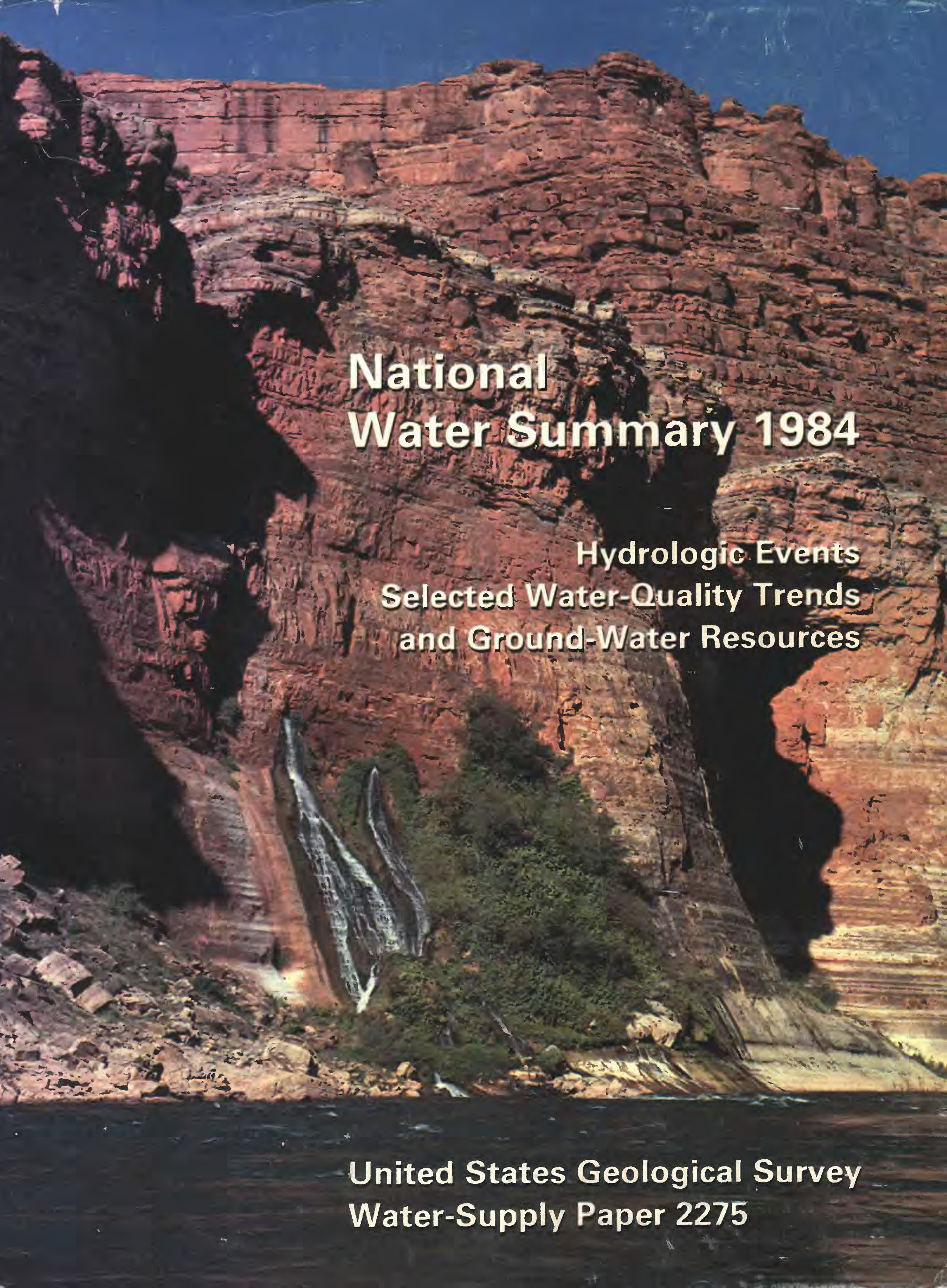


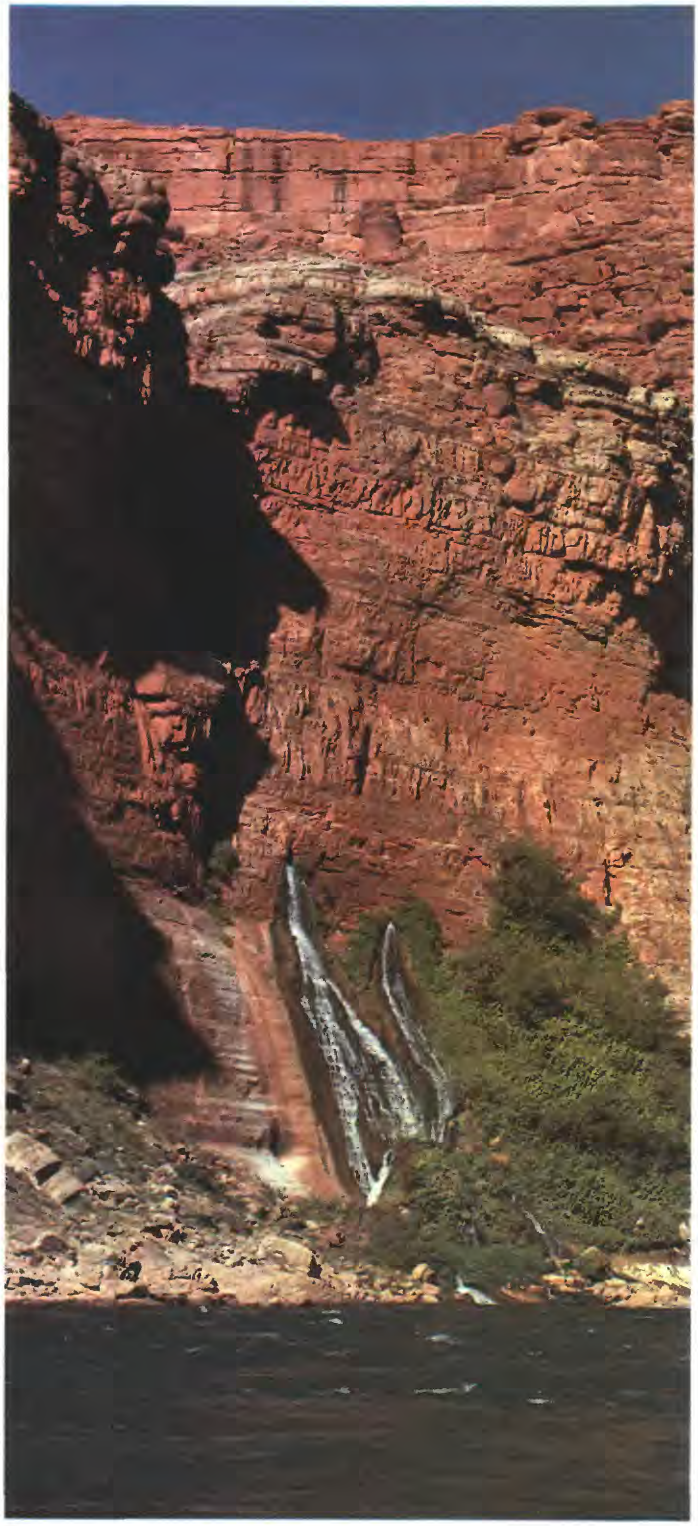
National Water Summary 1984

Hydrologic Events
Selected Water-Quality Trends
and Ground-Water Resources

United States Geological Survey
Water-Supply Paper 2275

Cover:

Vasey's Paradise, 1984. Ground water, discharging from the Redwall Limestone, feeds the spring that cascades into the Colorado River, 31.7 miles below Lees Ferry, Arizona.
Photograph by R. D. Mac Nish, U.S. Geological Su.vey.



Riding down a short distance, a beautiful view is presented. The river turns sharply to the east, and seems inclosed by a wall, set with a million brilliant gems. What can it mean? Every eye is engaged, every one wonders. On coming nearer, we find fountains bursting from the rock, high overhead, and the spray in the sunshine forms the gems which bedeck the wall. The rocks below the fountain are covered with mosses, and ferns, and many beautiful flowering plants. We name it Vasey's Paradise, in honor of the botanist who traveled with us last year.

—John Wesley Powell
August 9, 1869

Director, U.S. Geological Survey, 1881–94

From Powell, J. W., 1875, Exploration of the Colorado River of the West and its tributaries explored in 1869, 1870, 1871, and 1872: Washington, D.C., U.S. Government Printing Office, p. 76.

National Water Summary 1984

Hydrologic Events, Selected Water-Quality Trends, and Ground-Water Resources

By United States Geological Survey

United States Geological Survey
Water-Supply Paper 2275

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1985

For sale by the Superintendent of Documents,
U.S. Government Printing Office,
Washington, DC 20402

FOREWORD

National Water Summary 1984 is the second of an annual series of reports prepared by the U.S. Geological Survey that describes the conditions, trends, availability, quality, and use of the Nation's water resources. The first report, *National Water Summary 1983—Hydrologic Events and Issues*, documented a broad range of water-resources issues from both a national and State perspective. Prominent among those issues was the increasing importance of ground water as a source of water supply in many parts of the country, the widespread concern over declining ground-water levels, and issues associated with ground-water quality.

Ground water is one of the Nation's most valuable resources, and many find it one of the most difficult to understand. It provides 35 percent of the fresh water withdrawn for municipal water supplies, 97 percent of rural drinking water, 40 percent of irrigation water, and about 26 percent of the water used by industry, excluding thermoelectric power uses. Ground water is now the source of drinking water for more than 50 percent of the population. The widespread availability of ground water in most parts of the country, its dependability in times of drought, and its relatively good quality have led to an increase in ground-water withdrawals of nearly 190 percent since 1955.

