Solley and others, 1988). Self-supplied commercial users withdrew 7.3 Mgal/d, which was all ground water. Total consumptive use by all commercial users was 25 Mgal/d.

INDUSTRIAL AND MINING

Industries and mines withdrew 85 Mgal/d of freshwater in 1985 (fig. 4). Industries used 3.6 Mgal/d, whereas mines used 82 Mgal/d. All water used for mining was self-supplied, but industries received some publicly supplied water. The combined consumptive use was 37 Mgal/d. Industries in New Mexico used water primarily for manufacturing, construction, and the extraction and processing of minerals and fuels.

New Mexico has an abundance and large variety of fuel and mineral resources. The State produces oil, gas, coal, uranium, copper, molybdenum, potash, gold, silver, and carbon dioxide. The largest oil and gas fields are in the northwestern (Four Corners) and southeastern parts of the State. Oil and gas companies use water for oil refineries, gas-processing plants, and the drilling and completion of wells.

New Mexico has large uranium reserves and has been one of the leading States in the production of uranium for the last 30 years. In 1985, 15 mines in Cibola and McKinley Counties produced uranium, but the depressed market caused most mines to close during the year (New Mexico Energy and Minerals Department, 1986).

The major coal fields are in the northwestern and north-central parts of the State. The State's two largest coal-fired powerplants in the Four Corners area consume 60 percent of the coal produced in New Mexico (New Mexico Energy and Minerals Department, 1986). Coal mines use water for soil compaction, dust control, and land reclamation.

THERMOELECTRIC POWER

All 18 thermoelectric powerplants in New Mexico are fossil fueled. The State's two largest powerplants—Four Corners and San Juan—are in San Juan County, are coal fired, and are operated by the Arizona Public Service Company and the Public Service Company of New Mexico, respectively. These two plants generated 89 percent of the 27,000 gigawatthours of electricity produced in the State in 1985. Sixteen smaller oil- and gas-fired plants generated the remaining 11 percent (New Mexico Energy and Minerals Department, 1986). All powerplants are cooled by either water towers or pond evaporation. In 1985, freshwater withdrawals for cooling purposes totaled 59 Mgal/d, and 43 Mgal/d was consumed (fig. 4). Sur-

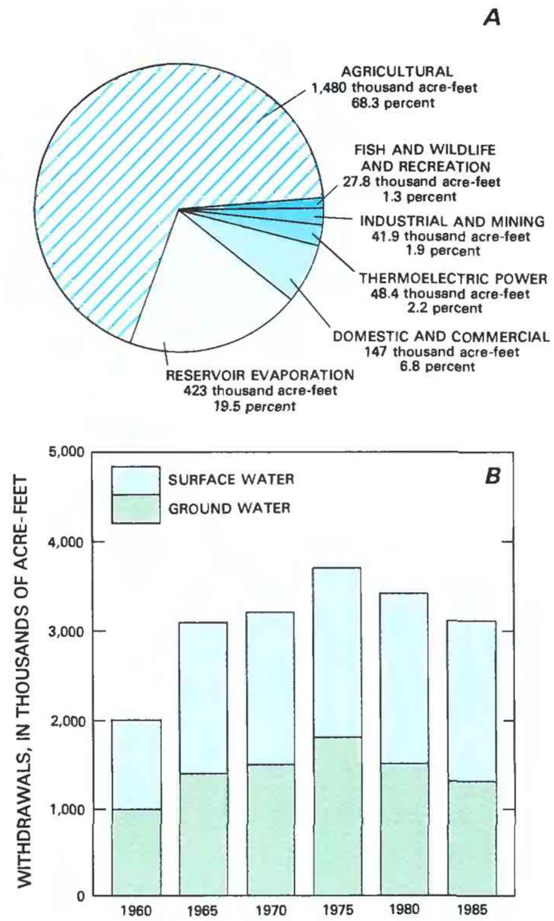

Figure 5. Selected data on water use in New Mexico. *A*, Consumptive use of water in New Mexico, 1985. *B*, Irrigation withdrawals in New Mexico, 1960 to 1985. (Sources: *A*, Wilson, 1986; Solley and others, 1988. *B*, MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972; Sorensen, 1977, 1982; Wilson, 1986.)

face water was the source for 81.7 percent of the withdrawals in 1985, mainly by the Four Corners and San Juan powerplants. As of 1986, there were no geothermal powerplants in the State. However, the U.S. Geological Survey and the New Mexico State Land Office have designated areas that have the potential for using geothermal resources to generate electricity (New Mexico Energy and Minerals Department, 1986).

AGRICULTURAL

Agriculture was the largest water use in 1985; withdrawals were 2,870 Mgal/d (fig. 4), or 3,220 thousand acre-ft/yr (acre-feet per year). Irrigation accounted for 98 percent of all agricultural withdrawals. About 58 percent (1,690 Mgal/d) of irrigation withdrawals was from surface water in 1985; most withdrawals were made in the San Juan and the Rio Grande basins (Wilson, 1986). The southeastern region of New Mexico withdrew the most ground water for irrigation. In this part of the State, the main source of water for irrigation and other uses is the High Plains aquifer, which is a basin-fill aquifer (fig. 3*B*) that underlies large parts of Curry, Roosevelt, and Lea Counties.

Irrigation withdrawals decreased 8 percent and the total acreage irrigated decreased about 13 percent from 1980 to 1985 (Wilson, 1986). Increasing ground-water pumping costs, declining crop prices, and declining ground-water levels have all contributed to these decreases. Trends in withdrawals for irrigation from 1960 to 1985 (at 5-year intervals) are shown in figure 5*B*.

The principal crops irrigated in New Mexico are alfalfa, wheat, grain sorghum, and pasture. These crops accounted for 74 percent of the total irrigated acreage in 1985 (Lansford and others, 1986). Other irrigated crops include corn, barley, vegetables, and small grains. New Mexico also has irrigated orchards and vineyards. Of the 946,000 irrigated acres in 1985, 39 percent was sprinkler or drip irrigated, and 61 percent was flood irrigated (Wilson, 1986).

Withdrawals of water for agricultural use other than irrigation totaled 50 Mgal/d in 1985. Livestock, agricultural industries, and evaporation from stock ponds accounted for the consumptive use of almost all water withdrawn for nonirrigation agricultural purposes (Wilson, 1986).

WATER MANAGEMENT

Water law in the State evolved along with water-resources development. The appropriation doctrine practiced in New Mexico was applied first by custom and then by law long before the State Constitution was adopted in 1912. In 1851, the Territorial Legislature established water laws based on the Indian–Spanish concept of public control of water (Harris, 1984). New Mexico's surface-water law was enacted in 1907. Most of the surface water in the State is fully appropriated.

In addition to surface water, New Mexico possesses large quantities of water in underground storage. New Mexico's ground-water code dates from 1931. When the State Engineer assumes jurisdiction over the appropriation of ground water by declaring a ground-water basin, ground water also is subject to regulation under the appropriation doctrine. As of 1986, the State Engineer had declared 31 such basins, embracing 70 percent of the State's area (fig. 6). Ground water outside the boundaries of declared ground-water basins belongs to the public and may be appropriated without a permit from the State Engineer. New Mexico has long been a leader among Western States in managing surface and ground water, using interstate compacts, and handling the transfer of water rights.

The New Mexico State Engineer is responsible for the supervision, measurement, appropriation, and distribution of the waters of the State. The State Engineer Office (SEO) and the Interstate Stream Commission (ISC) together are responsible for the administration, development, conservation, and protection of the State's water resources (New Mexico State Engineer Office, 1986). Duties of the State Engineer Office include water-rights administration, water-resources studies, dam safety, flood mitigation programs, issuance of water-well-driller licenses, and hydrographic surveys for water rights adjudication. The Interstate Stream Commission administers interstate stream compacts; funds water research, conservation, and development projects; cooperates in major Federal water projects; assists in the construction of irrigation works; and conducts litigation over interstate waters.

Another State agency with major responsibilities in water management is the Environmental Improvement Division (EID) of the Health and Environment Department. The Division enforces regulations related to environmental management and consumer protection, such as those pertaining to water supply, water-pollution control, liquid- and solid-waste disposal, radiation control, and hazardous-waste control.

New Mexico contains the headwaters of three river systems. Two of the largest rivers in the State, the Rio Grande and the San Juan, originate in Colorado and flow through New Mexico; the Pecos River originates in New Mexico and flows into Texas. In addition to water rights, water-resource developers also must comply with eight interstate compacts (U.S. Bureau of Reclamation, 1976,

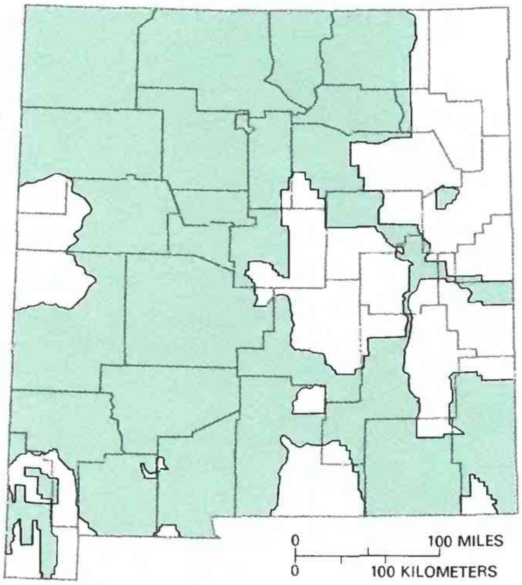

Figure 6. Areal extent of declared ground-water basins designated by the New Mexico State Engineer. (Source: New Mexico State Engineer Office, 1986.)

p. 58–59). These compacts, agreed upon by New Mexico and its neighboring States, provide an equitable apportionment of water in the shared stream systems. The eight compacts and the other States involved are as follows: Rio Grande (Colorado and Texas), Pecos River (Texas), Canadian River (Oklahoma and Texas), La Plata River (Colorado), Animas-La Plata Project (Colorado), Costilla Creek (Colorado), Upper Colorado River Basin (Arizona, Colorado, Utah, and Wyoming), and Colorado River (Arizona, California, Colorado, Nevada, Utah, and Wyoming). The Colorado River and the Rio Grande are also subject to the terms of international treaties with Mexico.

About 45 percent of the land in the State is in Federal ownership and within Indian pueblos and reservations (U.S. Bureau of Reclamation, 1976). As a result, Federal reserved and Indian water-rights determinations are a major issue in the State. Of 12 ongoing lawsuits to adjudicate water rights in the State, 10 involve to a large degree Federal and Indian claims (New Mexico State Engineer Office, 1986).

The applications for New Mexico ground water and the 1980 lawsuit by the city of El Paso, Tex., for the out-of-State use of New Mexico's ground water are landmark actions reshaping State policy on out-of-State transportation and use of its ground water. In 1983, the U.S. District Court found that New Mexico's prohibition of the out-of-State use of its ground water was unconstitutional. Shortly thereafter, New Mexico enacted legislation that permits such export under certain conditions. Administrative proceedings in the applications of the city of El Paso to appropriate 296,000 acre-ft/yr are continuing.

Precipitation and streamflow in New Mexico fluctuate over the years in an apparent cyclic pattern of wet and dry (Tuan and others, 1973). Greater-than-normal flows are persisting in major New Mexico streams because of above-average snowmelt runoff. Flows

Sprinkler irrigation in northern New Mexico near the Colorado State line. (Photo by L.A. Garrabrant.)

of the Rio Grande have been greater than normal each year since 1979, except for 1981 (Waltemeyer, 1987). Reservoir storage also continues to be much greater than normal. The 1987 water-supply outlook for the Rio Grande and the Pecos River basins is again for greater-than-normal runoff (U.S. Soil Conservation Service and National Weather Service, 1987). Water-management problems between 1985 and 1987 have related to excess supply rather than shortages. Great variability and scarcity, however, are characteristics of New Mexico's surface-water supplies, and the current situation is likely to change.

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Prepared by L.A. Garrabrant and H.S. Garn, U.S. Geological Survey; History of Water Development section by Linda G. Harris, New Mexico Water Resources Research Institute

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 4501 Indian School Road NE, Suite 200, Albuquerque, NM 87110

NEW YORK
Water Supply and Use

New York, which is part of the "water-rich" East, has abundant rainfall, surface water, and ground water. Average annual precipitation ranges from about 30 inches in the lowlands to about 50 inches in the mountains.

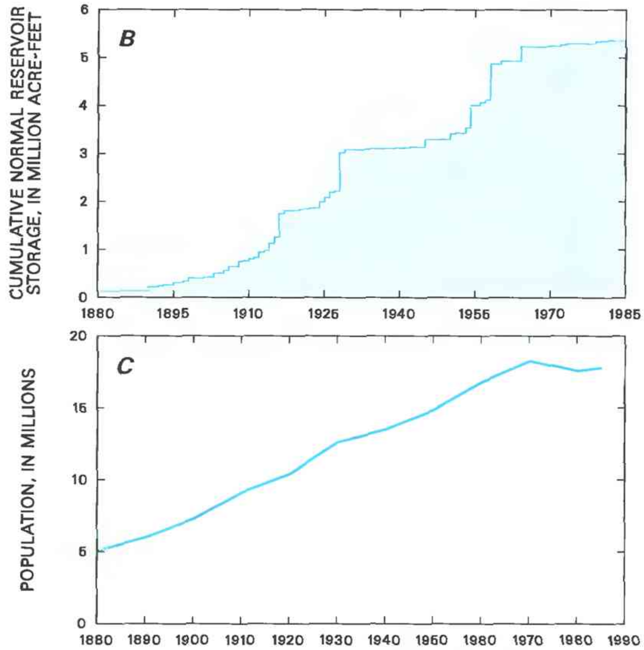
The general water budget is shown in figure 1*A*. Because major river systems originating in New York flow into 16 States, the Great Lakes, and two Canadian Provinces, New York is designated as a headwaters State. In 1985, about 9,050 Mgal/d (million gallons per day) of freshwater was withdrawn from rivers, streams, lakes, and aquifers for offstream use, and 515,000 Mgal/d was used instream for hydroelectric power generation. Of the 9,050 Mgal/d withdrawn, 1,400 Mgal/d was consumed use, and 7,640 Mgal/d was returned to natural water sources for future use. About 6,150 Mgal/d of saline water was withdrawn in 1985 for thermoelectric powerplant cooling.

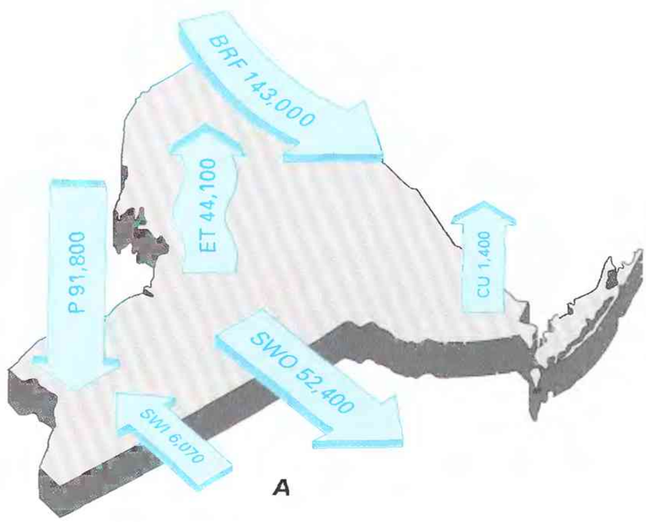
Many of New York's large population centers have developed along major surface-water bodies, such as the Hudson and the Mohawk Rivers and Lakes Erie and Ontario. As a result, about 93 percent of the offstream withdrawals in 1985 was from surface-water sources. Water storage by reservoirs was greatly increased in the early 1900's (fig. 1*B*) to meet the demands of a growing population. The New York City metropolitan area, which developed at the mouth of the Hudson River, is served by a series of reservoirs, natural channels, and aqueducts that begin as far north as Schoharie County. In 1985, this system used 52 percent (1,500 Mgal/d) of the water withdrawn in the State for public supply.

Between 1980 and 1985, the State's population increased 1.1 percent from 17.6 million to 17.8 million. The population trend since 1880 and the population distribution are shown in figures 1*C* and 1*D*, respectively.

The region most dependent on ground water is Nassau and Suffolk Counties on Long Island. In 1985, 43 percent of the ground-water withdrawals was in these two counties. The unconsolidated aquifers of Long Island are continuous across most of the Island, whereas upstate aquifers (those north of New York City and Long Island) generally consist of discontinuous glacial stratified-drift (lacustrine, ice-contact, and valley-fill) deposits. Upstate bedrock aquifers of sandstone and carbonate rocks are locally important.

In 1985, freshwater used for domestic, commercial, industrial, and mining purposes (including public-supply deliveries) in New





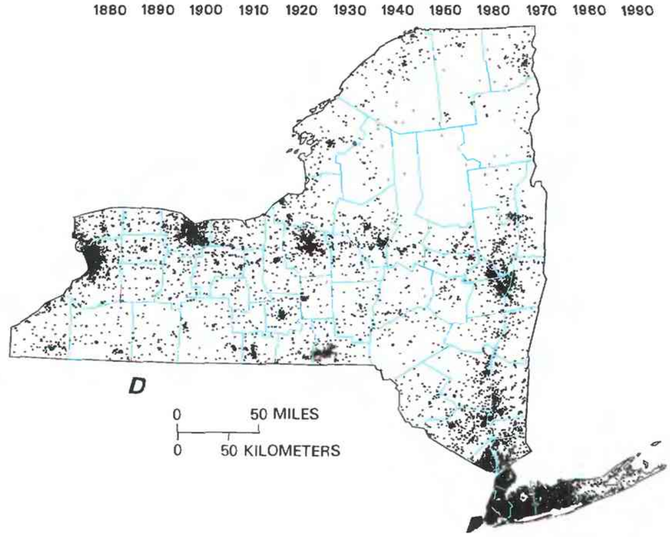


Figure 1. Water supply and population in New York. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, U.S. Environmental Data Service, 1968; Hood and others, 1986. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

York was 47.2 percent (4,270 Mgal/d) of total freshwater withdrawals. Of the freshwater offstream withdrawals, 52.2 percent was for thermoelectric power generation; of the total (freshwater and saline water) offstream withdrawals, 72 percent was for thermoelectric power generation. The largest ground-water withdrawals were for public supply, self-supplied domestic and commercial use, and industrial use (excluding mining). Together, these categories represent 97.1 percent (1,060 Mgal/d) of the total ground-water withdrawals.

HISTORY OF WATER DEVELOPMENT

Water resources have been a key factor in New York's development. The coastlines and harbors on the Atlantic Ocean, the Hudson River estuary, and the Great Lakes–St. Lawrence waterway system promoted and shaped development by providing access to the interior wilderness. The original settlement of New York City depended, in part, on its excellent natural harbor and its waterway connection to the interior wilderness. This connection was through the Hudson River estuary and the Mohawk River valley. The latter was one of only two commercially usable water routes to the interior wilderness through the eastern mountain chains that stretch between the Arctic Circle and Georgia. The other usable route was the St. Lawrence River, which forms part of the border between New York and Canada.

Water transportation was fundamental in determining the nature and scope of Indian and European development. The headwaters of several major rivers and waterways that radiate from the seat of the Iroquois Confederacy in central New York were essential to the expansion of the Iroquois fur-trading empire that ultimately stretched from New England to the Mississippi River and from southern Ontario to the Potomac River in Maryland and Virginia. These water routes also were used by European settlers as they began to populate the interior wilderness.

The Erie Canal was built along the Mohawk River gateway route to the interior to facilitate commercial water transportation from the Port of New York westward to the Great Lakes. Rivers were used to transport logs as New York became the Nation's leading producer of forest products by the mid-1800's.

The development of steam-powered shipping eliminated the need for a towpath along the State's canals. The Erie Canal system was rebuilt as the New York State Barge Canal, which used the main channels of the Mohawk and other rivers rather than dredging a separate channel paralleling these streams, as in the original Erie Canal. The New York State Barge Canal was completed in 1918 and is the only State-run inland waterway in the Nation. It represents a major water use and has rights to more than 40 percent of the freshwater flow in New York.

The Great Lakes became accessible to ocean shipping when the St. Lawrence Seaway on New York's northern border was completed in 1959. The Seaway supplanted an earlier Canadian canal around the St. Lawrence rapids that was used by smaller ships.

Today, thermoelectric powerplants, which require large withdrawals of water for cooling, are the largest water users in New York and dominate all offstream uses of water. About 59.4 percent of the fresh surface-water withdrawals are for this purpose, and 77 percent of total surface-water (fresh and saline) withdrawals are for thermoelectric power generation.

The New York City water supply system, which has six major reservoirs in the Catskill Mountains (Sullivan and Ulster Counties), dominates the surface-water use in eastern New York. Recent droughts in the 1960's and again in the 1980's have indicated that these supplies cannot be taken for granted as an adequate water supply for the New York City metropolitan area. Population growth, increasing use of water, and water losses through transmission and distribution systems have added to the stress on public supplies throughout the State.

Recreation is an increasingly important water use. The inland water area includes more than 7,500 lakes, ponds, and reservoirs. Abundant waterfalls add to the scenic value of many streams. By 1985, 82 stream segments has been placed under the protection of the State's Wild, Scenic and Recreational Rivers system, including 13 wild-river segments. Recreational use of these water resources increasingly is competing with the interests of other water users.

The establishment of the Adirondack Forest Preserve and Park in northeastern New York also has affected the State's water resources. Commercial interests were instrumental in the creation of the Forest Preserve in 1884 to prevent further deforestation by timber companies. It was feared that continued deforestation would diminish the flow of water necessary to sustain the Erie Canal, which, at that time, was seen as a commercial lifeline for New York City and for many cities along its route. Subsequent enlargements of the State's Forest Preserve and Park System, which includes the central Catskill Mountains, have kept pace with population growth in terms of its area per capita.

Flooding of Forest Preserve lands by reservoirs to maintain streamflow for downstream hydroelectric power generation became an issue in the first one-half of the 20th century. In 1953, this culminated in the rescinding of a State constitutional amendment that allowed reservoirs to be built on Forest Preserve lands for streamflow regulation.

WATER USE

The State has a substantial supply of water, although not usually at all the places where it is needed. The water budget (fig. 1*A*) indicates the volumes of water that flow to and from the State. Withdrawals and uses of surface water differ from those of ground water. Total freshwater withdrawals, surface-water withdrawals, and ground-water withdrawals are shown by county in figures 2*A*, 2*B*, and 2*C*, respectively.

More freshwater is withdrawn for fossil-fueled thermoelectric plants (by overall volume) than for any other single category; domestic and commercial is second, and industrial and mining use is third. The greatest withdrawals for public supply are in the population centers and in southeastern New York, where water is withdrawn for use in the New York City area. Thermoelectric power generation from fossil and nuclear fuel accounts for the major freshwater withdrawals around Lakes Erie and Ontario and in Tompkins County (fig. 2*A*).

The distribution of surface- and ground-water withdrawals by county (figs. 2*B*,*C*) demonstrates the dependence of the State on surface water except in Schenectady and Orange Counties and in Nassau and Suffolk Counties on Long Island. Long Island accounts for 43 percent of the State's total ground-water withdrawals; the largest withdrawals are for public supply and for industrial and commercial uses. In Schenectady County, ground water is the source for public-supply and industrial withdrawals for the city of Schenectady and surrounding areas. The ground-water sources in Schenectady County and Long Island have been designated sole-source aquifers by the U.S. Environmental Protection Agency.

The largest withdrawals of surface water in New York are from the Southeastern Lake Ontario basin, the Eastern Lake Erie–Lake Erie basin (fig. 3*A*). The three largest categories of fresh surface-water uses statewide are public supply and fossil-fueled thermoelectric and nuclear power-plants.

Ground-water use in 1985, by aquifer, is shown in figure 3*B*. Of the total ground-water withdrawals, 57 percent was from upstate aquifers (excluding New York City and Long Island). Of the water withdrawn from upstate aquifers, 45 percent was from valley fill, 13 percent was from other stratified drift, 29 percent was from bedrock, and 13 percent was from locally important aquifers.

Of the ground-water withdrawals on Long Island, 78 percent was from the Magothy aquifer (33.5 percent of the statewide total). The least was withdrawn from the Lloyd aquifer (4 percent).

The principal stratified-drift (valley-fill) upstate aquifers are used primarily for public supply; the other upstate stratified-drift aquifers (valley fill, lacustrine, and ice-contact deposits) are used almost equally for public supply, domestic and commercial, and industrial and mining purposes (fig. 3*B*). The main use of aquifers on Long Island is for public supply.

The source, use, and disposition of freshwater in New York are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that the 7,950 Mgal/d of surface water withdrawn is 87.9 percent

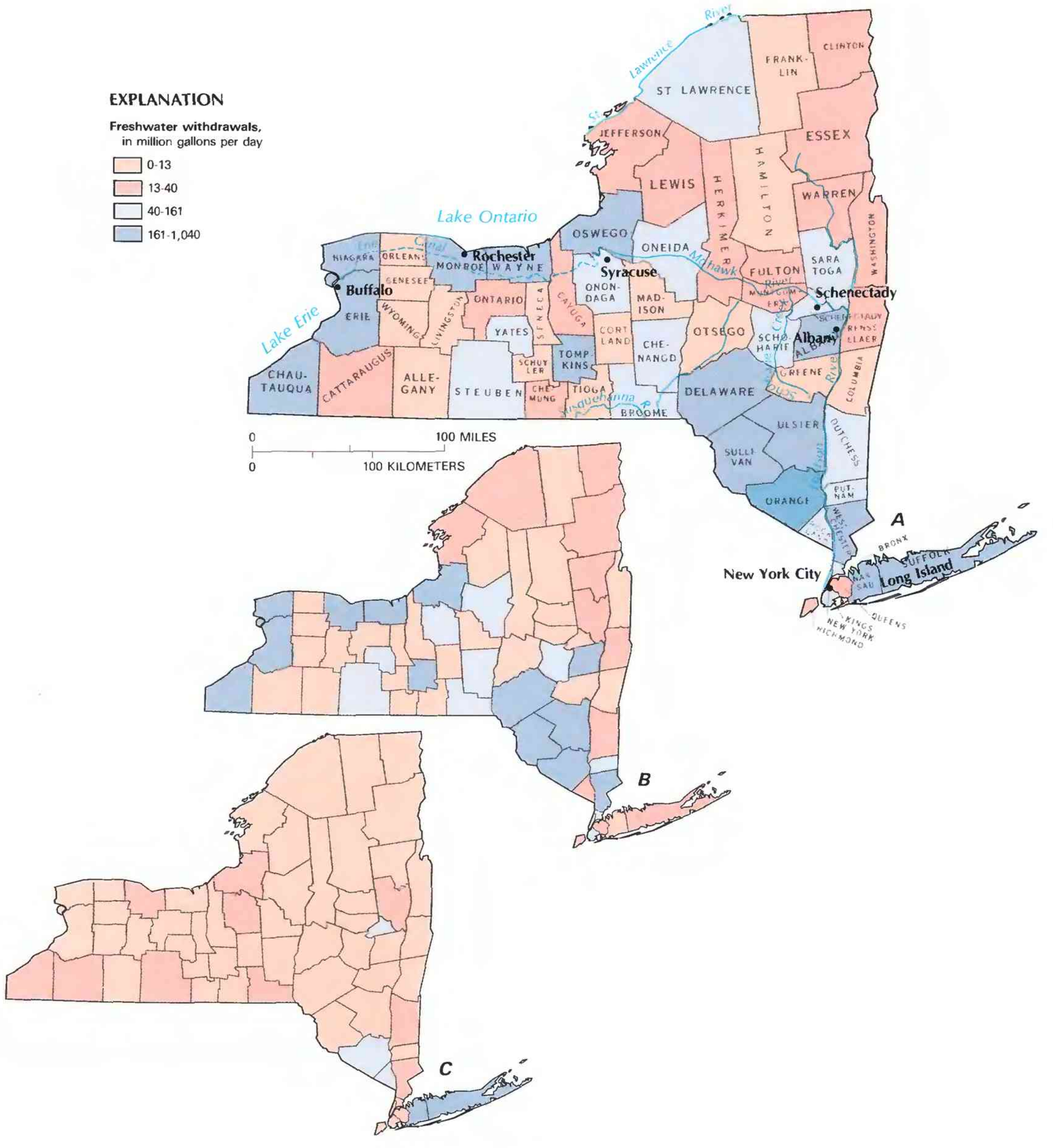


Figure 2. Freshwater withdrawals by county in New York, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

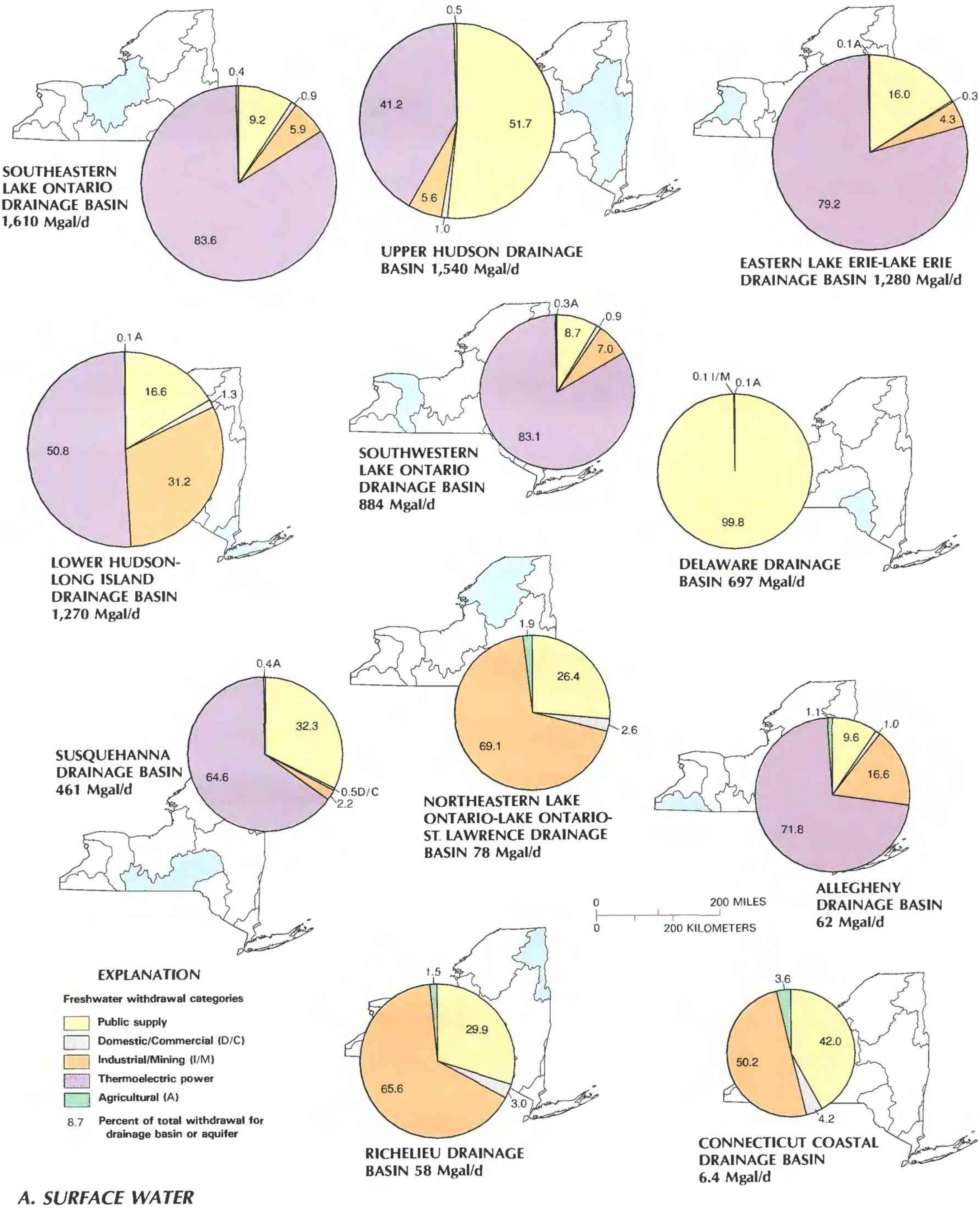
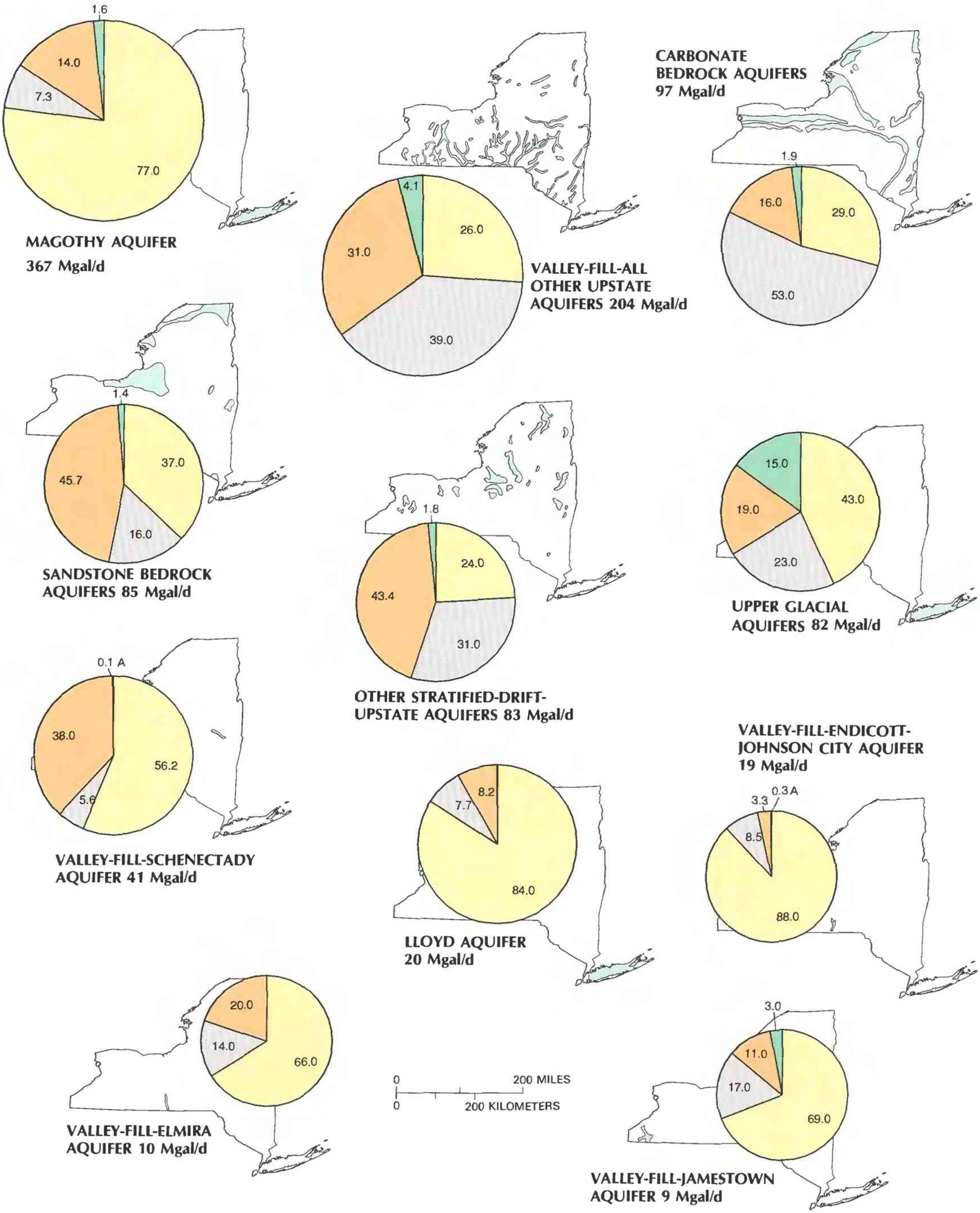


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in New York, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basin units from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from various reports of the U.S. Geological Survey, New York State Department of Environmental Conservation, and New York State Department of Health.)



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in New York, 1985—Continued.

of the total fresh surface- and ground-water withdrawals. Of that quantity, 0.8 percent is directly withdrawn (self-supplied) for domestic and commercial use; 10.2 percent is self-supplied by industrial and mining facilities; 59.4 percent is self-supplied for thermoelectric power generation; 0.3 percent is withdrawn for agriculture; and 29.3 percent is withdrawn by public-supply systems. (Saline water is not included in figure 4 but is included in the discussion of thermoelectric power.) The use data indicate, for example, that domestic and commercial freshwater withdrawals account for 24.0 percent (2,170 Mgal/d) of the State's total freshwater use. Of the quantity, 3.0 percent was from surface-water sources, 11.8 percent was from ground-water sources, and the remaining 85.2 percent was from public suppliers. During use, 9.5 percent of the water is consumed and is no longer readily available for reuse, and after use 90.5 percent is returned to natural water sources for further use. The disposition data indicate that 15.5 percent (1,400 Mgal/d) of all freshwater withdrawn in the State is consumed and 84.5 percent (7,640 Mgal/d) is returned. Domestic and commercial use accounts for 14.8 percent of total consumptive use and for 25.7 percent of total return flow.

Instream use has been significant because water power has been an important part of New York's history, and its availability has affected the development of many cities and industries. One of the largest instream uses of water today is hydroelectric power generation, which supplied 27.8 percent, or 31,400 GWh (gigawatt-hours), of the State's electricity in 1985. New York ranks second among the States in its use of rivers for hydropower (Solley and others, 1988). Water use for this purpose is the largest of all categories, almost 515,000 Mgal/d, in 1985. Two major hydroelectric powerplants dominate hydropower production in New York State—the Robert Moses powerplant in Erie County, which was completed in 1962 and is one of the largest hydropower plants in the world, and the St. Lawrence–Franklin D. Roosevelt Power Project in St. Lawrence County, which was completed in 1959 in cooperation with the Hydro-Electric Power Commission of Ontario. The consumptive use of water in this process, as with other instream uses, is mostly from evaporation, and the amount of consumptive use is negligible. Instream uses are not included in figure 4.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. In New York, nearly 1,800 public-supply systems provide water to about 16 million people (89 percent of the State's total population). The largest, comprising 235 systems (13 percent of the number of systems), provides water to 95 percent of the State's population served by public-supply systems (New York State Senate Research Service, 1985, p. 9). About 40 percent of the State's water suppliers purchase all or part of their water from other public suppliers. New York City, for example, sells water to municipalities in counties in which the city reservoirs are located (New York State Senate Research Service, 1985, p. 10).

Most people in New York are served by publicly owned water systems. Investor-owned systems supply about 1.7 million people and range in size from systems that serve 25 people to one system that serves more than 500,000 people in Queens and Nassau Counties on Long Island (New York State Senate Research Service, 1985, p. 11).

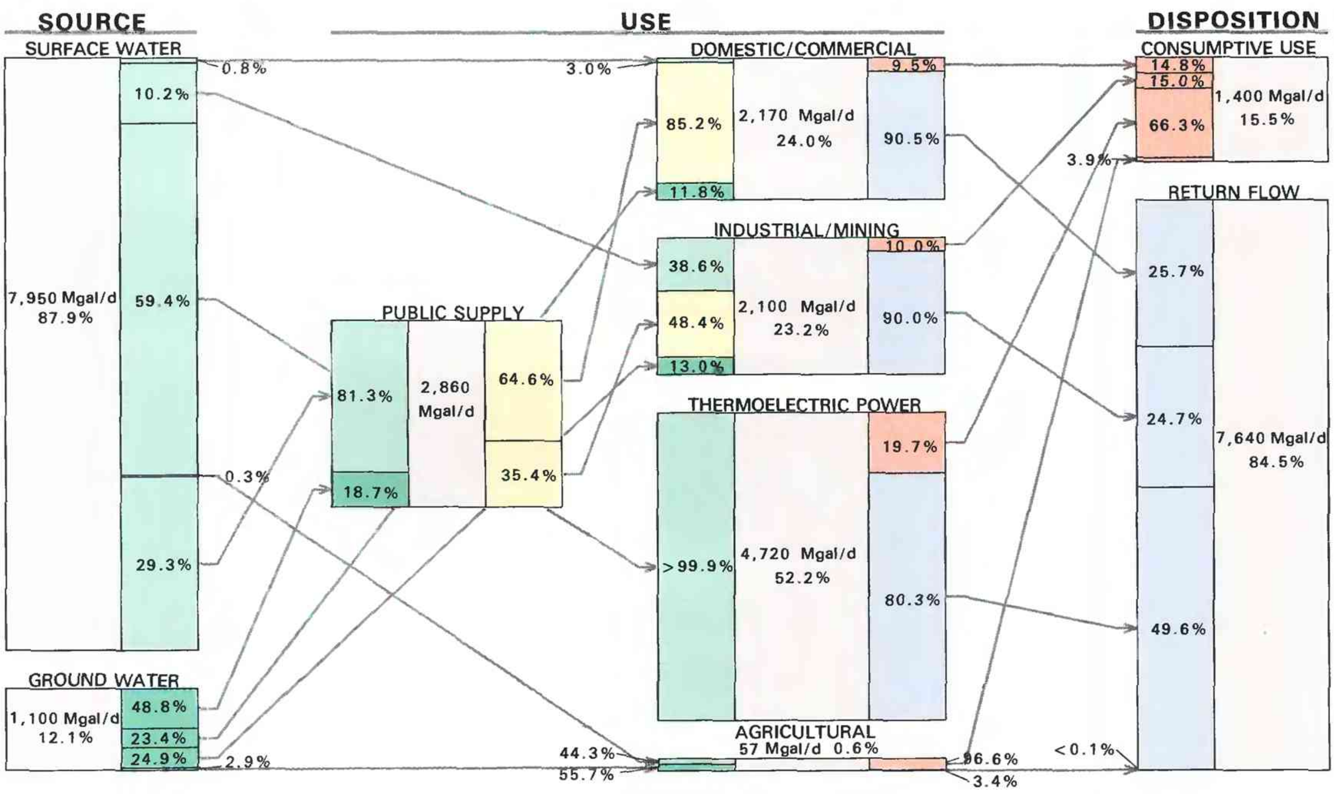


Figure 4. **Source, use, and disposition of an estimated 9,050 Mgal/d (million gallons per day) of freshwater in New York, 1985.** Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Total public-supply withdrawals in 1985 were 2,860 Mgal/d, of which 2,330 Mgal/d was from surface-water sources and 535 Mgal/d was from ground-water sources. Nearly 74 percent of the people served are supplied by surface-water systems. The areas of most intensive withdrawal are near large cities.

The New York City area relies largely on surface water, but the withdrawals are many miles from the point of use (fig. 5). New York City's population of 7.25 million is supplied by a complex network of natural and artificial channels, reservoirs, and aqueducts that originate as far as 125 miles away. This system delivers about 1,500 Mgal/d to the five boroughs of New York City (Bronx, Kings, New York, Queens, and Richmond). The counties of Westchester, Putnam, Ulster, Sullivan, Schoharie, Delaware, and Orange withdraw large amounts of surface water, but, except for Westchester

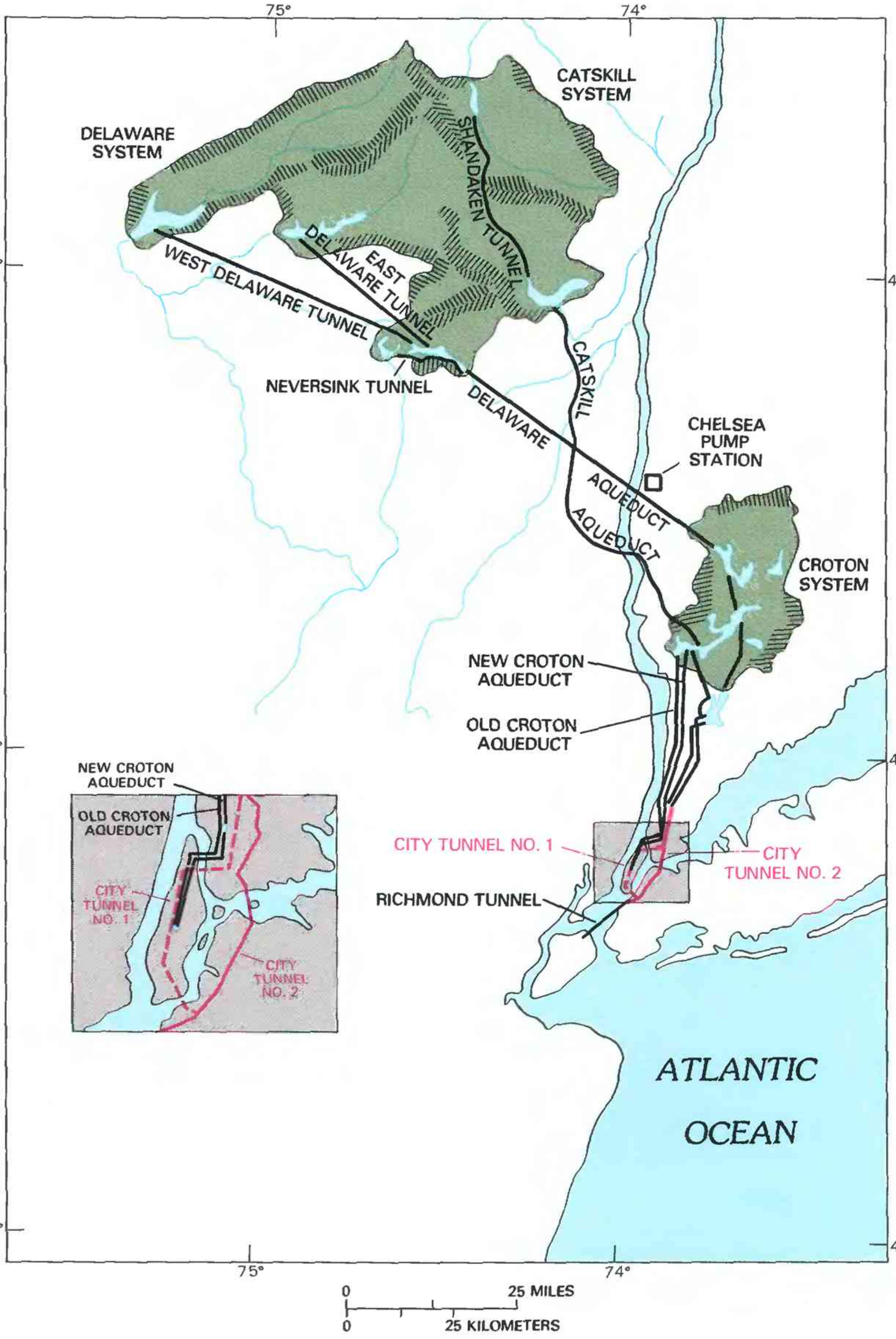


Figure 5. New York City water-supply system. (Source: New York City Department of Environmental Protection, Bureau of Water Supply files.)

and Orange Counties, less than 1 percent of the surface-water withdrawn for public supply is actually used within the source county. Most of the water is delivered to New York City.

Two areas that depend on ground water for public supply are Schenectady County and Long Island. Within Schenectady County, the Schenectady aquifer is extremely productive, providing water for about 157,000 people. On Long Island, public-supplied ground water is provided for about 2.8 million people. Other areas that have substantial ground-water public-supply systems are the Endicott-Johnson City area in Broome County, whose aquifer provides water for 110,400 people, and the Ramapo–Mahwah River valley area in Rockland County, whose aquifer provides water for 74,500 people (Schenectady County Planning Department, 1985, p. viii).

Temporary droughts, which result in diminished streamflow, seriously affect the surface-water supplies of New York. In 1985, for example, annual precipitation was less than normal in most of eastern New York. Streamflows in the lower Hudson and the Delaware basins and in Schoharie Creek were 40 to 60 percent of average values (fig. 6*A*). The diminished streamflow throughout southeastern New York during 1985 prompted implementation of water-conservation measures in several communities that are dependent on surface-water sources (Firda and others, 1986, p. 3). A drought emergency was declared for New York City on April 26, 1985, as storage in the city's reservoir system decreased to 61.5 percent of capacity; the long-term average month-end storage for April is 99.8 percent of capacity (fig. 6*B*).

Domestic and Commercial

Domestic and commercial water users receive water from public-supply systems and self-supplied facilities. Combined total use in 1985 was 2,170 Mgal/d (fig. 4). Included in this category is 95.4 Mgal/d for public uses, such as for fire fighting and street cleaning, and water lost during conveyance from public water-treatment plants to the points of use. Domestic use was about 1,660 Mgal/d, of which 1,470 Mgal/d was from public-supply systems that served 89 percent of the population. The remaining 11 percent of the population withdrew 191 Mgal/d from their own wells or springs. Consumptive use was estimated to be 166 Mgal/d.

The counties that have with the greatest numbers of people who use wells or springs for supply also contain large urban centers. Erie, Onondaga, Saratoga, Rensselaer, Dutchess, Orange, and Ulster Counties have populations of 50,000 or more that supply their own domestic water. These counties all contain a major urban center, which indicates a large number of people living in rural or suburban settings who commute to cities for employment.

Commercial withdrawals and deliveries in 1985 were 413 Mgal/d, of which 130 Mgal/d was self supplied and 282 Mgal/d was provided by public-supply systems. Consumptive use was estimated to be 40 Mgal/d. Although domestic and commercial water uses were 24 percent of total statewide use in 1985, such use is increasing as New York continues to expand its service-oriented commercial enterprises and to decrease its industrial production.

Industrial and Mining

In 1985, water withdrawals and deliveries for industrial and mining use were 2,100 Mgal/d, of which 49.6 Mgal/d was surface water for mining (fig. 4); the remaining surface water and ground water was for industry. Self-supplied systems provided about 38.6 percent (810 Mgal/d) of surface water and 13.0 percent (272 Mgal/d) of ground water to industry and mines; the remainder, 48.4 percent (1,010 Mgal/d), was from public supplies.

The surface-water withdrawals for industry occur principally in and around major cities. The greatest demand for ground water

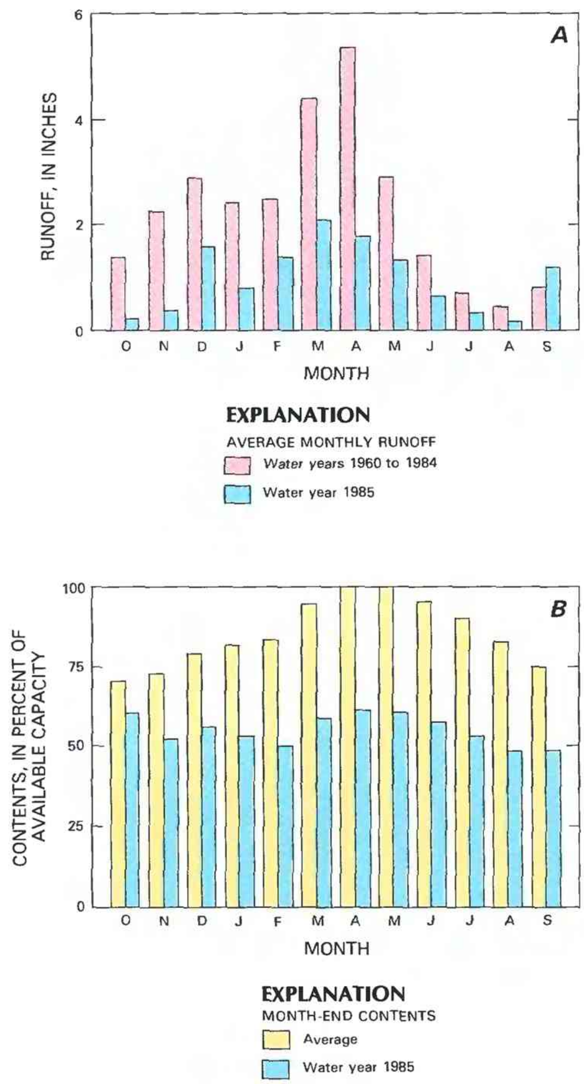


Figure 6. Comparison of average and water year 1985 data for Schoharie Creek and the New York reservoir in New York. *A*, Comparison of monthly runoff for water year 1985 and average monthly runoff for water years 1960 to 1984 for Schoharie Creek at the Prattsville streamflow-gaging station (station 01350000). *B*, Comparison of average month-end reservoir contents and month-end contents during water year 1985 for the New York City reservoir system. (Source: *A*, *B*, Firda and others, 1986.)

by industry is in Schenectady, Orange, and Rockland Counties and on Long Island.

Thermoelectric Power

In 1985, fossil-fueled and nuclear powerplants withdrew a total of 10,900 Mgal/d for cooling. Of this quantity, 4,720 Mgal/d was freshwater (fig. 4), and 6,150 Mgal/d was saline surface water. Fossil-fueled powerplants withdrew more than three times as much water as did nuclear powerplants. The fossil-fueled powerplants also generated three times more power than nuclear powerplants—60,700 GWh compared to 20,800 GWh. The consumptive use for fossil-fueled powerplants was 84 Mgal/d, whereas consumptive use for nuclear powerplants (through evaporation) was about 2,230 Mgal/d.

The areas that have concentrated withdrawals for thermoelectric power generation are the counties bordering Lakes Erie and Ontario, the Oswego River basin (Oswego County), the Hudson River basin, and on Long Island. Much of the withdrawals in the southeastern part of the State are saline water from the Atlantic Ocean and the Hudson River estuary.

AGRICULTURAL

Agricultural water use statewide amounted to 0.6 percent of the total freshwater withdrawals and was the smallest of the categories of offstream use (fig. 4). In 1985, about 57 Mgal/d was withdrawn for agriculture, of which 38 Mgal/d was for irrigation. Nearly equal amounts of surface water and ground water were used for irrigation, whereas 62.8 percent of nonirrigation agricultural use was from ground water.

Most of the large surface-water withdrawals for irrigation were in Lakes Erie and Ontario and in the middle to lower Hudson valley. Of the ground water withdrawn for irrigation, 83 percent was in Suffolk County.

The primary nonirrigation agricultural use of water is for dairy operations in southwestern New York and in central New York from St. Lawrence and Jefferson Counties south to Delaware County.

WATER MANAGEMENT

The primary agency for water-resources management in New York State is the New York State Department of Environmental Conservation (NYSDEC), which is charged with exercising its powers in any matter affecting the construction of improvements to or developments of water resources for the public health, safety, or welfare. The New York State Departments of Health (NYSDOH) and of Transportation also have direct water-resource-management responsibilities pertaining to public-supply systems and to the Barge Canal System, respectively.

The Delaware River Basin Commission and the Susquehanna River Basin Commission, under compacts among New York State, other States, and the Federal Government, each have specific water-resource-management authority within their areas of responsibility. The Hudson River–Black River Regulating District is a corporation that operates and maintains reservoir facilities in those basins for flood control, low-flow augmentation, and hydroelectric power generation. The International Joint Commission, established by treaty between the United States and Canada, has jurisdiction over boundary waters in the event of management disputes. Many authorities and local entities function within the context of the State's jurisdiction to ensure proper management of their permitted quantities.

The NYSDEC is responsible for administering the State's environmental quality and natural resource programs, including those relating to the control of water pollution. Major elements of the NYSDEC's water program include water-resource planning, establishment of water-quality standards and classifications, water-quality monitoring, issuance of water-discharge permits, administration of municipal wastewater-treatment programs, and administration of the New York State Pollutant Discharge Elimination System Program, which regulates point-source wastewater discharges.

The Water-Supply Permit Program, established in 1905 and administered by the NYSDEC, remains a major facet of the NYSDEC's water-resource management programs. This statewide program requires a permit for all proposed withdrawals for public-supply purposes. An additional well-permit program, implemented in 1933, applies to all ground-water withdrawals on Long Island. Recent legislation pertaining to Long Island eliminated an agricultural exclusion from the well-permit program and required a specific resource evaluation in conjunction with the permit program.

The NYSDEC has developed ground-water-management programs for Long Island and upstate New York. These programs identify ground-water quality and quantity problems within the State and set forth recommendations and actions to be taken by all responsible authorities to protect, enhance, and ensure the long-term availability of this resource.

The NYSDEC, in the cooperation with the NYSDOH, is now preparing a Water Resources Management Strategy for New York State to meet the water-resource requirements of residential, agricultural, industrial, institutional, and commercial users for the next 50 years. The statewide plan will consist of separate strategies for 13 upstate areas. The enacting legislation requires review of these strategies every 2 years, and revisions are to be incorporated as necessary.

Southeastern New York, including Long Island, contains two-thirds of the State's population and historically has suffered the most severe droughts in the State. Efforts are intensifying to manage the water resources in this densely populated area and will remain a challenge in the future. New York City, which now supplies a demand of 1,500 Mgal/d, has formed an intergovernmental task force in recognition of the need to evaluate the short- and long-term water-supply issues of the city and region. The city has announced a 10-year program to implement residential metering, has invested in an extensive leak-detection program, and, in conjunction with 10 subcommittees of the task force, will consider recommendations for future action to balance the demands for the supply to the needs of the area and region.

The Hudson River is the most obvious source for future development of water supply in southeastern New York. Northward migration of the saltwater front that separates the freshwater part to the north from the saline part (in the estuarine reach of the river) to the south and the effects of this migration on future withdrawals will remain a major management concern, as will development of methods to ensure equitable apportionment of this source to all riparian owners.

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Prepared by Deborah S. Snavely, U.S. Geological Survey; History of Water Development section by Ellen Z. Harrison and Lyle Raymond, The Water Research Institute for the State of New York; Water Management section by Howard C. Pike, New York State Department of Environmental Conservation

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Post Office Box 1669, Albany, NY 12201

NORTH CAROLINA
Water Supply and Use

North Carolina ranks sixth in the Nation in average annual precipitation (50 inches) and has a mild, humid climate. About 72 percent of the precipitation is returned to the atmosphere by evapotranspiration, and about 20 percent recharges the ground-water system (Winner and Simmons, 1977). In 1986, the State experienced the fifth driest year on record, and precipitation was less than normal in most areas.

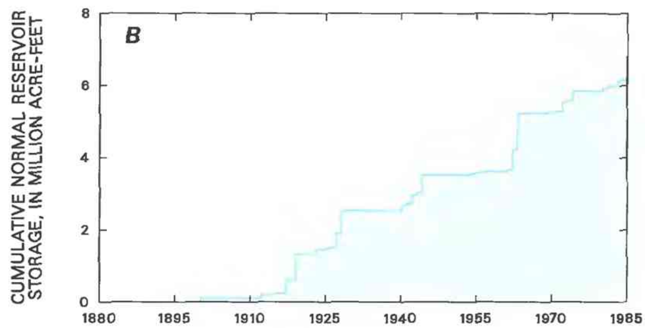
The water budget (fig. 1*A*) diagrammatically indicates a total of 7,410 Mgal/d (million gallons per day) of surface-water inflows and 47,600 Mgal/d of surface-water outflows. Of the surface-water outflows, about 20,000 Mgal/d flows into adjacent States, and 27,600 Mgal/d discharges to the Atlantic Ocean. Presently, North Carolina has no major diversions or interstate transfers of water; however, a proposal to construct a pipeline to divert water from Lake Gaston in Northampton County to Virginia Beach, Va., has become a major water issue.

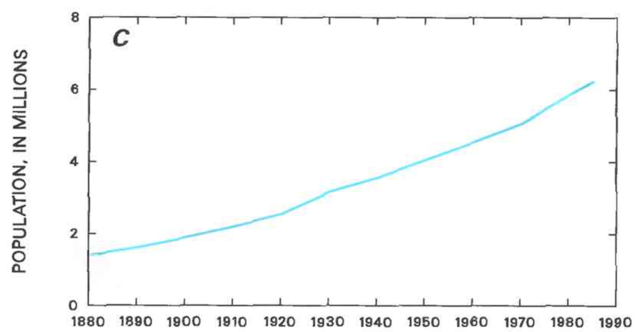
North Carolina is as diverse in water resources as it is in geography. The State comprises three physiographic provinces—the Blue Ridge province is in the west, the Piedmont province is in the center, and the Coastal Plain province is in the east. The Blue Ridge and Piedmont provinces are west of the Fall Line (fig. 2*A*), and the Coastal Plain province is east of the Fall Line. Streams on the eastern slope of the Blue Ridge Mountains drain to the Atlantic Ocean, and streams on the western slope drain into both the Ohio and the Tennessee Rivers in adjacent States (Meikle, 1983).

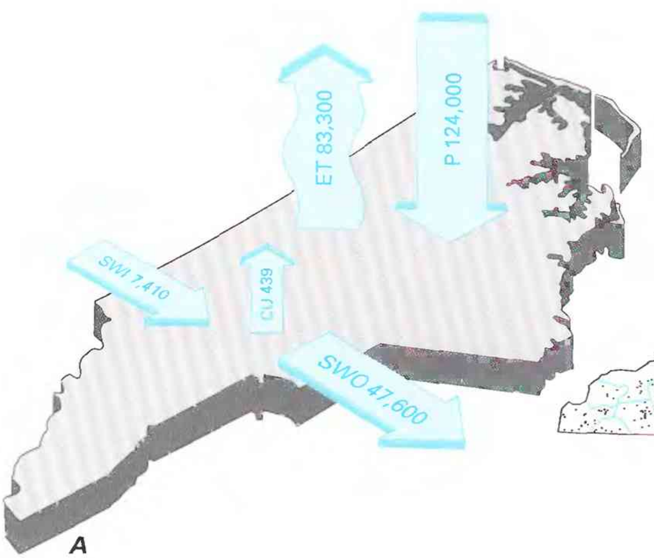
In 1985, about 7,880 Mgal/d of freshwater was withdrawn from surface- and ground-water sources. About 439 Mgal/d was consumed, and the remaining 7,450 Mgal/d was returned to natural water sources. Of the total withdrawals, 94.5 percent was surface water. Withdrawals associated with thermoelectric power generation constituted the largest single category of water use—6,400 Mgal/d, or 85.9 percent of the total surface-water withdrawals. Thermoelectric power facilities are mainly along the Catawba River and in the Chowan-Roanoke and Cape Fear basins.

Surface water is the source for most municipal, industrial, and agricultural uses west of the Fall Line. Surface water was the source for 62.0 percent of all water used for industrial and mining purposes and for 76.6 percent of the water used for agricultural purposes in 1985. About 42.4 percent of ground-water withdrawals was used for domestic and commercial purposes, which accounted for 36.2 percent of the State's total consumptive use.

East of the Fall Line, aquifers supply water in many areas for domestic, public-supply, and mining use. In Beaufort County,







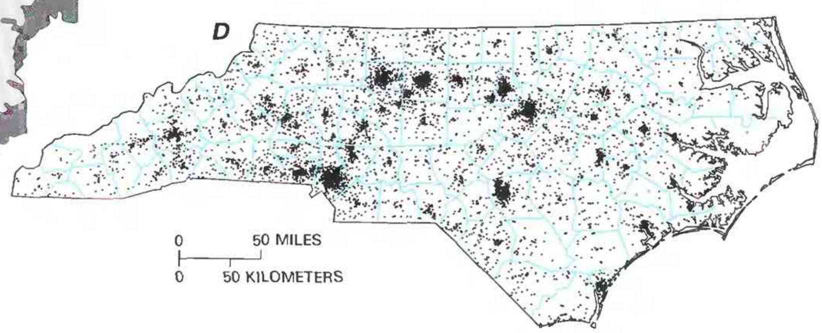


Figure 1. Water supply and population in North Carolina. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Data from various reports of the U.S. Geological Survey. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

67 Mgal/d is withdrawn from the Castle Hayne aquifer for phosphate mining operations. The Cretaceous aquifer also is a principal water source in the central and southern Coastal Plain. Water levels in the Cretaceous aquifer have declined as a result of large ground-water withdrawals in the central Coastal Plain (Winner and Lyke, 1986). Water-level declines and the possibility of saltwater intrusion are important considerations for ground-water-resource management.

HISTORY OF WATER DEVELOPMENT

Although a treacherous coast, which became known as the "Graveyard of the Atlantic," and a lack of good ports delayed early colonization, North Carolina was settled in the north by expansion from the nearby colonies of the Chesapeake Bay areas of Virginia and Maryland, and in the south by expansion from Charleston, South Carolina. Early settlers traveled down the streams in southeastern Virginia into the Chowan River–Albemarle Sound area in search of fertile farmlands and fresh hunting grounds. The Piedmont province was settled by people moving along the valleys from Virginia and South Carolina rather than upstream from the Coastal Plain province. Many major Piedmont rivers rise in the Blue Ridge Mountains in the western part of the State, but turn southeastward to flow through South Carolina to the Atlantic. Settlers found the Catawba and Yadkin Rivers easy to navigate and, therefore, settled in South Carolina instead of the Coastal Plain of North Carolina.

A natural network of rivers and inland waterways exists along the coast. In the mid-19th century, public funds were used to provide capital for several navigation companies. The dominant commercial routes, however, were inland and perpendicular to the general direction of the streams; therefore, the State supported the development of roads and railroads as primary modes of transportation instead of developing inland waterways.

Urbanization of the Piedmont region of the State and development of electric power were two factors that contributed to the development of the rivers. As late as 1880, less than 5 percent of the population was in the urban areas. Industrialization, primarily in textiles and tobacco products, caused more of the population to move to the cities of the Piedmont province during the late 1800's and early 1900's. By 1920, more than 19 percent of the population resided in cities. Development of electric power was largely responsible for the rapid industrialization during the early 1900's. The rapid increase in reservoir storage (fig. 1*B*) between 1910 and 1930 is indicative of the development of hydroelectric power facilities. Although only one-half of the population now lives in urban areas, the process of urbanization has coincided with steady population growth since 1880 (fig. 1*C*). With the growth of urban centers came the demand for larger, more dependable water supplies. The topography, hydrology, and geology of the Piedmont Province favored the use of impounded surface water, which led to the construction of many multipurpose reservoirs. The Piedmont province remains the most populated region (fig. 1*D*) and the hub of industrial and economic activity.

Growth of the textile industry in the Piedmont province initially was fostered by the direct use of water power from many small mill ponds, but, by 1900, the textile industry was dependent on steam for nearly two-thirds of its energy. The first hydroelectric facility was Idols Dam, which was built on the Yadkin River near Winston-Salem in 1898 by a manufacturing firm that transmitted electricity to its plant 11 miles away. That initiative ushered in a quarter century of intensive activity by the private sector to develop hydroelectric power in the Piedmont. In 1904, James B. Duke, bought a small company that was generating power on the Catawba River. The Duke Power Company invested intensively in further development of the Catawba River, and, by 1927, had built at least 10 hydroelectric powerplants. Later, demand for electricity to manufacture aluminum was a major force for hydroelectric development of the Yadkin River.

Federal water-resource development of the rivers of North Carolina began with the work of the Tennessee Valley Authority in the western part of the State in the late 1930's. Comprehensive planning activities of the post-World War II era led to additional multipurpose projects on the Yadkin (1958) and Roanoke (1955) Rivers and in the Cape Fear (1980) and the Neuse–Pamlico (1983) basins. Those reservoirs were constructed for flood control, water supply, and recreation; hydroelectric power is generated only at the John H. Kerr Reservoir on the Roanoke River.

WATER USE

North Carolina has abundant water resources, but water supplies are not always adequate in areas and at times of local demands. In recent years, rapid population growth, urbanization, and industrial growth have resulted in an ever-increasing demand for water. The water supply is stressed by increasing domestic, commercial, industrial, mining, agricultural, and other water use demands. In addition, proper resource management requires greater protection of water quality.

Total freshwater withdrawals in 1985 are presented by county in figure 2. The counties with the largest withdrawals (fig. 2*A*) generally have thermoelectric powerplants or large populations. The most thermoelectric power generation is in Mecklenburg, Person, and Catawba Counties, where the demand for water to cool the powerplants is great. Excluding withdrawals for thermoelectric power, surface-water withdrawals accounted for more than 70 percent of the total freshwater withdrawals. The large withdrawals in Charlotte, Greensboro, and Winston-Salem, and in the Raleigh-Durham area reflect a large population and concentrated industrial activity.

West of the Fall Line, surface water is the source for irrigation, most public supply, and industries. Primarily east of the Fall Line, irrigation makes significant demands on the State's water supply. The distribution of surface- and ground-water withdrawals by county (figs. 2*B*,*C*) reflects the availability of surface water west of the Fall Line and ground water east of the Fall Line. In 1985, surface-water withdrawals were greatest in the Edisto–Santee and Chowan–Roanoke basins (fig. 3*A*) because of the large amount of thermoelectric power generation in these areas. Large withdrawals in Beaufort and Martin Counties in the northern Coastal Plain reflect the presence of phosphate mining and the paper industry. More than 40 percent of the self-supplied industrial withdrawals are for paper production in the Upper Tennessee, Cape Fear, Neuse–Pamlico, and Chowan–Roanoke basins, and an additional 20 percent is withdrawn by the chemical industry in the Neuse–Pamlico, Chowan–Roanoke, and Cape Fear basins (North Carolina Department of Natural Resources and Community Development, 1983a).

Instream uses, which are not included in figures 2, 3, and 4 are important to the welfare of the State. The largest instream use of water is hydroelectric power generation, which supplies about 8 percent of the State's electricity. In 1985, more than 53,400 Mgal/d was used to generate about 6,580 GWh (gigawatthours) of electricity. The Catawba and Yadkin Rivers are the most developed rivers; eight major dams on the Catawba regulate more than 85 percent of its flow (U.S. Geological Survey, 1986). Hydroelectric facilities along the Catawba River generated about 712 GWh of electricity in 1985. The Yadkin River has seven major multipurpose dams that provide flood control, navigation, and electric power production, in addition to recreation and water-supply benefits. Instream uses, such as recreation, navigation, flood control, and provision for fish and wildlife habitats, are significant but are difficult to quantify.

Ground-water withdrawals are dominant in eastern areas where mining is the largest use. Mining accounts for 19 percent of the total ground-water withdrawals. Many public and private supply systems east of the Fall Line rely on ground water. In 1985, wells and springs furnished water to about 2.8 million people for domestic use in rural areas; public suppliers delivered ground water to 803,000 people. Fifty-eight percent of the 6.2 million population was supplied by ground water.

The principal aquifers, all present east of the Fall Line, are the Cretaceous, the Castle Hayne, the Yorktown, and the surficial. West of the Fall Line, the low-yielding crystalline rock aquifers are the dominant source of ground water (fig. 3*B*), and most large municipalities depend on surface water as a source of supply. The Cretaceous aquifer is a principal ground-water source that supplies about 58 Mgal/d for public supply. The Castle Hayne aquifer is another productive aquifer that supplies about 13 Mgal/d for public supply. Maximum yields of individual wells are also greater in the Castle Hayne aquifer than from wells in other aquifers. The Castle Hayne aquifer is the only source of freshwater in many coastal areas where deeper and some shallower aquifers contain saltwater. In 1985, about 125 Mgal/d was withdrawn from the Castle Hayne aquifer for domestic, commercial, industrial, mining, and agricultural purposes. Mining and quarrying operations in Beaufort, Craven, Onslow, and New Hanover Counties withdraw water from the Castle Hayne aquifer and account for 96 percent of the total ground-water withdrawals associated with mining. The Yorktown and the surficial aquifers are principal aquifers, although they are not pumped as extensively as the Cretaceous and the Castle Hayne aquifers.

The source, use, and disposition of freshwater during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that the 7,450 Mgal/d of surface-water withdrawals was 94.5 percent of total freshwater withdrawals. Of that quantity, 85.9 percent was withdrawn for thermoelectric power generation. The use data indicate that thermoelectric power was the largest water use category, accounting for 81.1 percent (6,400 Mgal/d) of all the water used in 1985. Thermoelectric power consumptive use was about 0.6 percent (36 Mgal/d). The disposition data indicate that 94.4 percent (7,450 Mgal/d) of all water withdrawal was returned to natural sources. Of this total, 85.4 percent (6,360 Mgal/d) was returned by thermoelectric power facilities.

The use of saline water is not extensive owing to its limited usefulness and the cost of desalinization. In 1985, about 866 Mgal/d was withdrawn from the estuary of the Cape Fear River for cooling purposes at the Brunswick nuclear plant in Brunswick County. In New Hanover County, about 6 Mgal/d of saline ground water was withdrawn for mining operations.

Water-quality considerations need to be evaluated for the proper development and management of water resources. Water-quality concerns have prompted governmental officials to propose more stringent water-quality monitoring programs. Also, phosphate detergents, which enhance algal growth in surface waters, have been banned statewide as of 1988. Wastewater discharges by municipalities

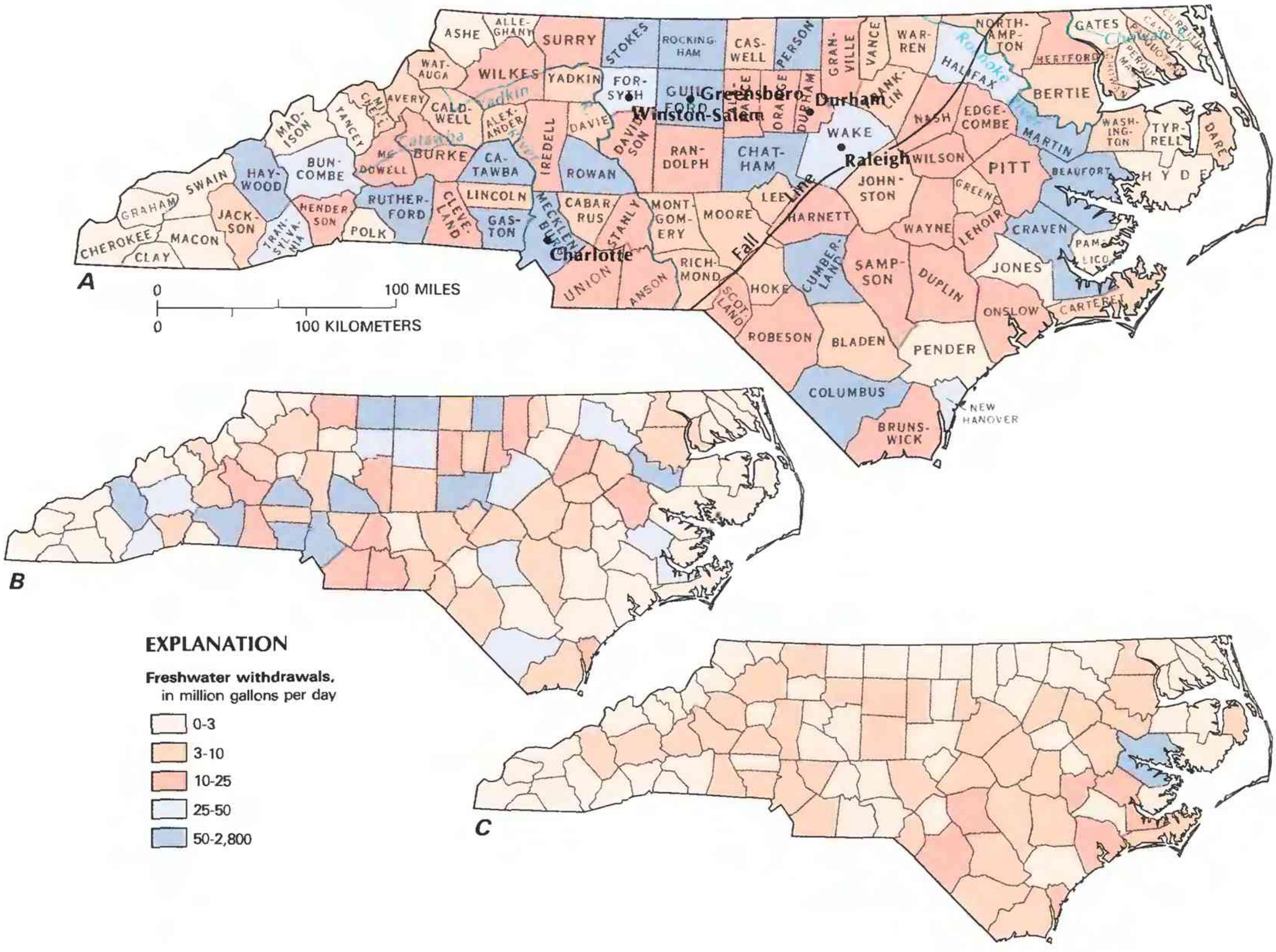


Figure 2. Freshwater withdrawals by county in North Carolina, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

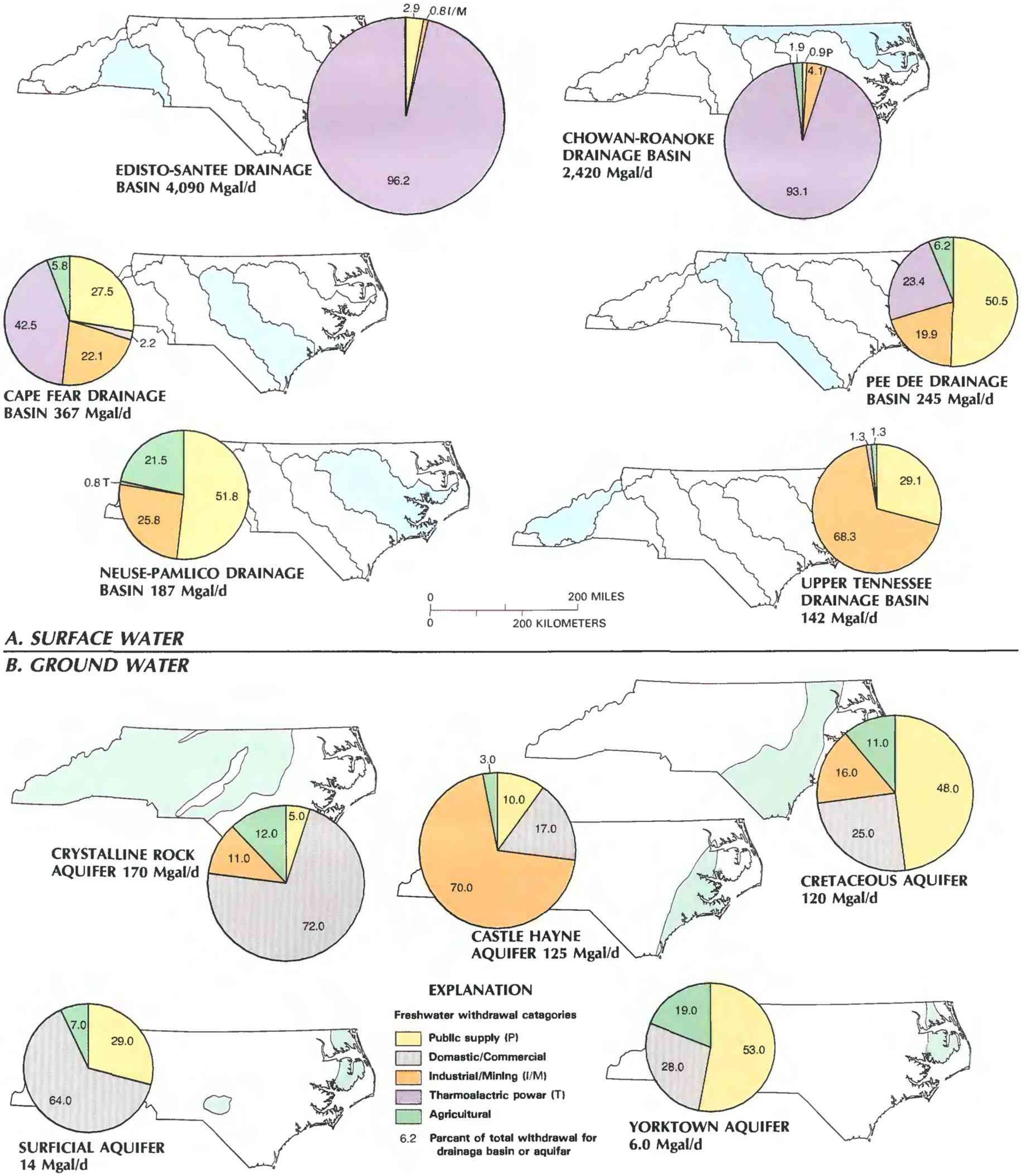


Figure 3. *Freshwater withdrawals by category of use and hydrologic unit in North Carolina, 1985. A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System: *B,* Data from various reports of the U.S. Geological Survey and State agencies.)

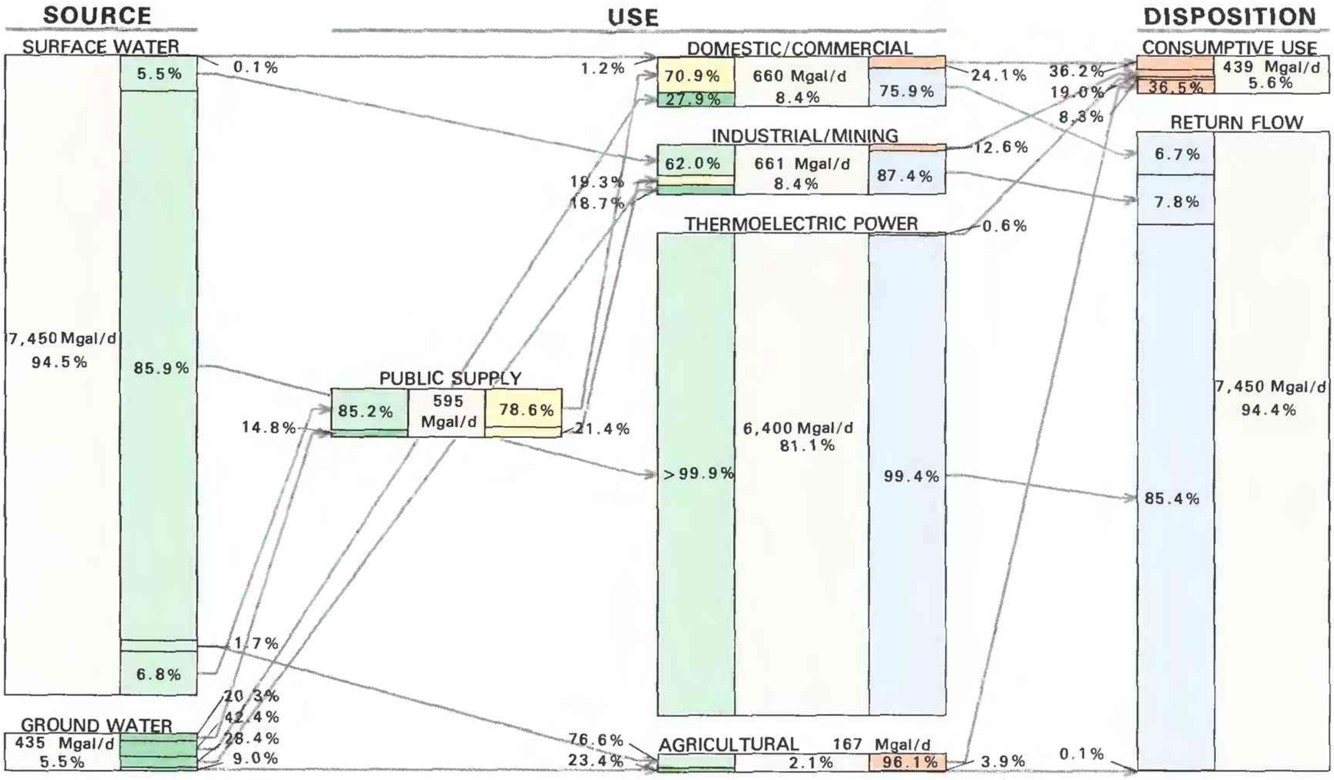


Figure 4. Source, use, and disposition of an estimated 7,880 Mgal/d (million gallons per day) of freshwater in North Carolina, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

and industries upstream from some water bodies have caused questions about the suitability of these resources as future drinking-water supplies. In 1985, more than 300 municipal sewage-treatment facilities discharged 481 Mgal/d of wastewater into surface waters.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. Withdrawals for public supply nearly doubled between 1960 and 1985 (fig. 5A). Many municipalities expanded their service areas in the last two decades, and many self-supplied rural areas became connected to county water systems. In 1985, public-supply systems served about 55 percent of the State's population. The drought of 1986 prompted many public and private water suppliers to explore alternative emergency supplies and to consider connecting to nearby community systems. Of the 595 Mgal/d withdrawn for public supply in 1985, 85.2 percent (507 Mgal/d) was surface water and 14.8 percent (88 Mgal/d) was ground water (fig. 4). Public-supply systems delivered water for three major water uses. Domestic deliveries accounted for 53 percent (315 Mgal/d), commercial deliveries accounted for 23 percent (137 Mgal/d), and industrial facilities accounted for 21 percent (128 Mgal/d) of public-supply deliveries. About 3 percent (16.5 Mgal/d) of withdrawals was lost in the conveyance of water from public-supply systems to the facilities that use the water. This quantity is calculated as the difference between water withdrawals and deliveries.

The larger metropolitan areas depend extensively on surface water for public supply. Mecklenburg County, which includes the city of Charlotte, had the largest withdrawal for public supply (8.6 percent of the total public-supply withdrawals or 51 Mgal/d). Public-supply systems served more than 354,000 people in the county. The Catawba River is the major source of supply for most of the municipalities in Mecklenburg County, including Charlotte, and several other towns and cities in the Catawba River basin. Guilford (Greensboro) and Wake (Raleigh) Counties, which were the second and third largest users of public-supply water, had withdrawals of 42 and 34 Mgal/d, respectively. Public-supply facilities served about 3.45 million people, of which about 77 percent was served by surface-water sources. The 1985 per capita use for public supply, including domestic, commercial, and industrial use, was 172 gal/d (gallons per day), which is a decrease from the 184 gal/d used in 1980.

Domestic and Commercial

In 1985, combined domestic and commercial water use, including conveyance losses, totaled 660 Mgal/d, of which 70.9 percent was delivered by public supply (fig. 4). Self-supplied domestic and commercial water withdrawals totaled 192 Mgal/d, of which 96 percent was withdrawn from ground-water sources. Withdrawals for domestic purposes in 1985 were about 484 Mgal/d. Public suppliers delivered 315 Mgal/d to about 3.4 million domestic users. Withdrawals for self-supplied domestic use (169 Mgal/d) were the fourth largest in the Nation (Solley and others, 1988). About 2.8 million people in North Carolina rely on private wells or springs. Per capita use for self-supplied households was about 60 gal/d, compared to 91 gal/d for people served by public supplies.

In 1985, commercial use totaled an estimated 160 Mgal/d, of which about 85 percent (137 Mgal/d) was delivered by public suppliers. Self-supplied commercial withdrawals were 23 Mgal/d, of which 15 Mgal/d was from ground-water sources. Military installations are included in the commercial water use category and represent a large part of the withdrawals. Military bases accounted for 85 percent of the total self-supplied commercial withdrawals, 7.9 Mgal/d of the self-supplied surface-water withdrawals, and 12 Mgal/d of the self-supplied ground-water withdrawals. Consumptive use at military bases was about 5 Mgal/d.

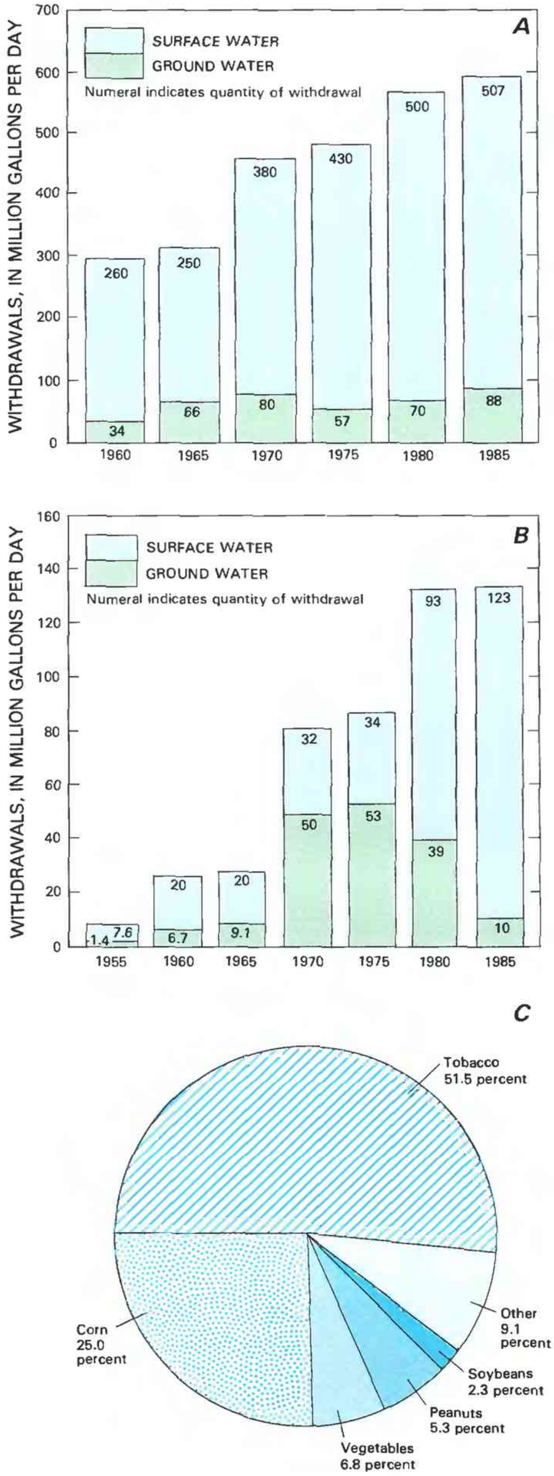


Figure 5. Water use in North Carolina. *A*, Water withdrawals for public water supply, 1960 to 1985. *B*, Water use for irrigation, 1955 to 1985. *C*, Percentage of water applied for irrigation by crop in 1985. (Source: *A*, *B*, Data from various reports of the U.S. Geological Survey. *C*, Compiled by the U.S. Geological Survey from data of the North Carolina Agricultural Extension Service and the North Carolina Division of Water Resources.)

Industrial and Mining

In 1985, industrial and mining use totaled 661 Mgal/d, which accounted for 8.4 percent of the total freshwater use. Of that quantity, 62.0 percent was withdrawn from surface-water sources, 18.7 percent was from ground-water sources, and 19.3 percent was delivered by public suppliers. Self-supplied industrial freshwater withdrawals from more than 350 industrial facilities was about 533 Mgal/d, of which 77 percent (410 Mgal/d) was from surface-water sources and 23 percent (123 Mgal/d) was from ground water. The major self-supplied industrial water use is for the manufacture of paper products, which accounted for approximately 40 percent (210 Mgal/d) of the total withdrawals for self-supplied industries in 1985. The paper industry is significant in the Upper Tennessee, Cape Fear, Neuse–Pamlico, and Chowan–Roanoke basins (North Carolina Department of Natural Resources and Community Development, 1983a).

The second largest self-supplied industrial withdrawals are used for mining, including quarrying and dewatering operations. Withdrawals for mining totaled 119 Mgal/d, of which 68 percent (81 Mgal/d) was from ground-water sources. Other industrial users include the textile industry, which used about 12 percent (62 Mgal/d) of the total self-supplied industrial water withdrawals, and manufacturers of chemical products. Major chemical plants operate in the Neuse–Pamlico and the Cape Fear basins.

Thermoelectric Power

Thermoelectric power generation facilities are by far the largest water users in the State, accounting for 81.1 percent (6,400 Mgal/d) of the total withdrawals in 1985. Of the water withdrawn, 99.4 percent was returned to the original source. Thermoelectric powerplants produced almost 72,000 GWh of electricity in 1985, which was about 92 percent of all electricity generated in the State. Thermoelectric facilities are concentrated in the central counties of the Edisto–Santee, the Chowan–Roanoke, and the Pee Dee basins. Two large plants in the Chowan–Roanoke basin withdrew about 2,250 Mgal/d, which was more than one-third of the total withdrawals for thermoelectric power generation. North Carolina ranks 10th nationally in withdrawals for thermoelectric power generation (Solley and others, 1988). In 1985, North Carolina had 16 thermoelectric powerplants in operation; 14 fossil-fueled plants accounted for 58 percent (3,700 Mgal/d) of the total thermoelectric power freshwater withdrawals, 1 nuclear facility accounted for the other 42 percent (2,690 Mgal/d), and another nuclear powerplant withdrew 866 Mgal/d of saline water from the estuary of the Cape Fear River. In late 1986, a new nuclear powerplant began operation in Wake County, which has the capacity to increase the water withdrawals by more than 200 Mgal/d.

Agricultural

Withdrawals for agriculture are small in comparison to other water use categories. Irrigation, however, has become necessary during droughts, such as occurred in 1986. Total agricultural withdrawals in 1985 were 2.1 percent (167 Mgal/d) of total freshwater withdrawals. Irrigation withdrawals were 133 Mgal/d in 1985, which accounted for nearly 80 percent of the agricultural water use. Several drought-stricken seasons and the unpredictability of rainfall forced many farmers to invest in irrigation equipment and to search for alternative sources of water. Consequently, water use for irrigation has increased substantially during the past 30 years (fig. 5*B*). Water use for irrigation in North Carolina during 1985 was only 0.10 percent of the national total (Solley and others, 1988); however, irrigation withdrawals increased by 61 percent, from 82 to 132 Mgal/d, between 1970 and 1980 and remained fairly constant from 1980 to 1985. More than 90 percent (123 Mgal/d) of the water withdrawn for irrigation in 1985 was from surface-water sources, most of which was from streams and impoundment ponds.

In the rolling topography of the western part of the State, many small irrigators use impoundment ponds to capture surface water. In the relatively flat, low-lying topography east of the Fall Line, large irrigators use primarily ground water and ponds that intersect the water table as their sources of supply.

The predominant method of irrigation in North Carolina is by sprinklers. Most irrigated acreage is sprinkled using portable hand-line and "traveling-gun" systems. These same systems are used to irrigate small, irregularly shaped fields in the Blue Ridge and the Piedmont regions (North Carolina Department of Natural Resources and Community Development, 1983b). In the Coastal Plain, center-pivot and solid-set systems also are used for larger tracts of land. Most irrigation is practiced in the eastern Piedmont and western Coastal Plain regions.

Most irrigation water is used for tobacco (fig. 5*C*), which accounts for an estimated 60 percent (133,000 acres) of the total acres irrigated. The large percentage of tobacco that is irrigated reflects the value of increased crop yield and quality resulting from irrigation (North Carolina Department of Natural Resources and Community Development, 1983b). The greatest concentration of irrigated tobacco acreage is in Harnett, Rockingham, Granville, Nash, Pitt, and Johnston Counties. Other substantial crops that are irrigated include corn (36,000 acres), truck vegetables (17,000 acres), peanuts (10,900 acres), soybeans (5,800 acres), and other crops (19,000 acres).

Nonirrigation agricultural water use includes livestock watering, aquaculture, and other farming operations. The quantity of water withdrawn for nonirrigation agriculture is small in relation to irrigation. Water withdrawals for nonirrigation agriculture totaled 34 Mgal/d in 1985, which is a decrease of 45 percent from 1975. Of the water withdrawals for nonirrigation agriculture, 85 percent was from ground-water sources.,

WATER MANAGEMENT

Indications that North Carolina's water supplies are not limitless were exemplified by the drought of 1986, when some local governments had to restrict the use of water. The dramatic water-level declines in some central Coastal Plain aquifers (Winner and Lyke, 1986) and the possibility of water shortages in some areas of the Outer Banks (the islands off the coast of North Carolina) during the tourist season have increased awareness of the importance of effective water-resource management. In addition, a dispute has arisen between the city of Virginia Beach, Virginia, and the State of North Carolina concerning the interstate transfer of water withdrawn from Lake Gaston, which is located in North Carolina but is a part of the interstate Roanoke River system. These examples indicate the need for comprehensive management of the State water resources.

Water supplies are managed by several local, State, and Federal agencies. Primary regulatory responsibilities are within the jurisdiction of the North Carolina Department of Natural Resources and Community Development (NRCD) and the North Carolina Department of Human Resources (DHR).

The Division of Environmental Management (DEM) within the NRCD manages an integrated program to protect surface-water quality. The DEM also is responsible for ground-water management and regulatory programs. The Environmental Management Commission has authority over the ground-water use permitting process and may designate an area as a "Capacity-Use Area" if the renewal and replenishment of water supplies are potentially threatened. To date (1987), the Commission has established only one such area in east-central North Carolina (fig. 6). Additional areas are being considered for Capacity-Use Area designation.

A permit must be obtained from the DEM for (1) the construction of a public-supply, industrial, or irrigation well, (2) wells that have a designed capacity of 100,000 gal/d or greater, (3) wells to be used for injection, recharge, or disposal purposes, and (4) a well other than a domestic well located in a designated Capacity-Use Area (North Carolina General Statutes, 1967). Injection wells for waste disposal currently (1987) are prohibited by State statute. The DEM also establishes the minimum water levels below which pumping may not continue and may require users to adhere to established maximum withdrawal rates.

The Division of Water Resources (DWR) within the NRCD collects data on the use of surface and ground water and investigates regional or river-basin water resources. The emphasis of these regional investigations is the availability of water to meet needs for public supply, industry, and irrigation. The DWR also provides local governments with technical assistance on water-supply problems and

Figure 6. Capacity-Use Area in North Carolina. (Source: North Carolina Environmental Management Commission, 1976).

conducts investigations of water shortages and multiple demands for limited supplies.

The DHR oversees the human health aspects of public-supply systems. This responsibility includes reviewing plans and specifications for water-treatment and distribution facilities, approving sources of raw water, establishing drinking-water standards, and requiring the monitoring of the quality of drinking water delivered by public suppliers.

Local governments and water-supply authorities are the primary providers of water and sewer services to most North Carolina citizens. Local agencies also are important in the protection of the quality of water supplies through operation of wastewater-treatment plants and control of nonpoint sources of pollution.

Federal agencies have a major role in the protection and the development of water supplies in North Carolina. The U.S. Environmental Protection Agency provides financial assistance for water-quality protection programs and determines Federal water-quality standards. The U.S. Army Corps of Engineers, the U.S. Soil Conservation Service, and the Tennessee Valley Authority are involved in planning, development, and management activities related to the State's water supplies. The U.S. Geological Survey provides the essential water-resources data and interpretive study results that are used by all water-management agencies.

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Prepared by M.W. Treece, Jr., and J.D. Bales, U.S. Geological Survey; History of Water Development section by D.H. Moreau, North Carolina Water Resources Research Institute

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, P.O. Box 2857, Room 440, Century Postal Station, Raleigh, NC 27602

North Dakota
Water Supply and Use

North Dakota is a prairie State and has a semiarid climate. The water budget (fig. 1A) indicates that surface-water outflow exceeds inflow and that evapotranspiration nearly equals annual precipitation. Runoff contributes to the flow of the Red River of the North. The streamflow increases in volume more than 40 times northward along the eastern boundary. Water stored in aquifers and reservoirs provides a constant supply for various water uses in the State.

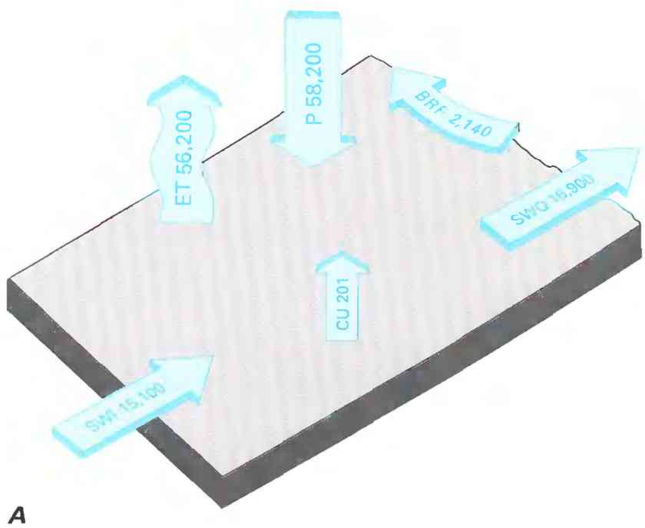
All larger cities are near major rivers, and most of them use surface water as the source of supply. Water from the mainstem of the Missouri River and the lower Red River of the North is abundant and suitable for most uses. Other rivers are not as reliable because of smaller flows and more variable water quality. To ensure a constant source of supply, surface water may be supplemented by ground water, or a low-head dam may be constructed to store water within a river channel.

North Dakota is rural and agricultural. Almost one-third of the population lives on farms or ranches, and more than 80 percent of the communities have populations of less than 1,000. Farms, ranches, and almost all smaller cities and villages (about 63 percent of the population) depend on ground water as a source of supply. Livestock production is dominant in the western one-half of the State, and dryland crop production is dominant in the eastern one-half of the State.

Thermoelectric power generation is the largest use of water. In 1985, 76.6 percent of all withdrawals, or 892 Mgal/d (million gallons per day), was for thermoelectric use. Virtually all these withdrawals were from the Missouri River and Lake Sakakawea (a reservoir on the Missouri River) in west-central North Dakota. About 2.6 percent of the water withdrawn for thermoelectric power generation was consumed.

Agriculture is the second principal water use. In 1985, 15.1 percent (176 Mgal/d) of the total water withdrawn was for agricultural use. About 56.2 percent of the water withdrawn for agriculture was from surface-water sources. Irrigation is practiced throughout areas of the State near rivers. Surface water was applied to about 39 percent of the total acres irrigated. Ground water supplied the remaining irrigated acreage, primarily in the central, northern, and eastern parts of the State. About 82.9 percent of the water withdrawn for agriculture was consumed.

Withdrawal for all industrial uses in 1985 accounted for less than 1 percent of all water withdrawn. The oil industry, which is



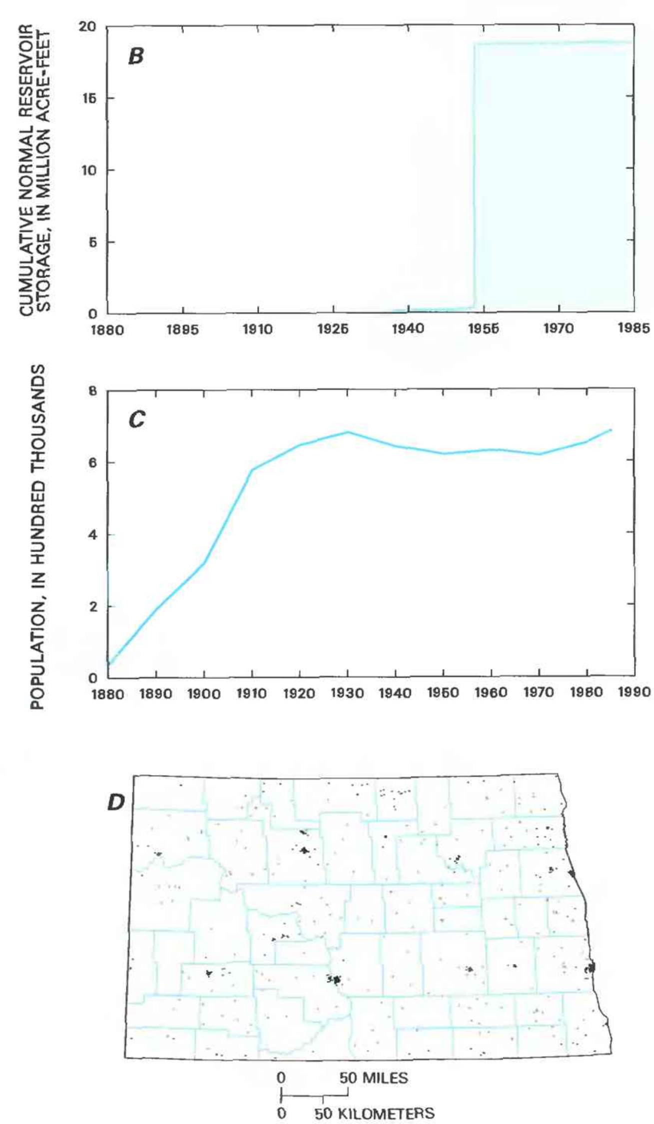


Figure 1. Water supply and population in North Dakota. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from National Oceanic and Atmospheric Administration, 1982; U.S. Geological Survey, 1985, 1986b–e; U.S. Geological Survey National Water Data Storage and Retrieval System; U.S. Department of Agriculture. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

primarily in western North Dakota, is important to the economy of the State but is a small user of water.

In 1985, about 1,170 Mgal/d of freshwater was withdrawn from rivers and aquifers for all offstream water use categories and was equivalent to about 1,690 gal/d (gallons per day) per capita. Of the 1,170 Mgal/d withdrawn in 1985, 201 Mgal/d was consumed, and 963 Mgal/d was returned to surface- or ground-water sources for future use.

HISTORY OF WATER DEVELOPMENT

Water was important in the early settlement and development of North Dakota. From 1832 to 1870, steamboats on the Missouri River, the Red River of the North, and the Sheyenne River and Devils Lake (Ramsey County) provided a navigation service for settlers, military personnel, business entrepreneurs, and other passengers. Easy access to a water supply made settling near a river desirable. Military forts, such as Fort Abraham Lincoln (near Bismarck) on the Missouri River and Fort Abercrombie (near Fargo) on the Red River of the North, and larger cities, such as Fargo, Bismarck, Grand Forks, and Minot, were established along rivers.

Historically, North Dakota has had the dilemma of too much surface water during the spring and too little water later in the year. To some extent, this dilemma has been alleviated by the construction of dams on some of the major rivers. In areas farther away from the rivers, an adequate supply of ground water was a problem for many rural residents, although, in some areas, ground-water supplies seemed to be ample. Some progress is being made in the distribution of the water supply by the construction of two surface-water projects and of rural water systems.

The importance of surface-water storage was recognized by the settlers, and reservoir construction started in the late 1800's. The reservoirs were small and generally had a single purpose. Many early reservoirs were constructed by the railroads to supply water for their steam locomotives. Many of these reservoirs still exist but now are used mostly for recreation and fish and wildlife propagation. Other early reservoirs were constructed for industrial purposes, such as water power for a flour mill, or a more constant water source for public water supply. The first reservoir in North Dakota to store more than 5,000 acre-ft (acre-feet) of water was built in 1937 (fig. *1B*). Gradually, larger multipurpose reservoirs were built. These reservoirs provide water for public supply, recreation, agriculture, wildlife, and flood control. Reservoir storage increased in 1953 when construction of the Garrison Dam on the Missouri River was completed and Lake Sakakawea was created. Construction of Garrison Dam was made possible by the 1944 Flood Control Act, which included the Pick-Sloan Plan for the management and development of the Missouri River basin. Impetus for the Pick-Sloan Plan came largely from the ravages of the droughts of the 1930's and the floods of the early 1940's.

As of 1985, the two largest water-development projects are the Garrison Diversion Unit Project and the Southwest Pipeline Project. The Garrison Project, which is about 20 percent complete, will provide water for irrigation, public supply, rural and industrial water use, and fish and wildlife enhancement in central and eastern North Dakota. The Southwest Pipeline Project, a State and Federal-funded project initiated in 1977, will deliver water to municipal and domestic water users in southwestern North Dakota. Both projects will withdraw water from Lake Sakakawea.

A correlation is not evident between the increase in reservoir storage and the increase in population (figs. *1B,C*). The historical rise in water use probably is more closely related either to increases in the number of thermoelectric powerplants or to irrigation.

North Dakota's population growth peaked about 1930, declined during the next 20 years, and generally remained constant during the following years (fig. *1C*). Since 1930, the rural population has decreased steadily, while the urban population has increased steadily. This shift in population resulted in a decrease in withdrawals for domestic use in rural areas and an increase in withdrawals for domestic use by public-supply systems in urban areas. From about 1970 to 1985, the population increased chiefly in the western one-half of the State because of expansion in the energy industry (figs. *1C,D*). During this period, the population increased an estimated 5.5 percent, from 652,000 to 688,000 (R.W. Rathge, Department of Agricultural Economics, North Dakota State University, written commun., 1986).

State officials have estimated that the population will increase to about 720,000 by the year 2000. The growth rate figures on which this estimate was based are being revised, however, because the population has decreased since 1985 (estimates range from 2 to 5 percent). The recent decrease is due largely to the decline in energy-resource exploration and development and related businesses and to the decline in the economy in general. The downward trend may continue for the next 2 to 3 years (R.W. Rathge, oral commun., 1987). North Dakota has the water supply necessary to serve the population (720,000) estimated for the year 2000.

Ground water has met much of North Dakota's rural and urban water-supply needs. The early settlers used dug wells; however, virtually all these wells were replaced by drilled wells. Because drilled wells were better constructed, they were more sanitary and produced more water than dug wells. Windmills and hand pumps were used exclusively before the arrival of the rural electric movement in the late 1940's.

North Dakota farmers indicated their interest in irrigation early in the State's history and held their first irrigation congress in 1903. Two years later, construction started on the first federally funded irrigation project in North Dakota. The U.S. Bureau of Reclamation's Lower Yellowstone Irrigation Project encompassed 60,000 acres, about 22,500 acres of which are in northwestern North Dakota. Most of the early irrigation developments were large and employed flooding or water-spreading methods. Since the mid-1970's, however, most irrigation developments have been smaller, privately funded projects on individual farms, where water from unconsolidated aquifers has been the principal source of supply. The use of ground water for irrigation in North Dakota was aided by the development of center-pivot sprinklers and completion of county ground-water studies. The county ground-water program, which involved mapping and quantifying the volume of water in the State's aquifers, was begun in 1955 by the North Dakota State Water Commission in cooperation with the U.S. Geological Survey. Ground-water resource studies have been completed in all 53 counties in North Dakota. Water of unsatisfactory quality for domestic use, limited local supplies of ground water, and cost-effective techniques of building distribution systems contributed to the formation of rural water systems. The first rural water system was built in 1972.

WATER USE

North Dakota receives a moderate average annual precipitation of 17.3 inches, which ranks the State 44th nationally (Geraghty and others, 1973). Precipitation varies from year to year and has ranged from 4 to about 35 inches (Bavendick, 1952). Precipitation has followed cyclic trends; for example, the 1930's was a period of less-than-average precipitation, and the 1940's was a period of greater-than-average precipitation. The amount and timing of precipitation affect water use and the economy because of the State's dependence on agriculture.

The Missouri River is the most significant source of surface water in North Dakota. Flow of the Missouri River accounts for more than 80 percent of the mean annual streamflow in the State (Winter and others, 1984). Without surface-water storage, North Dakota would be a water-poor State. Total normal reservoir storage for all 24 of the large (over 5,000 acre-ft) reservoirs is estimated to be 18.8 million acre-ft. Lake Sakakawea alone has an estimated normal reservoir storage of 18.3 million acre-ft. In addition to reservoirs that have normal storage greater than 5,000 acre-ft, hundreds of smaller reservoirs serve as stock ponds and wildlife refuges and provide recreation, limited flood control, irrigation, and public supply. Natural wetlands, which provide an important water resource for migrating waterfowl and wildlife, cover more than 2 million acres in the central part of the State (Stewart and Kantrud, 1973).

Ground water provides another source of stored water. Major unconsolidated aquifers in parts of central, northern, and eastern North Dakota are significant sources of shallow ground water of variable quality (Winter and others, 1984). The North Dakota State Water Commission (1982) has estimated that these major unconsolidated aquifers contain 60 million acre-ft of water; properly constructed wells completed in these aquifers generally yield 50 to 500 gal/min (gallons per minute). Water also is available from minor unconsolidated aquifers (generally yields 10 gal/min or less), which are located in most of the State, and from bedrock aquifers, which generally are located in the southwestern part of the State. In some areas, particularly in the southwest, ground water is unsatisfactory for domestic supply but is the only source available (U.S. Geological Survey, 1988). In 1965, ground water supplied about 20 percent of the State's water needs, excluding water used to generate power (North Dakota Geological Survey, 1973); during 1985, ground water supplied nearly 47 percent of those same needs.

Total withdrawals, surface-water withdrawals, and ground-water withdrawals by county for 1985 are shown in figures 2*A*, *B*, and *C*, respectively. Although thermoelectric power generation facilities withdraw large volumes of surface water in McLean, Mercer, Morton, and Oliver Counties along the Missouri River in west-central North Dakota, agricultural water use is the dominant use of water throughout the State. Of all agricultural activities, ranching predominates in the western one-half of the State, and dryland farming predominates in the eastern one-half. Generally, surface water is the source of irrigation supplies in the northwestern part of the State (Williams and McKenzie Counties) and along larger rivers, and ground water generally is the source of irrigation supplies elsewhere. Unconsolidated aquifers are moderately developed for irrigation use, except in a few counties in the southeastern part of the State. The remaining large water withdrawals are for public supply and, to a lesser extent, industrial purposes.

Surface-water withdrawals in principal drainage basins during 1985 are shown in figure 3*A*. The largest withdrawals (930 Mgal/d) were in the Missouri–Oahe basin; 95.3 percent (886 Mgal/d) of this water was used for thermoelectric power generation. The second-largest withdrawals (54 Mgal/d) were in the Missouri–Little Missouri basin; 80.8 percent (44 Mgal/d) of this water was used for agricultural activities. The third-largest withdrawals (29 Mgal/d) were in the Red basin, where 43.5 percent of the State's population is concentrated; 74.4 percent (22 Mgal/d) of this water was withdrawn for public supplies. The largest withdrawals from the four remaining drainage basins were for agricultural use.

Instream water use by hydroelectric powerplants is an additional significant use of water because hydropower is a major source of electrical power in North Dakota. Hydropower accounts for about 92 percent of the total water (instream and offstream) use. In 1985, about 12,700 Mgal/d was used to generate about 2,200 GWh (gigawatthours) of electricity. The consumptive use of water in this process is negligible. The power generated varies depending on

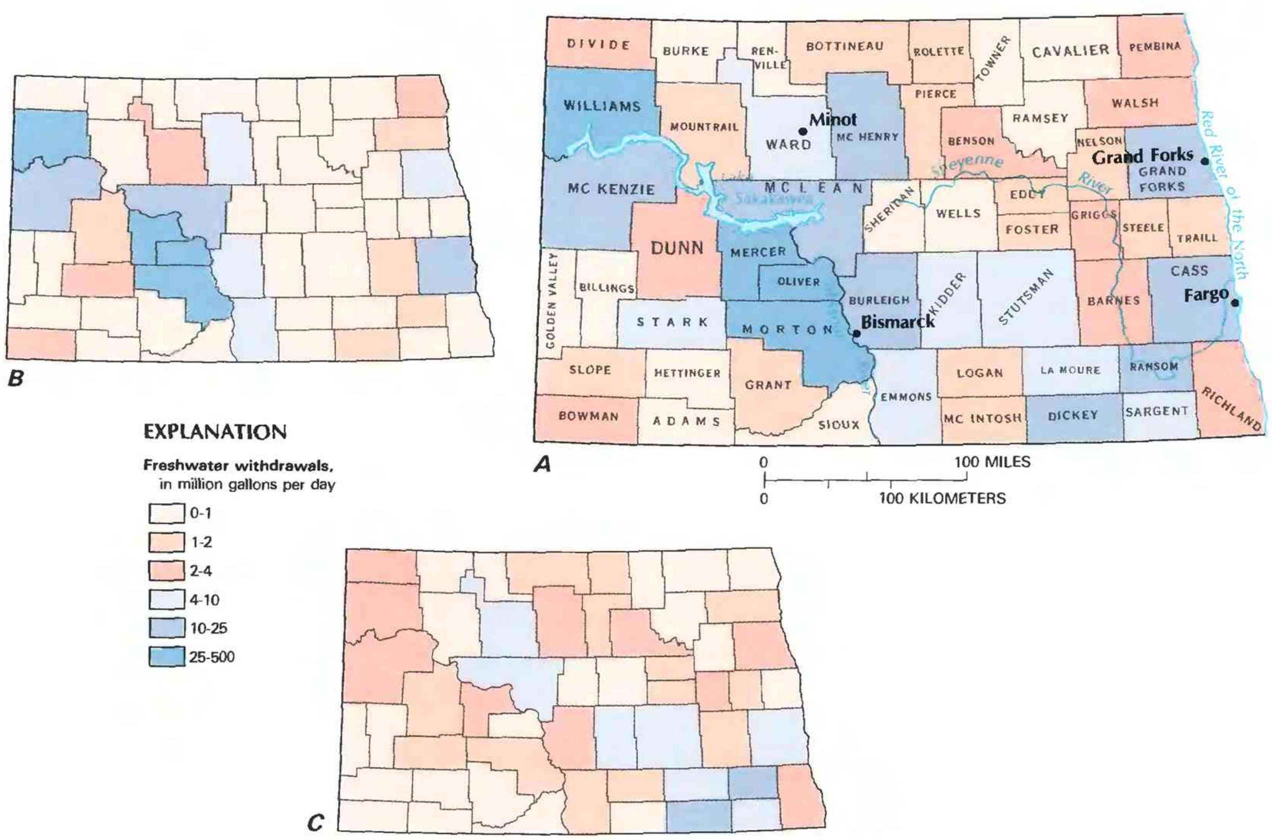


Figure 2. Freshwater withdrawals by county in North Dakota, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

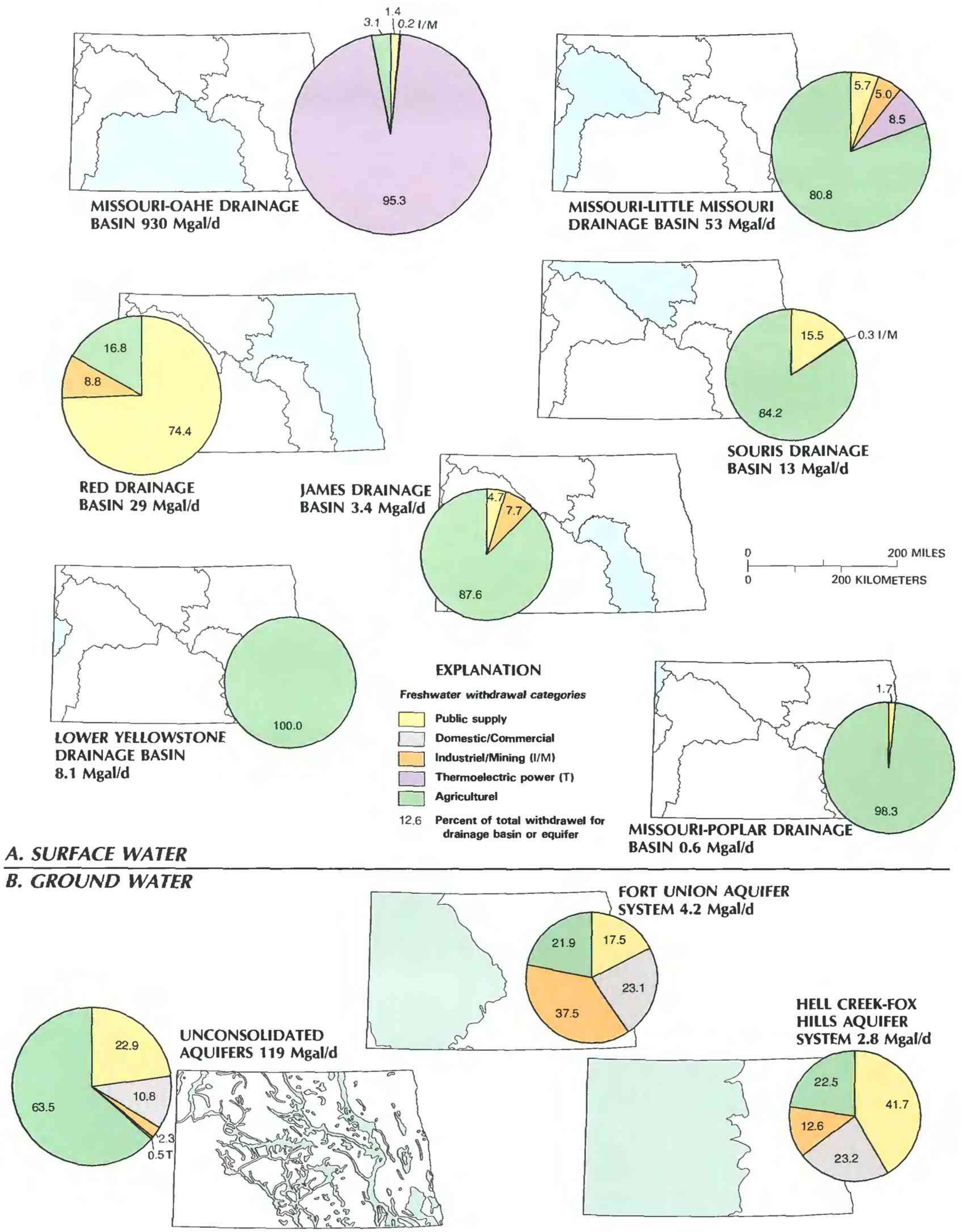


Figure 3. Freshwater withdrawals by hydrologic unit and category of use in North Dakota, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (*Sources: A,* Drainage basin units from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System; aquifer map from U.S. Geological Survey, 1985, p. 337.)

power demand and water availability but averages 2,700 GWh annually (U.S. Geological Survey, 1986a).

Ground-water withdrawals from unconsolidated and bedrock (Fort Union and Hell Creek–Fox Hills) aquifers for 1985 are shown in figure 3*B*. Unconsolidated aquifers provide almost 94 percent of the total ground-water withdrawals (119 Mgal/d), of which 63.5 percent (76 Mgal/d) is for agricultural use, primarily irrigation, and 36.5 percent (43 Mgal/d) is for other uses. Bedrock aquifers generally are developed in the southwestern one-fourth of the State and are used almost equally for agricultural, public-supply, domestic, industrial, and mining purposes.

The source, use, and disposition of freshwater in North Dakota in 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate, for example, that surface-water withdrawals of 1,040 Mgal/d comprise 89.1 percent of the total surface- and ground-water withdrawals. The distribution of surface-water withdrawals by use is as follows: less than 0.1 percent was withdrawn for domestic and commercial use by self-supply users, 0.7 percent was withdrawn for industrial and mining purposes by self-supply users, 85.9 percent was withdrawn for thermoelectric power generation, 9.5 percent was withdrawn for agricultural purposes, and 3.8 percent was withdrawn by public-supply systems for domestic, commercial, industrial, and mining uses.

Some users in all four categories of water use (fig. 4)—domestic and commercial, industrial and mining, thermoelectric power generation, and agricultural—are self-supplied. In addition, some domestic and commercial users and some industrial and mining users receive water deliveries from public supply. Public supply serves to transfer water from a surface- or ground-water source to each water use category. The use data indicate, for example, that domestic and commercial withdrawals and deliveries were 82 Mgal/d and represent 7.0 percent of the State's total withdrawals during 1985. Of this 82 Mgal/d, 17.9 percent was from ground-water sources, and 82.1 percent was delivered by public-supply systems. Of the water withdrawn for domestic and commercial uses, 75.4 percent was returned to surface-water or ground-water sources and 24.6 percent was consumed and was not available for immediate future use. The disposition data indicate the final destination of the water withdrawn from a surface- or ground-water source. The disposition data also indicate that, of all water withdrawn in the State, 201 Mgal/d (17.3 percent) was consumed and 963 Mgal/d (82.7 percent) was available for reuse. Domestic and commercial consumption was 10.0 percent of the total consumed water, and return flow was 6.4 percent.

PUBLIC SUPPLY

Throughout the State, most municipalities that have more than 7,500 people obtain public supplies from surface-water sources. Public-supply systems withdraw, treat, and distribute water to users. Some municipalities that have populations of less than 5,000 are near surface-water sources but do not use them because the supply is undependable during dry years or because the costs to construct and operate a treatment plant are prohibitive.

Public-supply systems, including rural water systems, furnish water for domestic, commercial, and industrial uses. In 1985, the State had 19 rural water systems that serve about 10 percent of the

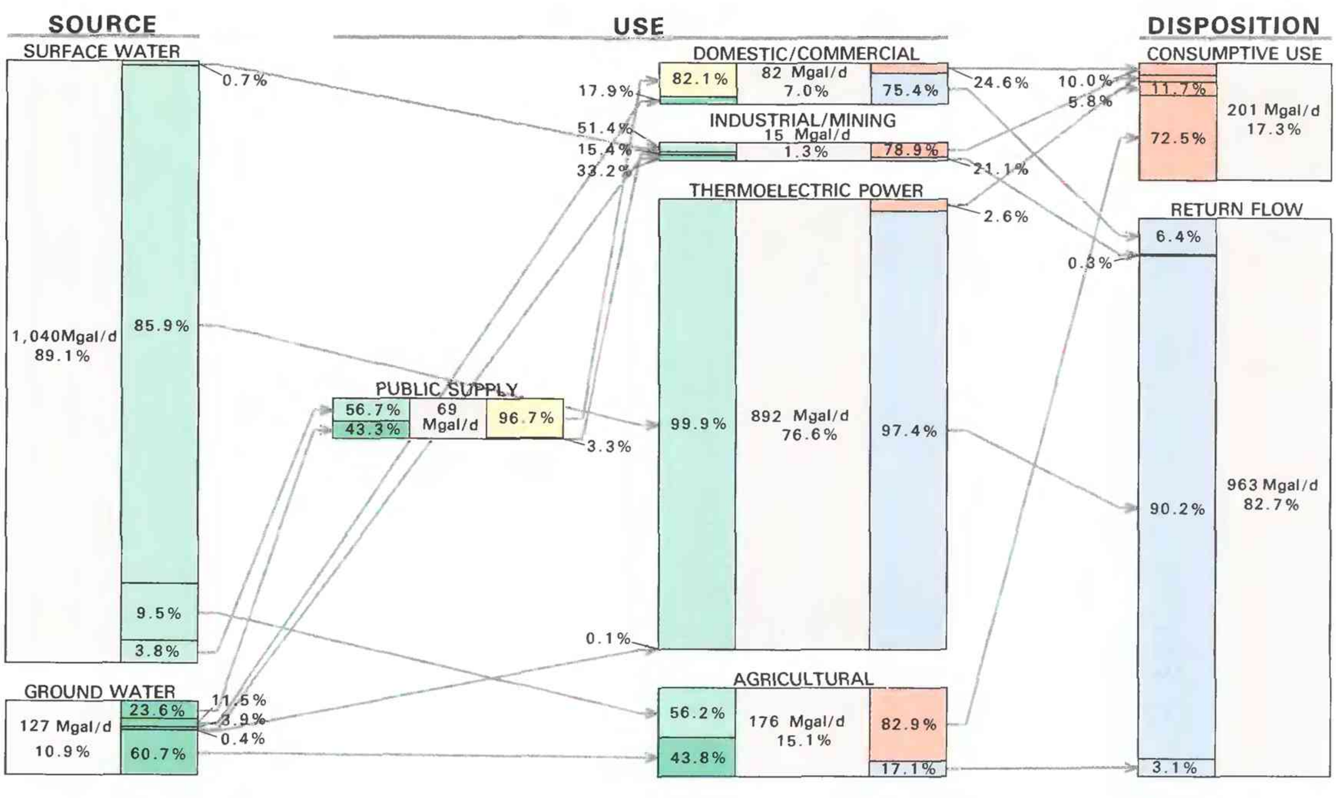


Figure 4. Source, use, and disposition of an estimated 1,170 Mgal/d (million gallons per day) of freshwater in North Dakota, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

population. More than 100 small communities receive all, or part, of their water supply from rural water systems.

Water use by individuals served by public supplies in North Dakota is one of the smallest in the Nation—135 gal/d per capita (Solley and others, 1988). In 1985, the State ranked 47th in population served by public supplies, and withdrawals from public-supply water ranked 49th (Solley and others, 1988). Total public-supply withdrawals during 1985 were 69 Mgal/d; about 39 Mgal/d (56.7 percent) was surface water, and 30 Mgal/d (43.3 percent) was ground water. Public-supply deliveries were made to about 512,000 people.

Domestic and Commercial

Domestic and commercial water users receive water from public-supply and self-supplied facilities. Combined total use during 1985 was 82 Mgal/d. Per capita use of water from public-supply and self-supplied sources by domestic users was about 80 gal/d. Domestic use during 1985 was 54 Mgal/d, of which 40 Mgal/d was from public-supply systems that served 74 percent of the population and 14 Mgal/d was from self-supplied sources for 26 percent of the population. Domestic consumptive use was 18 Mgal/d. Commercial use during 1985 was 15 Mgal/d and was almost entirely provided by public supply. Commercial consumptive use was 2 Mgal/d. Public-supply water used for public purposes, such as street cleaning, irrigating parks, water treatment, and water lost during deliveries to domestic, commercial, and industrial users amounted to 13 Mgal/d.

Industrial and Mining

Industrial and mining water use during 1985 was 1.3 percent (15 Mgal/d) of the total use—the smallest of the water use categories (fig. 4). Self-supplied systems provided 84.6 percent of industrial and mining withdrawals (about 13 Mgal/d)—6.8 Mgal/d from surface water and 2.2 Mgal/d from ground water for industry and 0.9 Mgal/d from surface water and 2.8 Mgal/d from ground water for mining. Public-supply systems delivered the remaining 2 Mgal/d of the 15 Mgal/d. Consumptive use of withdrawals and deliveries for industrial and mining was 12 Mgal/d. Industrial water use is primarily for coal gasification, sugar refining, oil refining, and malt processing, which collectively used 86.3 percent of the self-supplied industrial water.

The major types of mining activities are coal and gravel excavation and oil and gas extraction. Fifty-six percent of the withdrawals for mining were in two adjacent counties, McLean and Mercer, where coal mining is common. Lignite coal is used for thermoelectric power generation and coal gasification.

Thermoelectric Power

The largest quantity of water withdrawn was used for thermoelectric power generation (fig. 4). North Dakota has 11 active fossil-fueled thermoelectric powerplants, 5 of which were built in response to increased energy demand and have been operational since 1979. Power production has increased from about 11,700 GWh in 1979 to about 20,200 GWh in 1985 (Marcy Dickerson, North Dakota State Tax Department, oral commun., 1987). During 1985, these plants withdrew 892 Mgal/d of water for cooling purposes. Most of this water was withdrawn from surface-water sources, primarily the Missouri River and Lake Sakakawea. Thermoelectric cooling accounted for 76.6 percent of all withdrawals in North Dakota; 2.6 percent of the water withdrawn was consumed. The largest potential for water-resource development is for the generation of thermoelectric power because of extensive lignite coal reserves.

Agricultural

Agricultural water use in North Dakota, which includes crops and livestock, is dominated by irrigation. Withdrawals for irrigation during 1985 were 88 percent of the total agricultural withdrawals. Of the total withdrawals for agricultural purposes, 56.2 percent was surface water, and 43.8 percent was ground water (fig. 4). Irrigation withdrawals are not distributed equally throughout the year. Irrigation generally is practiced from April through October, and peak use occurs during July and August.

During 1985, 154 Mgal/d of water was withdrawn for irrigation of corn, pasture and hay, sugar beets, beans, and some small grain crops. Irrigation is practiced in almost all counties in North Dakota; however, 75 percent of irrigation from surface-water sources occurred in McKenzie, McHenry, and Williams Counties. Ground-water withdrawals for irrigation are most common in the south-central and southeastern parts of the State. Most of this water is withdrawn from unconsolidated aquifers; bedrock aquifers accounted for less than 0.1 percent of the ground water used for irrigation. About 80.5 percent (124 Mgal/d) of withdrawals for irrigation was consumed.

Although irrigation development has been increasing steadily since 1980 and is expected to continue to increase, the growth rate has been less each year. This decrease in growth rate may reflect the uncertain economic outlook for farming. The State has the potential for water-resource development for irrigation. The 1986 Garrison Diversion Reformulation Act authorizes irrigation of 130,940 acres of North Dakota farmland; this Act could increase the number of irrigated acres by more than 60 percent compared to 1985.

In 1985, agricultural water use for livestock and other farm purposes was 22 Mgal/d, which almost equals the quantity withdrawn during 1980. Although the number of livestock operations has been decreasing steadily since 1966 (North Dakota Agricultural Statistics Service, 1986), the water demand has remained fairly constant. Most water withdrawn for livestock supply is from wells or excavated ponds. All nonirrigation agricultural water use is considered to be consumptive use.

WATER MANAGEMENT

Authority for the State of North Dakota to manage its water resources is provided in the Constitution of North Dakota, which states, "All flowing streams and natural watercourses shall forever remain the property of the State for mining, irrigating, and manufacturing purposes."

North Dakota has developed a water-management system that is responsive to development needs. The strength of this system is the emphasis on securing accurate baseline data from research projects and monitoring programs, from the development of State water plans, and from construction of water projects. The stage and flow of the rivers are monitored by a network of streamflow-gaging stations. The major aquifer systems were delineated and quantified as part of 53 county ground-water studies. The major aquifers are monitored to detect changes in water levels and water quality.

Planning also is important in the State's water-management process. Comprehensive statewide water plans were developed in 1937, 1962, 1968, and 1983. The 1983 State Water Plan (North Dakota State Water Commission, 1983) described North Dakota's current water-development needs.

Water demand and water use are managed using a permit system, which is based on the doctrine of prior appropriation and is administered by the North Dakota State Water Commission. A water user must obtain a permit before construction of an impoundment capable of retaining more than 12.5 acre-ft of water or before the construction of a well from which more than 12.5 acre-ft of water will be appropriated annually. Irrigation of more than 1 acre of land also requires a permit. Use of less than 12.5 acre-ft annually, which would include most rural domestic and livestock uses, does not require a permit.

The North Dakota State Water Commission, in Chapter 61–02 of the North Dakota Century Code, was given the primary authority to manage and develop the State's water resources.

Several other water-management organizations in North Dakota also develop and manage use of the State's water resources (fig. 5). These organizations are described below.

Water-Resource Districts: All North Dakota counties are required to establish a water-resource district. Most water-resource districts are established along county boundaries; however, some counties have more than one district; for example, Cass County in eastern North Dakota has four water-resource districts—North Cass, Rush River, Maple River, and Southeast Cass. Water-resource district board members are appointed by their respective county commissioners. The water-resource districts have been given broad water-management authority to initiate, plan, and construct a variety of projects including, but not limited to, water-supply systems, drainage canals, reservoirs, and flood-control structures. Each district levies a limited tax to fund its operations. The water-resource districts work closely with the North Dakota State Water Commission and other State and Federal agencies.

Joint Water-Resource Boards: Although most water-resource districts were established along county boundaries, the legislature recognized that water does not respect political boundaries, and effective management often requires that two or more water-resource districts work together. Joint water-resource boards are composed of water-resource districts but conform in shape somewhat to drainage-basin boundaries; North Dakota has 11 joint boards. Water-Resource Districts are not required to participate as a member of a joint board. However, a Water-Resource District (usually a county) can belong to more than one joint board if the district is part of several drainage basins. The joint boards may levy limited taxes to fund their operations. These boards, among other duties, can initiate, plan, and develop water projects of common benefit to the member districts. Some boards are involved in several flood-control projects, including dam and reservoir construction. The 11 joint boards are Red River; Devils Lake; Upper Sheyenne; Hurricane Lake; West River; Rocky Run; James River; Burleigh, Oliver, Morton, Mercer, and McLean (BOMMM); Souris River; Tri-County; and Maple-Richland.

Garrison Diversion Conservancy District: The North Dakota Legislature created the Garrison Diversion Conservancy District, which encompasses 25 counties in north-central, central, and eastern North Dakota; the purpose was to sponsor the construction and management of the Garrison Diversion Unit Project. Each county is represented by an elected director. The Conservancy District Board of Directors may levy a tax not to exceed 1 mill to finance its operations. Some of the powers and duties of the Board of Directors are to acquire land; accept funds, property, and services or other assistance (financial or otherwise); cooperate and contract with government agencies to provide research and other investigations; and operate and maintain project features. The creation of the Conservancy District does not limit the functions of the North Dakota State Water Commission nor does the Conservancy District have authority over water-resource districts or the joint water-resource boards.

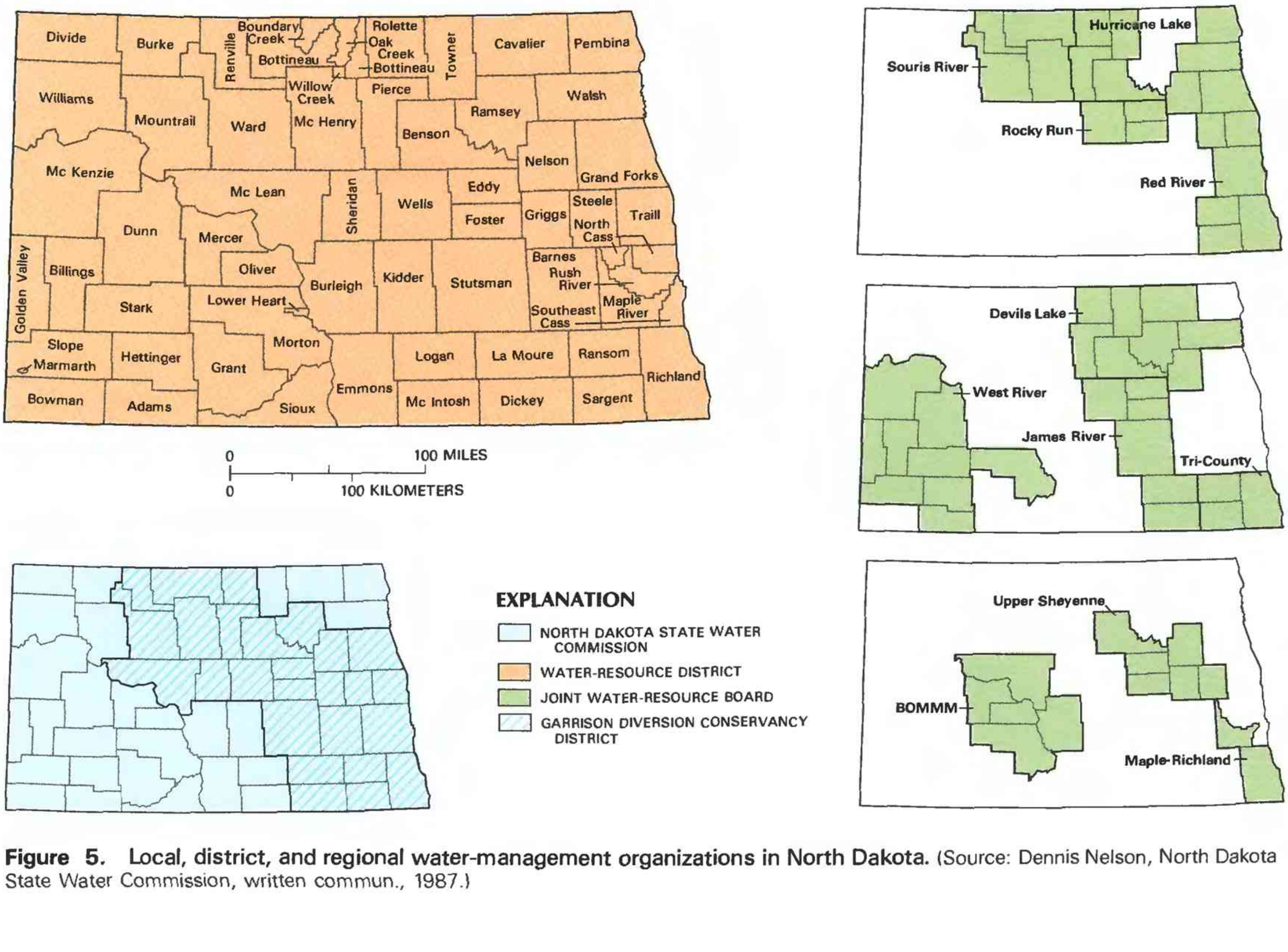


Figure 5. Local, district, and regional water-management organizations in North Dakota. (Source: Dennis Nelson, North Dakota State Water Commission, written commun., 1987.)

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Prepared by E.A. Wesolowski, U.S. Geological Survey; History of Water Development and Water Management sections by Dennis Nelson, North Dakota State Water Commission

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 821 East Interstate Avenue, Bismarck, ND 58501

OHIO
Water Supply and Use

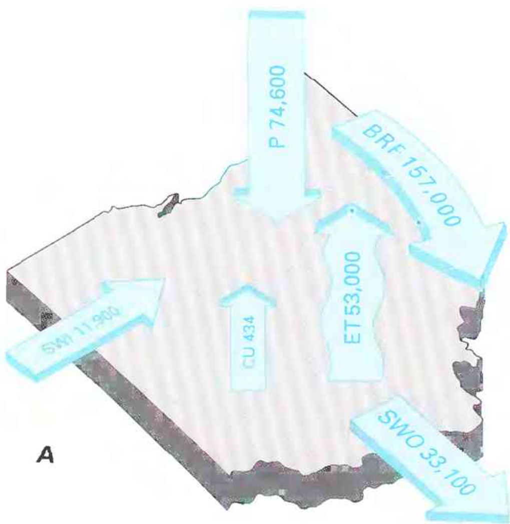
Ohio has many assets, among which is an adequate supply of water for many uses. Ohio is bordered on the north by Lake Erie, from which 120,000 Mgal/d (million gallons per day) of water is available for withdrawal. The mean discharge of the Ohio River increases from 20,000 Mgal/d on the southeastern boundary of the State to 70,000 Mgal/d on the southwestern boundary. An estimated 10,000 Mgal/d of water was withdrawn for use in Ohio directly from Lake Erie and the Ohio River in 1985. The average annual precipitation of 38 inches provides about 74,600 Mgal/d of water (fig. 1*A*). About 33,100 Mgal/d is lost in surface-water outflow, whereas 434 Mgal/d is consumed. An estimated 53,000 Mgal/d is returned to the atmosphere by evapotranspiration.

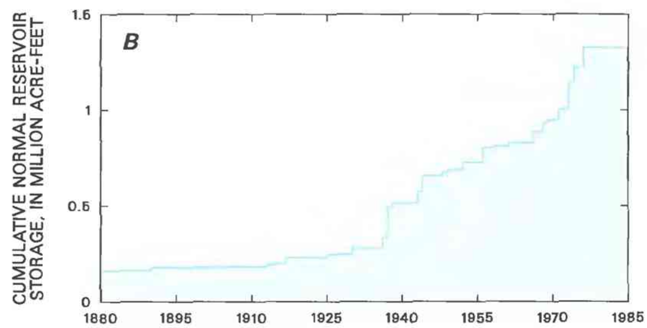
Agriculture is the major economic activity in the glaciated northern and western counties of the State because of flat topography, fertile soils, readily available water, and easy access to transportation. The northeastern, central, and southwestern counties are primarily urban and industrialized. The unglaciated southeastern counties are on a rugged plateau characterized by mining and timber industries.

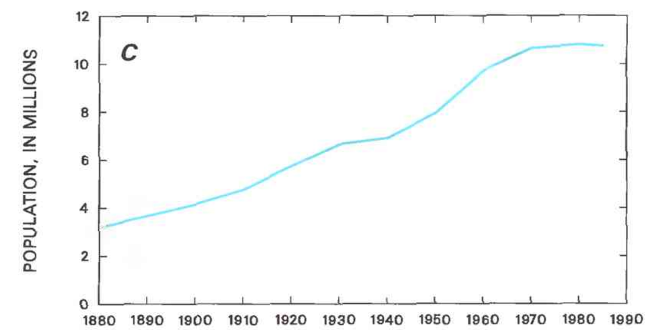
A total of 12,700 Mgal/d of freshwater was withdrawn from all sources in Ohio in 1985. Although thermoelectric power generation accounted for 82.7 percent of total withdrawals, it accounted for 16.2 percent of the total consumptive use. Industrial and mining uses accounted for 6.9 percent of the total water withdrawn and for 42.1 percent of the total consumptive use. Surface-water withdrawals for all categories of use were 12,000 Mgal/d; ground-water withdrawals were 730 Mgal/d, of which 54.0 percent was withdrawn by public supply.

HISTORY OF WATER DEVELOPMENT

"Beautiful Ohio," the State's official anthem, tells of the beauty of the watercourse that shapes its southern and part of its eastern boundaries. Ohio was the second State of the Union, after Connecticut, to relate its name to water. Ohio comes from an Iroquois word meaning "beautiful river."







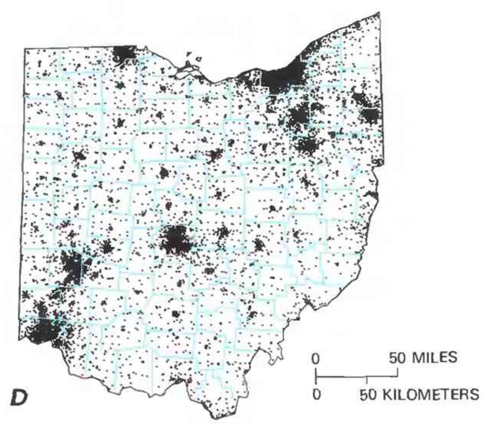


Figure 1. Water supply and population in Ohio. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey files; National Oceanic and Atmospheric Administration, 1985, p. 2–9. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

The presence of waterways along the eastern, southern, and northern boundaries of Ohio determined the location of settlements and the development of industry. Many industrial communities developed along the Ohio River, the first of which was Marietta (established July 15, 1788). Cleveland was the first settlement along Lake Erie. An estimated 2,000 gristmills and lumbermills were built along waterways near the early settlements. These mills were the first large industries in Ohio to use water power.

On July 4, 1825, the era of Ohio canals began. Canal systems were built to connect the Ohio River and Lake Erie and to provide a shortcut for water traffic from the Great Lakes to the Gulf of Mexico. The State's agricultural exports were stimulated by canals because of the ease of transporting farm products. The Ohio and Erie Canal connected Cleveland on Lake Erie to Portsmouth on the Ohio River and the Miami and Erie Canal connected Toledo on Lake Erie to Cincinnati on the Ohio River.

The first public-use reservoir in the United States, Buckeye Lake (Muskingum County), was built east of Columbus to provide a water supply for the Ohio and Erie Canal (Frost and Nichols, 1985). As canal usage declined around 1896, the reservoir was declared the first State Park in Ohio (Ohio Law 92–265).

On June 25, 1839, Cincinnati became the first major municipality in Ohio to have a public water supply (Frost and Nichols, 1985), when the citizens of that city voted to purchase a private water company. A diptheria epidemic in 1880 led to construction of the first wastewater-treatment plant, which was completed in 1893 at Canton (Stark County), Ohio. It was a chemical precipitation plant that discharged about 0.5 Mgal/d of effluent.

Flooding in Ohio in 1913 led to the organization of drainage-basin conservancy districts. The first district was the Upper Scioto Conservancy District, which was organized in 1915. In 1921, the Miami Conservancy District began work on the first flood-control system. The Muskingum Watershed Conservancy District was the first to address multipurpose water-management and land-conservation issues by river basin.

The amount of water stored in reservoirs increased 75 percent from 1880 to 1930 and more than tripled from 1930 to 1985 (fig. 1*B*). The population nearly doubled from 1880 to 1930 and increased 61 percent from 1930 to 1985 (fig. 1*C*). The population-density map (fig. 1*D*) shows that residential areas are concentrated in the northeastern, central, and southwestern counties and along the shore of Lake Erie. Comparison of the change in reservoir storage with the change in population indicates an increased reliance on Ohio's surface-water supply. This is due, in part, to reservoir projects of the State Water Conservation Districts after 1930 and to the economics of surface-water impoundment compared with the economics of well drilling for large water supplies. In addition to storing water, the reservoirs regulate runoff and provide flood control, sediment control, and recreation areas. After droughts in 1953 and 1954, the Ohio Department of Natural Resources, Division of Water, was directed to prepare river-basin reports that would index water resources and uses, locate potential reservoir sites, and discuss water development, water quality, recreation, flood control, and drainage. These reports are updated periodically to reflect the changing needs of the basin population and industry.

A statewide network of observation wells was established in 1941 by the U.S. Geological Survey and the Ohio State University Engineering Experiment Station. Later, responsibility for the network was transferred to the Ohio Department of Natural Resources, Division of Water.

WATER USE

Ohio's water budget, shown in Figure 1*A*, is an overview of the approximate proportions of water that entered and left the State in 1985. The amount of water that enters as precipitation and stream inflow equals the amount that leaves the State by evapotranspiration, stream outflow, and consumptive water use. The total budget is 86,500 Mgal/d; incoming water consisted of 74,600 Mgal/d of precipitation and 11,910 Mgal/d of surface-water inflow. Water leaving the State consisted of 53,000 Mgal/d of evapotranspiration, 33,100 Mgal/d of surface-water outflow, and 434 Mgal/d of consumptive water use.

Precipitation in northern Ohio ranges from 32 to 34 inches per year, in contrast to the southern counties, where it is 42 inches per year. The northwestern counties have flat topography and runoff is slow; hence, evapotranspiration and infiltration are greater than in the southern and eastern counties, where terrain is more rugged and runoff is more rapid.

Water withdrawals by county for 1985 are presented in figure 2. The largest withdrawals were in Adams, Gallia, Jefferson, and Lucas Counties (fig. 2*A*) for thermoelectric power generation, and totaled more than 6,100 Mgal/d—nearly one-half of the State's total water withdrawals in 1985. Other areas of large withdrawals have large population densities, such as the counties along the northeastern, central, southwestern, and western shores of Lake Erie (fig. 1*D*). The distribution of surface-water withdrawals by county (fig. 2*B*) indicates the availability of surface water along the Ohio River, the Lake Erie shore, and inland reservoirs, mostly in the Ohio River drainage areas. The distribution of ground-water withdrawals by county (fig. 2*C*) indicates the use of water from unconsolidated aquifers in the northeastern, central, and southwestern counties of Ohio.

Surface-water withdrawals by principal drainage basins are shown in figure 3*A*. Of the major river basins, the largest surface-water withdrawals were in the Upper Ohio and the Middle Ohio basins and in the Southern Lake Erie basin. The Upper Ohio and the Middle Ohio basins supplied surface water for thermoelectric power generation, whereas the Southern Lake Erie basin supplied large amounts of surface water for thermoelectric power generation and for public supply.

Ground-water withdrawals by principal aquifer are shown in figure 3*B*. Unconsolidated sand and gravel comprise the most productive aquifers, which yield from 25 to 2,000 gal/min (gallons per minute). These aquifers underlie parts of the counties in the northeast, central, and southwest and the three most northwestern counties. The others are bedrock aquifers that yield from 0 to 500 gal/min; sandstones and carbonates are the most productive. Public suppliers and self-supplied domestic users accounted for 80 percent of all ground water withdrawn in 1985.

The source, use, and disposition of water by public supply, domestic and commercial, industrial and mining, thermoelectric power and agricultural users are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The withdrawal data indicate that 94.3 percent (12,000 Mgal/d) of the water withdrawn in Ohio in 1985 was surface water, whereas 5.7 percent (730 Mgal/d) was ground water. For surface water, less than 0.1 percent (0.40 Mgal/d) was withdrawn for domestic or commercial use, 3.8 percent (452 Mgal/d) for industrial and mining use, 87.5 percent (10,500 Mgal/d) for thermoelectric uses, 0.2 percent (25 Mgal/d) for agricultural use, and 8.5 percent (1,020 Mgal/d) was withdrawn for public supply. The same type of distribution for ground-water withdrawals also is shown. Other withdrawals of water (saline and reclaimed sewage) are not included in figure 4.

The use data indicate that 9.9 percent of all water withdrawn (1,270 Mgal/d) was used for domestic and commercial purposes. Less than 0.1 percent (0.40 Mgal/d) of this amount was self-supplied from surface water, 15.0 percent (190 Mgal/d) was self-supplied from ground water, and 85.0 percent (1,080 Mgal/d) was delivered by public suppliers. In the domestic and commercial category, 8.7 percent (110 Mgal/d) of the water was consumed, and the remaining

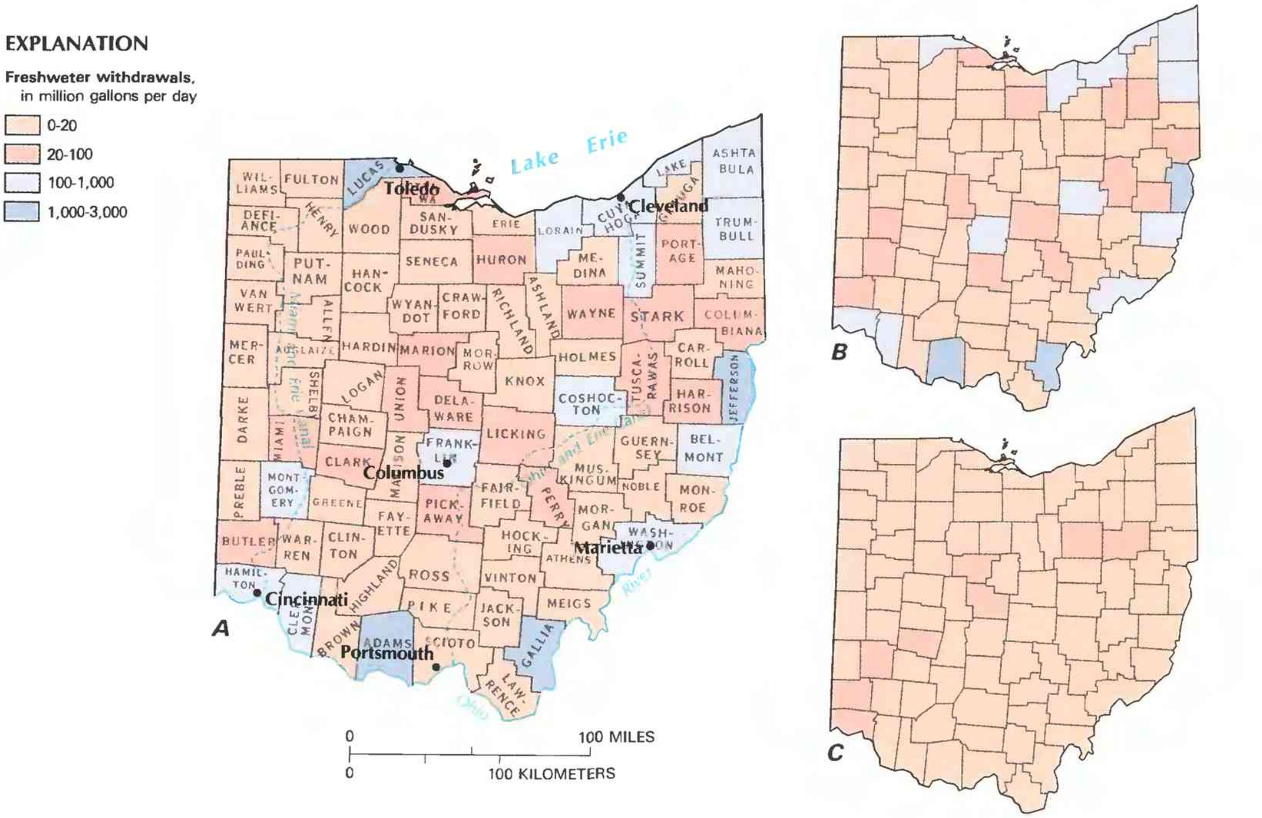


Figure 2. Freshwater withdrawals by county in Ohio, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

91.3 percent (1,160 Mgal/d) was returned to a natural water source and was available for reuse. Industrial and mining, thermoelectric, and agricultural categories in figure 4 may be interpreted in the same manner.

The disposition data indicate that 3.1 percent (396 Mgal/d) of water withdrawn was consumed in 1985 in Ohio, and 96.9 percent (12,300 Mgal/d) was returned to a natural water source for reuse. Instream uses of water, such as hydroelectric power generation, are not shown in figure 4. One hydroelectric powerplant in Meigs County used 8,290 Mgal/d to generate 169 GWh (gigawatthours) of electricity in 1985.

PUBLIC SUPPLY

Public-supply systems withdraw water, treat it, and distribute it to users. Public-supply facilities in Ohio withdrew 1,420 Mgal/d in 1985. The State ranked seventh in the Nation in public-supply withdrawals and sixth in the number of people served (8.9 million) (Solley and others, 1988). Total withdrawals by public supply consisted of 1,020 Mgal/d of surface water and 395 Mgal/d of ground water.

Availability of surface water and ground water of suitable quality determines the dominant water source in a given area of the State. The southwestern counties are underlain by unconsolidated buried-valley aquifers that produce one-half of the public-supply water in that area. The northeastern and central counties also are underlain by buried-valley aquifers, but the public suppliers are less dependent on ground water. The central, northern, and northwestern counties primarily depend on surface water for public supplies. The eastern, southeastern, and southern counties withdrew mostly ground water for public supplies because demands are relatively small and within the yield capability of available aquifers.

DOMESTIC AND COMMERCIAL

Domestic and commercial water users received water from public supplies and self-supplied systems. Total domestic and commercial use was 1,270 Mgal/d (fig. 4) in 1985. Of this total, 283 Mgal/d was for public use, such as fire fighting, or was lost in public-supply distribution systems. Self-supplied surface-water withdrawals accounted for less than 0.1 percent of the total water used for all domestic and commercial purposes; self-supplied ground-water withdrawals accounted for 15.0 percent; and the remaining 85.0 percent was delivered by public suppliers. During use, 8.7 percent of the water was consumed; after use, 91.3 percent was returned to natural sources.

Withdrawals and deliveries for domestic use totaled 606 Mgal/d in 1985. Of this total, 467 Mgal/d served 83 percent of the population and was delivered from public-supply systems, and the other 17 percent of the population depended on self-supplied water (139 Mgal/d), primarily from ground-water sources. The total consumptive use by domestic users was estimated to be 91 Mgal/d in 1985.

Withdrawals and deliveries for commercial use in 1985 totaled 377 Mgal/d. Public supplies provided 326 Mgal/d, and 51 Mgal/d was withdrawn by self-supplied facilities. Total consumptive use by commercial users was estimated to have been 19 Mgal/d.

INDUSTRIAL AND MINING

Industrial and mining use totaled 881 Mgal/d in 1985, or 6.9 percent of the total water used in Ohio. Of all industrial and mining water needs, 51.3 percent was self-supplied from surface water, 10.1 percent was self-supplied from ground water, and 38.6 percent was from public suppliers. Industrial water use totaled 802 Mgal/d, and mining water use was 78 Mgal/d. Mining also used an estimated 0.1 Mgal/d of saline ground water, which is not included in figure 4.

Industrial and mining consumptive water use was 167 Mgal/d, or 42.1 percent of all consumptive use, and return flow was 714 Mgal/d, or 5.8 percent of all return flow. Industrial users consumed the largest amount of freshwater in 1985—156 Mgal/d, or 39.4 percent of the State's total consumptive use.

Forestry and mining are the main industrial and mining water users in the southeastern counties, and the manufacture of fabricated metal products and nonelectrical machinery products are the main industrial water users in the other counties (Harris, 1985). Significant industrial water use in the northeastern counties also was for primary metal industries and for the stone-clay-concrete and petroleum industries in the central and northwestern counties.

Thermoelectric Power

In 1985, Ohio had 34 operating thermoelectric powerplants, 33 fossil-fuel generators, and 1 nuclear generator. These powerplants used 10,500 Mgal/d of water—82.7 percent of all water used (fig. 4)—and produced more than 111,000 GWh of electricity. The

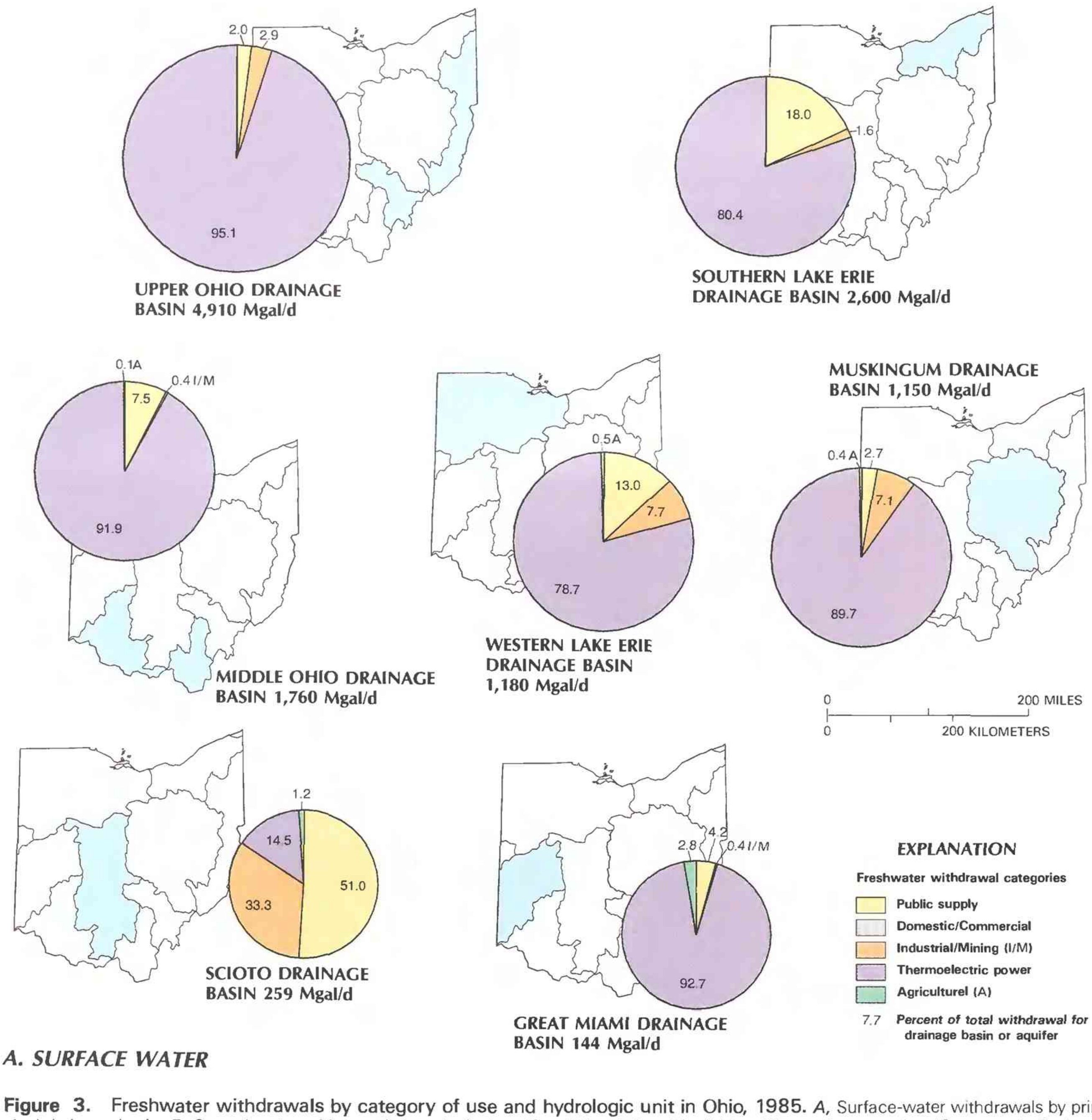


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Ohio, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files.)

nuclear plant used nearly 23 Mgal/d of water and produced almost 2,000 GWh of electricity. Self-supplied surface water accounted for 99.8 percent of the water used for thermoelectric power generation. The total consumptive use was 64 Mgal/d, which was 0.6 percent of all the water used for thermoelectric power generation. Return flow amounted to 10,500 Mgal/d, or 84.8 percent of all water returned to natural sources for reuse.

AGRICULTURAL

In 1985, agricultural water use was 57 Mgal/d, or 0.4 percent of the total water used in Ohio. Surface-water sources supplied 43.8 percent (25 Mgal/d) (fig. 4) of agricultural use, and ground-water sources supplied 56.2 percent (32 Mgal/d).

Agricultural water used for purposes other than irrigation (livestock watering; cleaning and cooling of livestock, equipment, and buildings; and processing of livestock products and produce) amounted to 71 percent (41 Mgal/d) of all agricultural use. About 29 percent (17 Mgal/d) was used for crop irrigation. Less than 0.3 percent of Ohio's farm acreage was reported to be irrigated in 1985. An estimated 96.8 percent of all agricultural water was consumed (fig. 4).

WATER MANAGEMENT

The Ohio Environmental Protection Agency (EPA) is the principal regulatory agency for water quality in Ohio and is the State

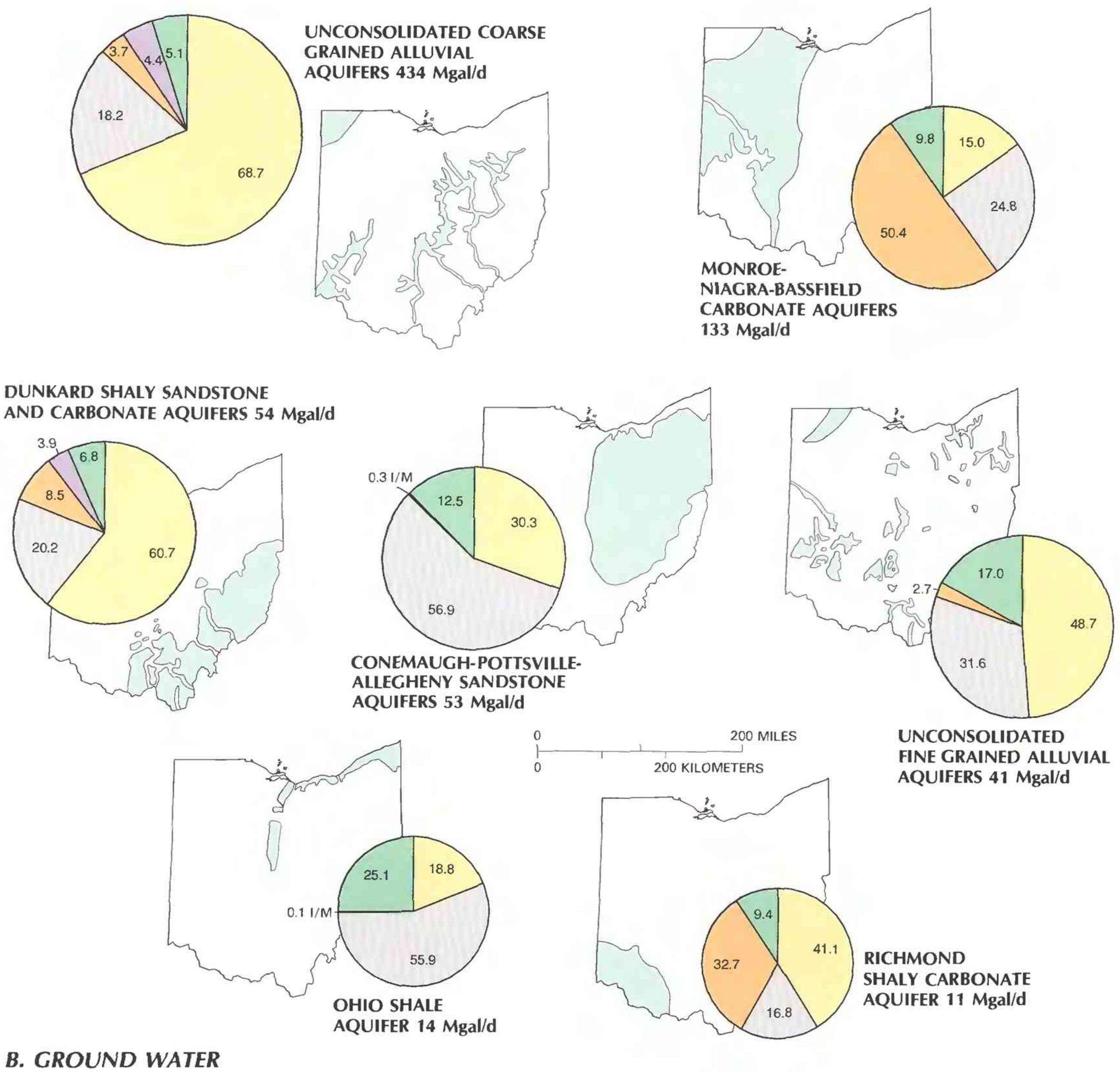


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Ohio, 1985—Continued.

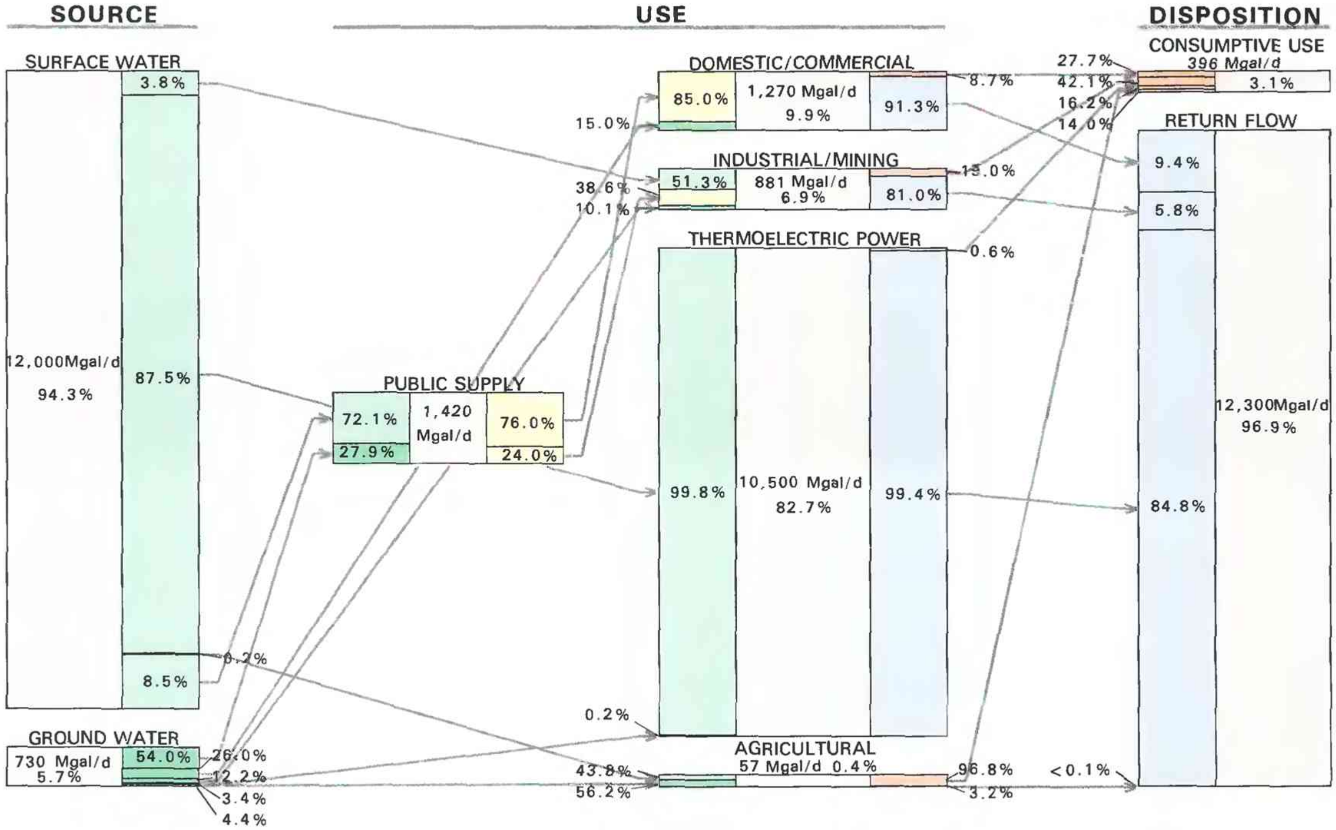


Figure 4. Source, use, and disposition of an estimated 12,700 Mgal/d (million gallons per day) of freshwater in Ohio, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Administrator of PL 95-217—the Clean Water Act. The Ohio EPA Division of Public Water Supply reviews plans and issues plan approvals for construction of all public water systems and oversees compliance with and monitoring of maximum contaminant levels for public drinking water. The Division of Public Water Supply also has primary responsibility for onsite sanitary survey investigations of public water systems and maintains a laboratory-certification program for commercial, private, State, and industrial facilities conducting biological or chemical analyses of potable water. The Ohio EPA Division of Wastewater Pollution Control issues National Pollution Discharge Elimination System Permits and enforces the requirements for industrial wastewater facilities and public sewage systems.

The Ohio EPA Office of Planning oversees nonpoint-source pollution control planning and develops the Ohio Nonpoint Source Assessment and Management Program, as identified in the Water Quality Act PL 100-4 (Clean Water Act Amendments). It also develops and manages the Agency's geographic information system, which accesses most of its water- and land-related data bases. The Office of Planning also works closely with Ohio Water Quality Management Plan Basin Policy Advisory Committees, which include citizens and local and regional officials.

The Ohio EPA Office of Emergency Response reacts to toxic spills and assists in the cleanup of spills and other sudden releases that may affect water. In cooperation with other State water-management agencies, the Ohio EPA encourages local governments to provide more effective water protection and management.

The Ohio Department of Natural Resources, through its Division of Water, has primary responsibility for investigations related to public water supplies and to the distribution of water-resources information. The Division of Water coordinates State and regional water-resources programs, such as water planning, coastal management, dam safety, ground- and surface-water inventories, and flood-plain management. The Division of Water also coordinates with the U.S. Army Corps of Engineers in preparing regional plans and projects for water management. The Ohio Department of Natural Resources, Division of Oil and Gas, administers the State's injection-well control program.

The Ohio Department of Health regulates the design and permitting of private residential water-supply and waste-disposal systems. It also administers a water-well permit system and a local inspection and sampling program, in cooperation with local health departments, for private water supplies.

The U.S. Soil Conservation Service furnishes water conservation information to all Ohio residents through their local county soil and water conservation districts. It also helps plan and complete small flood prevention and watershed-protection programs under Federal Public Law 83-566.

In 1948, the Ohio River Valley Water Sanitation Commission was organized among the eight States located within the Ohio River drainage area. This committee's charge is to protect the water quality of the Ohio River by guiding and overseeing improvements to wastewater-discharge facilities and suggesting uniformity and continuity among the State's pollution-restriction regulations.

Reaeration study on the Scioto River downstream from Columbus, Ohio to determine the capability of the water to absorb gasses. The water is to be used by an upstream water treatment plant. The dye is harmless but brilliant red for detection at concentrations as small as 1 part per million. (Photograph by Janet Hern.)

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Prepared by Vance E. Nichols

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 975 West Third Avenue, Columbus, OH 43212

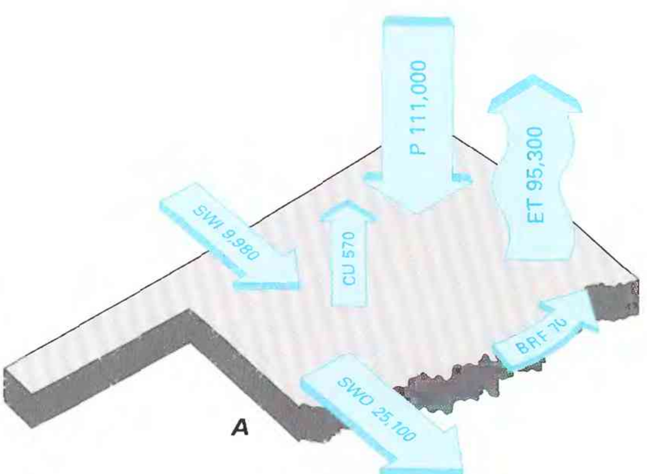
OKLAHOMA
Water Supply and Use

The water budget for Oklahoma (fig. 1A) indicates the average daily gains and losses of water by various natural and human-caused processes. About 8 percent or 9,980 Mgal/d (million gallons per day) of the available water is from surface-water inflows; the remaining 92 percent, or 111,000 Mgal/d, is from precipitation. Average annual precipitation in Oklahoma ranges from about 16 inches in the west to about 50 inches in the east (U.S. Geological Survey, 1986). During 1985, about 1,280 Mgal/d of freshwater was withdrawn from rivers, reservoirs, and aquifers in Oklahoma. Of that quantity, 576 Mgal/d (45.2 percent) was consumed, and the remaining 699 Mgal/d (54.8 percent) was returned to the hydrologic environment. Although consumptive use may be a large part of the total water withdrawn, consumptive use represents only a small part of total losses in the water budget. In fact, consumptive use is less than 1 percent of the total water budget, whereas evapotranspiration is about 79 percent of the total water budget. Surface-water outflows from the State are about 21 percent (25,100 Mgal/d) of the water budget. Surface-water outflows are about 2.5 times larger than surface-water inflows to the State.

The eastern part of Oklahoma relies primarily on plentiful surface-water supplies, whereas the western part relies primarily on ground-water resources. Major withdrawals in the eastern part of the State were from surface-water sources and were used for the public supplies of Oklahoma City and Tulsa, thermoelectric power generation, and pulp and paper manufacturing. Major withdrawals in the western part of the State were from ground-water sources and were used for irrigation; the largest withdrawals were in the Oklahoma panhandle, which overlies the High Plains aquifer.

During 1985, more water was withdrawn for public supply than for any other offstream water use category; withdrawals for this purpose amounted to about 521 Mgal/d, which was mostly from surface-water sources. The next major offstream water use category was agriculture, including irrigation; withdrawals for this purpose amounted to 450 Mgal/d, mostly from ground-water sources. The combined withdrawals for three other water use categories—domestic and commercial, industrial and mining, and thermoelectric power generation—were 825 Mgal/d.

Population projections for Oklahoma indicate a 13-percent increase in population by the year 2000 (Oklahoma Employment Security Commission, 1981). Most of this increase probably will occur in the major urban areas of the State. These areas already rely on large transfers of surface water to meet water-supply demands. Demand for ground water in the State also will increase. Water levels in areas of some aquifers already have been lowered to the point that use of the aquifers for water supply is no longer economically



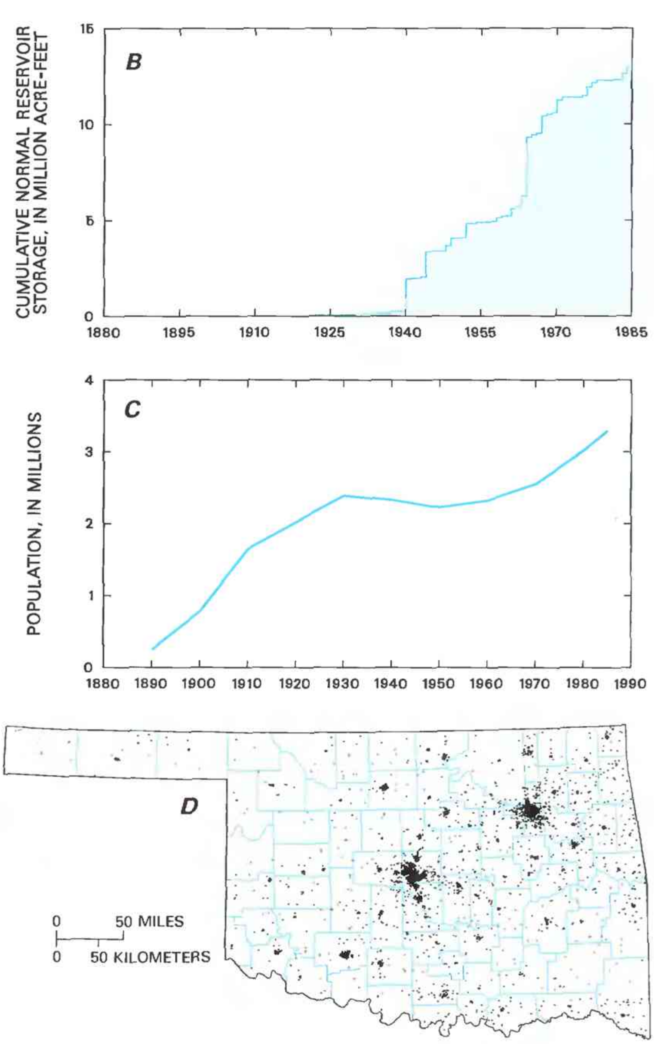


Figure 1. Water supply and population in Oklahoma. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Oklahoma Water Resources Board, 1984; compiled by U.S. Geological Survey from Oklahoma Water Resources Board and U.S. Geological Survey data: *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

feasible. Careful planning will be needed to ensure that future water demands are met with an adequate supply of surface and ground water.

HISTORY OF WATER DEVELOPMENT

The settlement of Oklahoma by people other than the Native Americans began in the 1860's. By the 1920's, the population had increased greatly, and reservoirs were constructed to serve Oklahoma City and Tulsa (fig. 1*B*). Drought combined with farming and ranching practices caused the dust bowl in Oklahoma during the 1930's, and the population decreased as thousands of people migrated westward looking for new land and a better life (fig. 1*C*). During the 1940's, Oklahoma implemented water-resources and soil-conservation programs that helped create a positive population trend beginning in the early 1950's. Population centers (fig. 1*D*) expanded along the major rivers—Oklahoma City on the Canadian and Tulsa on the Arkansas.

The River and Harbor Act, which was passed by Congress in 1946, authorized development of an inland waterway in Oklahoma and Arkansas. Completed in 1971, the McClellan-Kerr Arkansas River Navigation System connects Oklahoma with the Gulf of Mexico and provides flood control and inland navigation. Nine reservoirs in eastern Oklahoma store water for the operation of the McClellan-Kerr Arkansas River Navigation System. Three of the reservoirs are on the Arkansas River—Robert S. Kerr, Webbers Falls, and Keystone Lake; six reservoirs are on its tributaries—Oolagah Lake on the Verdigris River, Eufaula Lake on the Canadian River, Tenkiller Ferry Lake on the Illinois River, and Lake O' the Cherokees, Lake Hudson, and Fort Gibson Lake on the Grand (Neosho) River (fig. 6).

By 1954, the addition of four new reservoirs—Lake Heyburn in 1950, Hulah Lake in 1951, Tenkiller Ferry Lake in 1952, and Fort Gibson Lake in 1953 (all U.S. Army Corps of Engineers projects)—increased the cumulative normal reservoir storage to about 5 million acre-ft (acre-feet), as shown in figure 1*B*. About 30 reservoirs have been constructed in Oklahoma during the past 25 years. Cumulative normal reservoir storage in 1985 was slightly less than 13 million acre-ft (fig. 1*B*). Six more reservoirs authorized for Federal construction, but not yet funded, could add to the future surface-water supply. They are Tuskahoma Lake on the Kiamichi River in southeastern Oklahoma, Lukfata Lake on Glover Creek in McCurtain County in southeastern Oklahoma, Shidler Lake on Salt Creek in Osage County, Sand Lake on Sand Creek in Osage County, Boswell Lake on Clear Boggy Creek in southeastern Oklahoma, and Parker Lake on Muddy Boggy Creek on the Coal-Hughes County border.

Water resources in Oklahoma also include an estimated 309 million acre-ft of ground water, of which about 40 percent is recoverable. Ground water, particularly in the High Plains aquifer, is the primary source of water for irrigation in western Oklahoma.

WATER USE

The total freshwater withdrawals by county during 1985 are shown in figure 2*A*. Six counties in Oklahoma each withdrew more than 50 Mgal/d; these withdrawals were for public supply for the Oklahoma City and the Tulsa metropolitan areas, irrigation in Texas and Caddo Counties, and thermoelectric power generation in Muskogee County. Because of the uneven distribution of the water resources in the State, counties in eastern Oklahoma generally rely on abundant surface-water resources (fig. 2*B*), whereas counties in western Oklahoma generally rely on ground-water resources because of undependable surface-water supplies (fig. 2*C*).

Surface-water withdrawals during 1985 for each major river basin are shown in figure 3*A*. The largest total surface-water withdrawals (190 Mgal/d) were in the Neosho-Verdigris basin and were used primarily for public supply. The second-largest total surface-water withdrawals (175 Mgal/d) were in the Lower Arkansas basin, where the major water use was thermoelectric power generation. Other basins from which large surface-water withdrawals were made include the Red-Washita basin (110 Mgal/d), the Red-Sulphur (98 Mgal/d), and the Lower Canadian and North Canadian (94 Mgal/d); withdrawals in those areas were used primarily for public supply.

Instream water use was the major use during 1985. Hydroelectric power generation was the major instream water use, accounting for 68,800 Mgal/d to produce 4,010 GWh (gigawatthours) of electricity. Recreation, transportation, and fish and wildlife protection also are important instream uses of water in Oklahoma. However, these uses are small in relation to the instream use of water for hydroelectric power generation. No estimates are readily available for the quantity of these other miscellaneous instream water uses.

Ground-water withdrawals during 1985 from the major aquifers are shown in figure 3*B*. About 44 percent of the ground-water withdrawals in the State was from the High Plains aquifer, and 97.0 percent of the withdrawals from this aquifer was for irrigation. Water from the Dog Creek-Blaine aquifer is unsuitable for drinking because of large concentrations of dissolved-solids—2,000 to 6,000 mg/L (milligrams per liter). All withdrawals from this aquifer were for irrigation. The major use of water from most of the central and eastern aquifers was public supply. Withdrawals from these aquifers have caused declines in water levels. Water levels in some areas of the High Plains aquifer have declined as much as 100 feet since the 1970's because of irrigation (Havens, 1983). Water levels in the Garber-Wellington aquifer, which is used primarily for public supply in the Oklahoma City metropolitan area, have declined as much as 200 feet in some areas since the early 1940's (Wood and Burton, 1968).

Water quality is an important factor affecting the use of water in Oklahoma. In general, surface water in the western part of the State is unsuitable for public supply because of large concentrations of dissolved minerals. Therefore, water for public supply is obtained from aquifers or major reservoirs developed on streams containing water of acceptable quality. Some major aquifers, such as the Dog Creek-Blaine, do not yield potable water, and others, such as the Arbuckle-Timbered Hills aquifer, produce water that contains as much as 35 mg/L of fluoride. Water quality does not restrict the use of most water-supply sources in the eastern part of the State. However, most freshwater in Oklahoma is underlain by brine, and overpumping can cause upwelling of brine, which makes the water unsuitable for public supply.

The source, use, and disposition of freshwater in Oklahoma during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate, for example, that surface water supplied 707 Mgal/d, or 55.5 percent of the total freshwater withdrawals. Of that quantity, 58.6 percent of the surface-water withdrawals was withdrawn for public supply, 1.2 percent was withdrawn directly (self-supplied) for domestic and commercial uses, 12.0 percent was self-supplied by industrial and mining facilities, 18.8 percent was self-supplied for thermoelectric power generation, and 9.5 percent was self-supplied for agricultural purposes, including irrigation. The use data indicate that the 317 Mgal/d used for industrial and mining purposes represented 24.9 percent of the total withdrawals in the State. Of that percentage, 26.7 percent (85 Mgal/d) was self-supplied from surface-water sources, 64.4 percent (204 Mgal/d) was from public-supply systems, and 8.9 percent (28 Mgal/d) was self-supplied from ground-water sources. Of the water used for industrial and mining purposes, 8.8 percent (28 Mgal/d) was consumed use, and the remaining 91.2 percent (289 Mgal/d) was returned to the natural surface- or ground-water systems. The disposition data indicate that 45.2 percent (576 Mgal/d) of the total withdrawals was consumed

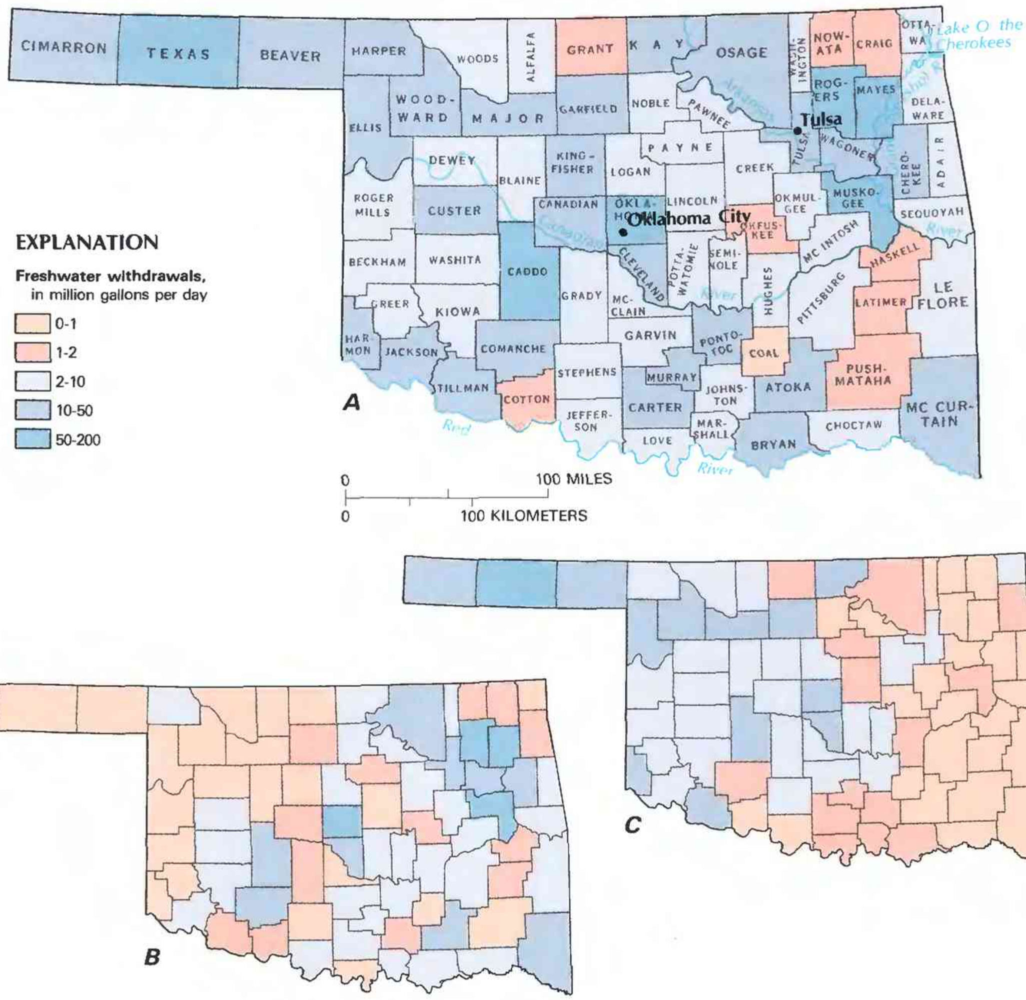


Figure 2. Freshwater withdrawals by county in Oklahoma, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

and 54.8 percent (699 Mgal/d) was returned to the natural water systems after use. These data also indicate that industry and mining were responsible for 4.9 percent (28 Mgal/d) of the total consumptive use and 41.4 percent (289 Mgal/d) of total return flow.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. During 1985, the quantity of water withdrawn for public supply in Oklahoma was 521 Mgal/d, which was the largest amount ever reported for this use and the largest offstream use for the year. The general trend in public-supply use since 1966 is shown in figure 5. Surface water was the source of 79.6 percent (414 Mgal/d) of the water used for public supply.

Oklahoma City and Tulsa were the largest users of water from public suppliers, and both relied extensively on surface-water interbasin transfers for their water supplies. Oklahoma City pumps nearly 20 Mgal/d from Atoka Reservoir, located about 130 miles southeast of Oklahoma City, into Stanley Draper Lake, which serves as the storage facility for the imported water. The newly constructed McGee Creek Reservoir in the same general area also will serve as a water-supply source for Oklahoma City. Oklahoma City also diverts water from the Canadian River into Lake Overholser and Lake Hefner for public-supply purposes. Tulsa obtains most of its public-water supply by transfers from Spavinaw and Oolagah Lakes. These and other surface-water resource developments in Oklahoma are shown in figure 6.

Population projections indicate that about 90 percent of the population increase in the State through the year 2000 will be in urban areas (Oklahoma Employment Security Commission, 1981). If the projections are accurate, then public-supply withdrawals, as well as a corresponding increase in surface-water withdrawals, will continue to increase. This increase would result in additional demand on reservoirs that already provide most of the water for public supply.

DOMESTIC AND COMMERCIAL

Withdrawal of water for domestic use is the only consumptive use category in Oklahoma that does not require a permit; therefore, domestic water use was estimated by using population figures and an estimated water use rate of 56 gallons per day per capita (Stoner, 1984). The estimated 1985 domestic water use in Oklahoma was 185 Mgal/d. Of this 185 Mgal/d, 85.4 percent was from public supplies, and the remainder was self-supplied. Oklahoma City and Tulsa accounted for 19 and 15 percent, respectively, of the total domestic water use in the State. Consumptive use was estimated to be 56 Mgal/d.

Commercial water use, discounting delivery losses, totaled 90 Mgal/d during 1985. About 65 percent of this water was from public supplies, and the remainder was self-supplied. Commercial consumptive use was estimated to be 6.3 Mgal/d. Commercial water use in Oklahoma represents the aggregate water use by many small businesses. Because no major commercial entities in Oklahoma use water, this use is small when compared to the other water-use categories. An additional 97 Mgal/d is used for other purposes, such as fire fighting, or is lost in conveyance.

Industrial and Mining

The total water withdrawals and public-supplied deliveries for industrial and mining use during 1985 were 317 Mgal/d. The largest single use of water for industrial purposes in Oklahoma was for paper production near the southeastern corner of the State. About 95 percent of the water used for paper production is self-supplied from surface-water sources. For the State's total, public-supplied deliveries accounted for 66 percent of the water used for industrial purposes. Water used for mining, primarily for oil and gas production, was 7.1 Mgal/d. Industrial and mining consumptive use was estimated to be 8.8 percent (28 Mgal/d).

Thermoelectric Power

The total withdrawals and deliveries for thermoelectric power generation during 1985 were 136 Mgal/d. Of the water used for this purpose, 97.7 percent was from self-supplied surface-water withdrawals. All 16 thermoelectric powerplants in the State, which are fossil-fueled, generated a total of 40,100 GWh of electricity during 1985. Of the 16 thermoelectric powerplants, 13 use surface water, 2 use ground water, and 1 uses reclaimed sewage wastewater for cooling purposes. Most of the thermoelectric powerplants are in the eastern part of the State.

Agricultural

Since the inception of water-use data collection in the early 1960's, irrigation has been identified as the major agricultural water

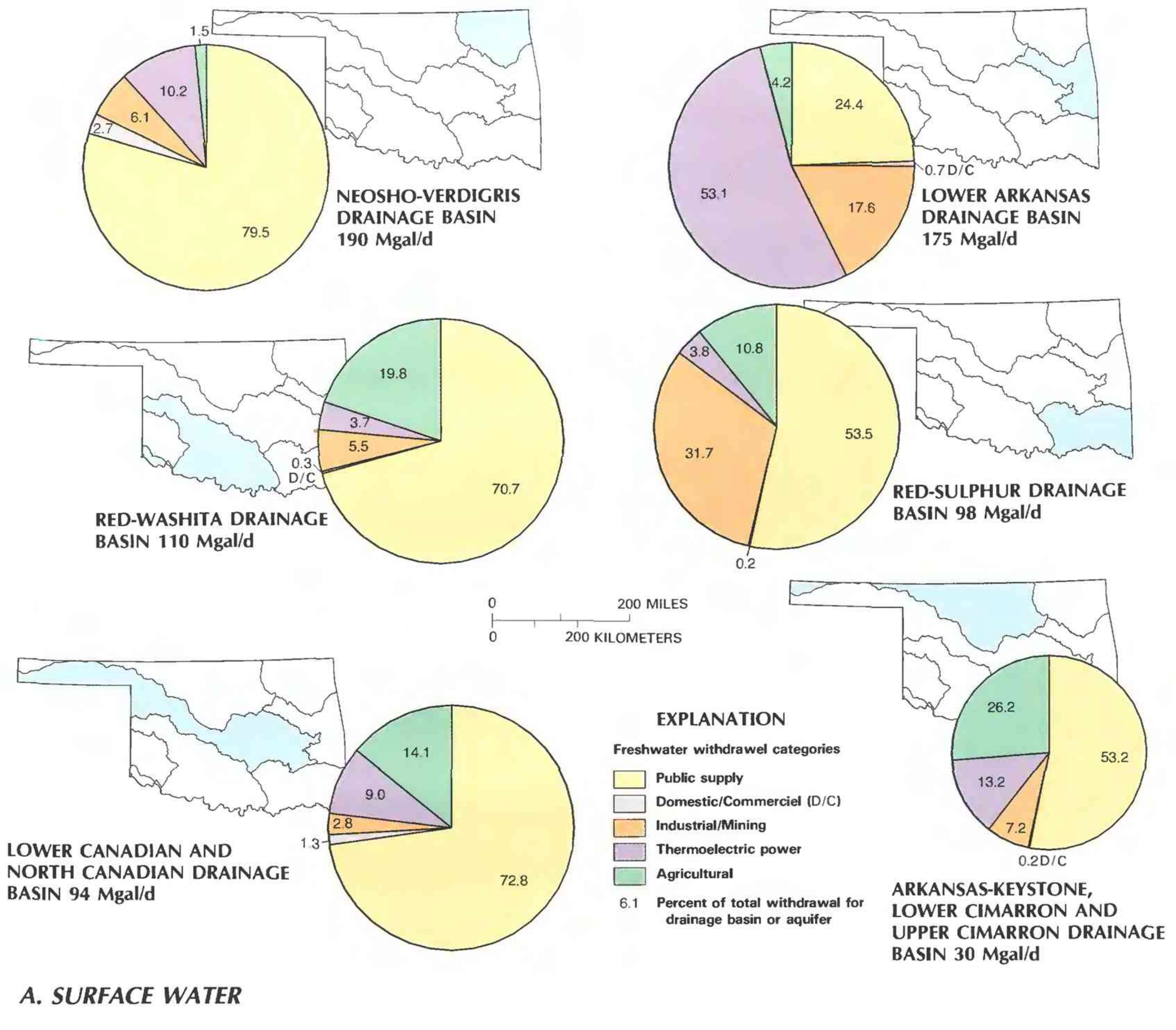


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Oklahoma, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from Oklahoma Water-Use Data System, Oklahoma Water Resources Board; aquifer map from U.S. Geological Survey 1985, p. 181.)

use in the State. Irrigation also was the major offstream water use until 1985. Trends in total irrigation water use and acres irrigated are shown in figure 5. During 1985, irrigation water use was 445 Mgal/d for about 700,000 acres irrigated. The marked decrease in estimated irrigation water use between 1979 and 1980 probably was caused by the implementation of a new, more conservative accounting system than was used in past years (Oklahoma Water Resources Board, 1967–87). Since 1980, the decrease in irrigation water use is due primarily to fewer acres irrigated. The main factors contributing to the decrease in acres irrigated are decreased farm commodity prices; increased energy costs, both in terms of price per unit of energy and increased energy needed to pump the water from greater depths, which results from declining ground-water levels (M.A. Kizer, Oklahoma State University, Cooperative Extension Service, oral commun., 1987); and in some years, rainfall in irrigated areas that have been greater than average. The consumptive use by agriculture was 437 Mgal/d, which represents 98.2 percent of the total water used for this purpose.

About 50 percent of the irrigation withdrawals in the State was in the three panhandle counties of Texas, Beaver, and Cimarron. About 90 percent of the irrigation use was in the western part of the State. About 85 percent of the water used for irrigation was

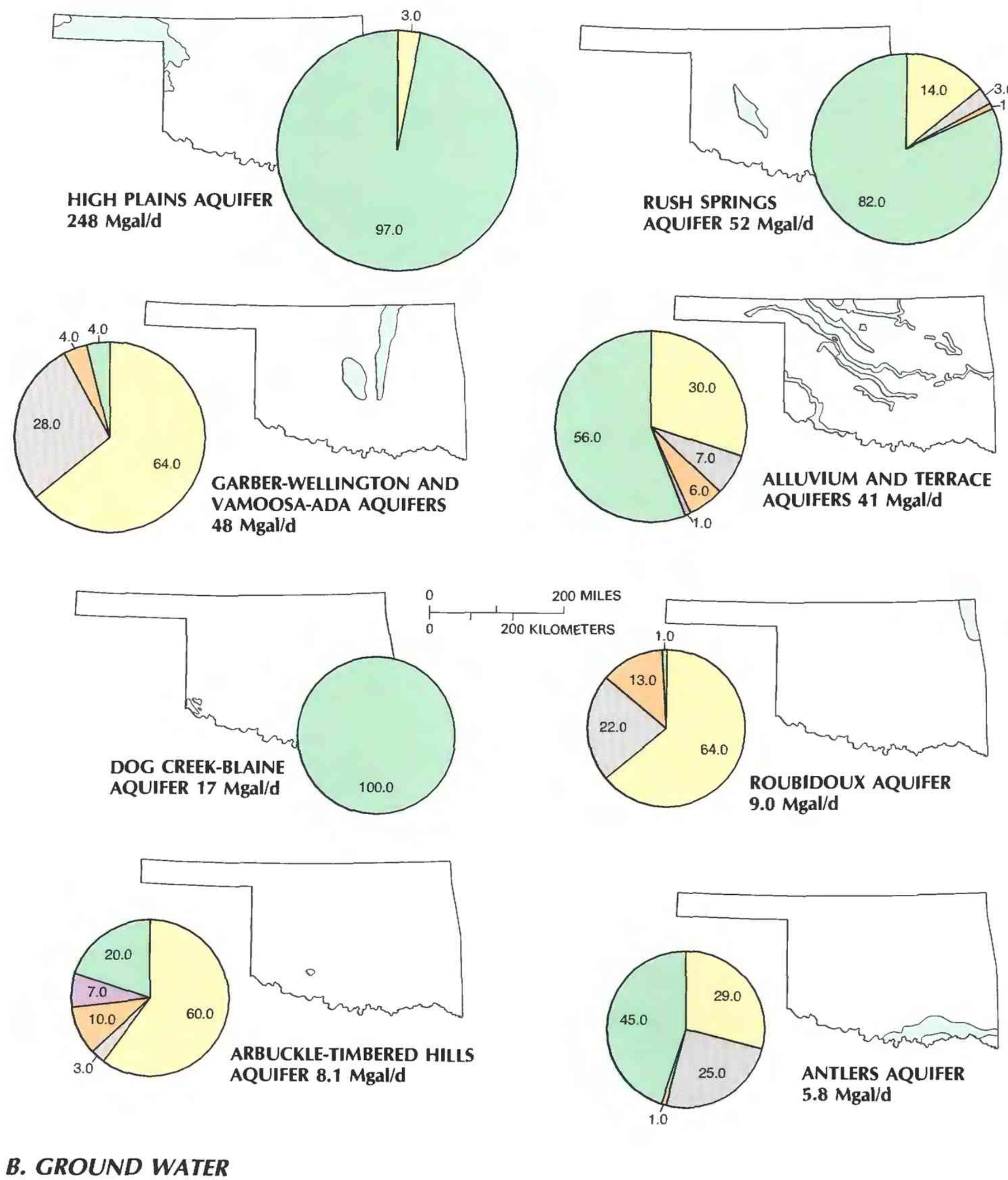


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Oklahoma, 1985—Continued.

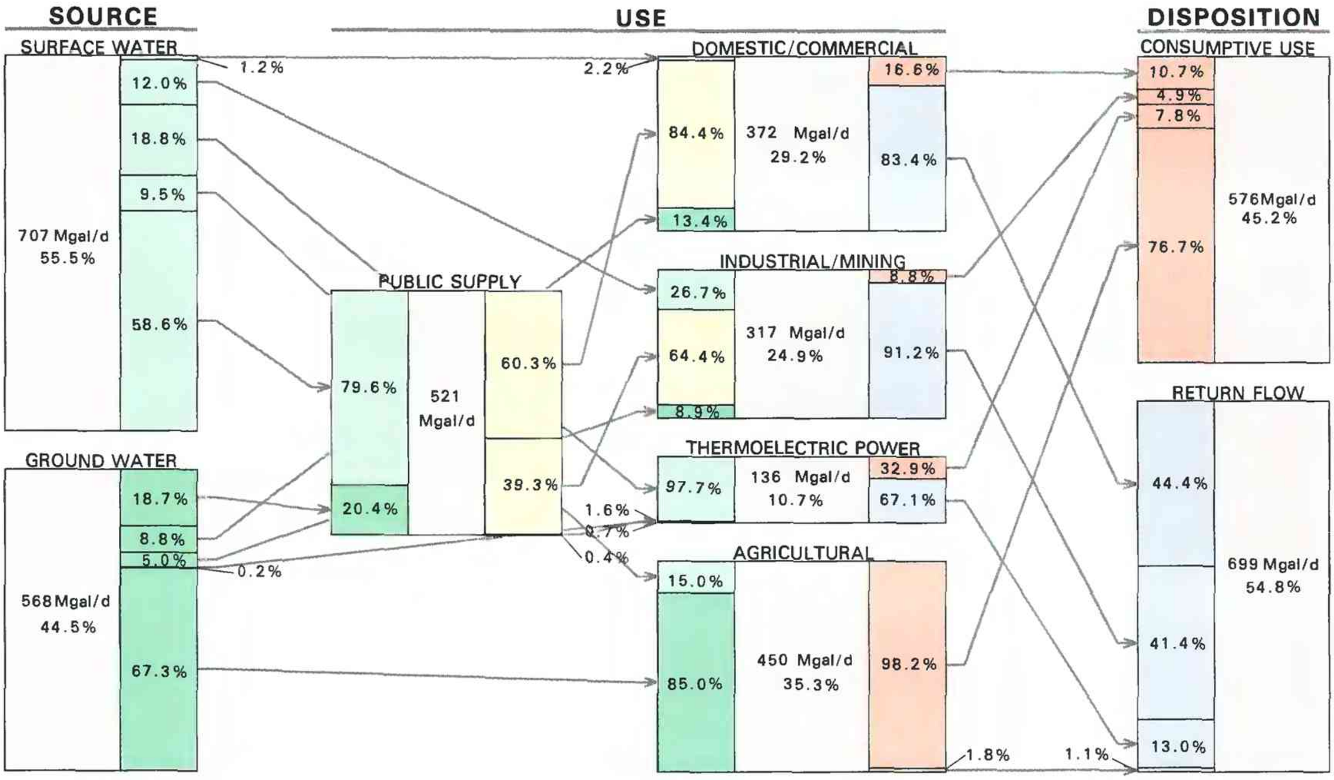


Figure 4. Source, use, and disposition of an estimated 1,280 Mgal/d (million gallons per day) of freshwater in Oklahoma, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

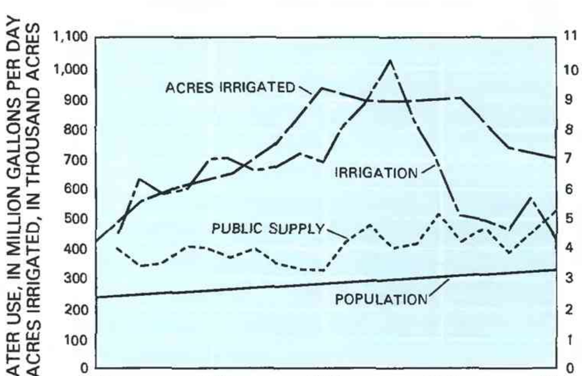


Figure 5. *Major categories of water use in Oklahoma, 1965 to 1985.* (Sources: Irrigation data from Schwab, 1965, 1967–83, Kizer, 1986; water use data from Oklahoma Water Resources Board, 1967–87, and from U.S. Geological Survey National Water Data Storage and Retrieval System; population data compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

ground water; the High Plains aquifer supplied about 63 percent of this total. During 1985, the principal irrigated crops in terms of acres irrigated were wheat, 28 percent; sorghum (both grain and forage), 26 percent; alfalfa, 15 percent; and peanuts, 8 percent (Kizer, 1986).