In response to the growing awareness of the importance of ground-water resources, the 1984 *National Water Summary* presents an overview of the occurrence, distribution, and use of ground water in each State, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, the Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. Each of the many aquifers which comprise the Nation's ground-water systems has a distinct hydrogeologic setting, flow pattern, quality of water, and degree of use; consequently, analyses of aquifer conditions are complex and require much detailed information. Because of that complexity, and because of the formidable array of information on ground-water quality, it is not practical to address in this volume both the physical characteristics of the Nation's aquifers and the chemical quality of water flowing in them. Accordingly, consideration of ground-water quality, including the natural occurrence of chemical constituents in ground water and the contamination of ground water by man-induced processes, will be presented in a future edition of the *National Water Summary*.

In the meantime, the U.S. Geological Survey will continue to emphasize programs that characterize the important aquifers of the country and to develop ground-water quality information at local, regional, and national scales. Specific examples of these programs are the Federal-State Cooperative Program, the Regional Aquifer-System Analysis Program, and the Toxic Waste–Ground-Water Contamination Program. In aggregate, these activities are producing much of the hydrologic, hydraulic, and chemical information that is essential to define aquifer systems and to understand the movement, alteration, and eventual fate of contaminants introduced into those systems.

In addition to the description of ground-water systems, the 1984 *National Water Summary* reviews significant hydrologic and water-related events that occurred during the year and presents articles that expand on a number of specific water issues that were discussed in the 1983 report. These include an analysis of the occurrence of nitrate in ground water, an explanation of ground-water declines in selected areas of the country representing different hydrogeologic environments, and discussions of the distribution and trends of several water-quality constituents in major rivers.

The reports in the *National Water Summary* series are designed to inform government officials, water-resource managers, and the general public of various aspects of the hydrologic system from which our water supplies are obtained. This is a broader audience than we usually address in our technical hydrologic and geologic reports. Therefore, we are particularly interested in receiving comments regarding the contents, style, and usefulness of this report and suggestions for future reports in this series. Such remarks may be addressed to the Chief Hydrologist, U.S. Geological Survey, 409 National Center, Reston, VA 22092.