Self-supplied water for nonirrigation agricultural use was 4.6 Mgal/d during 1985. In the western counties, many of the large feedlots are supplied by public-supply systems and rural water districts; this use is not accounted for in the 4.6 Mgal/d. Also, the quantity of water supplied to pasture taps by rural water districts is not known. The most reasonable estimate of total nonirrigation water use from these sources is about 10 Mgal/d.

WATER MANAGEMENT

The use of surface water in Oklahoma is governed by the doctrine of prior appropriation (State of Oklahoma, 1981a) The major features of the Ground Water Law (State of Oklahoma, 1981b) combine aspects of individual property ownership and the regulatory aspects of reasonable use and regulation of ground water.

The Oklahoma Water Resources Board administers permits for surface- and ground-water withdrawals and is responsible for planning long-range needs. As a provision of the permit, annual water use reports are required of each permit holder on forms supplied by the Oklahoma Water Resources Board in January. Only domestic use is exempt from permit requirements.

The statutory system to regulate ground-water use in Oklahoma underwent a major revision in 1972. The current regulatory system consists of the 1972 framework, with only minor amendments since. Hydrologic surveys of each ground-water basin or subbasin containing freshwater are required to determine the maximum annual yield—the quantity of water that can be removed from the basin during a minimum of 20 years. These surveys are updated at least once every 10 years. Since 1982, a well driller's log and well-completion report for any water well drilled in the State must be filed with the Oklahoma Water Resources Board.

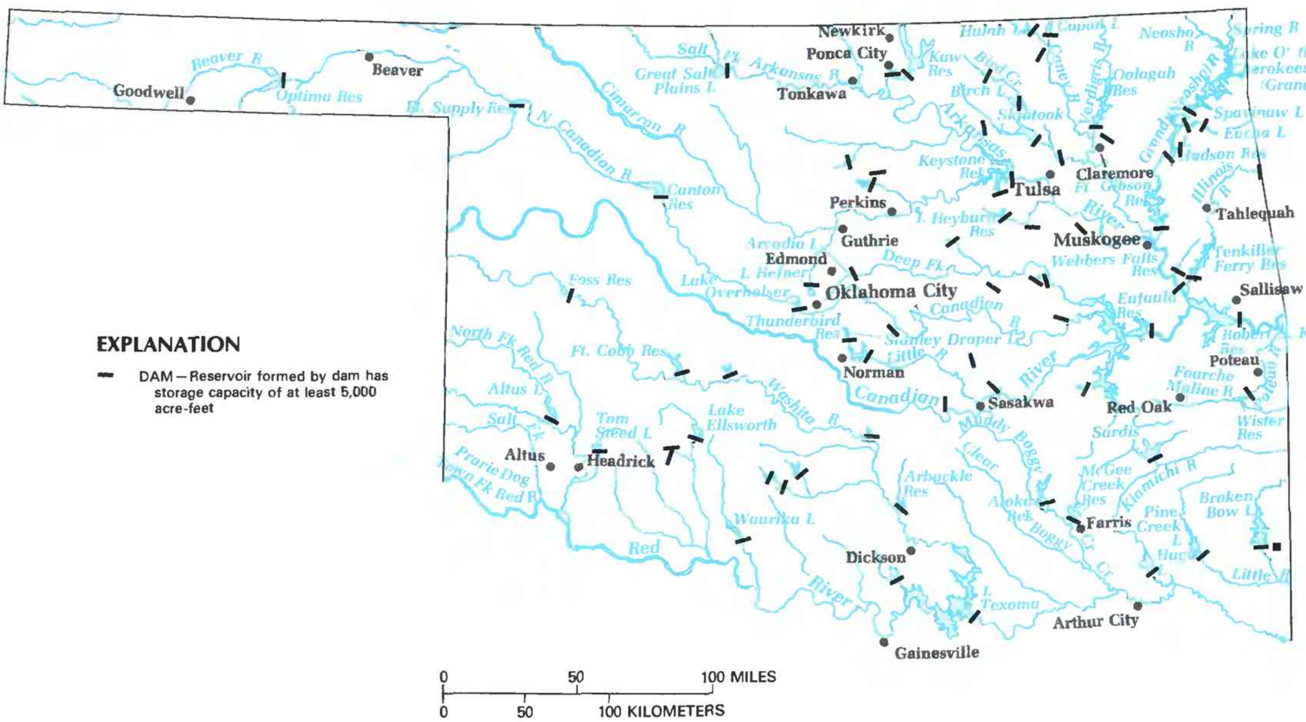


Figure 6. Surface-water resource developments in Oklahoma. (Source: Hitt, 1985.)

Oklahoma statutes require hydrologic studies of each stream system to determine the total quantity of unappropriated stream water. These studies also are regularly updated. One aspect of the Stream Water Law requires that all permits be reviewed annually. Permit holders who do not completely use the authorized quantity within a continuous 7-year period are subject to a decrease in withdrawal or cancellation of the permit. The water that is released then reverts to the public domain and is again available for appropriation.

A few stream systems in southwestern Oklahoma are fully appropriated, and restrictions apply on withdrawals from streams in other parts of the State. Stream-water permits are not required in the Grand (Neosho) River drainage basin, which is under the jurisdiction of the Grand River Dam Authority.

Water use forecasts prepared during the formulation of the State Water Plan predict water shortages in five of the eight planning regions in the State by the year 2040. During seasonal drought emergencies, local governments restrict water use and curb demand. Water resources in the three easternmost regions probably will be adequate to satisfy the entire demand through the planning period.

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Prepared by David C. Heimann and Jerry D. Stoner, U.S. Geological Survey; History of Water Development section by Elizabeth M. McTernan, Oklahoma Water Resources Research Institute; Water Management section by James W. Schuelein, Oklahoma Water Resources Board

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 215 Dean A. McGee Avenue, Room 621, Oklahoma City, OK 73102

OREGON
Water Supply and Use

The Cascade Range, which extends approximately from Hood River to Klamath Falls, divides Oregon into two distinct climatic zones, each having different water supplies and demands. Statewide, the average annual precipitation is 27 inches; this amount is equivalent to 124,000 Mgal/d (million gallons per day) (fig. 1*A*). However, areas to the west of the Cascades (western Oregon) average between 40 and 140 inches, whereas areas to the east (eastern Oregon) average between 10 and 20 inches (Phillips and others, 1965).

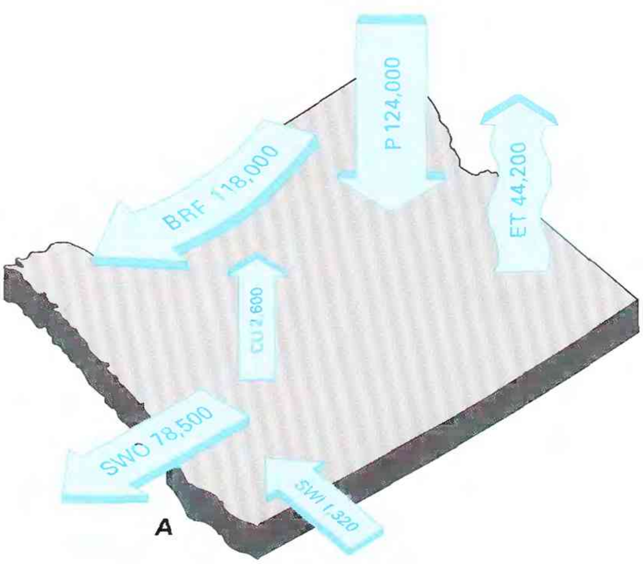
Of the estimated 6,540 Mgal/d of water withdrawn in 1985, 89.9 percent was from surface-water sources and 10.1 percent was from ground-water sources (Solley and others, 1988). Eastern Oregon accounted for 80 percent (5,230 Mgal/d) of these withdrawals. Thus, the demand is greatest in a part of the State where supplies are the most limited. Of the total withdrawals, 39.7 percent (2,600 Mgal/d) was consumed, and 60.3 percent (3,940 Mgal/d) was returned to streams and ground water.

In 1985, 87 percent of the 2.69 million residents lived west of the Cascade Mountains, primarily in the Willamette River valley. Of the withdrawals in this valley, 64 percent was for industrial, domestic, and commercial uses. East of the Cascade Mountains, 97 percent of the withdrawals was for irrigation. Of the irrigated lands, 81 percent was in eastern Oregon.

Since 1980, the population of Oregon has increased by 19,500 inhabitants, or about 0.7 percent (Portland State University, 1986). As a result of this slow growth, coupled with a decrease in the amount of irrigated acreage, the demand for water statewide has increased only slightly since 1980.

HISTORY OF WATER DEVELOPMENT

Water has been important to Oregon's settlement. About 7,000 years ago, Native Americans began living along the banks of the Columbia River to take advantage of the abundant fish resources and the transportation opportunities (Loy, 1977). When the first European trading posts were established in the area during the early 1800's, they were located along the Columbia and the Willamette Rivers.



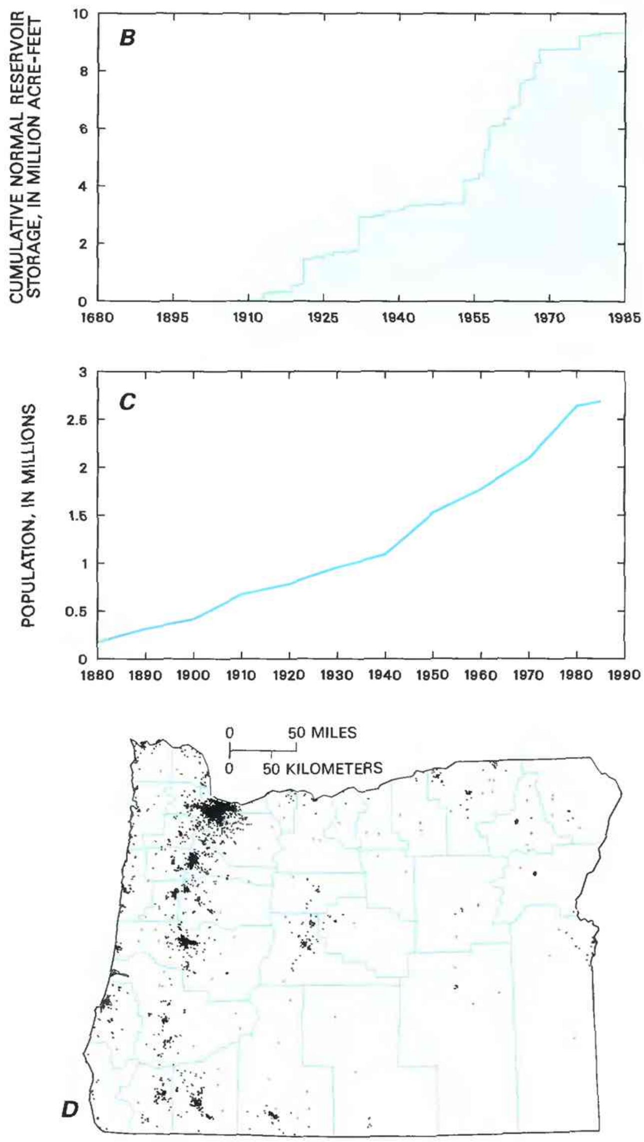


Figure 1. Water supply and population in Oregon. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Phillips and others, 1965; Hubbard and others, 1986a; 1986b; California Department of Water Resources, 1983. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Inspired by the availability of free land from the U.S. Government, settlers began migrating to Oregon in 1841, primarily along the Oregon Trail. Most of these pioneers settled along waterways of the Willamette basin. These waterways served as a means of transportation and as a source of power. After the introduction of the steamship to the Willamette River in 1850, settlement along the river and its tributaries increased rapidly. By 1859, as many as 30 towns had been platted next to these waterways to take advantage of scheduled steamship runs as far inland as Eugene. After the introduction of a railroad line from Portland to Eugene in 1870, however, the importance of river transportation decreased, and most of the towns founded after this date were built away from the banks of the rivers (Loy, 1977).

The discovery of gold in southwestern and eastern Oregon during the 1850's and 1860's was a catalyst for the development of regions outside of the Willamette River valley. The large movement of miners into these remote areas necessitated the development of a local food source. However, extensive crop production using dryland farming methods was not feasible in these arid and semiarid regions, and the practice of diverting streams to irrigate fields was begun.

As the railroad and the availability of land brought additional settlers into southwestern and eastern Oregon, the number of stream diversions for irrigation increased. Irrigation districts and ditch companies were formed in Deschutes, Umatilla, Malheur, and Josephine Counties to construct small-scale storage and diversion projects. The biggest boost to irrigation development, however, resulted from the passage of the National Reclamation Act of 1902. This Act gave the Federal Government the authority to assist in the construction of large irrigation projects in the Western United States. Between 1908 and 1921, the U.S. Bureau of Reclamation constructed six such projects in Oregon; they are located in Umatilla, Deschutes, Klamath, Jackson, Malheur, and Crook Counties.

In 1890, the first long-distance electrical transmission line in the United States was constructed between a hydroelectric power-generating facility at Oregon City and Portland. Since that time, hydroelectric power has been significant in the growth and settlement of the State. In 1937, the construction of Bonneville Dam on the Columbia River (Multnomah County) by the U.S. Corps of Engineers not only increased the amount of normal reservoir storage (fig. 1*B*), but also provided a large supply of inexpensive electricity to the region. Such a supply encouraged large electrical users, like the aluminum industry, to locate along the lower Columbia River. During World War II, the presence of the aluminum industry, coupled with the presence of a port facility, made the Portland area an important center for aircraft-materials manufacturing and ship construction (Pacific Northwest River Basins Commission, 1969). This development brought about a rapid increase in the State's population during the 1940's (figs. 1*C,D*).

Dams continue to be important to the economic development of Oregon. In addition to hydroelectric power generation and navigation, some of the major dams in the western part of the State provide flood-crest reduction and low-flow augmentation by storing the high runoffs of the winter and spring for release during the low-flow periods of summer and fall. However, these benefits have not been without cost. The construction of dams on free-flowing rivers has affected esthetics, whitewater recreational opportunities, water quality, land use, and anadromous fish populations (anadromous fish hatch in freshwater, mature in saltwater, and return to spawn in freshwater). Economic, environmental, and political concerns over protection of anadromous fish now place increasing constraints on the construction of dams on streams that contain these fish.

WATER USE

The areas of the State that have the largest supplies of water commonly are not the areas where demands are largest. The water budget (fig. 1*A*) shows that the major source of water is precipitation. Most precipitation occurs in western Oregon. Water also is available locally from boundary rivers (the Columbia and the Snake). Some of the areas of greatest demand, however, are in eastern Oregon (fig. 2*A*), where there are few rivers and little precipitation.

Agriculture, primarily irrigation, is the largest water use; consequently, the counties that have large irrigated acreage also are those that have large total withdrawals (fig. 2*A*). However, in some western counties (Clackamas, Multnomah, and Clatsop), the large withdrawals are indicative of large public-supply and industrial demands. Because surface water comprises 89.9 percent of the total withdrawals, the distribution of surface-water withdrawals (fig. 2*B*) resembles the distribution of total withdrawals (fig. 2*A*). The remaining 10.1 percent of the total withdrawals are from ground water. The counties that have the largest ground-water withdrawals (fig. 2*C*) use substantial amounts of water for irrigation.

Agriculture (mostly irrigation) is the largest user of surface water (fig. 3*A*). The Willamette basin is an exception to this generalization because withdrawals for agricultural, public-supply, and industrial and mining categories are about the same. An estimated 505 Mgal/d (about 77 percent) of the ground water withdrawn in the State (fig. 3*B*) comes from the basin fill and alluvial aquifers.

Instream uses also are important considerations when evaluating water supply in Oregon. During 1985, 437,000 Mgal/d was used by hydroelectric powerplants to produce 45,700 GWh (gigawatthours) of electricity. This use was roughly 67 times the amount of water withdrawn for all offstream uses combined. The flows of the Columbia, the Willamette, and the Snake Rivers must be sufficiently maintained to allow passage of ocean-going vessels as far inland as Portland and barge traffic as far inland as the Washington–Idaho border. Instream flows also are necessary for the maintenance of fish habitat and water quality. Because the anadromous fish population depends on adequate streamflow and temperature for migration and spawning, storage facilities often must release water to maintain the necessary habitat.

Sewage treatment plants and other facilities that discharge treated waste also depend on adequate surface-water flows for the dilution of their discharges. Beginning in the 1950's, augmentation of summer low flows on the Willamette River by upstream storage facilities contributed significantly to the improvement of the river's quality (Gleeson, 1972). Today, sewage-treatment plants that discharge into certain tributaries of the Willamette are not allowed to release effluent during the summer, and must either store the effluent or use it for irrigation.

The source, use, and disposition of water in Oregon in 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to totals indicated because of independent rounding. Surface water was the source for most withdrawals in every category of use. Agriculture used 87.6 percent (5,730 Mgal/d) of the water withdrawn and accounted for 95.2 percent (2,480 Mgal/d) of consumptive use.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. Most of the withdrawals for public supply are from surface-water sources (figs. 4 and 5*A*), especially in western Oregon, where streamflow is usually of sufficient quantity and quality and the majority of the State's population resides. A larger number of systems, however, rely on ground water as their primary source, as is shown in figure 5*B*. These tend to be smaller systems in the drier parts of the State, where reliance on ground water generally is due to the small quantity of potable surface water.

Many public water systems in western Oregon withdraw their water from headwater regions of rivers. Laws have been passed to

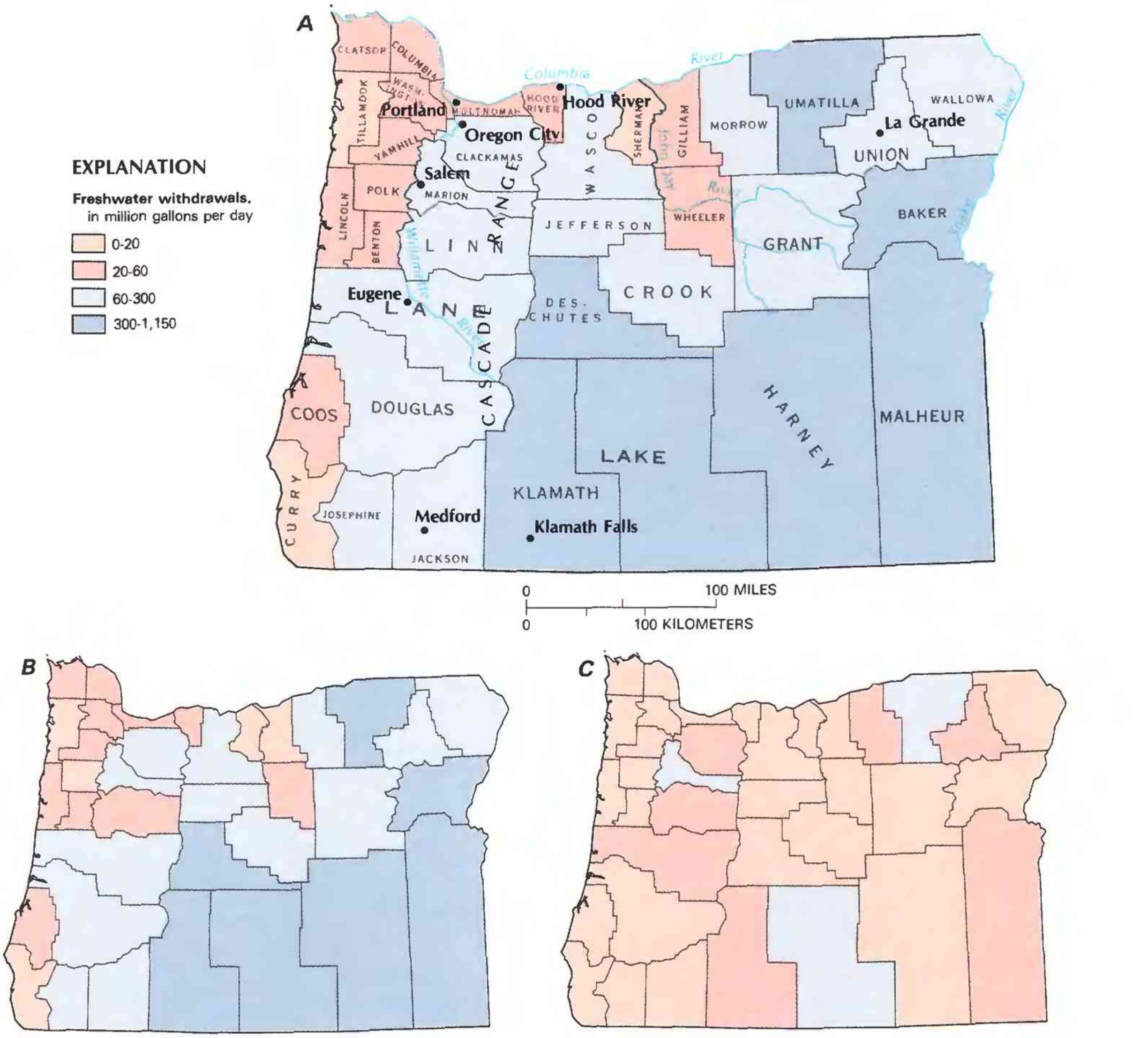


Figure 2. Freshwater withdrawals by county in Oregon, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

protect watersheds in these regions and to assure a consistently satisfactory quality of water. Portland, which during its early history took its water from the Willamette River, sought a new source of water at the turn of the century to avoid the effects of already declining water quality. The establishment of the Bull Run watershed near Mount Hood (Clackamas County) as a protected area has provided Portland and 32 water-supply districts with a reliable source of good-quality water for most uses. Although the water quality of the Willamette River has improved markedly since the 1970's only three cities currently (1987) identify the river as a primary or secondary source.

Typical deliveries from a public-supply system are shown in figure 5*C*. Approximately 59 percent of the water withdrawn is delivered for domestic use, 23 percent is for commercial and industrial uses, and about 17 percent can be attributed to public uses of water (firelines, system flushing, supply to public facilities) and transmission losses. These public uses and transmission losses range from 5 percent in Medford and Eugene to about 20 percent in Portland, Salem and La Grande.

Several factors can affect the water delivery by public suppliers to industry. For example, silicon-processing and other high-technology industries need small amounts of water and commonly rely on public supplies. Industries that require large volumes of water generally have their own systems for withdrawals; examples are the pulp and paper industry, which commonly withdraws water from rivers directly, and the aluminum smelters, which withdraw water from wells close to the Columbia River.

Domestic and Commercial

Water used for domestic and commercial purposes accounts for 6.8 percent (445 Mgal/d) of total offstream water use in the State. This amount includes 72 Mgal/d of public uses and transmission losses from public systems.

Approximately 72 percent of the State's population (1.9 million residents) obtained water from public-supply systems in 1985. These systems delivered 75 percent (246 Mgal/d) of the water used for domestic purposes, excluding public supply and transmission losses; the remainder of the domestic supply came from private systems.

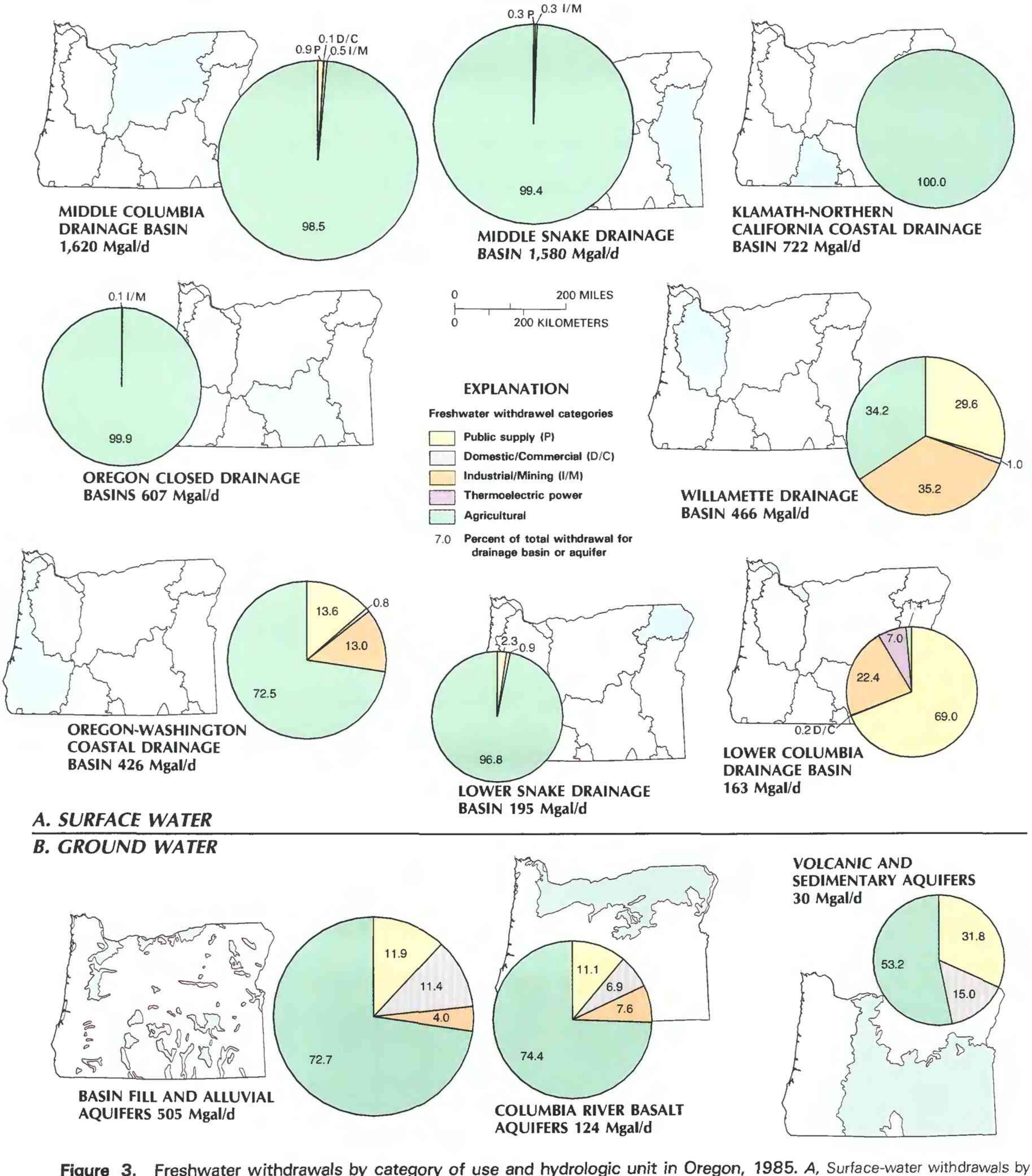


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Oregon, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

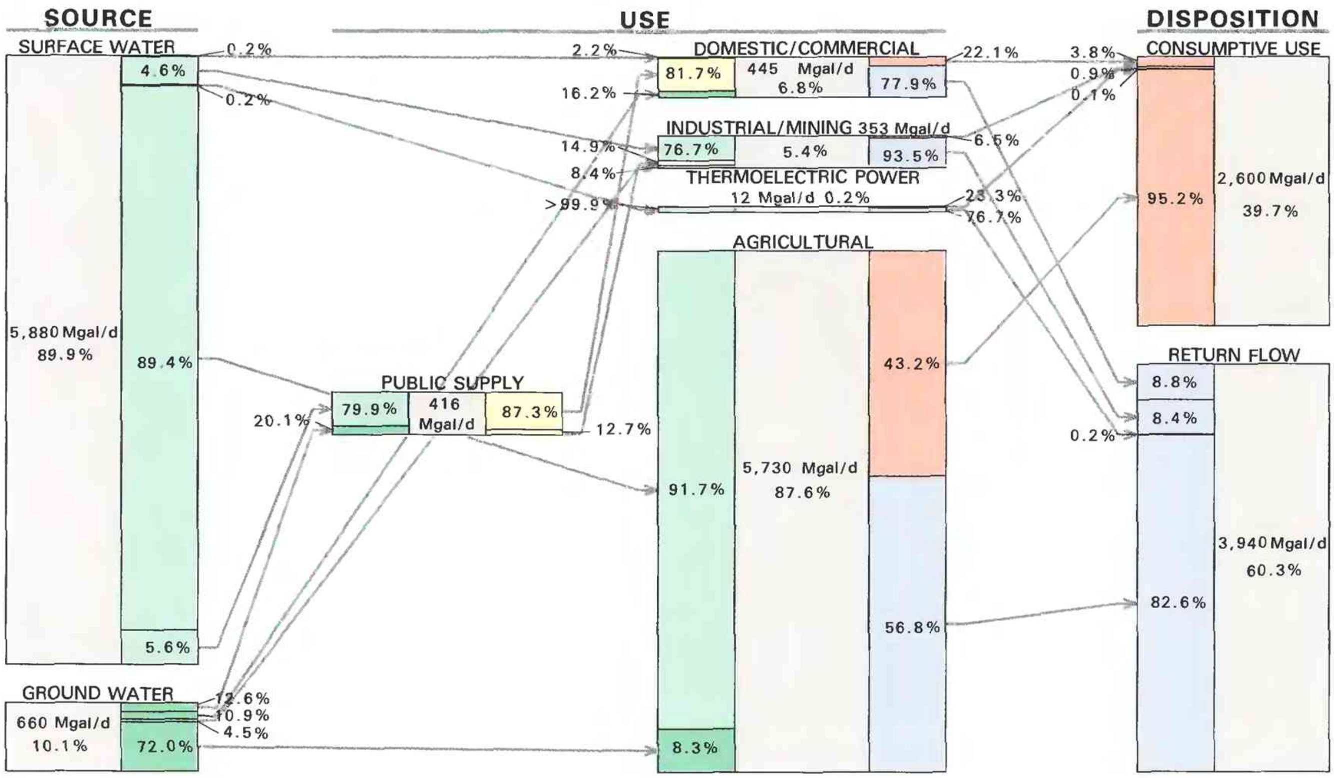


Figure 4. Source, use, and disposition of an estimated 6,540 Mgal/d (million gallons per day) of freshwater in Oregon, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Statewide, 88 percent (70 Mgal/d) of the withdrawals from private systems for domestic use was from ground water; springs, streams, and irrigation ditches were the remaining sources. In the Willamette River valley, 22 percent of the population relied on these private systems; outside the valley, 36 percent relied on private systems.

Of the water used for commercial purposes, 96 percent (45 Mgal/d) was supplied by public systems. Of the remaining amount used by commercial facilities obtaining their own water, 91 percent came from ground water.

Industrial and Mining

About 353 Mgal/d of water was used for industrial and mining purposes in 1985. Of this amount, 98 percent (346 Mgal/d) was for industry, and 2 percent (7 Mgal/d) was for mining. About 6.5 percent (23 Mgal/d) of the water withdrawn for industrial and mining was consumed.

The lumber and wood-products industry accounts for most industrial water uses in Oregon. The 11 major pulp and paper mills in the State are responsible for roughly 55 percent (191 Mgal/d) of all the industrial water withdrawn. The location of these mills along the Columbia and the Willamette Rivers and the smaller coastal rivers is due, in part, to the need for large volumes of water.

The remaining 155 Mgal/d of industrial withdrawals is made by several groups, three of which are discussed. The chemical industry, which is located primarily in the Portland area, accounts for approximately 7 percent of the total industrial withdrawals and depends on surface water as its primary source. Fruit- and vegetable-canning facilities and potato processing account for about 6 percent of the industrial withdrawals. These facilities, located in Marion, Jackson, Hood River, Umatilla, Morrow, and Malheur Counties, either supply their own water or purchase it from a public supplier. The primary-metals industries, concentrated in Linn, Multnomah, and Wasco Counties, account for 2 percent of the industrial withdrawals. Withdrawals by this group historically have been greater, but, during the past few years, the aluminum plants have not been operating at full capacity. These plants depend on ground water for their supply, but several of the other metals industries have surface-water supplies.

The largest water users in the mining industry are placer operations located in Josephine, Jackson, Grant, and Baker Counties. These operations rely on surface-water sources and are worked only during periods of adequate flow (usually early spring until midsummer).

Thermoelectric Power

Only two major thermoelectric facilities are currently operated in Oregon. Most of the electrical power generated is produced by hydroelectric facilities. (Oregon ranks second in the Nation in terms of hydroelectric production.) In 1985, the thermoelectric facilities—a nuclear plant in Columbia County and a coal-fired plant in Morrow County—produced about 14 percent (7,500 GWh) of the total power generated in the State. The nuclear facility has an installed capacity of 1.22 GW (gigawatts) and is used to supplement the hydroelectric facilities during periods of large demand, usually October through April. The coal-fired facility has an installed capacity of 0.56 GW and provides an additional power supply should streamflows be inadequate for hydroelectric power generation. Both of these plants

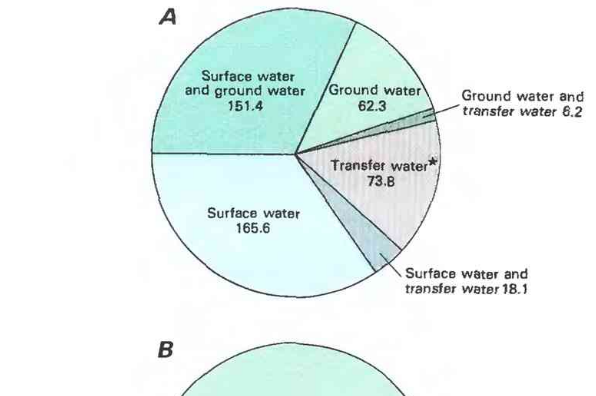


Figure 5. Sources of water for public-supply systems in Oregon, 1985. Values are based on a sample size of 493 of the largest public suppliers. *A*, Withdrawal rates by source, in million gallons per day. Values will be greater than totals because transfer water is included. *B*, Number of supply systems by source. *C*, Use of water from supply systems by water use categories, in percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

use water from the Columbia River, mainly for cooling purposes. In 1985, they withdrew 12 Mgal/d, roughly 23 percent of which was consumed.

AGRICULTURAL

The estimated 5,730 Mgal/d withdrawn for agricultural purposes accounts for 87.6 percent of all the water withdrawn in the State. Within this category, irrigation accounts for more than 99 percent (5,710 Mgal/d) and livestock use accounts for the remainder.

In 1985, Oregon ranked eighth in the United States in the amount of irrigated acreage (2.0 million acres)(Solley and others, 1988). Of these lands, 55 percent was irrigated by sprinkler irrigation and the rest by flood gravity-flow irrigation. Of the water withdrawn for irrigation, an estimated 91.7 percent came from surface water, 8.2 percent was from ground water, and 0.1 percent was from reclaimed sewage. About 14 percent (772 Mgal/d) of the irrigation withdrawals was lost in conveyance, and about 43 percent (2,450 Mgal/d) was consumed and not returned to the natural system.

The distribution of irrigated acreages, application methods, water sources, water losses, and crop consumption differs between eastern and western Oregon. Of 1.65 million acres irrigated in eastern Oregon in 1985, 53 percent was irrigated by flood irrigation, and 47 percent was irrigated by sprinkler irrigation. Surface-water withdrawals accounted for 93.6 percent (4,770 Mgal/d) of the water used for irrigation east of the Cascades, and ground water and reclaimed sewage accounted for 6.3 percent (321 Mgal/d) and 0.1 percent (2.6 Mgal/d), respectively. Conveyance losses equaled about 14 percent (727 Mgal/d) of the withdrawals, and consumptive use equaled 41 percent (2,080 Mgal/d).

West of the Cascades, the 387,000 acres were irrigated primarily (89 percent) by sprinkler irrigation. Surface water accounted for 75.2 percent (464 Mgal/d) of the withdrawals, ground water accounted for 24.5 percent (151 Mgal/d), and reclaimed sewage accounted for 0.3 percent (2.1 Mgal/d). Conveyance losses were about 7 percent (45 Mgal/d) of the total withdrawals, and consumptive use was about 60 percent (372 Mgal/d).

With the exception of dryland farming of grains in Sherman, Gilliam, Morrow, and Umatilla Counties, most farming in eastern Oregon requires irrigation for successful crop production. Irrigable plots tend to be large (average of 196 acres) and are located away from adequate water supplies. Consequently, much of this land is irrigated by means of large-scale storage and distribution projects. The U.S. Bureau of Reclamation manages most of these projects, which are located in Jackson, Klamath, Deschutes, Crook, Jefferson, Wasco, Morrow, Umatilla, Baker, and Malheur Counties. In 1985, 26 percent of all irrigated lands in eastern Oregon was in Bureau of Reclamation projects.

Privately financed irrigation projects are smaller in scale but still account for a large part of the withdrawals. Many of these projects are temporary structures placed in streams during periods of high flow to irrigate nearby meadows. This practice, referred to as "wild flooding," is common in Klamath, Lake, and Harney Counties. More elaborate schemes involve the use of diversion ditches and flooding to irrigate plots of land beside streams; this type of irrigation is practiced throughout the State. Privately financed irrigation projects also use center-pivot sprinkler systems. Introduced to Oregon in the late 1960's, these systems provide an efficient method to irrigate lands that are either too sandy and undulating to be watered by gravity or too labor intensive to be watered by traditional sprinkler techniques (Muckleston and Highsmith, 1978). Corporate farms in Umatilla and Morrow Counties have installed large pumps to withdraw water from the Columbia River and to irrigate fields on the nearby plateau by center pivot. The introduction of center-pivot irrigation also has led to large increases in the use of ground water for irrigation, especially in the Fort Rock basin of Lake County (Hall, 1982).

Hay and pasture grasses are the largest irrigated crop in eastern Oregon, especially in areas of extensive livestock production, such as Klamath, Lake, Harney, and Malheur Counties. Crop production in Morrow, Umatilla, and northeastern Malheur Counties is somewhat more diversified. Potatoes and sugar beets, along with vegetables, such as asparagus, carrots, onions, corn, and watermelons, are irrigated in publicly and privately financed projects. In Hood River, Wasco, and Umatilla Counties, approximately 25,000 acres of apple, pear, and cherry orchards are irrigated (U.S. Department of Commerce, 1984; Oregon State University, 1986).

Hay and pasture grasses also are grown on most of the irrigated lands in western Oregon, but large parts of the land are planted in high-value crops. In the Willamette River valley (primarily in Marion, Linn, and Clackamas Counties) these crops include sugar beets, corn, mint, snap beans, onions, berries, and hops. Outside of the valley, the high-value crops are pears (Jackson County) and cranberries (Coos County). A large number of wholesale nurseries that use irrigation are located in Multnomah, Clackamas, and Washington Counties.

Lack of available surface water during the late summer is a major problem associated with irrigation. This deficiency is especially true in areas, such as the John Day River basin in north-central Oregon, that do not have adequate storage facilities. Because of the economic, environmental, and political problems associated with the construction of new dams, nonstructural methods for increasing storage now are being examined. These methods center on improvement of land-use practices in the watersheds (Oregon Water Resources Department, 1986).

An additional problem associated with irrigation has been overdrafts of ground water in Washington, Wasco, Morrow, Umatilla, and Baker Counties. Areas of declining ground-water levels in these counties have been declared "Critical Ground Water Areas" by the Oregon Water Resources Department (1984) and have been restricted from additional development.

The number of irrigated acres statewide decreased by 3 percent (64,000 acres) between 1980 and 1985 (Solley and others, 1983, 1988). This decrease is attributable to the decline in market prices of agricultural products and to an increase in the costs of equipment, fertilizers, transportation, and electricity.

Besides irrigation, agricultural water use includes water used for livestock production. In 1985, 25 Mgal/d was withdrawn—85 percent from surface water and 15 percent from ground water. Consumptive use was 100 percent. Beef and dairy cattle accounted for 82 and 12 percent, respectively, of all the water withdrawn for livestock production. The largest water withdrawals for beef cattle were in Malheur, Harney, Lake, and Baker Counties, and the largest withdrawals for dairy cattle were in Tillamook and Marion Counties.

WATER MANAGEMENT

Water policy in Oregon is under the direction of the Water Resources Commission (WRC), a seven-member citizen panel appointed by the Governor. Its policies are administered by the Oregon Water Resources Department, whose Director is also an appointee of the Governor. It is the Director's responsibility to regulate the appropriated water of the State and to issue rights for the use of unappropriated water. The surface water-rights system is based on prior appropriation and has been in existence since 1909. The use of ground water also requires a right, but a permit system for its allocation was not enacted until 1927. These water rights are enforced by 19 watermasters, one located in each of the major drainage basins (League of Women Voters, 1984).

Although other State agencies are involved with water resources, their policies by law must be consistent with those of the WRC. The Department of Environmental Quality oversees the quality of surface and ground water. In this capacity, the department regulates the discharge of treated wastewater. The State Health Division is responsible for overseeing the water quality of public drinking-water systems. Other agencies, such as the Division of State Lands, the Department of Fish and Wildlife, the Department of Transportation, the Department of Agriculture, and the Land Conservation and Development Commission, have, as part of their charter, responsibilities for protecting and enhancing the waterways.

Federal agencies assist in the management of Oregon's water resources. The Forest Service and the Bureau of Land Management oversee 51 percent of the State's land; these lands contain the headwaters for many of the State's rivers and streams. The Army Corps of Engineers manages 18 reservoirs, and the Bureau of Reclamation oversees 24 reservoirs; these reservoirs are managed for a variety of purposes, including hydroelectric power generation, irrigation, flood control, navigation, and recreation. The Bonneville Power Administration oversees the marketing of power generated by these facilities.

The timing and the quantity of water releases from these facilities are regulated by treaties, compacts, and statutes, especially along the interstate and international waters of the Columbia River. A treaty between the United States and Canada regarding the development of water resources in the Columbia River basin has existed since 1961, but no interstate compact exists among the Columbia Basin States (Pacific Northwest River Basins Commission, 1970). Since 1980, however, the Northwest Power Planning Council, composed of appointees from the basin States, has provided some regional coordination for mitigating the conflicts between hydroelectric power generation and the anadromous fish populations (League of Women Voters, 1984).

Oregon has several innovative programs that encourage better management and use of the State's water resources. The WRC has the authority to establish a minimum perennial streamflow (MPSF) for a stretch of river to preserve aquatic life and to minimize pollution. The establishment of an MPSF essentially creates an instream water right. The Strategic Water Planning Group, composed of 10 State agencies involved in natural resource management, was established in 1983 to develop a coordinated planning process for the revision of the 18 river-basin plans in the State (Oregon Water Resources Department, 1984).

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Prepared by T.M. Broad and D.D. Nebert

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 10615 S.E. Cherry Blossom Drive, Portland, OR 97216

PENNSYLVANIA
Water Supply and Use

Pennsylvania receives an annual average of 44 inches of precipitation (U.S. Geological Survey, 1984), or 90,500 Mgal/d (million gallons per day) (fig. 1A). About 33 percent (30,000 Mgal/d) of the precipitation infiltrates the soil surface and recharges aquifers (Makuch and Ward, 1986). Almost one-half of the precipitation returns to the atmosphere through evapotranspiration, and about one-sixth is discharged as direct surface runoff. Surface-water inflows to Pennsylvania total 12,300 Mgal/d; surface-water outflows total 58,800 Mgal/d. The increase in streamflow is a result of direct runoff of precipitation and discharge of ground water to streams. Pennsylvania has abundant ground-water resources. Ground-water withdrawals in 1985 were 799 Mgal/d, or 5.6 percent of all water withdrawn in the State.

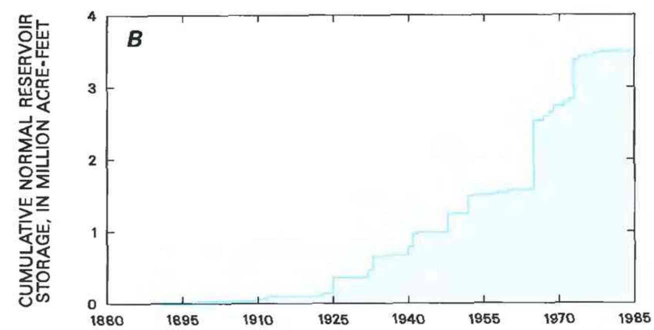
In 1985, freshwater withdrawals from streams and aquifers were about 14,300 Mgal/d, which is equivalent to about 745 gal/d (gallons per day) per capita. Of that quantity, 589 Mgal/d was consumed, and 13,700 Mgal/d was returned to the hydrologic system. Domestic, commercial, industrial, and mining uses totaled 4,020 Mgal/d, or 28.0 percent of the total withdrawals. Thermoelectric power generation used 71.3 percent (10,200 Mgal/d) of total withdrawals, which was 32.8 percent (193 Mgal/d) of all consumptive use. Agriculture used 0.6 percent (81 Mgal/d) of all withdrawals and accounted for 12.2 percent (72 Mgal/d) of all consumptive use.

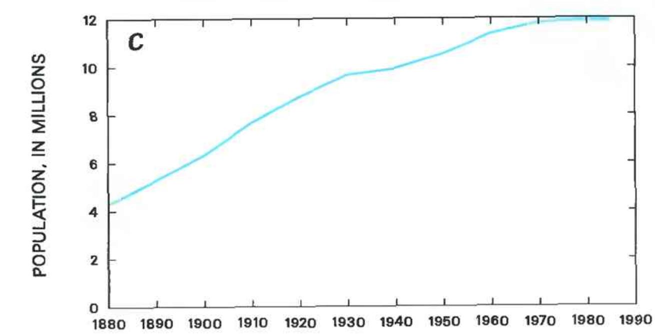
From 1980 to 1985, withdrawals decreased about 13 percent—from 3,650 Mgal/d in 1980 to 2,060 Mgal/d in 1985. The decrease was due largely to less water being used for self-supplied industry.

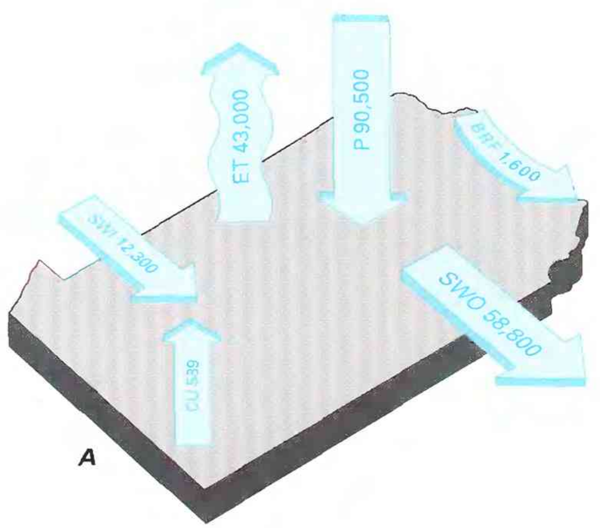
HISTORY OF WATER DEVELOPMENT

The Delaware River on Pennsylvania's eastern boundary, formed by headwaters rising in New York's Catskill Mountains, is the third largest of the seven major river basins that drain the State. In 1681, William Penn led colonists to the port of Philadelphia on the Delaware River upstream from the mouth of the Schuylkill River (Philadelphia County). The Delaware River's deep channel near Philadelphia accommodated the draft of any ship constructed before the end of the 19th century. Only 88 miles from the Atlantic Ocean, Philadelphia provided a harbor for transporting goods to ports in England and Europe. A visionary, Penn foresaw rapid commercial and residential development of the land between the Delaware River and its principal tributary, the Schuylkill River (U.S. Department of the Interior, 1976).

In 1690, Penn proposed another settlement farther west along the Susquehanna River and identified a water route to connect it







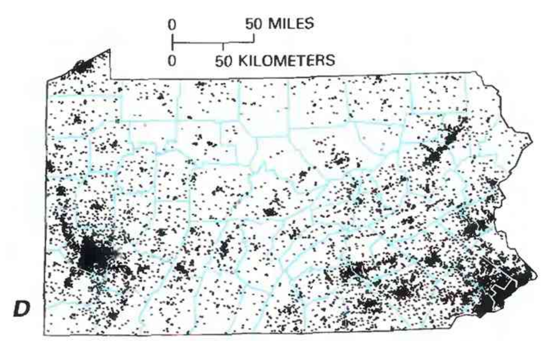


Figure 1. Water supply and population in Pennsylvania. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

with Philadelphia. Penn's "water route," known as the Union Canal (connecting Berks and Dauphin Counties), was the first to be surveyed in America (1762); construction began in 1792 and was completed in 1828, connecting the manufacturing and farming areas of central Pennsylvania to the port of Philadelphia. The Union Canal, the Conewago Canal (parallel to the west bank of the Susquehanna River in York County), and the Main Line Canal (connecting Philadelphia and Pittsburgh) were significant in the development of the rich farmland and communities of the Susquehanna River basin and represented a major water use in their time. These canals, however, were largely replaced by railroads within 25 years of their completion in 1834.

As the earliest plans for the survey of the "water route" were being developed in Philadelphia in the middle 18th century, a company of Virginia militia found the flood plain at the confluence of the Allegheny and the Monongahela Rivers suitable as a site for a stockade. From this location at the head of the Ohio River, the three rivers, which together drain 35 percent of the State, could be controlled, and the region's commercial resources, such as timber, coal, and iron, could be floated to market in New Orleans. By the time the Main Line Canal breached the Appalachian Mountains in 1834, the stockade had become the city of Pittsburgh. As a result of competition from less expensive steamboat traffic and the newer Erie Canal from New York City to Lake Erie (northwest corner of Pennsylvania), the growth of Pittsburgh decreased awhile. When the Erie Extension of the Pennsylvania Canal, connecting New Castle and Sharon to Pittsburgh and Erie, was completed in 1844, Pittsburgh once again flourished as water resources were used for transportation.

Fertile farmlands and jobs in such growing industries as coal and iron mining and lumbering prompted wave upon wave of immigrants from Europe. Since 1880, the population of the Commonwealth has nearly tripled. Along the State's many streams, gristmills, sawmills, flourmills, papermills, blacksmith shops, iron furnaces, and tanneries could, at one time, draw on swift-flowing water for power, cleaning, and cooling purposes. Potable water throughout the State was obtained from many springs in the earlier periods. Cisterns, dug wells, hydraulic rams, wooden pumps, and windmills were popular alternatives.

Today, the Commonwealth relies on about 3.5 million acre-feet of surface water (fig. 1*B*) stored in 2,500 reservoirs and lakes and 45,000 miles of streams and rivers—more than any of the other contiguous States—for much of its water supply. This surface-water resource is used to supply a population of almost 12 million (fig. 1*C*) that is distributed rather unevenly within the Commonwealth (fig. 1*D*).

WATER USE

Pennsylvania has a large water reserve. The water budget (fig. 1*A*) provides a view of the amount of water that flows to and from the State. Owing to the abundant supply of surface water, Pennsylvania relies on that source to meet most of its water use needs.

The major areas of large withdrawals (figs. 2*A*–*C*) reflect the major categories of offstream water use. The Philadelphia and Pittsburgh areas reflect the density of population (fig. 1*D*) and industry, and the area south of Harrisburg reflects large withdrawals for thermoelectric power generation. Of the major river basins (fig. 3*A*), the largest withdrawals are in the Delaware and the Susquehanna. The major withdrawal in each of these basins is for thermoelectric power generation—70.9 and 89.4 percent in the Delaware and the Susquehanna basins, respectively. Ground-water withdrawals are from four principal aquifers (fig. 3*B*), which collectively underlie the entire State.

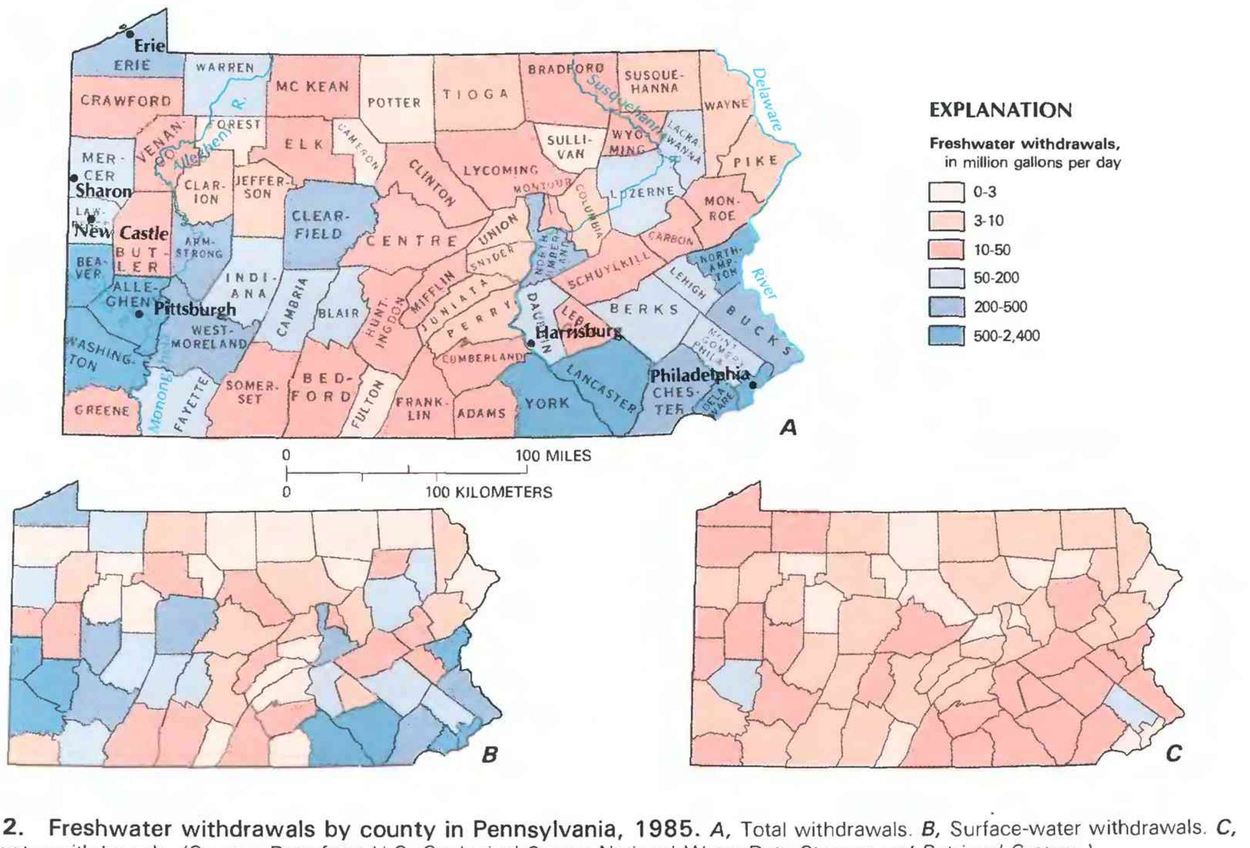


Figure 2. Freshwater withdrawals by county in Pennsylvania, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

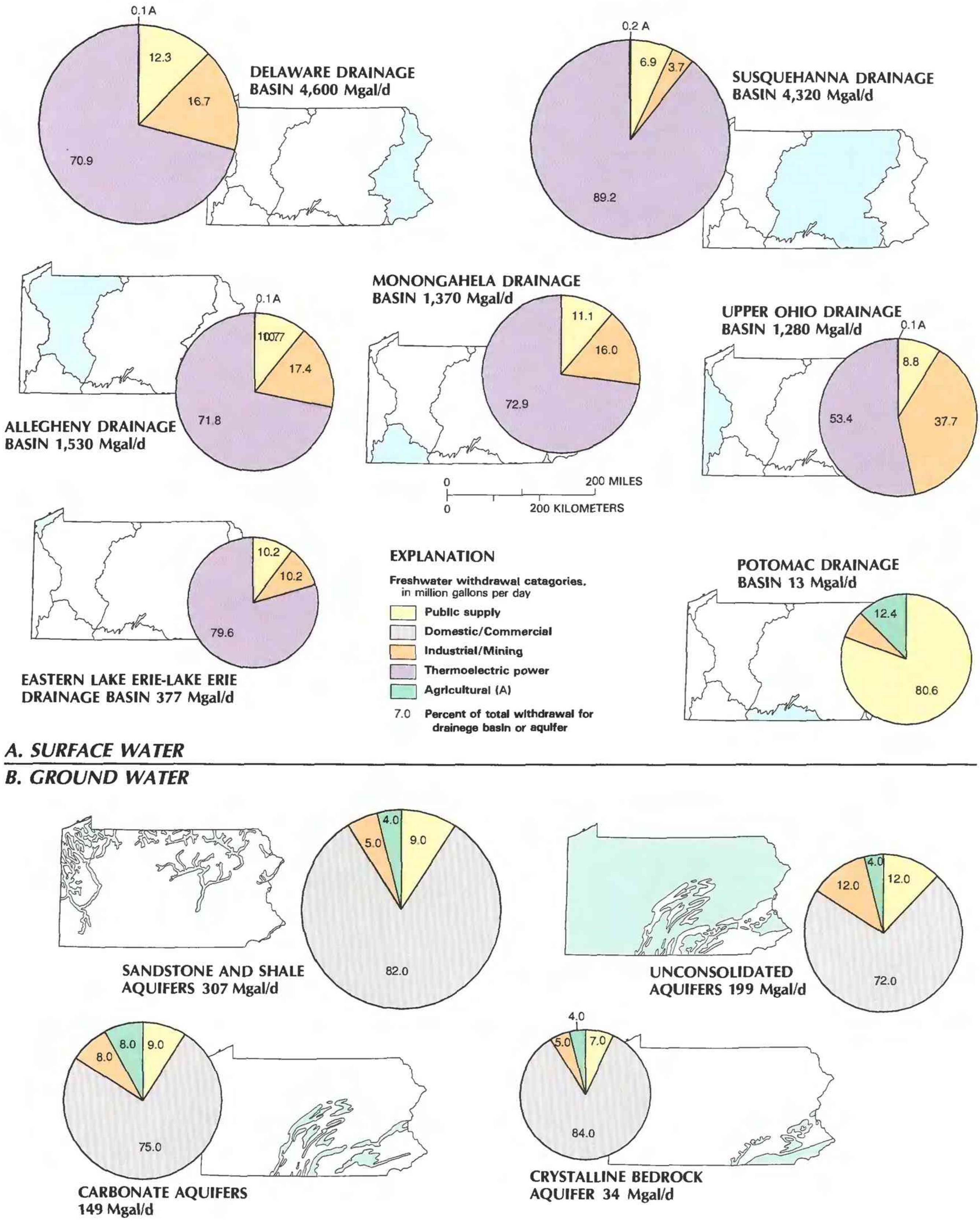


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Pennsylvania, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System; aquifer map from U.S. Geological Survey, 1985, p. 363).

Instream uses also are significant in Pennsylvania. Although there are many forms of instream use, including recreation, waste assimilation, and natural uses for aquatic life, hydroelectric power generation is the only one for which estimates are available. In 1985, an estimated 60,700 Mgal/d was used to generate electricity at hydroelectric sites in seven counties. Thus, hydroelectric power generation is by far the greatest use, accounting for 81 percent of combined instream and offstream uses.

The source, use, and disposition of freshwater in Pennsylvania in 1985 are shown diagrammatically in figure 4. The quantities of water shown in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 94.4 percent (13,500 Mgal/d) of total withdrawals was from surface water. About 75.6 percent (10,200 Mgal/d) of the surface water was withdrawn for thermoelectric power generation. Of the total surface-water withdrawals, less than 0.1 percent (less than 0.01 Mgal/d) was for self-supplied domestic and commercial use, 14.4 percent (1,940 Mgal/d) was for self-supplied industry and mining, 0.1 percent (18 Mgal/d) was for agriculture, and 9.9 percent (1,340 Mgal/d) was for public supply.

The ground-water withdrawals of 799 Mgal/d account for 5.6 percent of total withdrawals. Of that 799 Mgal/d, the major use is by self-supplied industry and mining, which accounts for 33.4 percent (267 Mgal/d). Of total ground-water withdrawals in 1985, 32.2 percent (258 Mgal/d) was for public supply, 26.4 percent (211 Mgal/d) was self-supplied for domestic and commercial use, less than 0.1 percent (less than 0.01 Mgal/d) was for thermoelectric power generation, and 8.0 percent (64 Mgal/d) was for agriculture. Other sources of water (saline water and reclaimed sewage wastewater) are not included in figure 4.

The use data indicate that industry and mining used 17.1 percent (2,450 Mgal/d) of the total withdrawals for the State. Of that quantity, 79.1 percent (1,940 Mgal/d) was from surface-water sources, 10.0 percent (246 Mgal/d) was from public supply, and 10.9 percent (267 Mgal/d) was from ground-water sources. About 8.4 percent (205 Mgal/d) was consumed or no longer readily available for reuse, and 91.6 percent (2,240 Mgal/d) was returned to natural water sources where it was available for reuse.

The disposition data indicate that, of all water withdrawn in the State, 4.1 percent (589 Mgal/d) was consumed and 95.9 percent (13,700 Mgal/d) was returned. Industrial and mining use accounted for 34.9 percent (205 Mgal/d) of the total consumptive use and for 16.4 percent (2,240 Mgal/d) of the return flow.

Public Supply

In Pennsylvania, public-supply systems furnish water to the following major water use categories: (1) domestic and commercial and (2) industrial and mining (fig. 4). In 1985, Pennsylvania ranked sixth in water withdrawn for public supply and fourth in population in the United States. Withdrawals for public supply increased from 9.6 percent of total water withdrawn in 1980 to 11.2 percent (1,600 Mgal/d) in 1985. This increase, which occurred even though the population of the State had decreased slightly during this period, probably is related to decreases in percentages of self-supplied in-

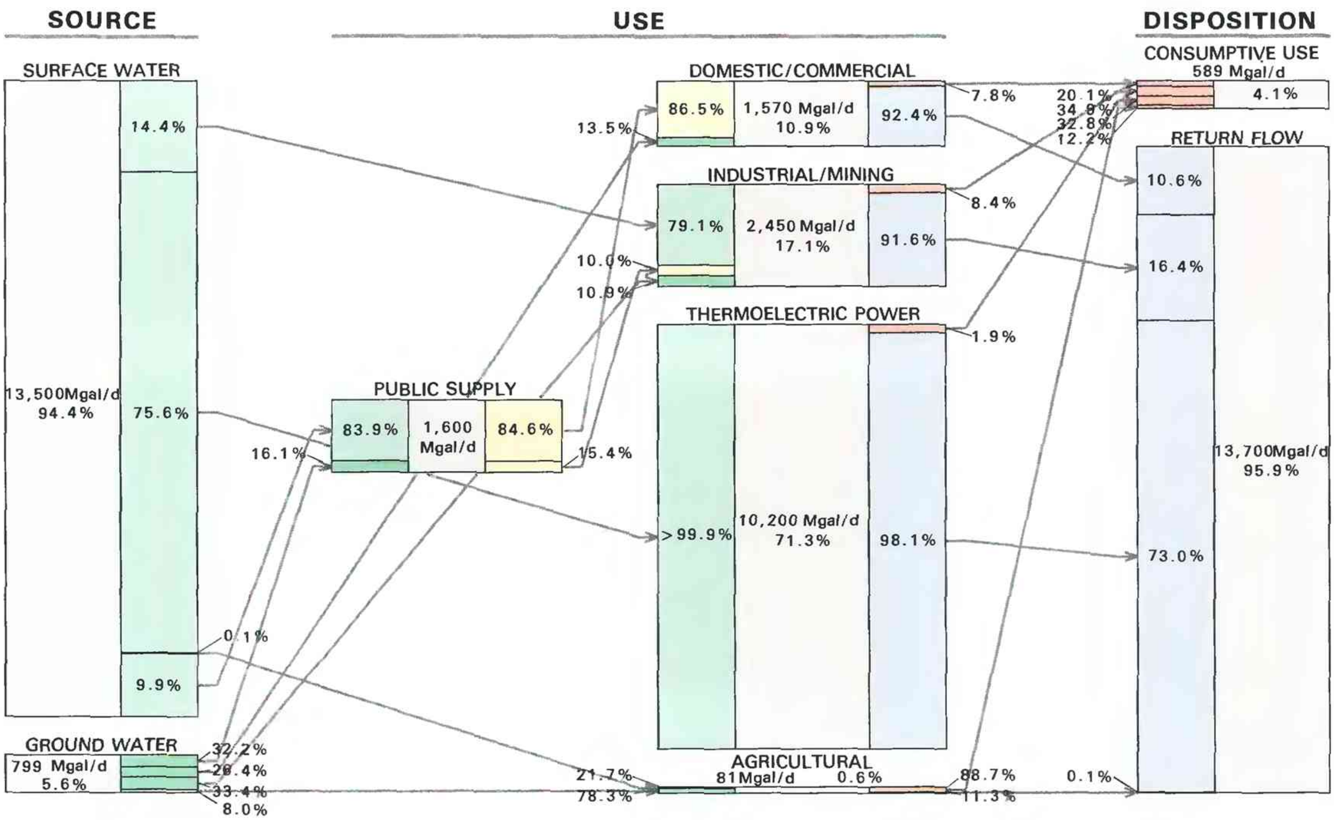


Figure 4. Source, use, and disposition of an estimated 14,300 Mgal/d (million gallons per day) of freshwater in Pennsylvania, 1985. *Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow.* All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

dustrial and thermoelectric uses rather than to actual per capita increases in domestic water use.

Total water withdrawals for public supply in 1985 were 1,600 Mgal/d, of which 83.9 percent (1,340 Mgal/d) was from surface-water sources and 16.1 percent (258 Mgal/d) was from ground-water sources. About 69 percent of Pennsylvania's population is served by public supplies. Allegheny County (which includes Pittsburgh) and Philadelphia County (which includes the city of Philadelphia) had the greatest withdrawals for public supply—219 and 356 Mgal/d, respectively. Counties in the northern part of the State, with the exception of Erie County, had small withdrawals—less than 8 Mgal/d. Of the water delivered by public suppliers, 84.6 percent (1,350 Mgal/d) went to domestic and commercial users, and 15.4 percent (246 Mgal/d) went to industrial and mining users (fig. 4). Of the 1,350 Mgal/d supplied for domestic and commercial use, 46.6 percent (629 Mgal/d) is unaccounted for or included in public use, such as fire fighting, street cleaning, filter backwash, and leakage loss. Some unaccounted water also results from meter inaccuracy.

Domestic and Commercial

Domestic and commercial use accounted for 1,570 Mgal/d. Excluding 629 Mgal/d of unaccounted water, domestic and commercial use was 6.6 percent (937 Mgal/d) of all water withdrawn in 1985. Water was from public suppliers (86.5 percent) and from self-supplied sources (13.5 percent). Domestic use totaled 723 Mgal/d, of which 184 Mgal/d was from self-supplied systems. An average of 66 gal/d is used by each person who purchases water from a public supplier. Self-supplied domestic use is estimated to be 50 gal/d per capita (C.A. Loper, U.S. Geological Survey, written commun., 1986). About 10 percent (72 Mgal/d) of water for domestic use is consumed. Commercial use in 1985 totaled about 214 Mgal/d and was about 22.8 percent of total domestic and commercial uses. About 186 Mgal/d of commercial use was from public supplies. Commercial consumptive use was 46 Mgal/d.

Industrial and Mining

Industry and mining used 2,450 Mgal/d in 1985 (fig. 4). Industrial use was 94.2 percent of this total. Manufacturing industries were second only to thermoelectric power generation in the total quantity of water withdrawn in Pennsylvania in 1985. Industrial water use totaled 16.2 percent (2,310 Mgal/d) of the State's water use. Self-supplied industrial use of freshwater was 2,060 Mgal/d—1,910 Mgal/d from surface-water sources and 149 Mgal/d from ground-water sources. About 246 Mgal/d was delivered to industries by public suppliers.

The greatest industrial use can be attributed to steel and oil industries that require large quantities of water in their operation. Total withdrawals for self-supplied industry—498 Mgal/d—were largest in Allegheny County. More than 100 Mgal/d was withdrawn in five other counties—Beaver (298 Mgal/d), Bucks (235 Mgal/d), Delaware (234 Mgal/d), Northampton (175 Mgal/d), and Philadelphia (119 Mgal/d).

Total withdrawals for self-supplied industry were largest in the Delaware, the Allegheny, and the Upper Ohio basins (fig. 3*A*). The total withdrawals for these units were 1,600 Mgal/d, which was 65 percent of the industrial water use.

Industrial water use has been decreasing since 1970 (fig. 5). The decrease is due, in part, to a decrease in production attributed to recent economic conditions.

Pennsylvania has always been rich in nonmetallic mineral resources. In 1985, self-supplied systems provided all the freshwater withdrawn for mining industries—30 Mgal/d of surface water and

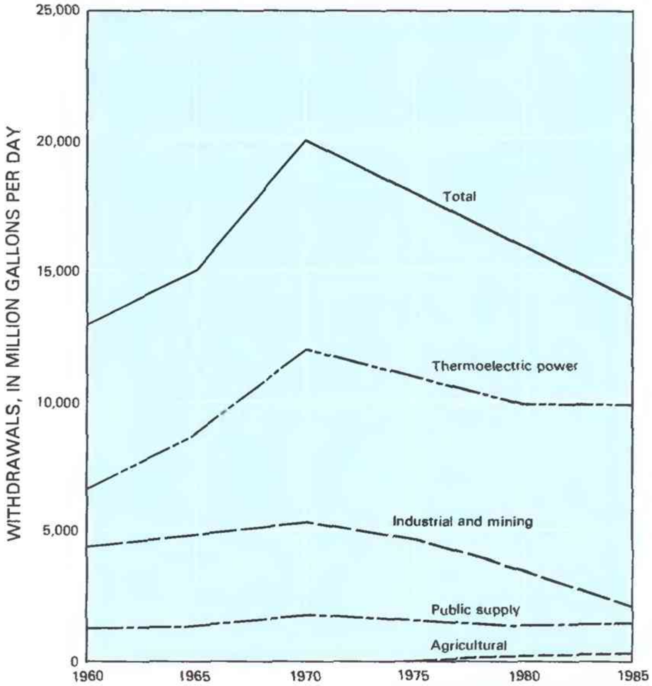


Figure 5. Withdrawals by water-use categories in Pennsylvania, 1960 to 1985. (Sources: MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; data from the U.S. Geological Survey National Water Data Storage and Retrieval System.)

118 Mgal/d of ground water. More than 10 Mgal/d was withdrawn for mining in five counties—Allegheny (18.6 Mgal/d), Greene (17.1 Mgal/d), York (12.6 Mgal/d), Schuylkill (11.7 Mgal/d), and Lehigh (10.2 Mgal/d).

The largest withdrawals were in the Susquehanna basin where much of the mining was for limestone, sand, and gravel (C.A. Loper, U.S. Geological Survey, written commun., 1986). Coal-mining activities in the western part of the State account for large withdrawals in the Allegheny and the Monongahela basins. Small quantities of water are used for mining in the northern one-half of the State.

Industrial and mining consumptive use was 8.4 percent (206 Mgal/d—of withdrawals and deliveries—186 Mgal/d for industries and 20 Mgal/d for mining). Industrial and mining use accounted for 34.9 percent of the total consumptive use (fig. 4).

Thermoelectric Power

Water used for thermoelectric power generation accounts for 71.3 percent (10,200 Mgal/d) of the total withdrawals (fig. 4). The State has 35 thermoelectric powerplants—31 are fossil-fueled units, 3 are nuclear powered units, and 1 has hydroelectric turbines and fossil-fueled units. In 1985, these units used 71.3 percent (10,200 Mgal/d) of total ground- and surface-water withdrawals. Less than 0.1 percent (less than 0.01 Mgal/d) of these withdrawals was from ground water. Consumptive use totaled 1.9 percent (193 Mgal/d). Nearly all the water withdrawn for thermoelectric power generation is returned to the streams from which it is withdrawn. Water losses during thermoelectric power generation accounted for 32.8 percent of the State's total consumptive use.

Philadelphia, Lancaster, and Delaware Counties have the largest withdrawals for thermoelectric power generation. The service areas for these powerplants include some of the most densely populated areas of the State (fig. 1*D*). Some electricity from these facilities is supplied to parts of New York, Ohio, Virginia, West Virginia, New Jersey, and Delaware (C.A. Loper, U.S. Geological Survey, written commun., 1986). The Susquehanna basin had the largest withdrawals for this category and the Potomac basin had no withdrawals for thermoelectric power generation.

Withdrawals for thermoelectric power generation increased steadily from 1960 to 1970 (fig. 5) but have decreased since then, in spite of the construction of new facilities. Part of this decrease is attributable to the gradual replacement of the once-through cooling systems by more efficient water-recirculating closed-loop cooling towers. Although this replacement has resulted in a decrease of water withdrawals, more consumptive use results through evaporation from the closed-loop cooling towers.

AGRICULTURAL

Agricultural withdrawals, including water for irrigation and livestock, were 81.1 Mgal/d (fig. 4). In 1985, 10.7 Mgal/d was withdrawn in Pennsylvania to irrigate 18,100 acres. Of this total, 86 percent (9.2 Mgal/d) was withdrawn from surface-water sources. Withdrawals for irrigation were greatest in Lancaster (1.2 Mgal/d) and Franklin Counties (1.1 Mgal/d) followed by withdrawals in Adams County (1.0 Mgal/d) and Chester County (0.6 Mgal/d). Fifteen counties, generally in the north-central and western parts of the State, did not report any irrigation of crops or trees. Agricultural use accounted for 12 percent of the water use in the Potomac basin in Pennsylvania (fig. 3*A*).

The withdrawals for livestock increased about 72 percent from 41.0 Mgal/d in 1980 to 70.4 Mgal/d in 1985. This increase probably is related to improved accuracy in methods for calculating agricultural use of water. Of the total withdrawals in 1985, 88 percent was from ground-water sources and 12 percent was from surface-water sources.

Almost all the water withdrawn for irrigation is consumed. Consumptive use for nonirrigation agricultural activities was about 87 percent (61.2 Mgal/d). Although total agricultural withdrawals account for 0.6 percent of total withdrawals in Pennsylvania, agriculture accounts for 12.2 percent (72 Mgal/d) of all consumptive use.

WATER MANAGEMENT

Surface-water withdrawals by public suppliers are regulated statewide by the Pennsylvania Department of Environmental Resources. The 1939 Water Rights Act stipulates that no public-water supplier shall withdraw surface waters in the Commonwealth without first having applied for and received a water-allocation permit from the Department. No other withdrawals are regulated by State law at this time.

Before issuing a surface-water allocation permit, the Pennsylvania Department of Environmental Resources must determine that (1) the quantity of water requested is reasonably needed for current and future use by the water supplier, (2) the proposed acquisition will not conflict with the rights to such water held by any other public water-supply agency, and (3) the taking of such water will not interfere with navigation, jeopardize public safety, or cause substantial injury to the Commonwealth. Permits that are issued require appropriate conservation releases from dams or bypass flows at intakes. The permit holders are required to (1) submit monthly reports of daily takings, (2) implement water-conservation programs within their service areas, (3) meter their customers' water usage and sources, (4) develop drought contingency plans and submit them to the Department for approval, and (5) report to the Department annually on the effectiveness of their water conservation and metering programs.

Surface- and ground-water withdrawals exceeding 100,000 gal/d are regulated in the Susquehanna and the Delaware River basins by the Susquehanna River Basin Commission (SRBC) and the Delaware River Basin Commission (DRBC). These two commissions were created in 1960 and 1971, respectively, by compacts between the basin States and the Federal Government and were granted authority to manage and regulate the waters within the two basins. The Susquehanna and the Delaware River basins compose about two-thirds of the area of the Commonwealth.

The SRBC requires that all surface-water users be able to provide water to replace consumptive losses for all new or additional uses initiated after the date of the compact. This water is needed only when streamflows at the withdrawal point are at a decreased level—less than the 7-day, 10-year low-flow value plus the quantity of consumption. If water losses cannot be replaced, then the use must be discontinued or alternative sources must be used.

The DRBC has purchased water-supply storage in two U.S. Army Corps of Engineers reservoirs—Beltzville (Carbon County) and Blue Marsh (Berks County). The purpose was to obtain water for making releases for water supply, water-quality enhancement, consumptive-use replacement, and salinity control in the estuary of the Delaware River.

As indicated by the DRBC "Level B Basinwide Water Resources Study" and the "Good Faith" agreement, additional upstream reservoir storage is thought to be needed for the basin to cope with severe droughts and increasing water needs. Accordingly, the DRBC is pursuing the recommendations of the "Good Faith" agreement by planning to develop additional water storage through the modification of the existing F.E. Walter (Carbon and Luzerne Counties) and Prompton (Wayne County) Reservoirs.

As a result of existing and potential overdevelopment of ground water in southeastern Pennsylvania, the DRBC established a Southeastern Pennsylvania Ground Water Protected Area in all or parts of the five southeastern counties—Bucks, Chester, Lehigh, Montgomery, and Schuylkill. Within the protected area, all ground-water withdrawals exceeding 10,000 gal/d must be by permit.

The SRBC and the DRBC have implemented water-conservation policies that apply to all regulated users. Primarily as a data-collection procedure, the DRBC has required the registration of all wells or well fields basinwide from which withdrawals exceed 10,000 gal/d. As of January 1987, the DRBC required the metering of surface- and ground-water withdrawals that exceed 100,000 gal/d. In the protected areas, ground-water withdrawals that exceed 10,000 gal/d are also metered.

Similar compacts do not exist for the remaining one-third of the Commonwealth, which encompasses the Allegheny, the Monongahela, the Eastern Lake Erie–Lake Erie, the Upper Ohio, and the Potomac basins. Within these areas, only surface-water withdrawals for public supply are regulated under the Commonwealth's Water Rights Act.

The Commonwealth currently is without a comprehensive water-management code. Consumptive water use continues to increase and is predicted to be 850 Mgal/d by 1990. Agricultural uses are shifting from dispersed small family farms to large centralized swine, dairy, and poultry operations, where large water uses will be concentrated in single locations. Conflicts between public-water suppliers and other major industrial and agricultural users have been occurring in recent years.

Interbasin transfers, largely unmonitored in the past, are beginning to create problems in some areas. Mass migration of populations away from the urban cores of Philadelphia, Pittsburgh, and Harrisburg, for example, is shifting water demands from public suppliers, which have access to abundant river sources, to the smaller suburban water systems, which are supplied predominantly by small-

Three Mile Island Unit 1, on the Susquehanna River, generates 850 megawatts of electricity for about 1.8 million customers in an area covering one-half the land mass of Pennsylvania and New Jersey. Each of the plant's two cooling towers evaporate 3,000 to 5,000 gallons per minute of cooling water when operating at full power. (Photograph by Bob Helm.)

yield aquifers or smaller streams. Combined with the effects of migration, there is a shift from predominantly self-supplied heavy industry in the urban cores to predominantly public-supplied commercial and light industrial uses in the suburban growth areas that place even greater burdens on the smaller water-supply systems. Because suburban sprawl precludes surface-water development in most of these areas, these systems are being forced to import water from outlying basins.

Several droughts in the 1980's demonstrated the need for effective local and regional drought-management programs. Interstate cooperation in drought management continues to be addressed through the DRBC; similar efforts need to be initiated in other basins.

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Prepared by Kim L. Wetzel and Barbara Johnson, U.S. Geological Survey; Water Management section by William Gast, Pennsylvania Department of Environmental Resources

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 228 Walnut Street, Federal Building, 4th Floor, P.O. Box 1107, Harrisburg, PA 17108

Puerto Rico
Water Supply and Use

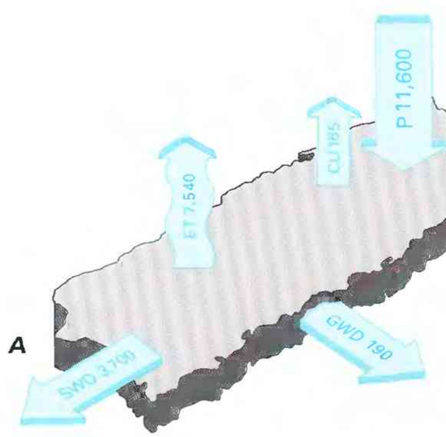
Puerto Rico and its two principal offshore islands—Vieques and Culebra—have an overall area of 3,470 square miles. Average annual precipitation ranges from 30 inches along the western parts of its offshore islands and in the western part of the southern coast to about 200 inches in the northeastern corner of the island (Gómez-Gómez and Heisel, 1980). The average annual rainfall in Puerto Rico is about 70 inches or about 11,600 Mgal/d (million gallons per day) (fig. 1A). Of this amount, 65 percent (7,540 Mgal/d) is lost in evapotranspiration. About 32 percent (3,700 Mgal/d) of the island's precipitation becomes surface-water runoff.

In the last 25 years, freshwater withdrawals have increased from 440 Mgal/d in 1960 (Arnow and Crooks, 1960) to 598 Mgal/d in 1985. Industrial and agricultural water use, however, has declined as a result of the reduction in the sugar production and the cessation of operations of most sugar mills. Surface-water sources provide about 70.7 percent of the total freshwater usage, excluding surface water used for hydroelectric power generation and for cooling at sugar mills. During this 25-year period, development of ground-water resources for public supply and industrial use has increased significantly. In 1985, aquifers provided about 175 Mgal/d of freshwater. Public supply accounted for 47.9 percent (84 Mgal/d) of total ground-water withdrawals, whereas industry and agriculture accounted for 10.5 percent (18 Mgal/d) and 33.4 percent (59 Mgal/d), respectively.

The island's population increased from about 3.2 million in 1980 to about 3.4 million in 1985 (Margarita Santini, Puerto Rico Planning Board, written commun., 1985). Estimates from the Puerto Rico Planning Board indicate that the population of Puerto Rico will be approximately 3.9 million by the year 2000. This increase in population, accompanied with expanding industrial development, will cause unprecedented demands on the island's water resources. Future demands can be partly satisfied with further development of the ground-water resources. Long-term plans by the Commonwealth of Puerto Rico also include additional development of surface-water sources throughout the islands.

HISTORY OF WATER DEVELOPMENT

Puerto Rico has had abundant surface- and ground-water resources throughout the history of its development (fig. 1A). However, these resources are unevenly distributed. The northern part of the island has a more abundant water supply than the southern part. A rainy season usually occurs from August to November, and a dry season occurs from January to April. In spite of significant differences in the availability of water resources throughout the island, the population has adjusted to the hydrologic conditions. Initially, towns were established near rivers or lakes and economic activities were controlled by the availability of nearby water



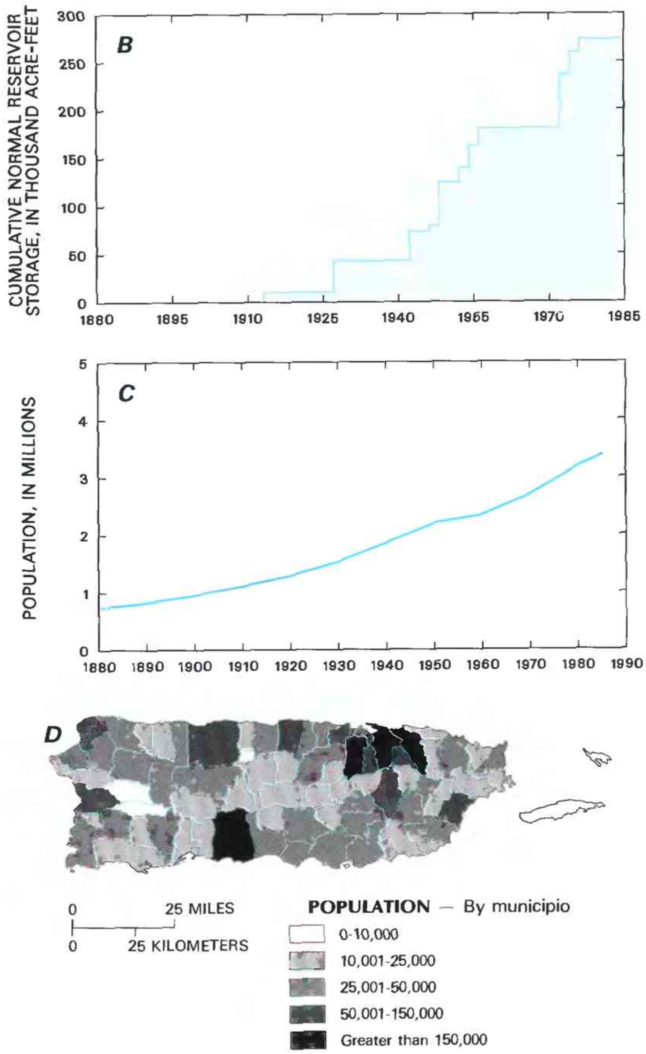


Figure 1. Water supply and population in Puerto Rico. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985. Abbreviations: CU, consumptive use; ET, evapotranspiration; GWD, ground-water discharge; P, precipitation; SWO, surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey files. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

resources. Later, technical innovations were introduced to the island for expansion of the sugarcane industry and industrial development. Projects that were completed to develop water resources included reservoirs and complex systems of tunnels, pipelines, and canals. Construction of reservoirs began in 1910—the first was finished in 1913 and two others were finished in 1914 (fig. 1*B*). The lakes had an original capacity of 33,351 acre-feet. At the same time, the Commonwealth of Puerto Rico implemented the development of hydroelectric facilities and completed the first dam in 1907.

The development of large projects for water supply began early in this century and made possible the extensive growth of the sugarcane industry in the alluvial valleys of the southern coastal area. Conditions are favorable for growing sugarcane in the area, except for an insufficient water supply during some years. For this reason, various public projects for irrigation were developed in an effort to provide water-supply alternatives. In 1908, the development of a complex system of canals was authorized to provide irrigation water for about 32,010 acres of sugarcane. This process was accompanied by a substantial increase in population—155,426 in 1800, 1.1 million in 1910, and about 3.2 million in 1980 (fig. 1*C*) (Margarita Santini, Puerto Rico Planning Board, written commun., 1985). The distribution of population in 1985 is shown in figure 1*D*.

The success of these initial projects prompted the Commonwealth of Puerto Rico to develop other large public projects for irrigation and a significant number of reservoirs for the production of energy and public water supply. In addition to the development of the surface-water resources, many wells were constructed for agriculture uses, particularly along the southern coast. In 1946, McGuiness (1946) inventoried about 1,000 wells—the majority of which were constructed after 1910. Ward and Truxes (1964) documented 2,282 wells in 1964. By 1986, the number of wells had almost doubled to about 4,211 (H.M. Colón-Ramos, U.S. Geological Survey, written commun., 1987).

WATER USE

Areas of major freshwater withdrawals are near centers of large population concentrations (fig. 2*A*). In the San Juan metropolitan area withdrawals average 162 Mgal/d, which is 27 percent of the total freshwater withdrawal. The distribution of surface- and ground-water withdrawals by municipio, as shown in figures 2*B* and 2*C*, respectively, reflects the availability of the resource and the economic activity of the area. In north-central Puerto Rico, which is the area of major industrial development, ground-water resources supply most of the water requirements for the pharmaceutical and electronic industries. Ground water is also the main resource for public supply and irrigation of crops on the southern coast.

Surface water is the major source of freshwater throughout Puerto Rico. More than 100 streams flow to the ocean. Surface water provided approximately 70.7 percent (423 Mgal/d) of the population's freshwater needs in 1985. This water was withdrawn mainly for public supply and agricultural purposes (fig. 3*A*). The surface-water resources in Puerto Rico have been divided into four major areas (U.S. Water Resources Council, 1978). The northern coastal area extends from the Río Grande to the Quebrada Fajardo, the eastern coastal area from the Río Fajardo to the Caño de Santiago, the southern coastal area from the Río Maunabo to the Río Loco, and the western coastal area from the Quebrada Boquerón to the Río Grande de Añasco. The principal streams of the northern coastal area are the Río Grande de Loíza, the Río de la Plata, and the Río Grande de Arecibo. The Río Grande de Loíza is the principal source of water for metropolitan San Juan. The Río de la Plata and the Río Grande de Arecibo are regulated for water supply and power generation. In the eastern coastal area, the Río Blanco is the principal source of water for public supply. The Río Grande de Patillas, the Río Toa Vaca, the Río Jacaguas, the Río Loco, the Río Yauco, the Río Coamo, and the Río Guamaní are the principal sources for water supply and irrigation in the southern coastal areas. The Río Grande de Añasco and the Río Guanajibo satisfy the water-supply demands for most of the western coastal area.

Ground-water withdrawals amount to 175 Mgal/d. Most of this amount was withdrawn for public supply, irrigation, and industrial purposes (fig. 3*B*). During the last 10 years, development of ground-water sources for public supply has increased at an annual rate of about 5 Mgal/d (U.S. Geological Survey, 1985).

The source, use, and disposition of freshwater in Puerto Rico are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 72.6 percent (307 Mgal/d) of all the surface water and 47.9 percent (84 Mgal/d) of all the ground water were withdrawn by public suppliers (mainly for domestic and commercial use). The use data indicate that, of all the water used for domestic and commercial purposes, 95.4 percent was publicly supplied. The disposition data

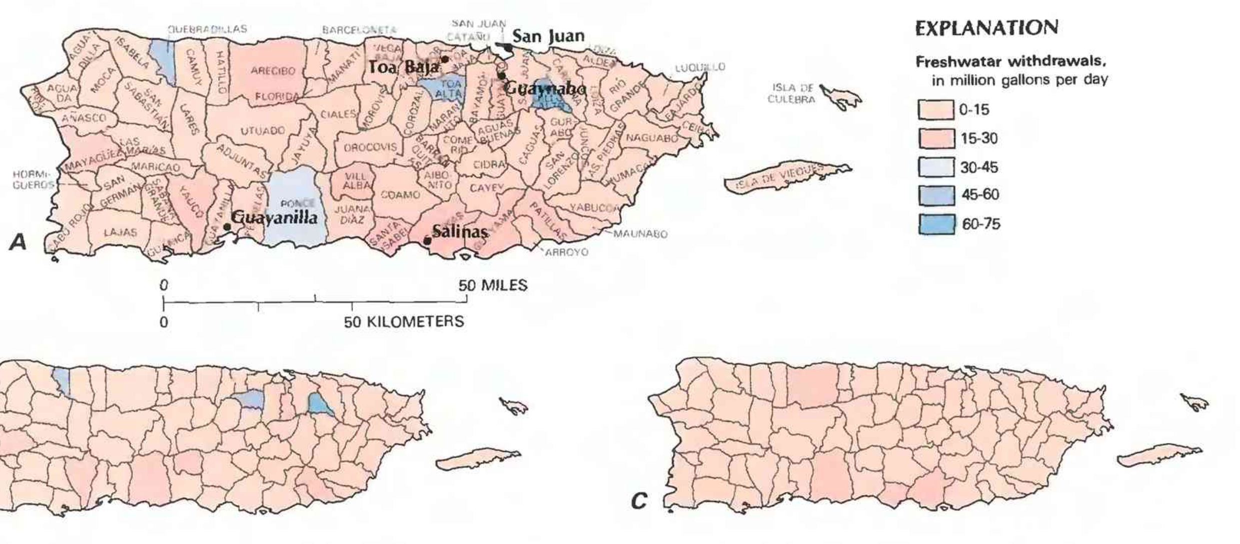


Figure 2. Freshwater withdrawals by municipio in Puerto Rico, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

indicate that domestic and commercial consumptive use amounted to 27.7 percent of the total consumptive use in Puerto Rico.

Hydroelectric power generation is the only reported instream use of water in Puerto Rico. Water used for hydroelectric power generation has increased from 270 Mgal/d in 1980 to 884 Mgal/d in 1985. The consumptive use of water during the generation of hydroelectric power is mostly by evaporation, is a negligible amount, and is not included in figure 4.

Public Supply

Public-supply systems withdraw, treat, and deliver water to users. The responsibility for constructing and operating the public-supply systems in Puerto Rico lies with the Puerto Rico Aqueduct and Sewer Authority. In 1959, public-supply systems withdrew 93 Mgal/d and served about 75 percent of the population of the island (Arnow and Crooks, 1960). Of that amount, 89 percent came from streams and reservoirs and 11 percent came from wells and springs. Withdrawals by public-supply systems increased from 100 Mgal/d in 1960 (Bogart and others, 1964) to 391 Mgal/d in 1985 and reflect increasing population and industrial development. The abundance of water resources was one of the attractions the Government of Puerto Rico used to promote new industries on the island. As of 1987, water supplies are not sufficient, and new studies are being conducted to seek solutions.

About 410 wells and 170 surface-water treatment facilities furnish water to a population of about 2.9 million, or 86 percent of

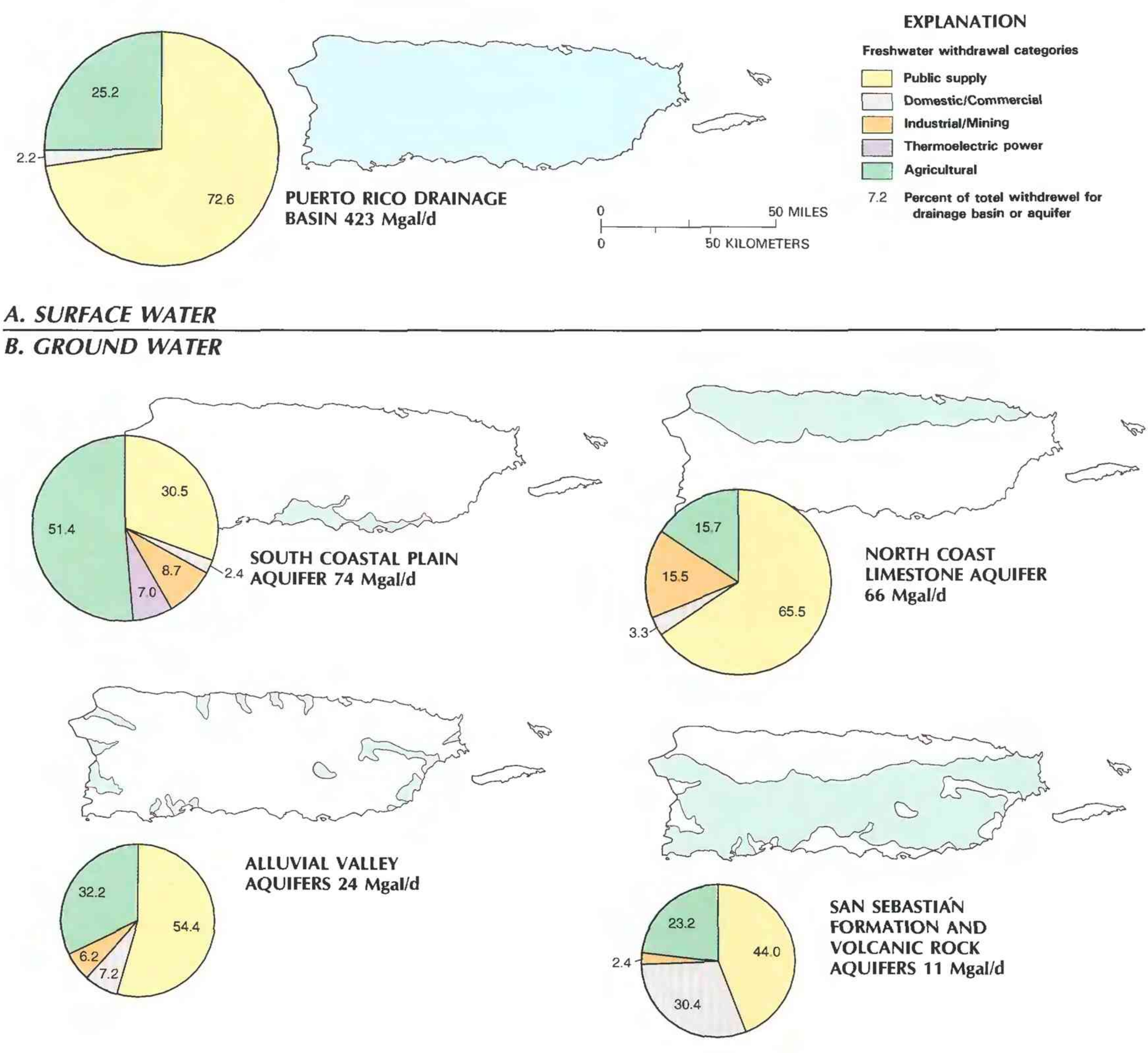


Figure 3. **Freshwater withdrawals by category of use and hydrologic unit in Puerto Rico, 1985.** *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

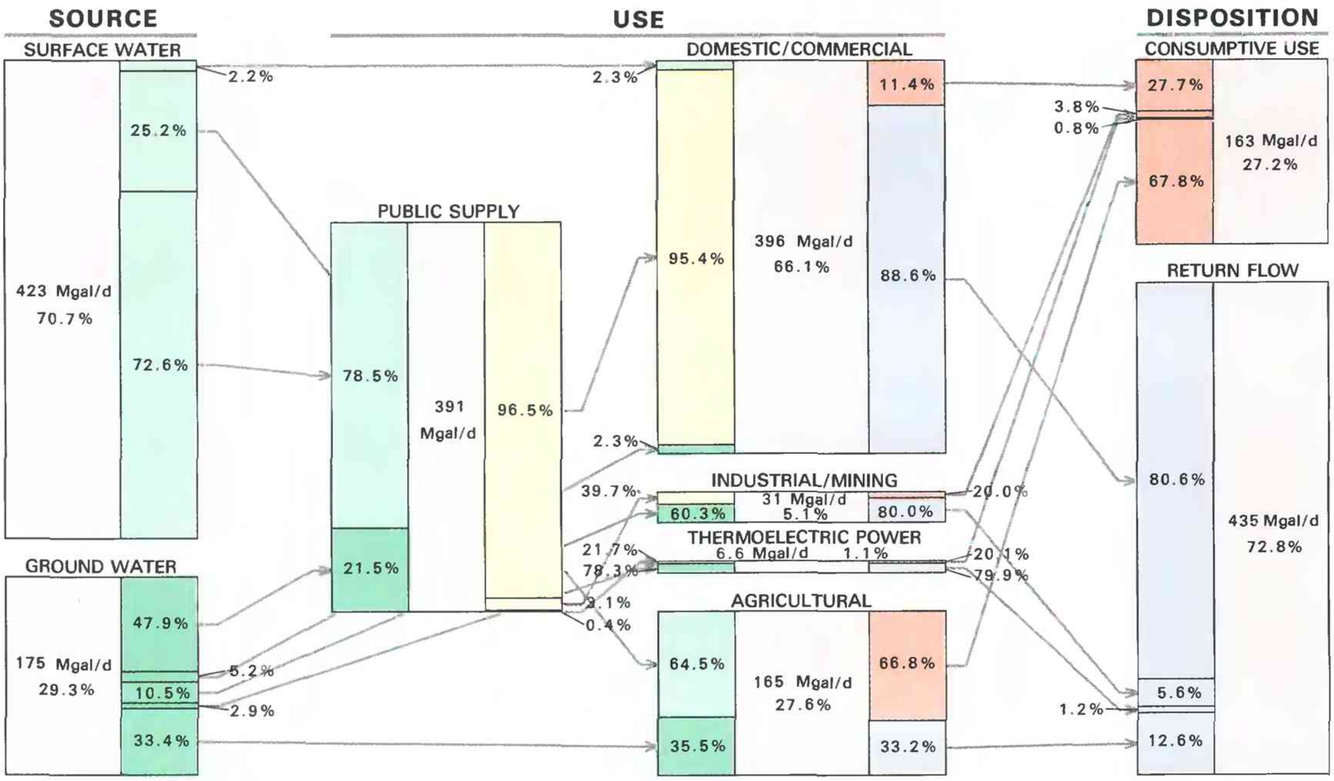


Figure 4. Source, use, and disposition of an estimated 598 Mgal/d (million gallons per day) of freshwater in Puerto Rico, 1985. Conveyance losses in public-supply systems and some public water uses, such as fire fighting, are included in total shown for domestic and commercial use; losses for irrigation distribution systems are included in total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

the total population. These systems withdrew about 391 Mgal/d in 1985 (fig. 4). Surface- and ground-water withdrawals accounted for 78.5 and 21.5 percent, respectively, of the total public-supply withdrawals. In the last 5 years, public-supply withdrawals have increased by 11.7 percent, but the ratio of surface- to ground-water withdrawals has remained the same.

Since 1978, the island of Vieques has been served by a submarine pipeline from Puerto Rico. Water deliveries to Vieques amounted to 0.6 Mgal/d during 1985. Before that connection, the population of 8,000 depended entirely on water withdrawals from the Esperanza and the Resolución Valley aquifers for domestic and commercial use.

Water losses from the public-supply systems in Puerto Rico were estimated to be 41 percent of the production in 1960 and about 50 percent in 1985. An increase in the efficiency of these systems might allow an increasing population to be served without having to make additional extensions of existing systems.

The water quality of streams in Puerto Rico is generally suitable for water supply after appropriate treatment to remove bacteria. Large concentrations of suspended solids, resulting partly from poor land conservation and farming practices, affect the streams and reservoirs of the island. On the northern coast, annual losses in reservoir storage capacity are 2 percent for Lago Loíza. Lago Loíza has already lost 50 percent of its capacity (Quiñones-Marquéz, 1980). The main ground-water quality problem appears to be contamination by organic compounds. Since 1981, about 15 wells have been found to be contaminated with volatile organic chemicals. Saltwater encroachment has limited the potential for ground-water development in coastal areas.

Domestic and Commercial

During 1985, public-supply systems delivered 178 Mgal/d for domestic use and were the main source of water for that purpose. In 1980, public-supply systems furnished 198 Mgal/d for domestic use (Torres-Sierra and Avilés, 1986). The reduction of water served to domestic users is mainly because of larger conveyance losses. In 1985, the self-supplied population was only 458,000 people, who withdrew a total of 18 Mgal/d—50 percent from surface water and 50 percent from ground water (Solley and others, 1988). Of the 196 Mgal/d used for domestic purposes, consumptive use was 39 Mgal/d. Per capita use for 1985 was estimated to be 61 gal/d (gallons per day).

Public-supply systems delivered 30 Mgal/d for commercial use in 1985. Consumptive use was 5.9 Mgal/d. Goméz-Goméz and others (1984) estimated deliveries from public-supply systems to be about 33 Mgal/d in 1980. The decrease in deliveries from 1980 to 1985 was the result of greater conveyance losses.

Principal reservoirs (fig. 5) on the northern coast of Puerto Rico—Loíza, La Plata, and Carite—are used mainly to supply water for domestic use in metropolitan San Juan. Four reservoirs on the southern coast—Toa Vaca, Patillas, Luchetti, and Guayabal—are also used to supply water for domestic use and irrigation.

Industrial and Mining

About 31 Mgal/d of freshwater was used by industry in Puerto Rico during 1985 (fig. 4), and no water was reported used for mining. Of this quantity, public-supply systems furnished 12 Mgal/d. Ground-water sources furnished about 18 Mgal/d. Of the industrial ground-water withdrawals, 27 percent comes from artesian wells along the

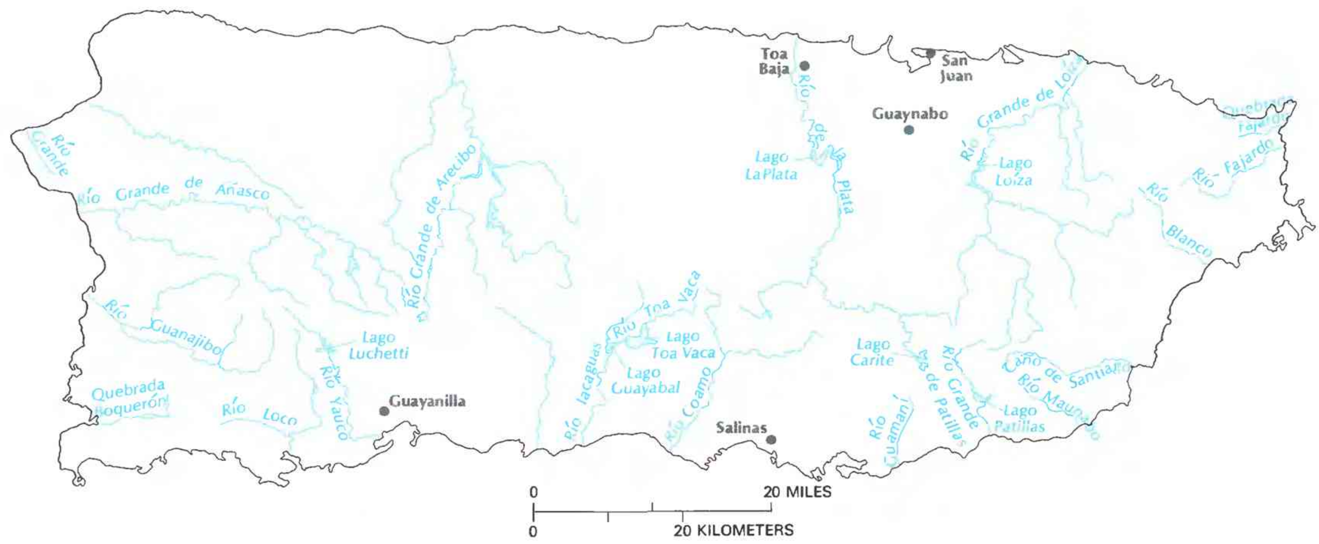


Figure 5. Location of selected rivers, dams, and reservoirs in Puerto Rico. (Source: U.S. Geological Survey, 1985.)

northern coast. Consumptive use was 6.1 Mgal/d. In 1960, an average of 16 Mgal/d was used by industries in Puerto Rico (Bogart and others, 1964). In the early phase of the industrial development of Puerto Rico, obtaining water supplies for industries was not a problem. The industries established during this period were small water users and, for the most part, were adequately provided for by an improved public-supply system. The existing industries consisted mainly of light industries that produced wearing apparel from cloth and leather and those that assembled electronic equipment and similar products from component parts. The only large industries—not including sugar mills—were rum distilleries and a cement plant.

Emphasis during the past years, however, has been to encourage the establishment of larger industries, such as pharmaceutical and electronic industries. These require greater amounts of water than can be provided by the existing facilities. Requirements of these industries have been a major stimulus for evaluating the water resources of Puerto Rico.

Thermoelectric Power

Total fresh and saline withdrawals for thermoelectric power generation increased from about 492 Mgal/d in 1960 (Bogart and others, 1964) to about 2,010 Mgal/d in 1985 (Solley and others, 1988). During that period, saline withdrawals for this purpose increased from 490 to 2,003 Mgal/d. Withdrawals of seawater for thermoelectric cooling account for all the saline withdrawals in Puerto Rico. Freshwater usage for thermoelectric power generation was 0.3 percent of the total water use and was provided by withdrawals from ground water and deliveries from public-supply systems. In 1985, thermoelectric power generated 11,500 gigawatthours. There are four fossil-fueled facilities in Puerto Rico located at Guayanilla, Guaynabo, Salinas, and Toa Baja. Consumptive use during 1985 was estimated to be 1.3 Mgal/d.

Agricultural

Agricultural water use in Puerto Rico was about 165 Mgal/d in 1985. Irrigation accounts for 95 percent of all the water withdrawn for agricultural use. Three major irrigation systems provide water to the south-central, southwestern, and northwestern sections of the island. In the 1960's, the systems consisted of 12 major reservoirs and 387 miles of irrigation and drainage canals that provided water for about 46,000 acres of irrigated land (Bogart and others, 1964). On the southern coast, irrigation generally is needed to raise any crops, whereas, on the northern coast, irrigation may be used to supplement rainfall.

In 1985, water used for irrigation was estimated to be 157 Mgal/d, of which 68.1 percent was provided by surface-water sources and the remaining 31.9 percent was provided by ground-water sources (Solley and others, 1988). About 37,600 acres of land were irrigated. The crops consisted mainly of sugarcane, vegetables, and rice. Conveyance losses amounted to 16 Mgal/d. Consumptive use for irrigation activities was estimated to be about 102 Mgal/d in 1985.

In the last 25 years, irrigation water use has decreased by 42 percent, mainly as a result of a decline in the sugarcane industry. In 1951, about 10,501 million tons of sugarcane were produced, whereas, in 1985, only about 1,271 million tons were produced.

Non-irrigation agricultural water use in 1985 was about 5 percent of the total agricultural water use. In 1985, ground-water withdrawals for livestock use amounted to 8.6 Mgal/d; consumptive use was 100 percent of this amount.

WATER MANAGEMENT

The Puerto Rico Department of Natural Resources (PRDNR), under Law 136 of June 3, 1976—Act for Conservation, Development, and Use of the Water Resources of Puerto Rico—has authority to establish the planning and the administrative mechanisms necessary to guarantee the protection and proper use of water resources. The PRDNR is responsible for preparing, adopting, and maintaining a comprehensive plan for the conservation, development, and use of the water resources of Puerto Rico. The plan, now in preparation, will establish the base and the guidelines to administer a system of permits and franchises for the utilization of these resources.

In 1984, the PRDNR adopted the Regulation for the Appropriation, Use, Conservation, and Administration of the Waters of Puerto Rico. Through this regulation, procedures were established for the granting of permits for the construction of intakes and wells, as well as for systems of aquifer recharge. The system of franchises establishes conditions for water use, including rate of extraction and total volume of water that may be extracted, water-quality tests, and a fee for the right to use the specific amount of water. According to the law and to the prevailing regulations, no person or any public or private entity shall develop a system for the use of the water resources without previous authorization of the PRDNR.

At present, the PRDNR is proposing a law to the Legislature of Puerto Rico that would make the installation of water-saving sanitary equipment in any future construction mandatory. This action, accompanied by an educational program, will generate a savings of about 20 percent of the per capita use—about 10 gal/d per capita. Estimates indicate that about 50 Mgal/d could be saved by the year 2020.

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Prepared by Heriberto Torres-Sierra and Teresita Rodríguez-Alonso, U.S. Geological Survey; History of Water Development and Water Management sections by Felix Aponte, Puerto Rico Department of Natural Resources

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, G.P.O. Box 4424, San Juan, PR 00936

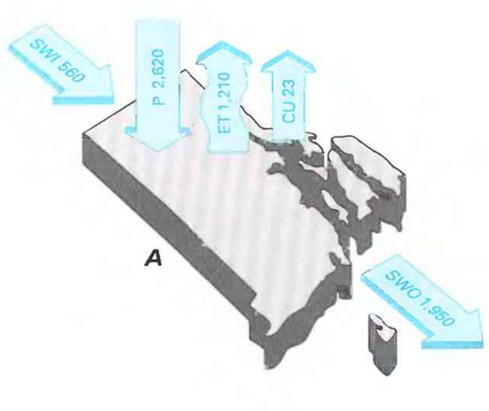
RHODE ISLAND
Water Supply and Use

Rhode Island's abundant precipitation and numerous perennial streams provided a ready source of potable water and power to its early settlers. The abundance of these freshwater resources, together with easy access to commercial sea lanes from the port cities of Providence and Newport, were important in the development of Rhode Island from an agrarian colony in the 1600's to an industrial State during the 1800's and early 1900's. Today, freshwater resources are an important, but less dominant, aspect of the economy of Rhode Island. At the height of the American Industrial Revolution, most of the State's work force was employed by industries that largely depended on water for power and processing. In 1985, most of the State's work force was employed by nonmanufacturing industries that depended less on water.

A generalized water budget for Rhode Island (fig. 1A) shows the abundance of its water resources. The average annual supply of water to Rhode Island is 3,180 Mgal/d (million gallons per day), which is derived from precipitation (2,620 Mgal/d) and surface-water inflows from Massachusetts and Connecticut (560 Mgal/d). This quantity of inflow is sufficient to cover the State's land area of 1,212 square miles to an annual average water depth of 4.6 feet. About 38 percent of the supply is lost by evapotranspiration. The remaining 1,970 Mgal/d comprises surface-water outflows (1,950 Mgal/d) and consumptive use (23 Mgal/d).

Total freshwater withdrawals in Rhode Island in 1985 were 147 Mgal/d, of which 102 Mgal/d was for domestic and commercial use, 40 Mgal/d was for industrial and mining use, and 5.7 Mgal/d was for agricultural use. No freshwater was used in the generation of thermoelectric power. Most of the freshwater was obtained from surface-water sources (81.5 percent); the remainder (18.5 percent) was from ground water. Of the total freshwater used, 15.4 percent was consumed, and the remainder was returned to surface- or ground-water systems for possible additional use.

Rhode Island's reservoir system is the source of water for 76 percent of the State's population. Scituate Reservoir in Providence County, which is part of that system, provides the water supply for Providence and accounts for more than 80 percent of the reservoir storage capacity of Rhode Island (fig. 1B). Demands on some of the State's developed freshwater resources, including Scituate Reservoir, are approaching the available safe yields. The need for additional supplies of water would be even greater had the population growth not slowed in 1970 (fig. 1C). The proposed Big River Reservoir in Kent County, which is in the design stage (1988), could provide most of the projected water demands well into the next century. The reservoir yield of 27 Mgal/d would include required downstream releases, which are not yet defined. However, the onset of an extended drought before completion (7 years to build) and filling (3 years to fill) of the reservoir could result in demands exceeding supplies. The greatest demands would be in the Providence metropolitan



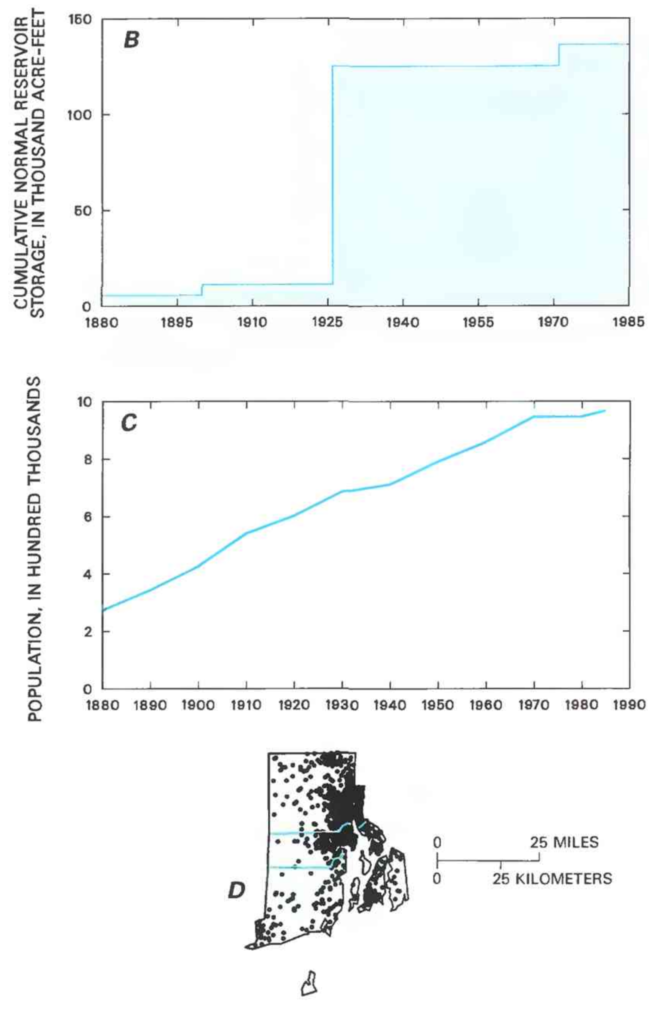


Figure 1. **Water supply and population in Rhode Island.** *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Knox and Nordenson, 1955; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, U.S. Army Corps of Engineers, 1981a. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

area, where most of the State's nearly 1 million people reside (fig. 1*D*).

HISTORY OF WATER DEVELOPMENT

In 1636, Roger Williams and his followers founded the city of Providence, and, within a few years, Newport and several other communities on the shore of Narragansett Bay had been settled. The early settlers obtained their drinking-water supplies from springs and shallow dug wells. As the population of settlements increased, it was common practice to dig community wells in the middle of the streets to provide easy access to drinking water. At the same time, wastewater from homes, tanneries, slaughterhouses, and other commercial enterprises was discharged to nearby ditches and natural drains. Although most water from wells then was considered to be pure and wholesome (Rhode Island Water Resources Board, 1970), these methods of waste disposal probably caused many community wells to become contaminated. Unsanitary conditions resulting from improper waste disposal almost certainly contributed to a violent smallpox epidemic in Newport in 1690 and to yellow fever epidemics in Providence in 1717, 1791, and 1798 (Rhode Island Water Resources Board, 1970).

The epidemics provided incentives for development of public water-distribution systems. The first of such water-distribution systems was constructed following issuance of charters of incorporation by the State legislature in 1772 to three companies known as Fountain Societies. These societies sold water to customers in Providence through distribution systems constructed of drilled wooden logs. In 1871, the first public-supply system in Rhode Island went into service, when water piped from the Pawtuxet River was used to supply Providence. Thirteen years later, reservoirs and public-supply systems also had been built to serve three other Rhode Island communities—Newport, Pawtucket, and Woonsocket (Rhode Island Water Resources Board, 1970). In 1926, the Scituate Reservoir was completed in the headwaters of the Pawtuxet River; it replaced the mainstem of the Pawtuxet River as the source of supply for Providence.

Limited industrial use of water in Rhode Island began when early settlers built dams to provide power for gristmills and sawmills. The major period of industrial water use began following establishment of the Nation's first successful cotton mill in 1793 at the beginning of the American Industrial Revolution. During the 1800's, hundreds of dams were constructed to provide water for power, processing, and waste disposal for a booming textile industry. Many of these dams created reservoirs of small to moderate size (generally smaller than 5,000 acre-feet). The textile industry boom peaked about 1881 and ended about 1910 (Jones, 1981, p. 4).

The State's streams were little used for commercial transport of goods. A major canal system was built along the Blackstone River in the early 1800's to provide transportation of articles of trade inland from the Providence. This system of canals was abandoned about 1830, soon after its completion, because more efficient railroad transportation systems were developed.

Ground water was not used extensively for other than domestic purposes in Rhode Island until methods of well drilling and pumping were improved in the early 1900's. Since then, many wells have been drilled for industrial use, mainly for cooling and process water, and most shallow dug wells that supplied drinking water to homes have been replaced by deeper drilled wells. The use of ground water as a source for public-supply systems did not become common until after World War II.

WATER USE

A comparison of freshwater withdrawals by county indicates that total withdrawals and total surface-water withdrawals from Providence County substantially exceeded those of other counties (figs. 2*A*,*B*). About two-thirds of the freshwater withdrawals from Providence County was from Scituate Reservoir. The largest ground-water withdrawals were in Washington County, which has large reserves of water available from sand and gravel aquifers of glacial origin. The smallest ground-water withdrawals were in Bristol and Newport Counties, where ground-water resources are limited (fig. 2*C*).

Virtually all fresh surface-water withdrawals in Rhode Island are from the Massachusetts–Rhode Island Coastal basin (fig. 3*A*). Of the 120 Mgal/d of surface-water withdrawals from this basin, 83.9 percent was withdrawn by public suppliers. The largest ground-water withdrawals (21 Mgal/d) were from the stratified-drift aquifers (fig. 3*B*). These aquifers are composed of extremely permeable sand and gravel deposits that underlie most of the State's major river valleys. The remaining ground-water withdrawals (6.1 Mgal/d) were from the till and bedrock aquifers.

The source, use, and disposition of water in Rhode Island in 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that surface water supplied most (81.5 percent) of the 147 Mgal/d of freshwater used offstream and that surface water was the source of 86.7 percent of the water distributed by public-supply systems. The dominant use of freshwater was to supply domestic and commercial needs (69.2 percent), whereas most of the remainder was used by industry (26.9 percent). Water use for mining was negligible. Water used by by agriculture was less than 5 percent of the total water used. About 15.4 percent of the water used was consumed, about 84.6 percent was returned to streams or to the ground and became available for reuse.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. A public water-supply system in Rhode Island is any system that has at least 15 service connections that regularly serve 25 or more people for 60 days or more during the year. There were more

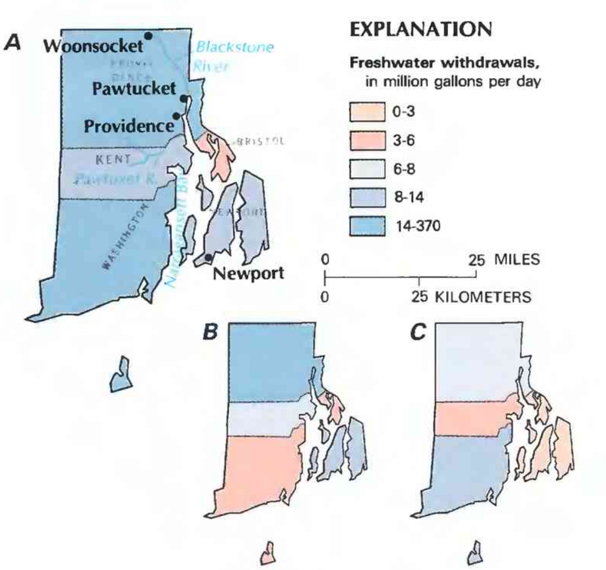


Figure 2. Freshwater withdrawals by county in Rhode Island, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

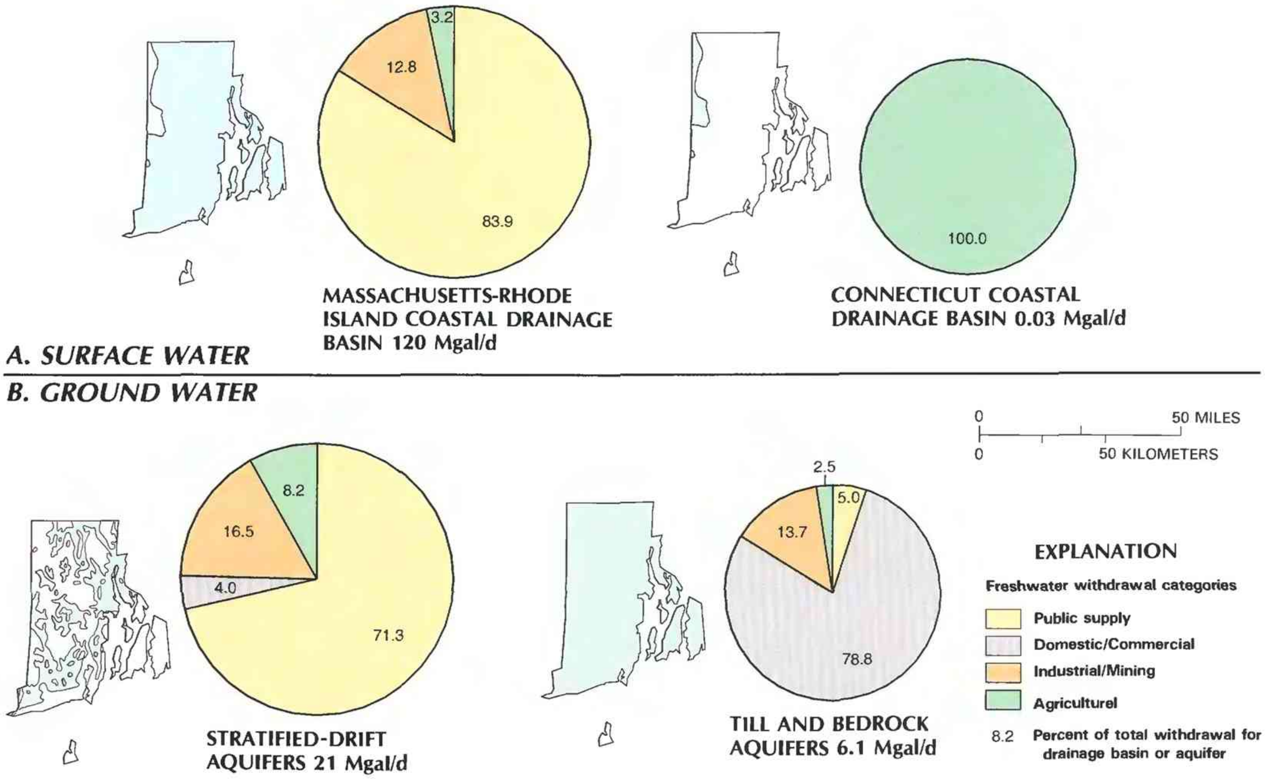


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Rhode Island, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System: *B*, Data from U.S. Geological Survey files.)

than 400 such systems in 1985. Most of the water supplied to the 884,100 people on public-supply systems was distributed by 25 major systems owned and operated by municipalities, county water authorities, fire districts, and private companies. Most of the remaining systems furnish water to State institutions, nursing homes, condominiums, and small housing developments.

By far, the largest public-supply system in Rhode Island is that owned and operated by the Providence Water Supply Board. This system obtains its water from Scituate Reservoir and five feeder reservoirs, which have a combined yield of 77 Mgal/d, after minimum downstream releases of 12 Mgal/d (U.S. Army Corps of Engineers, 1981b, table 14). This system distributed 68 Mgal/d to users in Providence and Kent Counties in 1985 and provided water to 50 percent of the State's population.

Freshwater withdrawals and deliveries by public water-supply systems in 1985 averaged 116 Mgal/d—86.7 percent (101 Mgal/d) from surface water and 13.3 percent (15 Mgal/d) from ground water. Of that water, 82.9 percent was distributed to meet domestic and commercial needs, and the remaining 17.1 percent was distributed to industrial users. No water from public-supply systems was used for cooling by thermoelectric powerplants.

All the major public-supply systems that depend wholly or partly on surface water obtain their supplies from reservoirs. All the major public-supply systems that rely partly or wholly on ground water obtain their water from wells in stratified-drift aquifers.

The population served by public-supply systems increased from 864,000 in 1980 to 884,000 in 1985, an increase of 2.3 percent. Although the population increased, water distributed by public-supply systems was 11 percent less in 1985 (116 Mgal/d) than in 1980 (130 Mgal/d). Of the 14-Mgal/d decrease, 9 Mgal/d was surface water, and 4 Mgal/d was ground water. The overall decrease is attributed to a decrease in industrial use.

Domestic and Commercial

Combined domestic and commercial use of water in 1985 averaged 102 Mgal/d and accounted for 69.2 percent of total freshwater use (fig. 4). Of this total, 64 Mgal/d was for domestic use, and 15 Mgal/d was for commercial use. Water lost in conveyance or delivered for public use (fire fighting) accounted for the remaining 23 Mgal/d. Ninety-one percent of the State's population and most of its commercial establishment obtained water from public-supply systems.

An estimated 84,000 people obtained their domestic drinking-water supplies from about 31,000 private wells. Well records available in the Rhode Island Office of the U.S. Geological Survey indicate that most domestic wells are completed in bedrock aquifers. However, an accurate accounting of the number of domestic wells that obtain water from bedrock, till, and stratified-drift aquifers is not available. Till aquifers, which overlie bedrock aquifers in about two-thirds of the State, are minor sources of water. Most of the water pumped from wells in areas where bedrock aquifers are overlain by till aquifers is believed to be from bedrock. Till aquifers generally are no more than 10 to 25 feet thick and provide small, commonly unreliable supplies to wells.

Domestic use of water by customers served by public-supply systems ranged from 60 gal/d (gallons per day) per capita in Washington County to 81 gal/d per capita in Kent County; the statewide average was 70 gal/d per capita. Use by families with private wells is estimated to average 67 gal/d per capita.

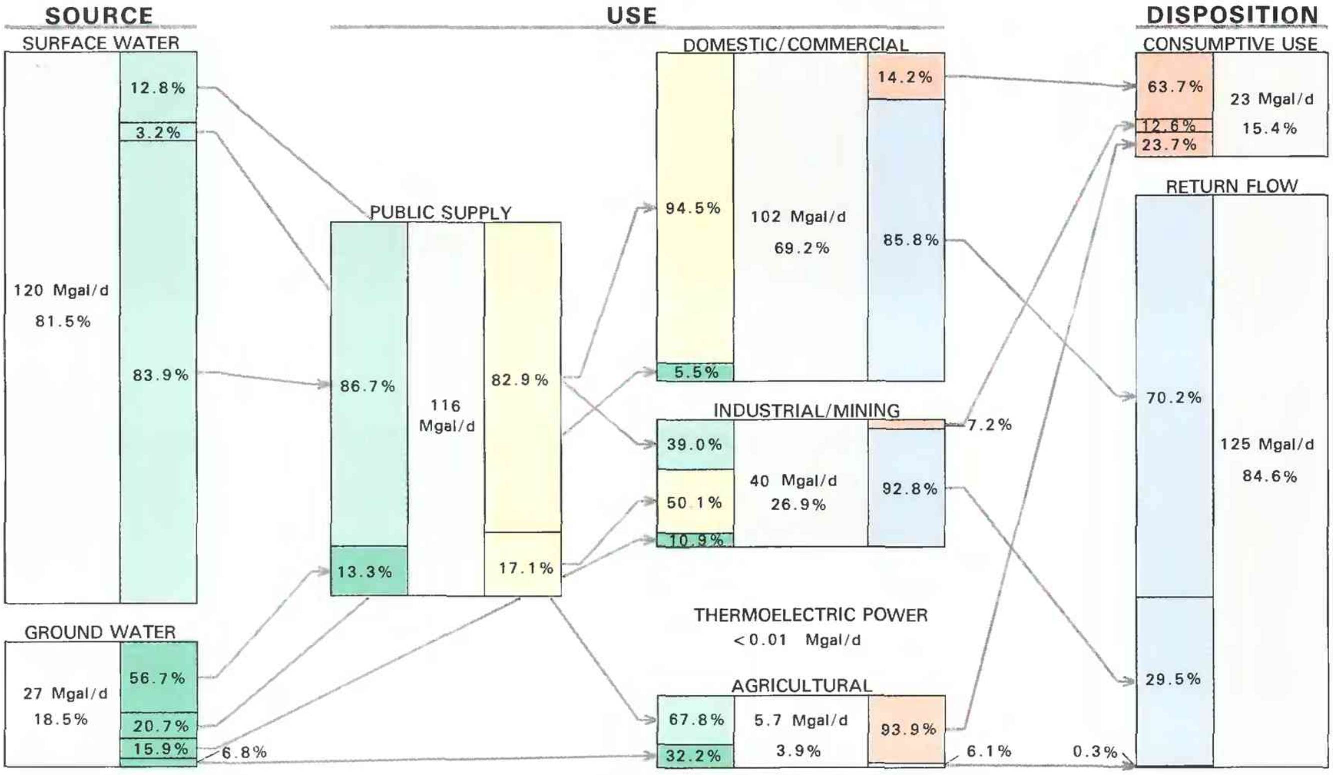


Figure 4. Source, use, and disposition of an estimated 147 Mgal/d (million gallons per day) of freshwater in Rhode Island, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Industrial and Mining

Industry and mining operations accounted for 26.9 percent of the freshwater used in Rhode Island in 1985 (fig. 4). Industry used 37 Mgal/d, and mining operations used 2.7 Mgal/d. Industry obtained a little more than one-half (19.9 Mgal/d) of its water from public-supply systems; the balance (17.1 Mgal/d) was self-supplied. Of the self-supplied water, 13.2 Mgal/d was surface water, and 3.9 Mgal/d was ground water. Industry also used 0.17 Mgal/d of saline surface water. Most of the water used by industry is used for noncontact cooling, washing, and processing.

Of industrial water use, 85 percent is in Providence and Kent Counties, where the principal users are the textile, jewelry, and fabricated metal products industries. Historical records of industrial water use are incomplete, but available data indicate decreasing quantities. Self-supplied industrial water use decreased 43 percent (from 35 to 20 Mgal/d) between 1980 and 1985. Water distributed to industries and commercial facilities by public-supply systems decreased 30 percent (from 50 to 35 Mgal/d) between 1980 and 1985 (Solley and others, 1983, 1988). Most of this decrease is believed to have been in industrial water use and probably is related, in part, to conservation measures implemented by many industries to cope with the increased cost of disposing of wastewater.

All the water used for mining was self-supplied; 84 percent was from surface-water sources, and 16 percent was from ground-water sources. Mining activities in 1985 included operation of a single limestone quarry and several sand- and gravel-washing operations. About 7 percent of the water used for industry and mining was consumed.

Thermoelectric Power

All water used in the generation of thermoelectric power in Rhode Island in 1985 was saline. Virtually all the 261 Mgal/d used for this purpose was withdrawn from the headwaters of Narragansett Bay at Providence to provide cooling water for two fossil-fueled powerplants. These two plants produced 98 percent of the 548 gigawatthours of thermoelectric energy produced in Rhode Island in 1985. Two smaller fossil-fueled thermoelectric plants, which produced the balance of this energy, used little or no water. About 1 percent (2.6 Mgal/d) of the water withdrawn was consumed by evaporation.

In northern Rhode Island near Massachusetts, construction of a natural gas thermoelectric plant that would require 4 Mgal/d of freshwater has been proposed. All the freshwater would be lost by evaporation. The Blackstone River is being evaluated as a primary source of cooling water for this plant. Scituate Reservoir also is being considered as an alternate source for cooling water. In 1986, a State law was enacted that will permit the Providence Water Supply Board to transfer water by pipeline from Scituate Reservoir to this proposed plant (Rhode Island Statewide Planning Program, 1986, p. 22).

Agricultural

In the 1700's and 1800's, about 80 percent of Rhode Island's area was farmland. Since then, however, the percentage of land devoted to farming has decreased steadily. In 1984, about 11 percent (73,000 acres) of the State was farmland, and 4 percent (31,000 acres) was cultivated. In 1985, the value of agricultural products produced in Rhode Island was $105 million, of which 71 percent was accounted for by nurseries, lumbering (fuel wood and sawmills), and turf farms (Volpe, 1986).

The small amount of land under cultivation, in combination with precipitation that is normally abundant and evenly distributed, result in relatively small water use by agriculture. In 1985, agricultural water use averaged 5.7 Mgal/d, of which 60 percent (3.4 Mgal/d) was used to irrigate crops and 40 percent (2.3 Mgal/d) was used for livestock watering and other nonirrigation purposes. Two-thirds of the water used by agriculture was pumped from streams and ponds; all the rest was obtained from wells. Of the water used for agricultural purposes, 93.9 percent was estimated to be consumed.

Most of the water used for irrigation in 1985 was applied to potatoes and turf by sprinkler-irrigation methods. The 4,500 acres used to grow these two crops in 1985 accounted for about 15 percent of the cultivated land in Rhode Island. Most of the water used for irrigation in 1985 was in Washington County, where 2.3 Mgal/d was used for this purpose. Much of the land in Washington County that was formerly used to grow potatoes is now (1987) being converted to growing turf, a crop that is more profitable but requires more water.

WATER MANAGEMENT

Because of the abundance of freshwater resources in Rhode Island, few laws or regulations have been established to manage water use. Few regulations govern withdrawals of surface water, and none relate to withdrawals of ground water. Supply problems commonly have been resolved by extending distribution lines from existing public-supply systems to areas of need or by development of new sources of supply. The principal mechanism used by public water-supply agencies to manage water use during prolonged drought has traditionally been the imposition of water-use restrictions.

Controversies involving water rights in Rhode Island historically have been resolved by the courts, which have relied on the common-law doctrine of riparian rights. The riparian-rights doctrine essentially accords to owners of property bordering streams the right to have the water flow past their properties undiminished in quantity and quality. These property owners also have the right to put the water to a reasonable and beneficial use.

State agencies whose regulations and policies affect water use in Rhode Island include the Department of Administration, Division of Planning (DA/DP), the Water Resources Board (WRB), the Public Utilities Commission (PUC), the Department of Environmental Management (DEM), and the Department of Health (DH). In 1986, revisions to Rhode Island General Laws (RIGL) transferred to the DA/DP several water-related authorities and responsibilities previously assigned to the WRB. These include (1) the responsibility for long-range planning for development of major water resources and transmission systems needed to furnish water to regional or local public water systems, and (2) the authority to provide for cooperative development, conservation, and use of water resources by the State, municipal agencies, the WRB, and privately owned public water systems. The DA/DP is also responsible for developing plans to provide safe drinking water to the State's inhabitants when a water emergency has been declared by the governor. Authority to implement water-emergency plans, which may include the imposition of conservation measures and the allocation of water supplies, rests with the governor (RIGL 46–15–6).

The WRB, whose responsibilities include the development of public water-supply facilities, is empowered to acquire sites for reservoirs, dams, treatment plants, transmission lines, and other facilities, within limits of approved funding (RIGL 46–15–6). The PUC is an arbiter of rates charged by public water-supply systems and public sewer systems (RIGL 39–11, 39–21). In this role, the PUC affects the quantity of water use by the water rates it approves. The DH is responsible for ensuring the quality of all public water systems in Rhode Island. No source of water can be developed for a public water system without approval of the director of the DH (RIGL 5–8).

The DEM, in its role as the State's principal water-pollution control agency, also affects water use to the extent that it controls point-source discharges of wastewater to the State's waterways. Implementation of the DEM's waste-water permit system, which is related to the quality of the discharge and waste-load allocations to streams, probably is partly responsible for the decrease of water use by industry between 1980 and 1985. The increased cost of wastewater disposal may have inspired more efficient use and reuse of water by industry. Also, some marginally efficient manufacturing plants may have closed rather than invest in equipment needed to treat wastewater.

One of the most controversal water issues in Rhode Island is associated with the construction of the proposed Big River Reservoir in Kent County which, like Scituate Reservoir in Providence County, is in the headwaters of the Pawtuxet River. There is concern that, if the construction of the reservoir is not begun soon, demands for water in northern and central Rhode Island soon will be greater than available supplies (P.P. Calise, Rhode Island Water Resources Board, oral commun., 1987). There is also a possibility that its construction will harm the environment. Out-of-basin transfers of water from the proposed Big River Reservoir and Scituate Reservoir will diminish flows of the Pawtuxet River, thereby diminishing its capacity to dilute wastewater discharges to its own downstream reaches. In 1985, municipal and industrial wastewater discharges to the Pawtuxet River averaged 24.5 Mgal/d, which, at low flow, constituted about one-half of the flow of the river near its mouth. The 7-day, 10-year low flow of the Pawtuxet River about 4 miles upstream from its mouth is 47 Mgal/d.

Documentation of water use in Rhode Island is sparse. Four State agencies—the DH, the WRB, the DEM, and the DA/DP—collect selected water use data; the U.S. Army Corps of Engineers has collected and published data on industrial and commercial water use from public supply systems (U.S. Army Corps of Engineers, 1986); and the U.S. Geological Survey has compiled estimates of water use in Rhode Island every 5 years since 1950 (MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988). However, the State does not have a comprehensive program of on-going water use data collection, and most of the available water-use data are not in computerized data bases.

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Prepared by Herbert E. Johnston and Michael J. Baer

FOR ADDITIONAL INFORMATION: Office Chief, U.S. Geological Survey, John O. Pastore Federal Building and U.S. Post Office, Providence, RI 02903–1720

SOUTH CAROLINA
Water Supply and Use

South Carolina's ample supply of freshwater (fig. 1*A*) is sufficient to meet all the State's current water use needs. The statewide average annual precipitation is more than 48 inches (Snyder and others, 1983). The average annual runoff ranges from 10 inches in the southeastern one-half of the State to about 50 inches in the northwestern section, and the annual potential evapotranspiration ranges from 29.6 inches near Spartanburg to 46.6 inches at the southern tip of the State (U.S. Geological Survey, 1986). In 1985, 6,810 Mgal/d (million gallons per day) of freshwater was withdrawn from South Carolina's streams, rivers, lakes, and aquifers; of that amount, about 5.0 percent was consumed and 95.0 percent was returned to natural water sources for future use.

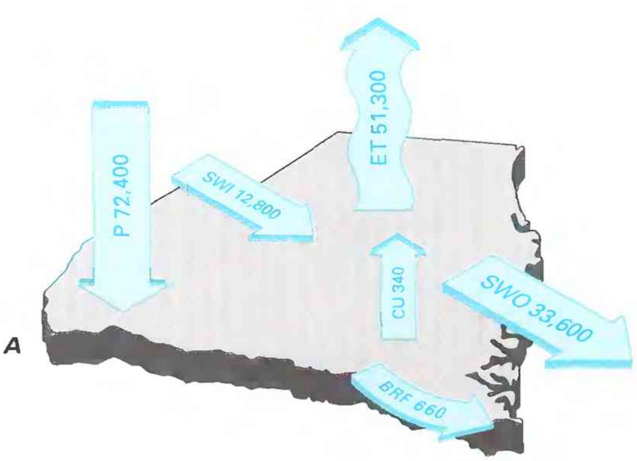
Surface-water withdrawals occur throughout the State, and ground-water withdrawals are largest in the southeastern part of the State. In the northwestern part of South Carolina, urban and industrial users rely primarily on surface water, and rural users rely primarily on ground water. In the southeastern part of the State, surface water supplies some industrial and agricultural needs, but ground water is the primary supply for urban, industrial, and agricultural regions. This area is underlain by four aquifers. Wells completed in these aquifers are capable of producing from 700 to 2,000 gallons per minute.

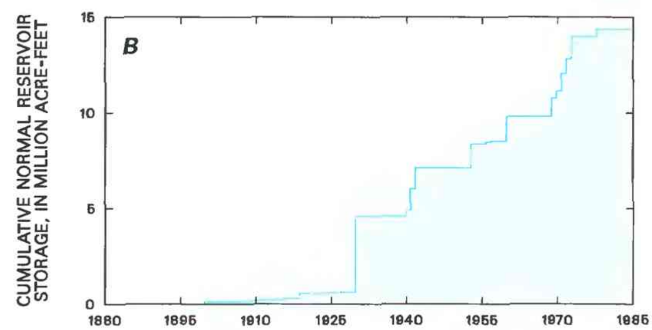
In 1985, water withdrawn directly (self-supplied) for domestic, commercial, industrial, and mining uses totaled 1,230 Mgal/d. Of the total surface- and ground-water withdrawals, 76.0 percent was for thermoelectric power generation; this use accounted for 16.3 percent of consumptive water use in the State. In contrast, 0.6 percent of total surface- and ground-water withdrawals was for agriculture, which accounted for 12.9 percent of consumptive use.

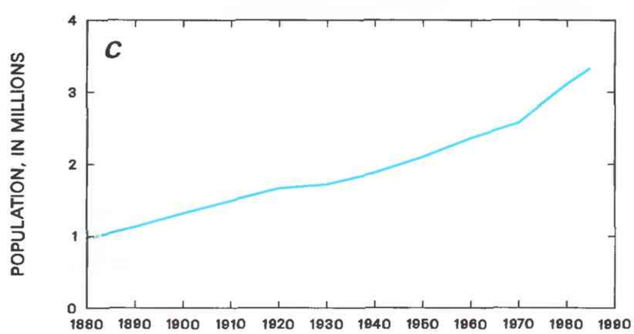
The first major dam was constructed in 1900 to help meet the needs of increasing population; within 30 years, water storage had increased 3,000 percent (fig. 1*B*). From 1970 to 1985, South Carolina's population increased 29 percent (fig. 1*C*), from 2.60 million to 3.35 million. State officials have predicted that, by the year 2000, the population will be 4.12 million, an increase of 58 percent since 1970 (South Carolina Division of Research and Statistical Service, 1986). The population distribution for 1985 is shown in figure 1*D*. By the year 2000, water use is expected to increase by 195 Mgal/d statewide; most of this increase will be the result of the growth of population and tourism. This growth, in turn, will increase domestic and commercial demand, as well as irrigation for crops (Strom Thurmond Institute, 1987). Domestic water use is projected to account for 21 percent of the water use in the State, and irrigation use will account for 15 percent of daily water use during the summer. The only expected decrease in water use is industrial use, which is predicted to decline 6 percent by the year 2000 (Strom Thurmond Institute, 1987).

HISTORY OF WATER DEVELOPMENT

"That Blessing Divine Providence Intended" was the description used by some South Carolinians 175 years ago to describe the







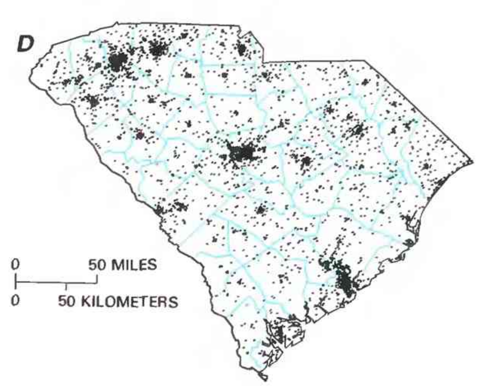


Figure 1. Water supply and population in South Carolina. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Data from U.S. Geological Survey files. *B*, U.S. Army Corps of Engineers, 1981. *C, D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

water resources of South Carolina. The great rivers that flowed into the Atlantic Ocean—the Savannah, the Pee Dee, the Santee, and the Cooper—had beckoned people to sail into the interior from the settlement of the first colony in 1670. The colonists first used the rivers as avenues to trade with the Indians and then to transport farm products to Charleston. For the early settlers, these inland waterways were an indispensable means of communication, transportation, and trade.

Other uses for the abundant water resources began to develop—rice culture during 1700–1900, power for mills and hydroelectric plants, irrigation, domestic and industrial supplies, transport and dilution of wastes, recreation, and commercial and recreational fishing. The 48-inch average rainfall in the State and the volume of surface water available were sufficient to meet all the demands. Water has been significant to South Carolina's history and economy.

Past efforts have partly developed the State's water resources. During 1817–28 the State embarked on a program to improve streams and build canals for navigation that ended with eight canals and 2,400 miles of improved streams. In the mid-1800's, inland navigation was at its maximum development and use, but entry into the railroad age started the decline of inland navigation in South Carolina. Many of the inland waterways were not maintained and quickly became unusable. Steamships continued to navigate the Pee Dee, the Catawba–Wateree (in the Edisto–Santee basin), the Santee, and the Savannah Rivers but never on a regular basis.

Beginning in the 1880's, the State experienced a rapid increase in the development of hydroelectric power. The northwestern one-half of the State was ideally suited for this type of development, because of its abundance of free-flowing water and relatively large land-surface relief. Industry quickly took advantage of the conditions and built factories that had hydropower facilities at many of the available sites, thus providing each factory with its own source of electricity (Snyder and others, 1983). A milestone in South Carolina's hydropower development was the transmission of power in Anderson County from Portman Shoals to Anderson in 1897, the longest electric power transmission in the United States at the time (Confederation of South Carolina Local Historical Societies, 1978).

Early textile mill development was linked to the need for water power, whereas later industrial development was linked to the need for water as part of the industrial process and for waste disposal. Because of the abundance of water throughout the State, adequate water supplies never were a factor in the location of industry or the development of cities. Presently (1987), certain municipalities are beginning to have some difficulty in guaranteeing adequate water supplies.

WATER USE

The State's water budget (fig. 1A) shows the quantity of water that flows to and from the State. The substantial supply of clean incoming freshwater is sufficient to meet the current demands for water, which differ across the State.

Total freshwater withdrawals by county in South Carolina are shown in figure 2A. The largest concentrations of population are in Greenville, Charleston, Richland, and Spartanburg Counties, which contain one-third of the State's population and withdraw 50 percent of the water used for public supply. Industrial water use is evenly distributed across the State, with the exception of Aiken County where the Savannah River Plant accounts for more than one-half of the statewide industrial water use. The largest industrial water users produce chemical and allied products; the second largest produce paper and related products. Agricultural irrigation is greatest in a band from southwest to northeast through the middle of the Coastal Plain (the southeastern one-half of the State), whereas withdrawals for sand-and-gravel mining are greatest in the northeastern corner of the State.

Surface- and ground-water withdrawals by county (figs. 2B,C) reflect the dependence on surface water in the northwestern part of the State, and the abundance of ground water southeast of the Fall Line (fig. 2A) in the Coastal Plain. Of the major river basins (fig. 3A), the largest surface-water withdrawals are in the Ogeechee–Savannah and the Edisto–Santee basins. Both basins support large withdrawals for thermoelectric power; the Ogeechee–Savannah basin, however, also supports a large concentration of industry, whereas the Edisto–Santee basin supplies a large popula-

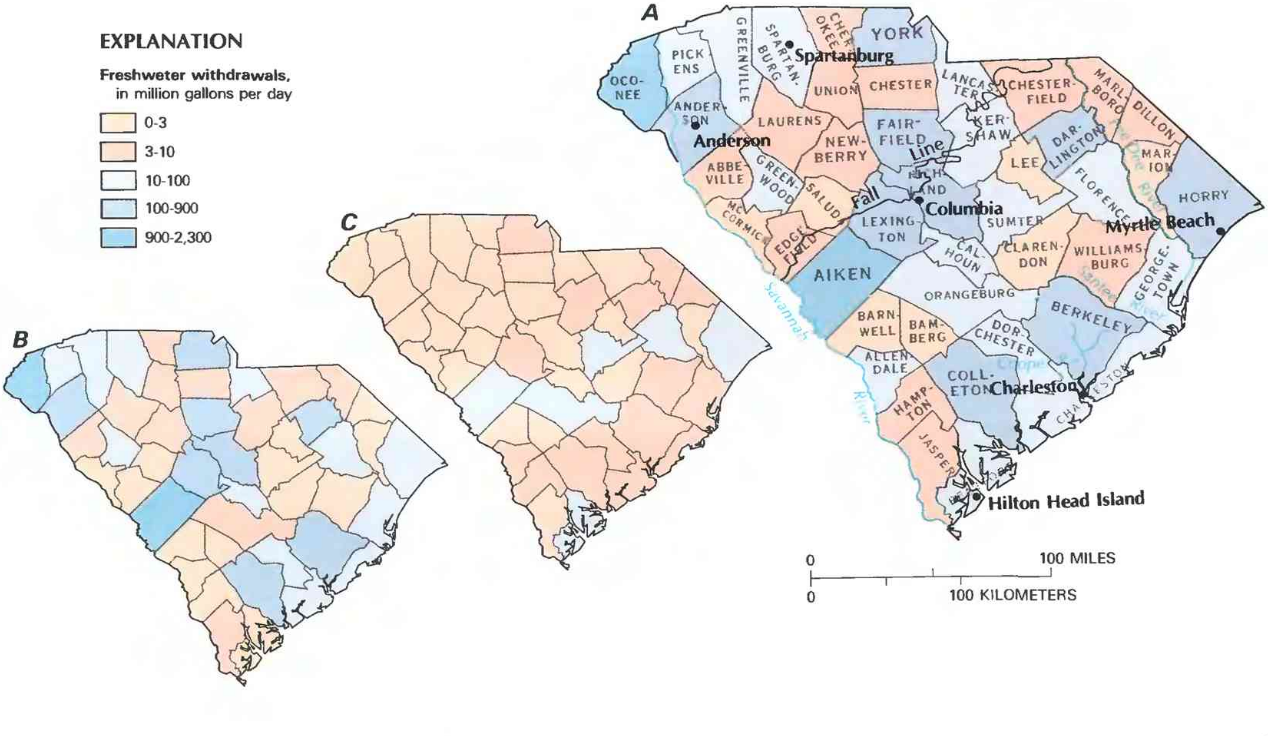


Figure 2. Freshwater withdrawals by county in South Carolina, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

tion. Withdrawals are predominantly ground water southeast of the Fall Line where public supply accounts for about 35 percent of the total ground-water withdrawals (fig. 3*B*). Of this quantity, Horry and Beaufort Counties use 39 percent.

Instream use also is important in South Carolina's development. The adequate, dependable water sources have affected the growth of many of the State's industries; for example, the largest instream use of water is for hydroelectric power generation. In 1985, 38 hydroelectric powerplants used a total of 42,100 Mgal/d. This instream use is more than six times greater than all the combined offstream uses. Nearly all hydropower water use is in the northwestern region, except for two stations on Santee–Cooper Lakes in Berkeley County. Hydropower is an efficient method of producing electricity, and efforts are being made by the electric-power companies to utilize it fully. In recent years, however, difficulties have arisen with the production of electricity from hydropower because of drought conditions and low reservoir levels. Consequently, less hydroelectricity was generated in 1985 than in 1980. About 5 percent of the State's electricity was produced by hydropower in 1985 compared with 7 percent in 1980.

The source, use, and disposition of freshwater in South Carolina are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The

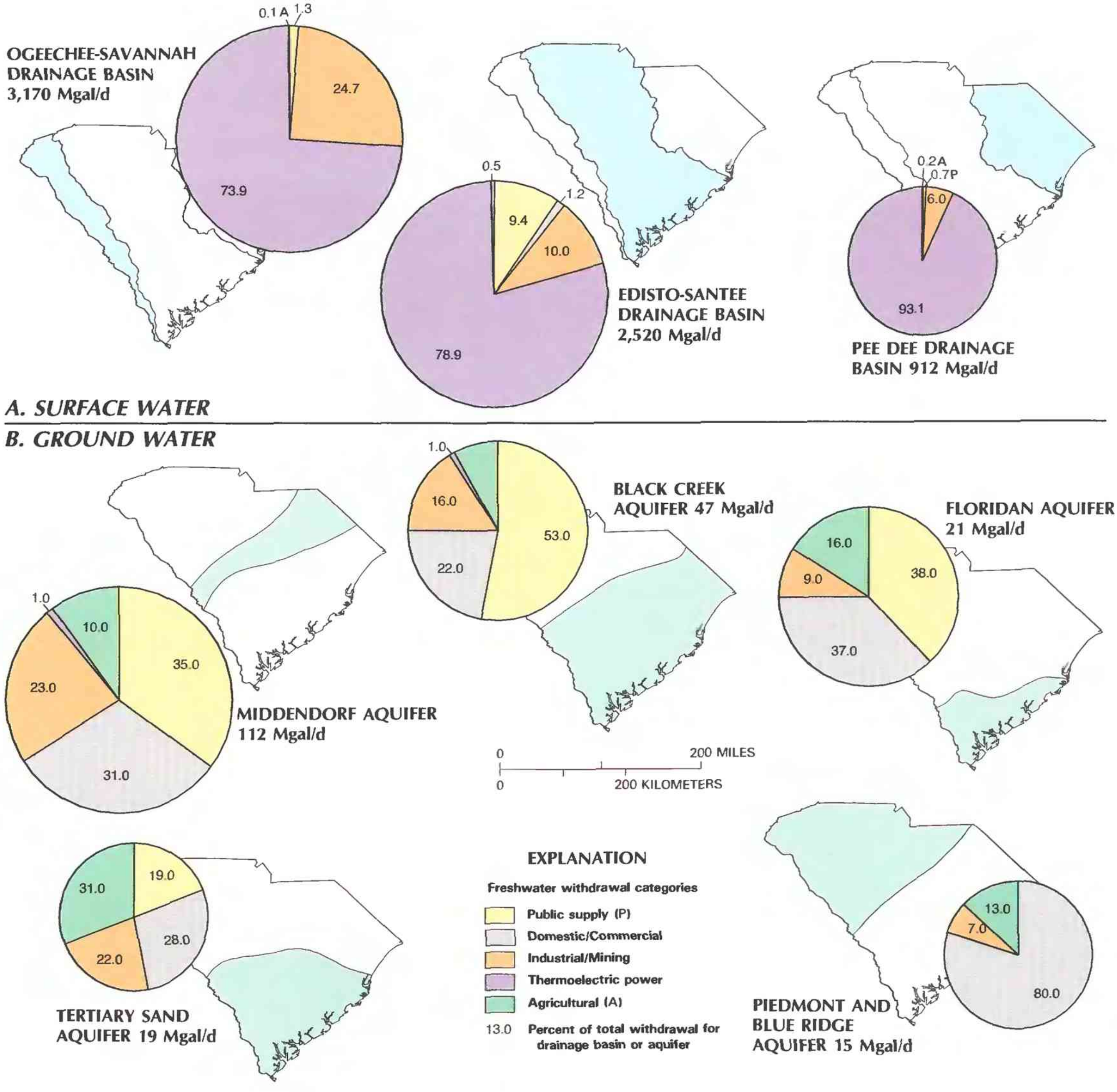


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in South Carolina, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey reports and files.)

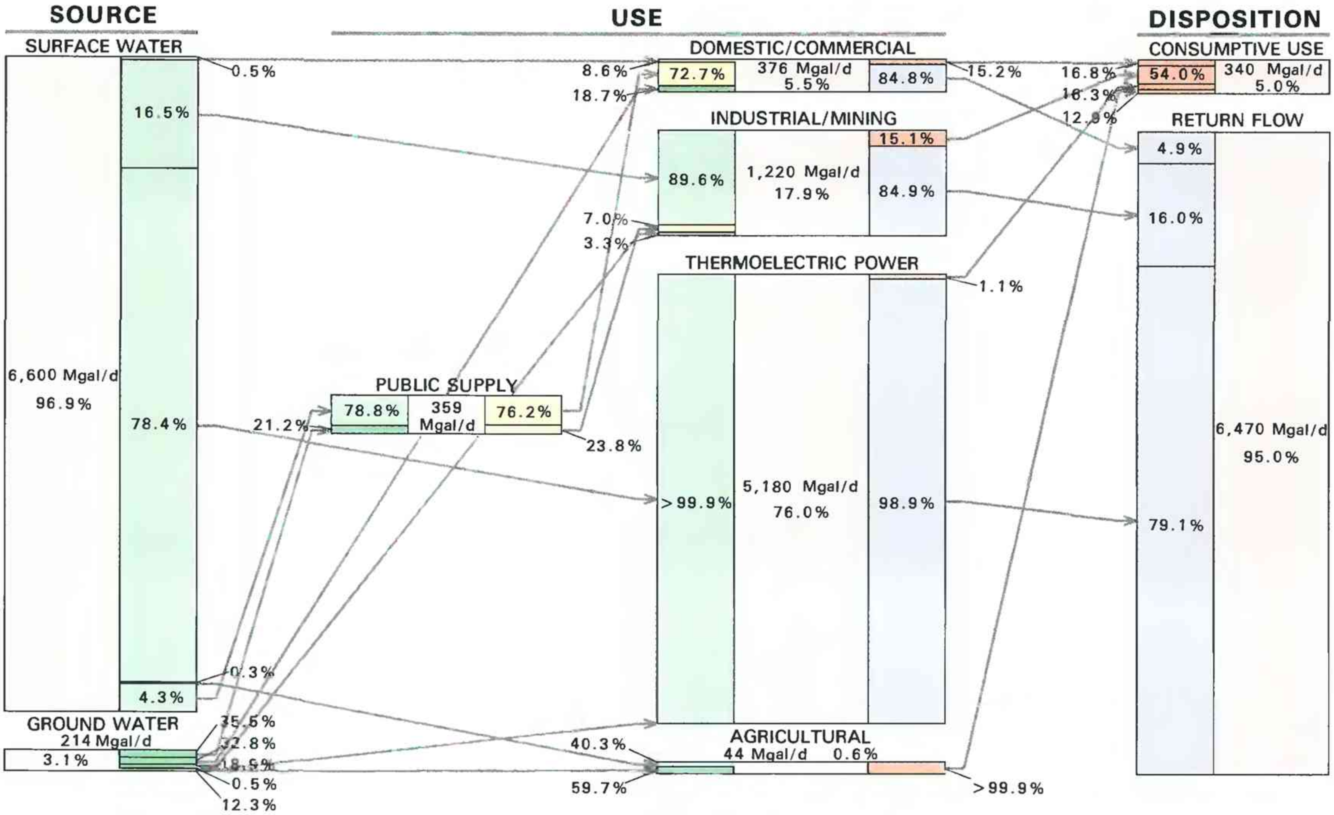


Figure 4. Source, use, and disposition of an estimated 6,810 Mgal/d (million gallons per day) of freshwater in South Carolina, 1985. Conveyance losses in public-supply systems and some public water uses, such as fire fighting, are included in total shown for domestic and commercial use; losses for irrigation distribution systems are included in total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

source data indicate that the 6,600 Mgal/d of surface water withdrawn is 96.9 percent of the total withdrawals. Of the surface water withdrawn, 0.5 percent is directly withdrawn (self-supplied) for domestic and commercial use, 16.5 percent is withdrawn for industrial and mining use, 78.4 percent is withdrawn for thermoelectric power generation, 0.3 percent is withdrawn for agriculture, and 4.3 percent is withdrawn for public-supply systems. Saltwater, another source of water in South Carolina, is not included in figure 4, but is included in the discussion of thermoelectric power. The use data indicate, for example, that industry and mining used 1,220 Mgal/d, which represents 17.9 percent of the State's total withdrawals. Of that 1,220 Mgal/d, 89.6 percent is self-supplied from surface-water sources, 7.0 percent is from public-supply systems, and 3.3 percent is self-supplied from ground-water sources. Of the total industrial and mining quantity used, 15.1 percent is consumed, and 84.9 percent is returned to a natural water source where it is available for additional use. The disposition data indicate that, for all water withdrawn in South Carolina, 5.0 percent (340 Mgal/d) is consumed, and 95.0 percent (6,470 Mgal/d) is returned. Industrial and mining use accounted for 54.0 percent of the consumptive water use and 16.0 percent of all return flow.

The quality of water is a major concern in the State. Ground-water quality is adequate for most uses. Contamination of ground water generally is localized and is associated with chemical spills, waste disposal, and saltwater contamination. Withdrawals in Savannah, Ga. (located just south of Jasper County, S.C.), have produced a cone of depression that extends into southern South Carolina. Water levels in the Floridan aquifer system on Hilton Head Island are now below sea level. This condition has created the potential for saltwater intrusion at and north of Port Royal Sound, which is just north of the island. Increased pumping on Hilton Head Island also has contributed to the water-level declines. Ground-water supplies in the Myrtle Beach area also may be affected by saltwater intrusion. Large withdrawals by public supply in that area have lowered water levels in the Black Creek aquifer, but a clay confining bed has prevented saltwater from entering the aquifer. However, lowered water levels have created the potential for lateral and upward intrusion of saltwater.

Public Supply

In 1985, the largest use of public-supply water was for domestic purposes. Public-supply withdrawals increased slightly from 21 percent of total water withdrawals (excluding thermoelectric power generation) in 1980 to 22 percent in 1985. From 1960 to 1985, South Carolina's population increased 40 percent (fig. 1*C*), and withdrawals for public supply increased 94 percent. The larger increase in withdrawals for public supply compared to population growth can be attributed partly to industrial and commercial growth during the same period. In an attempt to bring more industry into the State, many cities offer to supply water to industrial facilities.

Withdrawals for public supply in 1985 totaled 359 Mgal/d, of which 78.8 percent (283 Mgal/d) was surface water and 21.2 percent (76 Mgal/d) was ground water (fig. 4). The surface-water sources are located primarily in the northeast and in the more populated areas of the southeast. The southeastern area, the Coastal Plain region, has many excellent aquifers capable of storing and transmitting large quantities of water. All large ground-water withdrawals occur in this region. The counties that have the largest ground-water withdrawals are, in decreasing order, Horry, Beaufort, Sumter, and Florence. In contrast, limited quantities of ground water are withdrawn in the northwestern area of the State, where most of the State's population is located. This area is underlain by metamorphosed sedimentary, volcanic, and igneous rocks that yield small supplies of ground water. For this reason, most large towns and cities in the northwest depend on surface water, which supplies more than 99 percent of the water used in the area.

Public-supply systems consist of complex networks that withdraw, treat, transfer, buy, and resell water. They are primarily publicly owned and associated with municipalities, counties, or rural water districts. As a rule, the counties that purchase the greatest amount of water for public supply are, or adjoin, the counties that have the greatest surface-water withdrawals. The city of Charleston, which is the largest public supplier in the State, receives most of its surface-water deliveries from neighboring Dorchester County. Public suppliers that have access to dependable sources of water commonly expand their water-treatment plants and sell water to public suppliers whose water sources are insufficient. Also part of the water network in South Carolina are the 675 wastewater-treatment facilities that release a total of 270 Mgal/d of treated wastewater. This water is a valuable asset to the State, especially during drought when smaller surface-water supplies are depleted.

Domestic and Commercial

Domestic and commercial water users obtained 376 Mgal/d (fig. 4) of water from self-supplied facilities and public-supply systems. This total included 78 Mgal/d for public use and losses and 251 Mgal/d for domestic use. Of the amount for domestic use, 189 Mgal/d was delivered by public-supply systems that served 75 percent of the population, and the remaining 62 Mgal/d was self-supplied from wells. A per capita use of 75 gal/d (gallons per day) was assumed for those domestic users who were self-supplied (Kammerer, 1976, p. 56). Domestic consumptive use was 50 Mgal/d.

Commercial withdrawals in 1985 were 47 Mgal/d; 41 Mgal/d was provided by self-supplied systems, and the remaining 6 Mgal/d was provided by public-supply facilities. Commercial consumptive use was 7.1 Mgal/d. Although commercial water use is relatively small compared to other categories, it is an important category that is expected to increase in the future because of increases in population and tourism (Strom Thurmond Institute, 1987, p. 4).

Industrial and Mining

In 1985, industrial and mining use in South Carolina totaled 1,220 Mgal/d (fig. 4). Industrial water use (1,210 Mgal/d) was the second largest use in the State and the eighth largest in the United States. Self-supplied systems withdrew 1,090 Mgal/d of surface water and 38 Mgal/d of ground water for industrial use. Self-supplied systems also provided 2 Mgal/d of surface water and 3 Mgal/d of ground water for mining activities. In addition, 86 Mgal/d was purchased by industry from local public suppliers and other industries. Since 1980, total industrial and mining water use increased 224 Mgal/d, or 23 percent. Consumptive use was 15.1 percent (184 Mgal/d).

Surface-water withdrawals for industry are similar throughout the State. Facilities producing chemical and allied products dominate industrial water use; the Savannah River Plant in Aiken County is the largest user in this water use category. About 70 percent of the total surface water used by industry was withdrawn by the Savannah River Plant.

Thermoelectric Power

South Carolina ranks 12th in the Nation in the withdrawal of water for the production of electricity by thermoelectric powerplants. This generation of electricity, which is the largest off-stream use in the State, accounts for 76.0 percent of all withdrawals. South Carolina has 17 thermoelectric powerplants, of which 13 are operated by fossil fuel and 4 are operated by nuclear power. Two of the nuclear plants have become operational since 1980. In 1985, these 17 plants used a total of 5,180 Mgal/d for cooling (fig. 4); surface water was the principal water source. Of this total, the fossil-fueled plants used 1,400 Mgal/d of fresh surface water. An additional 6 Mgal/d of saline surface water was withdrawn; the Hagood plant (Charleston County) was the major user of saline water. Saline water is not included in figure 4. Nuclear plants accounted for 73 percent (3,780 Mgal/d) of the total freshwater use by thermoelectric plants; the Oconee nuclear plant (Oconee County) was responsible for 43 percent of all thermoelectric withdrawals. Withdrawals of ground water for use by thermoelectric plants in 1985 were small (1.1 Mgal/d). Consumptive use was 25 Mgal/d for fossil-fueled plants and 30 Mgal/d for nuclear plants. In 1985, 1.1 percent of the water used for thermoelectric power was consumed and 98.9 percent was returned to the State's rivers and streams (fig. 4).

Agricultural

Agricultural water use in 1985 was 44 Mgal/d (fig. 4), which was used mainly for irrigation (34 Mgal/d). Surface-water withdrawals for irrigation were 13 Mgal/d, and ground-water withdrawals were 21 Mgal/d. Between 1980 and 1985, irrigation use decreased by 20 Mgal/d, and farm acreage decreased by 16 percent. Although total withdrawals for irrigation have decreased since 1980, the quantity of ground water used for irrigation has increased about 30 percent. In 1980, ground water supplied 31 percent of irrigation use, but, by 1985, this amount had increased to 62 percent.

Withdrawals for irrigation were largest in the middle and lower parts of the area east of the Fall Line. Of the total irrigation withdrawals, 62 percent was from Allendale, Orangeburg, Beaufort, and Horry Counties. Moderate quantities of surface water were used to irrigate peaches in the northwestern one-half of the State.

In 1985, surface-water use was reported by farmers to be about 24 Mgal/d less than that reported in 1980. This decrease was due largely to a late freeze that destroyed South Carolina's peach crop, which was irrigated mostly by surface water. Irrigated acreage of peach orchards represents 17 percent of all irrigated acreage.

Corn and soybean crops represent 55 percent of all irrigated acreage in South Carolina and most of the water supplied for irrigation. Irrigation use is seasonal (primarily from April through August); center pivots and "traveling guns" are the two main types of sprinkler systems used to irrigate crops.

In 1985, nonirrigation water use for livestock and other farm purposes was 10 Mgal/d. Of the total withdrawals, 5 Mgal/d was surface water, and 5 Mgal/d was ground water. The number of livestock and the amount of water withdrawn for livestock supply have remained relatively constant since 1980. Consumptive use for all agricultural activities, irrigation and nonirrigation, was virtually 100 percent.

WATER MANAGEMENT

Three State agencies have water-management responsibilities in South Carolina. The South Carolina Water Resources Commission (SCWRC) was established in 1967 as the principal coordinating agency for water-resources planning and policy activities. The South Carolina Department of Health and Environmental Control (SCDHEC) is the agency primarily responsible for protecting and maintaining the quality of South Carolina's water resources. In accordance with State and Federal regulations, the SCDHEC has established a water-classification and standards system, a statewide water-quality monitoring network, and several water-quality control programs. The South Carolina Coastal Council is responsible for implementing a comprehensive coastal program and permitting system for the critical areas in the State's eight coastal counties. Critical areas include the beaches, primary ocean-front sand dunes, tidelands, and coastal waters. The SCWRC is responsible for permitting activities in the navigable waters of the other 38 counties.

The Ground-Water Use Act of 1969 authorizes the SCWRC to regulate ground-water withdrawals within designated capacity-use areas. Two such areas have been designated along the northern and southern coastal regions of the State. The capacity-use area program is designed to minimize the effects of intensive localized pumping by regulating the design, construction, abandonment, and spacing of wells in these areas. All persons who withdraw ground water in excess of 100,000 gal/d must obtain a permit from the SCWRC and report monthly water use on a quarterly basis.

The South Carolina Water Use Reporting and Coordination Act of 1982 requires the centralized collection of water use information by the SCWRC. All users of more than 100,000 gal/d on any day are required to report this use to SCWRC. Two types of information are collected—that which describes water users, their sources of supply, and how and where the water is used and quarterly reports on the monthly volume of water use. Agricultural users must report their use annually to their county extension agent. Compliance with these reporting requirements has not been complete. In 1985, slightly more than one-half of the users reported their water withdrawals. Percentages of users reporting 1985 withdrawals are agricultural irrigation, 54; public supply, 49; industry, 61; power utilities, 80; and golf courses, 68.

Other State programs that address water demand in South Carolina include the following:

- All significant interbasin transfers of surface water (more than 1 Mgal/d or 5 percent of the 7-day, 10-year low flow, whichever is less) between the 15 major river basins of the State must receive a permit from the SCWRC. Regulations to implement this program were promulgated in June 1986.
- The Drought Response Act of 1985 requires all municipalities, counties, public service districts, and commissions of public works in the business of supplying water to adopt a local drought ordinance or plan. Such ordinances or plans enable these purveyors to achieve the greatest benefit from public water use. The Act designated the SCWRC as the primary agency to monitor drought conditions or potential for drought throughout the State and to coordinate the State's response. The Act applies to every person and to all ground and surface waters of the State except private ponds.

South Carolina's greatest challenge concerning water policy will be the design and development of institutions to allocate water in an efficient manner. The concept of regionally based water systems is receiving attention, as is the fostering of increased financial responsibility by local water purveyors.

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FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 1835 Assembly Street, Suite 677A, Columbia, SC 29201

SOUTH DAKOTA
Water Supply and Use

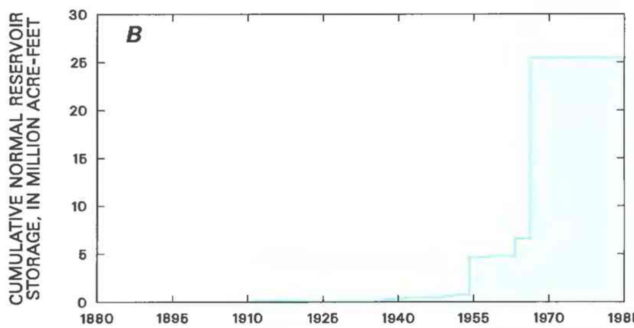
South Dakota is a rural, agricultural State with a surface area of 77,047 square miles. Annual precipitation averages 17.6 inches, about 75 percent of which occurs during the growing season (May–Oct.) (W.F. Lytle, South Dakota State Climatologist, oral commun., 1987). Precipitation can vary considerably from year to year. Droughts during the 1930's, 1950's, and 1970's adversely affected agriculture, the State's major economic activity.

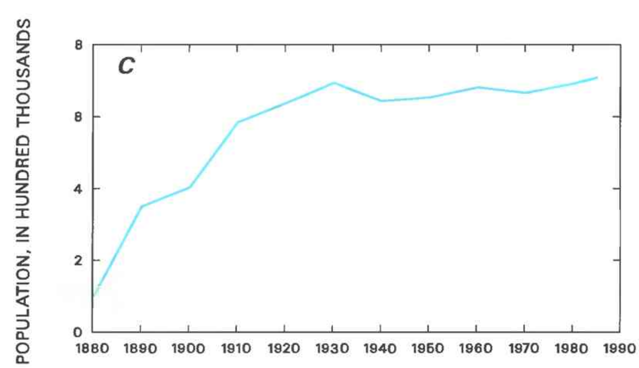
The water budget for the State (fig. 1*A*) diagrammatically indicates that precipitation exceeds evapotranspiration, and surface-water outflows exceed surface-water inflows. Stored water in reservoirs and aquifers stabilizes the supply. Total storage for reservoirs that have a capacity of at least 5,000 acre-ft (acre-feet) is estimated to be more than 25 million acre-ft (fig. 1*B*). An estimated 50 million acre-ft of recoverable water is contained in glacial-drift and alluvial aquifers, and about 3.8 billion acre-ft of recoverable water is contained in sedimentary-bedrock aquifers (Allen and others, 1985; Hedges and others, 1982).

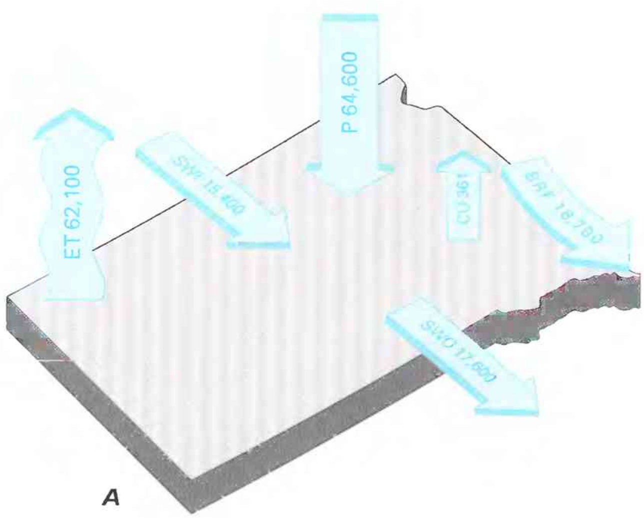
During 1985, 674 Mgal/d (million gallons per day) of freshwater was withdrawn from South Dakota's rivers, streams, and aquifers. This is a small decrease from the 690 Mgal/d of freshwater that was withdrawn during 1980 (Solley and others, 1983, p. 38). Of the total withdrawn, 361 Mgal/d was consumed, and 313 Mgal/d was returned to the hydrologic system.

The area west of the Missouri River, which has a ranching-based economy, had withdrawals of about 382 Mgal/d during 1985 (77 percent surface water, and 23 percent ground water). The area east of the Missouri River, which has a farming-based economy, had withdrawals of about 292 Mgal/d during 1985 (44 percent surface water, and 56 percent ground water). Statewide, about 75.2 percent of the total water withdrawn was for agriculture, 16.2 percent was for domestic and commercial use, 7.6 percent for industry and mining, and 1.0 percent was for thermoelectric power use. Agricultural consumptive use accounted for 90.5 percent of total consumptive use.

South Dakota's population has been increasing since 1970, although the rate of increase has been small (fig. 1*C*). This small rate of increase can be attributed, in part, to agricultural economic problems. The State is actively pursuing new industrial development; however, the establishment of some industries is inhibited by the lack of sufficient surface- or ground-water resources in certain locations. The principal population centers are distributed primarily along the major rivers (fig. 1*D*).







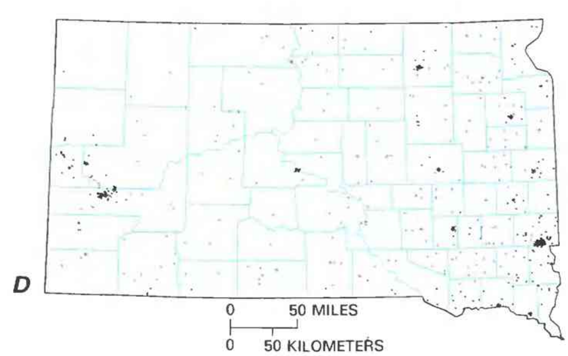


Figure 1. Water supply and population in South Dakota. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, South Dakota State Climatologist and the U.S. Geological Survey. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

HISTORY OF WATER DEVELOPMENT

The most visible of South Dakota's geographic features is probably the Missouri River, which divides the State between "east-river" and "west-river" areas. The river, referred to as the "Old Mizzou" and "Big Muddy," was the primary transportation corridor during early settlement and development of South Dakota. During the 16th century, the Arikara Indians migrated to central South Dakota and established their villages on the banks of the Missouri River (Schell, 1975). From the LaVerendrye expedition in 1743 to the establishment of the Dakota Territory in 1861, the Missouri River was the route that French voyageurs, fur traders, and explorers journeyed to and from the prairie wilderness (Karolevitz, 1981). Steamboat traffic on the Missouri River reached Pierre, the State capital, in 1831 (Thompson, 1961). As early as 1857, lumbermills and gristmills were established along the river. Lumber was produced from the native timber and shipped down the river or was offered to settlers for cash or trade. Brick kilns and plaster factories were other industrial facilities that developed along the Missouri River (Bates, 1939).

Runoff in the semiarid climate of South Dakota has a tendency to produce flooding in the spring and early summer followed by low-flow conditions later in the year. Even with the threat of periodic flooding, settlers recognized the advantages of locating near a river. Consequently, many of the State's major cities—Sioux Falls, Rapid City, Aberdeen, Watertown, Brookings, Mitchell, Pierre, Huron, and Yankton—are adjacent to a stream or river. Early settlers also realized that storage was necessary if surface water was to be used as a continuous supply. Early reservoirs usually were small and constructed for a single purpose, such as providing water for industry, stabilizing a public supply, or providing recreation.

The first dam built to store more than 5,000 acre-ft of water was the Belle Fourche, which was completed in 1911. The dam was a feature of the Belle Fourche Project in the Cheyenne basin (see fig. 5), the second Federal reclamation project undertaken in the United States. Federal plans for management and development of water resources within the entire Missouri River basin culminated with the passage of the Flood Control Act of 1944, which included the Pick–Sloan Missouri River Basin Plan. A major part of the Pick–Sloan program included construction of six multipurpose dams (four in South Dakota) on the upper Missouri River to provide flood control and hydroelectric power, as well as to make water available for irrigation and for commercial navigation downstream. The dams in South Dakota constructed in the 1950's and 1960's are Gavins Point, Fort Randall, Big Bend, and Oahe. Combined normal storage of the reservoirs created by the four dams is almost 24.9 million acre-ft, which represents almost 98 percent of the reservoir storage shown in figure 1*B*. Substantial flood-control and navigation benefits of the Pick–Sloan program have been achieved. The six dams on the Missouri River are estimated to have prevented $2.3 billion in flood damages since they were constructed (U.S. Army Corps of Engineers, 1986).

About 500,000 acres of land in South Dakota were inundated as a result of construction of four of the dams. Irrigation, however, has been developed for only about 24,000 of the 961,000 acres included in the Pick–Sloan program for South Dakota. The Pick–Sloan irrigation developments include the Angostura, Shadehill, and Rapid Valley Units in the western part of the State. The Oahe Unit, a multipurpose Pick–Sloan project that was being constructed to provide irrigation water to 190,000 acres in eastern South Dakota, became the subject of controversy during the 1970's, and construction eventually was terminated. Because South Dakota has realized only a small part of the irrigation benefits to date, the State considers the Pick–Sloan Missouri River Basin Plan to be the cornerstone for planning and implementing major water-resource developments.

Ground water has been developed to meet many rural and urban supply needs. Ground-water quality that is unsuitable for domestic use in many areas of the State has accelerated the development of an extensive network of rural water systems that distribute water for domestic and livestock uses in rural areas and for public-supply and industrial uses in small communities. Since the 1970's, irrigation development has been by individual landowners using center-pivot sprinklers to apply ground water. Ground-water development has been assisted by the completion of county ground-water studies in all but seven eastern counties. Results of U. S. Geological Survey Regional Aquifer-System Analysis studies have provided valuable information on ground-water resources in western South Dakota (Downey, 1984, 1986; Gutentag and others, 1984).

As of 1987, several important water-resource developments are being considered or constructed. Major development efforts include rural water systems; river improvement, such as bank stabilization and channel clearing; lake restoration; irrigation development; and flood control.

WATER USE

The Missouri River is, by far, the most significant source of surface water in the State. The sum of the average recorded flow of all streams tributary to the Missouri within the State is only 12 percent of the average recorded flow of the Missouri as it leaves the State at Sioux City, Iowa—18,740 Mgal/d, or about 29,000 cubic feet per second. Most other streams do not provide a dependable supply unless reservoir storage is available.

Most of South Dakota is underlain by aquifers that yield differing quantities of water. Sedimentary-bedrock aquifers underlie most of the State, and glacial-drift and alluvial aquifers underlie most of the State east of the Missouri River. Although the quality of some supplies is less than desirable because of excessive mineral content, ground water commonly constitutes the only available source of water for domestic, public-supply, and agricultural use. About 95 percent of all self-supplied domestic water and about 80.6 percent of the public-supplied water are from ground-water sources.

The distribution of surface- and ground-water withdrawals shows interesting differences across the State. Total, surface-water, and ground-water withdrawals by county during 1985 are shown in figure 2. The major areas of large total freshwater withdrawals (fig. 2*A*) reflect large agricultural (mostly irrigation) withdrawals in Butte, Fall River, Pennington, Hughes, and Sully Counties, as well as major withdrawals for public supply by the two largest cities (Sioux Falls and Rapid City). The distribution of surface- and ground-water withdrawals by county (figs. 2*B*,*C*) reflects the predominance of surface water in the unglaciated area west of the Missouri River and the availability of ground water in the glaciated area east of the Missouri River. About 69 percent of total surface-water withdrawals was from west of the Missouri River, and about 65 percent of total ground-water withdrawals was from east of the river. Hughes County had the largest surface-water withdrawal (32.2 Mgal/d) east of the river, 98 percent of which was for agriculture. Minnehaha County had the largest ground-water withdrawal (23.0 Mgal/d) east of the river, about 61 percent of which was for public supply. Butte County had the largest surface-water withdrawal (about 153 Mgal/d) west of the river, all of which was used for agriculture. Pennington County had the largest ground-water withdrawal (33.8 Mgal/d) west of the river, 77 percent of which was for public supply.

Of the major river basins (fig. 3*A*), the largest withdrawals were in the Cheyenne (261 Mgal/d), the Missouri–Oahe (59 Mgal/d), and the Missouri–White (57 Mgal/d). The largest withdrawals within each basin were for agricultural use (91.2 percent in the Cheyenne, 95.6 percent in the Missouri–Oahe, and 93.2 percent in the Missouri–White).

Instream water use is substantial because of the hydroelectric powerplants associated with the four dams built by the U.S. Army

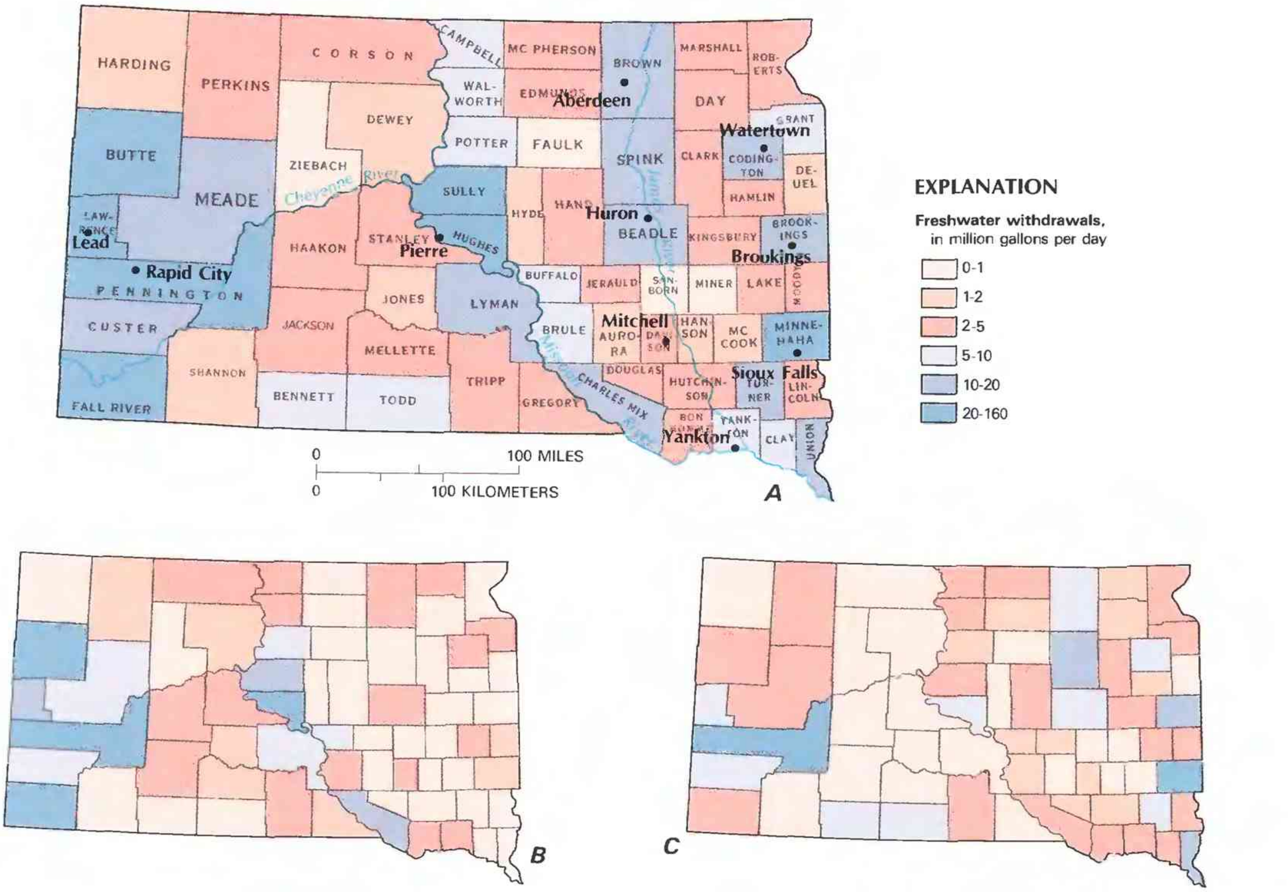


Figure 2. Freshwater withdrawals by county in South Dakota, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Corps of Engineers on the Missouri River. During 1985, about 60,500 Mgal/d was used to generate about 6,090 gigawatthours of electricity. Instream uses of water are not included in figure 3.

Of the principal aquifers (fig. 3*B*), the largest withdrawals were from the glacial-drift and alluvial aquifers. About 187 Mgal/d, or 75 percent of total ground-water withdrawals, was withdrawn from these aquifers. Water from the glacial-drift and alluvial aquifers was used principally for agriculture (about 104 Mgal/d, or 55.4 percent).

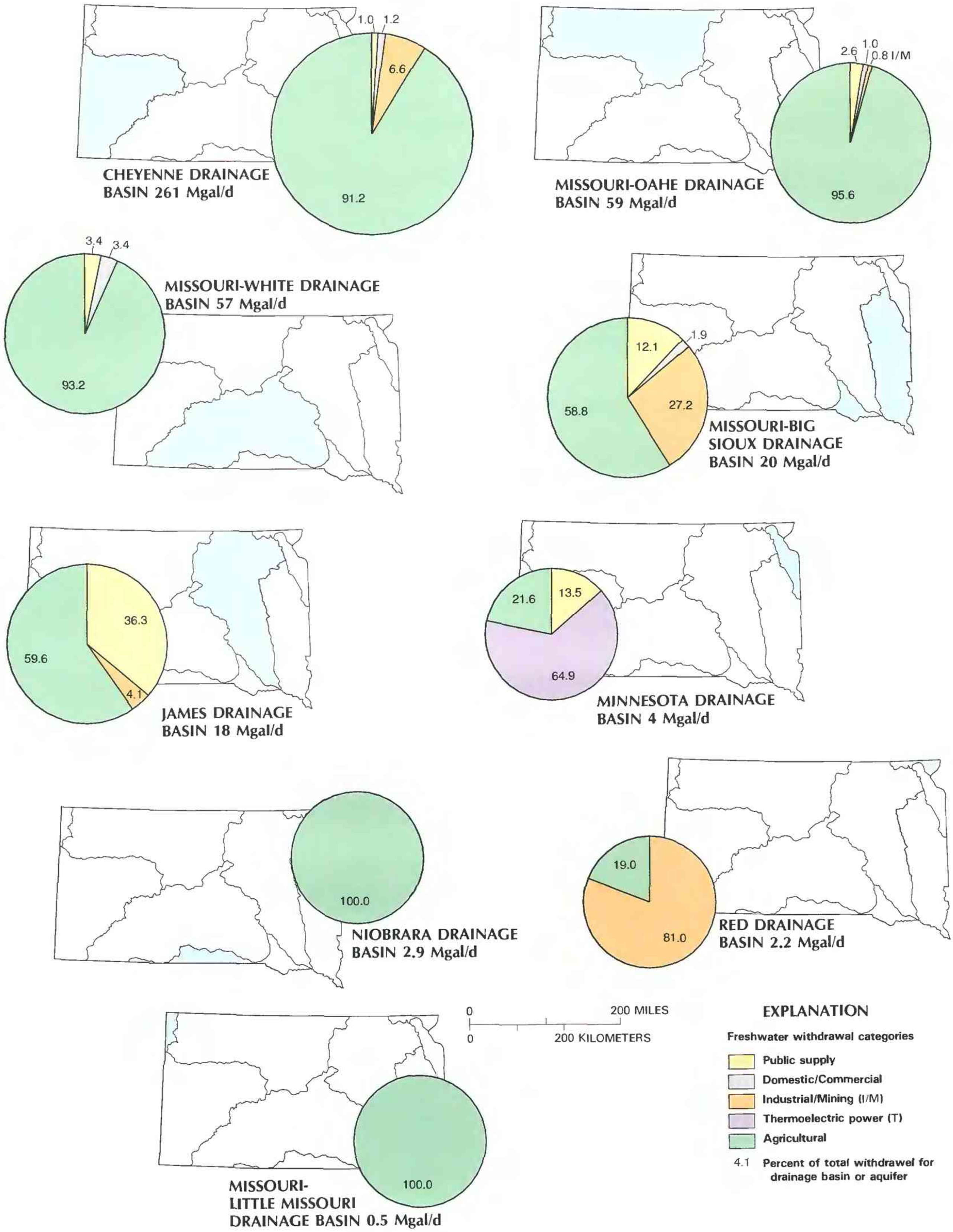
The source, use, and disposition of freshwater during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 425 Mgal/d of surface water was withdrawn, which was 63.0 percent of the total surface- and ground-water withdrawals in South Dakota during 1985. Of that quantity, 1.4 percent was directly withdrawn (self-supplied) for domestic and commercial use, 6.0 percent was self-supplied by industrial and mining facilities, 0.6 percent was withdrawn for thermoelectric power generation, 88.3 percent was withdrawn by agriculture, and 3.7 percent was withdrawn by public-supply systems. The use data indicate that domestic and commercial uses (109 Mgal/d) represented 16.2 percent of the State's total use. Of that quantity, 69.0 percent was obtained from public-supply systems, 5.6 percent was self-supplied from surface-water sources, and 25.4 percent was obtained from ground-water sources. Of the water used for domestic and commercial purposes, 20.6 percent was consumed, and 79.4 percent was returned to surface- and ground-water sources. The disposition data indicate that of all water withdrawn in the State, 53.6 percent (361 Mgal/d) was consumed, and 46.4 percent (313 Mgal/d) was returned to surface- and ground-water sources. Domestic and commercial uses accounted for 6.2 percent of total consumptive use and 27.5 percent of total return flow. Instream water uses of water are not included in figure 4.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In 1985, about 450 public-supply systems provided water for domestic, commercial, and industrial uses. From 1980 through 1985, total withdrawals for public supply increased from 76 to 80 Mgal/d, or about 6 percent; the population served by public-supply systems increased from 455,000 to 548,000, or about 20 percent. During the same period, the total population increased about 2 percent (from 691,000 to 706,000). The large increase in the population served by public-supply systems can be attributed to the construction of several rural water systems. In 1985, withdrawals by rural water systems accounted for about 11 percent of total withdrawals for public supply.

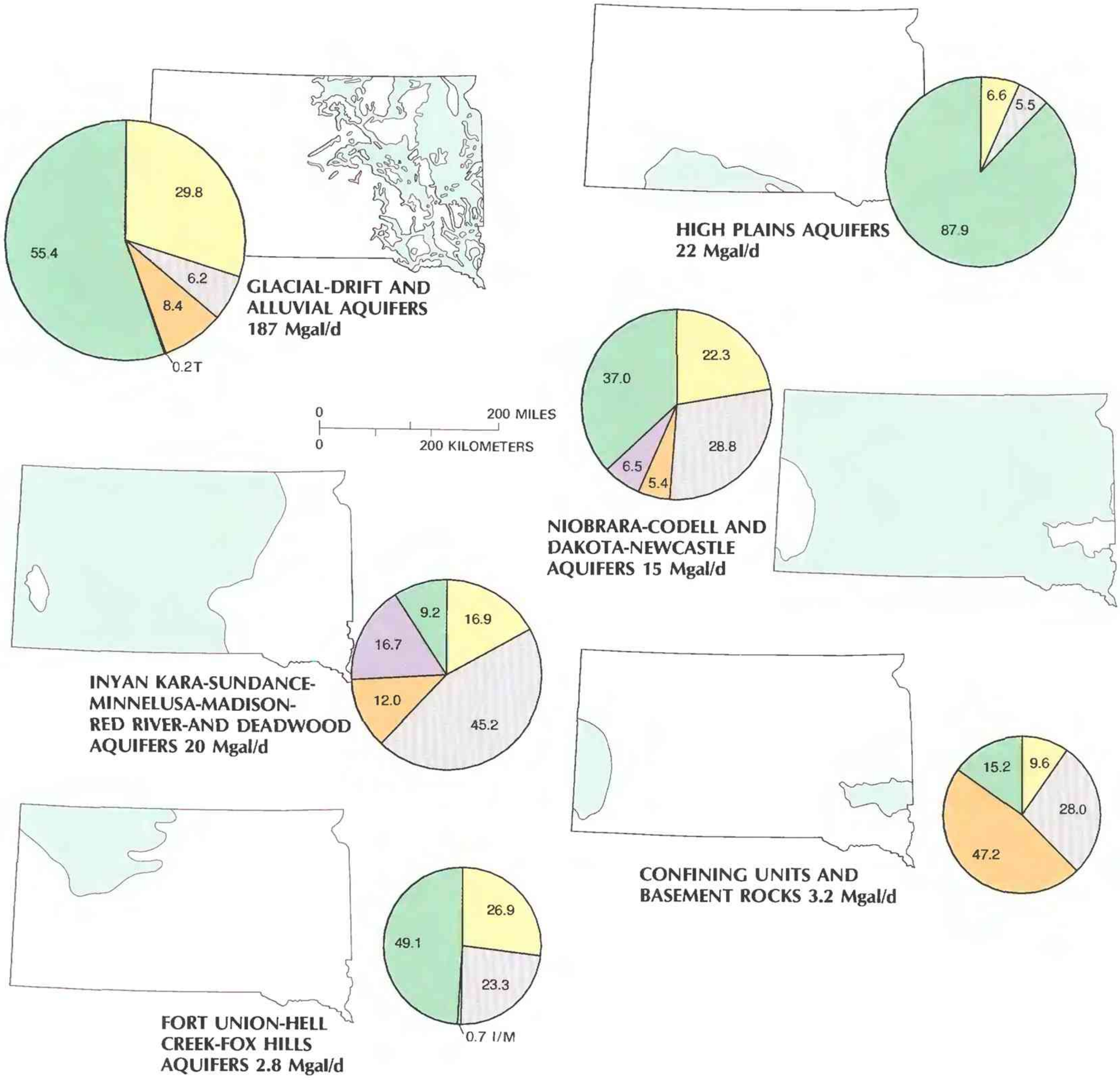
The largest withdrawal by a municipality during 1985 was 25.0 Mgal/d by Rapid City. This withdrawal rate, however, was about three times the rate for the previous year and is due to increased lawn watering during the 1985 drought in western South Dakota. Sioux Falls, the largest city, withdrew 12.8 Mgal/d during 1985. The largest withdrawal by a rural water system during 1985 was 1.39 Mgal/d by the Randall Community Water District, which delivers water to towns and rural customers within three southeastern counties (fig. 5).

About 19.4 percent (16 Mgal/d) of total withdrawals for public supply was from surface water (fig. 4), and 78 percent of the surface-water withdrawals was in the area east of the Missouri River. About



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in South Dakota, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey.)



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in South Dakota, 1985—Continued.

80.6 percent (65 Mgal/d) of total withdrawals for public supply was from ground water, and 51 percent of the ground-water withdrawals was in the area east of the Missouri River area. Of the total withdrawals for public supply (80 Mgal/d), about 75 percent was for domestic use, 18 percent was for commercial use, and 7 percent was for industrial use.

Domestic and Commercial

Domestic and commercial water users receive water from public-supply systems and self-supplied facilities. Total domestic withdrawals and deliveries during 1985 were 77 Mgal/d, of which 61 Mgal/d was delivered by public-supply systems that served 78 percent of the population and 16 Mgal/d was self-supplied. Per capita domestic use during 1985 was 110 gal/d (gallons per day) for public-supply users and 103 gal/d for self-supplied users. Commercial water use during 1985 was 32 Mgal/d. Of this quantity, 14 Mgal/d was delivered by public-supply systems, and 18 Mgal/d was self-supplied.

Industrial and Mining

During 1985, water withdrawals for industrial and mining use were 51 Mgal/d (fig. 4). Self-supply systems provided 0.9 Mgal/d of surface water and 4.8 Mgal/d of ground water for industrial uses. The remainder of the water used by industry, 5.4 Mgal/d, was obtained from public-supply systems. Major industrial water users are a cement plant near Rapid City and numerous meatpacking plants and creameries.

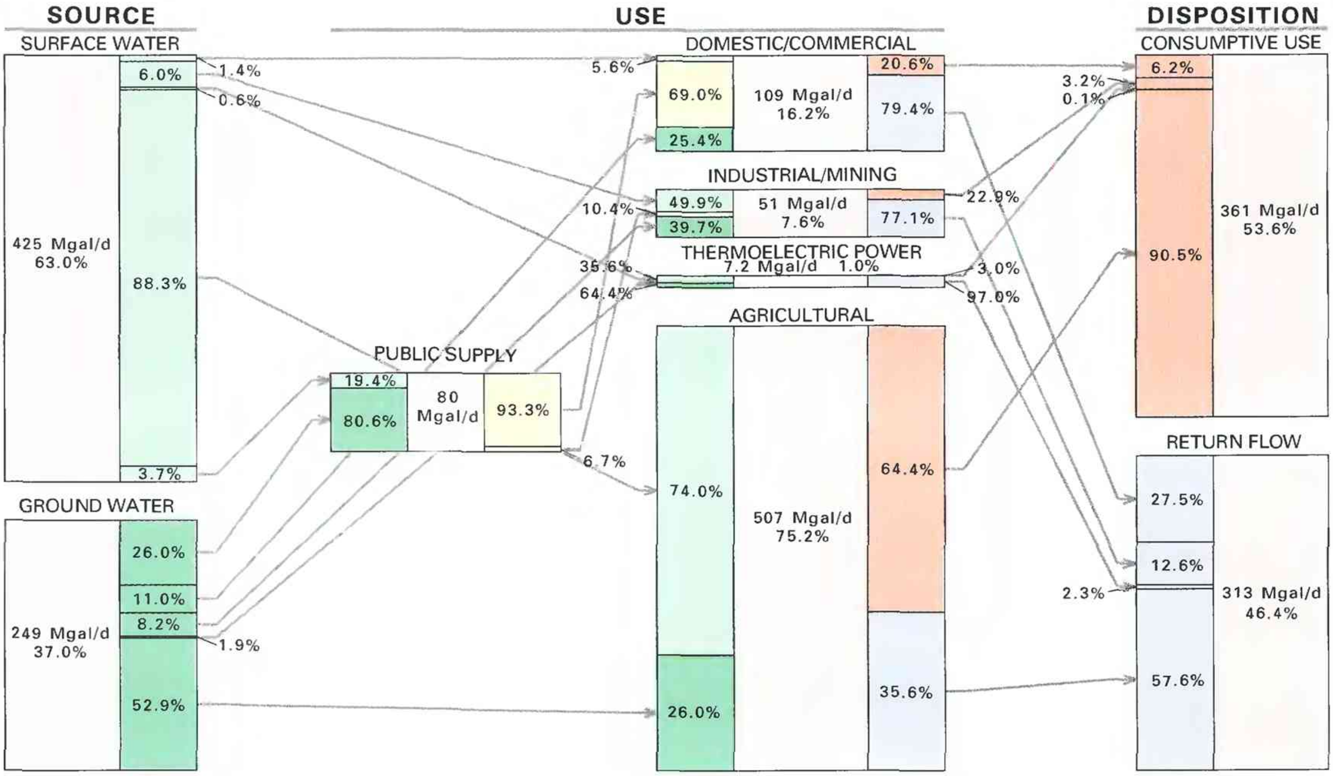


Figure 4. **Source, use, and disposition of an estimated 674 Mgal/d (million gallons per day) of freshwater in South Dakota, 1985.** Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Self-supply withdrawals for mining activities were estimated to be 40 Mgal/d; about 61 percent was surface water and about 39 percent was ground water. A major user of water for mining is in Lead (Lawrence County), where gold production makes South Dakota the leading gold-producing State in the Union.

THERMOELECTRIC POWER

Withdrawals for this category were 4.2 Mgal/d for power generation and 3.0 Mgal/d of geothermal water for heating. These withdrawals represent 1.0 percent of the total offstream water use in the State. Of the total, 64.4 percent was surface water, and 35.6 percent was ground water. A fossil-fueled powerplant in Grant County was the largest thermoelectric water user, with a surface-water withdrawal of 2.6 Mgal/d. South Dakota has no nuclear powerplants.

AGRICULTURAL

Irrigation was the dominant agricultural water use in 1985, and irrigation withdrawals totaled 460 Mgal/d (516,000 acre-ft). Irrigation withdrawals during 1980 also were 460 Mgal/d. Non-irrigation withdrawals, mainly for livestock use, were 47 Mgal/d during 1985.

About 397,000 acres were irrigated during 1985—324,000 acres by sprinkler methods and 73,000 acres by flooding. The statewide withdrawal rate was 1.30 acre-ft/acre (acre-feet per acre), or 15.6 inches per acre. Considering conveyance losses of about 135,000 acre-ft, the average farm delivery rate was about 0.96 acre-ft/acre, or 11.5 inches per acre. Primary irrigated crops included corn, alfalfa, and soybeans. Center pivots were used for about two-thirds of the sprinkler irrigation. Electricity was the source of power used to irrigate almost 80 percent of the acreage.

Comparison of withdrawal and delivery rates between the east-river and west-river areas also is of interest. For the east-river area, about 195,000 acre-ft was withdrawn to irrigate about 251,000 acres, resulting in a withdrawal rate of 0.78 acre-ft/acre, or 9.3 inches per acre. With conveyance losses of about 7,500 acre-ft, the farm delivery rate was about 0.75 acre-ft/acre, or 9.0 inches per acre. For the west-river area, about 321,000 acre-ft was withdrawn to irrigate about 146,000 acres, resulting in a withdrawal rate of 2.20 acre-ft/acre, or 26.4 inches per acre. Considering conveyance losses of about 127,000 acre-ft, the farm delivery rate was about 1.33 acre-ft/acre, or 16.0 inches per acre.

The largest withdrawals of water for irrigation are in the Belle Fourche Project area (fig. 5) in Butte County, where 161,620 acre-ft of water was used to irrigate 53,825 acres during 1985. The second largest withdrawals are in the Angostura Unit in Fall River County, where 48,441 acre-ft of water was used to irrigate 11,423 acres during 1985. During 1985, about 17,035 acre-ft was used to irrigate 7,735 acres in the Rapid Valley Unit in Pennington County (U.S. Bureau of Reclamation, 1986).

Two Indian tribes also irrigate large acreages in South Dakota. During 1985, the Lower Brule Sioux Tribe withdrew 7,500 acre-ft to irrigate 5,500 acres in Lyman and Stanley Counties, and the Crow Creek Sioux Tribe withdrew 5,780 acre-ft to irrigate 3,910 acres in Buffalo and Hughes Counties (Lowell Erichsen, U.S. Bureau of Indian Affairs, oral commun., 1986). The largest private irrigation development is in Hughes and Sully Counties; in that development, 13,287 acre-ft was withdrawn to irrigate 12,219 acres during 1985 (James Winterton, South Dakota Department of Water and Natural Resources, written commun., 1986).