Director

Contents

Foreword - v
Overview and Introduction - 1
  Overview of National Water Summary 1984 - 2
  Introduction to National Water Summary 1984 *(D. W. Moody and E. B. Chase)* - 5
Hydrologic conditions and water-related events, water year 1984 - 7
  Overview of water year 1984 hydrologic conditions and related events *(H. F. Lins, J. C. Kammerer, and E. B. Chase)* - 8
  Seasonal summaries of hydrologic conditions, water year 1984 *(H. F. Lins)* - 22
    Fall season—October to December 1983 - 22
    Winter season—January to March 1984 - 24
    Spring season—April to June 1984 - 26
    Summer season—July to September 1984 - 28
  Selected hydrologic events, water year 1984 - 30
    Rising lake levels - 30
      Rise of Great Salt Lake, Utah *(Ted Arnow)* - 31
      Rise of Devils Lake, North Dakota *(G. J. Wiche)* - 34
    Floods - 36
      Record late-spring 1984 floods in New England *(R. A. Fontaine)* - 37
      June 1984 floods on the Missouri River and tributaries *(I. L. Burmeister)* - 40
      Spring 1984 runoff in the Colorado River basin *(D. L. Collins)* - 42
    Water quality - 44
      Selenium in the San Joaquin Valley of California *(S. J. Deverel)* - 45
Hydrologic perspectives on water issues - 47
  Introduction - 48
  Water-quality issues - 49
    Sediment in rivers of the United States *(R. H. Meade and R. S. Parker)* - 49
    Loads and concentrations of dissolved solids, phosphorus, and inorganic nitrogen at U.S. Geological Survey National Stream Quality Accounting Network stations *(J. E. Kircher, R. J. Gilliom, and R. E. Hickman)* - 61
    Trends in concentrations of dissolved solids, suspended sediment, phosphorus, and inorganic nitrogen at U.S. Geological Survey National Stream Quality Accounting Network stations *(R. A. Smith and R. B. Alexander)* - 66
    Dissolved solids—Case studies - 74
      Dissolved solids in the Colorado River basin *(J. E. Kircher)* - 74
      Dissolved solids in the Arkansas River basin *(J. D. Stoner)* - 79
    Pesticides in rivers of the United States *(R. J. Gilliom)* - 85
    Overview of the occurrence of nitrate in ground water of the United States *(R. J. Madison and J. O. Brunett)* - 93
  Water-availability issues - 106
    Ground-water-level changes in five areas of the United States *(L. J. Mann)* - 106
    Declining ground-water levels and increasing pumping costs: Floyd County, Texas—A case study *(J. E. Schefter)* - 114
State summaries of ground-water resources - 117
  Introduction *(R. C. Heath)* - 118

Alabama - 123
Alaska - 129
Arizona - 135
Arkansas - 141
California - 147
Colorado - 153
Connecticut - 161
Delaware - 167
Florida - 173
Georgia - 179
Hawaii - 185
Idaho - 193
Illinois - 199
Indiana - 205
Iowa - 211
Kansas - 217
Kentucky - 223
Louisiana - 229
Maine - 237
Maryland and the District of Columbia - 243
Massachusetts - 249
Michigan - 255
Minnesota - 261
Mississippi - 269
Missouri - 277
Montana - 285
Nebraska - 291
Nevada - 297
New Hampshire - 303
New Jersey - 309

State summaries of ground-water resources—Continued

New Mexico 317
New York 323
North Carolina 329
North Dakota 335
Ohio 341
Oklahoma 347
Oregon 355
Pennsylvania 361
Puerto Rico 367
Rhode Island 373
South Carolina 379
South Dakota 385
Tennessee 391
Texas 397
Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa 403
U.S. Virgin Islands 409
Utah 415
Vermont 421
Virginia 427
Washington 433
West Virginia 439
Wisconsin 447
Wyoming 453

Glossary, national drinking-water regulations, and water conversion factors 459
Glossary 460
National drinking-water regulations 465
Water conversion factors 466
Geologic age chart 467

Figures

1. Map showing streamflow in water year 1984 as a percentage of normal (1951–80) in the United States and Puerto Rico 9
2. Map showing precipitation in water year 1984 as a percentage of normal (1951–80) in the United States and Puerto Rico 9
3. Graphs showing monthly discharges for selected rivers in the United States for water years 1983 and 1984 compared with monthly median discharges for the reference period 1951 to 1980 10
4. Graphs showing month-end storage of selected reservoirs in the United States for water years 1983 and 1984 compared with median of month-end storage for reference period 1961 to 1982 11
5. Map showing location or extent of significant hydrologic and water-related events in the United States, Puerto Rico, U.S. Virgin Islands, Guam, and American Samoa, August 1983 to September 1984 13
6. Maps showing hydrologic conditions during the fall season, October to December 1983 22
7. Maps showing hydrologic conditions during the winter season, January to March 1984 24
8. Maps showing hydrologic conditions during the spring season, April to June 1984 26
9. Maps showing hydrologic conditions during the summer season, July to September 1984 28
10. Landsat thematic mapper image of Great Salt Lake, Utah 32
11. Graphs showing changes of water level and dissolved-mineral concentrations of Great Salt Lake, Utah, 1847 to 1984 33
12. Photograph of Great Salt Lake showing entrance to Antelope Island Causeway underwater, June 16, 1984 33
13. Map showing the drainage basin of Devils Lake, N. Dak. 34
14. Graph showing water levels of Devils Lake, N. Dak., 1867 to 1983 34
15. Photograph showing flooding along Route 7 in New Milford, Conn., caused by overflow of the Housatonic River, May 31, 1984 36
16. Photograph showing aftermath of flooding in central Vermont, June 7, 1984 37
17. Index map showing areas of New England flooded in 1984 by late-spring floods 38
18. Graph showing monthly occurrence of annual peak discharges for the period of record of the Salmon River near East Hampton, Conn., and the Piscataquis River near Dover-Foxcroft, Maine 39
19. Index map showing area of June 1984 floods on the Missouri River and tributaries 40
20. Photograph showing aftermath of flooding of the Missouri River at Rulo, Nebr., June 18, 1984 41
21. Index map of the Colorado River basin 42
22. Photograph showing flow being released from Glen Canyon Dam, Ariz., May 23, 1984 43
23. Photograph of the Kesterson Reservoir, San Joaquin Valley, Calif., showing the San Luis Drain and evaporation ponds 44
24. Index map showing the location of the existing and the proposed San Luis Drain, San Joaquin Valley, Calif. 45