Of the 47 Mgal/d of nonirrigation agricultural withdrawals, about 60 percent was surface water, and 40 percent was ground

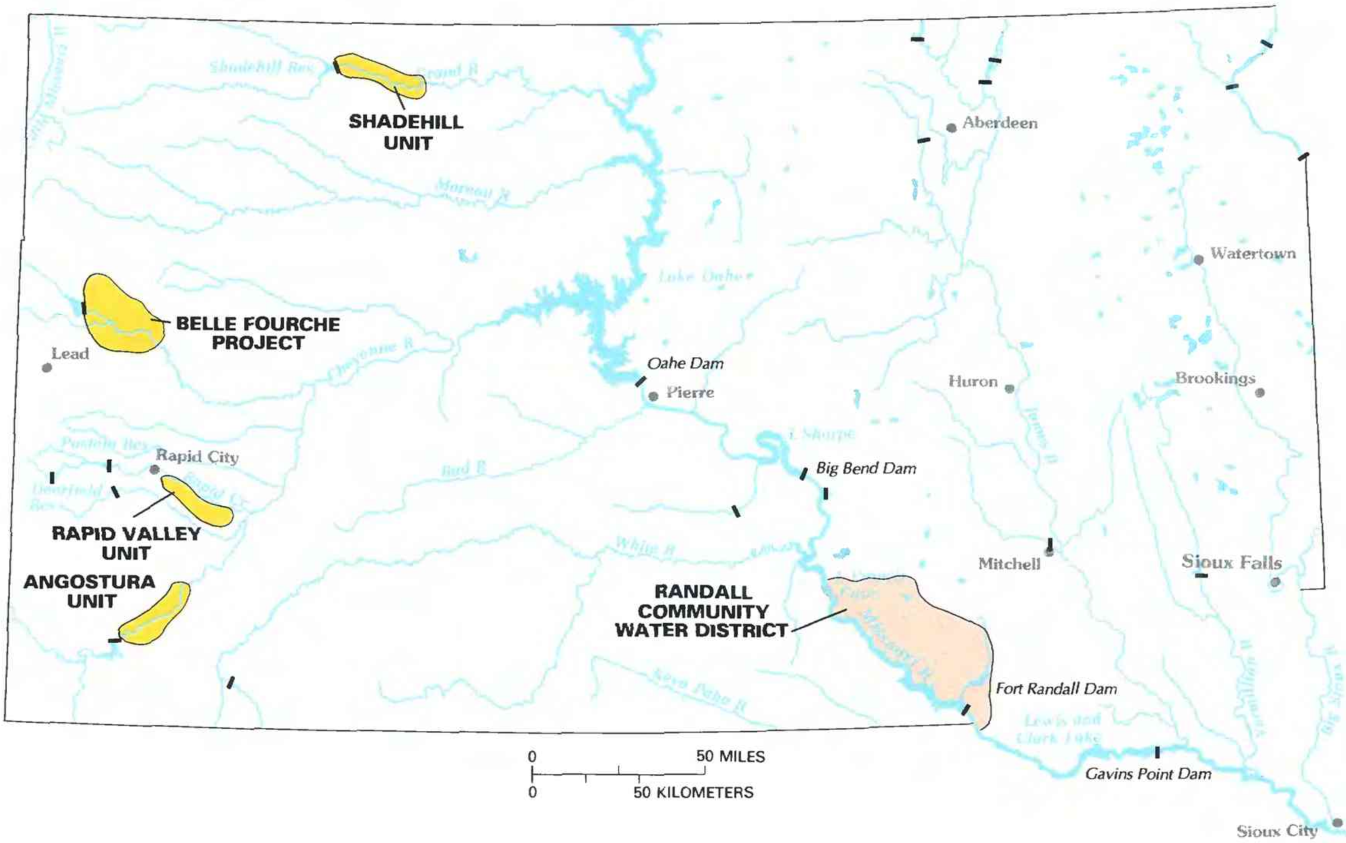


Figure 5. Selected surface-water resource developments in South Dakota. (Source: U.S. Geological Survey, 1986.)

water. This withdrawal was distributed among some 4 million cattle, 1,765,000 hogs, 753,000 sheep, and 1.8 million poultry (U.S. Bureau of the Census, 1984). All the water withdrawn was considered to be consumed use.

WATER MANAGEMENT

The State's water resources are managed through a record-and-permit system and a State Water Plan administered by the South Dakota Department of Water and Natural Resources (DWNR). Within the Department, the Division of Water Rights and the Division of Environmental Quality function as regulatory offices and provide staff to the Water Management Board. The Board regulates and controls the development, conservation, and allocation of water rights according to the principles of beneficial use and priority of appropriation. It has the general supervision of the waters of the State, including measurement, appropriation, and distribution. The Board also performs the quasilegislative, quasijudicial, special budgetary functions and all functions relating to water quality and control of water pollution.

The Division of Environmental Quality reviews surface- and ground-water-quality data to determine if contamination is occurring or if legal authority is required to protect the quality of the waters. The Division of Geological Survey is charged with studying and mapping the ground-water resources of the State.

In general, all withdrawals of surface and ground water are regulated by the Water Management Board; however, there are exceptions. Water for domestic use that is supplied by private wells or diversion points at rates that do not exceed 18 gallons per minute and stock dams on dry draws that have a capacity of less than 25 acre-ft are not regulated by the Board.

Because irrigation is the largest use of water in South Dakota, the Water Management Board requires that the quantity of water used by the holder of an irrigation permit be reported annually. Noncompliance subjects the user to potential suspension of a water use permit.

The development of surface and ground water is managed through the State Water Plan administered by the DWNR. The Division of Water Development provides technical policy analyses required to implement the State Water Plan and to monitor Federal legislation and policies that affect water resources. The Division also guides the planning, development, and implementation of water-resource projects to ensure maximum benefit to the public. This includes providing assistance to management organizations such as irrigation, watershed, water user, water-development, and drainage districts.

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FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, Room 408, Federal Building, 200 4th Street S.W., Huron, SD 57350

TENNESSEE
Water Supply and Use

Tennessee has abundant surface- and ground-water resources (fig. 1A). The average annual precipitation is 50 inches, which is among the largest in the Nation (U.S. Department of Commerce, 1968). A significant part of the precipitation is captured in a vast network of reservoirs that has a storage capacity of 8.1 million acre-ft (acre-feet) (fig. 1B). In addition, about 20 percent of the precipitation infiltrates into the ground to recharge the State's aquifers (Zurawski, 1978). During 1985, the quantity of freshwater withdrawn from rivers, streams, and aquifers was about 8,450 Mgal/d (million gallons per day), or 1,760 gal/d (gallons per day) per capita. About 275 Mgal/d of the total withdrawals was consumed and 8,180 Mgal/d was returned to natural water sources. All withdrawals in Tennessee are freshwater.

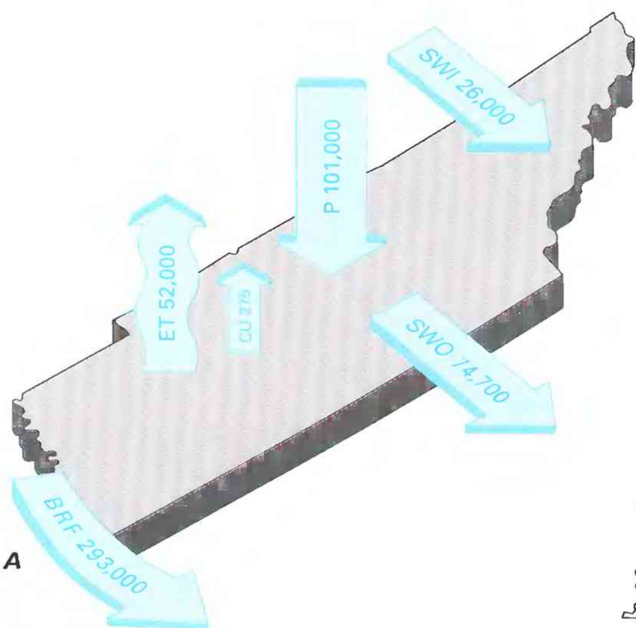
Surface water is the principal supply for the central and eastern parts of the State, where major urban, industrial, and agricultural centers are located; these areas are characterized by limited ground-water resources. In contrast, the western part of the State is supplied by abundant ground-water resources. Memphis, the largest urban area in the State, and major industrial and agricultural activities in western Tennessee are supplied by ground water. Western Tennessee is underlain by several extensive and productive aquifers, the most important being the Tertiary sand aquifer. Withdrawals from this aquifer in 1985 were 272 Mgal/d; yields of individual wells were as large as 2,000 gallons per minute.

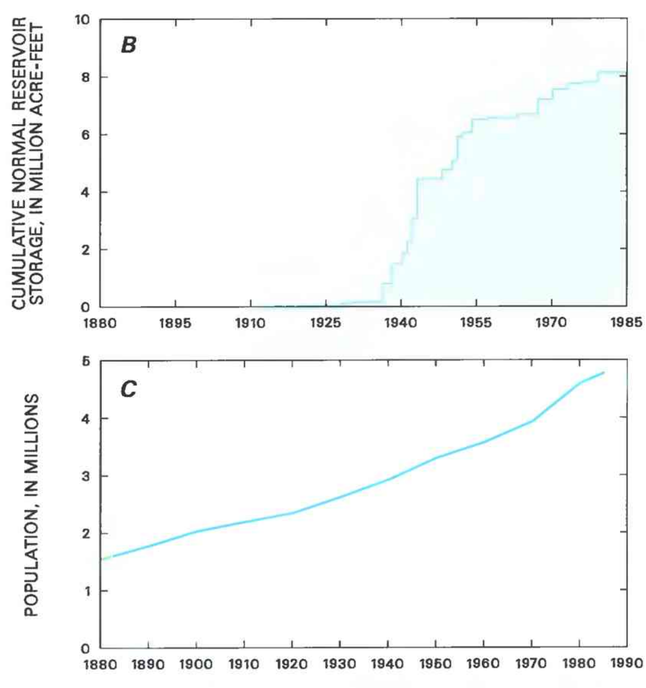
Water withdrawals during 1985 for domestic, commercial, industrial, and mining uses were 2,310 Mgal/d, of which 240 Mgal/d (10.7 percent) was consumed. About 6,060 Mgal/d was withdrawn for thermoelectric power generation; more than 99 percent of that was returned to streams. Withdrawals for agricultural uses totaled 74 Mgal/d, of which, 45.4 percent was consumed.

The population of Tennessee increased 33 percent from about 3.6 million in 1960 to about 4.8 million in 1985 (fig. 1C). Recent trends indicate that the population will increase by about 50,000 annually through the year 2000 (University of Tennessee, 1985). This projected population growth, along with the accompanying economic development, will increase the demands on Tennessee's supplies of freshwater. However, the abundant water resources probably will be adequate to support these additional demands.

HISTORY OF WATER DEVELOPMENT

When settlers migrated to Tennessee during the 18th century, they discovered a region of abundant rainfall and considerable challenge to develop the natural resources. Water was plentiful; thousands of miles of streams and productive springs and wells provided potable water where communities developed.





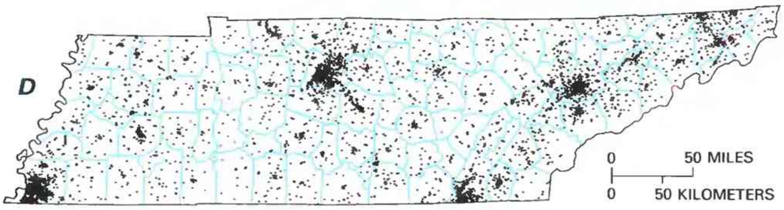


Figure 1. Water supply and population in Tennessee. ***A,*** Water budget, in million gallons per day. ***B,*** Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. ***C,*** Population trend, 1880 to 1985. ***D,*** Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF,** boundary-river flow; **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Compiled by J.F. Lowery from U.S. Geological Survey files. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Early patterns of settlement and development were related primarily to three rivers and their tributaries. The Tennessee and the Cumberland River systems affected settlements in the eastern and central regions of the State and in certain areas of western Tennessee. Shipping on the Mississippi River made Memphis the trading center for farm produce from the fertile lowlands in the western end of the State. After the development of the steamboat, which transported goods and passengers on the Mississippi River to and from the growing Nation's heartland, Memphis soon became the largest population center in Tennessee (fig. 1*D*).

The Tennessee and the Cumberland Rivers were not as navigable as the Mississippi River, and periods of torrential rains converted them into raging floodways. For much of the year, the Tennessee and the Cumberland Rivers were only one-way passages. Flatboats hauled goods downstream and then were dismantled so their timbers could be put to other uses at journey's end. Huge rafts of new-cut timber were floated from the region's forests to processing centers downstream. Travel upriver was difficult at best and impossible at times, even for steamboats. Rocky shoals, treacherous narrows, and low streamflow during droughts made reliable navigation of the Tennessee and the Cumberland Rivers impossible.

The rivers and their tributaries were vital resources and contributed to the agricultural development of flood plains, provided the power to turn millwheels, and served as transportation routes for commercial development of the newly settled territories. In addition, where sufficient springs were available to supply the drinking-water needs of a community, towns developed. These springs were supplemented by wells as the population increased. Even today, more than one-half the people of Tennessee, including the entire population of Memphis, depend on wells and springs for drinking water.

The U.S. Army Corps of Engineers (COE) was instrumental in developing the Tennessee (1769–1933) and the Cumberland (1769–1978) Rivers for navigation. Canals figured significantly in the early proposals for developing the rivers. Surveys were conducted to determine the feasibility of linking Tennessee to Virginia by using tunnels and canals through the Appalachian Mountains. Studies were made of potential routes that would connect the Tennessee River to the Gulf of Mexico by using canal systems through Georgia or Alabama. Another potential waterway route considered was a canal to the Mississippi River.

The initial development of the Tennessee and the Cumberland Rivers involved extensive excavation of rock and boulders. Canals were built at Muscle Shoals in Alabama, and a dam and lock were constructed at Hales Bar near Chattanooga. A project was started in the late 19th century to convert most of the Cumberland River into a canal, by constructing a series of low-level dams and locks reaching from Smithland, Ky., past Nashville and toward the northeast into the coal fields of south-central Kentucky. Fifteen dams and locks had been built by the early 20th century, but, by then, the expanded use of railroads almost brought steamboat commerce to an end, and the digging of the canal for the Cumberland River halted. Floating logs downriver was no longer practical because of the construction of locks and the availability of railroads.

Development of navigation and control of damaging floods, which affected Nashville and Chattanooga, were the principal benefits of the early water projects. Hydroelectric power development was started in the early 1920's.

Modern development of the Tennessee River began when the COE completed Wilson Dam in northern Alabama in 1924 to facilitate navigation through the Muscle Shoals barrier. When the Tennessee Valley Authority (TVA) was established in 1933, it assumed responsibility for the operation of Wilson Dam. The TVA then began a massive river-control program, building or acquiring 46 dams on the Tennessee River and its tributaries, including Great Falls Dam on the Caney Fork River. As a result, navigation, flood control, and electricity were established in Tennessee.

Modern development of the Cumberland River began in 1941 when the COE completed the Wolf Creek Dam, Kentucky (Russell County). Navigation of the river was made possible by Barkley Dam in Kentucky and Cheatham, Old Hickory, and Cordell Hull Dams in Tennessee. Other COE dams in the Cumberland River basin in Tennessee include J. Percy Priest Dam on the Stones River, Center Hill Dam on the Caney Fork River, and Dale Hollow Dam on the Obey River.

Reservoirs developed by the COE and the TVA add more than 600,000 acres of water surface to the resources of Tennessee. These reservoir systems, combined with others in neighboring States, contribute significantly to public supplies, navigation, flood control, power production, water quality, and fisheries and wildlife management and provide recreational and esthetic benefits. These COE and TVA projects provide a broad range of water-resource benefits on which Tennessee has built much of its economic progress. These projects support the sport and commercial fisheries and the tourist industry, and help to attract industry and commercial activity to the State.

WATER USE

The principal components of the water supply for Tennessee (fig. 1*A*) include precipitation, which amounts to 101,000 Mgal/d, and inflow from adjacent States, which is 26,000 Mgal/d. However, about 52,000 Mgal/d is lost through evapotranspiration, 275 Mgal/d is consumed, and 74,700 Mgal/d leaves the State as streamflow. Significant differences in the withdrawals of surface and ground water are evident across the State. Total, surface-water, and ground-water withdrawals by county are summarized in figures 2*A*, 2*B*, and 2*C*, respectively. Surface- and ground-water withdrawals are shown by principal drainage basin and principal aquifer in figures 3*A* and 3*B*, respectively. The source, use, and disposition of water by category of use are shown diagrammatically in figure 4. The quantities of water given in the figure and elsewhere in this report may not add to the totals indicated because of independent rounding.

From 1965 to 1985, surface- and ground-water withdrawals, excluding thermoelectric power use, increased from 1,340 to 2,390 Mgal/d (78 percent). These trends in withdrawals are shown in figure 5*A*. The quantity of water withdrawn by selected categories of users in 1980 and 1985 is illustrated in figure 5*B*.

Reservoirs on the Cumberland and the Tennessee Rivers store about 8.1 million acre-ft of water in the central and the eastern parts of Tennessee (fig. 6). Public supply, industry, and thermoelectric power generation are the principal users of water from these reservoirs. Six impoundments on the Cumberland River in north-central Tennessee account for about 2.3 million acre-ft. Reservoirs in the eastern and the south-central parts of the State on the Tennessee River provide 5.8 million acre-ft of storage. Management of reservoirs on both rivers also provides storage for flood control.

The Mississippi River, which forms Tennessee's western boundary, drains about 8,907 square miles of the State. Withdrawals of water from the Mississippi River for public supply, domestic, commercial, industrial, mining and agricultural uses are constrained by sediment loads and waste from upstream sources. However, 338 Mgal/d was withdrawn at Memphis for cooling during thermoelectric power generation. The abundance of ground water of excellent quality in western Tennessee has made it unnecessary to withdraw and treat water of the Mississippi River.

An assessment of the quality of water in streams, lakes, and aquifers throughout Tennessee indicated that the quality of water ranges significantly (Tennessee Department of Health and Environment, 1986). That assessment of 5,748 river miles indicated that most streams contain water that is suitable for most uses. The assessment also indicated that surface-mine discharge typically results in

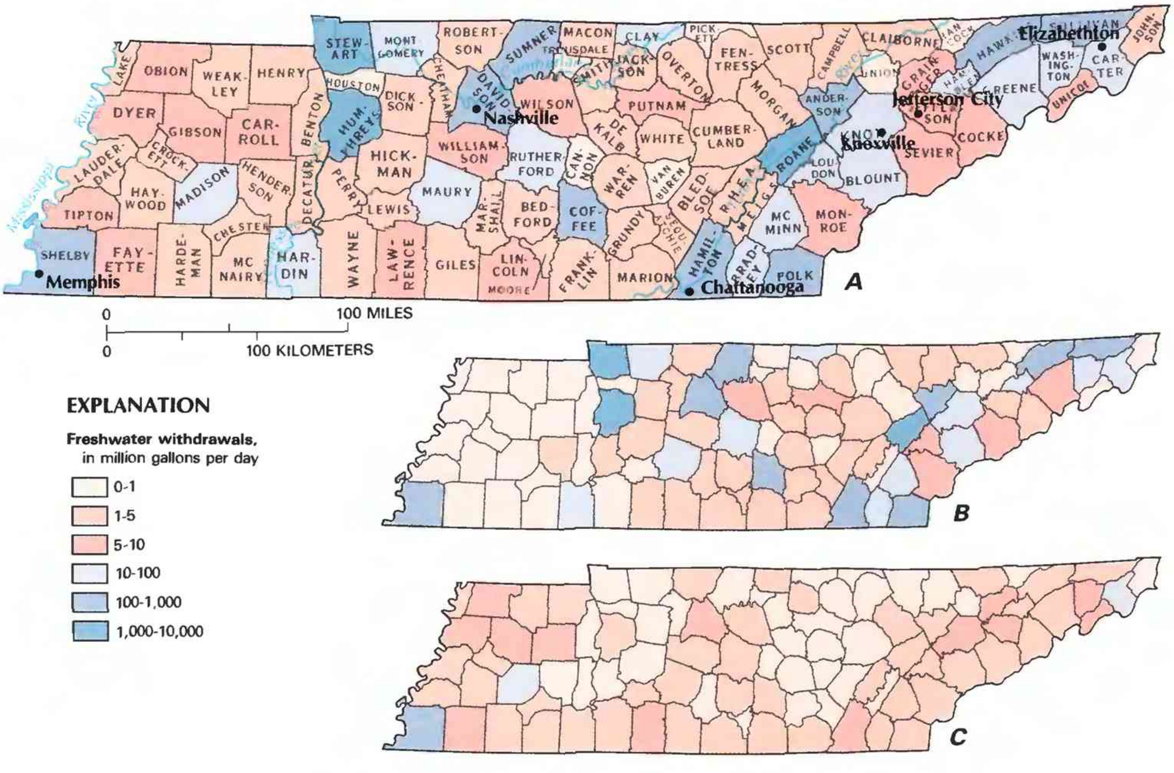


Figure 2. Freshwater withdrawals by county in Tennessee, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

waters that have increased acidity and sediment loads, and large concentrations of toxic metals. Also, eutrophication, which is primarily attributable to nutrients in agricultural runoff, is a significant water-quality problem in several lakes and reservoirs.

Tennessee's ground-water quality is rarely a limiting factor for use, although treatment for excessive iron and hardness is common. Local contamination of aquifers by toxic chemicals has forced the closing of about 100 wells (Tennessee Department of Health and Environment, 1986).

Hydroelectric power generation is the largest instream use of water in Tennessee. Water power has been and continues to be important to the State economy. The 28 hydroelectric plants generated about 8,420 gigawatthours of electric power during 1985. An average of about 118,000 Mgal/d of water was used to generate this power. Although hydroelectric power provides only about 10 percent of the total electricity generated in Tennessee, the relatively small cost and the great demand for power during peak-load periods add to the significance. The amount of electricity generated from hydroelectric power has decreased almost 21.3 percent since 1980. This decrease is a result of an extended drought in eastern Tennessee that decreased the average runoff available to operate power-generation plants. Although hydroelectric power generation requires large volumes of water, almost all is returned to its original sources.

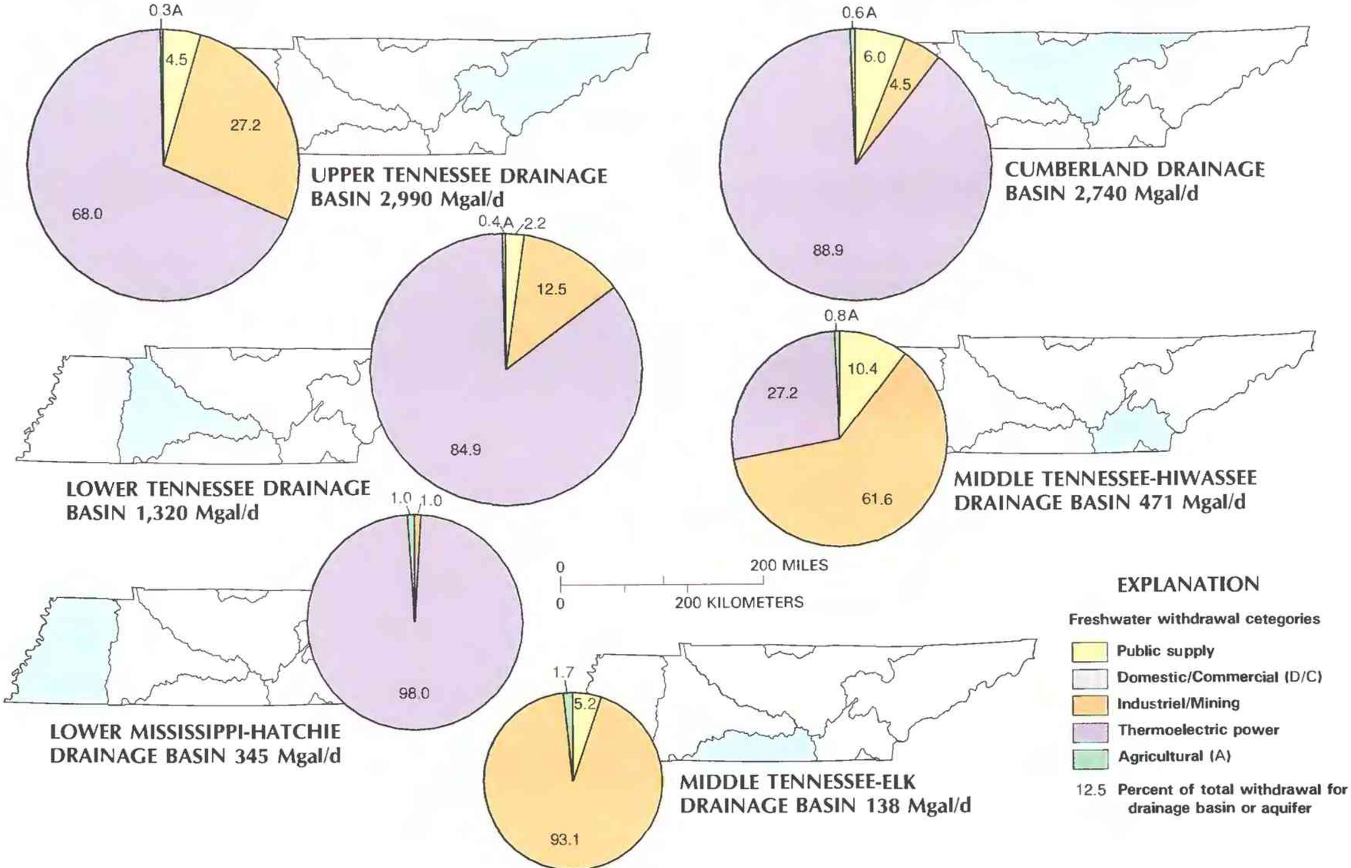
Surface water provides 94.8 percent (8,010 Mgal/d) and ground water provides 5.2 percent (444 Mgal/d) of the total offstream withdrawals (fig. 4). Public-supply facilities withdrew 627 Mgal/d from surface-water and ground-water sources. Water use in the remaining four categories shown in figure 4 is derived from surface- and ground-water sources in addition to purchases from public suppliers. Of the total water used, 3.3 percent (275 Mgal/d) was consumed, and the remainder was returned to a natural water source.

Public Supply

Public-supply systems withdraw water, treat it, and distribute it to users. Surface water accounted for 61.2 percent (384 Mgal/d), and ground water provided 38.8 percent (243 Mgal/d) of the withdrawals (fig. 4). About 90 percent of the withdrawals were delivered to domestic, commercial, and industrial users; the remainder was lost during conveyance. Water withdrawn by public-supply facilities (excluding water used for cooling for thermoelectric power generation) increased from 22.1 percent of all water used during 1980 to 26.2 percent during 1985. Increases in population and growth in commercial and industrial enterprises have resulted in additional water demands from public supplies. A decrease in self-supplied industrial water use also has contributed to the increase in percentage.

Sources of water for public supply differ across the State. Near Memphis in western Tennessee, ground water is the only source of public supply for 17 percent of the State's population. The productive aquifers underlying the Memphis area produce about 140 Mgal/d for public-supply uses. In the Cumberland basin, where dolomite and limestone aquifers yield limited quantities of water to wells, streamflow is the principal (98 percent) source of water for about 26 percent of the State's population. Nashville, the largest urban area in central Tennessee (population, 491,000), is supplied from the Cumberland and the Stones Rivers through many interconnected systems.

Surface water also provides most of the water (83 percent) withdrawn by public supply in the Upper Tennessee basin, where 27 percent of the State's population resides. The area is underlain by extensively faulted limestone, sandstone, and shale. Yields to wells range widely, and the largest yields occur in the valleys. The largest



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Tennessee, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

quantities of ground water withdrawn in eastern Tennessee are used by the cities of Chattanooga, Elizabethton, and Jefferson City.

Domestic and Commercial

Domestic and commercial water users in Tennessee purchased or withdrew about 604 Mgal/d during 1985 (fig. 4). Domestic use was 62 percent (373 Mgal/d) of domestic and commercial use, and commercial use accounted for 28 percent (168 Mgal/d); conveyance losses (10 percent) accounted for the remainder. Public-supply systems provided 81.2 percent (303 Mgal/d) of the domestic use. Nearly 77 percent of the State's population is served by public-supply systems, and the remaining 23 percent is self-supplied from wells and springs (70 Mgal/d). Consumptive use from domestic supplies was 37 Mgal/d.

Self-supplied domestic use during 1985 ranged from 60 to 70 gal/d per capita (Solley and others, 1988), in contrast to the 1980 estimates of 50 gal/d reported by Solley and others (1983). Public-supplied domestic use was 83 gal/d per capita.

Public-supply systems delivered 163 Mgal/d to commercial users, and 5 Mgal/d was provided by self-supplied systems. Consumptive use was 15 Mgal/d.

Industrial and Mining

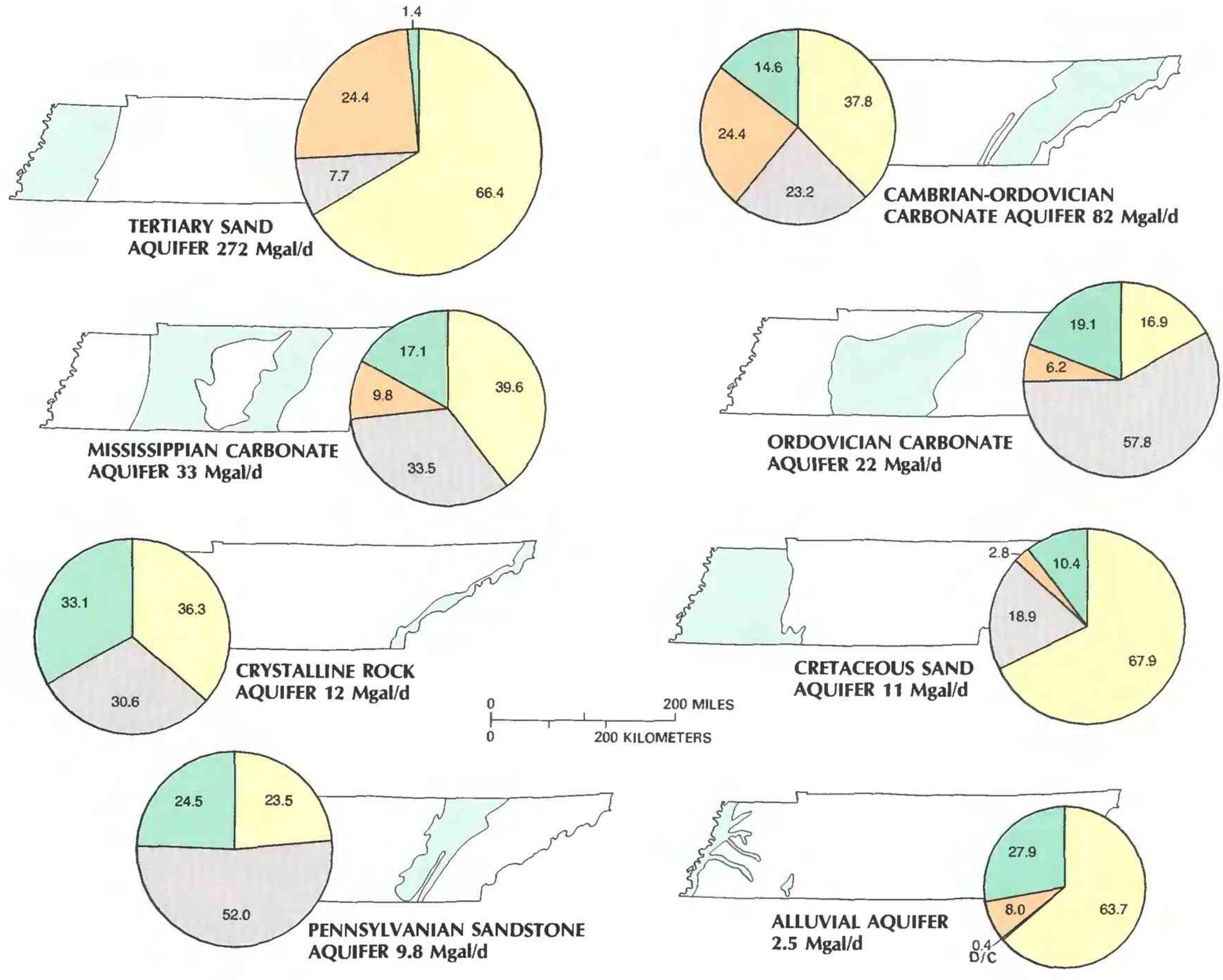
Public-supply deliveries and self-supplied withdrawals for industrial and mining use were 1,710 Mgal/d during 1985 (fig. 4). Industrial self-supplied systems, excluding mining, withdrew about 1,510 Mgal/d of surface water and about 89 Mgal/d of ground water. Self-supplied mining activities withdrew about 10 Mgal/d of surface water and 2.0 Mgal/d of ground water. Consumptive use for industrial and mining activities was 11.0 percent (188 Mgal/d) of industrial and mining withdrawals.

The chemical and the pulp and paper industries are the principal self-supplied industrial users. These industries use more water than all other Tennessee industries combined and account for nearly all individual withdrawals greater than 10 Mgal/d. Clay mines and sand-and-gravel operations are the major users of water for mining in western Tennessee. Phosphate mines and limestone quarries are prominent in central Tennessee, and metal and coal mining are prominent in the eastern part of the State.

Surface water provided about 98 percent of the 1,540 Mgal/d used for industrial purposes in central and eastern Tennessee. Several individual facilities withdraw 100 Mgal/d or more. Ground water is the principal source of the 65 Mgal/d used by industry in western Tennessee. In that part of the State, some industrial water uses have decreased as much as 50 percent during the past 5 years because of increased water recycling and declining economic activity.

Thermoelectric Power

Thermoelectric power generation is the largest use of Tennessee's total water withdrawals. The State has 10 thermoelectric



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Tennsessee, 1985—Continued.

powerplants, of which 8 are fossil-fueled plants and 2 are nuclear powered. During 1985, these plants used an average of 6,060 Mgal/d of freshwater for cooling purposes (fig. 4). Surface water supplied an average of 5,930 Mgal/d to the fossil-fueled plants. Public-supplied ground water was the source of 0.5 Mgal/d to replenish cooling water in a fossil-fueled plant near Memphis. Power was produced at one of two nuclear power plants during 1985; that plant withdrew 128 Mgal/d of surface water during 1985 and operated only part of the year. Consumptive use was 0.8 Mgal/d for the fossil-fueled plants and 0.01 Mgal/d for the nuclear power plant.

The withdrawal of water for thermoelectric cooling in the production of electricity accounts for 71.7 percent of all water withdrawals. However, virtually all (more than 99.9 percent) of this water is returned to streams.

AGRICULTURAL

Agricultural water use was 74 Mgal/d during 1985 (fig. 4). Most of the water (65 Mgal/d) was used for aquaculture and livestock. About one-half of this agricultural use was at fish hatcheries. Surface water provided about 33 Mgal/d of the withdrawals, and ground water supplied about 32 Mgal/d. Consumptive use for aquaculture was about 45 percent.

Although irrigation is a minor part of agricultural water use in Tennessee, its use to increase crop yields is steadily increasing. The number of irrigated acres increased nearly 53 percent (from 19,000 acres to about 29,000 acres) from 1975 to 1985. During 1985, total irrigation withdrawals (9 Mgal/d) were mostly from streams. The increase in irrigated acreage was affected by droughts, improved crop yields, and the introduction of new agricultural methods.

More than 40 percent of the irrigated acreage is in the western part of the State, where field crops, such as corn and soybeans, are common; the average size of irrigated fields is about 200 acres. Large-volume sprinkler systems generally are used. In contrast, the average size of irrigated fields in the central and eastern parts of Tennessee is much smaller—less than 50 acres. Specialty crops, such as tobacco, fruits, and vegetables, are most common in these areas.

WATER MANAGEMENT

The Office of Water Management (OWM) of the Tennessee Department of Health and Environment is the principal State agency that regulates the water resources in Tennessee. However, OWM regulatory activities are limited to water-quality issues and do not include authority to regulate surface- or ground-water withdrawals.

The Water Quality Act of 1977 (amended 1984) provides for the issuance of Aquatic Resource Alteration Permits by the OWM for stream-channel work, such as gravel dredging, construction of dams, and hydroelectric projects. Withdrawals are required to be registered with the OWM if deemed to have a potential negative effect on water quality. This negative effect is determined by the OWM on a case-by-case basis. A withdrawal larger than a set quantity is not a criterion, nor is withdrawal for a specific use. Water-quality effects can be physical, chemical, radiological, biological, or bacteriological in nature. Exemptions include agricultural and forestry activities, unless there is a discharge from a discernible, confined, and discrete conveyance, as described in the Tennessee Code Annotated 69-3-120.

The OWM, however, requires the registration of water withdrawals from all surface- and ground-water sources. This requirement, under the Water Withdrawal Registration Act of 1963, applies to withdrawals of 50,000 gal/d or more for any day during a year. The provision is not a permit, nor does it restrict riparian water rights. The withdrawal and the use of water are not conditional on registration; but registration provides information for the management of the State's waters.

In addition to the registration law, the OWM obtains limited water-use data through the Water Well Drillers Act of 1963. The Act requires drillers to submit water-well logs for every production well completed. The logs provide data on the use of water, well yield, and location. The Act requires the licensing of water-well drillers and allows the inspection of wells for proper construction.

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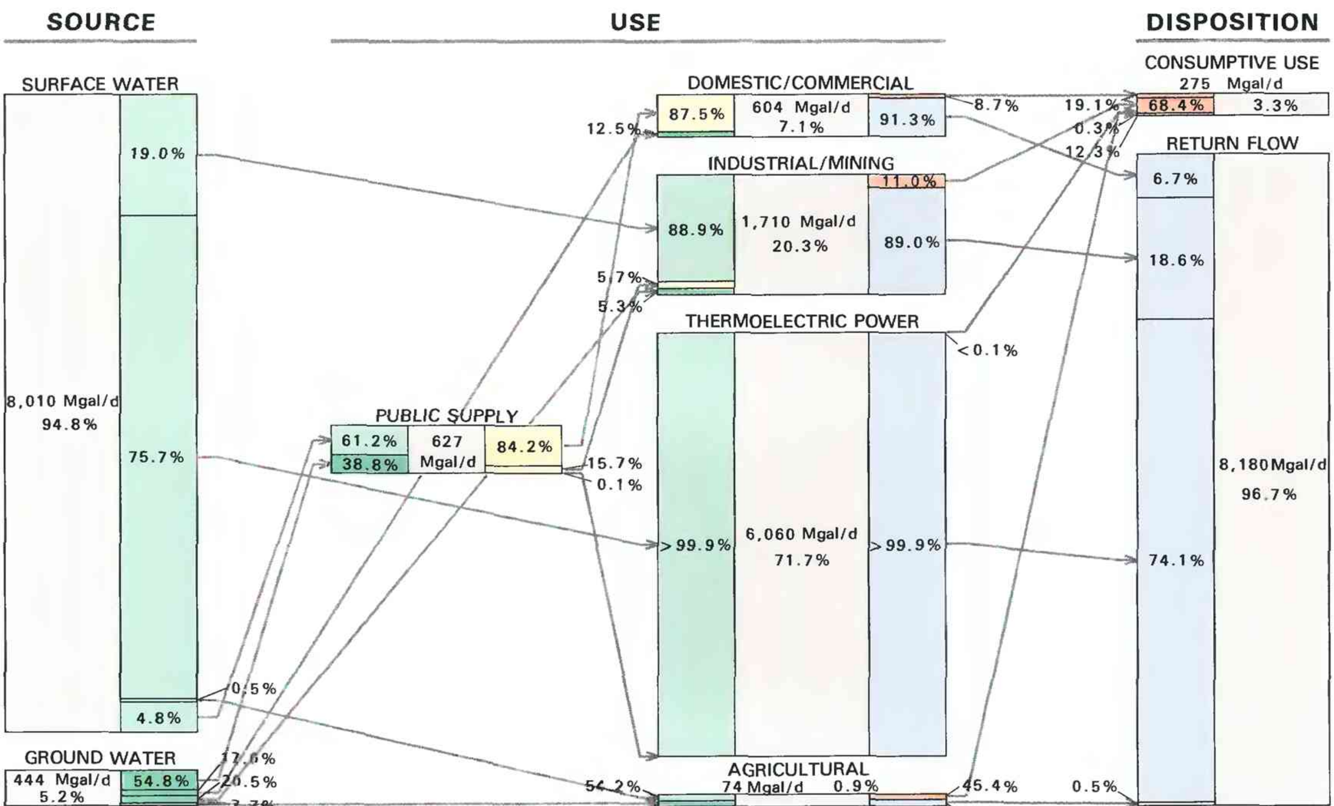
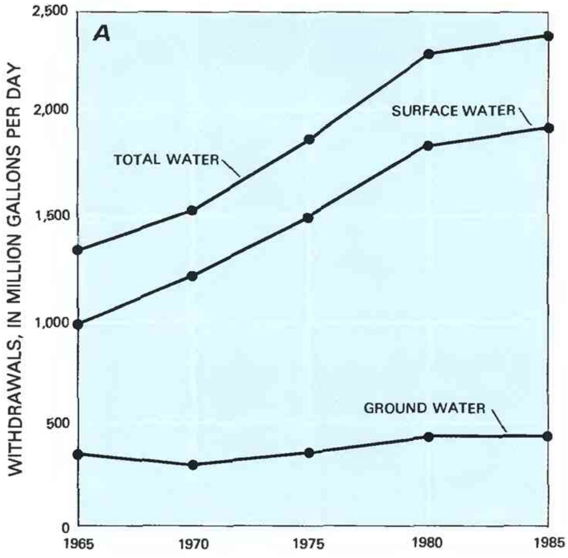


Figure 4. Source, use, and disposition of an estimated 8,450 Mgal/d (million gallons per day) of freshwater in Tennessee, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbols: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)



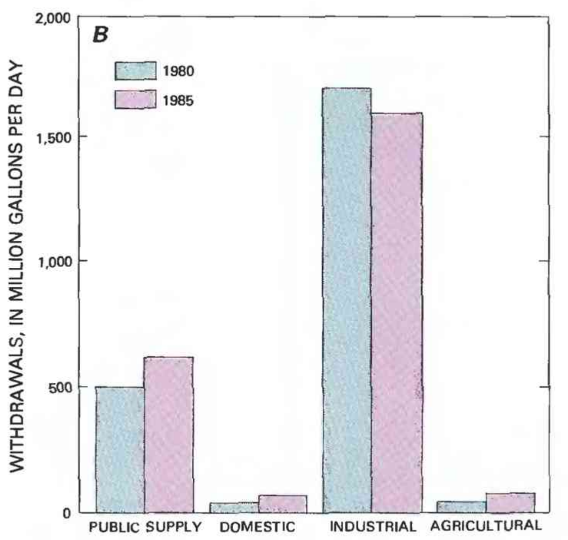


Figure 5. Selected water-use statistics for Tennessee. *A*, Offstream withdrawals excluding thermoelectric power, 1965 to 1985. *B*, Comparison of withdrawals for selected categories of use, 1980 and 1985. (Sources: *A*, *B*, Data from various reports of the U.S. Geological Survey.)

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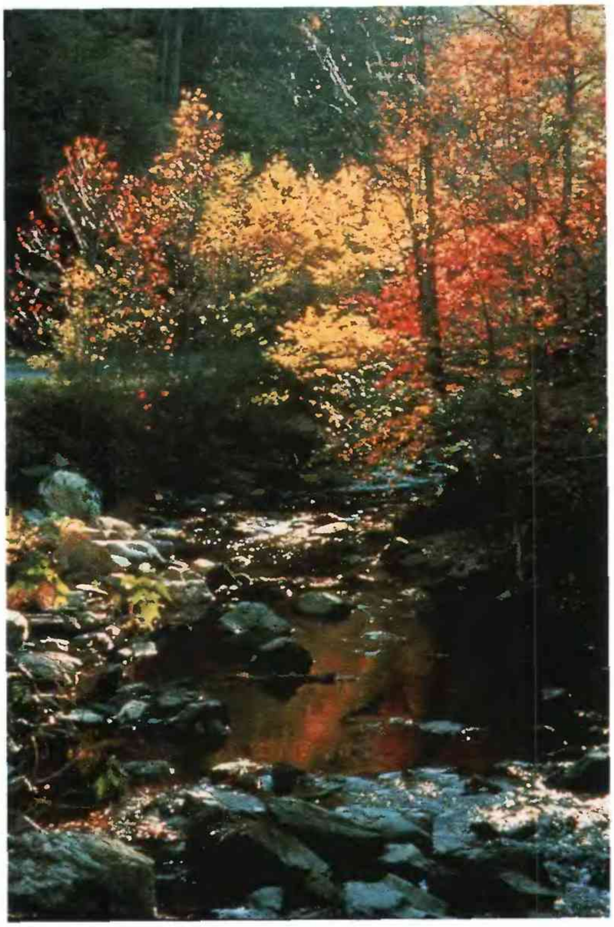

Tributaries in eastern Tennessee contribute water to the reservoirs downstream on the Tennessee River and enhance the beauty of Tennessee. (Photograph by Tennessee Photographic Services.)

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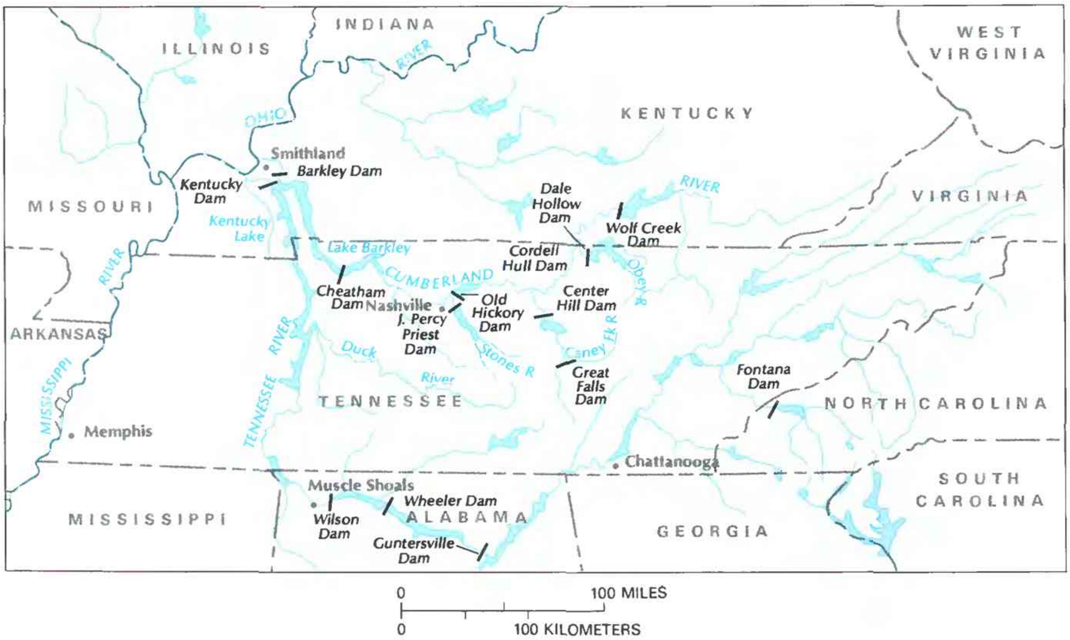


Figure 6. U.S. Army Corps of Engineers and Tennessee Valley Authority dams and reservoirs in and near Tennessee. (Source: Data from the files of the Tennessee Valley Authority.)

Prepared by S.S. Hutson, U.S. Geological Survey; History of Water Development section by C.A. Vines, Tennessee Valley Authority, Division of Air and Water Resources; Water Management section by L.A. Keck, Tennessee Department of Health and Environment, Office of Water Management

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, A-413 Federal Bldg., U.S. Courthouse, Nashville, TN 37203

TEXAS
Water Supply and Use

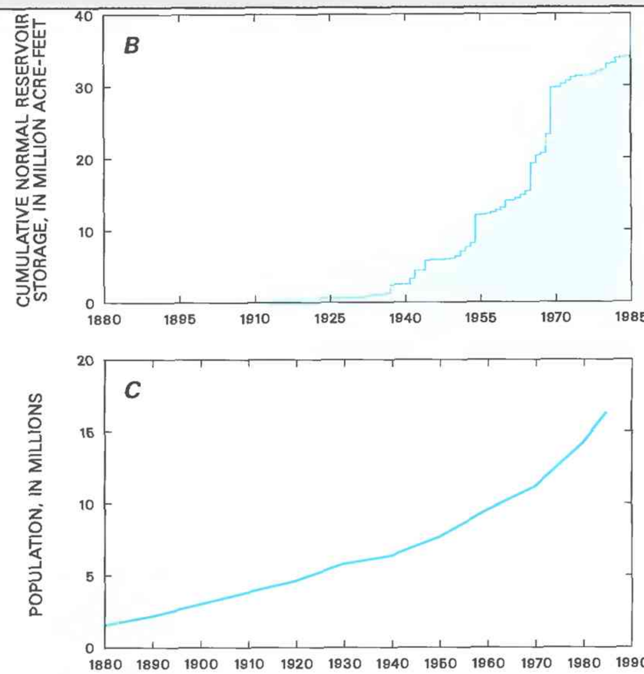
Texas, the second largest State, has a variety of hydrologic conditions. Average annual precipitation ranges from 8 inches in western Texas to 56 inches in the east, and droughts and floods are common; statewide precipitation annually averages 28 inches or 357,000 Mgal/d (million gallons per day). Evapotranspiration is estimated to be 265,000 Mgal/d. Surface-water outflows to the Gulf of Mexico are 87,300 Mgal/d (fig. 1A). Eastern areas rely on the plentiful surface-water supplies for industrial, power generation, irrigation, and other purposes. Because of the small volume of rainfall, western areas are dependent on ground water, especially for irrigation.

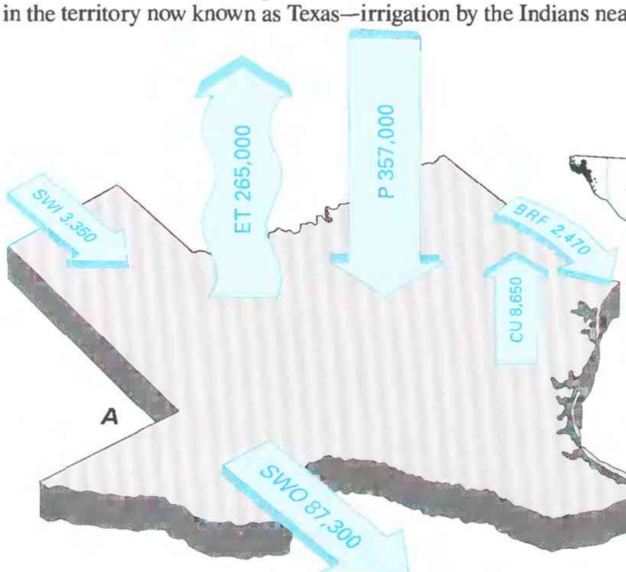
About 20,100 Mgal/d of freshwater was withdrawn in Texas during 1985. Industrial and mining water use, mainly in the Houston area, accounted for 6.9 percent of the total and was primarily from rivers. Water for thermoelectric power generation was 37.3 percent of the total use and was withdrawn primarily from the rivers of central and eastern Texas. Irrigation use, primarily surface water in the southeastern part of the State and ground water in the western part, accounted for 40 percent of the total withdrawal.

Water-development projects funded through the Texas Water Development Board are an important part of water-resources programs for the State. Water-use projections, such as those published by the Texas Department of Water Resources (1981, 1984a,b, 1985a,b), aid the Texas Water Development Board in making decisions regarding the future of State water resources. The water-use data cited in this report were compiled largely from information provided by William Moltz of the Texas Water Development Board.

HISTORY OF WATER DEVELOPMENT

In 1541, Coronado reported the earliest recorded use of water in the territory now known as Texas—irrigation by the Indians near





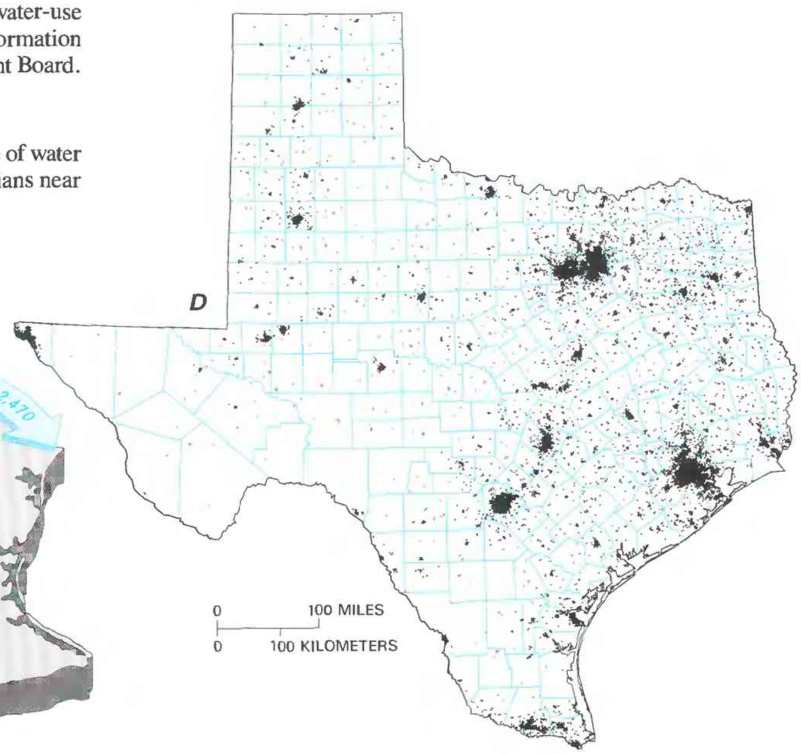


Figure 1. Water supply and population in Texas. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Texas Department of Water Resources 1984b; U.S. Geological Survey 1986a; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

the present city of El Paso. Spanish colonists traveling between the Mississippi River and Mexico routed the "Camino Real," or King's Highway, near the abundant springs of the region. These springs also were a necessity to American settlers and European immigrants traveling by covered wagon and stagecoach during the 1700's. Major springs provided water for forts and cattle-drive trails, and the city of San Antonio began as a mission established at a spring used by the Indians and, later, by the clergy for irrigation and water supply. The flow of many large springs provided power for mills, cotton gins, and later electric power-generating plants (Brune, 1975).

In the early 1800's, rivers provided transportation as well as water supplies. The Brazos River was a major transportation corridor for settlers because of the fertile land along the downstream reaches and the open grazing land along the upstream reaches. Seasonal flow variations of other rivers limited major traffic to the Brazos River. The exportation of cotton grown in the rich flood plains promoted the expansion of the ports at Galveston and Houston.

When Texas became a State in 1845, settlers had advanced no farther west than a strip of land between the Rio Grande and the Red River known as the Blacklands because of the color of the soil. This area remains the most populated in Texas. Railway expansion promoted settlement in the western part of the State during the 1880's when the railroad companies drilled water wells for use by steam locomotives. Railroad crew camps expanded into towns that used ground-water supplies.

The development of the High Plains in the Texas panhandle began with irrigation from the High Plains aquifer during the early 1900's, and irrigation increased markedly after World War II. By 1936, drought and improved efficiency of pumps and power units stimulated further interest in ground water. Farmers drilled about

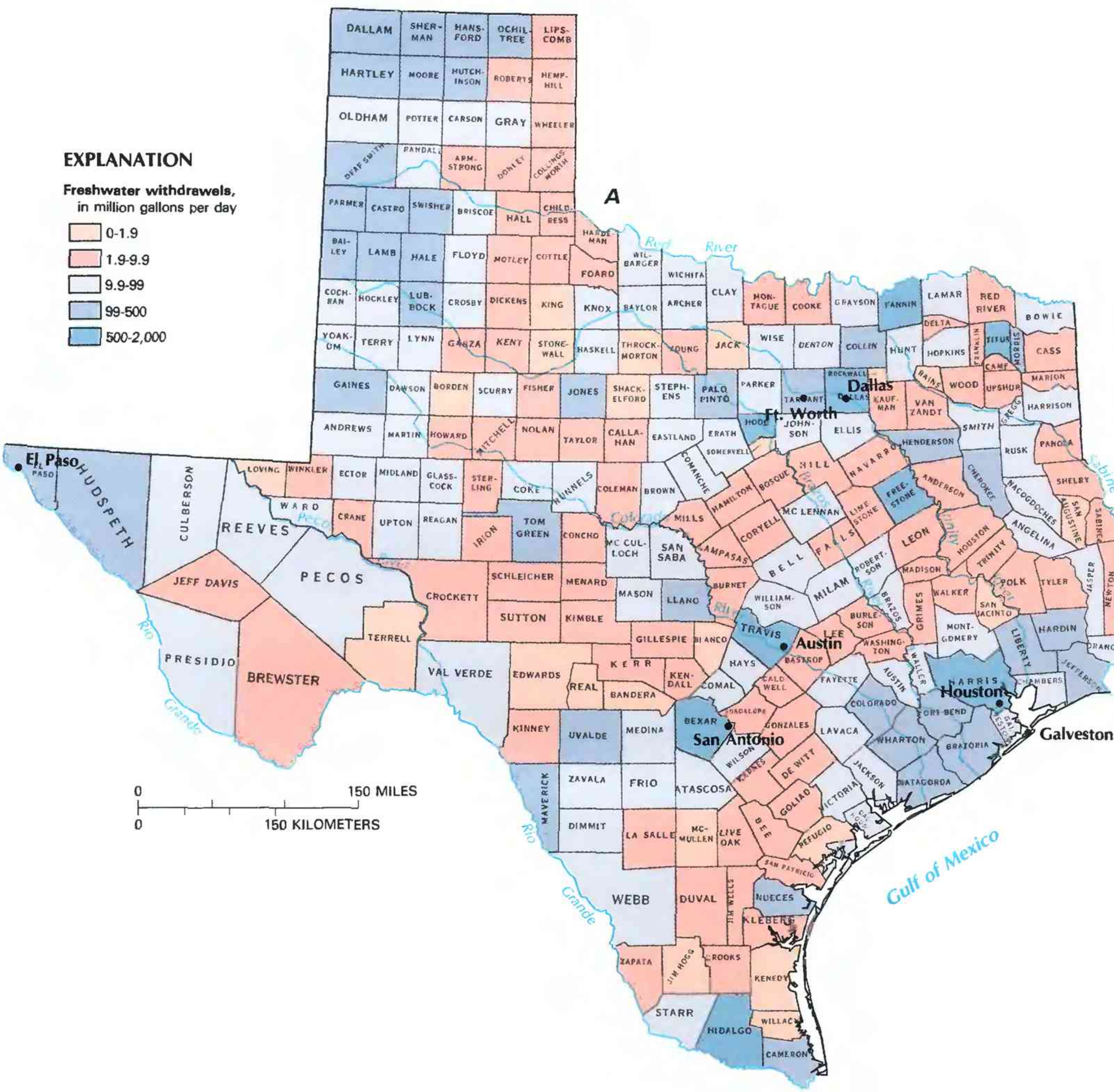


Figure 2. Freshwater withdrawals by county in Texas, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

43,000 irrigation wells in the High Plains between 1940 and 1958. Increased water demands due to population increases and droughts prompted development of ground water in other parts of the State.

The U.S. Army Corps of Engineers, State and county surface-water authorities, and cities built surface-water reservoirs to supplement water supplies during times of drought and to minimize flood damage. As late as 1913, there were only eight major reservoirs that had total storage capacity of 376,000 acre-ft (acre-feet), as shown in figure 1*B* (Kingston, 1985). To mitigate the effects of variable streamflow and to provide a dependable water supply for the increasing population (fig. 1*C*) in expanding metropolitan areas, such as Dallas–Fort Worth and Houston, Federal and local entities constructed 189 reservoirs that had a total storage capacity of 58.6 million acre-ft by 1983. By 1985, about 34 million acre-ft was normal storage (fig. 1*B*). The remaining 24.6 million acre-ft was flood-control storage or considered inactive. These reservoirs are located principally in the eastern part of the State to serve the majority of the population (fig. 1*D*).

WATER USE

Texas has a variety of hydrologic conditions that commonly dictate patterns of water use. The statewide average annual rainfall of 28 inches produces an equivalent of about 357,000 Mgal/d of water; however, precipitation ranges from 56 inches in the humid east to 8 inches in the semiarid west (Carr, 1967). Most rivers in Texas originate within the State and flow toward the south and east to the Gulf of Mexico. The upstream reaches of the larger rivers in the drier parts of western Texas contain little water supply, so large withdrawals in western Texas are mostly from ground water. Ground water underlies much of the State, but these resources are limited in the west because of slow recharge rates. Although aquifers in eastern Texas are recharged rapidly, large withdrawals from some aquifers have caused lowered water levels, land subsidence, saltwater encroachment and other water-quality problems, and decreased flow from springs.

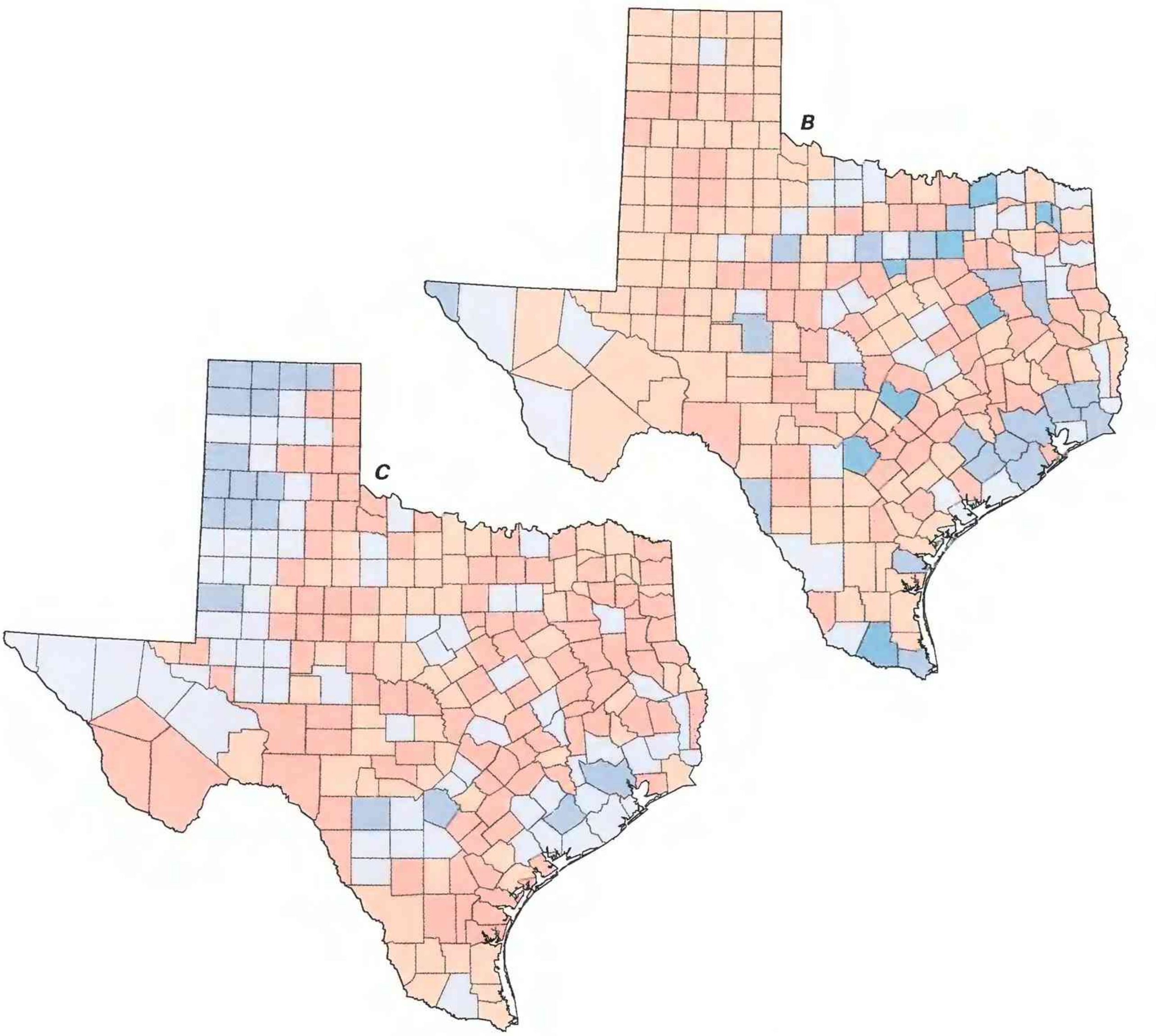


Figure 2. Freshwater withdrawals by county in Texas, 1985—Continued.

Much of the population is concentrated in the eastern one-half of the State (fig. 1*D*), where the largest cities are: Houston, which is near the gulf coast; and Dallas, Fort Worth, Austin, and San Antonio, which are in the Blacklands across the middle of the State. El Paso, which is located at the extreme western tip of the State on the Rio Grande, is the exception. Each city is the center of large freshwater withdrawal (fig. 2*A*), primarily for public supply. Most of the large cities depend on surface water (fig. 2*B*) for their water supply. Houston and San Antonio are the exceptions; ground water is used for at least some of their water supply (fig. 2*C*).

Most industries in Texas are concentrated in the northeastern coastal area where chemical and petroleum-refining operations withdraw large quantities of water from the Sabine, the Trinity, the Galveston Bay–San Jacinto, and the Lower Brazos basins (fig. 3*A*). These basins, along with the Central Texas Coastal and the Lower Colorado–San Bernard Coastal basins, also contain most of the thermoelectric power-generating facilities, which use large surface-water withdrawals for cooling. In coastal areas, some industrial and power-generating facilities use saltwater instead of freshwater for cooling and other processes where water quality is not a major factor.

Irrigation is the largest user of freshwater in Texas, and some irrigation occurs in most parts of the State. Surface water is most important for irrigating lands along the Rio Grande and rice fields along the coast. Large quantities of ground water are withdrawn for irrigation in the High Plains from the High Plains aquifer (fig. 3*B*), along the southeastern coastal area from the Gulf Coast aquifer, and in areas west of the Pecos River from the Edwards–Trinity and the alluvium and bolson aquifers.

The source, use, and disposition of about 20,100 Mgal/d of freshwater during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate, for example, that 12,900 Mgal/d of surface water was withdrawn in 1985, which was 64.2 percent of all freshwater withdrawals. Of the 12,900 Mgal/d, 0.1 percent (7.7 Mgal/d) was withdrawn (self-supplied) by domestic and commercial users, and 13.7 percent (1,760 Mgal/d) was withdrawn by public suppliers. The use data indicate that domestic and commercial use was 14.0 percent (2,810 Mgal/d) of all freshwater use. Of that quantity, 0.3 percent (7.7 Mgal/d) was self-supplied from surface water, and 95.4 percent (2,680 Mgal/d) was delivered by public suppliers. About 29.8 percent (839 Mgal/d) of the water used for domestic and commercial purposes was consumed. The disposition data indicate that, of all freshwater withdrawn in the State, 43.1 percent (8,650 Mgal/d) was consumed. Domestic and commercial consumptive use totaled 9.7 percent (839 Mgal/d) of all water consumed.

Instream uses of water also are substantial. A minimum volume of streamflow is needed to assimilate discharges of treated wastewater, but it accounts for the total streamflow in some reaches during certain seasons of the year. Large wastewater discharges to the Trinity River in the Dallas–Fort Worth metropolitan area make the river unusable for public supply and contact recreation from Dallas to Livingston Reservoir in Polk, San Jacinto, Trinity, and Walker Counties (Texas Department of Water Resources, 1984b). Improved wastewater treatment will decrease this problem in the future (Texas Department of Water Resources, 1985b).

Hydroelectric power generation used an average of 15,000 Mgal/d of instream water during 1985. However, the 21 hydroelectric powerplants produced less than 1 percent of all electric power generated in Texas. The largest hydroelectric powerplants are located on boundary rivers—Denison in Grayson County (Lake Texoma) on the Red River, Toledo Bend in Newton County on the Sabine River, and Amistad in Val Verde County on the Rio Grande.

PUBLIC SUPPLY

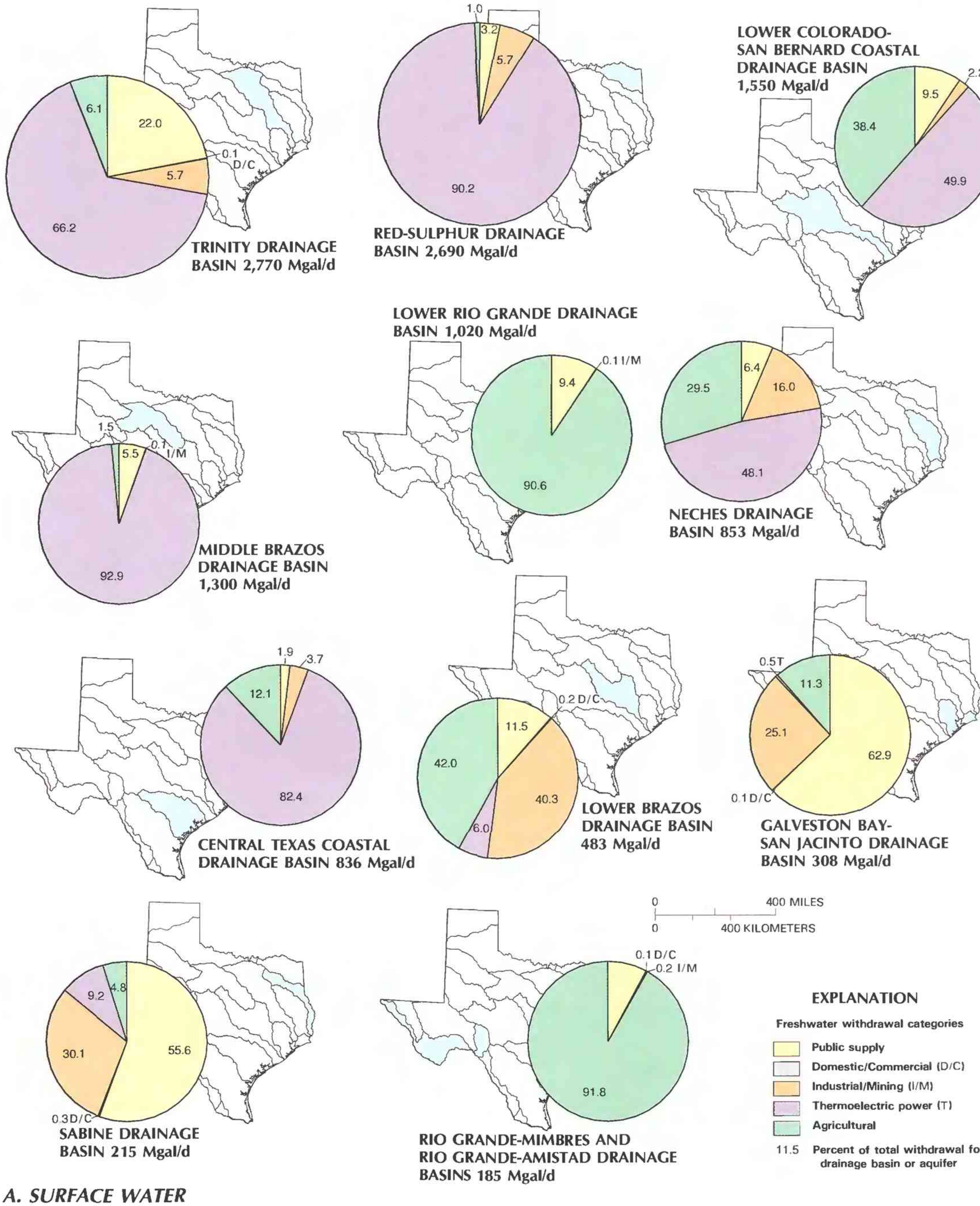
Public suppliers withdraw water, treat it, and deliver it to users. Withdrawals for public supply reflect the statewide distribution of population, with the largest withdrawals in the more humid east. During 1985, total public-supply withdrawals were 2,990 Mgal/d, of which 59.0 percent was from surface water and 41.0 percent was from ground water. About 89.7 percent (2,680 Mgal/d) of public-supply withdrawals is delivered to domestic and commercial users (fig. 4). As cities have continued to expand, increased demands on available water resources have forced changes in the pattern of water use.

Houston, the largest city in Texas, is the fourth largest city and the eighth largest metropolitan statistical area (MSA) in the United States (U.S. Bureau of the Census, 1985). The Houston MSA has a population of 3.5 million. Withdrawals during 1985 for Houston's public supplies were about 50 percent surface water and 50 percent ground water, but several suburban Houston public-supply systems rely solely on ground water. The city withdraws water from small reservoirs on the San Jacinto River in the Galveston Bay–San Jacinto basin and has water rights to 70 percent of the water stored in the Livingston Reservoir on the Trinity River (Texas Department of Water Resources, 1981). Because the city pumps so much water from the Gulf Coast aquifer, water levels have declined by as much as 250 feet in some areas. Ground-water withdrawals for public-supply and industrial uses and withdrawals of oil and gas in deeper reservoirs have caused land subsidence of as much as 9 feet (Gabrysch, 1982). Public-supply systems in the Houston area are decreasing ground-water withdrawals and increasing surface-water withdrawals to slow this subsidence (Texas Department of Water Resources, 1985b).

Dallas and Fort Worth, which compose the Nation's 10th largest MSA, have a population of 3.3 million (U.S. Bureau of the Census, 1985) in a region of limited surface and ground water. The metropolitan area is located in the upper Trinity basin, where streamflow is relatively small. Public-supply systems withdraw water from four major reservoirs in the Trinity basin, and additional water is imported from the Sabine and the Neches basins. One major aquifer, the Trinity Group, and several minor aquifers underlie the cities (fig. 3*B*). Water levels in the Trinity Group aquifer and the minor aquifers have declined markedly in response to public-supply and industrial withdrawals, resulting in increased pumping costs and the migration of more mineralized water into the aquifer underlying the area (Texas Department of Water Resources, 1981). Dallas–Fort Worth water withdrawals during 1985 were about 90 percent surface water and 10 percent ground water; surface water will become even more dominant in the future as interbasin transfers increase (Texas Department of Water Resources, 1985b).

The Edwards–Balcones aquifer is the sole source of water for San Antonio (population 840,000). Although this supply was adequate for 1985 needs, increased withdrawals could cause water shortages and decreased flow from major springs in the area. Water suppliers in the area are considering using water from the San Antonio and the Guadalupe Rivers in the Central Texas Coastal basin to supplement the ground-water supply (Texas Department of Water Resources, 1985b).

El Paso (population 464,000), which receives an average of 8 inches of precipitation annually, uses ground water from the alluvial basin-fill deposits and surface water from the Rio Grande. About 85 percent of El Paso's 1985 public-supply withdrawals were from ground water (Texas Department of Water Resources, 1985b). The Rio Grande Compact, which was approved by Texas, New Mexico, and Colorado in 1939, limits surface-water availability. Irrigation is the major use of the water delivered under the Compact. El Paso is purchasing land that has water rights to increase its allocation of water from the Rio Grande (Texas Department of Water Resources, 1984b), but the primary public-supply source will continue to be ground water. El Paso and Juarez, Mexico, withdraw water from the alluvial basin-fill deposits in the Rio Grande valley. Precipitation and streamflow recharge the bolson at a fraction of the current (1987) withdrawal rate; consequently, water from the aquifer is being mined. Mining of water probably will result in declining water levels,



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Texas, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Modified from Texas Department of Water Resources, 1984b.)

decreased well yields, and deteriorating water quality. El Paso is anticipating that water demand will exceed supply as early as 1995. The city is implementing a pilot project to recharge the bolson aquifer artificially with treated sewage wastewater effluent. If the water is of usable quality when the injected water reaches city wells, then the project will increase El Paso's supply. The city also is seeking additional water from aquifers in New Mexico.

Domestic and Commercial

Domestic and commercial use averaged 2,810 Mgal/d during 1985. Public-supply systems provided 95.4 percent of this quantity, reflecting the concentration of population in urban areas and the large number of rural public-supply systems serving areas that once relied on individual wells. About 29.8 percent (838 Mgal/d) of this water is consumed. Consumptive use by domestic users is greater in Texas than for the Nation—36 percent compared to 23 percent (Solley and others, 1988)—owing to the evaporative loss during lawn watering and the use of evaporative air-conditioning units in arid areas (William Moltz, Texas Water Development Board, oral commun., 1986).

Industrial and Mining

Total freshwater and saltwater use by industry and mining averaged 3,050 Mgal/d during 1985. Freshwater use was 1,390 Mgal/d, or 46 percent of the total industrial and mining use; this quantity was 6.9 percent of the State's total freshwater use (fig. 4). Saltwater sources supplied the remaining 1,660 Mgal/d, accounting for 32 percent of saltwater withdrawals in Texas. Industrial processes and evaporative losses resulted in consumptive use of 45.2 percent of total industrial and mining withdrawals of freshwater.

Industrial use was 2,700 Mgal/d during 1985; 47 percent was withdrawn from freshwater sources. Public-supply systems provided 10 percent of total use (22 percent of the freshwater). Self-supplied industrial withdrawals are concentrated in the coastal region and centered around Houston. This area has plentiful saltwater for use in cooling machinery. The petroleum-refining and chemical industries account for 80 percent of saltwater industrial use and 53 percent of the freshwater industrial use. Texas leads the Nation in refining petroleum (Kingston, 1985) and producing industrial chemicals (U.S. Bureau of the Census, 1986).

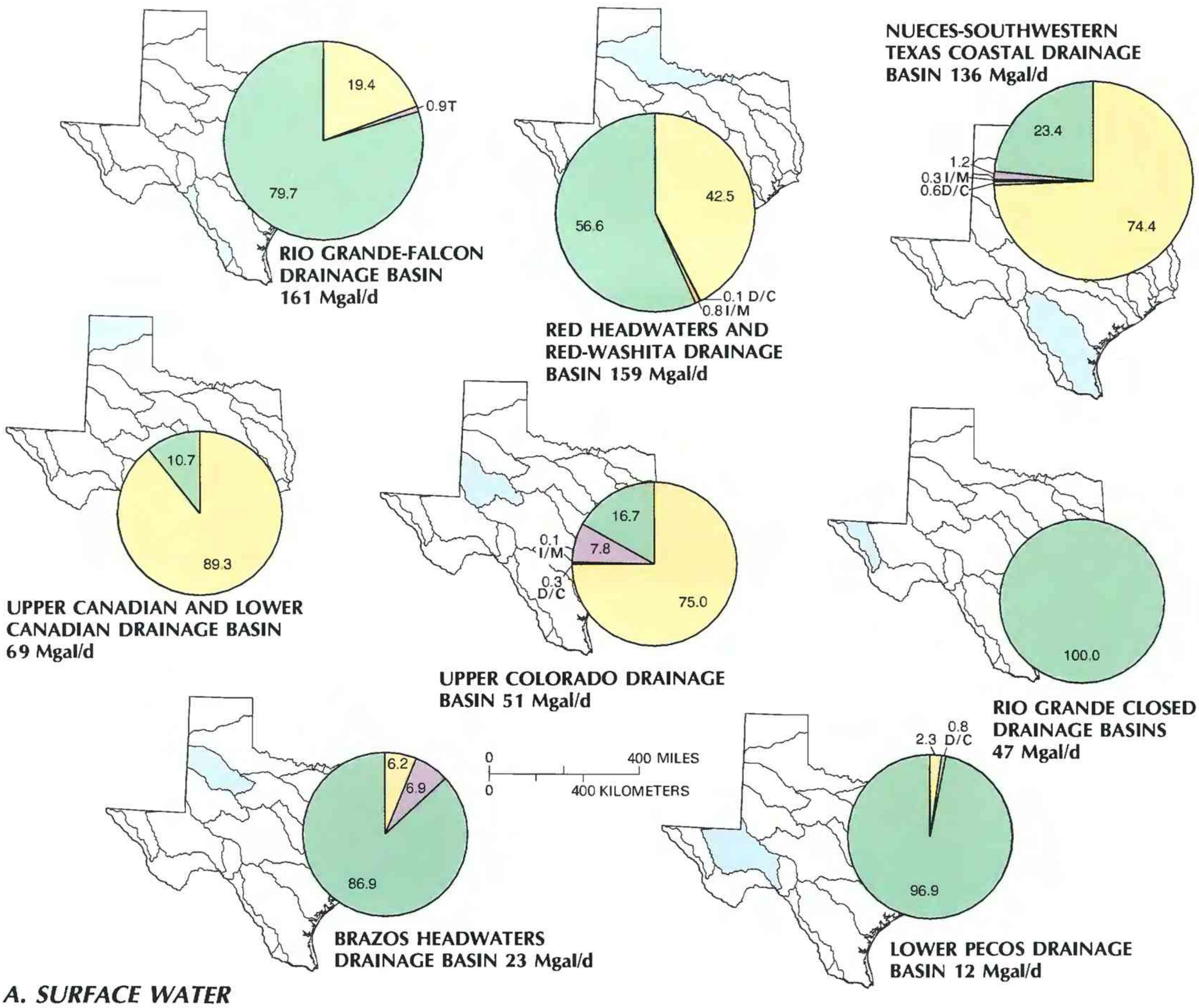


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Texas, 1985—Continued.

Mining withdrawals account for 9 percent (121 Mgal/d) of the industrial and mining freshwater uses and 14 percent (229 Mgal/d) of industrial and mining saltwater uses. The freshwater is used for washing and transporting sand and gravel. Saltwater withdrawals are incidental to oil and gas production. Some of this water is reinjected into the production zones to maintain or increase reservoir pressure.

Thermoelectric Power

During 1985, thermoelectric power generation accounted for 37.3 percent (7,480 Mgal/d) of freshwater use (fig. 4) and an additional 3,550 Mgal/d of saltwater use. Cooling is the major water use, and, because many powerplants do not have recirculating cooling systems, consumptive use is small—3 percent of the freshwater and less than 1 percent of the saltwater. During 1985, 41 large [more than 500 MW (megawatt) capacity] and 54 small (less than 500 MW capacity) thermoelectric powerplants produced about 217,000 gigawatthours of electricity, which is about 99 percent of all power generated in the State. Powerplants are concentrated near the major cities. During 1985, coal, oil, or natural gas fueled all operating plants. Two nuclear powerplants are under construction.

Agricultural

Agricultural use averaged 8,380 Mgal/d during 1985, or 41.8 percent of all freshwater used in Texas (fig. 4). Irrigation uses 97 percent of all agricultural withdrawals (8,120 Mgal/d); this water was used to irrigate about 6.7 million acres in 1985. Withdrawals for livestock watering averaged 261 Mgal/d. Consumptive use was 83.4 percent of total agricultural withdrawals, which is by far the largest single consumptive use.

The pattern of water use in the three largest irrigation areas demonstrates the diverse water supply and demand problems. The High Plains region (fig. 3*B*), the most intensively irrigated part of the State, contains almost 70 percent of all irrigated land in Texas. In some counties, the irrigated land is more than 50 percent of the county area. Cotton is grown on about 35 percent of the irrigated lands, and wheat is grown on about 25 percent; grain sorghum and

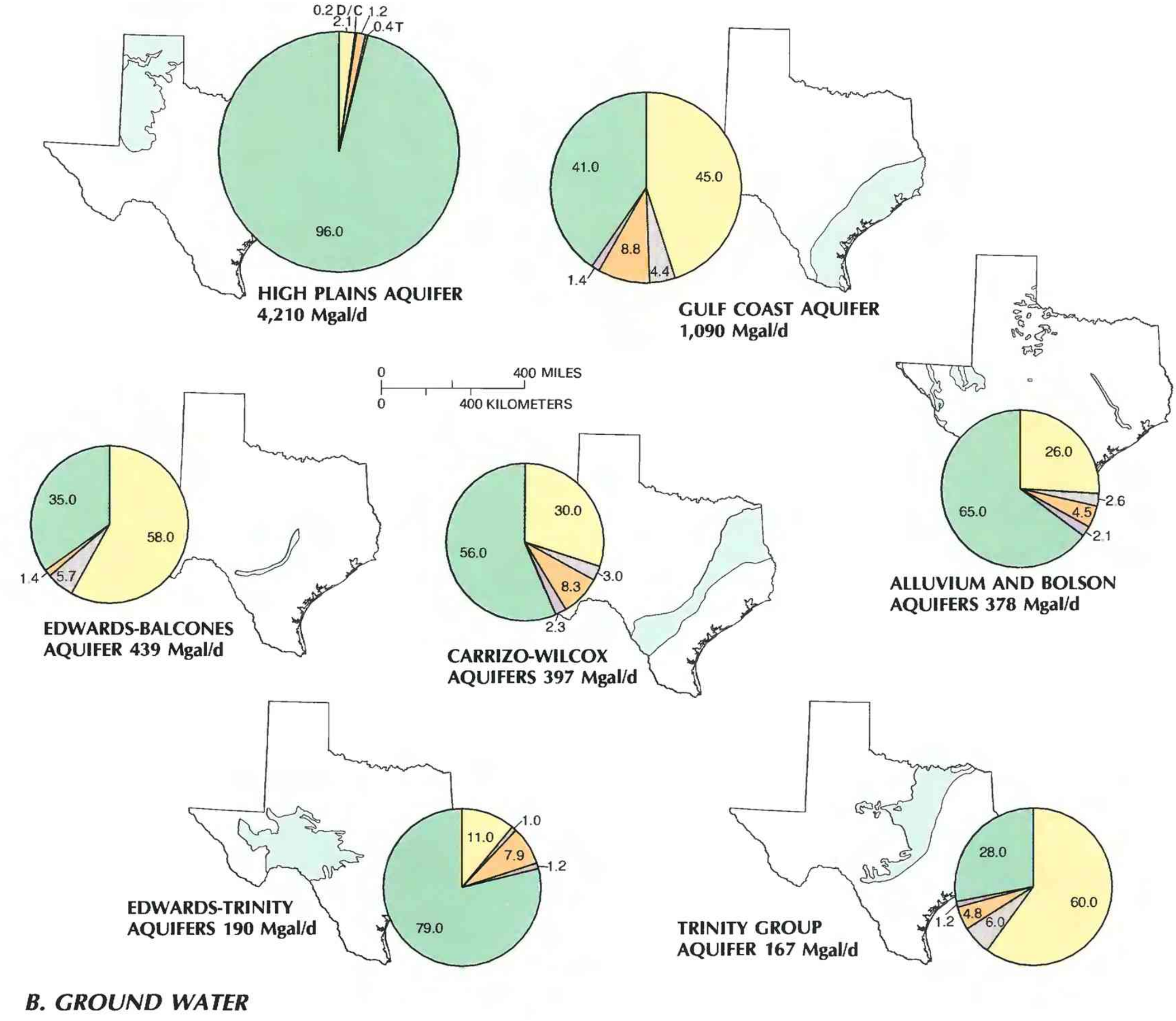


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Texas, 1985—Continued.

corn are other major irrigated crops. Crop acreages have fluctuated considerably in recent years because of the variations in "set-aside" programs and market prices (Texas Water Development Board, 1986a). Annual precipitation of 14 to 20 inches and limited surface-water resources force farmers to rely on ground-water irrigation for maximum crop yields, although, in some years, ephemeral playa lakes provide another source of water.

During 1985, the High Plains aquifer, which underlies the High Plains region, supplied 59 percent of all ground water withdrawn in Texas. The rate of withdrawal from the aquifer is much greater than the rate of natural recharge, and the water level in the aquifer has declined about 100 feet from predevelopment to 1980 in parts of the High Plains (Gutentag and others, 1984). Lowered water levels decrease well yields, require more energy to lift the water to land surface, and increase the farmer's cost of irrigation. The Texas Department of Water Resources (1984b) predicts further decreased withdrawals as the aquifer is depleted. Thus, irrigators in the High Plains are changing to more efficient irrigation practices to make better use of the available water, and some acreage has been converted to dryland farming. These trends will continue as irrigation costs increase (Texas Water Development Board, 1986a).

The lower Rio Grande valley, which is at the extreme southern tip of Texas, is the second-largest irrigated area in the State. The valley is a major citrus-growing area, although the severe freeze in 1983 decreased the acreage planted in orchards. The Rio Grande supplies almost all the water for irrigation in this area, primarily from water stored in the International Falcon Reservoir in Starr and Zapata Counties (Texas Water Development Board, 1986a). Much of the irrigated acreage is located in the adjacent Nueces–Southwestern Texas Coastal basin. Water from the Gulf Coast aquifer (fig. 3*B*) and the other minor aquifers can be used to supplement the surface-water supply during years of low flow in the Rio Grande.

Rice is the major crop in the Gulf Coast Prairie (Texas Water Development Board, 1986a), the coastal region extending from the Texas–Louisiana State line to Victoria and Calhoun Counties. Rice must be flooded at some stages for weed and disease control, so rice growing requires large volumes of water, 3.5 to 6 feet per acre, compared to conventional application rates for most crops of 15 to 18 inches per acre. Water from the Trinity and the Neches basins is used to irrigate large areas in Chambers and Jefferson Counties in the eastern part of the Gulf Coast Prairie, and water from the Brazos River is used for supply in Brazoria and Galveston Counties. Water from the Gulf Coast aquifer and additional water from the Colorado River (Lower Colorado–San Bernard Coastal basin) is used to flood rice fields in Wharton County in the western area of the rice-growing region. Farmers usually convey surface water across river basin and county lines from streams to where they own water rights to their fields. Transfer of water through open canals results in substantial conveyance losses, which, in a few instances, can be as much as 60 percent of the total withdrawal (Comer Tuck, Texas Water Development Board, oral commun., 1986).

WATER MANAGEMENT

At the beginning of this century, water management in Texas was primarily under the control of the individual—if people needed water, they withdrew it. Today, decisions regarding the development and use of water sources and the protection of water quality require detailed knowledge of surface- and ground-water rights and the local,

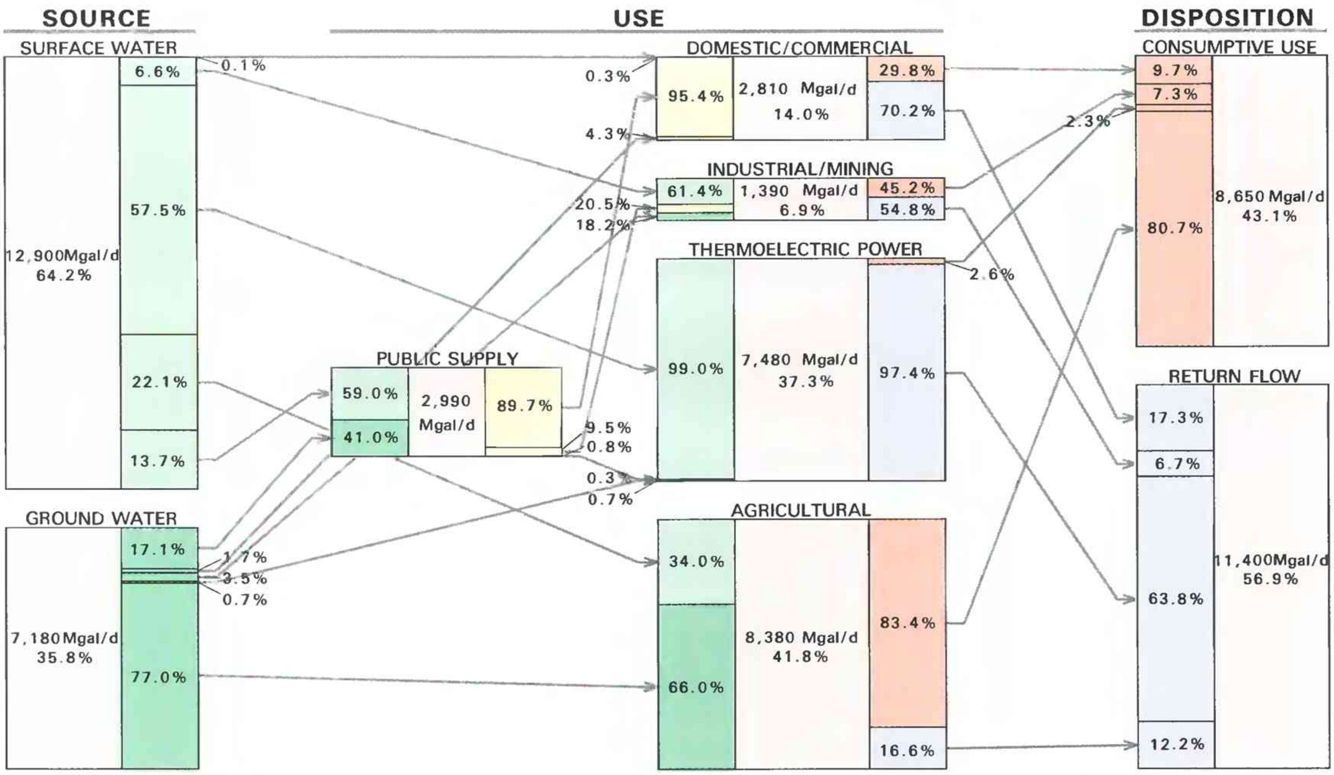


Figure 4. Source, use, and disposition of an estimated 20,100 Mgal/d (million gallons per day) of freshwater in Texas, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

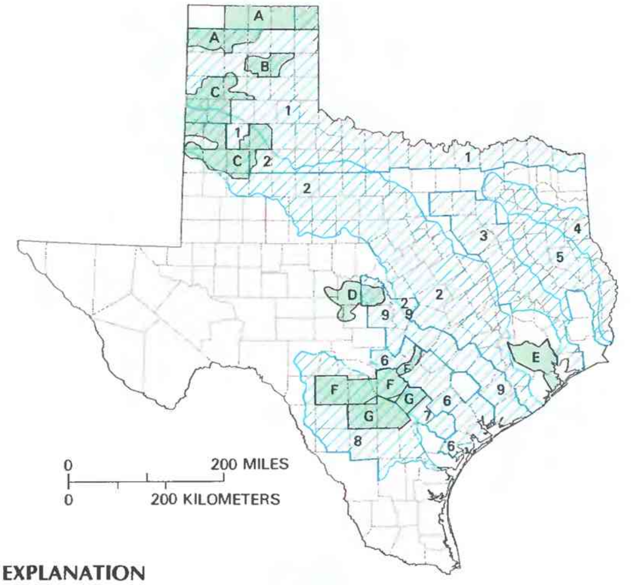
State, and Federal agencies that have the authority to manage the water resources.

Surface water is public property and is administered by the Texas Water Commission to ensure the availability of each user's supply. Any person, public or private corporation, city, county, river authority, State agency, or other political subdivision of the State must acquire a permit to appropriate these waters. Ground water is private property subject to use by landowners. State law has established some ground-water conservation districts to conserve and manage this resource.

Primary responsibility for water-resources management lies with the thousands of regional, local, and private entities that supply or regulate water for the public-supply, industrial, and agricultural customers. Selected river authorities and ground-water districts that are representative of the many such entities that have been created to develop and manage local water resources are identified in figure 5. Most, if not all, of these operate under the Conservation and Reclamation Amendment to the Texas Constitution adopted in 1917. Organizations created under this provision can be authorized to (1) control, store, preserve, and distribute waters for irrigation, power, and all other useful purposes, (2) reclaim and irrigate arid land, (3) reclaim and drain overflowed lands, (4) conserve and develop forests, water, and hydroelectric power, (5) provide for the navigation of coastal and inland water, (6) control, abate, and change shortage and harmful excess of water, (7) preserve and conserve all natural resources of the State, and (8) engage in fire-fighting activities. The legislature allows these entities to be created by petition to County Commissioner's Courts, petition to the Texas Water Commission, or through special consideration by the legislature.

Several State agencies have responsibility for implementing the Texas Legislature's mandate to encourage the development, conservation, and quality maintenance of water. The Texas Water Development Board prepares and updates the State Water Plan, collects and maintains data on water resources, and administers various funds designed to help finance State and local water projects. The Texas Water Commission (1) administers the State water-quality program, (2) grants permits allowing the discharge of effluents, (3) determines and allocates surface-water rights, (4) regulates dam construction, maintenance, and removal, (5) administers the hazardous-spill program, (6) licenses hazardous-waste disposal facilities, (7) administers the National Flood Insurance Program, (8) trains and certifies wastewater-treatment plant operators, and (9) establishes water and sewer rates. In addition, the Texas Department of Health enforces Federal standards for drinking water, the Texas Department of Parks and Wildlife develops and protects water-based recreational and wildlife resources, the Texas Water Well Drillers Board regulates water-well drillers, and the Railroad Commission of Texas enforces regulations that protect surface and ground water from wastes generated by oil and gas production. The Railroad Commission also oversees surface mining of coal and lignite and in situ mining of uranium to protect surface and ground waters.

Numerous Federal agencies are involved with water management in Texas. The U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation are principal planners and developers, and the U.S. Environmental Protection Agency regulates and funds Federal water-quality programs concerned with planning, water-quality standards, solid-waste management, underground injection of wastes, and the Federal Safe Drinking Water Act. Other Federal agencies, such as the U.S. Geological Survey, the U.S. Soil Conservation Service, the U.S. Forest Service, the National Park Service, the U.S. Fish and Wildlife Service, the U.S. Department of Housing and Urban Development, and the U.S. Farmers Home Administration, conduct programs that gather water data, develop and protect water and environmental resources, and administer loans, grants, and other programs to assist water-related projects. In addition, the International Boundary and Water Commission oversees the treaty-mandated division of surface water of the Rio Grande between the United States and Mexico. Also, interstate-compact agreements determine water allocation on the Rio Grande and the Canadian River in the Lower Canadian and North Canadian basin and the Red, the Pecos, and the Sabine Rivers.



EXPLANATION

RIVER AUTHORITIES

1 Red River Authority of Texas
2 Brazos River Authority
3 Trinity River Authority of Texas
4 Sabine River Authority of Texas
5 Angelina/Neches River Authority
6 Guadalupe-Blanco River Authority
7 San Antonio River Authority
8 Nueces River Authority
9 Lower Colorado River Authority

GROUND-WATER DISTRICTS

A North Plains Ground-Water Conservation District No. 2
B Panhandle GW Conservation District No. 3
C High Plains Underground Water Conservation District No. 1
D Hickory Underground Water Conservation District No. 1
E Harris-Galveston Coastal Subsidence District
F Edwards Underground Water District
G Evergreen Underground Water District

Figure 5. Selected river authorities and ground-water districts. (Sources: Texas Department of Water Resources, 1985b, and Texas Water Development Board, 1986b.)

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FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 8011 Cameron Rd., Building 1, Austin, TX 78753

U.S. Virgin Islands
Water Supply and Use

The U.S. Virgin Islands consist of more than 40 small islands and cays. The three principal important islands are St. Croix, St. Thomas, and St. John, which have areas of 82, 32, and 19 square miles, respectively. Streamflow occurs mostly during periods of intense rainstorms, and ground-water resources are limited. Average annual rainfall (fig. 1A) is about 44 inches, or 268 Mgal/d (million gallons per day) (Francois and others, 1983). About 94 percent, or 253 Mgal/d, of the precipitation is lost by evapotranspiration; the remaining water is consumed (1.2 Mgal/d) or is lost as surface- or ground-water outflow to the ocean (about 14 Mgal/d).

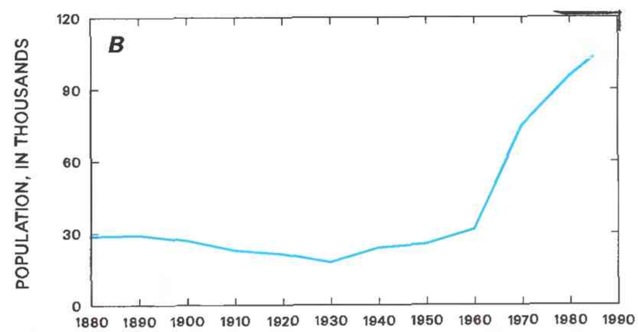
Urban areas of all three major islands—Christiansted, Frederiksted, Charlotte Amalie, and Cruz Bay (fig. 1C)—rely primarily on desalinated seawater. Rural areas depend mainly on rainwater collected from rooftop rainfall catchments and ground water. The principal aquifers in the U.S. Virgin Islands are the Kingshill aquifer in central St. Croix and the coastal embayment aquifers and volcanic rock aquifers in the three major islands.

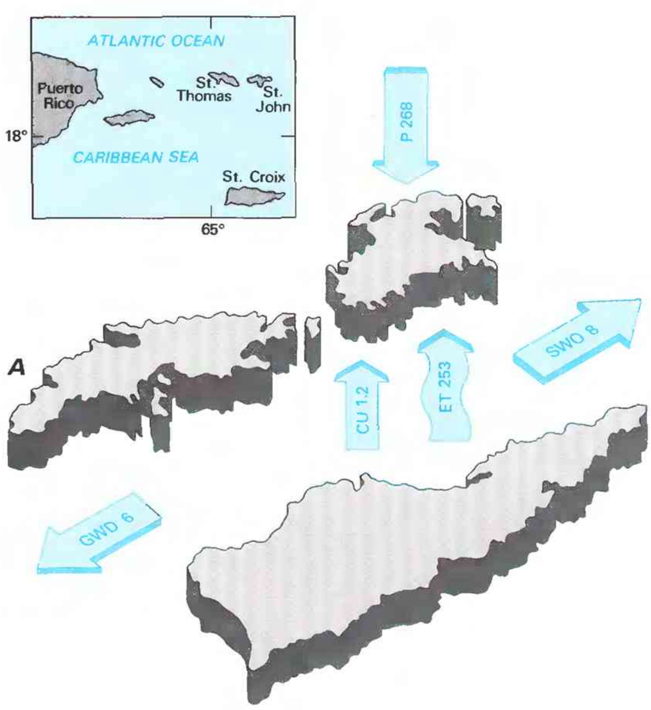
In 1985, total freshwater withdrawals were 7.1 Mgal/d (Solley and others, 1988). The largest freshwater use on the islands was by domestic and commercial users, which received water from public-supply systems and self-supplied facilities. About 117 Mgal/d of seawater was withdrawn, primarily for cooling purposes at thermoelectric powerplants. An additional 43 Mgal/d of seawater was used to produce 4.27 Mgal/d of desalinated water for distribution through the potable water-supply system.

HISTORY OF WATER DEVELOPMENT

The water resources of the U.S. Virgin Islands have never been abundant. Archeological, historical, and geological evidence, however, indicates that the water resources once were greater than at present (Jordan, 1972). According to journals and reports of the 17th and 18th centuries, water was a precious commodity even at that time. However, streams and springs that were mentioned in the early journals and shown on early maps no longer flow (Jordan, 1972).

Rainwater collected on roofs and stored in cisterns was the source of water for most rural and urban domestic supplies. Rainwater was so important in furnishing the basic water-supply needs that, in 1964, the Legislature of the U.S. Virgin Islands passed a bill requiring all residential, commercial, and industrial buildings to have a certain minimum storage per square foot of roof area. Before 1960, hillside rainfall catchments and a few dug wells were the major sources of water for public supplies (Jordan and Cosner, 1973). Transport of water by barge from Puerto Rico was initiated in 1955 to supplement island resources. The growing population in the 1960's and early 1970's, which was precipitated by the switch from an economy that was based on agriculture to one based on industry and tourism, created unprecedented demands on the public-





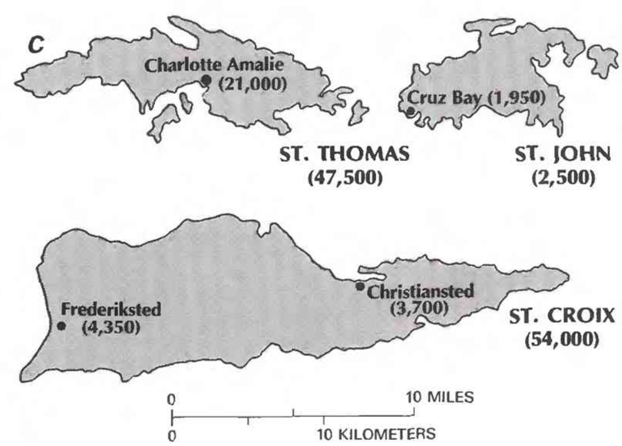


Figure 1. Water supply and population in the U.S. Virgin Islands. *A,* Water budget, in million gallons per day. Insert map indicates correct geographic relation of the principal islands. *B,* Population trend, 1880 to 1985. *C,* Population distribution, 1985. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **GWD,** ground-water discharge; **SWO,** surface-water outflow. (Sources: *A,* Data from U.S. Geological Survey files. *B,C,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

supply system (Francois and others, 1983). The population increased from 32,100 in 1960 to more than 85,800 in 1975 (fig. 1*B*). Desalination was introduced in 1964 by the Virgin Islands Water and Power Authority (VIWAPA) to supplement the existing water supply from rainfall and ground-water resources. The new source of freshwater created a dramatic increase in the water production over a short period of time. The increased production more than doubled the capacity of the water-supply system and introduced new challenges to the operating authorities.

During the 1970's, water production continued to expand mainly through desalination, but, by the end of the decade, aging of the desalination plants coupled with difficulty in obtaining replacement parts resulted in long periods of inactivity. In addition, periods of drought, overpumping of well fields, occasional failure of the distribution system, and lack of adequate storage capacity resulted in frequent shortages and rationing of water. In 1979, the Government of the U.S. Virgin Islands once again transported water by barge from Puerto Rico to meet the demands. In 1981–82, the VIWAPA expanded its desalination capacity by 2.5 Mgal/d on St. Thomas and by 1.25 Mgal/d on St. Croix and ended the need for rationing (Francois and others, 1983). Although the production of water increased with the installation of the seawater desalination plants, demands have not been satisfied as the population has increased. As of 1985, the population was about 104,000; the distribution is shown in figure 1*C*. System leakage, faulty metering, and illegal connections have resulted in a 50-percent water loss (CH2M Hill Southeast, Inc., 1983).

WATER USE

Total freshwater, surface-water, and ground-water withdrawals by island are shown in figure 2. The pattern of freshwater withdrawals in the U.S. Virgin Islands is governed principally by the availability of water—production of desalinated water and intensity and duration of rainfall—and by tourism. On the three major islands, seawater, rainwater collected from rooftop catchments, and ground water are the principal sources of water. Most of the streams are ephemeral and flow only during intense rainstorms. Seawater is used for cooling at thermoelectric power generating plants and at desalination plants for production of freshwater for public supply. Several industries and hotels use seawater to produce freshwater, and seawater also is used for fire fighting and for flushing toilets.

Rainwater collected from rooftop catchment systems and stored in cisterns is an important source of water for most rural residents (fig. 3*A*). Rainwater is used mostly by individual homeowners and by commercial and industrial facilities. In the U.S. Virgin Islands, the desalinated water and the rainwater collected from rooftop catchment systems are considered to be surface-water resources.

Ground water, which is an important resource in the three major islands, provides about 20 percent of the freshwater supply. The aquifers in these three islands have relatively poor yields and water quality. Throughout most areas, yields are less than 15 gallons per minute and dissolved-solids concentrations are greater than 1,000 milligrams per liter (U.S. Geological Survey, 1985). Ground water is withdrawn mainly by domestic and commercial users (fig. 3*B*), who are not connected to public-supply systems. In St. Croix, the Virgin Islands Department of Public Works (VIDPW) uses ground water to supplement desalinated water in the public-supply system. In St. John, ground-water resources supplement desalinated water that is barged from St. Thomas.

The source, use, and disposition of freshwater in the U.S. Virgin Islands during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this

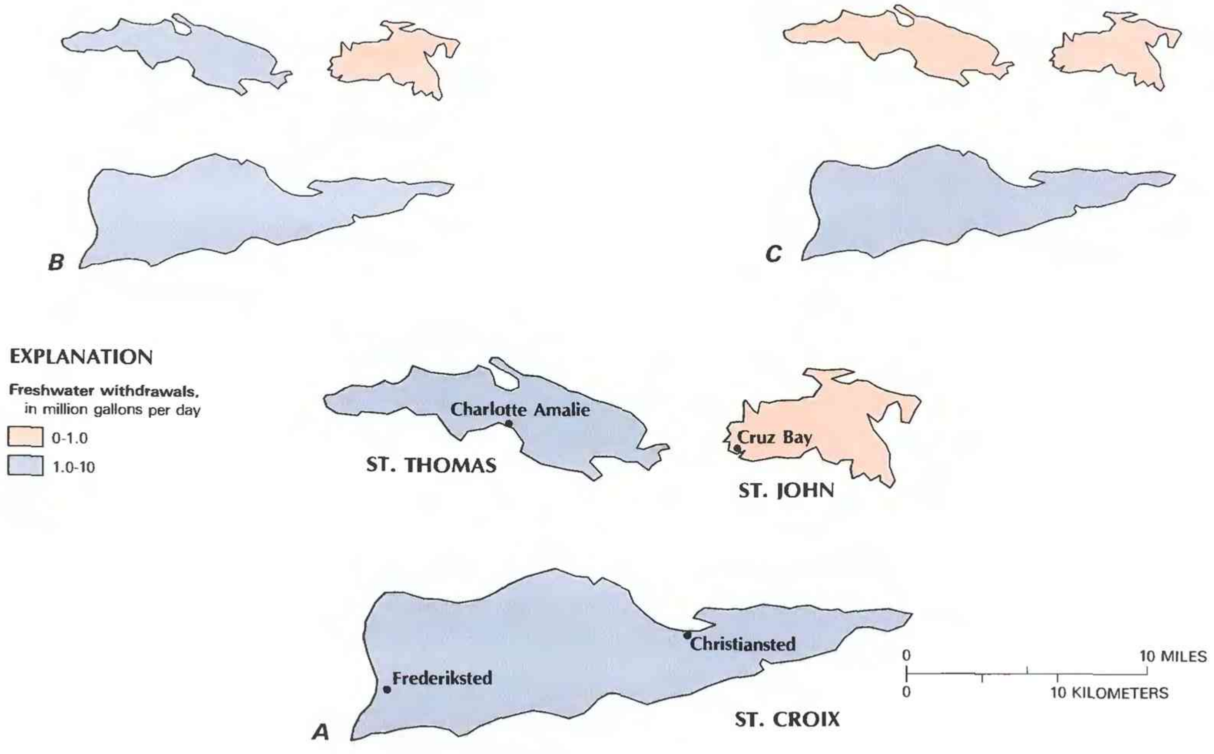


Figure 2. Freshwater withdrawals by island in the U.S. Virgin Islands, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

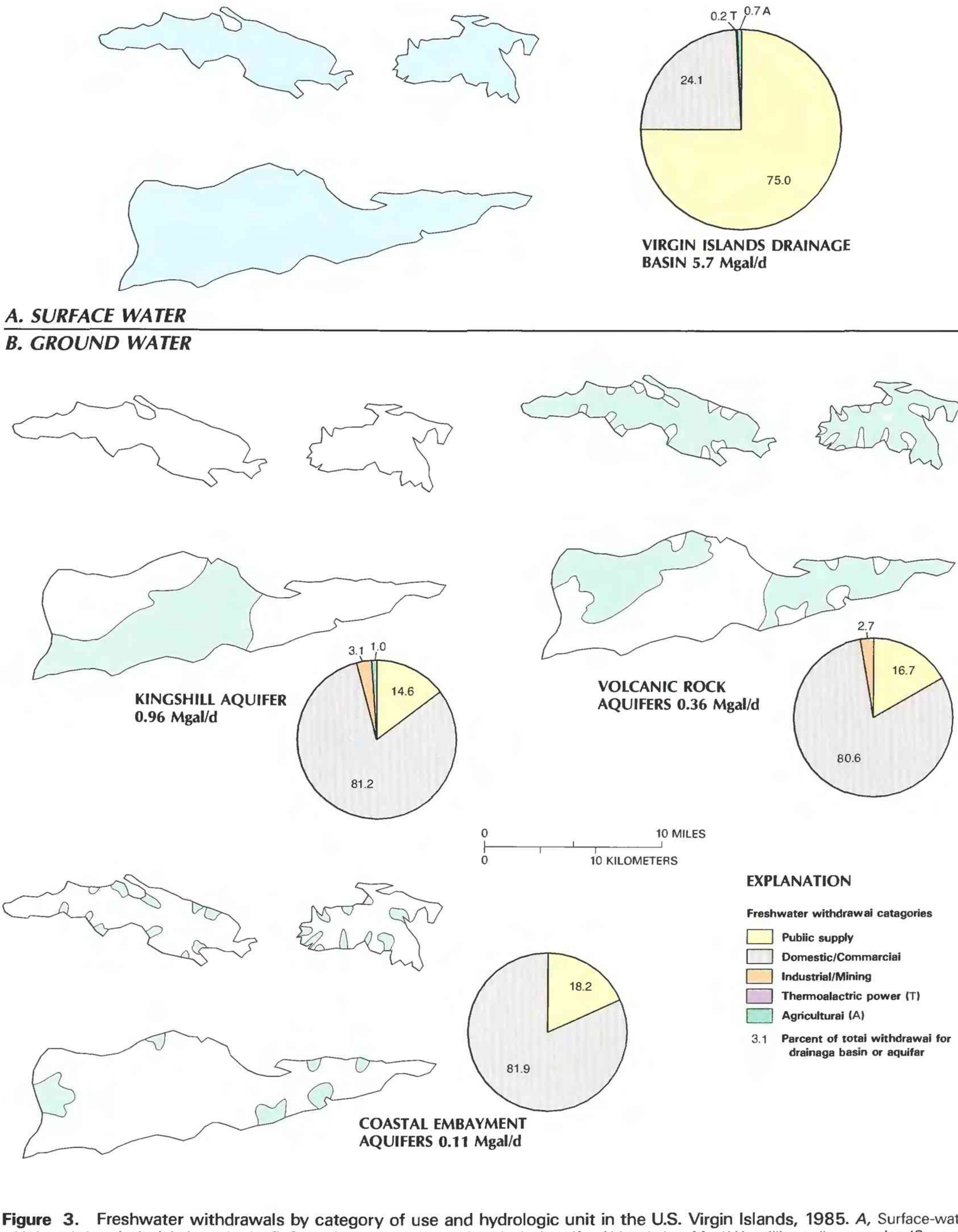


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in the U.S. Virgin Islands, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

report may not add to the totals indicated because of independent rounding. The source data indicate that surface water was the source for 79.9 percent (5.7 Mgal/d) of the total withdrawals in 1985. Of that amount, 75.0 percent (4.3 Mgal/d) was withdrawn by public suppliers. The surface-water data include desalinated water and rainwater collected from rooftop catchment systems; saline water use is not included. The use data indicate that 88.3 percent (6.3 Mgal/d) of all the water withdrawn was for domestic and commercial purposes. Public suppliers delivered 59.8 percent (3.8 Mgal/d) of the water withdrawn for domestic and commercial use. About 15.1 percent (0.9 Mgal/d) of the water publicly supplied and self-supplied for domestic and commercial use was consumed. The disposition data indicate that domestic and commercial consumptive uses accounted for 79.8 percent of the total consumptive use in the U.S. Virgin Islands.

PUBLIC SUPPLY

Public-supply systems in the U.S. Virgin Islands withdraw, treat, and deliver water to principally domestic and commercial users. Thermoelectric powerplants also receive some publicly supplied water for power generation. The public-supply systems in St. Thomas and St. Croix consist of separate potable water- and seawater-distribution systems. The potable water-distribution systems on the three major islands use desalinated water from the VIWAPA, which is supplemented by ground water withdrawn from the VIDPW well fields on St. Croix and St. John. The desalinated seawater is barged from St. Thomas and stored in tanks on St. John for later distribution through the system.

The seawater-supply systems of St. Thomas and St. Croix consist of single distribution systems serving only urban areas. The purpose of the seawater system is to provide a secondary water supply for sanitary use and provide fire protection. Water pumped into the seawater-distribution system averages 1.27 Mgal/d (Torres-Sierra and Dacosta, 1984; Torres-Sierra, 1986).

In 1985, public water-supply systems provided 3.8 Mgal/d (fig. 4) to about 47,400 people—30,000 in St. Croix, 15,900 in St. Thomas, and 1,500 in St. John for domestic and commercial use (Torres-Sierra and Dacosta, 1984; Torres-Sierra, 1986). About 94 percent (3.6 Mgal/d) of the water is produced by desalination plants. Ground water from the VIDPW well fields provides the remaining 6 percent. About two-thirds of the water withdrawn was delivered to users (Solley and others, 1988); the remaining was lost because of leaks in the distribution systems and unauthorized connections. Thermoelectric powerplants receive about 0.7 Mgal/d from the public-supply systems

DOMESTIC AND COMMERCIAL

Domestic and commercial water users are supplied by public supply and self-supplied facilities. Deliveries from public suppliers in 1985 for domestic and commercial use were 2.1 and 0.2 Mgal/d, respectively (Solley and others, 1988).

About 56,600 people in the U.S. Virgin Islands are not served by public-supply systems and are classified as domestic self-supplied users. Ground water and rainwater, which is collected from rooftop catchments and stored in cisterns, are the sources of water for domestic self-supplied users. Estimated water use for this category

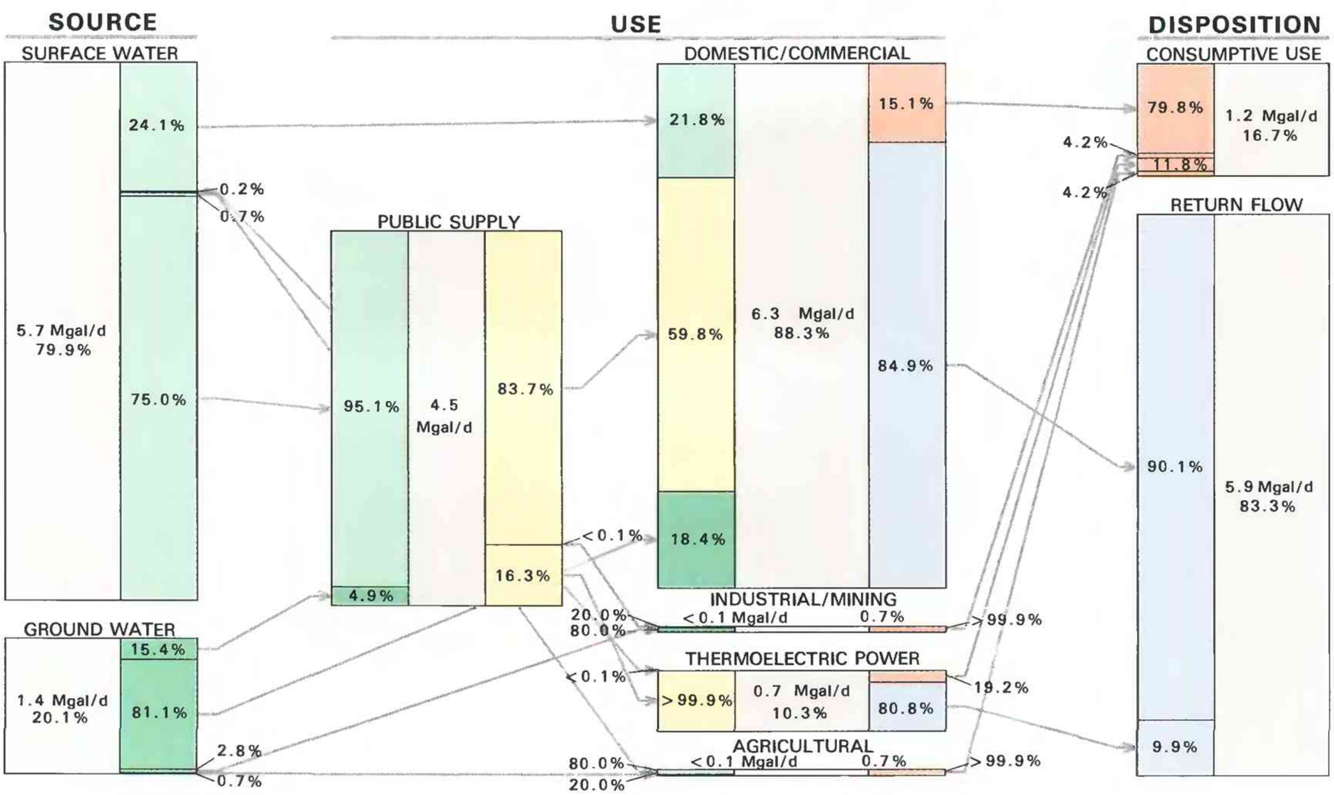


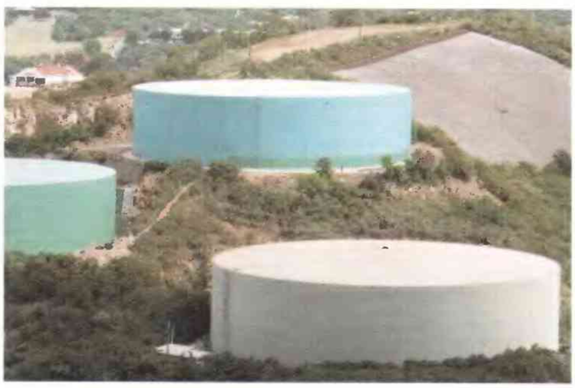
Figure 4. Source, use, and disposition of an estimated 7.1 Mgal/d (million gallons per day) of freshwater in the U.S. Virgin Islands, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbols: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

is about 1.6 Mgal/d (Solley and others, 1988). Of this amount, 61 percent (1.0 Mgal/d) is supplied from rainfall; this indicates that rooftop catchments are important in providing water to the domestic self-supplied users. The remaining 0.6 Mgal/d is obtained from private wells.

The principal commercial self-supplied users in the U.S. Virgin Islands are hotels and condominiums, which use about 0.9 Mgal/d of freshwater (Solley and others, 1988) and 3.0 Mgal/d of seawater. Seawater is used principally as feedwater for small desalination plants, for swimming pools, and for flushing toilets. Small desalination plants produce about 0.20 Mgal/d of freshwater. Additional sources of water include 0.39 Mgal/d from rainfall. Other facilities, such as airports, laundries, and gasoline stations, use about 0.15 Mgal/d of ground water (Torres-Sierra and Dacosta, 1984; Torres-Sierra, 1986).

INDUSTRIAL AND MINING

The principal industries in the U.S. Virgin Islands are classified as self-supplied users. The largest industrial self-supplied users—petroleum refinery and rum distilleries—are located in St. Croix. The petroleum refinery uses about 14 Mgal/d of seawater for cooling and desalination purposes (Torres-Sierra, 1986). About 0.15 Mgal/d of brackish ground water is used at the refinery to process crude oil. Rum distilleries use about 0.04 Mgal/d of ground water and 0.01 Mgal/d of rainwater collected in cisterns (Torres-Sierra, 1986).



THERMOELECTRIC POWER

Thermoelectric power generation is the largest saline water use in the U.S. Virgin Islands. The VIWAPA operates two thermoelectric powerplants, which use fossil fuel and furnish almost all their own water—one on St. Croix and one on St. Thomas. Fresh and saline water use in 1985 was 104 Mgal/d (Torres-Sierra and Dacosta, 1984; Torres-Sierra, 1986), 99 percent of which was seawater used for cooling of condensers. About 1 percent was freshwater from the desalination plants, which was used for boiler feed.

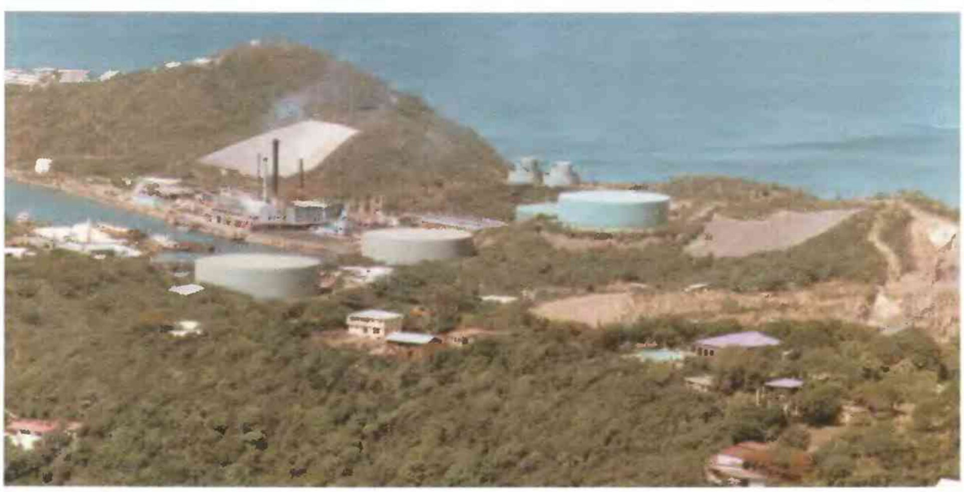
AGRICULTURAL

Europeans who first settled the U.S. Virgin Islands cleared much of the forest for crops. The cleared land was planted with sugarcane and with sea-island cotton in drier areas. Poorer land was used for pasture and forest. By the mid-1800's, the profitable sugar trade was in decline because of competition from other islands, and much of the planted land was converted to pasture. Between 1900 and 1970, wholesale abandonment of the agricultural land occurred (Jordan, 1972). In 1985, nonirrigation agricultural water use for livestock was 0.05 Mgal/d. Of this amount, 0.04 Mgal/d was surface water, and 0.01 Mgal/d was ground water. Water use for irrigation was less than 0.01 Mgal/d.

WATER MANAGEMENT

In 1965, the Legislature of the U.S. Virgin Islands passed the Water Resources Conservation Act [Act No. 1344, Title 12, Virgin Islands Code (V.I.C.), Chapter 5] to ensure that all water in the U.S. Virgin Islands is conserved and utilized to benefit the population. The Act prohibits wasteful use of water and establishes a comprehensive system for regulating the digging of wells and the withdrawal of water. Programs regulating water resources for beneficial uses are overseen by a Water Resources Commission (Peebles and others, 1979). The Commission is composed of the Commissioners of Public Works and Conservation and Cultural Affairs, the Executive Director of the Water and Power Authority, and one citizen from each of the Districts of St. Croix, St. Thomas, and St. John.

Water-resources policies, which are set forth in the Water Resources Conservation Act and the rules and regulations established by the Water Resources Commission, are implemented by various local agencies. The VIWAPA is responsible for ensuring an adequate



Seawater desalination plant, hillside rainfall catchments, and water storage tanks at Sub Base, St. Thomas, U.S. Virgin Islands. (Photograph by Rafael Dacosta.)

supply of water to benefit the public welfare and the economic health of the U.S. Virgin Islands (Title 30 V.I.C., Chapter 5). Long-range functional development planning, which includes comprehensive lands and water-resources planning, is performed by the Virgin Islands Planning Office (Title 3 V.I.C., Section 36). The VIDPW is responsible for the distribution of water (Title 30 V.I.C., Section 51) and monitors compliance with building codes, with respect to rooftop collection and storage of rainwater (Title 30 V.I.C., Section 65). The VIDPW is also responsible for ground-water withdrawals and the importation of water from Puerto Rico. Planning for emergency water supplies is delegated to the Department of Conservation and Cultural Affairs (Title 19 V.I.C., Section 1306).

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Prepared by Heriberto Torres-Sierra and Teresita Rodríguez-Alonso

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, G.P.O. Box 4424, San Juan, PR 00936

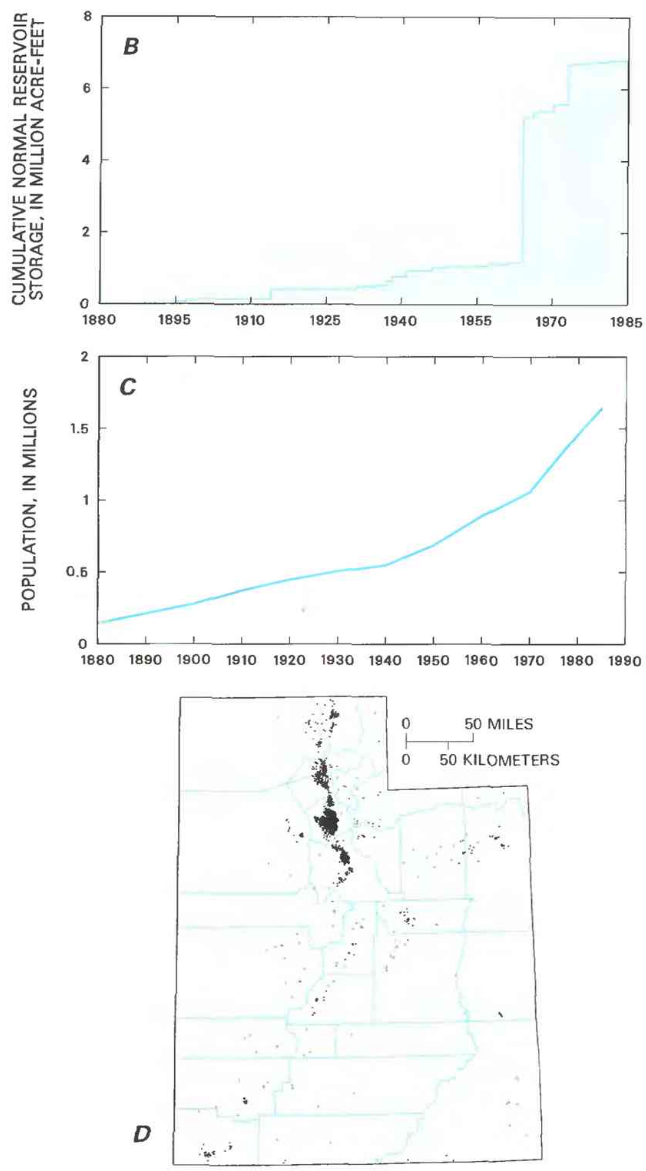
UTAH
Water Supply and Use

Utah, which is the second most arid State in the Nation, has a statewide average annual precipitation of 13 inches, or about 52,600 Mgal/d (million gallons per day). About 91 percent of this precipitation is returned to the atmosphere by evapotranspiration (fig. 1*A*). However, Utah has a substantial quantity of water in storage; about 7 million acre-ft (acre-feet) of water normally is stored in surface reservoirs (fig. 1*B*); about 100 million acre-ft is recoverable from the upper 100 feet of the aquifers (Price and Arnow, 1974; Eakin and others, 1976). In addition, about 30 million acre-ft of saline water is stored in the Great Salt Lake.

Utah was the sixth fastest-growing State in the Nation from 1980 to 1985, with a 12.6-percent increase in population (fig. 1*C*). However, the rate of Utah's growth has been decreasing slightly; the 1.4-percent growth rate from 1984 to 1985 was the least of any year since 1970 (Utah Office of Planning and Budget, 1987; Bureau of Economic and Business Research, 1983). Utah's population of about 1.65 million people in 1985 is projected to be 2.50 million by the year 2010, and planning for increased water use will continue to be a challenge for Utah's water managers. The projected increase will be greatest in the urban areas and smaller in the rural counties that have been dependent on natural resource extraction (State Economic Coordinating Committee, 1987). The more densely populated urban and industrial region of north-central Utah (fig. 1*D*), known as "the Wasatch Front," has the largest water use in the State.

Surface water provides about 81.1 percent of the State's freshwater withdrawals (U.S. Geological Survey, 1986). During 1985, ground water for domestic supply was used by about 65 percent of the population. Instream water use for hydroelectric power generation during 1985 was 3,340 Mgal/d for the generation of 1,010 GWh (gigawatthours) of electrical power. Agriculture is the largest user of ground water (52.6 percent) in most of Utah; the exceptions are the major populated areas, such as Salt Lake, Utah, Cache, Davis, and Weber Counties (which compose most of the Wasatch Front area), where the combined ground-water withdrawals for public supply, domestic and commercial, industrial and mining, and livestock uses are greater than withdrawals for irrigation (Mason and others, 1986).

During 1985, 4,180 Mgal/d of freshwater was withdrawn from surface- and ground-water sources. Of the water withdrawn, about



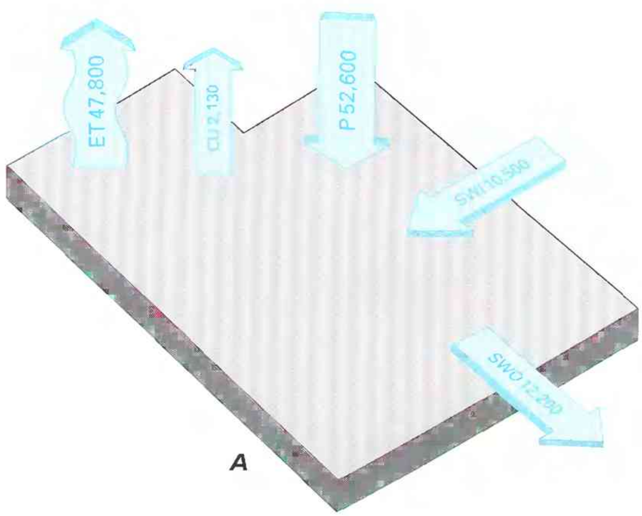


Figure 1. Water supply and population in Utah. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Data from National Oceanic and Atmospheric Administration, 1986; Farnsworth and others, 1982; ReMillard and others, 1986; and U.S. Geological Survey files. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

2,130 Mgal/d was consumed and 2,060 Mgal/d was returned to surface- or ground-water sources for future use. Of the water withdrawn for agriculture, which includes livestock and irrigation uses, 53.6 percent (1,940 Mgal/d) was consumed. This quantity was 91.5 percent of the total consumptive use. The largest quantity of water withdrawn for agriculture during 1985 was for irrigation (3,590 Mgal/d).

HISTORY OF WATER DEVELOPMENT

The history of Utah's water development can be divided into four phases. First (1847–52) was cooperative development, ownership, and administration; second (1852–80) was community control through the county courts and local community groups of water users; third (1880–97) was private development with recourse through the district courts in cases of conflict; and fourth (1897–1987) was private ownership and development combined with public administration and planning through State and Federal agencies. This history can be explained in terms of the people who settled in Utah, their backgrounds, the changing mix of settlers who came during various periods, and the activities of territorial, State, and Federal governments.

During the first phase, which included the early years of Mormon colonization of Deseret (Millard County) from 1847 to 1852, settlers were willing to accept communal ownership and distribution of water resources. All knew that water was scarce and cooperation was necessary to ensure survival. By cooperating in building canals, ditches, diversion dams, and the community in general, early settlers helped to develop Utah quickly. Utah's water was used primarily for agriculture and domestic purposes, although some water was allocated to sawmills and gristmills. In 1848, a gristmill was built and operated in the mouth of City Creek Canyon, as was a sawmill at the mouth of Mill Creek Canyon; both were near Salt Lake City (Little, 1946, p. 110).

As settlements spread and larger numbers of non-Mormons settled in Utah, administration of water resources changed from central church authority to local or community administration. The Utah Territory was established in 1851; in 1852, the Territorial Legislature declared water to be a public good and gave responsibility to the county courts for distributing water resources in their jurisdiction.

During the second phase from 1852 to 1880, there were important changes in the attitudes of the settlers toward water. Settlers realized that a "water right" was valuable property and essential for agriculture in Utah's arid environment, but it was also evident that, as population increased, competition for water would increase. By the mid-1870's, the capability of the traditional small irrigation companies to finance water development was essentially exhausted; communities began to assume the role of water developer. The first large storage reservoir was built in 1871 by the people of Newton (located in Cache County, 12 miles northwest of Logan); other communities followed Newton's lead. There was a push for even more private and local control of water development and for changes in the methods or institutions available for developing water resources.

In 1880, at the beginning of the third phase, the Territorial Legislature passed a law separating water ownership from land ownership. This law also allowed groups of water users to form corporations to provide water on a nonprofit basis. These mutual irrigation companies are the predominant water-development and management entities operating in the State today. The method of acquiring a water right also was changed—under the 1880 law, a person could claim water by diverting it, rather than by petitioning the county court. The result of this legislation was an increase in the number of water-development projects attempted, and an increase in water-related litigation.

Utah attained statehood in 1896, and sections of the new Utah Constitution reflected the prevalent sentiment—water was a scarce resource, it needed to be used efficiently, and State supervision was desirable to promote safety, equity, and efficiency. The constitution declared that all water in the State was the property of the public, and the procedures for allocating quantities to private ownership were prescribed legislatively.

In 1897, at the start of the fourth phase, a State water engineer was appointed to measure flow in Utah's streams; in 1903, the basic principles defining the appropriation process were legislated. Central to all subsequent water-related regulation was the philosophy that water belongs to the public and should be used efficiently. A State agency was responsible for allocating the use of water according to State laws. At the national level, creation of the Federal Reclamation Service (predecessor to the present U.S. Bureau of Reclamation) in 1902 greatly affected the pattern and character of water planning and development in Utah. Legislation provided for major Federal involvement in engineering, financing, construction, and water-resource developments in the West. The Strawberry Reservoir Project in central Utah was one of the first reclamation projects (1905) and was also one of the first major transbasin diversion projects in the West. The Weber Basin and the Central Utah Projects (in the Great Salt Lake and the Lower Green basins, respectively) of the 1950's and 1960's are classic examples of multipurpose, comprehensive water planning and development. The completion of Flaming Gorge Reservoir (on the Green River in Daggett County) in 1963 increased normal storage in Utah's surface reservoirs by a factor of about five (fig. *1B*).

In addition to Federal assistance, many agencies and commissions were created at the State level to promote and direct water development. Establishment of the Utah Water and Power Board in 1947 represented a substantial commitment for directing water-management policies and programs. This organization and its successor, the Division of Water Resources, have provided more than $162 million to organizations that use water for water-development and conservation projects that deliver an average of 900,000 acre-ft of water annually. In 1964, the legislature gave the Division responsibility for comprehensive State water-planning programs. Recent curtailment of Federal programs and construction has stimulated a more aggressive State program for planning, developing, financing, and managing water resources.

WATER USE

The State's annual water budget is diagrammatically shown in figure *1A* in terms of volumes of precipitation, evapotranspiration, consumptive water use, and surface-water inflows and outflows. Although Utah has substantial quantities of natural streamflow and ground water, this water is not always available when and where it is needed.

The recent series of wet years (1982–85) has required changes in water management. Examples include the sandbag-channeling of snowmelt runoff through the streets of Salt Lake City (1983) and the passing of legislation for the construction of a pumping station to lower the level of Great Salt Lake, which, in April 1987, was at the peak level of record (4,211.8 feet above sea level).

A part of the water in the Bear and Colorado River drainages is regulated by interstate compacts and agreements and is available only for instream uses, such as fish and wildlife habitat, hydroelectric power generation, and recreation. At present (1987), Utah is not utilizing its total compact allotment in either drainage.

Total freshwater withdrawals are shown by county in figure *2A*. Major surface-water withdrawals are in the northwestern, northeastern, central, and south-central counties (fig. *2B*). Major ground-water withdrawals are in the central and southwestern counties (fig. *2C*).

Of the major river basins (fig. *3A*), the largest withdrawals are from the Great Salt Lake basin (tributaries to the Great Salt Lake), the Escalante Desert–Sevier Lake basin (the Sevier River),

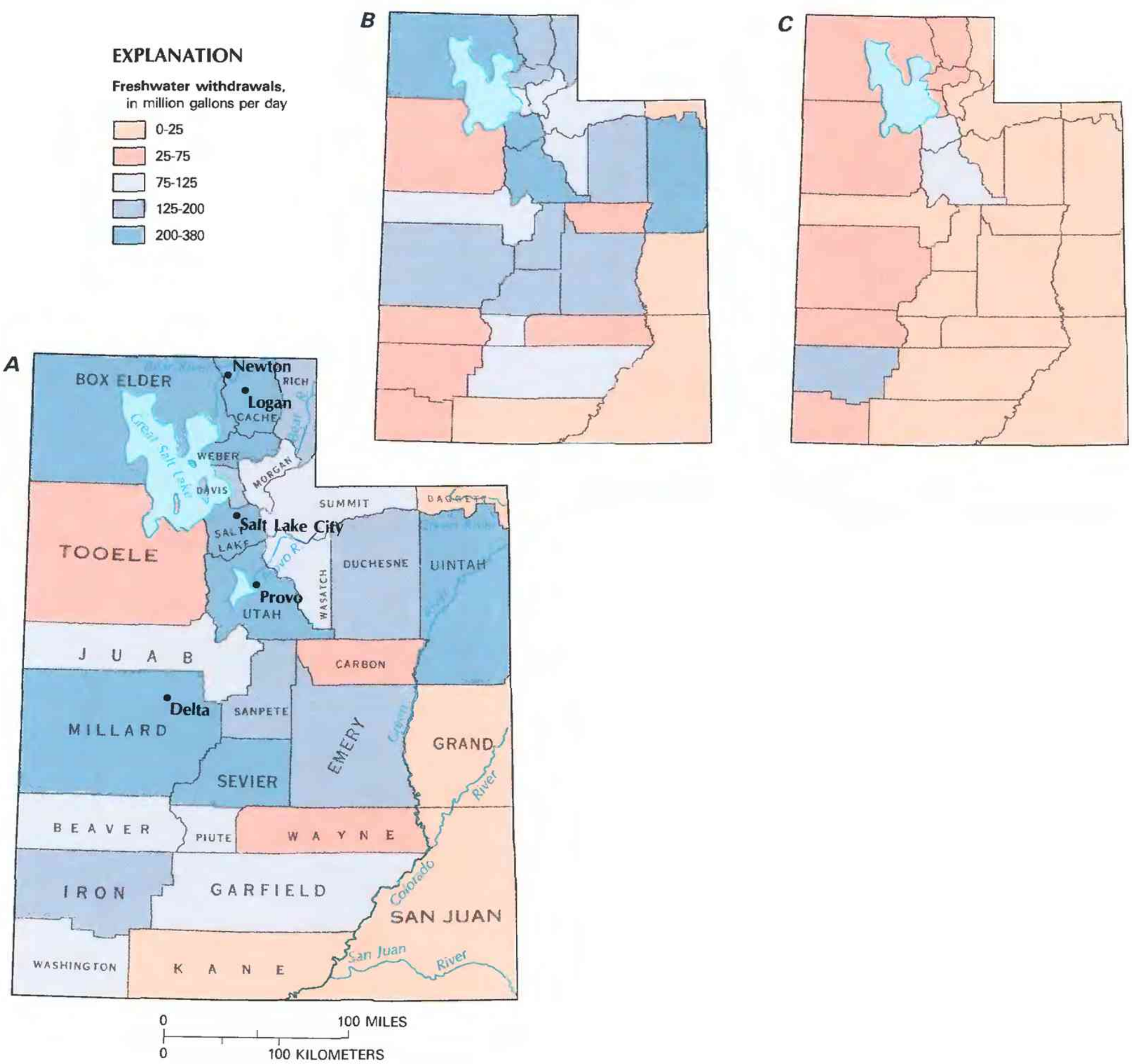


Figure 2. Freshwater withdrawals by county in Utah, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

the Bear basin (the Bear River), and the Lower Green basin (tributaries to the Green River). Agriculture is the largest surface-water user in all basins; however, the tributaries to the Great Salt Lake provide water for public supply to about 32 percent of Utah's population.

Instream use for hydroelectric power generation is an important water use in Utah. In 1985, the 45 hydroelectric plants that were operated in Utah used 3,340 Mgal/d of instream water to generate about 1,010 GWh of electricity. In contrast, only the Nunn hydroelectric plant established near Provo at the mouth of the Provo River was in operation in the 1890's. This hydroelectric plant supplied power by means of a 40,000 volt single transmission line to the Mercur mine 40 miles to the west (Bernick, 1958). Water use for hydroelectric power generation decreased about 19 percent from 1965 to 1985 (Murray, 1968; Solley and others, 1988); however, it constituted 6 percent of the total electrical power generated within the State.

The consumptive use of water in hydroelectric generation is negligible; however, evaporation losses from reservoirs can be substantial. Estimated annual freshwater evaporation from the principal reservoirs and regulated lakes of Utah accounts for an estimated 923 Mgal/d (more than 1.0 million acre-ft), which includes Lake Powell's average evaporation of 469 Mgal/d (U.S. Bureau of Reclamation, no date, p. 24). The remainder of the evaporation (454 Mgal/d) represents about 60 percent of the State's freshwater surface evaporation from other sources (Utah State University and Utah Water and Power Board, 1963, p. 16, 20). In contrast, Great Salt Lake's annual evaporation averages 2,590 Mgal/d (2.9 million acre-ft) (Waddell and Barton, 1980, p. 10).

The largest withdrawals of ground water (fig. 3*B*) are from basin-fill aquifers in the Great Basin region of western Utah; the water is withdrawn for public supply, industry, mining, and agriculture. The major ground-water withdrawals (fig. 2*C*) in Salt Lake County are for public supply and industry, in Utah County for public supply and agriculture, and in Iron County for mining and agriculture.

The source, use, and disposition of freshwater during 1985 are shown diagrammatically in figure 4. The quantities of water given

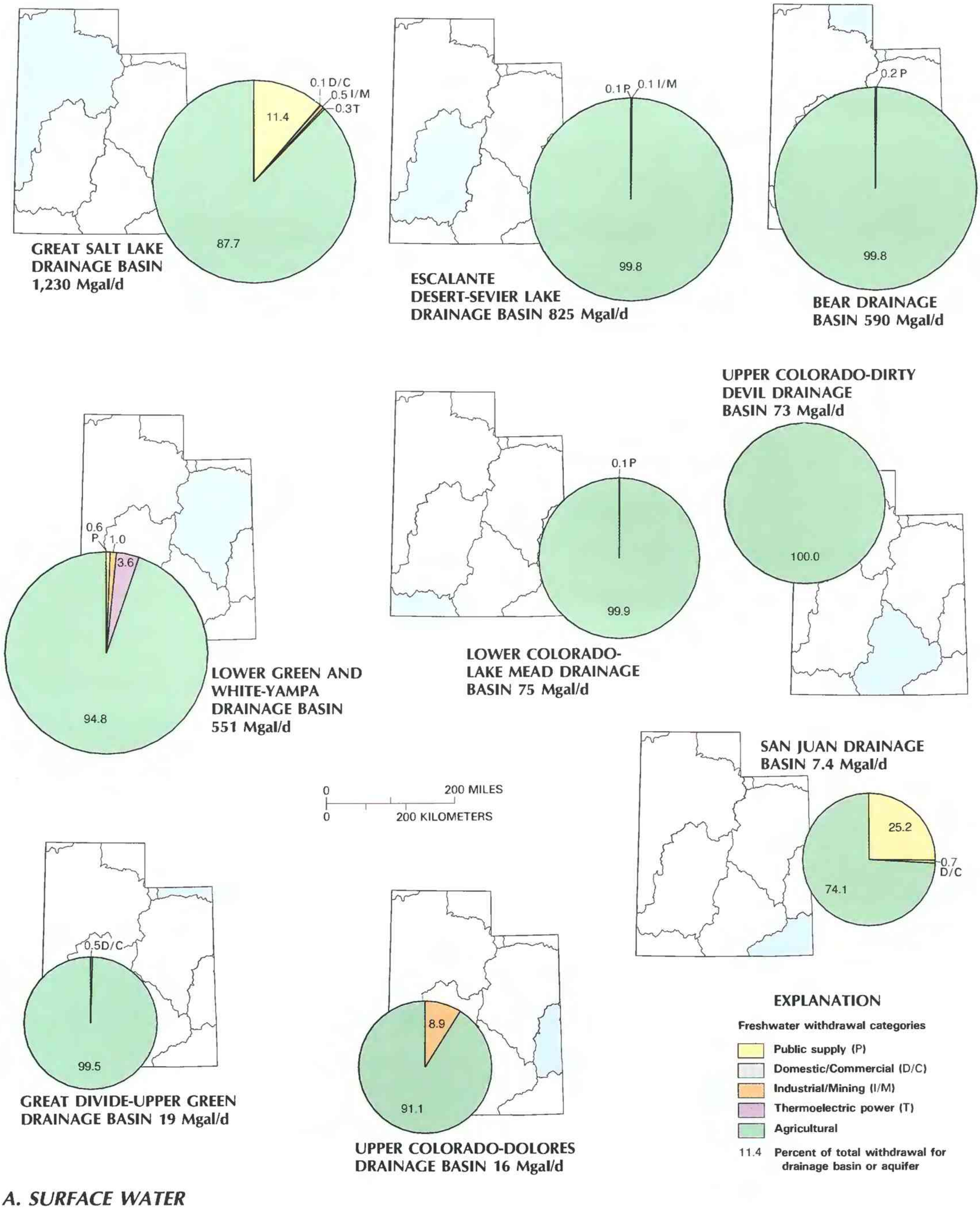


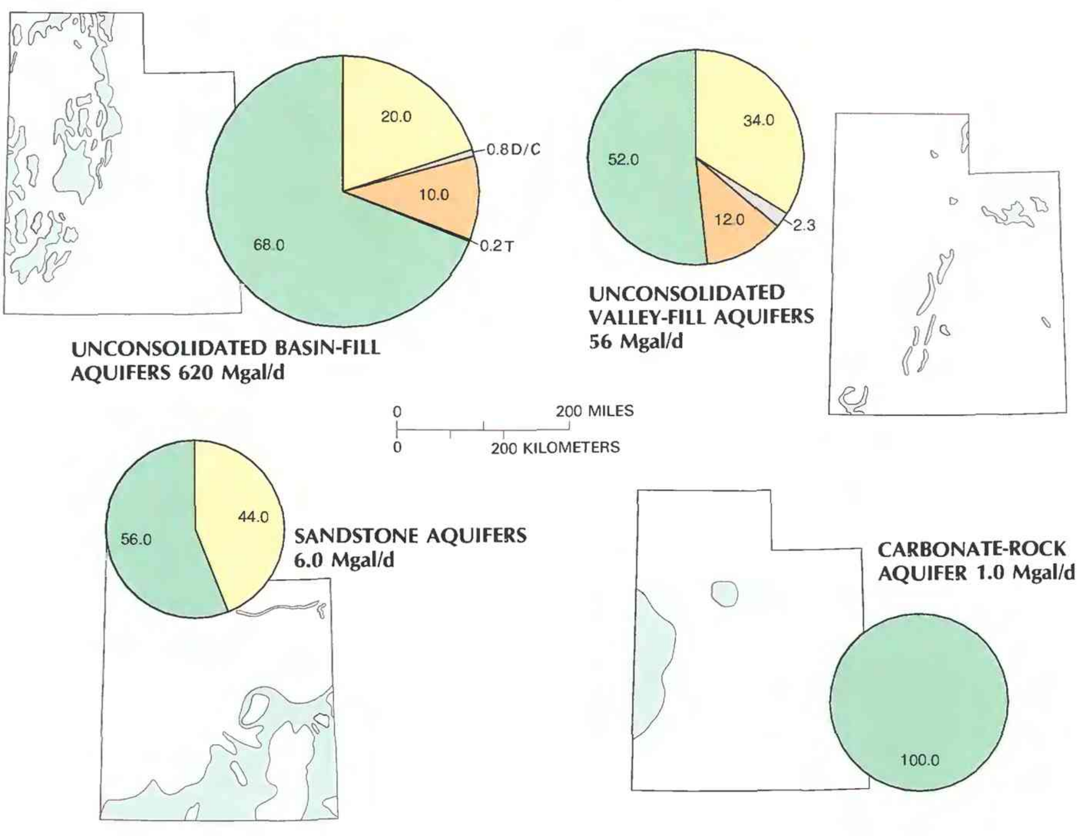
Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Utah, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from Mason and others, 1986; aquifer map modified from U.S. Geological Survey, 1985, p. 417.)

in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. Not included in these totals are saline water used for mining, water lost through reservoir evaporation, and instream use of water for hydroelectric power generation. The source data indicate that surface water provided about 81.1 percent (3,390 Mgal/d) and ground water provided 18.9 percent (790 Mgal/d) of Utah's total freshwater withdrawals for off-stream use. Of the fresh ground water withdrawn, 37.9 percent was for public supply, 0.6 percent was for self-supplied domestic and commercial use, 9.0 percent was for self-supplied industrial and mining use, 52.6 percent was for agricultural use, and almost no ground water was withdrawn for thermoelectric power generation. Public-supply systems withdrew and delivered 4.4 percent of the surface water and 37.9 percent of the ground water to consumers. The remaining withdrawals were made directly by the users. The use data indicate that public-supply systems provided 98.5 percent of the water used for domestic and commercial purposes and 15.0 percent of the water used for industrial and mining purposes. Agricultural uses were completely self-supplied, and thermoelectric powerplants primarily used self-supplied water. The use data also indicate that 10.5 percent (439 Mgal/d) of the total withdrawals was for domestic and commercial use, of which 98.5 percent was from public-supply systems, 0.4 percent was self-supplied surface water, and 1.1 percent was self-supplied ground water. About 28.6 percent of the water for domestic and commercial use was consumed, and 71.4 percent was returned to surface- or ground-water systems. The disposition data indicate that 50.8 percent (2,130 Mgal/d) of the total withdrawals was consumed and the remaining water was returned to ground- and surface-water sources. The 28.6 percent of water consumed during domestic or commercial use represents 5.9 percent of all water consumed in the State.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. Withdrawals and deliveries for public-supply increased from 2.6 percent of the total water withdrawals (excluding that for thermoelectric power generation) during 1950 (MacKichan, 1951) to 10.7 percent during 1985 (Solley and others, 1988). Utah's population increased 139 percent during the same period (fig. 1C), while withdrawals for public-supply increased 426 percent. One reason for the large increase in withdrawals for public supply is the shift in population from rural to urban areas. In 1870, the urban population was about 18 percent of the State population. In 1950, the urban population was 65 percent, and, by 1980, the urban population was about 84 percent of the total (U.S. Bureau of the Census, 1982, p. 7). In 1985, Utah was ranked 34th nationally in population but was ranked 22d nationally in withdrawals for public supply (Solley and others, 1988). Deliveries of water from public supply were 285 gal/d (gallons per day) per capita during 1985, the fifth largest in the Nation. A semiarid climate, inexpensive water, and a large proportion of single-family dwellings having lawns and gardens are some of the reasons for the large per capita water use.

Total withdrawals and deliveries for public supply during 1985 were about 447 Mgal/d (fig. 4), of which 33.1 percent (148 Mgal/d) was surface water and 66.9 percent (299 Mgal/d) was ground water (Brent Johnson, Utah Division of Water Rights, written commun., 1986). Surface water generally is transported less than 60 miles from point of diversion to use. Withdrawals of ground water generally



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Utah, 1985—Continued.

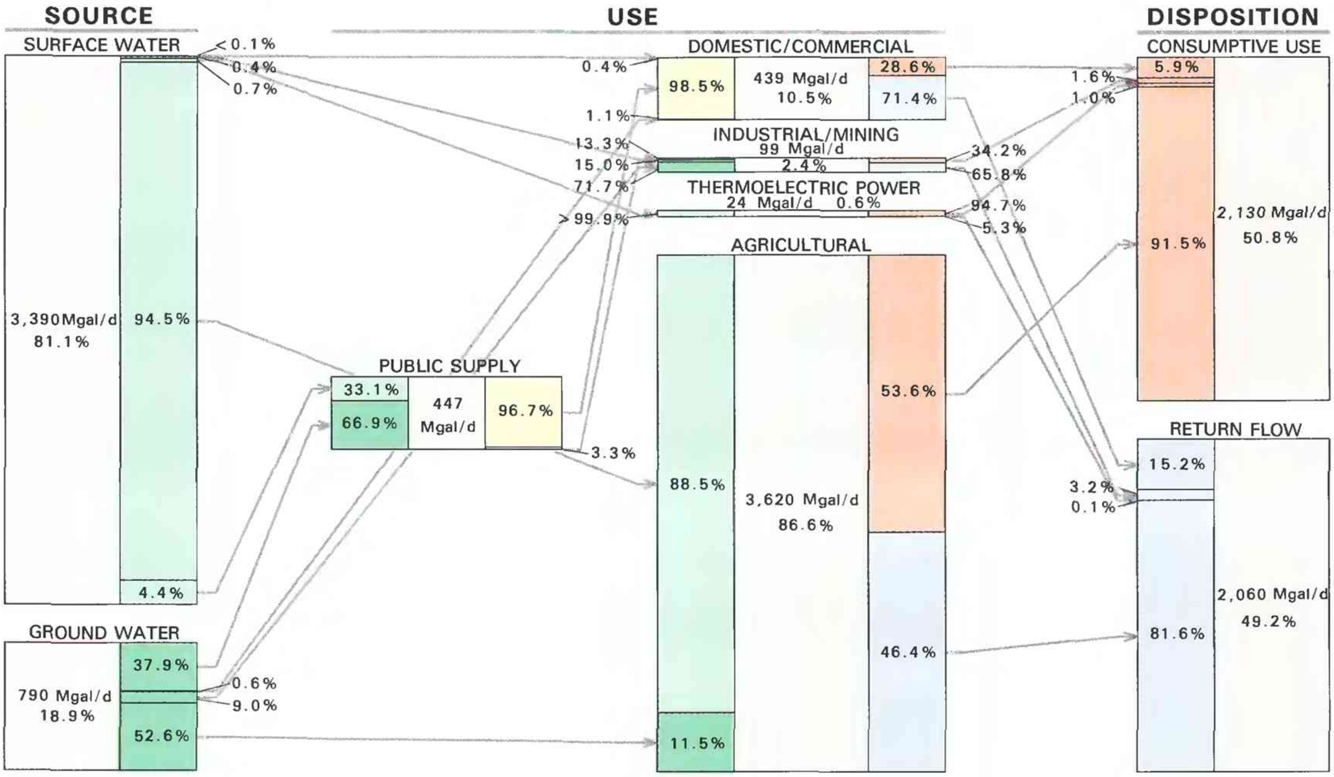


Figure 4. Source, use, and disposition of an estimated 4,180 Mgal/d (million gallons per day) of freshwater in Utah, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbols: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

are from springs and from wells completed in unconsolidated basin-fill aquifers (fig. 3*B*) (U.S. Geological Survey, 1985, p. 415) and are generally near the areas of use.

Utah's population increased about 4 percent per year from 1950 through 1985, whereas the withdrawals of surface water for public supply increased about 50 percent per year from 1950 to 1960 and about 1 percent per year from 1960 to 1985 (fig. 5). Withdrawals of ground water for public supply increased by about 5 percent per year from 1950 to 1960 and about 8 percent per year from 1960 to 1985 (fig. 5). The scarcity of undeveloped surface-water sources and the cost of water treatment are two of the reasons for the greater increase in use of ground water for public supply from 1960 to 1985. Generally, problems relating to ground-water quality are minimal, and ground-water sources are sufficient to meet the expanding demands. In general, ground-water depletion is not a problem; progressive basinwide water-level declines are occurring (1987) only in Iron County.

Six counties in the Bear basin and in the northern and eastern parts of Great Salt Lake basin include 83 percent of Utah's population. These counties account for 96 percent of the surface water and 74 percent of the ground water used for public supply. Salt Lake County includes 42 percent of Utah's population and accounts for 70 percent of the total surface water and 24 percent of the total ground water withdrawn for public supply (Brent Johnson, Utah Division of Water Rights, written commun., 1986). Public-supply systems also furnished some water for commercial, industrial, and mining purposes (fig. 4).

Domestic and Commercial

Total water use for domestic and commercial purposes during 1985 was 439 Mgal/d (fig. 4), including 42 Mgal/d lost in conveyance or used for public uses, such as fire fighting. Domestic use accounted for 346 Mgal/d, of which 340 Mgal/d was obtained from public-supply systems that serve about 95 percent of the population, and 6 Mgal/d was from self-supplied systems. Use by those purchasing water from a public-supply system averaged 217 gal/d per capita, whereas the self-supplied users averaged 81 gal/d per capita. Consumptive use of water for domestic use was 119 Mgal/d.

Commercial use, during 1985, was about 50 Mgal/d and was provided predominantly by public-supply systems. Self-supplied users did not report any withdrawals from surface-water sources for commercial use, and less than 1 Mgal/d was from self-supplied ground-water systems. Quantities of water used for commercial purposes were small compared to domestic quantities. However, the State Economic Coordinating Committee (1987, p. 66) projects an increase of about 3 percent per year in average annual employment in the industries related to trades, services, and government between 1985 and 2000. This increase could be an indication that commercial use will become more substantial by the year 2000.

Industrial and Mining

Water used for industrial and mining purposes during 1985 was 228 Mgal/d, of which about 99 Mgal/d was freshwater (fig. 4) and about 129 Mgal/d was saline water (not shown in fig. 4). Mining activities used about 185 Mgal/d, of which about 113 Mgal/d was surface water and about 72 Mgal/d was ground water. Saline water comprised about 96 percent of the surface water and 29 percent of the ground water withdrawn. Consumptive use by mining activities was 138 Mgal/d, which is 75 percent of the mining withdrawals. Consumptive use is a large part because it includes evaporation losses during the mineral extraction process.

Utah has a wealth of mineral and energy-related resources. Historically, Utah has ranked high nationally in the production of metals; for example, in 1979 the State's production ranked first in gold and beryllium, second in copper and vanadium, third in iron, fourth in molybdenum, and fifth in silver and uranium (Christy and Stowe, 1981, p. 197). Changes in climatic conditions and declines in energy-industry activities and in national and international economic conditions (State Economic Coordinating Committee, 1987) contributed to a decrease in the use of water for industry and mining between 1982 to 1985. However, employment projections to 2000 A.D. indicate possible increases in the use of water as industry and mining expand. Projected employment increases are about 25 percent for mining and about 50 percent for construction and manufacturing (State Economic Coordinating Committee, 1987, p. 66).

All other industrial uses amounted to about 43 Mgal/d, of which about 15 Mgal/d was furnished by public-supply sources, about 8 Mgal/d was self-supplied surface water, and about 20 Mgal/d was self-supplied ground water. Consumptive use was 19 Mgal/d.

THERMOELECTRIC POWER

During 1985, 24 Mgal/d of water was used by 14 thermoelectric powerplants for the generation of 14,400 GWh of electricity. Water use by fossil-fueled plants was about 24 Mgal/d; all was obtained from fresh surface-water sources. Water use for geothermal power generation was about 3.9 Mgal/d; all was obtained from thermal saline ground water, which is not included in figure 4. Consumptive water use by fossil-fueled plants generally accounts for more than 90 percent of the water withdrawn, which totals about 22 Mgal/d of freshwater, whereas less than 0.6 Mgal/d of thermal saline ground water was consumed. Between 1980 and 1985, water use for thermoelectric power generation decreased, mainly because of decreased activity in the steel and mining industries. However, a fossil-fueled plant near Delta, which began generating in 1986 and was to add another unit in 1987, plans to increase water withdrawn for thermoelectric power generation by an estimated 19 Mgal/d. This increase will nearly double the water use reported for 1985 for thermoelectric power generation (Ann Garrett, Intermountain Power Agency, oral commun., 1987). Based on projected demands for electrical power in the intermountain States, the use of water for thermoelectric power generation is expected to increase; however, some controversies related to environmental issues may occur.

AGRICULTURAL

Agricultural use of water has increased about 3 percent since 1965 and is Utah's largest water use. During 1985, withdrawals of water for agriculture were 3,620 Mgal/d (fig. 4), which is 86.6 percent of the State's freshwater withdrawals. Of the 3,620 Mgal/d, 88.5 percent was from surface-water sources, and 11.5 percent was from ground-water sources. Consumptive use of water withdrawn for agriculture was 53.6 percent, whereas return flows to surface- and ground-water systems were 46.4 percent (fig. 4).

Irrigation, which is the largest agricultural use of water, withdraws 3,200 Mgal/d from surface water and 384 Mgal/d from ground water. An additional 6 Mgal/d from reclaimed sewage wastewater is not included in figure 4. The total withdrawals for irrigation have increased from 3,200 Mgal/d during 1980 (Solley and others, 1983, p. 18) to 3,590 Mgal/d during 1985, although the irrigated acreage in the State decreased by 58,600 acres—from 1.2 million acres in 1978 (U.S. Bureau of the Census, 1982, p. 1) to just over 1.1 million acres in 1985. Hay (76 percent alfalfa) is the leading irrigated crop, accounting for about 55 percent of Utah's irrigated acreage (Utah Department of Agriculture, 1986, p. 80, 81).

Surface-water withdrawals have increased about 19 percent since 1980, while ground-water withdrawals have decreased about

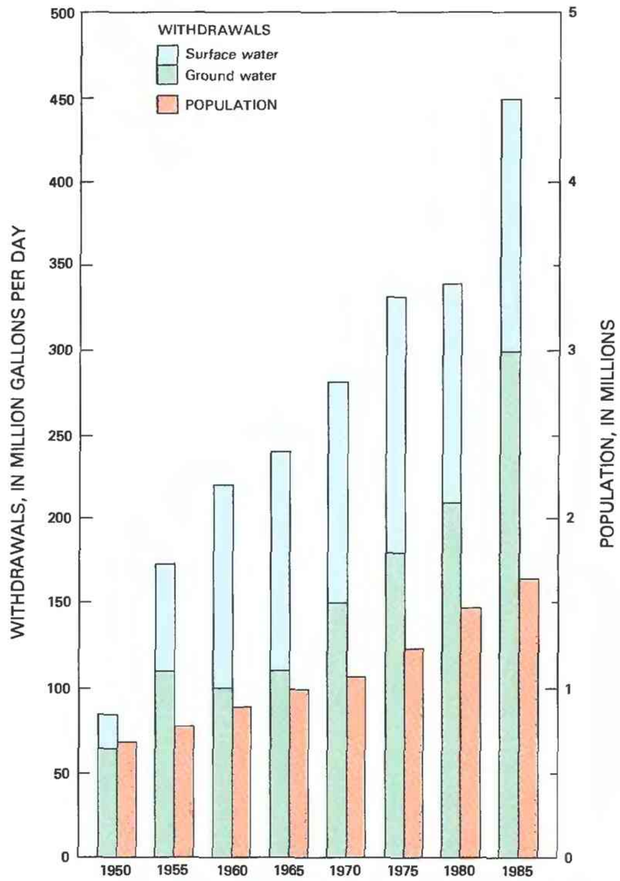


Figure 5. Population and withdrawals for public supply, 1950 to 1985. (Sources: MacKichan, 1951, 1957; MacKichan and Kammerer, 1961; Murray, 1968; Murray and Reeves, 1972, 1977; Solley and others, 1983, 1988.)

28 percent. The decrease in ground-water withdrawals probably is due to unstable farm-products prices, increased pumping costs, and, more importantly, an increase in the annual precipitation between 1982 and 1985, which resulted in increased availability of surface water and the observed increase in surface-water use. About 49 percent of Utah's total ground-water withdrawals is used for irrigation.

Use of water for agricultural purposes other than irrigation was 38 Mgal/d during 1985, which is a decrease of about 5 percent from 1980 (Solley and others, 1983, p. 14). Use of surface water was 7.2 Mgal/d, and use of ground water was about 31 Mgal/d.

WATER MANAGEMENT

The appropriation doctrine is the foundation of Utah water law. Under Utah law, no distinction is made between surface and ground water. A water right is treated as real property, but the ownership relates to the right to divert and is subject to conditions specified in the application to appropriate and to continued beneficial use of the water. Priority of right is determined by date of application to appropriate.

The State Engineer, who is the Director of the Division of Water Rights, which is an agency of the Department of Natural Resources, has general administrative supervision over the waters of Utah. All applications to appropriate water, to change existing rights to water, and to reallocate use of water must be approved by the State Engineer. The State Engineer may appoint water commissioners to distribute water from a given source among various users.

Owing to changing economic and social objectives, water uses are in a state of change, and applications to reallocate the use of water for other purposes are numerous and widely disputed. In 1980, a large quantity of water (40 Mgal/d) was reallocated from agricultural use to thermoelectric power generation. In this case, the water rights for irrigation were purchased from the irrigation companies by the power company and approved by the State Engineer.

Utah has an integrated administrative-judicial procedure for determining the rights to use water from any source within the State. Such a determination can be initiated by the State Engineer upon petition by water users or by an order of the court. After investigation, the State Engineer prepares a proposed determination of the water right, which is submitted to the district court. Following consideration of any protest, the court issues a decree to set forth the water right.

The Division of Water Resources, another agency of the Department of Natural Resources, is charged with conservation and development of the State's water resources. The Division is governed by a policymaking Board of Water Resources and provides technical and financial assistance for the design and construction of facilities related to water development. The Division is responsible for State water planning and for interstate coordination and negotiations pertaining to water.

Water-quality control is supervised by the Water Pollution Control Committee and its associated Bureau of Water Pollution Control and by the Safe Drinking Water Committee and its associated Bureau of Drinking Water and Sanitation. These agencies are affiliated with or are part of the Division of Environmental Health of the Department of Health. The Bureau of Water Pollution Control has been granted primacy by the U.S. Environmental Protection Agency in administering provisions of the Federal Clean Water Act; similar authority has been granted to the Bureau of Drinking Water and Sanitation with respect to the same.

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FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 1016 Administration Building, 1745 West 1700 South, Salt Lake City, UT 84104

VERMONT
Water Supply and Use

Vermont, known for Lake Champlain and the Green Mountains that trend northward through the center of the State, contains many lakes, ponds, and rivers. Average annual precipitation is about 40 inches, ranging from 33 inches in the Lake Champlain Valley (northwestern Vermont) and Connecticut Valley (along the Connecticut River) to about 53 inches in the Green Mountains (U.S. Geological Survey, 1986). Average annual runoff ranges from about 13 inches in the Lake Champlain Valley to about 33 inches in the southern Green Mountains.

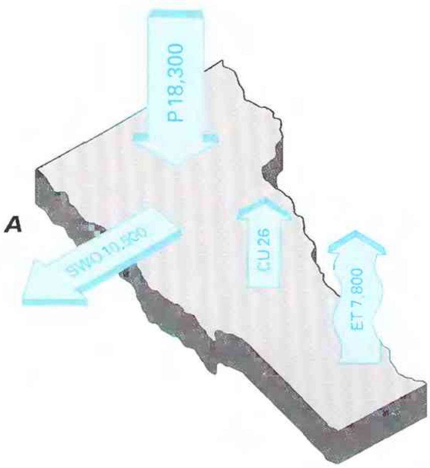
Precipitation contributes an average 18,300 Mgal/d (million gallons per day) of water to the State (fig. 1*A*). Annual surface-water inflow to Vermont from surrounding States and Canada is negligible. Annual surface-water outflow totals 10,500 Mgal/d, and annual evapotranspiration is 7,800 Mgal/d. The total water consumed during use in 1985 was 26 Mgal/d.

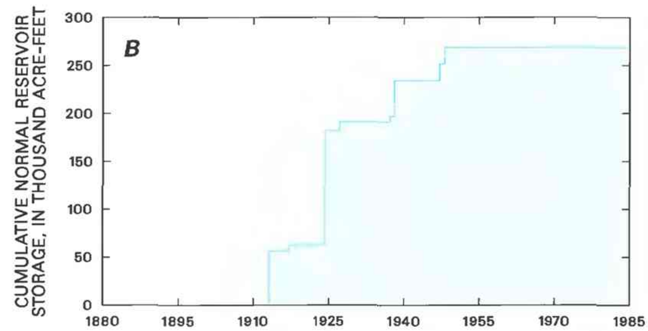
Total instream water use was 8,640 Mgal/d, almost all of which is used by hydroelectric powerplants. Offstream use totaled 126 Mgal/d, of which 51 Mgal/d was for domestic and commercial use, 68 Mgal/d was for industrial and mining use, 0.8 Mgal/d was for thermoelectric power generation, and 6.1 Mgal/d was for agricultural use. Of the 126 Mgal/d, 53 Mgal/d was distributed by public-supply systems, and the remainder was self-supplied. Wastewater return flows were about 100 Mgal/d (Solley and others, 1988).

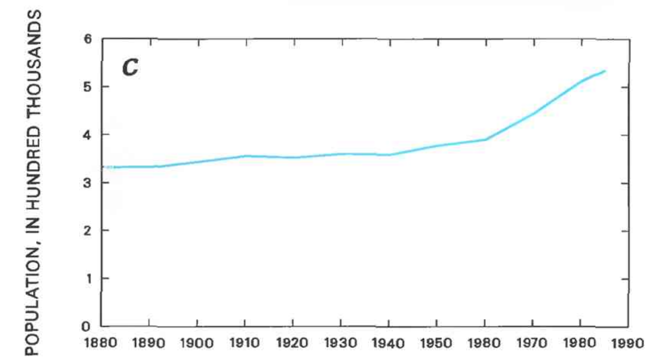
Vermont is sparsely populated; however, during the past 35 years, population has increased from less than 400,000 to about 530,000 in 1985. About 54 percent of the State's population resides in Chittenden, Rutland, Washington, and Windsor Counties. Rutland, Franklin, and Chittenden Counties accounted for 55 percent of all freshwater withdrawals in 1985. Water use is greatest in Rutland County (26.7 Mgal/d), followed by Franklin County (26.2 Mgal/d) and Chittenden County (16.0 Mgal/d).

The major source of water in Rutland, Franklin, and Chittenden Counties is surface water. Almost two-thirds of all surface-water withdrawals was in these counties. Most (86 percent) of the surface-water withdrawals in Chittenden County were by public-supply systems. Industry and mining accounted for 88 percent of the total self-supplied surface water used in Franklin County and 74 percent of the total self-supplied water used in Rutland County.

Total ground-water withdrawals were 37 Mgal/d, or 29.2 percent of the total freshwater withdrawals; ground-water withdrawals ranged from 0.3 Mgal/d in Grand Isle County to 7.2 Mgal/d in Wind-







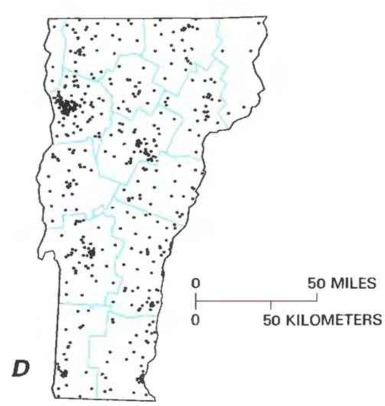


Figure 1. Water supply and population in Vermont. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWO,** surface-water outflow. (Sources: *A,* Data from Rand McNally and Company, 1976; Knox and Nordenson, 1955; Gebert and others, 1985; and from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

sor County. Ground water withdrawn by public suppliers accounted for 64 percent of all water used in Windsor County.

HISTORY OF WATER DEVELOPMENT

The early history of Vermont is closely related to the water resources of the State. Early settlements usually were in areas that had access to major surface waters, which provided routes for transportation and commerce; for example, Brattleboro is adjacent to the Connecticut River near the original site of Fort Dummer, which was the first settlement in Vermont.

To improve transportation on natural waterways, several canals, locks, and dams were constructed. In 1802, the first canal in America was built on the Connecticut River near Bellows Falls in Windham County (Maunsell and others, 1966). The Champlain Canal, connecting Lake Champlain and the Hudson River in New York State, was completed in 1823. During the mid-1800's, the use of rivers and streams for transportation gradually decreased. Overland travel was enhanced greatly by improved roads, vehicles, and railroads.

During the early 19th century, many people came to Vermont to take the "water cure." The water from mineral springs was said to cure anything. People from all over southern New England and New York came to be "cured," and, until the Civil War, Vermont had a monopoly on a lively summer tourist trade (Maunsell and others, 1966). This tradition of summer tourism remains today; the "water cure," however, is no longer the main attraction.

During early settlement, drinking water was supplied from dug wells, springs, and surface water. In 1867, 1 year after acquiring a spring-supplied system that served 200 customers, Burlington installed an intake 50 feet into Lake Champlain. This was the beginning of a water utility that now delivers 10 Mgal/d to its customers (Richards, 1974).

In 1865, the Brush Swan Light and Power Company constructed a hydroelectric powerplant at Winooski Falls and provided electricity to Burlington (Merrill, 1975, p. 148). The Vergennes Electric Company, which later became part of the Green Mountain Power Company, constructed a hydroelectric plant below the waterfall on Otter Creek in 1891. The development of hydroelectric power and electrical distribution systems allowed development of areas that were not located near water-power sources. Initially, small impoundments of water were used to store water for hydroelectric power generation; later, in the 1900's, larger reservoirs were built for storage (fig. 1*B*).

Drilled wells probably were introduced to the region in the early 1900's. However, they were not used extensively until electric distribution systems became generally available, allowing the use of electric pumps.

The water resources were used not only for water supply, power, and transportation, but also for waste disposal. The State enacted laws to prevent contamination of surface water as early as 1890. The Acts of 1890 prohibited, in part, the deposition of sawdust, shavings, or mill waste in certain bodies of water. In 1892, the pollution of Otter Creek was prohibited, and, in 1902, the legislature passed laws prohibiting pollution "of the water of Tyler Branch, the Black River in Orleans, the sources of drinking water supplies and the sources of Willoughby Lake" (Merrill, 1975). The Federal Clean Water Act has provided funding for sewage collection and treatment plants that have greatly improved surface-water quality in many areas.

Population increases were largest from the mid-1960's to 1985 (fig. 1*C*). The population in the Lake Champlain Valley has increased to the extent that 23 percent of the population now resides in Chittenden, Rutland, and Washington Counties. These counties, along with Windsor County in the Connecticut Valley, contain more than one-half of the population (fig. 1*D*). Light industries and high-technology industries are locating in these counties, and water use is rapidly changing.

Historically, water supply has been more than sufficient to satisfy demand. When conflicts have risen, compromises or court settlements have resolved the issues at the local level. Recently, contamination and large population increases in many areas resulted in demands that exceeded available supplies of clean water. The State is collecting information on some water uses to satisfy the statutory mandates of various agencies.

WATER USE

In 1985, instream water use by hydroelectric powerplants was 8,640 Mgal/d, and offstream water use totaled 126 Mgal/d. Total freshwater withdrawals are shown by county in figure 2*A*. Surface- and ground-water withdrawals by county are shown in figures 2*B* and 2*C*, respectively. Three counties—Rutland, Franklin, and Chittenden—accounted for 64 percent of the offstream water use.

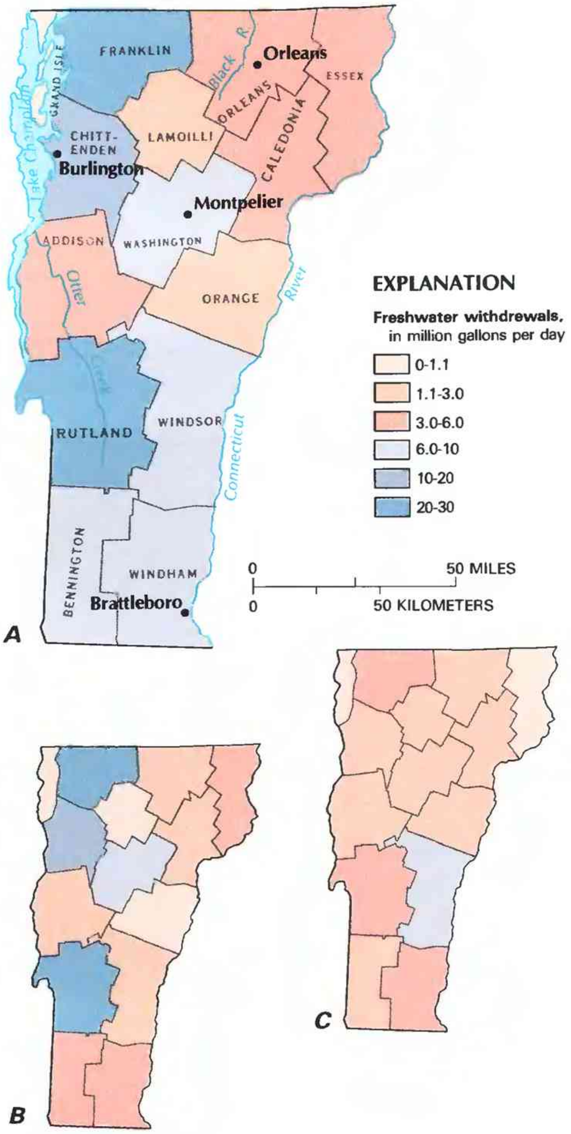


Figure 2. Freshwater withdrawals by county in Vermont, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Withdrawals in Rutland and Franklin Counties are large because of industrial water withdrawals, whereas in Chittenden County, which has 22 percent of the total population of the State, large quantities of water are provided for domestic use.

Surface-water use by major river basins is shown in figure 3*A*. Industrial and mining self-supplied uses are dominant in the Richelieu and Connecticut basins and account for 44 percent of total offstream water use in the State. Total withdrawals in the other basins are much less and are primarily for domestic purposes.

The distribution of ground-water withdrawals by principal aquifer is shown in figure 3*B*. Most major public-supply systems and large industrial self-supplied systems withdraw from the stratified-drift aquifers. The stratified-drift aquifers are the only aquifers that can supply the large amounts of water needed for public supply. Water supplies for most self-supplied domestic use are from the crystalline-bedrock and till aquifers and the carbonate-bedrock aquifer (fig. 3*B*). In general, water yields from bedrock aquifers are small, but sufficient for individual households and small public-supply systems.

The source, use, and disposition of water in Vermont during 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 56.8 percent (51 Mgal/d) of the total surface water withdrawn in the State was for industrial and mining use (self-supplied). Of the total ground water withdrawn, 46.0 percent (17 Mgal/d) was for public supply. The use data indicate that 54.0 percent (68 Mgal/d) of the total water used in Vermont was for industrial and mining purposes. The disposition data indicate that 20.5 percent (26 Mgal/d) of all withdrawals was consumed during use.

Public Supply

Public-supply systems withdraw, treat, and distribute water to users. About 343,000 people in Vermont, or about two-thirds of the population, are served by public-supply systems (Solley and others, 1988). The total population includes some seasonal residents. The population served by public supply and the total population are

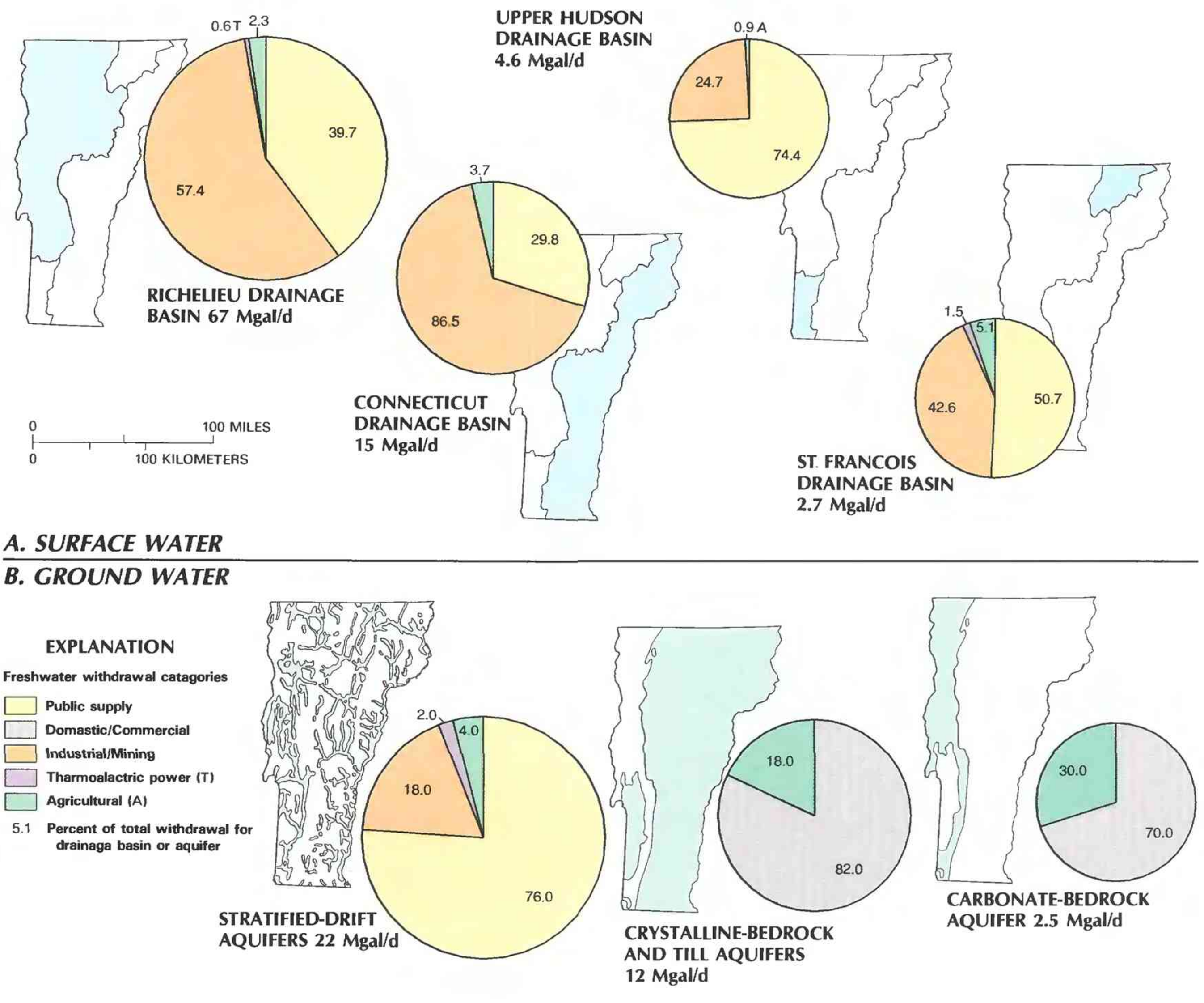


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Vermont, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Data from U.S. Geological Survey files.)

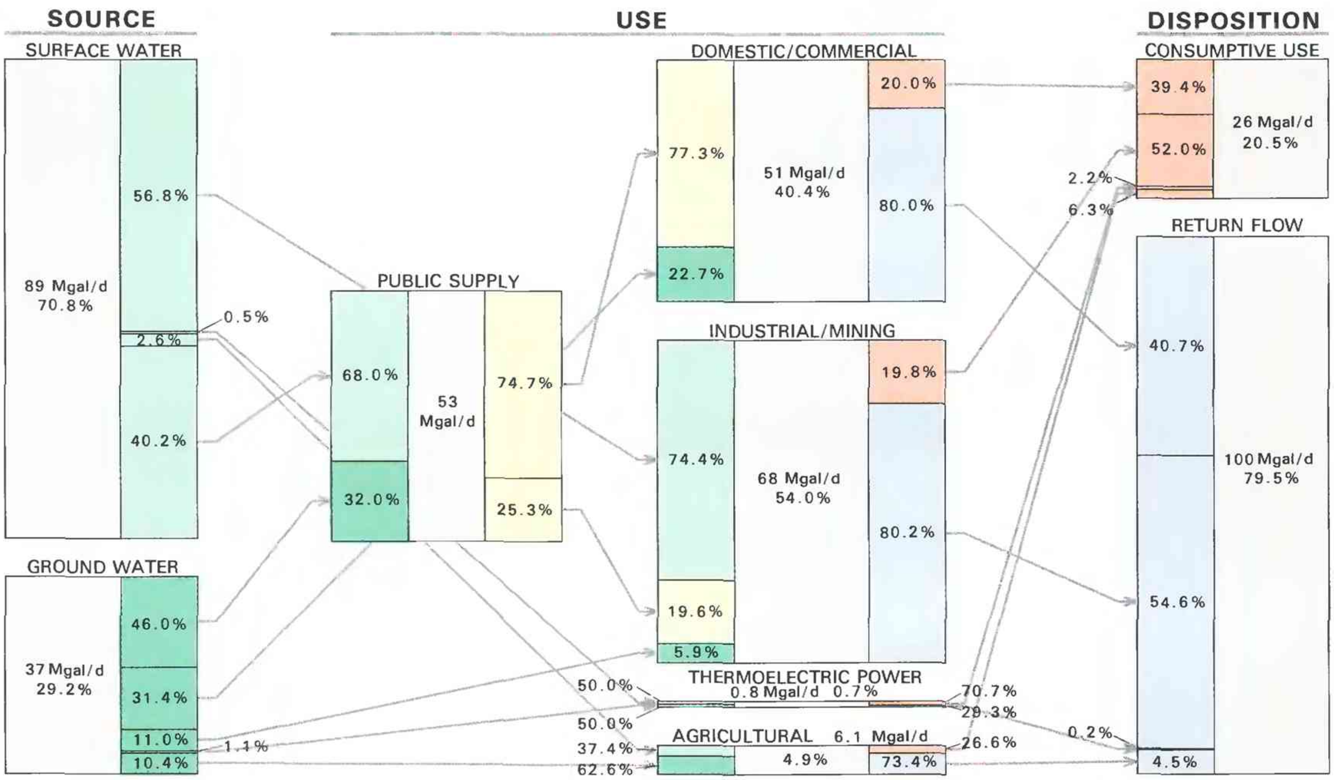


Figure 4. Source, use, and disposition of an estimated 126 Mgal/d (million gallons per day) of freshwater in Vermont, 1985. *Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)*

presented by county in figure 5*A*. Total withdrawals for public supplies in 1985 were about 53 Mgal/d. Of this total, about 68.0 percent was from surface-water sources, and 32.0 percent was from ground-water sources. Public-supply systems delivered 74.7 percent to domestic and commercial users, and the rest was delivered to industrial and mining use.

Impoundments on small drainages and lakes generally are the sources for surface-water supplies; however, some of the largest systems withdraw water from Lake Champlain. Public-supply withdrawals in Chittenden County, which includes Burlington, were about 32 percent (11 Mgal/d) of the total surface water withdrawn for public supply. Public-supply systems that withdraw surface water serve about 92 percent of the county population (figs. 5*A*,*B*).

Most large-yielding (0.05 Mgal/d or greater) wells, which provide water for public systems, withdraw water from the stratified-drift aquifers (U.S. Geological Survey, 1985, p. 425). Wells tapping stratified-drift, carbonate-bedrock, and crystalline-bedrock and till aquifers furnish water for small public-supply systems. About 34 percent of total ground-water withdrawals is for public supply in Windsor County; this withdrawal serves 25 percent of the total population that receives public-supplied ground water in the State.

Domestic and Commercial

Domestic and commercial water users receive water from public-supply systems and self-supply facilities. The total domestic and commercial use in 1985 was 51 Mgal/d, of which 39 Mgal/d was from public suppliers and 12 Mgal/d was self-supplied. Per capita use from public-supplied systems was 100 gal/d (gallons per day); the per capita use from self-supplied systems was 60 gal/d.

Domestic and commercial use accounted for 40.4 percent of all withdrawals during 1985. About 80.0 percent (41 Mgal/d) of all domestic or commercial withdrawals is returned to surface- or ground-water sources; the remaining 20.0 percent (10 Mgal/d) was consumed.

Industrial and Mining

Industrial and mining use accounted for 54.0 percent of the total offstream water used in the State in 1985. Public-supplied deliveries accounted for 19.6 percent of all the water used. Self-supplied surface water for industrial and mining uses was 51 Mgal/d (compiled from the U.S. Environmental Protection Agency's 1980 surface-water discharge permit information). Self-supplied ground water accounted for about 5.9 percent of all water used by industry and mines. About 19.8 percent of the total withdrawals for industrial and mining purposes was consumed, and the rest was returned to natural sources.

In 1980, 32 percent of the total industrial water use was in Franklin County, and 30 percent was in Rutland County. In Franklin County, paperboard processing accounted for 66 percent of the total county industrial water use. Tool and cutlery manufacturing accounted for 63 percent of the total industrial water use in Rutland County. Grand Isle, Lamoille, and Orange Counties use a negligible amount of water for industry. Industries that use self-supplied water and discharge to septic systems on their properties are not included in the totals.

Mining water use was small—0.9 percent (1.1 Mgal/d) of the total offstream water use in Vermont in 1985. Most of the water was used for washing at quarrying operations.

THERMOELECTRIC POWER

Thermoelectric power generation was greatest in Chittenden County. Withdrawals for thermoelectric powerplants in this county totaled 0.66 Mgal/d (80 percent of total), and power generation totaled 374 GWh (gigawatthours) (10 percent of total) in 1985. The Vermont Yankee Nuclear Plant in Windham County generated 3,340 GWh (90 percent of the total), but withdrew water from the Connecticut River in New Hampshire; consequently, the withdrawal for thermoelectric water is included with values for New Hampshire; however, the power produced is included with values for Vermont (Solley and others, 1988). About 70.7 percent of the total withdrawals for this category is consumed.

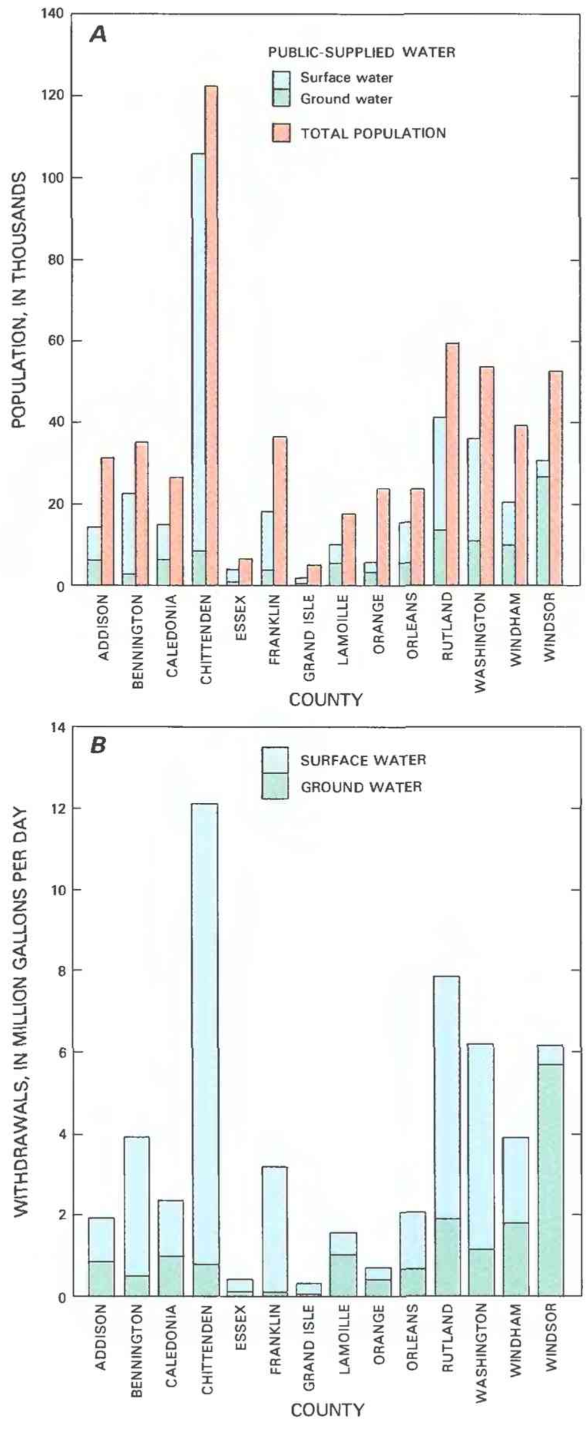


Figure 5. Public supply for Vermont, 1985. *A*, Population served by public supplies and total population, by county. *B*, Freshwater withdrawals for public supply, by county. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

AGRICULTURAL

The major agricultural activity in Vermont is dairy farming. Other agricultural activities include farming, and livestock and poultry production. About 82 percent of the market value of all farm products sold is attributed to dairy products. Water use is based on livestock and poultry population (U.S. Bureau of the Census, 1983, p. 1–2) multiplied by the estimated gallons per day used per animal type as listed by Horn (1986). Only 0.2 percent of the acreage used for crops is irrigated, mostly by spraying (U.S. Bureau of the Census, 1983, p. 1–2). Addison and Franklin Counties account for about 36 percent of the total agricultural withdrawals. Agriculture consumes 26.6 percent of the water it uses.

WATER MANAGEMENT

Water-management responsibilities in Vermont are divided among several agencies. The Department of Environmental Conservation (a part of the Agency of Natural Resources) protects, regulates, and, where necessary, controls the surface- and ground-water resources. Under the provisions of the Safe Drinking Water Act (Part B) and Title 18 of the Vermont Statutes Annotated, the Department of Health, which is a department of the Agency of Human Services, regulates the quality of water delivered by public-supply systems and protects surface- and ground-water sources for those systems (U.S. Geological Survey, 1988). Data bases developed by the Department of Health to monitor public systems provided water use information presented in figures 5*A*,*B*. The Department of Agriculture, the Department of Public Service, the State Geologist, the University of Vermont, and the Agency of Transportation also directly or indirectly manage the water resources (U.S. Geological Survey, 1984, 1985, 1986, 1988).

The Department of Environmental Conservation water-management programs are divided among the following Divisions: Water Quality, Public Facilities, Environmental Protection, Solid Waste Management, Hazardous Materials Management, and Agency Facilities (U.S. Geological Survey, 1985, 1986). The Division of Water Quality deals primarily with surface water. At present (1987), the State does not require the reporting of water use.

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Prepared by New Hampshire–Vermont Office, U.S. Geological Survey

FOR ADDITIONAL INFORMATION: Chief, New Hampshire–Vermont Office, U.S. Geological Survey, RFD 12, 525 Clinton Street, Bow, NH 03304

VIRGINIA
Water Supply and Use

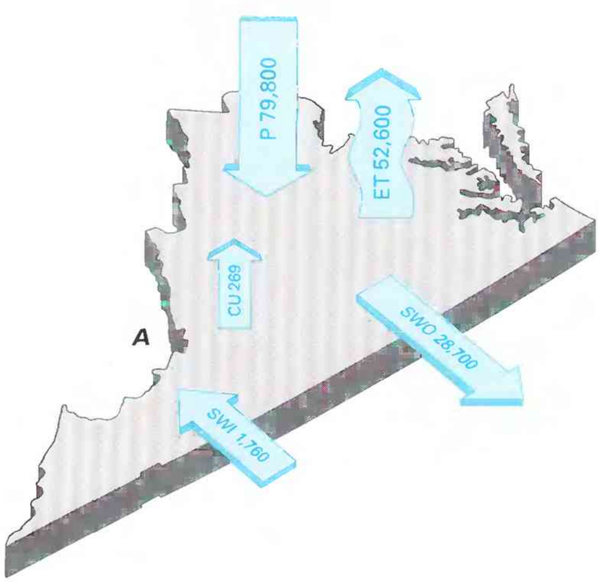
Virginia has sufficient supplies of freshwater available in most of the State. The water budget (fig. 1*A*) shows surface-water inflows of 1,760 Mgal/d (million gallons per day), an average annual precipitation of 79,800 Mgal/d, balance surface-water outflows of 28,700 Mgal/d, evapotranspiration losses of 52,600 Mgal/d, and consumptive use of 269 Mgal/d. Total freshwater withdrawals in 1985 were 4,870 Mgal/d, an equivalent of 854 gal/d (gallons per day) for each of Virginia's 5.7 million residents. Of total withdrawals, surface water accounted for 93.0 percent, and ground water accounted for 7.0 percent. Thermoelectric powerplants used 71.0 percent (3,460 Mgal/d) of total freshwater withdrawals, virtually all from surface-water sources; these withdrawals represent 20.4 percent of total freshwater consumptive use. Excluding thermoelectric power generation, freshwater withdrawals totaled 1,410 Mgal/d (247 gal/d per capita), of which surface water accounted for 76 percent and ground water for 24 percent. Saline-water withdrawals for industry and thermoelectric power generation were 2,380 Mgal/d during 1985.

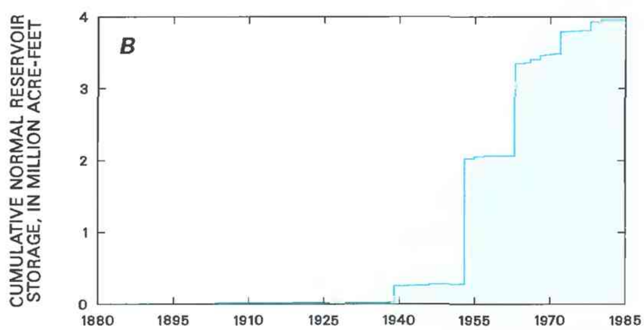
From 1960 to 1985, the population of Virginia increased about 43 percent—from 4.0 million to 5.7 million. The Virginia State Water Control Board (VSWCB) projects a population of about 8 million residents, which is a 40-percent increase, by the year 2030. If the 1985 per capita use remains the same in 2030, then total freshwater demand would be 6,820 Mgal/d, including thermoelectric use, and 1,980 Mgal/d, excluding thermoelectric use.

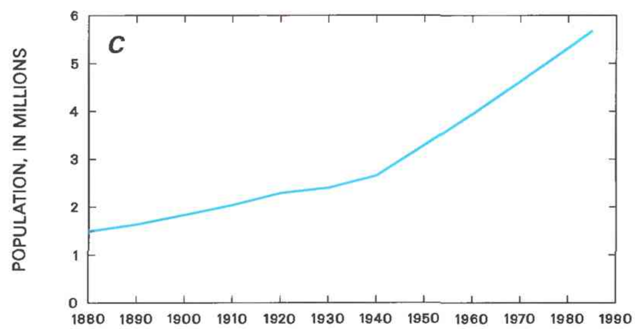
HISTORY OF WATER DEVELOPMENT

In Virginia, settlements were established along watercourses. Explorations of Virginia's river basins helped to open the interior of the continent to settlement, which transformed the State from a wilderness to a diverse urban, suburban, and rural environment. As early as 1646, waterpower was harnessed for gristmills, and, during the first two and one-half centuries of settlement, many small dams and mills were built.

The James River and its tributaries drain about 25 percent of Virginia and served as the chief transportation corridor from the settlement of Jamestown in 1607 through the Civil War in the mid-1860's. The first commercial canal in the United States was built on the James River in 1785 by the James River and Kanawha Canal







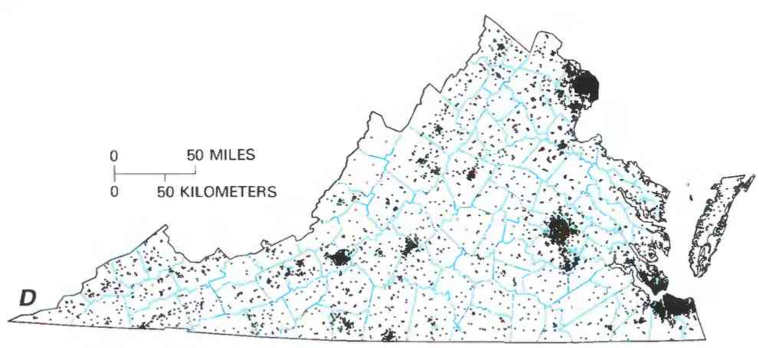


Figure 1. Water supply and population in Virginia. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System; the National Oceanic and Atmospheric Administration. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Company. Agriculture and commerce are dominant in the upper parts of the James River basin; industry and manufacturing rely on the navigable part of the river from the Chesapeake Bay to the Fall Line at Richmond.

Virginia has two natural lakes. In addition, many manmade reservoirs on creeks and rivers supply water, control flooding, generate power, and provide recreation. The first large reservoir was constructed for power generation, although most others were built to ensure adequate streamflow for navigation. George Washington and many of his contemporaries realized that a critical need of their time was cheap transportation. The War of 1812 and competition from railroads resulted in the conversion of many navigation reservoirs to power generation. The first large reservoir for public supply was constructed in 1871. Population increases near the turn of the century marked the beginning of a rapid increase in the capacity of reservoirs to provide water for domestic supply. Municipalities became increasingly dependent on reservoir storage because the minimum flow of most small streams was not adequate for continued development. Cumulative reservoir storage has increased dramatically since 1880; about 4 million acre-feet was available in 1985 (fig. 1*B*). At present (1987), the U.S. Army Corps of Engineers administers three large dams in Virginia, and the U.S. Soil Conservation Service oversees 125 smaller dams built by authority of the Watershed Protection and Flood Prevention Act and estimates that 50,000 farm ponds have been created in Virginia.

Ground water has been integral in development in Virginia since the first settlers at Jamestown relied on shallow wells for their principal water supply. Although shallow wells were used by early settlers throughout the State, it was not until the late 1800's that the deeper, confined aquifers of the Virginia Coastal Plain were recognized as an important water supply. As reported by Sanford (1913) and Cederstrom (1945), flowing wells completed in artesian sands bordering the bay or ocean and along rivers and major tributaries from the Fall Line to their mouths were preferred for natural delivery of uncontaminated water. Water from flowing wells remained the primary supply through the mid-1930's. Because of unrestricted flows and increased withdrawals, water levels declined below land surface in the mid-1940's, and large-capacity pumps and deeper wells were required to meet supply needs. Although historical trends are not available throughout the State, ground-water withdrawals in the Coastal Plain have increased more than tenfold from the turn of the century through 1985. Trends in population growth from 1880 to 1985 and population distribution in 1985 are shown in figures 1*C* and 1*D*, respectively, and reflect the increase and concentration of residents along major rivers throughout the State.

WATER USE

The water resources of Virginia are suitable for most purposes and are plentiful in most of the State, although localized conditions may affect source and availability. Virginia lies within five physiographic provinces. Each province is characterized by distinctive geologic features and topography that effect the character of streams and aquifers and determine ground- and surface-water availability. The five physiographic provinces are the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau (fig. 5*A*). The topography of the Coastal Plain generally is flat and underlain by an eastward-dipping, layered sequence of permeable, unconsolidated sand and gravel aquifers separated by intervening, relatively impermeable silt and clay confining units. The gentle hills and valleys of the Piedmont province are underlain by crystalline rock or consolidated sediments. Greater relief and rugged terrain characterize the Blue Ridge, which is underlain by fractured granite and gneiss, and the Appalachian Plateau, which is underlain by consolidated sediments, sandstone, shale, siltstone, and coal. Rolling hills and valleys characterize the Valley and Ridge, which is underlain by consolidated sediments, predominantly limestone and dolomite.

The topography and the climate within the State are diverse. The average annual precipitation of 42 inches is the primary source of recharge to the streams and aquifers in the State. The distribution of runoff, which ranges from an annual average of 12 to 24 inches, differs greatly among the physiographic provinces. Runoff rates are smaller in the Coastal Plain and eastern Piedmont provinces than in the western provinces. In 1985, runoff of 15 inches (28,700 Mgal/d) was 36 percent of precipitation. Annual recharge to the ground-water system from precipitation ranges from about 8 inches in each of the four western provinces to about 10 inches in the Coastal Plain province. The water budget for 1985 reflects the importance of the sources and the losses of water (fig. 1*A*).