Figures—Continued

25. Map showing average concentration of suspended sediment in rivers and average discharge of suspended sediment at the mouths of selected rivers of the conterminous United States - - - - - - - - - - 50
26. Map showing average concentration of suspended sediment in rivers and average discharge of suspended sediment at the mouths of selected rivers of Alaska - 50
27. Graphs of annual discharge of suspended sediment at six stations on the Missouri River and two stations on the Mississippi River showing the effects of reservoirs on downstream sediment loads, 1939 to 1982 - 52
28. Graphs of annual discharge of suspended sediment at six stations on the Rio Grande showing the effects of reservoirs on downstream sediment loads, 1906 to 1983 - 53
29. Graphs showing annual discharge of water (1905–64) and suspended sediment (1911–79) in the Colorado River at Yuma, Ariz. - 55
30. Maps showing average suspended-sediment discharge of major rivers in Georgia and the Carolinas during two periods, about 1910 and about 1980, that indicate the decrease in sediment loads caused by several reservoirs constructed during the intervening years - - - - - - - - - - - - - - - - 56
31. Graph showing suspended-sediment discharge in the lowermost 300 miles of the Mississippi River at three different stages of river flow - 57
32. Diagrams showing sources, sinks, and storage of sediment in the drainage basin of Coon Creek, Wis., 1853 to 1938 and 1938 to 1975 - 58
33. Graphs of annual suspended-sediment discharge of three rivers showing the frequencies of suspended-sediment discharges within individual years and the importance of infrequent heavy storms in producing large sediment loads - 59
34. Map showing dissolved-solids loads and mean annual concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - 62
35. Map showing phosphorus loads and mean annual concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - - - - - - - - - - 63
36. Map showing inorganic nitrogen (nitrate plus nitrite) loads and mean annual concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - 64
37. Map showing trends in dissolved-solids concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - - - - - - - - - - 67
38. Graph showing increase of salt application as a highway deicing chemical in the United States, 1947 to 1983 - - 67
39. Map showing trends in suspended-sediment concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - - - - - - - - - - 68
40. Map showing trends in total phosphorus concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - - - - - - - - - - 71
41. Map showing trends in inorganic nitrogen (nitrate and nitrite) concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 - - - 72
42. Graph showing median yield of inorganic nitrogen at National Stream Quality Accounting Network stations in relation to atmospheric deposition rate of nitrate in precipitation for the 18 water-resources regions of the conterminous United States - 73
43. Pie chart showing source of dissolved solids in the Colorado River basin - - - - - - - - - - - - - - - - - 74
44. Map showing maximum, mean, and minimum dissolved-solids loads for 26 stations in the Colorado River basin, 1965 to 1983 - 76
45. Map showing maximum, mean, and minimum dissolved-solids concentrations for 26 stations in the Colorado River basin, 1965 to 1983 - 77
46. Map showing trends in dissolved-solids concentrations at 26 stations, in the Colorado River basin, 1965 to 1983 - 78
47. Map showing maximum, mean, and minimum dissolved-solids loads for 18 stations in the Arkansas River basin, 1968 to 1982 - 79
48. Map showing maximum, mean, and minimum dissolved-solids concentrations for 18 stations in the Arkansas River basin, 1968 to 1982 - 82
49. Map showing trends in dissolved-solids concentrations at 18 stations in the Arkansas River basin, 1968 to 1982 - 83
50. Map showing location of stream-sampling stations in the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network in the conterminous United States, 1975 to 1980 - 85
51. Graph showing trends in national use of herbicides and insecticides on major crops, 1964 to 1982 - - - - - - 86
52. Graph showing frequency of detection of organochlorine insecticides in water and bed-material samples from stations in the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network, 1975 to 1980 - 87
53. Graph showing frequency of detection of organophosphate insecticides in water samples from the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network, 1975 to 1980 - - - - - - - 90

Figures—Continued

54. Generalized flow diagram showing sources, movement, and reaction of nitrogen in soils and ground water - - - 94
55. Simplified diagram of the biological nitrogen cycle showing some environmental important reactions of nitrogen 94
56. Map showing nitrate-nitrogen distribution in ground water of the United States and Puerto Rico - - - - - - - 97
57. Graph showing distribution of three ranges of nitrate-nitrogen concentrations in well water with well depth- - - 98
58. Map showing areas of the conterminous United States where water-table decline or artesian water-level decline in excess of 40 feet in at least one aquifer has occurred since development began - - - - - - - - - - 107
59. Hydrograph showing water levels in three observation wells in an alluvial basin aquifer near Mendota, Calif., 1935 to 1983- 108
60. Hydrograph showing water levels in observation wells in the sandstone aquifer at Elmhurst, Ill., and the dolomite aquifer at Itasca, Ill., 1953 to 1980 - 108
61. Hydrograph showing water levels in an observation well in the "2,000-foot" sand at Baton Rouge, La., 1943 to 1983- 109
62. Sketch showing saltwater front, water-level contours, and location of fault in the "2,000-foot" sand in the Baton Rouge, La., area - 109
63. Hydrographs showing water levels in observation wells in the middle Potomac aquifer, 1943 to 1984- - - - - - 110
64. Map showing approximate area in South Dakota where wells in the Dakota aquifer flowed freely at the land surface before development (about 1881) and at the present time (1983) - - - - - - - - - - - - - - - - - - 111
65. Hydrograph showing water levels in a well in the High Plains aquifer, Floyd County, Tex., 1940 to 1984 - - - - 114
66. Graph showing estimated pumping costs at an observation well in Floyd County, Tex., 1952 to 1981- - - - - - 115
67. Map showing ground-water withdrawals in 1980 for the United States, Puerto Rico, and the U.S. Virgin Islands - 119

State summaries of ground-water resources
Each summary has—
Figures 1–2. Map showing—
1. Areal distribution of principal aquifers
2. Areal distribution of major ground-water withdrawals and hydrographs showing trends in ground-water levels

Tables

1. Chronology of significant hydrologic and water-related events, August 1983 to September 1984 - - - - - - - 12
2. Peak discharges at selected stream sites caused by New England storm, May 28 to June 3, 1984 - - - - - - - - 38
3. Discharge of suspended sediment to the coastal zone by 10 major rivers of the United States, about 1980 - 51
4. Mean annual water discharge, dissolved-solids load, and dissolved-solids concentration for 26 stations in the Colorado River basin, water years 1965 to 1983 - 75
5. Mean annual water discharge, dissolved-solids load, and dissolved-solids concentration for 18 stations in the Arkansas River basin, water years 1968 to 1982 - 80
6. Selected characteristics and uses of pesticides monitored by the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network, 1975 to 1980 - - - - - - - - - - - 88
7. Summary of detections of pesticides in water and bed sediments at the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network stations, 1975 to 1980 - - - - - - - 89
8. Summary of nitrate-nitrogen concentrations in ground water, by State - - - - - - - - - - - - - - - - - - 96
9. Summary of fresh ground-water withdrawals, by State - 120

State summaries of ground-water resources
Each summary has—
Tables 1–2.
1. Ground-water facts
(Not included in Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa)
2. Aquifer and well characteristics
(Table 1 in Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa)

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Page 1, Hydrologist monitoring discharge from an irrigation pump north of Sterling, Colo. Well pumps 2,700 gallons per minute. (Photograph by D. E. Reed.)