Total offstream, surface-water, and ground-water freshwater withdrawals in 1985 are aggregated and delineated by source for each of Virginia's 136 counties in figures 2*A*, 2*B*, and 2*C*, respectively. Surface-water withdrawals from the State's six principal drainage basins (fig. 3*A*) and ground-water withdrawals from nine principal aquifers (fig. 3*B*) are illustrated for each category of use. Most surface-water withdrawals were in Chesterfield, Giles, and Louisa Counties (62 percent of total withdrawals and 67 percent of surface-water withdrawals in 1985). Excluding water for thermoelectric use, most surface water was withdrawn in Chesterfield County and in the cities of Hopewell and Suffolk (23 percent of total withdrawals and 32 percent of surface-water withdrawals). Isle of Wight, King William, and Rockingham Counties accounted for most ground-water withdrawals, representing 1 percent of total withdrawals (5 percent, excluding thermoelectric use) and 20 percent of ground-water withdrawals. The rivers of the Lower Chesapeake basin (fig. 3*A*), which represent about 41 percent of the area of the State, provided 73 percent of the surface water in 1985. The major rivers in the basin are the James, the Rappahannock, and the York. Withdrawals from unconsolidated aquifers of the Coastal Plain province totaled 132 Mgal/d, of which the Potomac aquifer supplied 60 percent (fig. 3*B*).

The source, use, and disposition of 4,870 Mgal/d of water withdrawn in Virginia during 1985 are summarized in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. Not included in this total are saline water uses and instream use of water for hydroelectric power generation. The source data indicate that 93.0 percent of all freshwater used in Virginia during 1985 was from surface-water sources and 7.0 percent was from ground-water sources. The source data also indicate that public-supply systems provided 11.1 percent (504 Mgal/d) of the surface water and 21.9 percent (75 Mgal/d) of the ground water. The remaining withdrawals were made directly by the users. Public-supply systems sold 90.2 percent (504 Mgal/d) of their water to domestic and commercial users, 9.8 percent (57 Mgal/d) to industrial users, and less than 1 percent to thermoelectric powerplants. Conveyance losses of 115 Mgal/d are included as a domestic and commercial use. Agricultural users are considered to be entirely self-supplied. The use data indicate that, among the four principal categories, thermoelectric use was predominant (71.0 percent of all use). About 99.9 percent (3,460 Mgal/d) of the water for thermoelectric use was surface water. The disposition data in figure 4 indicate that 5.5 percent of all water withdrawn was consumed; the remainder was returned to natural water sources. Domestic and commercial was the largest consumptive use of water (37.9 percent, or 102 Mgal/d), followed by industrial and mining consumptive use (27.0 percent, or 72 Mgal/d), thermoelectric consumptive use (20.4 percent, or 55 Mgal/d), and agricultural consumptive use (14.6 percent, or 39 Mgal/d).

Freshwater withdrawals of 1,410 Mgal/d (excluding thermoelectric use) delineated by source and category of use and by

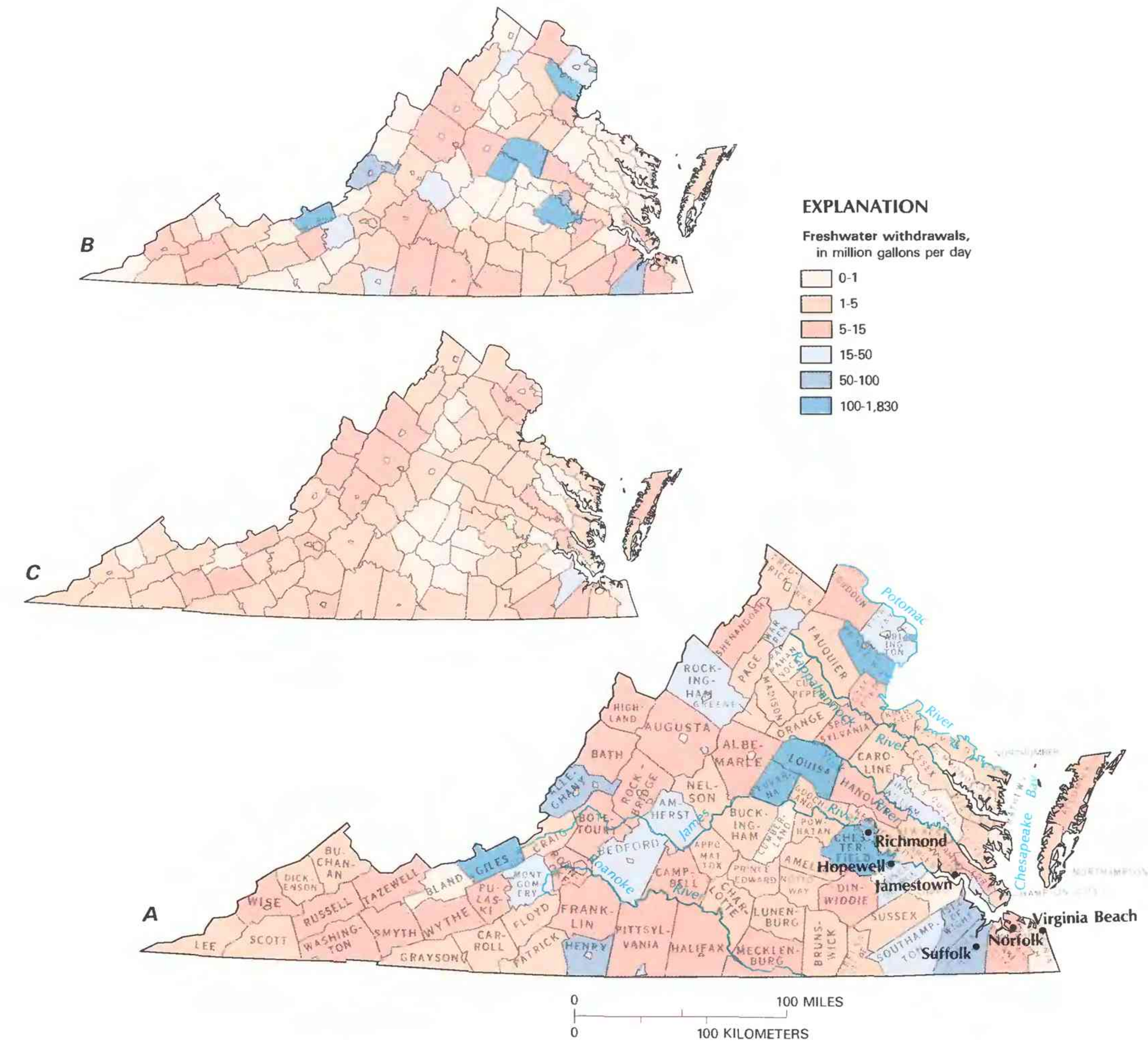


Figure 2. Freshwater withdrawals by county in Virginia, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

population distribution are identified for each physiographic province in figure 5. In 1985, the Coastal Plain province accounted for 622 Mgal/d (44 percent) of the total withdrawals; of that quantity, surface water contributed 79 percent and ground water contributed 21 percent.

Saline-water withdrawals totaled 2,380 Mgal/d. Three thermoelectric powerplants withdrew 2,300 Mgal/d of this quantity to produce 12,600 GWh (gigawatthours) of electricity. Industrial saline-water withdrawals were 81 Mgal/d. Total saline-water consumptive use was 35 Mgal/d.

Hydroelectric powerplants used 17,700 Mgal/d to generate 13,226 GWh of power during 1985. Of the 22 Federal, public utility, cooperative, and municipal hydroelectric powerplants, 20 utilize classic run-of-the-river design to drive the turbines. The remaining two plants rely on pumped storage for all or part of their water supply.

Public Supply

Public-supply systems withdraw, treat, and deliver water to users. In 1985, public-supply systems in Virginia withdrew 579 Mgal/d (fig. 4). These withdrawals represented 11.9 percent of the total freshwater withdrawals and 41 percent of the withdrawals excluding thermoelectric use. On the basis of 4.2 million people (74 percent of Virginia's total population) receiving water from public suppliers and of withdrawals of 579 Mgal/d, the per capita use in 1985 was 137 gal/d. Total water delivered by public suppliers in 1985 was estimated to be 80 percent (464 Mgal/d) of public-supply withdrawals; the remaining 20 percent was lost during conveyance and public use, such as fire fighting. Of total public-supply deliveries, domestic use accounted for 73 percent; commercial, 15 percent; and industrial, 12 percent.

Between 1960 and 1985, Virginia's total population increased 43 percent (fig. 1*C*). The percentage of population served by public-supply systems increased 92 percent and withdrawals increased 123 percent during the same period (MacKichan and Kammerer, 1961). Most of the population served by public-water suppliers resides in metropolitan areas near major rivers. Consequently, 87.1 percent (504 Mgal/d) of 1985 withdrawals for public supply was from surface-water sources. In 1985, 55 percent of surface-water withdrawals was from the rivers of the Lower Chesapeake basin (fig. 3*A*). About 12.9 percent (75 Mgal/d) of public-supply withdrawals was from ground-water sources.

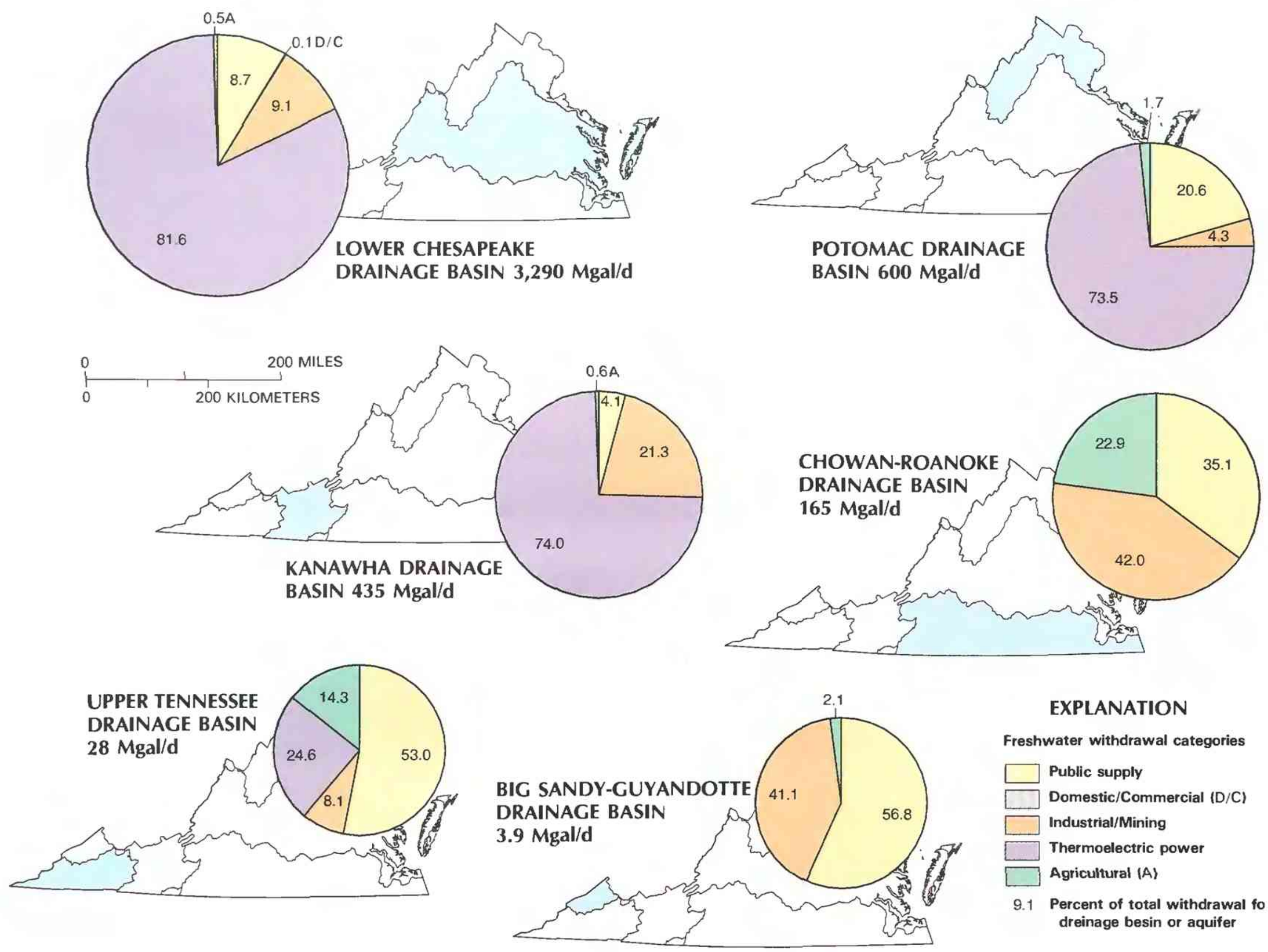
The largest public-supply withdrawals (281 Mgal/d) are from the Coastal Plain province—90 percent from surface-water sources and 10 percent from ground-water sources (fig. 5). Of the total population, 44 percent is in large cities along major rivers. About 78 percent of the population relies on public supplies from surface-water sources.

Domestic and Commercial

Public-supply deliveries and self-supplied withdrawals for domestic and commercial users were 540 Mgal/d in 1985. An estimated 115 Mgal/d was lost during conveyance. Public suppliers delivered 448 Mgal/d to domestic users and 92 Mgal/d to commercial users. Self-supplied domestic and commercial withdrawals were 3 percent of total withdrawals and 10 percent if thermoelectric usage is excluded. Surface water provided about 4 Mgal/d to these users; 97 percent of that quantity was withdrawn in the Lower Chesapeake basin. The Piedmont and Blue Ridge crystalline aquifers were the primary source (43 percent) of water for the self-supplied systems. Of total domestic and commercial withdrawals and deliveries, 15.6 percent (102 Mgal/d) was consumed.

Self-supplied domestic withdrawals were 2 percent (112 Mgal/d) of total freshwater withdrawals. On the basis of almost 1.5 million residents using self-supplied systems, per capita use was 75 gal/d. All domestic self-supplied systems relied on ground water from springs and wells. In 1985, 4.2 million people used 337 Mgal/d from public suppliers for their domestic water needs, which reflected a per capita use of 80 gal/d. Consumptive use for domestic purposes was estimated to be 90 Mgal/d.

Self-supplied commercial withdrawals were less than 1 percent (22 Mgal/d) of total freshwater withdrawals in 1985; surface-water withdrawals were 4 Mgal/d and ground-water withdrawals

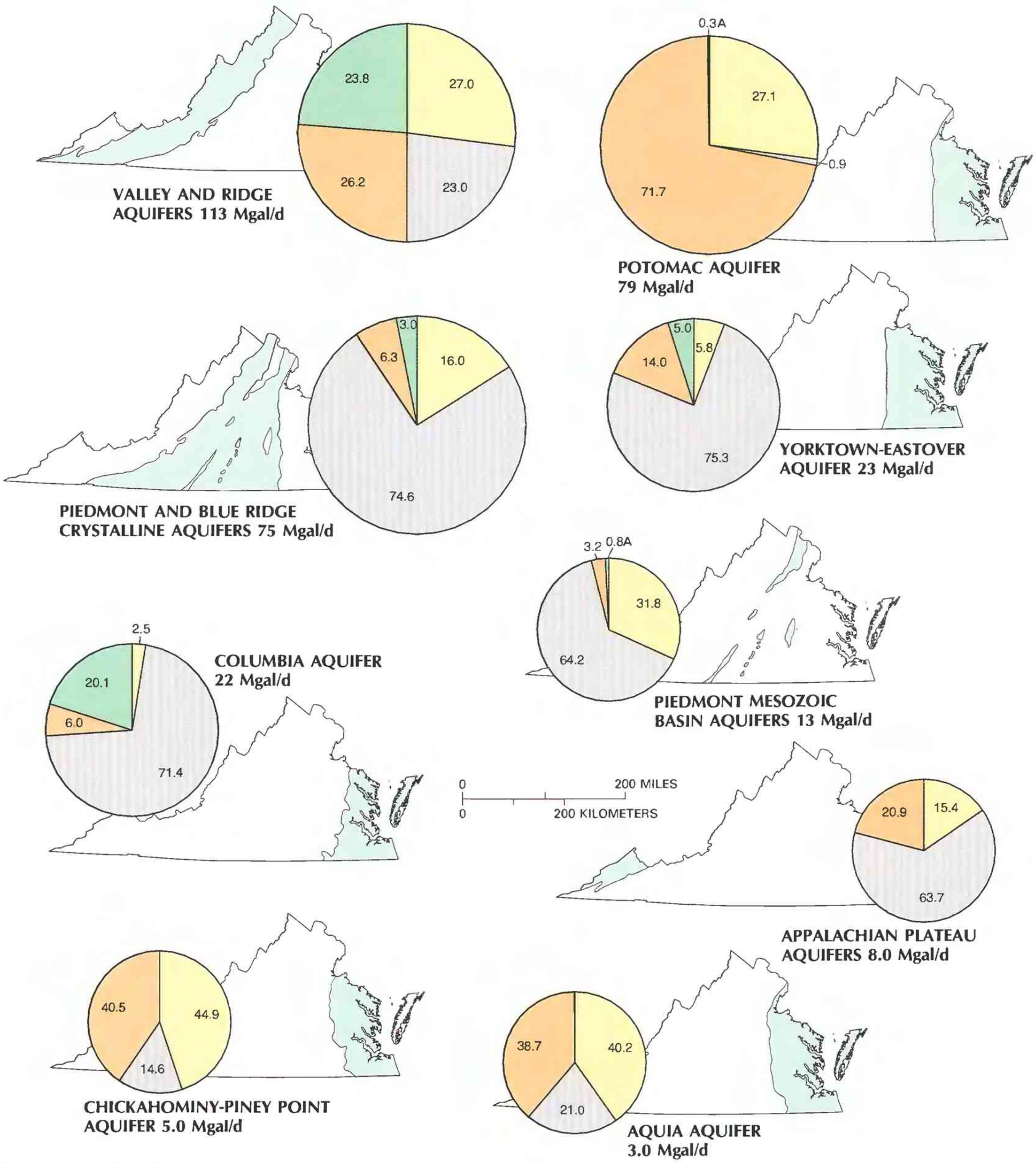


A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Virginia, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System; Harsh and Laczniak, 1987; Kull and Laczniak, 1987.)

were 18 Mgal/d. About 76 percent (70 Mgal/d) of commercial use was delivered by public suppliers. Consumptive use was estimated to be 12 Mgal/d.

The largest self-supplied domestic and commercial use was 55 Mgal/d of ground water in the Piedmont province, where 665,000 residents, or 34 percent of total population, rely on private wells and springs (fig. 5*A*). This province has the largest land area and rural population of the five physiographic provinces and is underlain by a shallow water-table aquifer that supplies most of the water for domestic needs.



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Virginia, 1985—Continued.

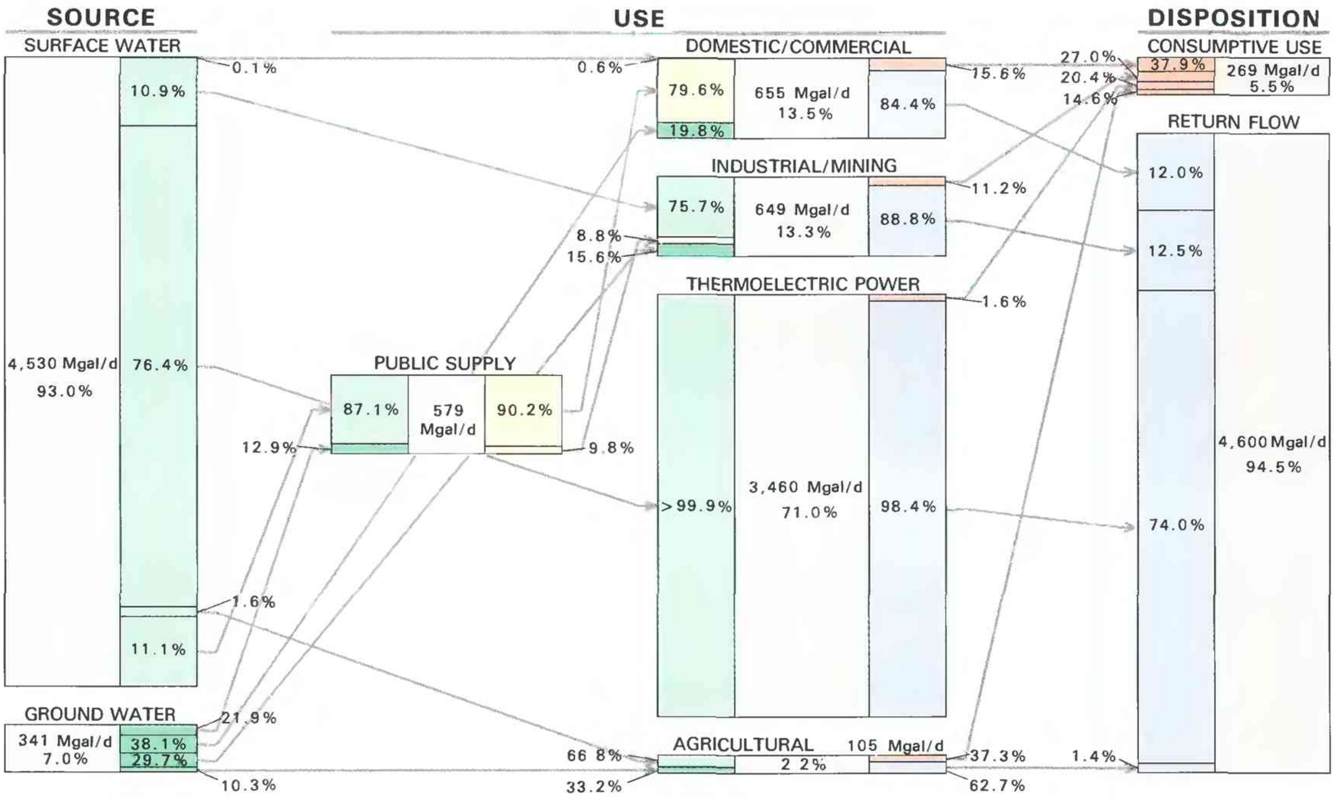


Figure 4. Source, use, and disposition of an estimated 4,870 Mgal/d (million gallons per day) of freshwater in Virginia, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

INDUSTRIAL AND MINING

Freshwater withdrawals and deliveries for industrial and mining use in 1985 averaged about 649 Mgal/d (fig. 4) and include 57 Mgal/d that was delivered from public suppliers. Self-supplied systems withdrew 477 Mgal/d of surface water and 99 Mgal/d of ground water for industrial use and 14 Mgal/d of surface water and 2 Mgal/d of ground water for mining activities. Both categories accounted for 12.1 percent of total freshwater withdrawal (42 percent, excluding thermoelectric). In addition to the freshwater withdrawals, shipbuilding and refineries withdrew about 81 Mgal/d of saline surface water and about 0.2 Mgal/d of saline ground water.

Chemical industries, which include the manufacture and processing of synthetics, used about 50 percent of industrial water use; the paper and pulp industry used about 20 percent. The remaining 30 percent was used for manufacturing of cars and trucks, office equipment, and other industrial uses.

The Lower Chesapeake basin (fig. 3*A*) accounted for 61 percent of self-supplied surface water withdrawn for industrial and mining use in 1985 (fig. 3*A*). The Potomac aquifer of the Coastal Plain province supplied 56 percent of ground-water withdrawals for industrial and mining use (fig. 4). Industrial and mining withdrawals in the Coastal Plain province in 1985 averaged 285 Mgal/d (fig. 5*A*).

Beginning in the 1960's, some industries became increasingly aware that water is a limited resource; therefore, they initiated conservation measures, primarily through water recycling or secondary-recovery methods. The State has encouraged industries to increase their water-use efficiency.

THERMOELECTRIC POWER

Two investor-owned utilities withdraw water in Virginia for the operation of nine thermoelectric powerplants. One utility that withdraws water in the District of Columbia for the operation of a fossil-fueled plant in Virginia is included in this report as a Virginia withdrawal. In 1985, about 5,760 Mgal/d of saline and fresh surface water was withdrawn by eight fossil-fueled and two nuclear powerplants to generate 41,200 GWh of power; consumptive use was estimated to be 89 Mgal/d.

Fresh surface-water withdrawals for thermoelectric power generation in 1985 were 71.0 percent (3,460 Mgal/d) of total freshwater withdrawals (fig. 4); the withdrawals were used in the generation of 28,590 GWh of power. Fresh ground-water withdrawals of 0.10 Mgal/d were used for drinking and sanitation. About 1.6 percent (55 Mgal/d) of withdrawals for thermoelectric power generation was consumed.

The Lower Chesapeake basin (fig. 3*A*) supplied 78 percent of fresh surface water withdrawn by thermoelectric powerplants in 1985. The largest quantity of fresh surface water for thermoelectric power generation in 1985 was withdrawn in the Piedmont province, where 1,960 Mgal/d was used to generate 13,700 GWh of electricity.

AGRICULTURAL

In 1985, agricultural water withdrawals averaged 2.2 percent (105 Mgal/d) of freshwater withdrawals (7 percent, excluding thermoelectric) (fig. 4). Withdrawals for nonirrigation agricultural use

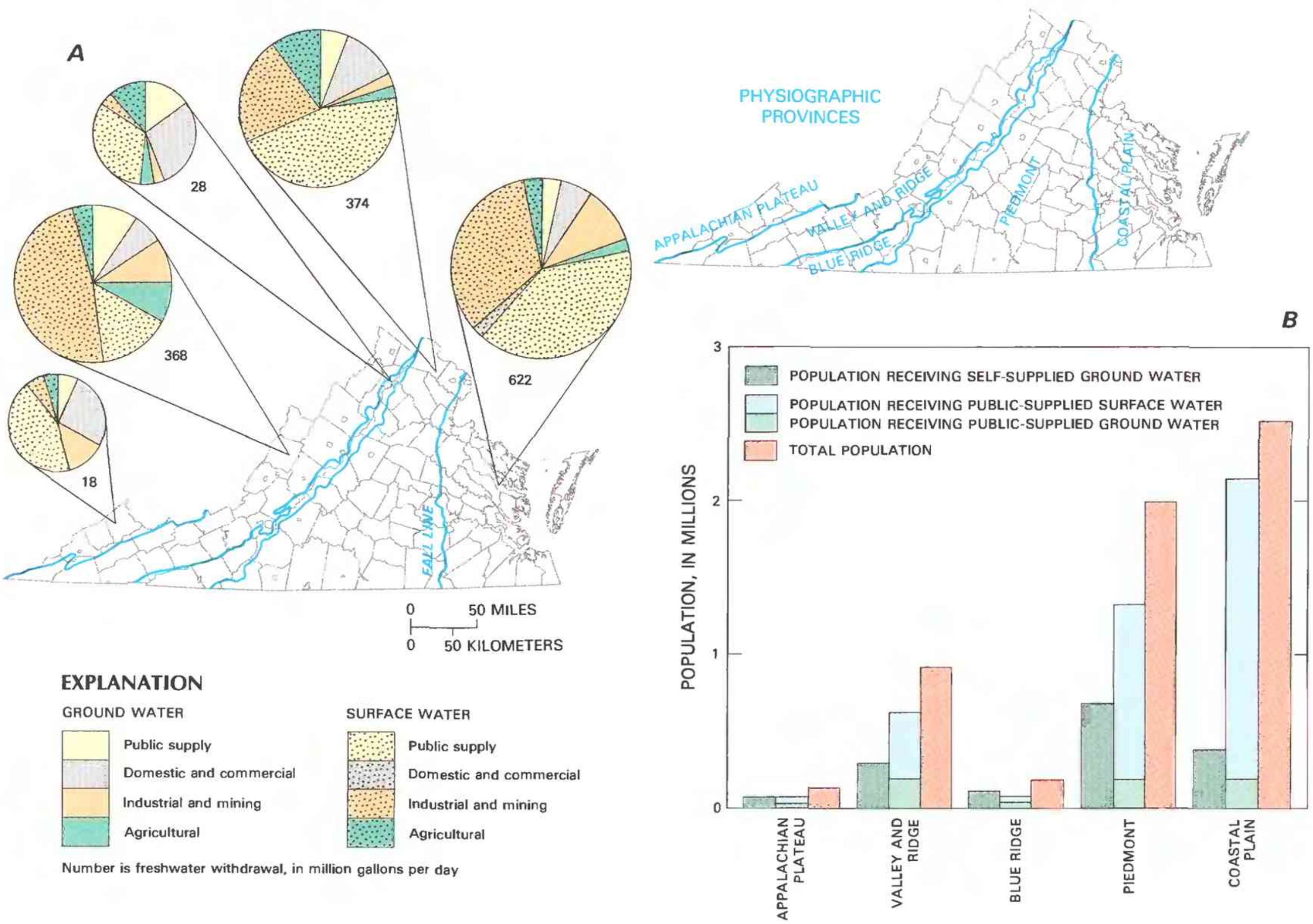


Figure 5. Freshwater withdrawals (excluding thermoelectric power) and population distribution by physiographic province. *A*, Withdrawals (1,410 million gallons per day) by source and category of use. *B*, Population distribution. (Sources: *A*, *B*, Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

were 53 Mgal/d. Nonirrigation agricultural use, which includes livestock watering and poultry and fish farming, increased nearly 90 percent from 1980 to 1985. This increase was due to the inclusion of fish farming in the agricultural category. Water for livestock use decreased about 5 percent from 1980 to 1985. Of the withdrawals for agricultural use, 66.8 percent was from surface-water sources and 33.2 percent was from ground-water sources (fig. 4). About 54 percent of surface-water withdrawals (5 Mgal/d for irrigation and 33 Mgal/d for nonirrigation agriculture) occurred in the Chowan–Roanoke basin (fig. 3*A*). Nearly 75 percent of ground-water withdrawals was in the eastern part of the Coastal Plain (fig. 3*B*). About 37.3 percent of the water withdrawn for agricultural use was lost through evapotranspiration and consumption by livestock. Most of the loss is by evaporation from spray systems that are used almost exclusively for crop irrigation. Drip-irrigation systems installed below or at the ground surface are used on less than 0.05 percent of irrigated crops. Cold-water fish aquaculture, primarily in the western part of the State, accounted for about 22 Mgal/d of ground-water withdrawals.

Withdrawals for irrigation totaled 52 Mgal/d in Virginia in 1985. About 39 percent (41 Mgal/d) of these withdrawals was in the Piedmont province. Surface water provided 97 percent of the withdrawals, and ground water provided 3 percent. The Coastal Plain province includes the two easternmost counties (Northampton and Accomack) of Virginia on the southern Delmarva Peninsula. This area, referred to as the Eastern Shore, is a gently eastward-sloping surface underlain by a seaward-thickening sequence of unconsolidated sediments. Although ample ground water is available, more than 85 percent of the withdrawals for irrigation in the Coastal Plain province, except for the Eastern Shore, are from surface-water resources. About 75 percent of withdrawals for irrigation on the Eastern Shore is water obtained primarily from ponds that intersect the water table.

The south-central part of the Piedmont province has an abundance of perennial streams, impoundments of intermittent streams, and springs that provide an ample supply of surface water for irrigation. Less than 5 percent of the withdrawals for irrigation in this area is from ground-water resources.

The first irrigation system in Virginia was installed during the 1920's; however, the development of lightweight, portable pipe during the 1940's and the extreme droughts of the early 1950's led to the first major use of irrigation in the State. During this period, most irrigation systems were developed for tobacco and vegetable crops by using farm ponds as water sources. Irrigation increased in the 1960's and 1970's, when more efficent systems, such as traveling guns and center-pivot systems, were developed.

Beginning in the late 1970's, the drip-irrigation system became a prominent method of irrigation for orchards in the western part of the State but has limited use in field crops, mainly on the Eastern Shore. In the middle to late 1970's, corn surpassed tobacco as the

Downstream side of Schoolfield Dam on Dan River, Danville, Virginia, August 5, 1987. The dam pool has been lowered to permit inspection and maintenance on intake racks for turbines in hydroelectric plant. Flow is about 100 cubic feet per second; monthly average is 846 cubic feet per second. (Photograph by Byron Prugh.)

leading irrigated crop, followed by vegetables and melons, soybeans, peanuts, and wheat.

The number of irrigation systems (and, consequently, water use) has increased in recent years. In addition to supplying soil moisture during drought, irrigation systems are now used to apply fertilizer and agricultural chemicals over extensive areas. Water withdrawals for irrigation increased about 40 percent from 1980 to 1985. Irrigation use probably will increase into the 1990's, but its use will be tempered by more efficient use of technological advances and reevaluation of the cost effectiveness of irrigation systems.

WATER MANAGEMENT

During Virginia's first 350 years, the water supply was sufficient to meet the demands from residents, industries, utilities, and agriculture. Judicial resolution of minor conflicts affected few parties beyond the litigants, and official water management was minimal until about 100 years ago. Virginia relies on "riparian doctrine," which is a common law that allocates surface water according to land ownership bordering waterways. Under riparian law, water may be used only within the drainage basin from which it has been withdrawn, and the quantity a user withdraws must be reasonable in relation to others with similar rights. The courts adjudicate water rights.

Management of Virginia's water resources and related land resources is the responsibility of 13 State agencies and 9 Federal agencies. Interstate agreements between Virginia and its neighbors define the management of surface and ground water shared by these States.

The Virginia Department of Health, created in 1872 as the Board of Health and Vital Statistics, administers and enforces the public safety of drinking water and other public-health issues concerning water. In 1916, legislation assigned the board the responsibility for the sanitary and physical quality of water from all water supplies and waterworks in the State. Responsibilities include the inspection of shellfish grounds and packing houses and the authority to prohibit the sale of shellfish that is unfit for market (1927); authority for the creation of mosquito-control districts, which is shared with counties and cities (1940); and overseeing sewage-treatment plants, which is shared with the VSWCB.

In 1946, State law created the VSWCB to administer and enforce a water-quality control program. The board establishes requirements for waste-treatment plants, regulates levels of discharges from marine craft, administers financial aid programs, and makes water-quality plans. The VSWCB also certifies projects that require Federal licenses, investigates significant fishkills, and monitors pollution from petroleum discharges.

The Virginia Groundwater Act of 1973 delegated to the VSWCB the responsibility for protection and limited management of the State's ground water. In the same year, the VSWCB declared two areas, southeastern Virginia and the Eastern Shore, to be ground-water-management areas, which requires that commercial and industrial users who withdraw more than 50,000 gal/d to report amounts withdrawn. Federal institutions, public suppliers, and agricultural users were exempted from reporting. A 1987 amendment to the Act requires the reporting of withdrawals greater than 300,000 million gallons per month, including withdrawals by public suppliers and excluding withdrawals for the operation of ground-water heat pumps.

In December 1981, the VSWCB adopted Regulation 11, which became effective March 1, 1982. This regulation requires the reporting of withdrawals of surface or ground water when the daily average rate exceeds 0.01 Mgal/d during any single month of the year; excluded are withdrawals for crop irrigation, withdrawals of saline (greater than 2.0 parts per thousand) surface waters, withdrawals from mines or quarries for the sole purpose of dewatering, withdrawals for the sole purpose of hydroelectric power generation, withdrawals by Federal agencies, and withdrawals of less than 0.01 Mgal/d during the peak month. Also exempt from the regulatory mechanism are users who do not withdraw their water but obtain it from other users (C. Martin, Virginia State Water Control Board, written commun., 1987).

The water-resources-protection activities of these and other State agencies have increased over the years as they have become more aware of the importance of clean and plentiful water. The public, including State legislators, has focused attention on preserving fish and wildlife habitats, regulating instream flows, upgrading water-recreation areas and navigation channels, and protecting water quality and supplies.

During the last 30 years, water withdrawals have increased steadily to meet the needs of an increasing population and related commercial and industrial expansion. Additional demands on the available water supply have been and will continue to be incurred by treatment facilities for returning this water to the environment. Moreover, in the last 10 years, withdrawals for agricultural use have increased rapidly, primarily for irrigation during drought.

Water-demand conflicts now facing the State include the interbasin water transfer by a proposed pipeline from Virginia Beach southwestward to Lake Gaston in North Carolina, a proposed interstate coal-slurry pipeline, hazardous-waste disposal sites, comprehensive management of water resources using a system of withdrawal permits, statewide standards for well construction, expansion of public supplies in rapidly growing urban areas, the control of agricultural runoff, and improved municipal sewage treatment.

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Prepared by T.K. Kull and H.T. Hopkins, U.S. Geological Survey; History of Water Development and Water Management sections by W.R. Walker, Virginia Water Resources Research Center

FOR ADDITIONAL INFORMATION: Office Chief, U.S. Geological Survey, 3600 West Broad Street, Room 606, Richmond, VA 23230.

WASHINGTON
Water Supply and Use

Water has been important to Washington's development. Presently, a large part of the State's economy depends on the availability of large quantities of water that are suitable for most uses.

Climatically, Washington is divided into a humid western part and a dry eastern part, separated by the crest of the north-trending Cascade Range. Water withdrawals in western Washington, where most of the population resides, are mainly for public supply. Withdrawals in eastern Washington are much larger and are mainly for irrigation. Of the water used for public supply and irrigation, 64.5 and 86.9 percent, respectively, are from surface-water sources. Almost one-half of all ground water withdrawn in Washington is from the Columbia River basalt aquifer.

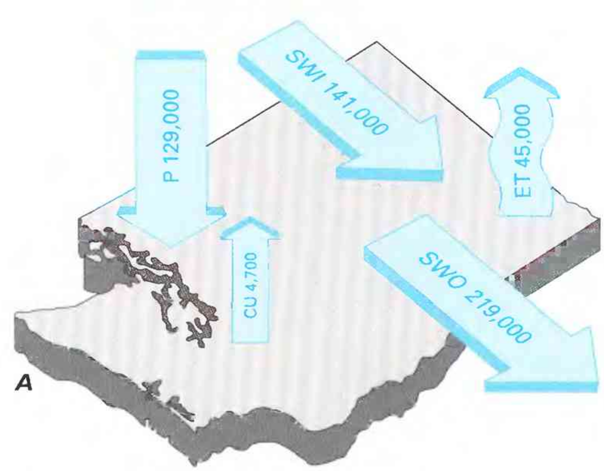
In 1985, total freshwater withdrawals for all uses in the State were 7,000 Mgal/d (million gallons per day). Of this amount, 67.1 percent (4,700 Mgal/d) was consumed and no longer available for reuse (fig. 1*A*). This quantity is small, however, compared to the instream use of 628,000 Mgal/d for the production of hydroelectric power, which is a nonconsumptive use.

Conflicts among competing uses of surface water have increased in Washington and have created a greater reliance on ground water. The Washington State Department of Ecology (WDOE), which is charged with protecting the State's water resources, has responded with broad-based programs to regulate water-right permits, to develop standards for minimum instream flows, and to assure the continued availability of good-quality ground water.

HISTORY OF WATER DEVELOPMENT

The first residents of Washington were Indians. The salmon and steelhead trout that migrated into coastal streams in large numbers provided a mainstay in the diet of the Indians along those streams and formed the basis of unique cultural, economic, and religious practices. Rivers and marine waterways also provided convenient transportation avenues to early explorers. The Lewis and Clark expedition, among others, traveled down the Snake and the Columbia Rivers to reach the Pacific Ocean.

Euro-American settlement of Washington began in earnest in the middle of the 19th century. Settlements that would become Seattle, Tacoma, Olympia, Walla Walla, Spokane, and others were located on or near water necessary for transportation, domestic supply, and power. Lumber mills and shipping facilities were started at many sites along Puget Sound. Rivers were used to transport logs downstream to the mills on Puget Sound. The earliest irrigation in Washington is believed to have been in the area of present-day Walla Walla before 1820, and intensive irrigation development of the Yakima basin began in the 1850's.



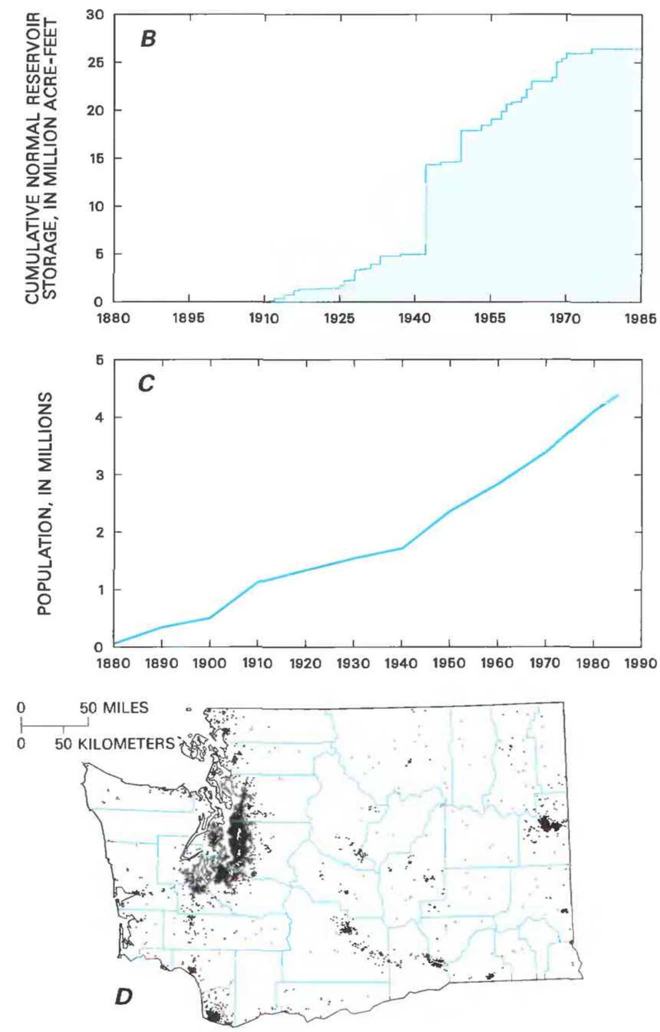


Figure 1. Water supply and population in Washington. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* McGavock and others, 1986; U.S. Geological Survey, 1986. *B,* U.S. Army Corps of Engineers, 1981. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

Because of the remoteness of the region, Washington's population increased slowly until completion of the first transcontinental railroad between the Pacific Northwest and the east coast in 1883. Washington became a State in 1889 and, by about 1900, its population had increased markedly. Rapid population growth in Washington resulted in and from increased development of water resources for public supply, industry, power, and agriculture. The growing cities of Seattle and Tacoma initiated development of large public-supply projects on nearby rivers in the early 1900's.

Construction of dams for hydroelectric power generation and other uses began in the early 1900's; in 1942, reservoir capacity nearly tripled (fig. 1*B*) after the completion of Grand Coulee Dam (northwestern corner of Lincoln County) on the Columbia River. In 1987, Washington had more than 80 large dams with a total storage capacity of more than 26 million acre-feet. Eleven dams span the Columbia River, and four span the Snake River. The main stem Columbia River, the largest river in Washington, is now almost completely regulated by multipurpose dams.

Development of Washington's water resources has not been without environmental effects; few major rivers remain in pristine condition. In many streams, including the Columbia River, large natural populations of anadromous fish have been decreased significantly, in many instances as a direct consequence of water-resources development. (Anadromous fish hatch in freshwater, mature in saltwater, and return to spawn in freshwater.) Wildlife, water quality, recreation, and esthetics also have been altered as a result of this development.

WATER USE

Washington is commonly regarded as having a wet climate; in reality, the climate differs geographically. Although the average annual precipitation is about 40 inches, the State contains some of the wettest and the driest spots in the Nation. It is not surprising, therefore, that great differences exist in the availability of water resources.

Water-demand patterns within Washington are largely a reflection of land use, population trends (fig. 1*C*), population distribution (fig. 1*D*), and availability of water. Despite the fact that only 23 percent of the population resides in the semiarid eastern part of the State, total water withdrawals in the east are almost five times greater than in the more humid west (fig. 2*A*). Most of the water withdrawn in eastern Washington is from surface-water sources and is used chiefly for irrigation (fig. 2*B*). Withdrawals in the more populous areas of western Washington also are predominantly from surface water, which is used chiefly for public supply, including delivery for commercial and industrial purposes. Despite these geographic differences in demand and availability, the quantity of water available in Washington is one of the largest in the Nation (Bodhaine and others, 1965).

A water budget (fig. 1*A*) shows the relative proportions of water that flow to and from the State. As a result of abundant average annual precipitation, the amount of water that flows out of Washington is 78,000 Mgal/d more than flows into Washington. Additionally, the State's water supply is depleted by 45,000 Mgal/d

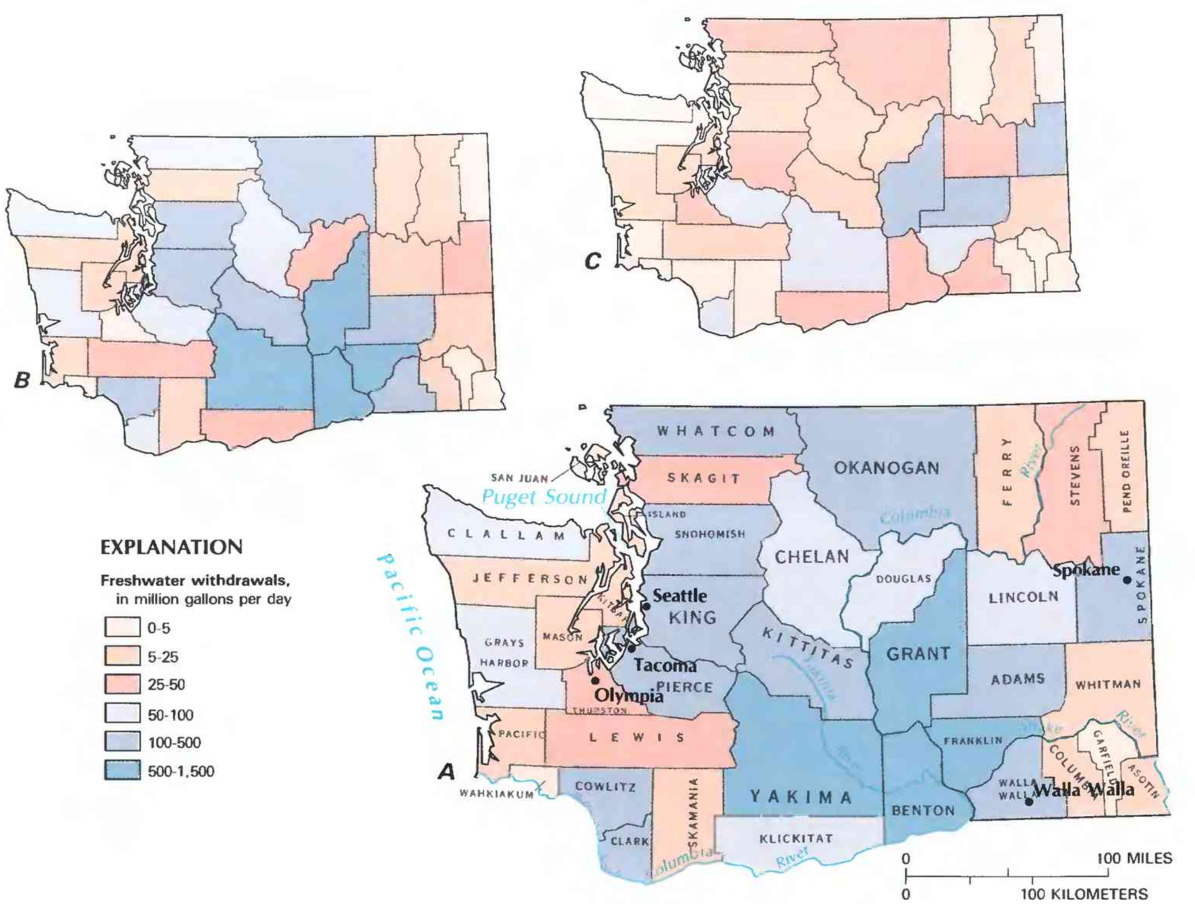


Figure 2. Freshwater withdrawals by county in Washington, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

because of evapotranspiration and by 4,700 Mgal/d because of various consumptive uses. Principal offstream uses are for agriculture, industrial and mining purposes, domestic and commercial purposes, and thermoelectric power generation. Principal instream uses include navigation, waste dilution, recreation, fish and wildlife propagation, and hydroelectric power generation. Although the instream uses do not deplete the overall supply, they compete for the use of water and all are capable of adversely affecting the physical and chemical quality of the resource.

Degraded water quality is not a widespread constraint on the use of water in Washington. Locally, however, there is evidence of saltwater intrusion, lake eutrophication, and contamination of ground water by organic compounds, toxic metals, or nitrates (U.S. Geological Survey, 1984).

Total freshwater withdrawals in 1985 for all uses were 7,000 Mgal/d. The largest surface-water withdrawals (82 percent) were from eastern Washington (fig. 2*B*). Large amounts of surface water were withdrawn in Franklin, Grant, and Yakima Counties for irrigation and from Benton County for irrigation and thermoelectric power generation. In western Washington, large amounts of surface water were withdrawn in King and Snohomish Counties for public supply and in Cowlitz County for industrial use. Ground-water withdrawals in individual counties in 1985 (fig. 2*C*) were generally smaller than surface-water withdrawals, although significant amounts of ground water were withdrawn in Spokane County for public supply and in Adams and Grant Counties for irrigation. Total offstream withdrawals in 1985 ranged from 1.2 Mgal/d in San Juan County to 1,460 Mgal/d in Grant County.

Surface-water withdrawals by major river basin are shown in figure 3*A*. Of the major river basins, the largest surface-water withdrawals in 1985 were from the Upper Columbia and the Yakima basins of eastern Washington, and were used predominantly for irrigation (fig. 3*A*). Large amounts of surface water also were withdrawn in the Puget Sound basin mostly for public supply.

Ground-water withdrawals by major aquifers are shown in figure 3*B*. Of all ground water withdrawn in Washington in 1985, 48.9 percent was from the Columbia River basalt aquifer, 37.0 percent was from the glacial-drift aquifer, and 13.0 percent was from the terrace and valley-fill aquifer. A small amount of water also was withdrawn from the alluvium and bedrock aquifers, chiefly for domestic purposes (fig. 3*B*). Of withdrawals from the basalt aquifer, 83.6 percent was for irrigation. Of water withdrawn from the glacial-drift aquifer, 50.6 percent was for public supply. Withdrawals from the terrace and valley-fill aquifer were divided almost evenly among public supply, industry and mining, and agriculture.

Withdrawals fluctuate annually, chiefly as a result of variable precipitation, especially in eastern Washington, where a large part of total withdrawals is used for irrigation. Because part of the crop moisture requirement is provided by rainfall during the growing season, withdrawals from other sources are not as essential in years of abundant precipitation. Conversely, in moisture-deficient years, withdrawals are likely to be greater than normal. In 1985, precipitation in eastern Washington was 70 to 85 percent of the long-term average. Therefore, irrigation withdrawals for 1985 probably were greater than what would be expected during a year of normal precipitation.

The source, use, and disposition of freshwater in Washington are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that surface water represented 82.6 percent of all withdrawals in Washington in 1985. Of that quantity, 74.8 percent (4,320 Mgal/d) was withdrawn for agricultural use, 10.7 percent (616 Mgal/d) was withdrawn for public-supply systems, 7.1 percent (412 Mgal/d) was withdrawn directly (self-supplied) by industrial and mining facilities, and 7.4 percent (427 Mgal/d) was withdrawn for thermoelectric power generation. Virtually no surface water was self-supplied for domestic and commercial purposes in 1985. Although more than 350 wastewater treatment facilities were in operation in 1985, none of the 436 Mgal/d of wastewater released by these facilities was reused.

The use data in figure 4 indicate that withdrawals for agriculture totaled 4,970 Mgal/d (71.1 percent of total withdrawals) in 1985. Of that amount, 86.9 percent (4,320 Mgal/d) was obtained from surface-water sources, and 13.1 percent (651 Mgal/d) was from ground-water sources. Of these withdrawals, 89.8 percent (4,460 Mgal/d) was consumed, and 10.2 percent (510 Mgal/d) was returned to natural water sources where it became available for other uses. The disposition data indicate that, for all water withdrawn in Washington in 1985, 67.1 percent (4,700 Mgal/d) was consumed, and 32.9 percent (2,300 Mgal/d) was returned.

Because of abundant water resources, hydroelectric power generation in Washington is greater than in any other State in the Nation (Solley and others, 1988). This single instream use is much larger than all offstream uses combined. In 1985, 628,000 Mgal/d of water was used to produce 76,900 GWh (gigawatthours) of electricity. Consumptive use of water in hydroelectric power generation is mostly from evaporation and the quantity involved is small. Instream uses, such as hydroelectric power generation, are not shown in figure 4.

Outstanding physical features—mountains, forests, lakes, streams, and beaches—make Washington a prime vacation and recreation area. Many recreational activities, such as boating, fishing, and swimming, depend on water. Recreation, therefore, also has developed into one of the State's most important instream water uses.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In 1985, about 1,200 public-water supply systems furnished water to 80 percent of the State's population of almost 4.4 million. Withdrawals for public supply were the second largest in the State, exceeded only by withdrawals for agriculture (fig. 4).

Withdrawals for public supply, which were 955 Mgal/d in 1985, were distributed to domestic and commercial, and industrial and mining users. Of that amount, 64.5 percent (616 Mgal/d) was from surface-water sources, and 35.5 percent (339 Mgal/d) was from ground-water sources. This proportion indicates that most of Washington's population resides in the humid Puget Sound basin, where streamflow is relatively abundant. One-third of the population served by all public-water systems resides in King County. The water department for the city of Seattle distributes surface water in the greater Seattle area to about 1.1 million people, which is about 25 percent of the State population.

Almost 68 percent of the public-supply withdrawn from ground-water sources in 1985 was from the glacial-drift aquifer (fig. 3*B*). The cities of Tacoma and Spokane rely principally on the glacial-drift aquifer for public supplies. Near Spokane, the aquifer is one of the most permeable and productive glacial-drift aquifers in the United States. Many smaller cities and towns throughout Washington overlie glacial deposits, which supply water in quantities sufficient for public supplies. In 1985, public-supply systems in 12 of 39 Washington counties relied exclusively on ground water for supply.

Of the 955 Mgal/d withdrawn for public supply in 1985, about 516 Mgal/d, or 146 gal/d per capita, actually was used for domestic purposes. The remaining 439 Mgal/d was supplied to commercial and industrial users, was lost during conveyance, or was put to such public uses as fire fighting, street cleaning, and swimming pools. The largest industrial users of public-supply water are in Clallam, Grays Harbor, and Whatcom Counties in western Washington; their chief products include chemicals, cellulose fibers, and pulp. Some

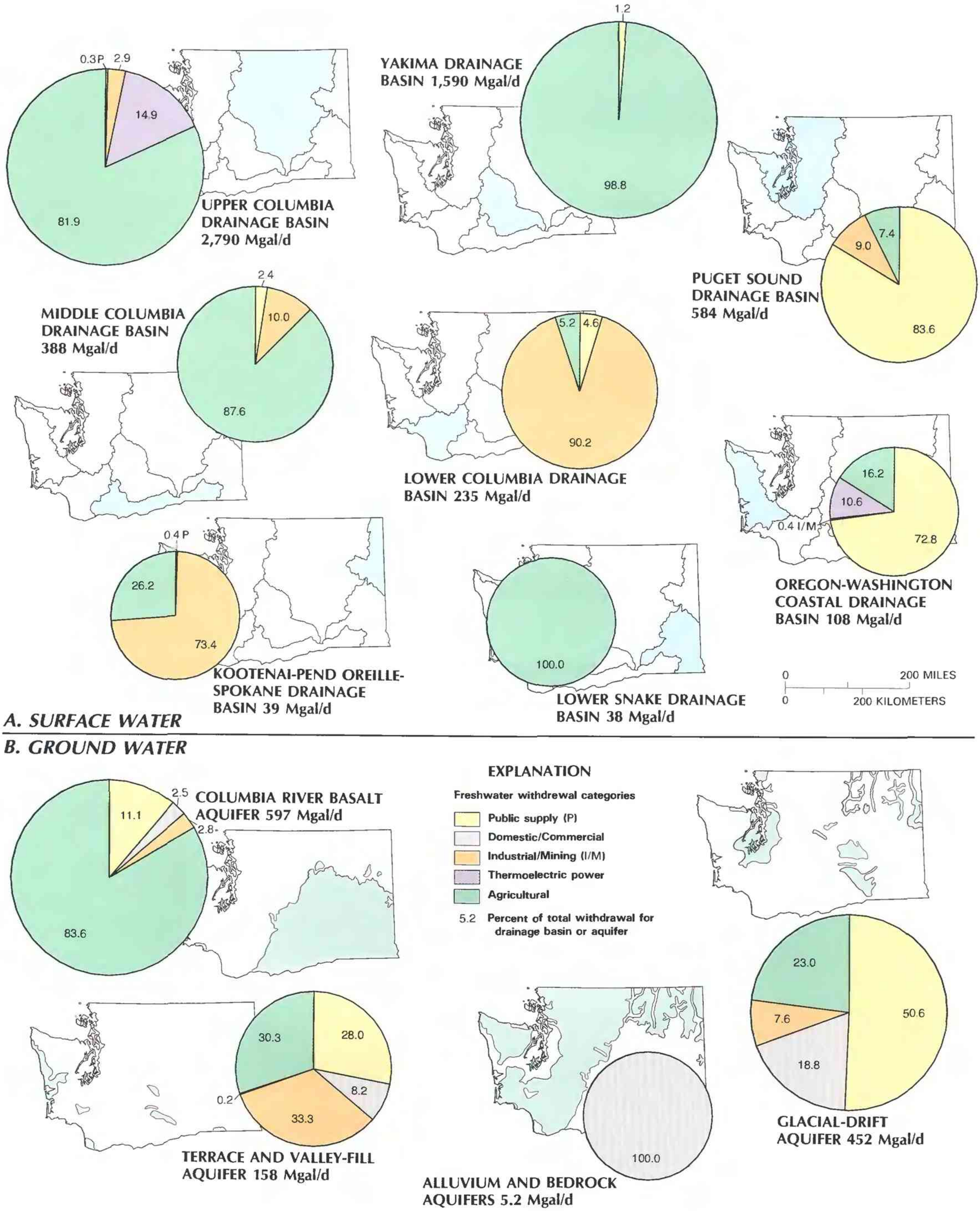


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Washington, 1985. *A*, Surface-water withdrawals by principal drainage basin. *B*, Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A*, Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B*, Molenaar and others, 1980.)

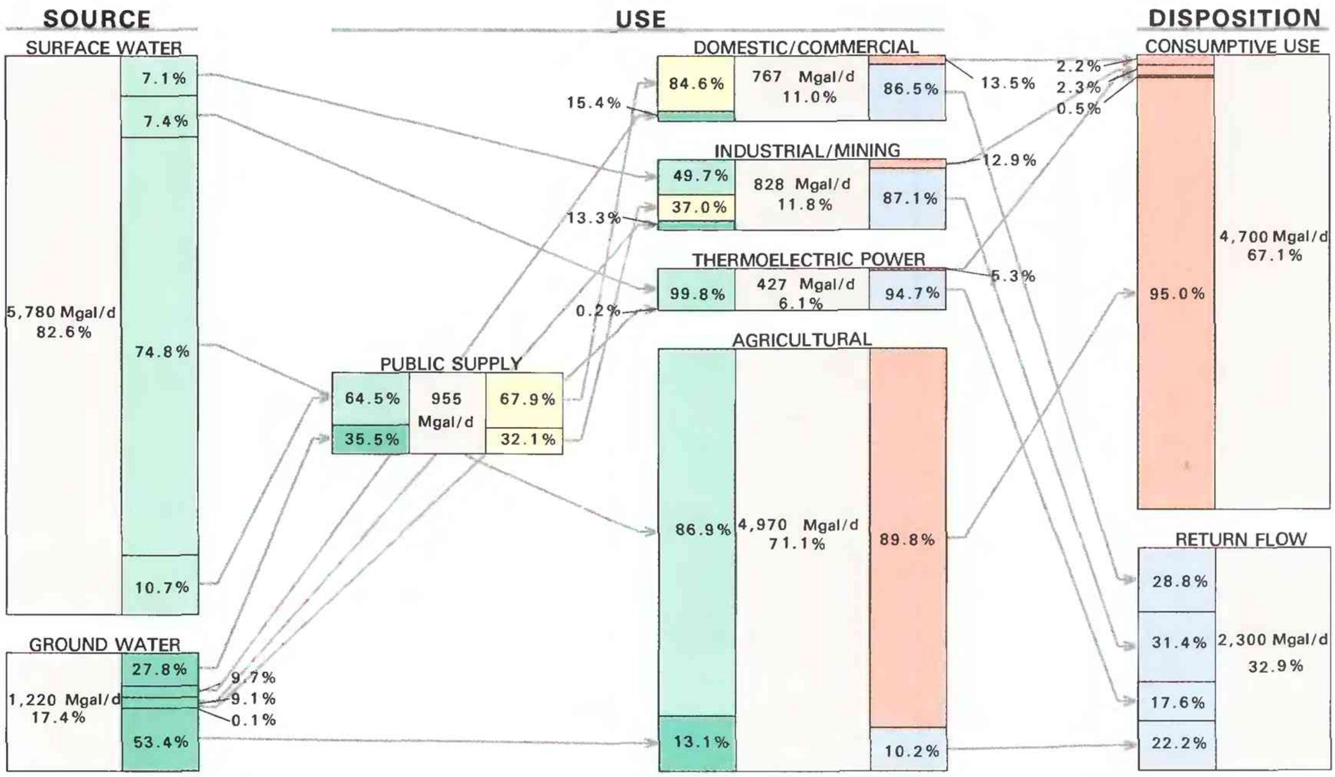


Figure 4. Source, use, and disposition of an estimated 7,000 Mgal/d (million gallons per day) of freshwater in Washington, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

large industries in western Washington have developed their own supply of process water and deliver part of that supply to neighboring communities.

Public-supply withdrawals increased 23 percent from 1975 to 1985; during that 10-year period, the population also increased 23 percent. Because withdrawals and population have increased similarly and because the population increase in Washington has been relatively constant since about 1940 (fig. 1*C*), withdrawals and use of public water supplies can be expected to increase in the future.

Domestic and Commercial

Domestic and commercial water users in Washington receive water from public-supply systems and self-supply facilities. In 1985, total withdrawals for those combined uses were 767 Mgal/d (fig. 4); of that quantity, 84.6 percent (649 Mgal/d) was from public supplies. During that same year, about 20 percent of the State's population supplied their own domestic water, predominantly from privately owned wells in rural areas; similarly, about 13 percent of the commercial establishments supplied their own water.

Combined withdrawals for self-supplied domestic use and self-supplied commercial use were 118 Mgal/d in 1985; domestic use accounted for 98 Mgal/d of the total withdrawal, and commercial use accounted for 20 Mgal/d. Of the total quantity withdrawn, 72 percent was from the glacial-drift aquifer. Self-supplied commercial withdrawals were greatest in Pierce and Spokane Counties. Because no records are available, withdrawals for self-supplied domestic and commercial purposes are estimates.

Industrial and Mining

Industries and mines in Washington use water from public-supply systems and self-supply facilities. In 1985, total freshwater use furnished by both was 828 Mgal/d (fig. 4); 37.0 percent (306 Mgal/d) of that was furnished by public-supply systems. Large water-intensive industrial facilities usually find it economically advantageous and more convenient to furnish their own process water rather than to depend on public supplies. In 1985, industries in Washington self-supplied almost twice as much water as they purchased from public-supply systems. Total self-supplied industrial freshwater withdrawals were 522 Mgal/d, less than 1 percent of which was for mining activities. About 79 percent of the self-supplied industrial freshwater was withdrawn from surface-water sources, and 21 percent was withdrawn from ground-water sources. An additional 37 Mgal/d of saline surface water was used in the manufacture of pulp, paper, and chemicals in Grays Harbor, Jefferson, and Pierce Counties, respectively. Of the total amount of water withdrawn for industrial use, 12.9 percent (104 Mgal/d) was consumed.

Self-supplied industrial water use in Benton, Clark, and Cowlitz Counties accounted for 65 percent of all industrial freshwater used in 1985 for industry. Most of the supplies in these counties were from surface-water sources, except for Clark County, where about one-half of the total was obtained from the terrace and valley-fill aquifer. Statewide, 49.1 percent of all ground-water withdrawals for industrial use was from that aquifer. The four largest water-intensive industrial categories in Washington are pulp and paper, lumber and wood, chemicals, and food products.

THERMOELECTRIC POWER

Washington has a limited number of thermoelectric powerplants—a coal-fired powerplant in Lewis County, a small wood-fired powerplant in Stevens County, and two nuclear powerplants in Benton County. In 1985, the four plants together used 427 Mgal/d of water (fig. 4) to produce 16,200 GWh of electricity. Although the coal and wood-fired powerplants and the nuclear powerplants generated approximately the same amount of electricity, the nuclear powerplants used about 97 percent of the water in this category, chiefly for cooling. All the water was self-supplied, and most of it was from surface-water sources (fig. 4). About 5.3 percent (22 Mgal/d) of the water was consumed, and the remainder was returned to streams, generally at a slightly higher temperature.

AGRICULTURAL

Washington has long been one of the major agricultural States in the Nation and ranks third in the production of hops, potatoes, wheat, and various fruits and vegetables (Washington State Office of Financial Management, 1986b). In addition, a large quantity of alfalfa is grown, mostly for local consumption by livestock. Most agricultural activity is in arid eastern Washington, where the growing season generally is long, but precipitation during the growing season is insufficient for most crops. Irrigation, therefore, is vital to Washington's economy.

As in previous years, irrigation in 1985 was the largest offstream water use (fig. 4). Total agricultural withdrawals were 71.1 percent (4,970 Mgal/d) of all withdrawals. Nonirrigation withdrawals constituted 30 Mgal/d of the agricultural total. Of the 4,940 Mgal/d withdrawn for irrigation use, 89.8 percent was consumed, and the remainder was returned to streams, ditches, drains, and canals or to aquifers.

Of the water withdrawn for agriculture, 86.9 percent (4,320 Mgal/d) was taken from surface-water sources, mainly the Columbia River and, to a lesser extent, the Yakima and Snake Rivers. The remaining 13.1 percent (651 Mgal/d) was from ground water, 77 percent of which was withdrawn from the thick, productive Columbia River basalt aquifer.

In 1985, 95 percent of the 1.6 million acres irrigated in Washington was in the eastern part of the State. Agricultural acreage in five counties (Adams, Benton, Franklin, Grant, and Yakima) on the Columbia Plateau in eastern Washington made up 71 percent of all land irrigated in the State. The total irrigated acreage in 1985 was 6.6 percent greater than that reported for 1975 (Dion and Lum, 1977) and was 1.2 percent greater than that reported for 1980 (Solley and others, 1983). The increase in irrigated acreage has slowed since 1980 because of numerous economic, hydrologic, and legal constraints on the availability of additional ground water.

In eastern Washington, automated large-acreage sprinkler-irrigation systems are replacing the older, less-efficient flood-irrigation systems. In 1985, 78 percent of all irrigation in Washington was by sprinkler systems, and 22 percent was by flood systems. The average irrigated acre received 3.4 feet of water throughout the growing season. Conveyance losses are commonly greater in flood-irrigation systems than in sprinkler-irrigation systems.

Irrigation water is usually altered in its physical and chemical quality during use. The kind and amount of change depend on the soil type in the irrigated field, amount and quality of water applied, crops grown, fertilizers and pesticides used, water-application method, and other agricultural practices. Physical changes in water quality include increases in temperature, color, and turbidity; chemical changes generally include increases in the concentrations of dissolved salts and pesticides.

WATER MANAGEMENT

In Washington, the WDOE is the designated water-resources agency. As such, it has the primary responsibility for development of a comprehensive water-resources program and for management of the State's water resources.

In 1917, the Washington Legislature enacted the State Water Code (chapter 90.03 of the revised code of Washington). Among other things, this code established procedures for issuance of water-right permits and certificates necessary to divert public surface water for beneficial uses. In 1945, the legislature adopted the Ground Water Code (chapter 90.44 of the revised code of Washington) to expand these provisions to include the State's ground-water resources. Currently (1987), any person or entity wishing to use public water for a beneficial use, such as irrigation, must receive a water-right permit from the WDOE before such use can begin. Domestic wells producing less than 5,000 gal/d are exempt from this requirement.

In recent years, a major component of the State's water-resources program has been the development of minimum instream-flow requirements for the protection of fish, wildlife, and other instream resources (Washington State Department of Ecology, 1987). Once such requirements are adopted, any subsequent water rights issued for those streams (or for ground water that is determined to be in hydraulic continuity with those streams) are subject to curtailment whenever the instream flows are not being satisfied. At present, the instream-flow program is in effect for 14 river basins and along the main stem Columbia River.

As competition for available surface water has increased, so have the conflicts among the various users. The conflicts have resulted in an increased interest in the development and the use of the State's ground-water resources. The WDOE is involved in several aspects of managing the State's ground-water resources to ensure that good-quality supplies will continue to be available. Current activities include measures for protection of shallow aquifers from excessive drawdown and water-quality degradation, development of policies related to saltwater intrusion in aquifers in island and coastal areas, and establishment of ground-water-management areas, which are being established to provide for efficient management of water

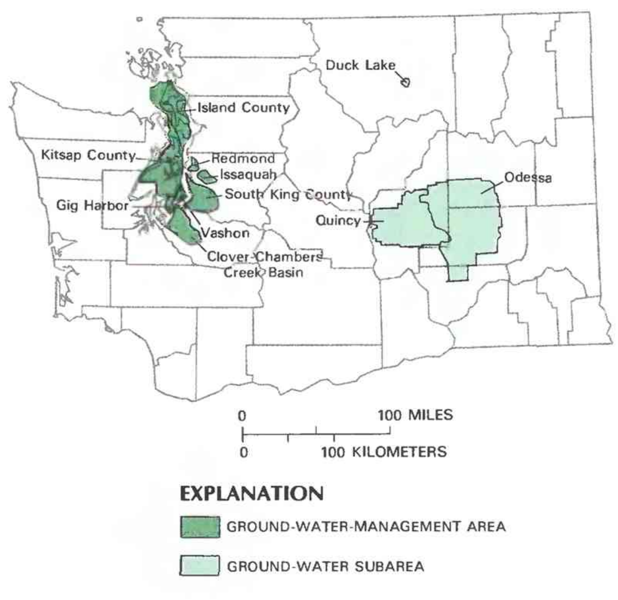


Figure 5. Ground-water-management areas and subareas in Washington, 1987. (Source: J.R. Bucknell, Washington Department of Ecology, written commun., 1987.)

Columbia River cutting through the Saddle Mountains of eastern Washington. Wanapum Dam and irrigated fields in foreground. View is looking to the south. (Photograph by Denzel R. Cline.)

resources to meet future needs, while recognizing existing water rights.

In addition, the WDOE has established three ground-water subareas in which depth zones are designated and withdrawals are regulated to maintain a safe sustaining yield of ground water. The location of ground-water-management areas and subareas in Washington as of April 1987 is shown in figure 5.

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FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 1201 Pacific Avenue, Suite 600, Tacoma, WA 98402

WEST VIRGINIA
Water Supply and Use

The rugged topography that has earned West Virginia the nickname "The Mountain State" has a major effect on hydrology. The western and central parts of the State are characterized by steep hillsides and narrow valleys. Elevation increases eastward to a maximum of 4,860 feet above sea level at Spruce Knob on the Pendleton–Randolph County line in the east-central part of the State. This area contains the headwaters of several rivers—the Potomac, the Monongahela (tributary to the Ohio River), the Elk and the Gauley (tributaries to the Kanawha River in central West Virginia), and the Greenbrier (southeastern West Virginia). East of this area, valleys widen and elevations decrease to about 250 ft above sea level at Harpers Ferry in Jefferson County.

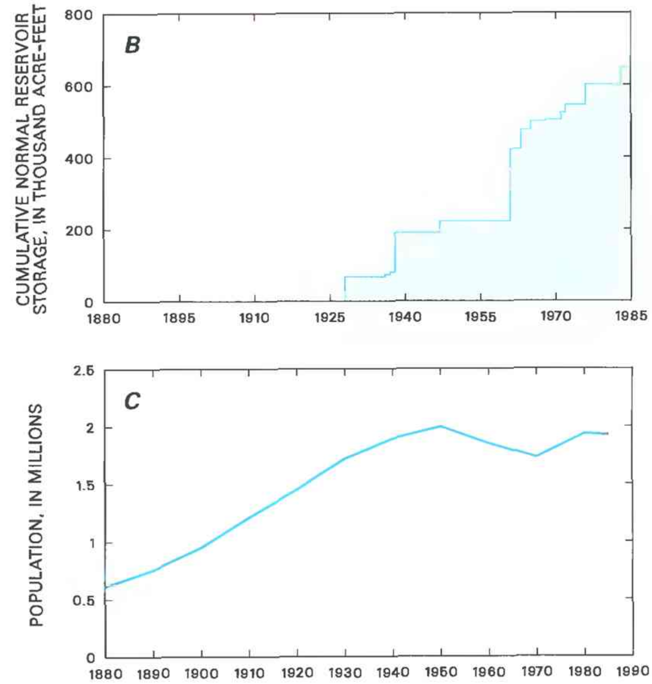
Statewide average annual precipitation is 44 inches, or about 51,000 Mgal/d (million gallons per day). Precipitation ranges substantially across the State, mainly because of orographic effects of the diverse topography. Average annual precipitation ranges from 40 inches at low elevations in the western and northern parts of the State to about 60 inches at high elevations in the east-central part. Because of westerly winds, most precipitation is on the western slopes of the mountains, and a "rain shadow" is formed east of the mountains. E.A. Friel (Hobba and others, 1972, p. 10) reported from the mountains eastward, "annual precipitation decreased 29 inches in only 15 miles." About one-half of the precipitation, or 26,000 Mgal/d, returns to the atmosphere through evapotranspiration (fig. 1*A*).

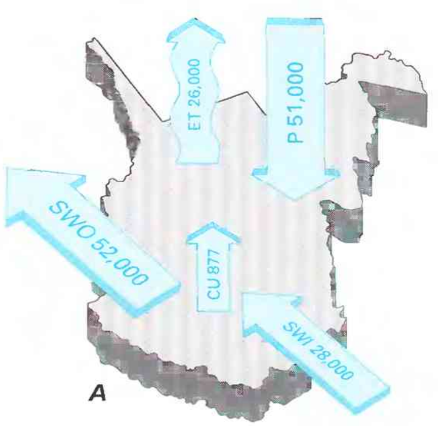
Although West Virginia has abundant surface-water resources, streamflow varies seasonally and geographically. Runoff is generally smallest from June through November—the period of greatest evapotranspiration—and largest from December through May—the period of least evapotranspiration. Average annual runoff ranges from about 16 inches in the western and southern parts of the State to 40 inches in the east-central mountains to 12 inches in the Eastern Panhandle.

About 95.8 percent of the total freshwater used is withdrawn from surface-water sources, and 49 percent of the population depends on surface water for domestic purposes. Although ground water provides only 4.2 percent of the total freshwater used, it is the source of water for 51 percent of the total population and nearly 100 percent of the rural population.

In 1985, in the southern part of the State, many abandoned underground coal mines that contain large volumes of potable water supplied about 9 Mgal/d to 81,000 domestic and commercial users in several counties. Withdrawals for public supply and industrial use from underground coal mines in Logan, Fayette, and McDowell Counties (the three largest users of mine water) ranged from 1.2 to 3.5 Mgal/d (Lessing and Hobba, 1981).

In 1985, 94 percent (5,100 Mgal/d) of offstream withdrawals was for thermoelectric power and industrial use, and one-half of





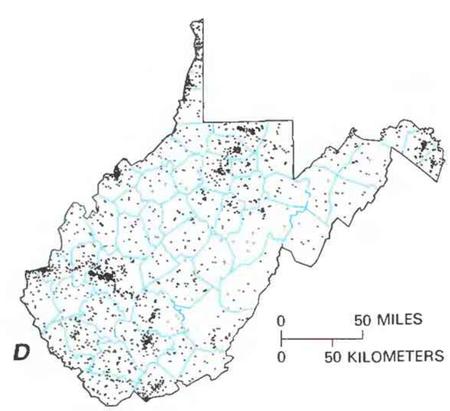


Figure 1. Water supply and population in West Virginia. *A,* Water budget, in million gallons per day. *B,* Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C,* Population trend, 1880 to 1985. *D,* Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU,** consumptive use; **ET,** evapotranspiration; **P,** precipitation; **SWI,** surface-water inflow; **SWO,** surface-water outflow. (Sources: *A,* Data modified from Lessing, 1982, p. 1; Doll and others 1963, p. 4–12. *B,* U.S. Army Corps of Engineers, 1981a. *C, D,* Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

the remaining 6 percent (151 Mgal/d) was withdrawn for public supply. Because West Virginia has abundant surface-water and coal resources, 20 thermoelectric powerplants and 8 hydroelectric powerplants have been constructed. The principal instream use of surface water in 1985 was hydroelectric power generation (16,000 Mgal/d). The State ranks 16th nationally in the amount of fresh surface water withdrawn for thermoelectric power generation (Solley and others, 1988).

Between 1980 and 1985, the statewide population decreased from 1.95 million to 1.94 million, or about one-half of 1 percent. During the same period, the population in Berkeley and Jefferson Counties in the Eastern Panhandle increased by 8 percent (from 77,077 to 83,400). The population in this area is expected to continue to increase, which will increase the demand for freshwater. The demand for water in the rest of the State is expected to remain nearly constant, although the construction of three thermoelectric powerplants in northern and central West Virginia is being considered by the State. The new powerplants probably would use streamflow as a source of water; therefore, surface-water use might increase in those regions during the next 5 to 10 years.

HISTORY OF WATER DEVELOPMENT

Water has been important to the early history of West Virginia. Rivers and streams provided Indians, explorers, and pioneers access to inland trade, a source of fish, and routes of travel. Rivers, especially the Kanawha, Elk, Potomac, and Monongahela, became natural navigable routes for early economic development. Point Pleasant (Mason County) and Charleston (Kanawha County), two of the State's first trading posts, were established in about 1670 by the French along the Ohio and the Kanawha Rivers (Conley and Stutler, 1952, p. 60).

West Virginia has many mineral and warm springs from which Indians obtained water and salt. Early settlers learned of one salt spring near Belle (Kanawha County) in 1755, when Mary Ingles, a settler who had been captured by the Indians, escaped and revealed the location of the salt spring (Price and others, 1937, p. 5). After discovery by settlers, some springs became centers of social and political life because the water was thought to be beneficial in the treatment of disease.

Settlers depended on eastern markets for salt before 1795, when a furnace was devised to aid in production of salt from the springs. To increase the supply of saltwater, wells were dug near the salty springs. As of 1987, little salt is produced from natural salt brines; however, two industries mine salt by injecting fresh ground water into salt beds through wells and pumping the resultant brine to the surface. In 1985, about 6 Mgal/d of ground water was used to yield about 1 million tons of salt.

During the late 1800's, the State established a network of streamflow-gaging stations to select suitable streams for the generation of electricity to operate grist, saw, and textile mills. Data from the present streamflow-gaging network, which includes about 100 continuous- and partial-record sites, are used by various State, Federal, and local agencies and communities to predict flood peaks, to determine flood routing, to estimate flows needed for public and industrial water supplies, and to improve recreation (boating, fishing) and power generation.

The invention and testing of Rumsey's steamboat in the late 1700's on the Potomac River at Shepherdstown (Jefferson County) demonstrated the importance of rivers as avenues of trade and commerce (Conley and Stutler, 1952, p. 286–287). After the invention of the steamboat, Wheeling (Ohio County) became an important steamboat-building center, and travel by steamboat on the Ohio, Kanawha, and Monongahela Rivers became commonplace.

In 1872, the Federal Government constructed the first 10 locks and dams on the upper Monongahela River. From 1885 to 1910, Congress directed the construction of 12 locks and dams on the Ohio River. From 1910 to 1929, a waterway system of 46 locks and dams was constructed on the Ohio River by the U.S. Army Corps of Engineers; eight of these locks and dams were in West Virginia. In 1898, 10 locks and dams were completed on the Kanawha River. The current system of three locks and dams was completed in 1937 on the same 91-mile reach of river (U.S. Army Corps of Engineers, 1986, p. 23–27). Coal and chemical products account for more than 80 percent of the tonnage shipped through the locks on the Monongahela and Kanawha Rivers (U.S. Army Corps of Engineers, 1981a).

The first hydroelectric dam was constructed on the Potomac River near Shepherdstown in 1910, and a second hydroelectric dam was built on the Cheat River near Morgantown (Monongalia County) in 1923. As of 1987, eight dams in the State are used for the generation of electricity, and proposals have been made to convert two flood-control dams to power generation.

Since 1959, the U.S. Soil Conservation Service has constructed about 150 small flood-control reservoirs in basins of less than 250,000 acres throughout the State. Many of these reservoirs also are used for recreation and public supply. The U.S. Army Corps of Engineers operates several large multipurpose dams and reservoirs in the State. Total usable reservoir storage in 1985 (fig. 1*B*) was about 650,000 acre-feet (212,000 million gallons).

WATER USE

West Virginia has an abundant supply of freshwater. In 1985, the State received about 51,000 Mgal/d from precipitation and 28,000 Mgal/d as inflow from adjoining States. Of that quantity, about 26,000 Mgal/d is returned to the atmosphere by evapotranspiration, 52,000 Mgal/d leaves the State as streamflow, and 877 Mgal/d is accounted for by consumptive use (fig. 1*A*).

Mason and Kanawha Counties had the largest total freshwater withdrawals (fig. 2*A*); Grant and Marshall Counties had the second largest withdrawals. Because surface water accounts for 95.8 percent of total withdrawals, the pattern of surface-water withdrawals by county (fig. 2*B*) resembles that of total withdrawals (fig. 2*A*), except for counties in the central-southwestern area that are underlain by the Lower Pennsylvanian aquifer.

Major water withdrawals are in areas of powerplants and near industrial and population centers. In Kanawha County, the Charleston area, which is one of the most densely populated in the State, is intensely industrialized and has five thermoelectric and two hydroelectric powerplants. In 1985 the Kanawha basin had the second largest surface-water withdrawals (1,590 Mgal/d). Thermoelectric power generation used 60.2 percent and industry and mining used 36.6 percent (fig. 3*A*).

Eight coal-fired powerplants and many industries that require large amounts of water are located in the Upper Ohio basin. In 1985, the upper Ohio basin had the largest surface-water withdrawals (fig. 3*A*). Of the 2,390 Mgal/d withdrawn, 87.7 percent was used for thermoelectric power generation, and 11.6 percent was used for industry and mining. Most of the powerplants along the Ohio River are located in Marshall, Pleasants, and Mason Counties.

Ground-water withdrawals were largest from the Lower Pennsylvanian aquifers, which were the source for 50 percent (114 Mgal/d) of total ground-water withdrawals (fig. 3*B*). Mining used 86.0 percent of the withdrawals from this aquifer. The second-largest ground-water withdrawals (53 Mgal/d) were from the alluvial aquifers—60.0 percent was used by industry and 39.0 percent was delivered to public supply.

The source, use, and disposition of freshwater in West Virginia for 1985 are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that total withdrawals were 5,440 Mgal/d, of which 95.8 percent (5,210 Mgal/d) was from surface-water sources

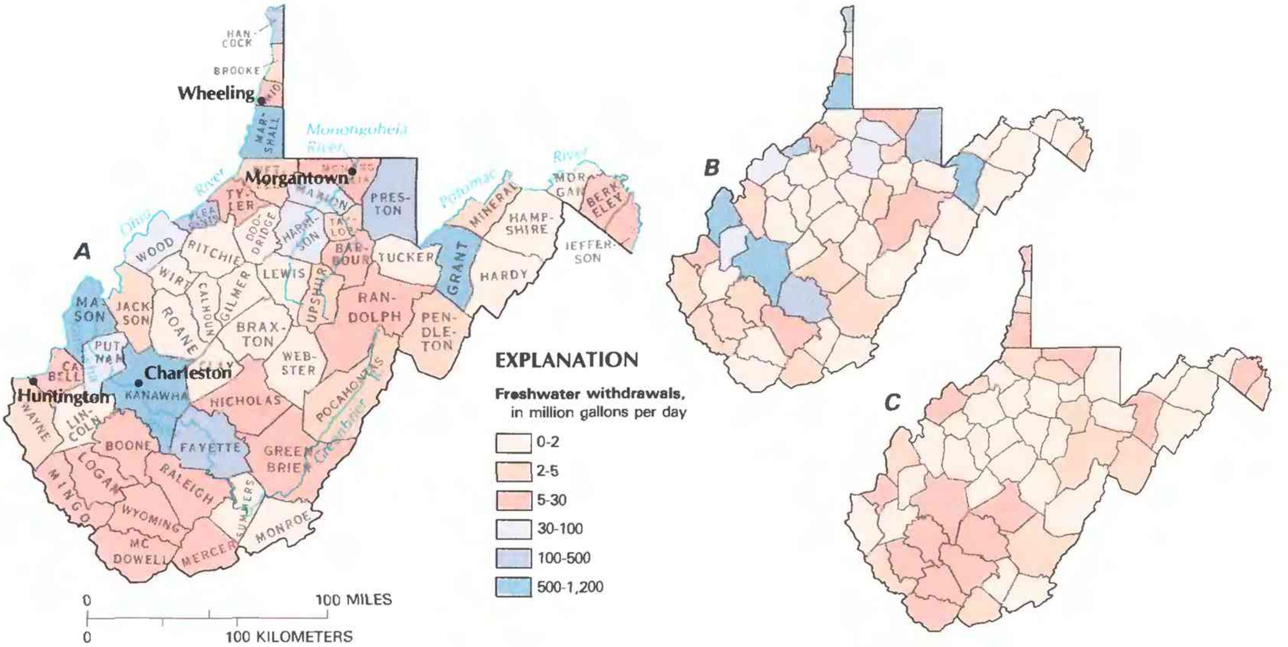


Figure 2. Freshwater withdrawals by county in West Virginia, 1985. *A,* Total withdrawals. *B,* Surface-water withdrawals. *C,* Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

and 4.2 percent (227 Mgal/d) was from ground water. Of the total surface-water withdrawals, 80.7 percent was for thermoelectric power generation. The use data indicate that domestic and commercial use was 2.8 percent (151 Mgal/d) of the total water used, that 85.4 percent of this water came from public supply, and that 79.1 percent of the water was returned to the hydrologic system for additional use. The disposition data indicate that, of the total water used, 16.1 percent was consumed and 83.9 percent was returned to the hydrologic system.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and distribute water to users. In 1985, West Virginia ranked 40th in withdrawals for public supply and 34th in population in the United States. From 1950 to 1980, withdrawals for public supply increased 175 percent (from 65 Mgal/d to 180 Mgal/d), although the population decreased about 2 percent (from 1.99 million to 1.95 million) (fig. 5). The public-supply systems have expanded for two reasons—the difficulty in obtaining water of acceptable quality and quantity from rural domestic wells and the disturbance of ground-water levels, water quality, and well yields by underground coal mining. From 1980 to 1985, total withdrawals for public supply decreased about 16 percent (from 180 Mgal/d to 151 Mgal/d), whereas population decreased less than 1 percent (from 1.95 million to 1.94 million). In 1985, withdrawals for public supply were 151 Mgal/d, of which 75.5 percent (114 Mgal/d) was from surface-water sources and 24.5 percent (37 Mgal/d) was from ground-water sources (fig. 4).

Four of the larger cities in West Virginia along major rivers (Charleston, Huntington, Wheeling, and Morgantown) use surface water as the major source of supply. Three other large cities along major rivers (Parkersburg in Wood County, Moundsville in Marshall County, and Weirton in Hancock County) obtained water from wells completed in alluvium along the rivers. Part of the water pumped from these wells generally is derived from surface-water sources.

Of the total ground water withdrawn and delivered by public suppliers (37 Mgal/d), about 22 percent (8 Mgal/d) is derived from coal mines. Most of these mines are in the low-sulfur coal fields of Fayette, Logan, McDowell, and Raleigh Counties in southern West Virginia. Abandoned coal mines could become an increasingly important source of ground water in the future. Where the chemical quality of mine water is suitable for domestic use, the flooded mines are usable sources of water because they can store large volumes of water, the temperature generally remains constant, and the stored water is somewhat protected from surface contamination.

Some cities in the eastern and southeastern counties are underlain by fractured and cavernous limestone, from which many large springs issue. Springs, flooded limestone quarries and mines, and wells in these counties commonly are used as sources of public supply. The population increased about 8 percent (6,323) from 1980 to 1985 in Berkeley and Jefferson Counties (U.S. Bureau of the Census estimates) and is projected to continue to increase because of their proximity to Baltimore, Md., and the District of Columbia. Water use also is projected to increase.

DOMESTIC AND COMMERCIAL

Domestic and commercial users received water from public-supply and self-supplied systems. Combined total water use in 1985 was 151 Mgal/d (fig. 4). The quantity includes 27 Mgal/d for public water uses and losses in the conveyance systems. Domestic use in 1985 was about 102 Mgal/d. About 81 Mgal/d was distributed by public-supply systems that served 68 percent of the population (an average of 62 gallons per day per capita), and 21 Mgal/d was used by 32 percent of the population that obtained water from private wells and springs. Rural domestic withdrawals increased from 19 Mgal/d in 1980 to 21 Mgal/d in 1985, primarily because rural population increased about 1 percent (619,640 to 625,810) during the same period. Consumptive use of all water for domestic purposes was 29 Mgal/d. The limited use of self-supplied water is expected because many wells are completed in aquifers that yield only small quantities of water. Also, many rural residents do not water lawns or use appliances that require water.

Withdrawals for commercial use in 1985 were about 22 Mgal/d; less than 1 Mgal/d was provided by self-supplied systems.

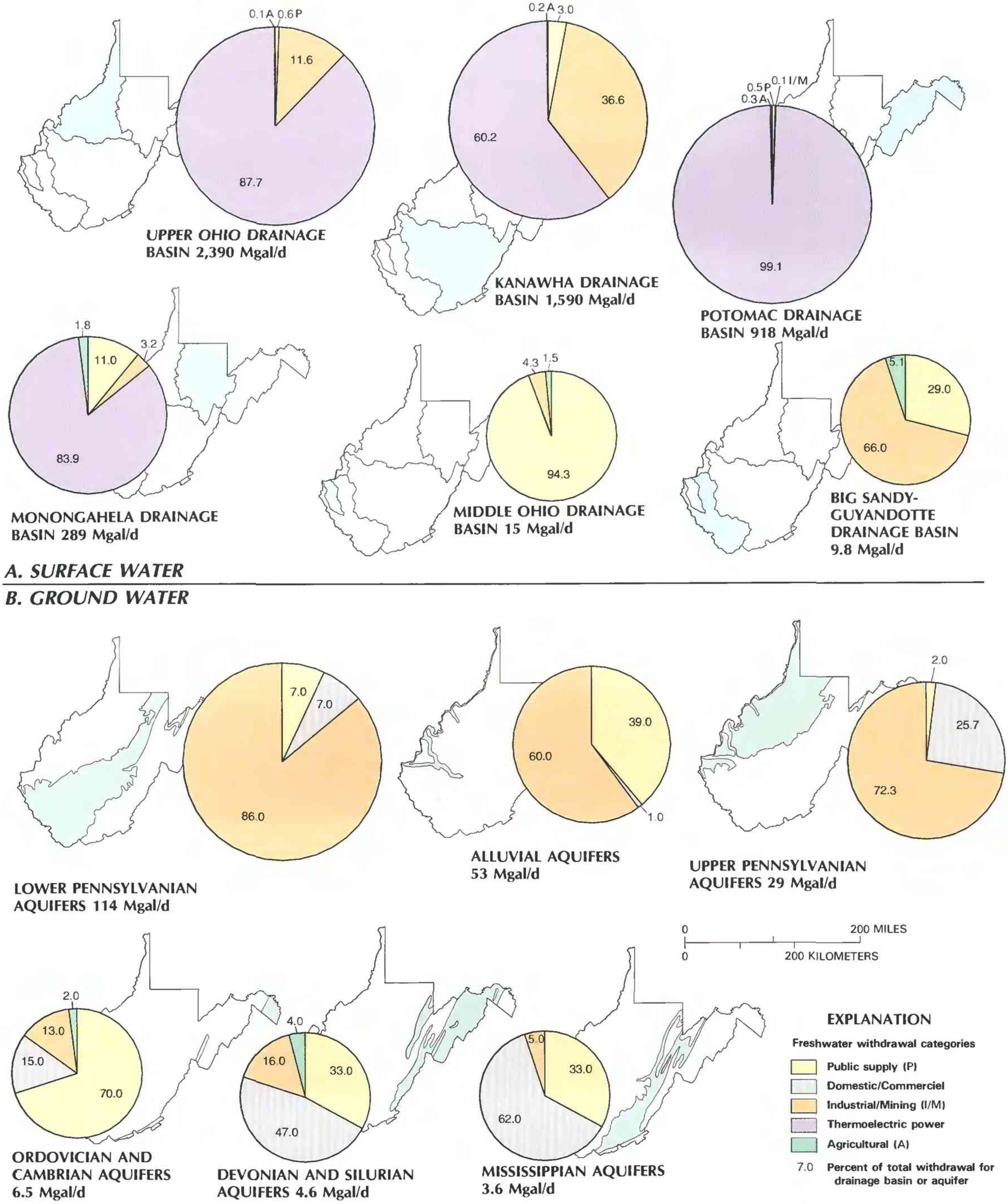


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in West Virginia, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey National Water Data Storage and Retrieval System. Aquifer map from U.S. Geological Survey, 1985, p. 441.)

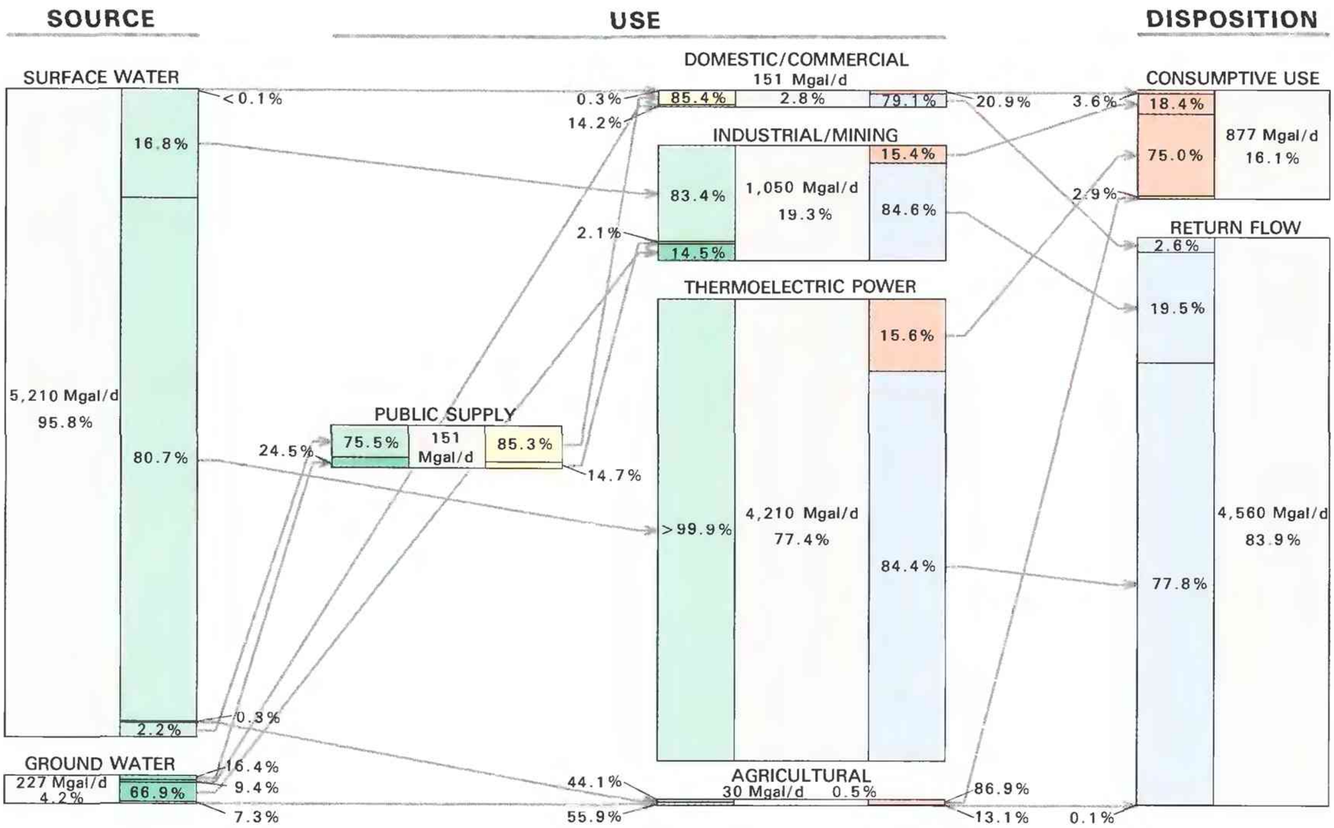


Figure 4. Source, use, and disposition of an estimated 5,440 Mgal/d (million gallons per day) of freshwater in West Virginia, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbols: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Total consumptive use is estimated to have been 2 Mgal/d. Although commercial use generally has been small, increases in recent years are attributable to snowmaking at new ski resorts.

Industrial and Mining

In 1985, freshwater withdrawals for industrial and mining use were 1,050 Mgal/d, of which 97.9 percent was self-supplied and 2.1 percent was from public-supply systems. Self-supplied systems withdrew 119 Mgal/d of ground water and 24 Mgal/d of surface water for coal- and limestone-mining activities. About 33 Mgal/d of ground water and 853 Mgal/d of surface water were used for all other industrial uses. Public supplies provided 23 Mgal/d to industrial and mining users. Estimated consumptive use by industries and mines was 162 Mgal/d.

Industrial water use is dominated by the steel and chemical industries, many of which are located along the Ohio and the Kanawha Rivers in counties that withdraw large amounts of surface water (fig. 2*B*). West Virginia is the third largest coal producer in the United States, and coal production uses large quantities of water. Mines are dewatered by pumping water from the mines, and the water is then treated and discharged to streams. Part of this water is used for dust control in the mines and on roads, and part is used for coal washing during processing. After processing, the coal is transported to market (powerplants, steel mills) by truck, railroad, or barges on the navigable rivers. After a mine has been abandoned, drainage from the mine can continue and significantly increase streamflow. For example, during the drought of 1930, drainage from coal mines in the Monongahela basin was about 30 Mgal/d, which accounted for about one-half of the annual runoff in the basin during 1928 and 1929 when precipitation was near normal (Carpenter and Herndon, 1933, p. 6–8).

Thermoelectric Power

As of 1987, West Virginia has 20 thermoelectric powerplants fueled by coal or oil. In 1985, these plants used 77.4 percent (4,210 Mgal/d) of total freshwater withdrawals for cooling; all the water was from surface-water sources. Most of the water was returned to the streams from which it was withdrawn. About 15.6 percent (658 Mgal/d) of the water used for cooling was consumed in 1985.

Three new State-owned powerplants are proposed for construction in northern West Virginia within the next 5 to 10 years. These plants probably will use more water than the older plants because they will be designed to burn high-sulfur coal and will have cooling towers that will increase the rate of evaporation. Potential secondary uses of the warm water discharged from these powerplants include hatching poultry or warming greenhouses. As of 1987, the State has eight hydroelectric plants that use 16,000 Mgal/d of water instream for power generation, which is about three times the total offstream withdrawal in 1985.

Agricultural

Agricultural water use in 1985 totaled 30 Mgal/d (fig. 4), which is about 0.5 percent of the total State water use. Withdrawals for nonirrigation use consisted of 6.4 Mgal/d for livestock (stockwatering, feedlots, dairy operations) and other farm purposes

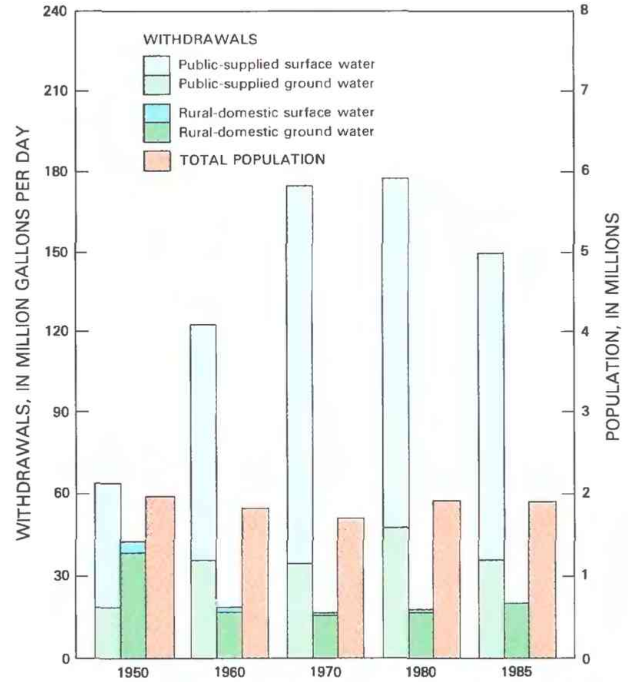


Figure 5. Withdrawals for public and rural domestic supplies and total population in West Virginia. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

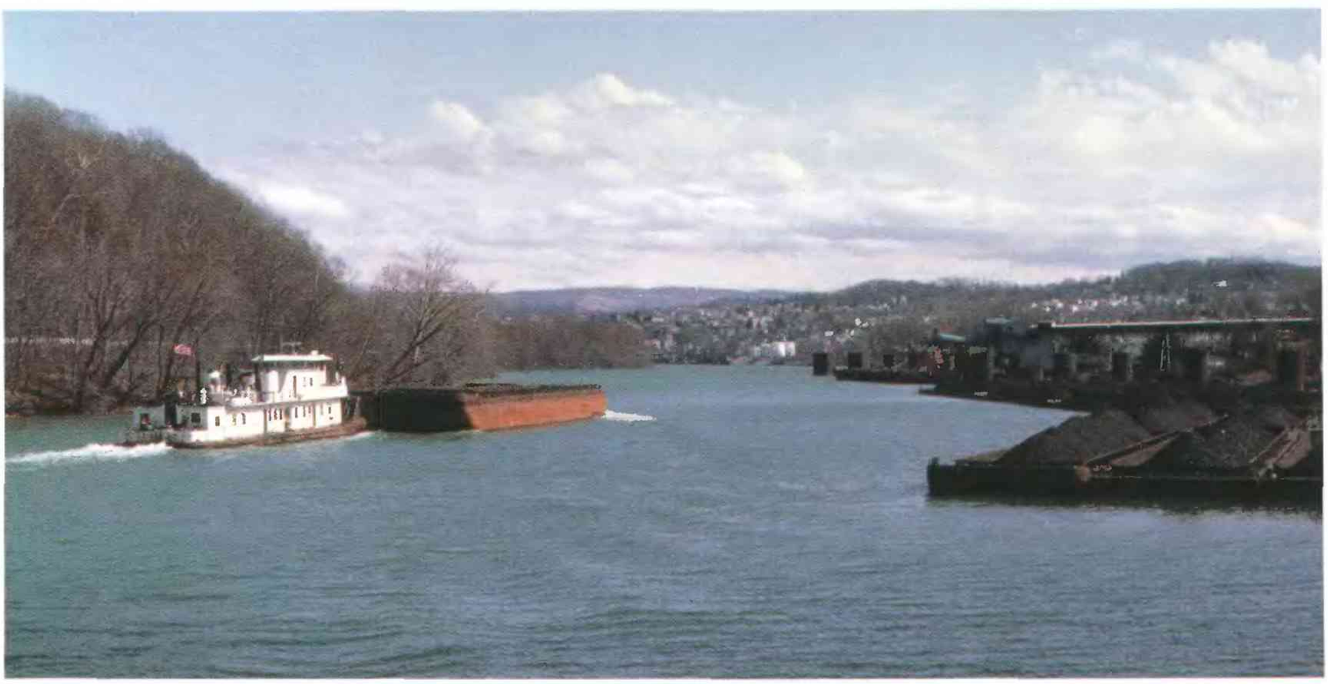
and about 19 Mgal/d for State, Federal, and private fish hatcheries. Of the total nonirrigation withdrawals, 16 Mgal/d was from ground-water sources, and 9.6 Mgal/d was from surface-water sources. Irrigation is not widespread in West Virginia; however, during a drought, some farmers irrigate corn fields, apple orchards, and strawberry fields by spraying. Rainfall in 1985 was at least 1.5 inches more than normal, except in the southwestern part of the State, where rainfall was 1 to 1.5 inches less than normal (National Oceanic and Atmospheric Administration, 1985). Most agricultural irrigation is practiced in the eastern part of the State, where average annual rainfall is least and where flat-lying land in river valleys is used for farming.

WATER MANAGEMENT

Laws that affect water management in West Virginia are based on a modification of the riparian doctrine. State organizations, such as the Water Resources Board, the Department of Natural Resources (Division of Water Resources), the State Department of Health, the Department of Mines (Division of Oil and Gas), and the Geological and Economic Survey, implement most of the regulatory, planning, and research programs for water protection and management (Bain and Friel, 1972).

The State Natural Resources Law of 1933, as revised by Chapter 133 of the Acts of 1961, created the Water Resources Board and the Division of Water Resources. The Division of Water Resources administers and enforces all laws relating to the conservation, development, protection, and use of the water resources in the State. Further revision in Chapter 20 of the Acts of 1964 places the responsibility for enforcement of water-pollution legislation with the Division of Water Resources.

The State Department of Health, under authority of the Public Health Laws of West Virginia, Chapter 16, Article 1, Section 9, regulates public-supply systems operated by individuals, companies,



A tug boat pushes an empty barge past barges that are loaded with washed and graded coal in the Monongahela River near Morgantown, West Virginia. Most of the coal will be used by thermoelectric powerplants along the Monongahela and Ohio Rivers. Water use by thermoelectric powerplants, river locks, and coal-preparation plants in the State is about 4,210, about 1,515, and about 40 million gallons per day, respectively. (Photograph by K.E. Suder.)

institutions, and county and municipal governments. Through its Division of Sanitary Engineering and the Board of Health, the State Department of Health regulates installation of public-supply systems and adherence to water-quality standards.

As of June 8, 1984, under Section 7 of this same authority, the Department of Health requires the certification of all water-well drillers in the State. Under legislative rules issued by the State Board of Health, the Department of Health also requires that a permit be obtained before any well is drilled or deepened, that certain minimum design standards be met, and that a well-completion report be filed with the County Health Department. The rules also require that a well be properly backfilled and sealed within 30 days after abandonment.

Permit applications for drilling oil and gas wells in the State and the responsibility for the protection of freshwater aquifers from contamination are vested in the Division of Oil and Gas, Department of Mines, as established in Article 4, Chapter 22 of the Code of West Virginia of 1931.

The U.S. Geological Survey, in cooperation with the West Virginia Geological and Economic Survey, the West Virginia Department of Natural Resources, Division of Water Resources, and other agencies, maintains a statewide data-collection network and is responsible for investigating the State's water resources. The research, data collection, and analyses provided by this cooperative program form an information base upon which water-management decisions are made by the West Virginia Department of Natural Resources and by other State agencies charged with the protection and management of the State's water resources.

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Prepared by W.A. Hobba, Jr., U.S. Geological Survey, and K.E. Suder, West Virginia Geological and Economic Survey

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 603 Morris Street, Charleston, WV 25301

WISCONSIN
Water Supply and Use

Wisconsin is a water-rich State that has Lake Michigan, Lake Superior, and the Nation's largest river, the Mississippi, forming parts of its border. The surface-water resources include 33,000 miles of streams and 15,000 lakes. The ground-water supply, most of which is potable, is abundant; about 1.2 quadrillion gallons, or an amount approximately equivalent to one-third the amount of water in Lake Superior, is stored as ground water.

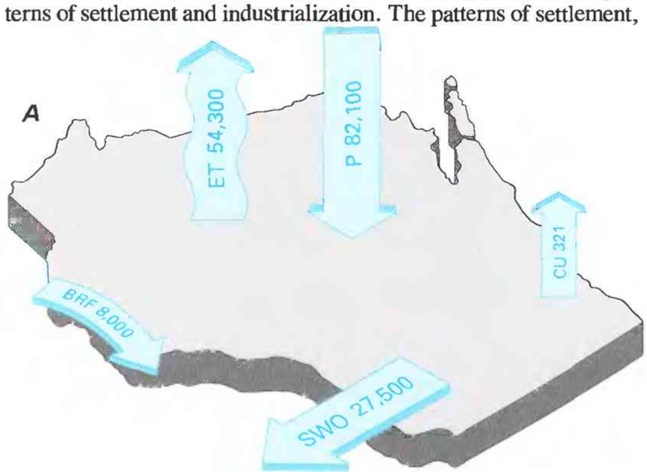
The water resources are renewed continuously by precipitation (fig. 1*A*). Long-term average precipitation is 31 inches per year, or 82,100 Mgal/d (million gallons per day), of which 54,300 Mgal/d returns to the atmosphere by evapotranspiration. Most of the remaining water (27,500 Mgal/d) finds its way into streams or ground-water reservoirs. Another 321 Mgal/d of water is accounted for by consumptive use. Boundary-river flow is about 8,000 Mgal/d, of which 714 Mgal/d is withdrawn for thermoelectric power generation.

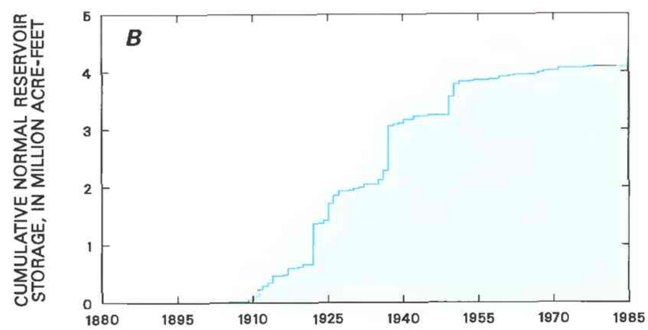
Withdrawals during 1985 were 6,740 Mgal/d—6,170 Mgal/d was surface water, and 570 Mgal/d was ground water. Thermoelectric power generation accounts for 80.7 percent of the water withdrawn (5,440 Mgal/d). One percent of the water used for thermoelectric power generation is consumed. Nearly all the water used for thermoelectric power generation is from surface-water sources. Withdrawals for other major water-use categories accounted for about 19 percent of all water used during 1985. These include withdrawals for domestic and commercial use of 510 Mgal/d, for industrial use of 614 Mgal/d, and for agricultural use of 174 Mgal/d.

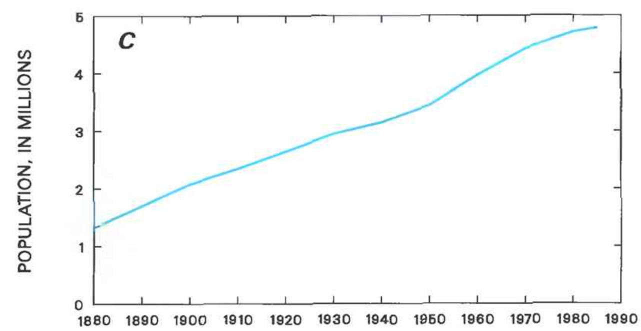
Water-resources development has increased as population has increased. The cumulative normal reservoir storage increased from near zero in 1910 to about 4 million acre-feet in 1950 (fig. 1*B*). Population has increased steadily since 1880 (fig. 1*C*). About 4.8 million people reside in Wisconsin, most of whom live in southeastern Wisconsin (fig. 1*D*). The largest quantities of water are withdrawn from areas of the major population centers (figs. 2*A*, *B*).

HISTORY OF WATER DEVELOPMENT

The development of water resources closely parallels the patterns of settlement and industrialization. The patterns of settlement,







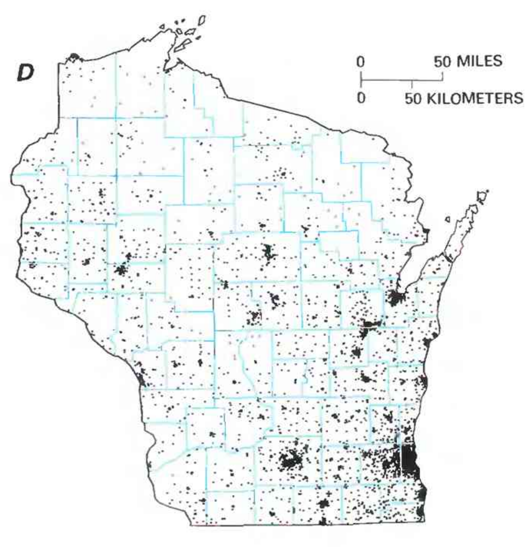


Figure 1. Water supply and population in Wisconsin. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **BRF**, boundary-river flow; **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWO**, surface-water outflow. (Sources: *A*, Data from U.S. Geological Survey files and National Oceanic and Atmospheric Administration. *B*, U.S. Army Corps of Engineers, 1981a. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

industrialization, and water-resources development were established from 1840 to 1940.

Wisconsin's population grew from about 31,000 people in 1840 to 776,000 in 1860—an increase of more than 2,400 percent. Steamships operating on the Great Lakes and, to a lesser extent, on the Mississippi River provided transportation during this period because Wisconsin was not connected to the Atlantic seaboard by rail until 1855 (Nesbit, 1973, p. 147-148). The population, therefore, was centered generally along the lower Lake Michigan shoreline from present day Ozaukee County toward Milwaukee in the south; smaller hubs of settlement were in the southwestern lead-mining region and along the Mississippi River (Nesbit, 1973, p. 319).

Later, settlers spread inland from the Lake Michigan shoreline and settled along the State's interior southern waterways; this pattern of settlement is reflected by the present population distribution (Raney, 1963, p. 138-142) (fig. 1*D*). Reliable sources of water power also were important to the growth of shoreline and interior population centers (Nesbit, 1973, p. 333-334).

The first substantial commercial navigation projects were undertaken in major ports of the Great Lakes between 1850 and 1910. Port development and harbor dredging were necessary to accommodate the deeper draft vessels that were bringing the settlers to Wisconsin's shores and carrying agricultural and industrial exports to markets. The first commercial navigation project was undertaken in 1852 in Milwaukee. Other early projects (10 of the 14 existing Great Lakes harbors) were completed between 1866 and 1882. Many of these projects were expanded during the first 40 years of the 20th century to meet the demand for shipping and the increasing size of the lake ships. The Mississippi River's first major commercial navigation project along the Wisconsin border—the 9-foot Channel Project—did not begin operation until 1940 (U.S. Army Corps of Engineers, 1981a, p. 43).

Lumber and flour mills, which were the dominant industries from 1865 to 1900, were dependent on available water power (Nesbit, 1973, p. 334). The 117 flour mills estimated to be in operation in 1849 increased to 705 by 1879 and reflected the prevalence of wheat production during that period. Flour milling was Milwaukee's leading industry until almost 1880 and peaked about 1892 (Raney, 1963, p. 223-224). The lower Fox River in Winnebago, Outagamie, and Brown Counties was an early source of power for lumber and flour milling; the cities of Neenah and Menasha, both in Winnebago County, had 13 operating mills by 1870 (Nesbit, 1973, p. 333). Other cities where flour milling was important included Racine and Madison (Raney, 1963, p. 224). However, by the end of the 19th century, wheat was being produced in more western areas, and flour milling declined throughout the State. The successor to the lumber and flour industries along the lower Fox River was the paper industry (Nesbit, 1973, p. 333-334).

The first paper mill in the State began operation in 1848 in the Southwestern Lake Michigan basin. Large-scale papermaking began on the lower Fox River in the Northwestern Lake Michigan basin. The lower Fox River's first paper mill was opened in 1865; the first woodpulp mill began operation in 1871 at Appleton (Nesbit, 1973, p. 334). The paper industry along the lower Fox River was expanding rapidly by the end of the 19th century.

The paper industry along the Wisconsin, Chippewa, and Menominee Rivers developed largely from 1900 to 1930. Unlike the lower Fox River paper mills that commonly were converted from flour mills, the paper mills on these northern rivers were built mainly by the lumber industry interests. By 1900, the paper and pulp industry had risen to eighth place among State industries; the value of the product had increased almost 10 times since 1880 (Nesbit, 1973, p. 334). The industry continued to grow throughout the first 40 years of the 20th century and became a leading industry in the State.

From 1880 to 1930, settlers began to harness the water power of the State's major rivers for energy. The Nation's first hydroelectric facility began operating in Appleton in 1882 (Raney, 1963, p. 331). Many dams and control structures on the Wisconsin River, originally built as early as 1846 for log booming and sawmill operations, were converted into hydroelectric generating facilities. Numerous new hydroelectric generating facilities also were built in the Wisconsin, the Chippewa, and the Northwestern Lake Michigan basins (Federal Power Commission, 1965, 1969, 1970). Hydroelectric power provided about 50 percent of Wisconsin's electricity by 1928; this amount decreased to about 9 percent by 1968 (Nesbit, 1973, p. 505). More than 400 hydroelectric generation dams were operating by 1934.

No central public-supply systems were constructed before the 1870's; residents of major cities, such as Milwaukee, secured domestic water from springs and wells much as their rural counterparts did. A temporary pumping station began distributing water from the Milwaukee River through newly laid mains to some of Milwaukee's residents in 1873; this was the first public-supply system in the State. In 1874, a permanent station, which diverted water from Lake Michigan through a 2,000-foot-long intake pipe, was built. Citywide public-supply systems were established between 1880 and 1900 and commonly began as private business enterprises. By 1935, public supplies served 318 communities. About two-thirds of these systems derived water from deep wells, and most others derived water from shallow wells (Raney, 1973, p. 329). Along the shores of the Great Lakes and Lake Winnebago, only a few cities depended on surface water for their supplies. This pattern remains largely unchanged.

WATER USE

The water resources of the State are renewed continuously, and only a small part of available water is consumed (fig. 1*A*). During 1985, 6,740 Mgal/d of water was withdrawn, and 4.8 percent of this amount was consumed. Of the water withdrawn, 91.5 percent (6,170 Mgal/d) was surface water.

The largest use of water amounted to about 63,600 Mgal/d for generating hydroelectric power. Hydroelectric power generation is considered an instream use and is not classified as a withdrawal. The larger hydroelectric plants are located along the Wisconsin and the Chippewa Rivers. Hydroelectric power generation provides about 5 percent of the State's total energy needs. The largest offstream use (5,440 Mgal/d) is for thermoelectric power generation, which is supplied by surface water; little water for this use is consumed (1.0 percent).

Lake Winnebago and the Great Lakes that border Wisconsin provide most of the surface water used, and three principal aquifers provide most of the ground water used. The distribution of total withdrawals, surface-water withdrawals, and ground-water withdrawals for 1985 are shown by county in figure 2. During 1985, Milwaukee and Manitowoc Counties withdrew the largest amounts of freshwater, most of which was surface water (figs. 2*A*,*B*). Dane County withdrew the largest amount of ground water (fig. 2*C*). Withdrawals during 1985 are shown by principal drainage basin and principal aquifer in figures 3*A* and 3*B*. The greatest amounts of freshwater were withdrawn from the Northwestern and Southwestern Lake Michigan basins (fig. 3*A*). The three principal aquifers (fig. 3*B*) are the unconsolidated sand and gravel, the sandstone, and the Silurian dolomite. The unconsolidated sand and gravel aquifer provided the largest amount of freshwater (297 Mgal/d), most of which was used for irrigation (150 Mgal/d). The sandstone and the Silurian dolomite aquifers were used primarily for public supply and domestic supply, respectively (fig. 3*B*).

The sand-and-gravel aquifer mantles much of the State. Yields generally are less than 100 gal/min (gallons per minute) but may be more than 1,000 gal/min in the central part of the State. The Silurian dolomite aquifer is present only along the eastern shore of Lake Michigan. Water yields from this aquifer depend on the number of fractures and solution openings intersected by a well and the thickness of the aquifer. Well yields of 1,000 gal/min or more are recorded in files of the Wisconsin Department of Natural Resources. The Silurian aquifer is underlain entirely by the sandstone aquifer. The sandstone aquifer is present in the southern two-thirds of the State and is largely sandstone but includes beds of dolomite and siltstone. From north-central Wisconsin, the sandstone aquifer thickens to the east, south, and west. Where the aquifer is thick, as in the southeast, well yields can exceed 1,000 gal/min.

The Precambrian aquifer is not a principal aquifer but may provide some freshwater where other sources are not available. The Precambrian aquifer is present throughout the State and underlies the principal aquifers. The aquifer generally consists of crystalline rocks. Small water yields (about 10 gal/min) can be obtained in areas where the rock is fractured.

The source, use, and disposition of freshwater during 1985 are shown diagrammatically in figure 4. The quantities of water given in the figure and elsewhere in this report may not add to the totals indicated because of independent rounding. The source data indicate that 6,170 Mgal/d of surface water was withdrawn during 1985. The source data also indicate that the 6,170 Mgal/d of surface water was the source for the following categories: 4.9 percent (301 Mgal/d) was withdrawn by public suppliers, 6.9 percent (424 Mgal/d) was self-supplied for industrial purposes, 88.2 percent (5,440 Mgal/d) was self supplied for thermoelectric power generation, and 0.1 percent (5.1 Mgal/d) was self-supplied for agriculture. In addition to the 301 Mgal/d of surface water, public suppliers also withdrew 275 Mgal/d (47.7 percent) of ground water. Of this total, 73.4 percent was delivered to domestic and commercial users, and 26.6 percent was delivered to industrial users. The use data indicate that 7.6 percent (510 Mgal/d) of all water withdrawn was for domestic and commercial use, 9.1 percent (614 Mgal/d) was for industrial use, 80.7 percent (5,440 Mgal/d) was for thermoelectric power generation, and 2.6 percent (174 Mgal/d) was for agricultural purposes. Of the 614 Mgal/d used for industrial purposes, 69.0 percent (424 Mgal/d) was from self-supplied surface water, 24.9 percent (153 Mgal/d) was from public supply, and 6.2 percent (38 Mgal/d) was from self-supplied ground water. The disposition data indicate that 4.8 percent (321 Mgal/d) of all water withdrawn was consumed and that 95.2 percent (6,420 Mgal/d) was returned to natural water sources. Of the 4.8 percent that was consumed, 16.3 percent (52 Mgal/d) was by domestic and commercial use, 17.9 percent (58 Mgal/d) was by industrial use, 17.0 percent (54 Mgal/d) was by thermoelectric use, and 48.8 percent (157 Mgal/d) was by agricultural use.

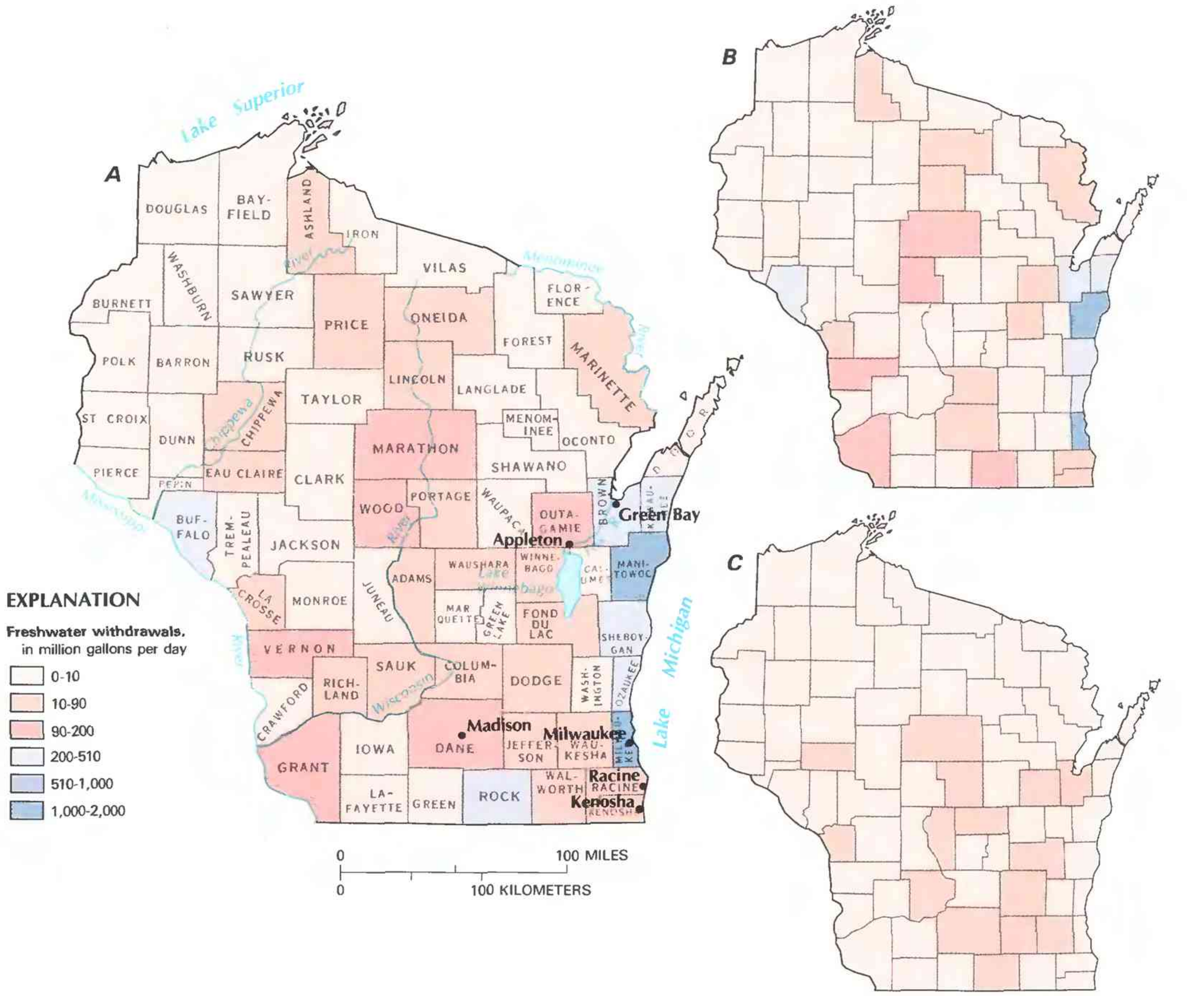
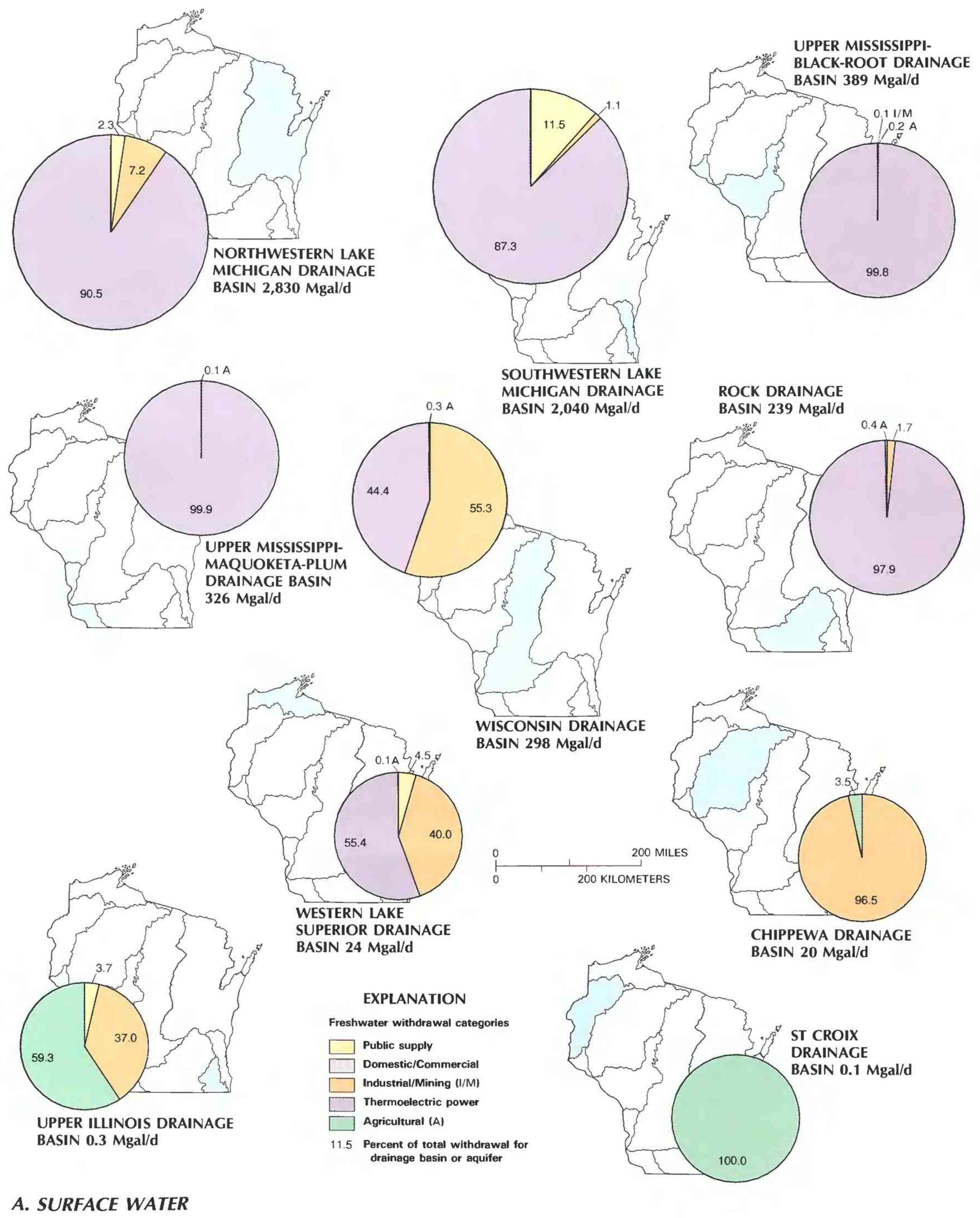
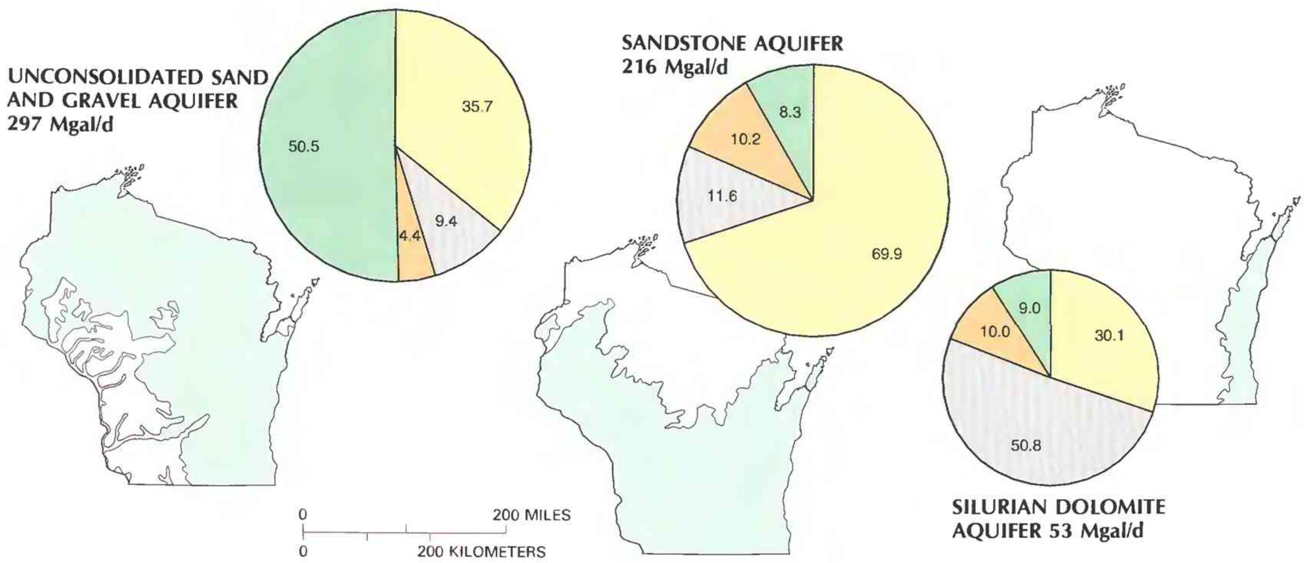


Figure 2. Freshwater withdrawals by county in Wisconsin, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)



A. SURFACE WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Wisconsin, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)



B. GROUND WATER

Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Wisconsin, 1985—Continued.

Public Supply

Public suppliers delivered 576 Mgal/d of freshwater during 1985 (fig. 4). Of this total, surface water accounted for 301 Mgal/d, and ground water accounted for 275 Mgal/d. Public supplies served about 3.13 million people, or about 65 percent of the population. Most of the largest cities—Milwaukee, Racine, Kenosha, and Green Bay—use Lake Michigan for their public-water supply. Milwaukee County is the largest public supplier of surface water (198 Mgal/d). All counties using surface-water sources for public supply are adjacent to Lakes Michigan, Superior, or Winnebago (fig. 2*B*). All other counties rely on ground water for public supply. Dane County has the largest withdrawals of ground water for public supply (42 Mgal/d).

Domestic and Commercial

Of the 510 Mgal/d of water used during 1985 for domestic and commercial purposes, 82.8 percent (422 Mgal/d) was delivered from public-supply systems and includes 155 Mgal/d of conveyance losses; the remaining 17.2 percent (88 Mgal/d) was self-supplied ground water (fig. 4).

Of a total of 253 Mgal/d of surface and ground water withdrawn and delivered for domestic purposes, 169 Mgal/d was delivered by public suppliers. The remaining 84 Mgal/d was self-supplied ground water. This quantity represents 54 gallons per day per capita for public-supplied domestic use based on the average per-capita use for 10 communities of differing size and location.

Public supply deliveries for commercial use were 98 Mgal/d. About 4 Mgal/d of ground water was self-supplied for commercial purposes.

Industrial and Mining

Of the 614 Mgal/d used for industrial purposes during 1985, 24.9 percent (153 Mgal/d) was public-supplied water, 69.0 percent (424 Mgal/d) was self-supplied surface water, and 6.2 percent (38 Mgal/d) was self-supplied ground water (fig. 4). Consumptive use was estimated to be 9.4 percent (58 Mgal/d) of withdrawals and deliveries. There is no mining in the State.

Major industrial areas are located along the southwestern coast of Lake Michigan and along the lower Fox River. Paper mills also are present along the Wisconsin, the Chippewa, and the Menominee Rivers. The principal intensive water-use industries include paper manufacturing, cheese making, and breweries.

Thermoelectric Power

A total of 5,440 Mgal/d of surface water was withdrawn during 1985 for thermoelectric power generation (fig. 4). Only 1.0 percent was consumed because most of this water is used for once-through cooling, and the remainder is returned to natural water sources. Of the 22 operating thermoelectric powerplants, 2 use nuclear power and 20 use fossil fuel. These plants generate 95 percent of the State's electricity.

Agricultural

About 174 Mgal/d of water was withdrawn for agricultural purposes (fig. 4). Of this total, about 84 Mgal/d of water was withdrawn to irrigate mainly potatoes, corn, and snap beans. All irrigation reported is of the sprinkler type. Ground water accounts for about 97 percent of the water withdrawn for irrigation. The greatest density of irrigators is in central Wisconsin. About 250,000 acres of land are irrigated, and almost all water withdrawn for irrigation is from the sand and gravel aquifer.

Consumptive use for irrigation was estimated to be 84 Mgal/d, or 100 percent of the total amount withdrawn for irrigation. The assumption is made that irrigators are applying water at a rate equivalent to evapotranspiration. However, irrigation consumptive use probably is less than 100 percent because some water is lost during conveyance and some irrigators apply excessive amounts of water; these amounts of water are difficult to measure but may be significant in some instances. Weeks and Stangland (1971, p. 36) reported that the consumptive water use for irrigation in central Wisconsin is 70 percent. Consumptive water use has increased with improved irrigation practices. David Curwen (University of Wisconsin-Extension, oral commun., 1987) estimates that the consumptive water use for irrigation is about 85 percent.

About 90 Mgal/d of water was withdrawn for other agricultural purposes, such as livestock watering. The consumptive use for nonirrigation water is 81 percent of this total, or 73 Mgal/d.

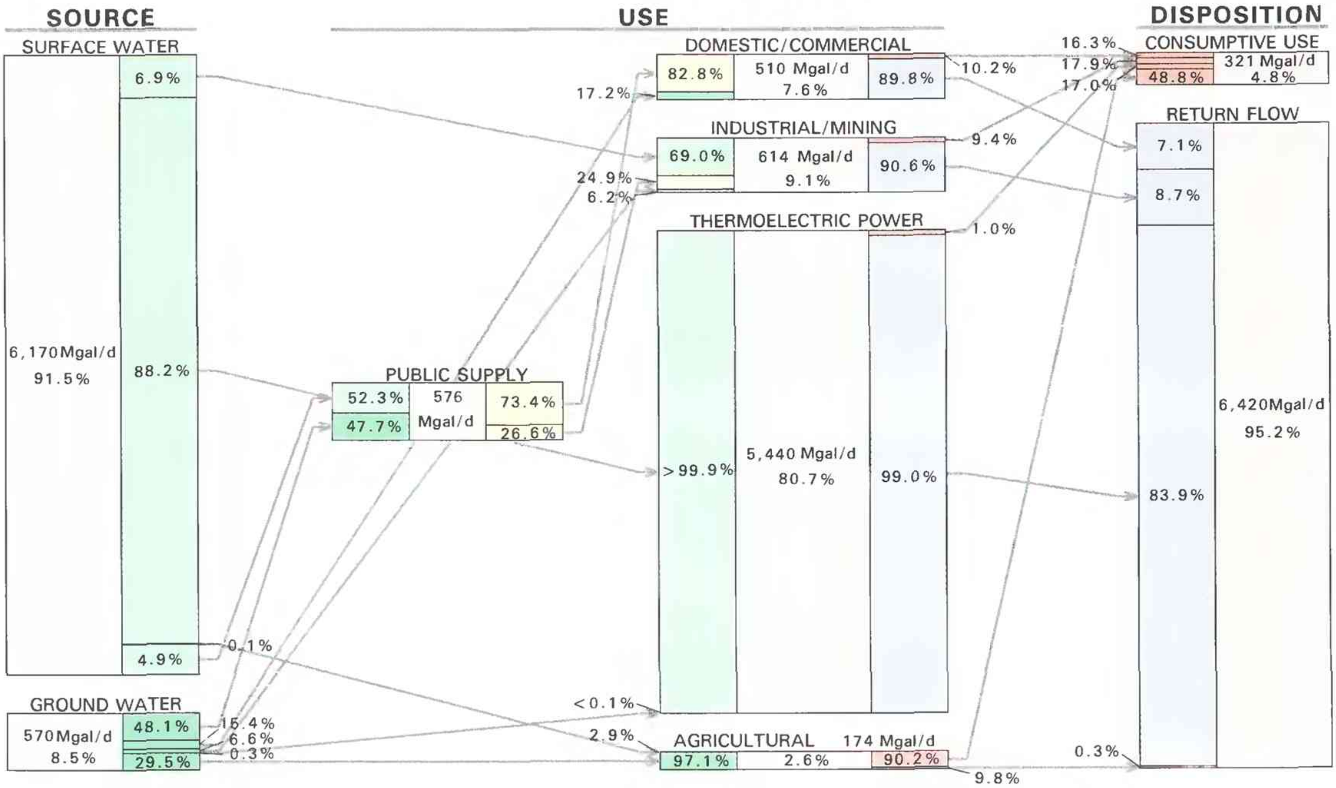


Figure 4. Source, use, and disposition of an estimated 6,740 Mgal/d (million gallons per day) of freshwater in Wisconsin, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. Symbol: < means less than; > means greater than. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

WATER MANGEMENT

Several State agencies, including the Public Service Commission and the Department of Agriculture, Trade, and Consumer Protection, have responsibilities for managing the water resources of Wisconsin. However, the Wisconsin Department of Natural Resources is the lead agency that regulates water-resources protection.

State law has modified the riparian rights concept of surface-water use and the absolute property rights doctrine of ground-water use. Property rights doctrine indicates that all water beneath a property belongs to the landowner.

Wisconsin has long had laws protecting public interest in water resources, but recently enacted legislation is substantially affecting water-management practices. The Wisconsin Water Resources Conservation and Management Act of 1985 (1985 Act 60) directs the Wisconsin Department of Natural Resources to respond to water-use conflicts. Act 60 was enacted because of concerns expressed by the Council of Great Lakes Governors about water use in the Great Lakes Basins. Comprehensive ground-water legislation (1983 Act 410) includes protection strategy and general rules for quality. Act 410 was enacted because of increased concern about protecting ground water from contamination.

Act 60 is the first major Wisconsin law to focus on water quantity. It requires the Wisconsin Department of Natural Resources to collect and assess data on all major water withdrawals and consumptive uses, to examine relations between ground and surfacewater, and to conduct a broad analysis of the relation between water quantity and quality for water-resource planning. Act 60 also directs the Wisconsin Department of Natural Resources to coordinate water-resource activities with other Great Lake States and with the Canadian provinces of Quebec and Ontario. These activities include a common water-use data base, a research program, and a process that ensures regional consultation before action by a Great Lakes State on an interbasin diversion proposal (Wisconsin Department of Natural Resources, 1986, p. 59).

Act 410 provides for establishing standards for ground-water quality and funds for replacing contaminated water supplies and associated environmental repair. The law also is designed to develop a water-quality monitoring network and to certify privately operated laboratories to analyze samples for ground-water quality. The Ground-Water Coordinating Council of State Agencies was created as part of Act 410. The Council helps State agencies coordinate their nonregulatory ground-water related activities and serves as a forum for exchange of ground-water information (Wisconsin Department of Natural Resources, 1986, p. 60–62).

In addition to Act 410, other regulations related to ground water are in effect. Injection of waste into wells is prohibited. Septic-system installers and well drillers must be licensed, and all large-capacity wells, public supply and private, must have permits.

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Center-pivot irrigation system in Gary Bula Valley, Adams County, Wisconsin. (Photograph by B.R. Ellefson.)

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Prepared by J.T. Krohelski, B.R. Ellefson, and K.S. Rury, U.S. Geological Survey; History of Water Development section by A.K. Shea, Wisconsin Department of Natural Resources

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 6417 Normandy Lane, Madison, WI 53719

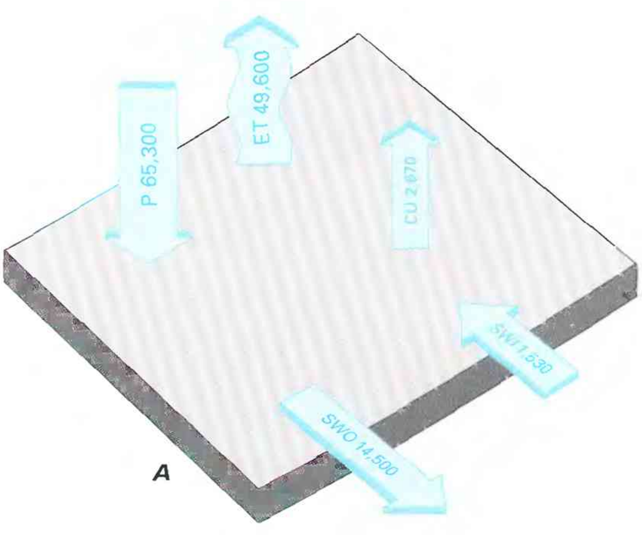
WYOMING
Water Supply and Use

Wyoming is a "headwaters" State; most available water originates within the State, and flows out in all directions into the Missouri, the Snake, the Great, and the Colorado River basins. The annual average precipitation is 14 inches, which ranks Wyoming 48th in the Nation (Geraghty and others, 1973). Annual precipitation ranges from about 7 inches in some areas of the plains in eastern Wyoming and in some intermontane basins to about 40 inches in the mountainous regions (U.S. Geological Survey, 1986, p. 493). During 1985, about 6,200 Mgal/d (million gallons per day) of freshwater was withdrawn from rivers, streams, and aquifers—an average equivalent of about 12,200 gal/d (gallons per day) per capita. Of that quantity, about 2,670 Mgal/d was consumed (fig. 1*A*) and unavailable for further use, and 3,520 Mgal/d was returned to the natural water source where it became available for reuse.

Surface water is the primary source of water supply; however, ground water is used where a sufficient surface-water supply is not available or needs to be supplemented. Surface water is a dependable source of water only along perennial mountain streams and the larger rivers and where surface-water reservoir storage is provided. Use of these surface-water supplies, however, is strictly limited by seven interstate compacts and two U.S. Supreme Court decrees. Streams in the plains areas are most commonly ephemeral and do not provide a dependable water supply throughout the year. Ground water is the predominant source of water in the plains areas. Ground water provides the major part of the water used for domestic, industrial, and mining purposes.

Agriculture, including irrigation and nonirrigation (livestock and other farm uses), accounts for 91.5 percent of all freshwater withdrawn (5,670 Mgal/d). Agricultural use accounts for 94.3 percent of all surface water and 60.2 percent of all ground water withdrawn. Consumptive use of freshwater for agriculture accounted for 96.4 percent (2,580 Mgal/d) of the total consumptive use during 1985.

Thermoelectric power generation is the second-largest user of water, but accounted for only 3.8 percent of all water withdrawals during 1985. Water withdrawn for public supply (98 Mgal/d) is distributed for all uses except agricultural. Freshwater withdrawn for domestic, commercial, industrial, and mining uses during 1985 was about 288 Mgal/d, or about 4.7 percent of total water withdrawals. The small percentages are a result of the small population and the absence of large industries that use water. The most com-



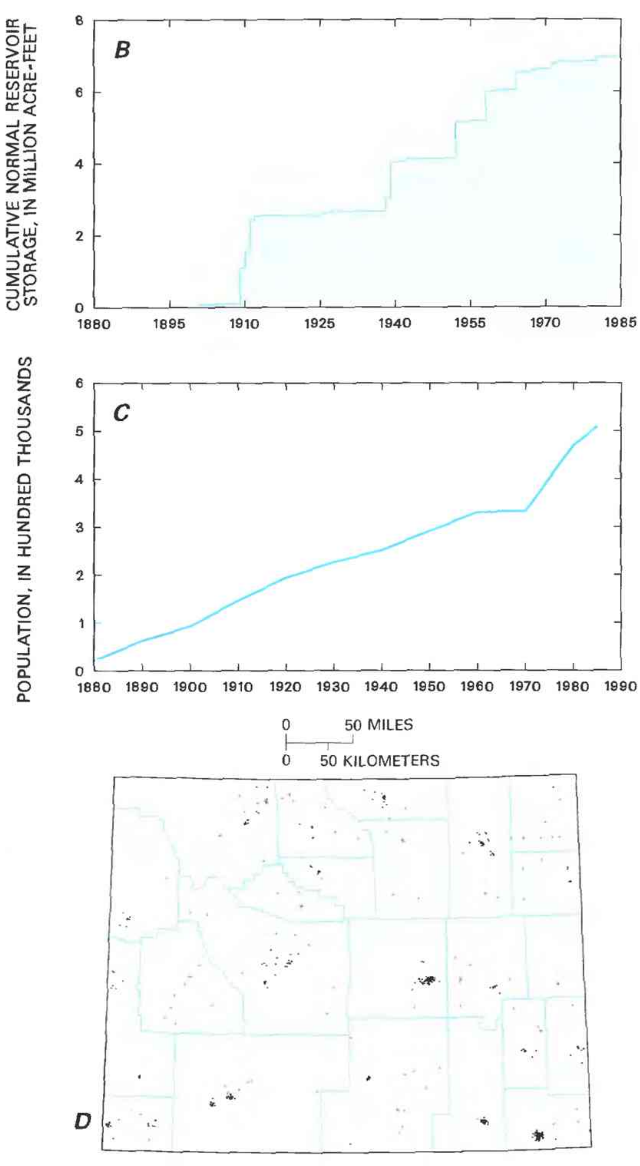


Figure 1. Water supply and population in Wyoming. *A*, Water budget, in million gallons per day. *B*, Cumulative normal storage of reservoirs with at least 5,000 acre-feet capacity, 1880 to 1985. *C*, Population trend, 1880 to 1985. *D*, Population distribution, 1985; each dot on the map represents 1,000 people within a census tract. Abbreviations: **CU**, consumptive use; **ET**, evapotranspiration; **P**, precipitation; **SWI**, surface-water inflow; **SWO**, surface-water outflow. (Sources: *A*, Geraghty and others, 1973. *B*, U.S. Army Corps of Engineers, 1981. *C*, *D*, Compiled by U.S. Geological Survey from U.S. Bureau of the Census data.)

mon industries in Wyoming are related to the extraction and production of minerals, oil, and gas.

From 1980 to 1985, the population of Wyoming increased an estimated 8 percent from 470,000 to 509,000. State officials estimate that the population will increase to about 557,000 by 1995 (Wyoming Department of Administration and Fiscal Control, 1985, p. 4). An increase in population would cause an increase in the demand for water. Under favorable economic conditions, the potential for a large expansion of the mining industry could result in substantial increases in water use. The major water-supply problem is having sufficient water available in the right place at the right time.

HISTORY OF WATER DEVELOPMENT

The availability of water has been vital in the development of Wyoming. Early settlers traveled along the North Platte and the Sweetwater Rivers, where abundant water and grass helped to ease their journey across semiarid Wyoming. Most early settlements were established along perennial streams in the North Platte basin and, later, in the Great Divide–Upper Green and the Bighorn basins.

During the territorial days, agriculture, which was the predominant use of water, was the principal reason for water development, as it is today. The first annual report to the Governor of Wyoming from the Territorial Engineer listed the total irrigated acreage in 1888 at about 1.2 million acres (Elwood Mead, Wyoming Territorial Engineer, letters in files of Wyoming State Engineer's Office, 1888). This acreage was somewhat speculative and was based only on a preliminary inventory by the Territorial Engineer. Although the 1888 estimate of irrigated acreage may include lands not actually irrigated, this magnitude illustrates the early significance of irrigation in Wyoming's history. Estimated irrigated acreage during 1985 was 1.8 million acres, which was based on mapped irrigated acreage actually in use. The mapping of irrigated acreage has been continuous since the late 1960's.

Streamflow became a more dependable source of water for irrigation after the construction of storage reservoirs. Surface-water use initially consisted of streamflow diversions from perennial streams to nearby lands. However, because most runoff occurs during the spring and the early summer, streamflow during the summer became an unreliable source for expanding irrigated acreages. Thus, potentially irrigable farmland and a need for streamflow storage, coupled with demands for electrical power, resulted in the construction of reservoirs (fig. 1*B*). The reservoirs have helped in the development of more reliable surface-water supplies, particularly those streams controlled by interstate compacts and court decrees, by providing carry-over storage from years of large runoff for use during years of drought.

Mining and oil and gas production are industries that have affected water use in Wyoming since territorial days. A major increase in coal mining that occurred during the early 1970's resulted in an increase in population (fig. 1*C*). Increasing population and population distribution (fig. 1*D*) can affect water use and add to the demand for water. The demand for coal has since decreased, and Wyoming's economy, population, and water-use trends reflect depressed conditions.

Ground water has always been an important part in the development of Wyoming, even though it accounted for less than 10 percent of total water use during 1985 (Solley and others, 1988). Much of the water withdrawn for rural domestic and livestock use is provided by ground water. The use of ground water for irrigation also has increased as more efficient pumps and center-pivot sprinklers have made ground-water withdrawals economically feasible.

WATER USE

Wyoming has abundant supplies of water in some areas and scarce supplies in other areas (U.S. Geological Survey, 1984, p. 236). The availability of surface water dictates the distribution of surface- and ground-water use across the State. Total freshwater, surface-water, and ground-water withdrawals are presented by county in figures 2*A*, 2*B*, and 2*C*, respectively. Large surface-water withdrawals (fig. 2*B*) primarily indicate areas where surface water is used extensively for irrigation.

The distribution of surface- and ground-water withdrawals by county (figs. 2*B,C*) also primarily reflects the availability of surface water. Surface water is the primary source of water supply; however, ground water is used when a sufficient surface-water supply is not available or when surface water needs to be supplemented. Of all the major river basins (fig. 3*A*), the Bighorn and the North Platte have the largest surface-water withdrawals; agriculture (irrigation) is the predominant use of water in both basins. Ground-water withdrawals are largest in southeastern Wyoming, where agricultural (irrigation) use accounts for about 89 percent of the water withdrawn from the High Plains and equivalent aquifers (fig. 3*B*).

The source, use, and disposition of freshwater are shown diagrammatically in figure 4. The quantities of water given in this figure and elsewhere in this report may not add to the totals indicated because of independent rounding. Saline water is not included in figure 4. The source data indicate that the 5,700 Mgal/d of surface water withdrawn was 91.9 percent of the total surface- and ground-water withdrawals in Wyoming. Of that amount, 0.9 percent was diverted for public-supply systems, 0.1 percent was directly withdrawn (self-supplied) for domestic and commercial uses, 0.8 percent was self-supplied by industrial and mining facilities, 3.9 percent was withdrawn for thermoelectric power generation, and 94.3 percent was withdrawn for agricultural use. The use data indicate that domestic and commercial use represented 2.0 percent of the State's total use. Of that 2 percent, 75.4 percent was from public-supply systems, 6.8 percent was from surface-water sources, and 17.8 percent was from ground-water sources. About 26.9 percent (33 Mgal/d) of the water withdrawn for domestic and commercial use was consumed, and 73.1 percent (90 Mgal/d) was returned to a natural water source. The disposition data indicate that 43.1 percent (2,670 Mgal/d) of all water withdrawn was consumed and 56.9 percent (3,520 Mgal/d) was returned to a natural source.

Instream use of water for hydroelectric power generation is significant in Wyoming, although consumptive use is very small. The U.S. Bureau of Reclamation has constructed many large-capacity reservoirs on major streams for the primary purpose of power generation. During 1985, 6,440 Mgal/d was used to generate about 1,070 gigawatthours of electricity. Instream uses of water, such as hydropower generation, are not included in the data in figure 4.

The instream use of water for recreational purposes also is significant in Wyoming. The reservoirs throughout Wyoming are used extensively for water sports and fishing. Perennial streams and rivers also are important fisheries for the tourism industry.

PUBLIC SUPPLY

Public-supply systems withdraw, treat, and deliver water to users. Public-supply withdrawals accounted for less than 2 percent of total freshwater withdrawals. The population of Wyoming was ranked 50th in the Nation in 1985 (Solley and others, 1988); the two largest cities, Casper and Cheyenne, have populations of about 50,000 each. Thus, water use for public supply in Wyoming is small compared to more populated and urbanized States.

Water withdrawals for public supply increased from 82 Mgal/d during 1980 to 98 Mgal/d during 1985. The primary source of withdrawal for public supply depends on whether surface water or ground water is readily available at any particular location.

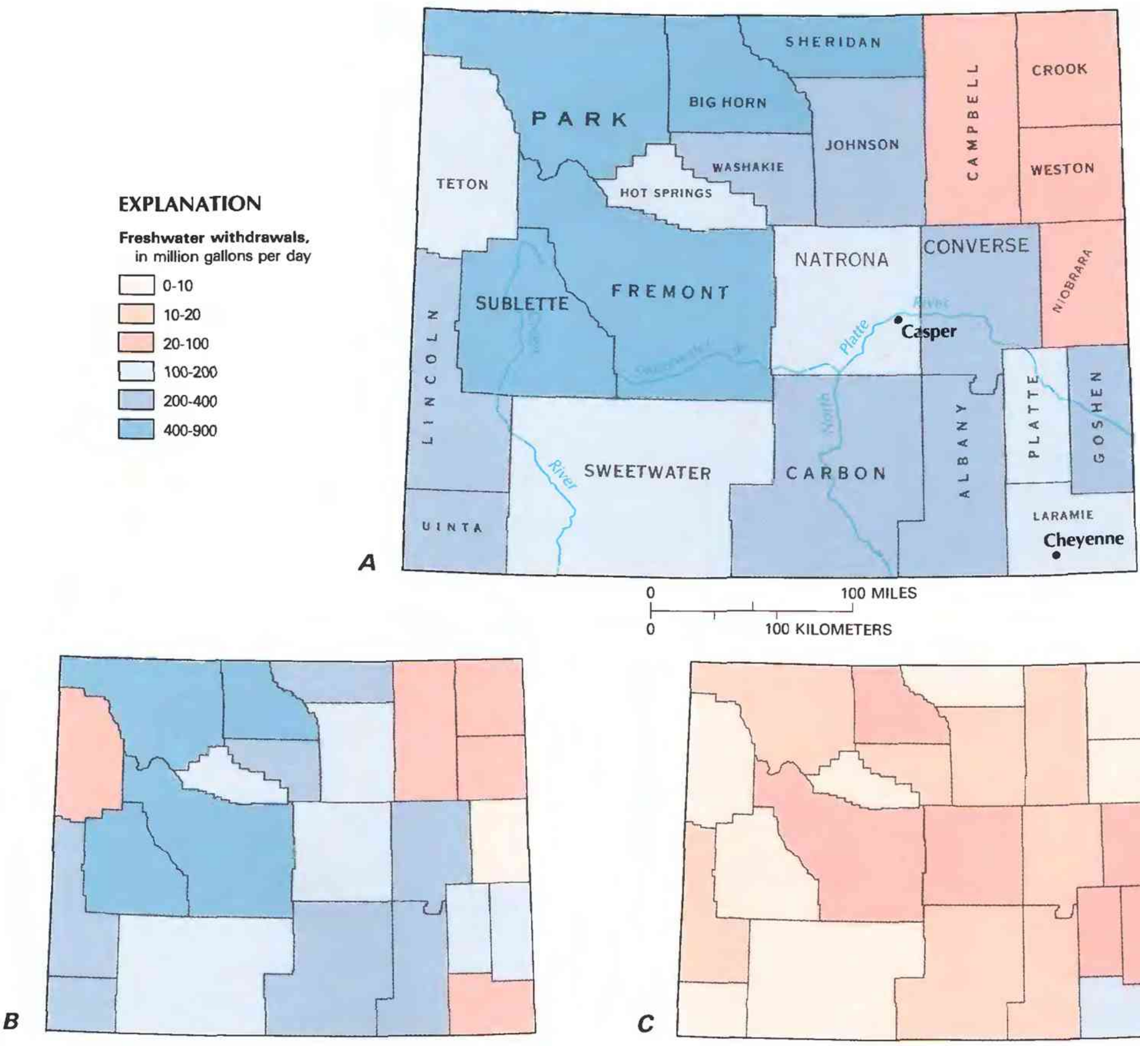


Figure 2. Freshwater withdrawals by county in Wyoming, 1985. *A*, Total withdrawals. *B*, Surface-water withdrawals. *C*, Ground-water withdrawals. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

Domestic and Commercial

During 1985, domestic and commercial use of water from public-supply systems and self-supply facilities totaled 123 Mgal/d (fig. 4). This total includes about 18 Mgal/d of water used for fire fighting, street washing, municipal parks and pools, and conveyance losses in public-supply systems.

Domestic use during 1985 was about 74 Mgal/d; of that quantity, 61 Mgal/d was from public-supply systems that served 65 percent of the population and 13 Mgal/d was self-supplied by 35 percent of the population. Domestic water use from public-supply systems during 1985 was 185 gal/d per capita; self-supplied domestic use was about 75 gal/d per capita (Solley and others, 1988). Total consumptive use for domestic purposes was about 30 Mgal/d.

Commercial use during 1985 was about 31 Mgal/d, of which 14 Mgal/d was provided by public-supply systems and 17 Mgal/d was self-supplied. Consumptive use was 3 Mgal/d, which was less than 1 percent of the total consumptive use in Wyoming.

Industrial and Mining

During 1985, industrial and mining (including oil and gas) freshwater use was 165 Mgal/d (fig. 4). About 8 Mgal/d of ground water and about 4 Mgal/d of surface water were self-supplied for industrial activities (other than mining). About 39 Mgal/d of surface water, 111 Mgal/d of fresh ground water, and 22 Mgal/d of saline ground water were self-supplied for mining activities. Consumptive freshwater use for all industrial and mining activities was 26 Mgal/d; the quantity of saline water consumed was negligible.

Industrial and mining water use account for 2.7 percent of total freshwater use. The limited industry that does exist in Wyoming is related primarily to the extraction and the production of coal, trona, uranium, oil, and gas.

Thermoelectric Power

Water used to generate thermoelectric power accounts for only a small part (3.8 percent) of total water use; however, it is the second-largest category of use within the State. Several large fossil-fueled power-generating facilities have been built in recent years because of large available supplies of coal. During 1985, eight thermoelectric fossil-fueled powerplants used water totaling 238 Mgal/d for cooling purposes (fig. 4). Of this quantity, 224 Mgal/d was surface water, 12 Mgal/d was ground water, and 2 Mgal/d was supplied by a public-supply system. Consumptive use of water by fossil-fueled

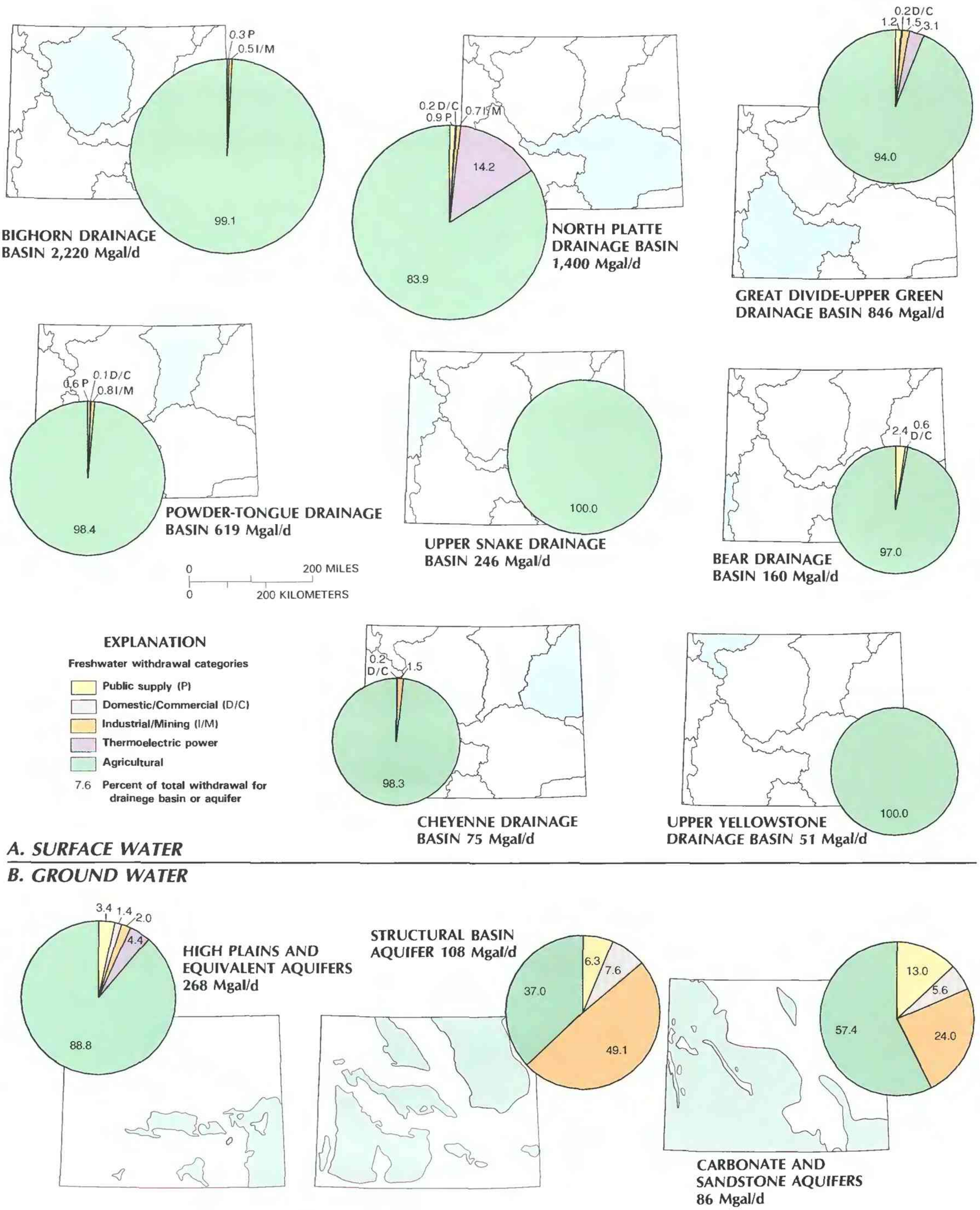


Figure 3. Freshwater withdrawals by category of use and hydrologic unit in Wyoming, 1985. *A,* Surface-water withdrawals by principal drainage basin. *B,* Ground-water withdrawals by principal aquifer. Abbreviation: Mgal/d is million gallons per day. (Sources: *A,* Drainage basins from Seaber and others, 1987; data from U.S. Geological Survey National Water Data Storage and Retrieval System. *B,* Data from U.S. Geological Survey files.)

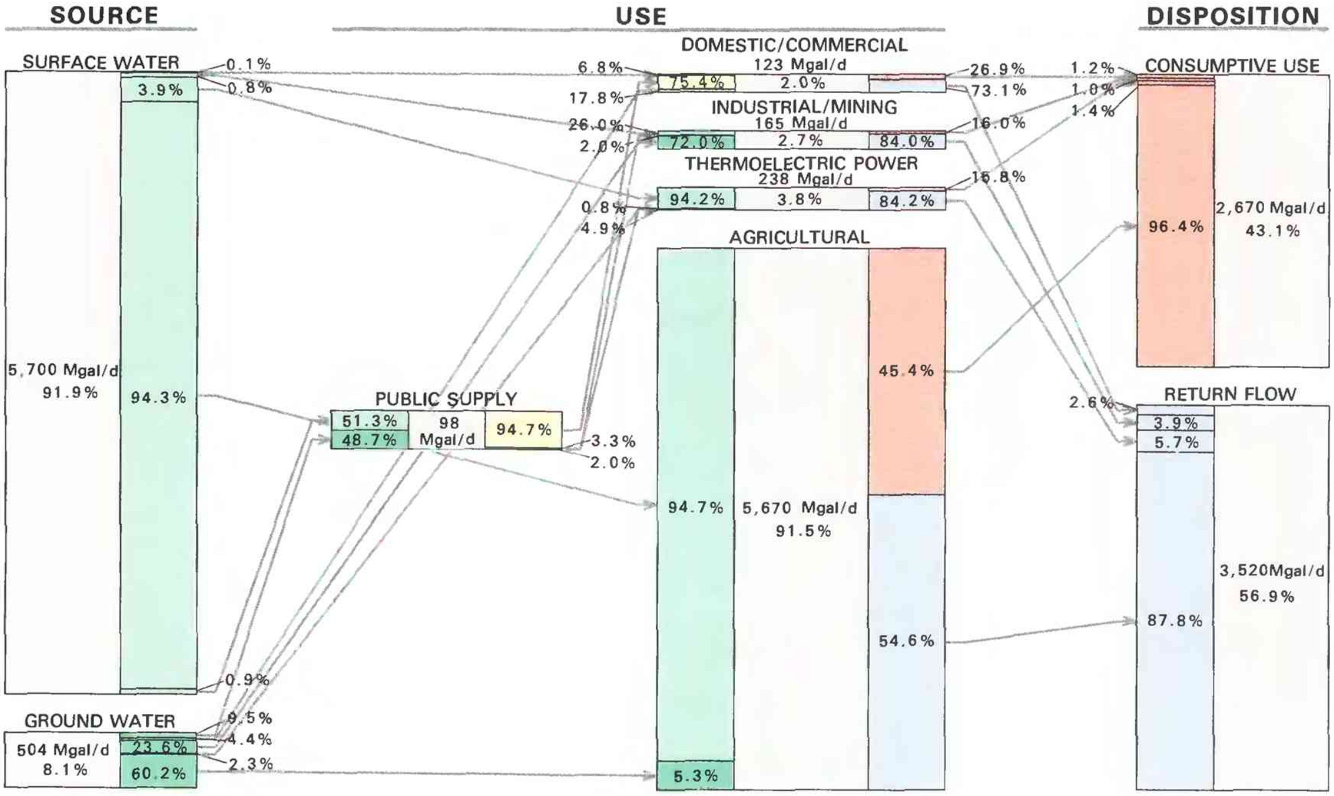


Figure 4. Source, use, and disposition of an estimated 6,200 Mgal/d (million gallons per day) of freshwater in Wyoming, 1985. Conveyance losses in public-supply distribution systems and some public water uses, such as fire fighting, are included in the total shown for domestic and commercial use; losses in irrigation distribution systems are included in the total shown for agricultural return flow. All numbers have been rounded and values may not add to totals. Percentages are rounded to the nearest one-tenth of 1 percent (0.1%) between 0.1 and 99.9 percent. (Source: Data from U.S. Geological Survey National Water Data Storage and Retrieval System.)

plants was 38 Mgal/d, or 1.4 percent of the total consumptive water use in the State.

AGRICULTURAL

Agriculture uses the largest quantities of water in Wyoming. During 1985, agriculture accounted for 94.3 percent of surface-water withdrawals and 60.2 percent of ground-water withdrawals (figs. 4, 5). Nearly all agricultural use of water during 1985 was for irrigation. Nonirrigation withdrawals totaled 16 Mgal/d compared to about 5,676 Mgal/d withdrawn for irrigation (fig. 5).

Most irrigation occurs along the perennial streams and rivers, where surface-water supplies are available. In southeastern and east-central Wyoming, ground water is an important source of irrigation water. In these areas, only small quantities of surface water are available, but ground water is available in sufficient quantities to support irrigation.

Agricultural water use for livestock and other farm purposes was about 16 Mgal/d in 1985. Of the total quantity withdrawn during 1985, 13 Mgal/d was from surface-water sources, and 3 Mgal/d was from ground-water sources. Consumptive use by these activities is estimated to be nearly 100 percent.

WATER MANAGEMENT

Surface- and ground-water withdrawals are regulated and administered under the "prior appropriations" doctrine by the Office of the Wyoming State Engineer. The basis of this doctrine is "first in time is first in right" (U.S. Geological Survey, 1986). In 1909, the State legislature established preferred uses for Wyoming water—domestic and stock water; public supply; water for steam engines

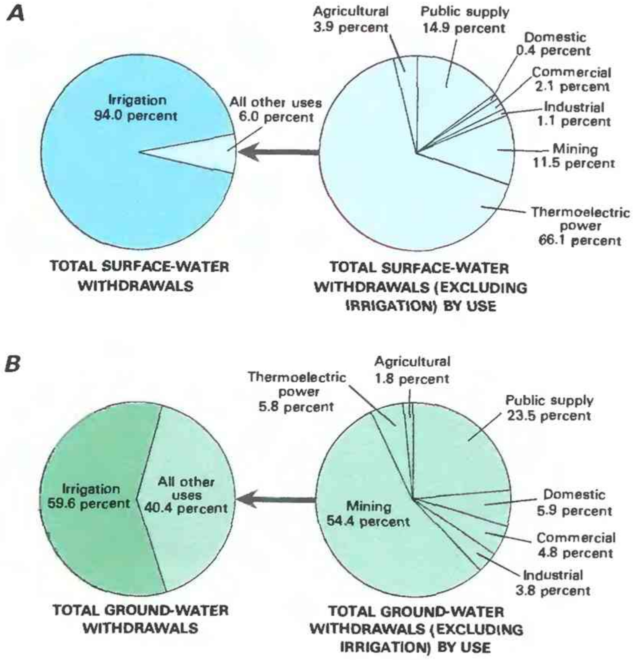


Figure 5. Freshwater use by categories in Wyoming, 1985. *A*, Surface-water withdrawals. *B*, Ground-water withdrawals. (Source: *A*, *B*, Data from the U.S. Geological Survey National Water Data Storage and Retrieval System.)

and general railway use, culinary, laundry, bathing, refrigeration, steam- and hot-water-heating plants, and steam powerplants; industry; irrigation; and hydropower (Trelease, 1978).

Because Wyoming is a "headwaters" State, the management of surface- and ground-water use is regulated by seven interstate compacts and two U.S. Supreme Court decrees, which specify the quantities of water that may be used within the State and that must be allowed to flow out of the State for downstream use. Nearly all waters in five Wyoming streams have been fully appropriated (Frank Trelease, Wyoming State Engineer's Office, oral commun., 1987).

A permit is required from the Wyoming State Engineer before drilling a well. If conditions warrant, the State Engineer may recommend that an area be designated as a ground-water control area. After due process, new wells may be prohibited within the control area, and withdrawals may be further regulated. The Oil and Gas Conservation Commission regulates the injection of ground water for secondary recovery of petroleum and also regulates the reinjection of water that was produced in conjunction with the oil (U.S. Geological Survey, 1985).

The U.S. Geological Survey routinely monitors streamflow, reservoirs, and ground-water conditions throughout Wyoming. It also provides technical assistance to surface- and ground-water users in cooperation with several State and other Federal agencies.

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Prepared by J.R. Schuetz

FOR ADDITIONAL INFORMATION: District Chief, U.S. Geological Survey, 2617 E. Lincolnway, Suite B, Cheyenne, WY 82001

Supplemental Information

Glossary

Water-Quantity Equivalents and Conversion Factors

Water-Resources Regions and Subregions

GLOSSARY

7-day, 10-year low flow—A discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value on the average once every 10 years.

Acre-foot (acre-ft)—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.

Alluvium—General term for deposits of clay, silt, sand, gravel, or other particulate material deposited by a stream or other body of running water in a streambed, on a flood plain, on a delta, or at the base of a mountain.

Anadromous fish—Migratory species, such as salmon, shad, and striped bass, that are born in freshwater, spend most of their lives in estuary and ocean waters, and return to freshwater to spawn.

Application rate—Rate at which irrigation water is applied per unit area; also, weight of a fertilizer, soil amendment, or pesticide applied per unit area.

Appropriation doctrine—The system of water law dominant in the Western United States under which (1) the right to water was acquired by diverting water and applying it to a beneficial use and (2) a right to water acquired earlier in time is superior to a similar right acquired later in time. Usually under modern statutes, approval must be secured from some State agency before acquiring a new water right or making a change in use of the water.

Aquaculture—Art and science of farming organisms that live in water, such as fish, shellfish, and algae.

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.

Base flow—Sustained low flow of a stream. In most places, base flow is ground-water inflow to the stream channel.

Bedrock—General term for consolidated (solid) rock that underlies soils or other unconsolidated material.

Beneficial use—A use of water that results in appreciable gain or benefit to the user, consistent with State law, which varies from one State to another. All appropriation-law States consider domestic, municipal, agricultural, and industrial uses to be beneficial uses. Some States also recognize instream flow use, such as fish and wildlife and recreation uses, as being beneficial. An underlying principle of the appropriation doctrine is that when water is put to a beneficial use and the user has first priority, the State may issue a water right.

Bolson—Extensive, flat, saucer-shaped, undrained alluvium-floored basin or depression that is almost or completely surrounded by mountains; a term used in the desert regions of Southwestern United States.

Center-pivot irrigation—*See* Irrigation.

Chemigation—Application of pesticides or fertilizers to farmlands through irrigation systems.

Commercial water use—Water for motels, hotels, restaurants, office buildings, commercial facilities, and civilian and military institutions. The water may be obtained from a public supply or be self-supplied. *See also* Public supply; Self-supplied water.

Common law—Those principles, usages, and rules of action applicable to the government and security of persons and property that do not rest for their authority upon any express or positive statute or other written declaration, but upon statements of principles found in the decisions of courts, including the Common Law of England.

Conjunctive water use—Combined use of ground water and surface water.

Consumptive use—That part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment. Sometimes called water consumed or water depletion.

Conveyance loss—Water that is lost in transit from a pipe, canal, conduit, or ditch by leakage or evaporation. Generally, the water is not available for further use; however, leakage from an irrigation ditch, for example, can percolate to a ground-water source and be available for further use.

Cooling tower—A device to remove excess heat from water used in industrial operations.

Cooling water—Water used for cooling purposes, such as of condensers and nuclear reactors.

Delivery/release—The amount of water delivered to the point of use and the amount released after use; the difference between these amounts can be the consumptive use.

Diversion—A turning aside or alteration of the natural course of a flow of water, normally considered physically to leave the natural channel. In some States, this can be a consumptive use direct from a stream, such as by livestock watering. In other States, a diversion must consist of such actions as taking water through a canal, pipe, or conduit.

Domestic water use—Water 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 can be obtained from a public supply or be self-supplied. *See also* Public supply; Self-supplied water.

Drainage basin—Land area drained by a river.

Drip irrigation—*See* Irrigation.

Dryfarming—Practice of crop production without irrigation in semiarid regions usually by using moisture-conserving farming techniques, such as fallowing.

Eminent domain—The authority of the Federal or State government or of an agency or party authorized by the Federal government to condemn for public purposes all private interest in land, after payment of just compensation.

Ephemeral stream—A stream or part of a stream that flows only in direct response to precipitation or snowmelt. Its channel is above the water table at all times.

Eutrophication—Process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.

Evaporation—Process by which water is changed from the liquid or solid state to the vapor state. *See also* Evapotranspiration; Transpiration.

Evapotranspiration—A 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. *See also* Evaporation; Transpiration.

Fallow—Cropland, either tilled or untilled, allowed to lie idle, during the whole or the greater part of the growing season.

Fall Line—Imaginary line or transition zone 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 indicated by waterfalls.

Fecal coliform bacteria—Bacteria that are present in the gut or the feces of warmblooded animals; they are indicators of possible sewage pollution.

Flood irrigation—*See* Irrigation.

Flood plain—A strip of relatively smooth land bordering a stream channel that is overflowed at times of high water.

Free-flowing well—An artesian well in which the potentiometric surface is above the land surface. *See also* Potentiometric surface.

Freshwater—Water that contains less than 1,000 mg/L (milligrams per liter) of dissolved solids; generally, more than 500 mg/L is considered undesirable for drinking and many industrial uses.

Furrow irrigation—*See* Irrigation.

Gigawatt—One thousand megawatts, or one billion watts. Large powerplants often have generating capacity of about 1 gigawatt.

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.

Gravity irrigation—*See* Irrigation.

Gristmill—A mill for grinding grain.

Ground water—Generally, all subsurface water as distinct from surface water; specifically, that part of the subsurface water in the saturated zone (a zone in which all voids, large and small, ideally are filled with water under pressure equal to or greater than atmospheric).

Ground-water mining—An imprecise term commonly used to denote a reduction of storage in an aquifer caused by withdrawals of ground water at a rate in excess of recharge. Groundwater "mining" takes place in different ways in different circumstances. If the term is used, then it should be defined as it pertains to the topic under discussion.

Hydroelectric power—Electrical energy generated by means of a power generator coupled to a turbine through which water passes.

Hydroelectric power water use—The use of water in the generation of electricity at plants where the turbine generators are driven by falling water; an instream use.

In-channel use—*See* Instream use.

Industrial water use—Water used for industrial purposes such as fabricating, processing, washing, and cooling, and includes such industries as steel, chemical and allied products, paper and allied products, mining, and petroleum refining. The water can be obtained from a public supply or be self-supplied. *See also* Public supply; Self-supplied water.

Injection water—Water that is injected into an aquifer or an unsaturated porous formation for storage or disposal.

Instream-flow rights—A doctrine used to preserve minimum river or stream flows for fish and wildlife, recreation, water quality, and scenic beauty, among other public purposes. Such rights are limited to the use of water within its natural course; not requiring diversion.

Instream use—Water use taking place within the stream channel for such purposes as hydroelectric power generation, navigation, water-quality improvement, fish propagation, and recreation. Sometimes called nonwithdrawal use or in-channel use.

Interbasin transfer of water—*See* Water exports; Water imports.

Irrigation—Generally, the controlled application of water to arable lands to supply water requirements of crops not satisfied by rainfall. (*See also* Irrigation water use.) Systems used include the following:

- Center-pivot—Automated sprinkler irrigation achieved by rotating the sprinkler pipe or boom, supplying water to the sprinkler heads or nozzles, as a radius from the center of the circular field to be irrigated. The pipe is supported above the crop by towers at fixed spacings and propelled by pneumatic, mechanical, hydraulic, or electric power on wheels or skids in fixed circular paths at uniform angular speeds. Water, which is delivered to the center or pivot point of the system, is applied at a uniform rate by progressive increase of nozzle size from the pivot to the end of the line. The depth of water applied is determined by the rate of travel of the system. Single units are ordinarily about 1,250 to 1,300 feet long and irrigate about a 130-acre circular area.
- Drip—An irrigation system in which water is applied directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, perforated pipe, and so forth) operated under low pressure. The applicators can be placed on or below the surface of the ground or can be suspended from supports.
- Flood—The application of irrigation water where the entire surface of the soil is covered by ponded water.
- Furrow—A partial surface flooding method of irrigation normally used with clean-tilled crops where water is applied in furrows or rows of sufficient capacity to contain the design irrigation stream.
- Gravity—Irrigation in which the water is not pumped but flows in ditches or pipes and is distributed by gravity.
- Sprinkler—A planned irrigation system in which water is applied by means of perforated pipes or nozzles operated under pressure so as to form a spray pattern.
- Subirrigation—A system in which water is applied below the ground surface either by raising the water table within or near the root zone or by using a buried perforated or porous pipe system that discharges directly into the root zone.
- Traveling gun—Sprinkler irrigation system consisting of a single large nozzle that rotates and is self-propelled. The name refers to the fact that the base is on wheels and can be moved by the irrigator or affixed to a guide wire.

Irrigation district—In the United States, a cooperative, self-governing public corporation that is organized as a subdivision of the State government, has definite geographic boundaries, and has taxing power to obtain and distribute water for irrigation of lands within the district; created under the authority of the State legislature with the consent of a designated fraction of the landowners or the citizens.

Irrigation return flow—Part of irrigation water that is not consumed by evapotranspiration and that drains from the irrigated area to an aquifer or surface-water body.

Irrigation water use—Artificial application of water on lands to assist in the growing of crops and pastures or to maintain vegetative growth on recreational lands such as parks and golf courses. *See also* Irrigation.

Karst—A type of topography that is formed on limestone, dolomite, gypsum beds, and other rocks by dissolution and is characterized by closed depressions, sinkholes, caves, and underground drainage.

Keelboat—A riverboat that is usually rowed, poled, or towed and that is used for freight.

Livestock water use—Water for stock watering, feed lots, dairy operations, fish farming (aquaculture), and other on-farm needs. Livestock as used here includes cattle, sheep, goats, hogs, and poultry. Also included are animal specialities such as horses, rabbits, bees, pets, fur-bearing animals in captivity, and fish in captivity. *See also* Rural water use.

Million gallons per day (Mgal/d)—A rate of flow of water.

Mining water use—Water use for the extraction of minerals occurring naturally—solids, such as coal and ores; liquids, such as crude petroleum; and gases, such as natural gas. Also includes uses associated with quarrying, well operations (dewatering), milling (crushing, screening, washing, flotation, and so forth), and other preparations customarily done at the mine site or as part of a mining activity.

Navigable waters—Rivers or other bodies of water used or susceptible of being used in their ordinary condition, as highways of commerce over which trade and travel are or can be conducted by customary modes of trade or travel on water. Exact definition varies by State.

Nonwithdrawal use—*See* Instream use.

Normal storage—The total storage space in a reservoir below the normal retention level, including dead and inactive storage and excluding any flood control or surcharge storage.

Off-channel use—*See* Offstream use.

Offstream use—Water withdrawn or diverted from a ground- or surface-water source for public-water supply, industry, irrigation, livestock, thermoelectric power generation and other uses. Sometimes called off-channel use or withdrawal use.

Overdraft—Withdrawals of ground water at rates perceived to be excessive. *See also* Ground-water mining.

Per capita use—The average amount of water used per person during a standard time period, generally per day.

Perennial stream—A stream that normally has water in its channel at all times.

Perfected water right—A water right that is recorded, or registered, or filed for record with the State, in accordance with State law.

Permafrost—Any frozen soil, subsoil, surficial deposit, or bedrock in arctic or subarctic regions where below-freezing temperatures have existed continuously from two to tens of thousands of years.

Permit system—A general term referring to a system of acquiring water rights under State law whereby the State must issue a permit for a new use of water. At one time, permit systems generally were associated with riparian, Eastern States; however, they are now used in other States.

Potable water—Water that is safe and palatable for human consumption.

Potentiometric surface—An imaginary surface representing the static head of ground water in tightly 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.

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. *See also* Riparian doctrine.

Public supply—Water withdrawn for all uses by public and private water suppliers and delivered to users that do not supply their own water. Water suppliers provide water for a variety of uses, such as domestic, commercial, thermoelectric power, industrial, and public water use. *See also* Commercial water use; Domestic water use; Industrial water use; Public water use; Thermoelectric power water use.

Public water use—Water supplied from a public water supply and used for such purposes as firefighting, street washing, and municipal parks and swimming pools. *See also* Public supply.

Reasonable use—A rule with regard to percolating or riparian water that restricts the landowner to a reasonable use of his own rights and property in view of and qualified by the similar rights of others, and the condition that such use not injure others in the enjoyment of their rights.

Recharge (ground water)—The addition of water to the ground-water system by natural or artificial processes.

Reclaimed sewage—Wastewater-treatment-plant effluent that has been diverted or intercepted for use before it reaches a natural waterway or aquifer.

Recycled water—Water that is used more than one time before it passes back into the natural hydrologic system.

Residential water use—*See* Domestic water use.

Return flow—Water that reaches a ground- or surface-water source after release from the point of use and thus becomes available for further use.

Reuse—*See* Recycled water.

Rural water use—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. *See also* Domestic water use; Livestock water use; Self-supplied water.

Riparian doctrine—The system of law dominant in Great Britain and the Eastern United States, in which owners of lands along the banks of a stream or waterbody have the right to reasonable use of the waters and a correlative right to protection against unreasonable use by others that substantially diminishes the quantity and (or) the quality of water. The right is appurtenant to the land and does not depend on prior use. *See also* Prior appropriation; Water rights.

Saline water—Water that contains more than 1,000 milligrams per liter of dissolved solids. It generally is considered unsuitable for human consumption and less desirable for irrigation because of its high content of dissolved solids. Salinity generally is 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

Saltwater intrusion—Replacement of freshwater by saline water in an aquifer or body of water.

Self-supplied industrial use—*See* Industrial water use; Self-supplied water.

Self-supplied water—Water withdrawn from a surface- or ground-water source by a user and not obtained from a public supply.

Sewage—Waste matter carried off by sewers and drains.

Sewage treatment—The processing of wastewater for the removal or reduction in the level of dissolved solids or other undesirable constituents.

Sewage-treatment return flow—Water returned to the hydrologic system by sewage-treatment facilities.

Sprinkler irrigation—*See* Irrigation.

Standard industrial classification (SIC) codes—Four-digit codes that were established by the Office of Management and Budget and that are used in the classification of establishments by type of activity in which they are engaged.

Subirrigation—*See* Irrigation.

Surface water—An open body of water, such as a stream or a lake.

Suspended sediment—Sediment that is transported in suspension by a stream. Fragmental material, both mineral and organic, that is maintained in suspension in water by the upward components of turbulence and currents and (or) by colloidal suspension.

Tailwater recovery—Process of collecting irrigation water runoff for reuse.

Thermoelectric power—Electrical power generated by using fossil-fuel (coal, oil, or natural gas), geothermal, or nuclear energy.

Thermoelectric power water use—Water used in the process of the generation of thermoelectric power. The water can be obtained from a public supply or be self-supplied. *See also* Public supply; Self-supplied water.

Transpiration—Process by which water absorbed by plants, usually through the roots, is evaporated into the atmosphere from the plant surface. *See also* Evaporation; Evapotranspiration.

Traveling gun irrigation—*See* Irrigation.

Turbidity—The opaqueness or reduced clarity of a fluid due to the presence of suspended matter.

Wastewater—Water that contains dissolved or suspended solids as a result of human use.

Water budget—An accounting of the inflow to, outflow from, and storage changes of water in a hydrologic unit.

Water consumed—*See* Consumptive use.

Water consumption—*See* Consumptive use.

Water exports—Artificial transfer (pipes, canals) of freshwater from one region or subregion to another.

Water imports—Artificial transfer (pipes, canals) of freshwater 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 drainage areas of a series of rivers; in the United States there are 21 regions—18 are in the conterminous States and 1 each is 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 includes that 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 system. *See also* Water-resources region.

Water rights—Legal rights to use a specific quantity of water, on a specific time schedule, at a specific place, and for a specific purpose. *See also* Beneficial use; Prior appropriation; Riparian doctrine.

Water use—As initially used in 1950 in the U.S. Geological Survey's 5-year water-use circulars, this term meant withdrawals of water; in time, it was redefined to include consumptive use of water. With the beginning of the Survey's National Water-Use Information Program (1977), the term was further defined to include return flow and offstream and instream uses.

Water table—*See* Potentiometric surface.

Water utility—*See* Public supply.

Wetlands—Lands that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support and that, under normal circumstances, do support a prevalence of vegetation typically adapted for life in saturated soil conditions.

Withdrawal—Water removed from the ground or diverted form a surface-water source for use. *See also* Offstream use; Self-supplied water.

Withdrawal use—*See* Offstream use.

WATER-QUANTITY EQUIVALENTS AND CONVERSION FACTORS

This water-quantity equivalents and conversion factors list is for those interested in converting units in reports that contain data on water-resources availability, supply, and use. The right-hand column includes units expressed in two systems—U.S. Customary and International System (metric). Units, which are written in abbreviated form below, are spelled out in parentheses the first time that they appear.

To convert from the unit in the left-hand column to that in the right, multiply by the number in the right-hand column. Most of the quantities listed were rounded to five significant figures. However, for many purposes, the first two or three significant figures are adequate for determining many water-quantity relations, such as general comparisons of water availability with water use or calculations in which the accuracy of the original data itself does not justify more than three significant figures. Quantities shown in italics are exact equivalents—no rounding was necessary. Regarding length of time, each calendar year is assumed (for this list) to consist of 365 days.

The data in this list were adapted largely from information found in the following publications:

Chisholm, L.J., 1967, Units of weight and measure—International (Metric) and U.S. Customary: U.S. National Bureau of Standards Miscellaneous Publication 286, 251 p.

U.S.Geological Survey, 1919, Hydraulic conversion tables and convenient equivalents (2d ed.): U.S. Geological Survey Water-Supply Paper 425-C, p. C71-C94.

U.S. CUSTOMARY		U.S.CUSTOMARY OR METRIC
	LENGTH	
1 in (inch)	=	*25.4* mm (millimeters)
1 ft (foot)	=	*0.3048* m (meter)
1 mi (mile, statute)	=	*5,280.* ft
	=	*1,609.344* m
	=	*1.609344* km (kilometers)
	AREA	
1 ft^2 (square foot)	=	*0.09290304* m^2 (square meter)
1 acre	=	*43,560.* ft^2
	=	*0.0015625* mi^2 (square mile)
	=	0.40469 ha (hectare)
	=	4,046.9 m^2
1 mi^2	=	*640.* acres
	=	259.00 ha
	=	2.5900 km^2 (square kilometers)
	VOLUME OR CAPACITY (liquid measure)	
1 qt (quart, U.S.)	=	0.94635 L (liter)
1 gal (gallon, U.S.)	=	*231.* in^3 (cubic inches)
	=	0.13368 ft^3 (cubic foot)
	=	3.7854 L
	=	0.0037854 m^3 (cubic meter)
1 Mgal (million gallons)	=	0.13368 Mft^3 (million cubic feet)
	=	3.0689 acre-ft (acre-feet)
	=	3,785.4 m^3
1 ft^3	=	*1,728.* in^3
	=	7.4805 gal
	=	28.317 L
	=	0.028317 m^3
1 Mft^3	=	28,317. m^3
1 acre-ft (volume of water 1 ft deep covering an area of 1 acre)	=	*43,560.* ft^3
	=	0.32585 Mgal
	=	1,233.5 m^3
1 mi^3 (cubic mile)	=	1,101.1 billion gal
	=	147.20 billion ft^3
	=	3.3792 million acre-ft
	=	4.1682 km^3 (cubic kilometers)

(Continued)

U.S. CUSTOMARY-Continued		U.S. CUSTOMARY OR METRIC-Continued
SPEED (or, when used in a vector sense, velocity)		
1 ft/s (foot per second)	=	*0.3048* m/s (meter per second)
	=	0.68182 mi/hr (mile per hour)
1 mi/hr	=	1.4667 ft/s
	=	*0.44704* m/s
VOLUME PER UNIT OF TIME (discharge, water supply, water use, and so forth)		
1 gal/min (gallon per minute)	=	*0.00144* Mgal/d (million gallons per day)
	=	0.0022280 ft^3/s (cubic foot per second)
	=	0.0044192 acre-ft/d (acre-foot per day)
	=	3.7854 L/min (liters per minute)
	=	0.063090 L/s (liter per second)
1 Mgal/d	=	694.44 gal/min
	=	1.5472 ft^3/s
	=	3.0689 acre-ft/d
	=	1,120.1 acre-ft/yr (acre-feet per year)
	=	0.043813 m^3/s (cubic meter per second)
	=	3,785.4 m^3/d (cubic meters per day)
	=	0.0013817 km^3/yr (cubic kilometer per year)
1 billion gal/yr (billion gallons per year)	=	2.7397 Mgal/d
1 ft^3/s	=	448.83 gal/min
	=	0.64632 Mgal/d
	=	1.9835 acre-ft/d
	=	723.97 acre-ft/yr
	=	28.317 L/s
	=	0.028317 m^3/s
	=	2,446.6 m^3/d
	=	0.00089300 km^3/yr
1 acre-ft/yr	=	892.74 gal/d (gallons per day)
	=	0.61996 gal/min
	=	0.0013813 ft^3/s
	=	3.3794 m^3/d
1 acre-ft/d	=	0.50417 ft^3/s
VOLUME, DISCHARGE, OR USE PER UNIT OF AREA		
1 in of rain or runoff	=	17.379 $Mgal/mi^2$ (million gallons per square mile)
	=	27,154. gal/acre (gallons per acre)
	=	*25,400.* m^3/km^2 (cubic meters per square kilometer)
1 in/yr	=	0.047613 $(Mgal/d)/mi^2$
	=	0.073668 $(ft^3/s)/mi^2$
	=	0.00080544 $(m^3/s)/km^2$
1 $(Mgal/d)/mi^2$	=	21.003 in/yr (inches–of rain or runoff–per year)
1 $(ft^3/s)/mi^2$	=	13.574 in/yr
	=	0.010933 $(m^3/s)/km^2$ (cubic meter per second per square kilometer)
MASS (pure water in dry air)		
1 gal at 15° Celsius (59 °Fahrenheit)	=	8.3290 lb (pounds avoirdupois)
1 gal at 4° Celsius (39.2 °Fahrenheit)	=	8.3359 lb
1 lb	=	0.45359 kg (kilogram)
1 ton, short (*2,000* lb)	=	0.90718 Mg (megagram) or ton, metric

Prepared by John C. Kammerer, U.S. Geological Survey

NAMES AND CODES OF THE WATER-RESOURCES REGIONS AND SUBREGIONS

NEW ENGLAND REGION (01)
0101, St. John
0102, Penobscot
0103, Kennebec
0104, Androscoggin
0105, Maine Coastal
0106, Saco
0107, Merrimack
0108, Connecticut
0109, Massachusetts-Rhode Island Coastal
0110, Connecticut Coastal
0111, St. Francois

MID-ATLANTIC REGION (02)
0201, Richelieu
0202, Upper Hudson
0203, Lower Hudson-Long Island
0204, Delaware
0205, Susquehanna
0206, Upper Chesapeake
0207, Potomac
0208, Lower Chesapeake

SOUTH ATLANTIC-GULF REGION (03)
0301, Chowan-Roanoke
0302, Neuse-Pamlico
0303, Cape Fear
0304, Pee Dee
0305, Edisto-Santee
0306, Ogeechee-Savannah
0307, Altamaha-St. Marys
0308, St. Johns
0309, Southern Florida
0310, Peace-Tampa Bay
0311, Suwannee
0312, Ochlockonee
0313, Apalachicola
0314, Choctawhatchee-Escambia
0315, Alabama
0316, Mobile-Tombigbee
0317, Pascagoula
0318, Pearl

GREAT LAKES REGION (04)
0401, Western Lake Superior
0402, Southern Lake Superior-Lake Superior
0403, Northwestern Lake Michigan
0404, Southwestern Lake Michigan
0405, Southeastern Lake Michigan
0406, Northeastern Lake Michigan-Lake Michigan
0407, Northwestern Lake Huron
0408, Southwestern Lake Huron-Lake Huron
0409, St. Clair-Detroit
0410, Western Lake Erie
0411, Southern Lake Erie
0412, Eastern Lake Erie-Lake Erie
0413, Southwestern Lake-Ontario
0414, Southeastern Lake Ontario
0415, Northeastern Lake Ontario-Lake Ontario-St.Lawrence

OHIO REGION (05)
0501, Allegheny
0502, Monongahela
0503, Upper Ohio
0504, Muskingum
0505, Kanawha
0506, Scioto
0507, Big Sandy-Guyandotte
0508, Great Miami
0509, Middle Ohio
0510, Kentucky-Licking
0511, Green
0512, Wabash
0513, Cumberland
0514, Lower Ohio

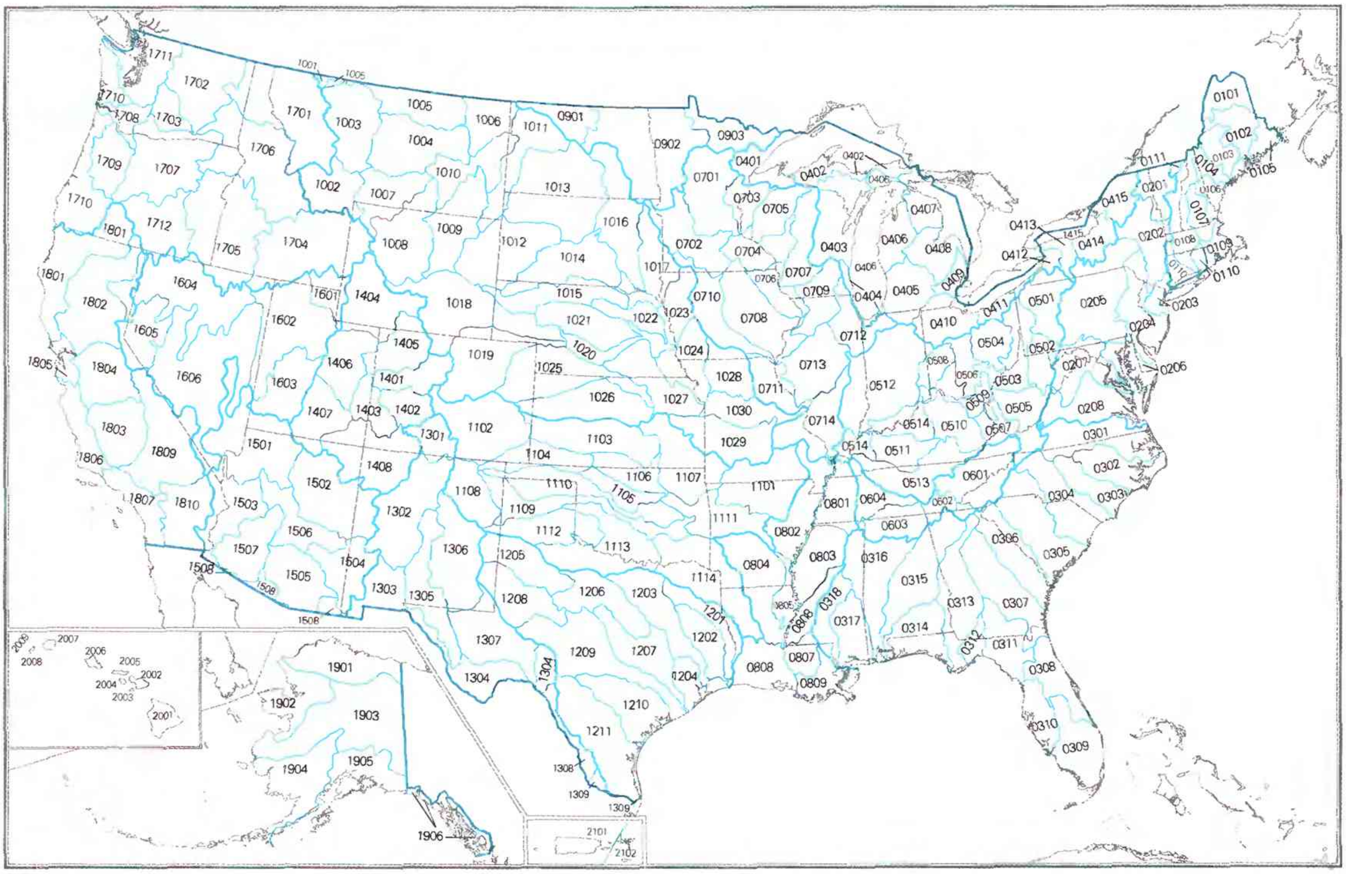
TENNESSEE REGION (06)
0601, Upper Tenssessee
0602, Middle Tennessee-Hiwassee
0603, Middle Tennessee-Elk
0604, Lower Tennessee

UPPER MISSISSIPPI REGION (07)
0701, Mississippi Headwaters
0702, Minnesota
0703, St. Croix
0704, Upper Mississippi-Black-Root
0705, Chippewa
0706, Upper Mississippi-Maquoketa-Plum
0707, Wisconsin
0708, Upper Mississippi-Iowa-Skunk-Wapsipinicon
0709, Rock
0710, Des Moines
0711, Upper Mississippi-Salt
0712, Upper Illinois
0713, Lower Illinois
0714, Upper Mississippi-Kaskaskia-Meramec

LOWER MISSISSIPPI REGION (08)
0801, Lower Mississippi-Hatchie
0802, Lower Mississippi-St. Francis
0803, Lower Mississippi-Yazoo
0804, Lower Red-Ouachita
0805, Boeuf-Tensas
0806, Lower Mississippi-Big Black
0807, Lower Mississippi-Lake Maurepas
0808, Louisiana Coastal
0809, Lower Mississippi

SOURIS-RED-RAINY REGION (09)
0901, Souris
0902, Red
0903, Rainy

MISSOURI REGION (10)
1001, Saskatchewan
1002, Missouri Headwaters
1003, Missouri-Marias
1004, Missouri-Musselshell
1005, Milk
1006, Missouri-Poplar
1007, Upper Yellowstone
1008, Bighorn
1009, Powder-Tongue
1010, Lower Yellowstone
1011, Missouri-Little Missouri
1012, Cheyenne
1013, Missouri-Oahe



NAMES AND CODES OF THE WATER-RESOURCES REGIONS AND SUBREGIONS—Continued

1014, Missouri-White
1015, Niobrara
1016, James
1017, Missouri-Big Sioux
1018, North Platte
1019, South Platte
1020, Platte
1021, Loup
1022, Elkhorn
1023, Missouri-Little Sioux
1024, Missouri-Nishnabotna
1025, Republican
1026, Smoky Hill
1027, Kansas
1028, Chariton-Grand
1029, Gasconade-Osage
1030, Lower Missouri

ARKANSAS-WHITE-RED REGION (11)

1101, Upper White
1102, Upper Arkansas
1103, Middle Arkansas
1104, Upper Cimarron
1105, Lower Cimarron
1106, Arkansas-Keystone
1107, Neosho-Verdigris
1108, Upper Canadian
1109, Lower Canadian
1110, North Canadian
1111, Lower Arkansas
1112, Red Headwaters
1113, Red-Washita
1114, Red-Sulphur

TEXAS-GULF REGION (12)

1201, Sabine
1202, Neches
1203, Trinity
1204, Galveston Bay-San Jacinto
1205, Brazos Headwaters
1206, Middle Brazos
1207, Lower Brazos
1208, Upper Colorado
1209, Lower Colorado-San Bernard Coastal
1210, Central Texas Coastal
1211, Nueces-Southwestern Texas Coastal

RIO GRANDE REGION (13)

1301, Rio Grande Headwaters
1302, Rio Grande-Elephant Butte
1303, Rio Grande-Mimbres
1304, Rio Grande-Amistad
1305, Rio Grande Closed Basins
1306, Upper Pecos
1307, Lower Pecos
1308, Rio Grande-Falcon
1309, Lower Rio Grande

UPPER COLORADO REGION (14)

1401, Colorado Headwaters
1402, Gunnison
1403, Upper Colorado-Dolores
1404, Great Divide-Upper Green
1405, White-Yampa
1406, Lower Green
1407, Upper Colorado-Dirty Devil
1408, San Juan

LOWER COLORADO REGION (15)

1501, Lower Colorado-Lake Mead
1502, Little Colorado
1503, Lower Colorado
1504, Upper Gila
1505, Middle Gila
1506, Salt
1507, Lower Gila
1508, Sonora

GREAT BASIN REGION (16)

1601, Bear
1602, Great Salt Lake
1603, Escalante Desert-Sevier Lake
1604, Black Rock Desert-Humboldt
1605, Central Lahontan
1606, Central Nevada Desert Basins

PACIFIC NORTHWEST REGION (17)

1701, Kootenai-Pend Oreille-Spokane
1702, Upper Columbia
1703, Yakima
1704, Upper Snake
1705, Middle Snake
1706, Lower Snake
1707, Middle Columbia
1708, Lower Columbia
1709, Willamette
1710, Oregon-Washington Coastal
1711, Puget Sound
1712, Oregon Closed Basins

CALIFORNIA REGION (18)

1801, Klamath-Northern California Coastal
1802, Sacramento
1803, Tulare-Buena Vista Lakes
1804, San Joaquin
1805, San Francisco Bay
1806, Central California Coastal
1807, Southern California Coastal
1808, North Lahontan
1809, Northern Mojave-Mono Lake
1810, Southern Mojave-Salton Sea

ALASKA REGION (19)

1901, Arctic Slope
1902, Northwest Alaska
1903, Yukon
1904, Southwest Alaska
1905, South Central Alaska
1906, Southeast Alaska

HAWAII REGION (20)

2001, Hawaii
2002, Maui
2003, Kahoolawe
2004, Lanai
2005, Molokai
2006, Oahu
2007, Kauai
2008, Niihau
2009, Northwestern Hawaiian Islands

CARIBBEAN REGION (21)

2101, Puerto Rico
2102, Virgin Islands
2103, Caribbean Outlying Areas