Page 7, San Luis Drain to Kesterson National Wildlife Refuge, San Joaquin Valley, Calif. (Photograph by S. J. Deverel.)

Page 47, Analyst operating automated wet chemical analyzer for nitrogen at U.S. Geological Survey's Denver Central Laboratory. (Photograph by D. E. Reed.)

Page 117, Old pump, east of Brighton, Colo. (Photograph by D. E. Reed.)

Overview *and* Introduction

OVERVIEW OF NATIONAL WATER SUMMARY 1984

Water year 1984 was a year of extreme hydrologic conditions. For the third consecutive year, precipitation and resulting runoff were well above long-term averages in most of the Nation and as much as 400 percent above average in the Southwest. National flood damages during the year were the third highest in a 10-year period (1975–84)—an estimated $3.5 to $4 billion. In many of the larger river systems, monthly stream discharges were above normal, as they have been for the last 2 water years, and, with the exception of a few reservoir systems, end-of-month reservoir storage also remained above normal. The Great Salt Lake reached its highest level since 1873 as a result of these conditions. During a 9.6-foot rise from September 1982 to July 1984, the area of the lake expanded by 600 square miles (an increase of 35 percent), resulting in an estimated $212 million in damages to recreational facilities and industrial installations built on the exposed lake bed during former lower levels. Other lake levels in closed basins of the Western United States also have risen over the past few years, thereby flooding communities, recreational facilities, and agricultural lands. In contrast to this predominant pattern of wet conditions, several areas of the country, mainly west Texas and Hawaii, have experienced persistent droughts. Most recently, very dry conditions existed in parts of northern Montana. These hydrologic conditions and 100 specific events are reviewed in the "Hydrologic Conditions and Water-Related Events, Water Year 1984" part of the 1984 *National Water Summary*.

Although it is not an event in the sense of a flood or a pollution spill, the discovery of relatively high and toxic concentrations of selenium in irrigation return flows along the west side of the San Joaquin Valley of California is a notable example of how human activities can affect water quality. Preliminary investigations indicate that irrigation in the valley has dissolved materials from the soil, and the dissolved materials have accumulated in ground and surface water. As a result, concentrations of selenium, which naturally occur in minute amounts in the soil, have reached toxic levels in the Kesterson National Wildlife Refuge.

Water managers generally agree that nonpoint-source pollution will require more attention in the years ahead if further improvements in surface-water quality are to be achieved. Similarly, point and nonpoint sources of ground-water pollution will need to be controlled to protect aquifers that may be used for future water supplies from contamination. As a contribution to the discussion of these issues, the "Water-Quality Issues Section" of the 1984 *National Water Summary* contains a national analysis of the distribution of and trends in suspended sediment, dissolved solids, nitrogen, phosphorus, and pesticides in major rivers and nitrate in ground water.

Sediment occurs in rivers as a natural consequence of geologic processes; these processes, however, may be accelerated greatly by human activities such as forest clearing, farming, surface mining, and urban or rural development. Although the erosion of soils under a specific set of conditions can be estimated, it remains difficult to predict how much soil eventually will be delivered to a stream because sediment may be stored on hillslopes or in stream valleys for periods of time ranging from a few days to hundreds of years. This storage complicates attempts to relate changes in erosion rates and soil-conservation practices to suspended-sediment concentrations in rivers. Suspended-sediment concentrations also are influenced by reservoirs that act as sediment traps and thereby greatly reduce the net transport of sediment downstream; for example, sediment discharges to the Gulf of Mexico by the Mississippi River are now less than one-half of what they were 30 years ago. In the last several decades, seaward transport of sediment in the Colorado River and the Rio Grande almost has been halted. Another aspect of sediment transport is that a large part of the long-term sediment load is carried by a few very large, but infrequent, floods. These floods further complicate attempts to estimate the long-term loads from relatively short records of sediment transport. Because fluvial sediments adsorb toxic substances, knowledge of sediment transport processes provides important insights into the fate of toxic substances in the aquatic environment.

Data from the U.S. Geological Survey National Stream Quality Accounting Network (NASQAN) stations for water years 1975 to 1981 (October 1974 to September 1981) show about equal numbers of stations with increasing and decreasing suspended-sediment concentrations. Decreasing concentrations of suspended sediment in the Missouri River basin may be related to the trapping effects of reservoirs that were constructed in the 1950's and 1960's. Trends in suspended-sediment concentration appear to correlate well with estimates of cropland-erosion rates. For example, in river basins where cropland-erosion rates exceed 2.5 tons per acre per year, the stations with increases in suspended-sediment concentrations outnumber those with decreases.

Dissolved-solids concentrations generally reflect the distribution of rocks and soils, human activities, and quality of atmospheric deposition. Streams draining the granitic rocks in New England, for example, contain concentrations of dissolved solids in the tens of milligrams per liter, whereas streams draining heavily irrigated areas with salt-bearing shales in the Southwest may have dissolved-solids concentrations in the thousands of milligrams per liter. Dissolved-solids loads, on the other hand, reflect concentration and flow volume. Thus, some of the highest loads may be associated with rivers that have relatively low concentrations of dissolved solids but large flow volumes. High concentrations and loads of phosphorus and nitrogen compounds that are found in the Mississippi River basin, especially in the Midwestern States, and in rivers of the Southwest are thought to reflect the distribution of agricultural activities in these regions.

Widespread increases in dissolved-solids concentrations between 1975 and 1981, for the most part, may be due to increases in irrigated agriculture and the increased use of salt as a highway deicing chemical in many Northeastern and North-Central States. Conversely, declines in dissolved-solids concentrations in the Colorado River basin may be due to improved irrigation practices and other salinity control measures.

Phosphorus concentrations increased and decreased at about equal numbers of NASQAN stations between 1974 and 1981. Decreases in the Great Lakes and Upper Mississippi regions probably are attributable to major pollution-control efforts in these areas during the late 1970's. Other phosphorus-concentration patterns appear to be related closely to those for suspended sediment and reflect the tendency for phosphorus to adsorb to the surface of sediment particles.

Inorganic nitrogen (expressed as nitrate plus nitrite) concentrations at NASQAN sites show widespread increases between 1974 and 1981, especially in the Eastern and Northwestern United States. The ratio of the number of increases to decreases in concentrations varies greatly with the types of land use and the magnitude of erosion rates upstream of the measuring sites; the highest ratios occur in basins where croplands contribute the most to soil erosion. A 38-percent increase in nitrogen fertilizer applied to agricultural lands between 1975 and 1981 may account for the increases in inorganic nitrogen concentrations observed in basins that include large areas of croplands.

Another source of inorganic nitrogen, which may prove to be significant, is atmospheric deposition. However, concentrations and loads of inorganic nitrogen and other constituents cannot be reliably attributed to specific sources without more detailed basin analysis.

Results from the analysis of almost 3,000 surface-water samples and nearly 1,000 bed-material samples from the Pesticide Monitoring Network, which was operated by the U.S. Geological Survey and the U.S. Environmental Protection Agency from 1975 to 1980, show that fewer than 10 percent of the water samples and fewer than 20 percent of bed-material samples contained detectable levels of the 22 pesticides for which analyses were made. Although the small number of detections is due, in part, to the difficulties of sampling and measuring very small concentrations of pesticides, the low frequency of detections suggests that the 22 pesticides do not occur in many rivers at concentrations that consistently exceed water-quality criteria.

The disposal of human wastes through septic system discharges and agricultural activities, including fertilizing of crops and raising livestock, may be the two largest sources of nitrate contamination of ground water throughout the United States. Of more than 124,000 wells for which nitrate values are available, more than 24,000 (20 percent) had water with maximum nitrate-nitrogen concentrations greater than 3 milligrams per liter (mg/L), which, for the purpose of this report, is considered to be indicative of the effects of human activity on the ground water. About 8,200 (6 percent) of these wells had water with maximum nitrate-nitrogen concentrations that exceeded the U.S. Environmental Protection Agency's regulatory limit of 10 mg/L for drinking water. In most instances, elevated nitrate concentrations occurred in water from wells in shallow aquifers although long-term increases of nitrate in deep aquifers are possible where the aquifers are recharged by nitrate-rich water from shallow aquifers or from the land surface.

In the section "Water-Availability Issues," the historical changes in ground-water levels in several areas of the country are described. These areas are the San Joaquin Valley, Calif., Chicago, Ill., area, Baton Rouge, La., Franklin, Va., area, and Dakota aquifer of South Dakota—where ground-water levels have declined 40 feet or more in at least one aquifer since development began. In the Floyd County, Tex., area, the costs of water, due to declining ground-water levels and increasing energy costs, have risen about 220 percent relative to the index of prices that farmers received for their crops over the 30-year period 1952 to 1981.

The "State Summaries" part of the 1984 *National Water Summary* describes the occurrence, use, and general quality of ground-water resources for each State, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, the Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. Nationwide, ground-water withdrawals range from less than 1 percent of the total water withdrawals in the District of Columbia to 85 percent in Kansas. Ground-water withdrawals constitute more than 50 percent of the total withdrawals in 10 States. By far, the largest use of ground water is for irrigation.

Each State summary consists of the following components: (1) introductory remarks highlighting the importance of ground water and the geologic framework of the ground-water system, (2) a table showing the amount of ground water used for different purposes in relation to total water use, (3) a map showing the extent of principal aquifers, (4) a table listing the principal aquifers and data on water-supply wells, (5) a map showing the major areas of withdrawals and hydrographs showing the long-term response of the aquifers to withdrawals or the effects of climatic changes, (6) a brief description of State ground-water-management activities including names of management agencies and reference to ground-water laws and regulations, and (7) selected references that pertain to the State's ground-water resources.

The emphasis of these State descriptions is on the distribution of major aquifers and their use. Ground-water quality is mentioned in general terms and where the quality has a major influence on ground-water development.

INTRODUCTION TO NATIONAL WATER SUMMARY 1984

By David W. Moody and Edith B. Chase

The initial volume in the annual National Water Summary series (U.S. Geological Survey, 1984) introduced a chronology of hydrologic and water-related events to document their importance to human activities and also outlined a number of water issues of concern to the Nation. This second volume, *National Water Summary 1984—Hydrologic Events, Selected Water-Quality Trends,* and *Ground-Water Resources,* continues the chronology of events and presents additional information on several issues discussed in the 1983 volume. The 1984 *National Water Summary* is organized in three parts.

The first part, "Hydrologic Conditions and Water-Related Events, Water Year 1984," provides a synopsis of the hydrologic conditions and water-related events that occurred during the 1984 water year (October 1, 1983–September 30, 1984). Streamflow variations are compared to precipitation, temperature, and upper-air atmospheric pressure for the four seasonal quarters of the year to relate surface-water flows to climatic conditions.

The second part, "Hydrologic Perspectives on Water Issues," contains two sections. In the section titled "Water-Quality Issues," the occurrence of sediment, dissolved solids, nutrients, and pesticides in the Nation's streams are discussed. Recently compiled information is used to show the distribution and trends of these constituents and to relate them to various natural sources and human activities. The occurrence and sources of nitrate in ground water also are discussed. The section entitled "Water-Availability Issues" provides hydrologic explanations for changes in ground-water levels in several areas of the country.

The articles in this part of the report complement a number of other reports, published during the past year, which provide information on the water quality of the Nation's rivers. The 1982 *National Fisheries Survey* (Judy and others, 1984), cosponsored by the U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency, provides an assessment of biological conditions in a statistical sample of river segments throughout the United States. The U.S. Environmental Protection Agency also sponsored an evaluation of the progress of water-pollution control efforts (Association of State and Interstate Water Pollution Control Administrators, 1984), an overview of nonpoint-source pollution (U.S. Environmental Protection Agency, 1984a), and the 1982 *National Water Quality Inventory* (U.S. Environmental Protection Agency, 1984b). Other recent studies that examine water resources from a national perspective include the 14th annual report of the U.S. Council on Environmental Quality (1983), the Conservation Foundation's (1984) *State of the Environment* report, and the Office of Technology Assessment's (1984) *Protecting the Nation's Groundwater from Contamination.*

The third and final part of the report, "State Summaries of Ground-Water Resources," summarizes for each State, the District of Columbia (combined with Maryland), Puerto Rico, the U.S. Virgin Islands, the Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa, the distribution, characteristics, and uses of principal aquifers. (The term "State" as used throughout the report is all inclusive of these geographic areas.) Each summary contains maps that show the location of aquifers and major areas of ground-water withdrawals and tables that describe the characteristics of the aquifers and present data on ground-water withdrawals. These descriptions of ground-water resources were prepared by the U.S. Geological Survey offices in each State.

Technical terms used in the report are defined in the Glossary. Selected references are given at the end of each article and State summaries to supplement the information provided. Numerous references are made to the National Drinking-Water Regulations; as an aid to the reader, these regulations follow the Glossary. A conversion table of water measurements and a geologic age chart also are provided for the reader's convenience.

ACKNOWLEDGMENTS

National Water Summary reports, because of their scope, are necessarily the work of many individuals. The coordinators of the 1984 *National Water Summary* wish to acknowledge the assistance of water-resources organizations in each State for their review of the descriptions of State ground-water resources and the assistance of the following Federal agencies, who provided unpublished data and advice in preparing parts of this report:

National Oceanic and Atmospheric Administration, National Weather Service
Tennessee Valley Authority
U.S. Army Corps of Engineers
U.S. Bureau of Reclamation
U.S. Bureau of Land Management
U.S. Coast Guard, National Response Center
U.S. Environmental Protection Agency
U.S. Fish and Wildlife Service
U.S. Soil Conservation Service

The authors of individual articles and State ground-water summaries are identified within the report. Richard H. Johnson, John S. McLean, Andrew

M. Spieker, and Lindsay A. Swain coordinated the preparation of the State summaries. David A. Aronson, Bruce L. Foxworthy, Kenneth J. Lanfear, Perry G. Olcott, Robert S. Roberts, and Michael Turtora reviewed the text and illustrations. Janet N. Arneson coordinated the assembly of the manuscript. Although individual credit is not feasible for all reviewers, graphic specialists, and typists who participated in the preparation and publication of this report, their cooperation and many contributions are gratefully acknowledged. Overall preparation of the 1984 *National Water Summary* was directed by David W. Moody, John N. Fischer, and Edith B. Chase.

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Hydrologic Conditions and Water-Related Events, Water Year 1984

Overview of Water Year 1984 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 result principally from climatic factors. The following annual and seasonal summaries of hydrologic conditions for water year 1984 are, therefore, described in a climatic context. Streamflow and precipitation are shown on maps for a water-year overview. They also are presented on a quarterly basis in the seasonal summaries where they are supplemented by maps showing temperature as a percentage of normal values and mean atmospheric pressure conditions near 10,000 feet (ft). The distribution of high and low pressure areas across the United States at about 10,000 ft, recorded in terms of the 700-millibar (mb) pressure surface, influences the distribution of surface temperature, precipitation and, thus, streamflow. Usually, floods and droughts that persist throughout a season will be observed in conjunction with persistent high- or low-pressure conditions in the upper atmosphere. Inasmuch as these maps depict conditions averaged over a 3-month period, ephemeral events, such as a single flood resulting from an individual storm, may not be associated easily with prevailing upper-air conditions.

The data used in preparing these summaries were taken from a number of publications. These include the National Oceanic and Atmospheric Administration's publications *Climate Impact Assessment, United States*; *Daily Weather Maps, Weekly Series*; *Monthly and Seasonal Weather Outlook*; *Storm Data*; and *Weekly Weather and Crop Bulletin* (prepared and published jointly with the U.S. Department of Agriculture); and the U.S. Geological Survey's monthly *National Water Conditions* reports.

Streamflow conditions across the United States during water year 1984 followed closely the pattern of normal to above-normal conditions experienced during the previous year. Indeed, with only minor differences, even the core areas of greatest departure from mean conditions persisted between each of the two periods. Although there tended to be fewer extreme or extraordinary flooding events, such as those experienced along the Gulf Coast in the winter of water year 1983, the frequency of more moderate floods was greater. This was especially true in the Middle Atlantic and New England States.

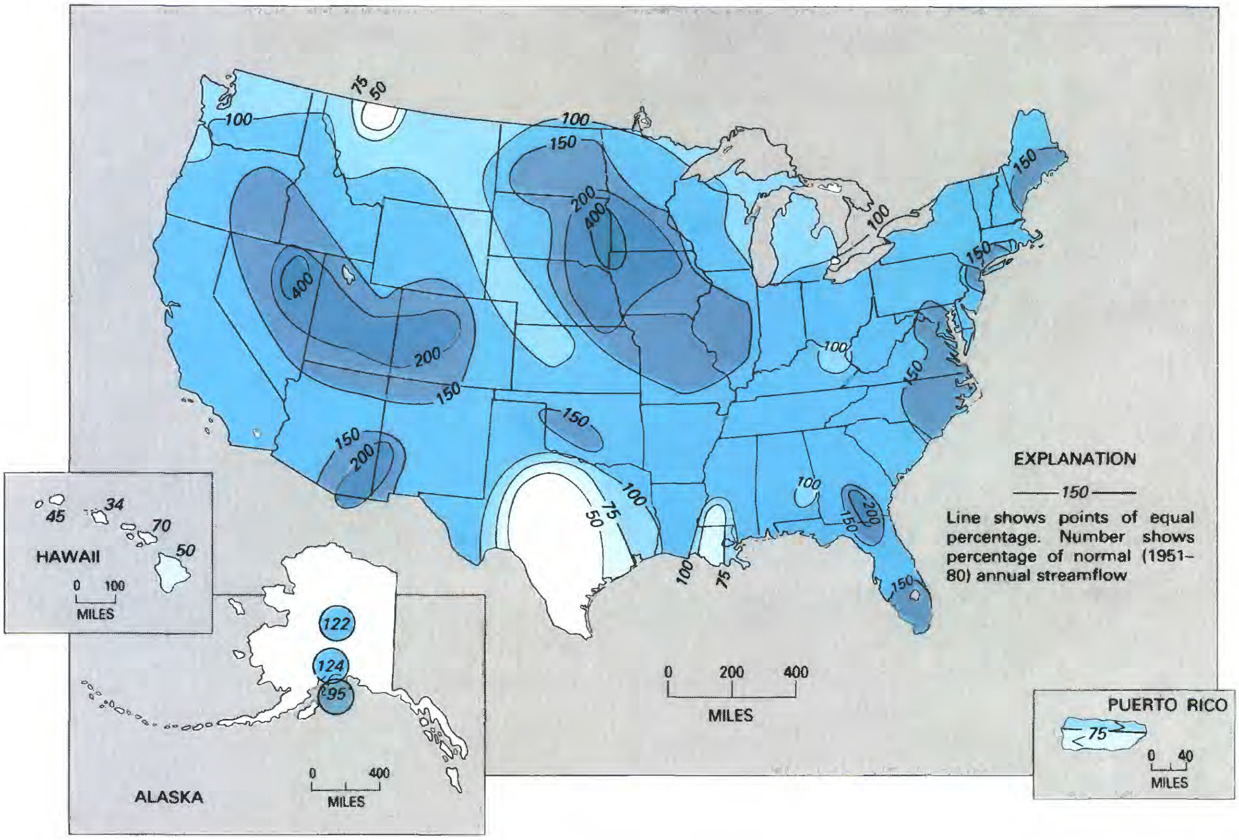
Interestingly, despite the geographical similarity in the patterns of annual streamflow departures that characterized the two periods, a major atmospheric phenomenon believed responsible, in large part, for the higher than normal runoff conditions in water year 1983 did not exist in water year 1984. Whereas the weather and climate, hence streamflow, of North America in water year 1983 was influenced considerably by the unusually intense El Niño Southern Oscillation (ENSO) of 1982–83, virtually all aspects of ENSO had ended by the fall of water year 1984 (Bergman, 1984). Why, then, did these two periods exhibit such similar patterns of streamflow? The answer appears to be that, even though the primary characteristics of ENSO in the tropical Pacific Ocean (that is, elevated sea surface temperatures, reversals in sea level pressure fields, and perturbations in both lower and upper level winds) had dissipated by the fall of water year 1984, other atmospheric features influencing North American weather and climate, not uniquely associated with ENSO occurrences, did not. For example, atmospheric circulation at the 700-mb level (about 10,000 ft), which is closely associated with surface weather patterns, had very similar mean seasonal patterns in each of the 2 years. Similarly, the patterns in each of the other three seasons exhibited close agreement in each of the 2 years; even though there was considerable within-year (season-to-season) variation.

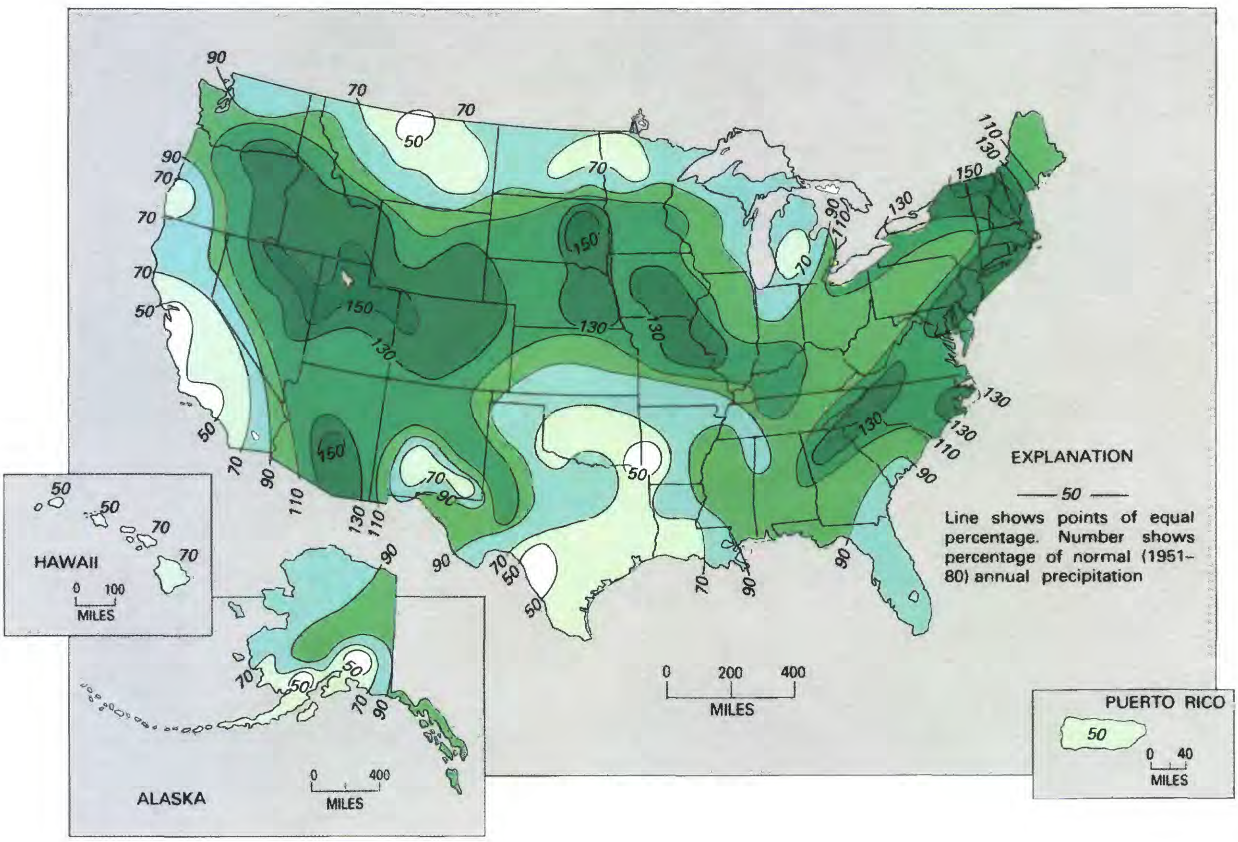
Figure 1. Streamflow in water year 1984 as a percentage of normal (1951–80) in the United States and Puerto Rico. (Source: Compiled by H. C. Tang from U.S. Geological Survey data.) ▶

The pattern of annual departures from normal or average streamflow conditions for water year 1984 appears in figure 1. Three broad areas of above-normal flows stand out along with two smaller areas of below-normal flows. Above-normal runoff occurred across the Great Basin and into the Central Rockies, in the middle and lower Missouri River valley, and throughout many of the States along the Atlantic coast. Below-normal runoff persisted in western Montana, central and southern Texas, and in Hawaii. These patterns match quite well the distribution of precipitation anomalies for the same period (fig. 2).

In general terms, despite the acute drought that occurred in several areas, water year 1984 was one of abundant to excessive streamflow in most of the United States (figs. 3 and 4). This condition is indicated clearly

Figure 2. Precipitation in water year 1984 as a percentage of normal (1951–80) in the United States and Puerto Rico. (Source: Compiled by H. F. Lins from National Oceanic and Atmospheric Administation, National Weather Service data.) ▶


EXPLANATION
—150—
Line shows points of equal percentage. Number shows percentage of normal (1951–80) annual streamflow
0 200 400
MILES
HAWAII
0 100
MILES
ALASKA
0 400
MILES
PUERTO RICO
75
0 40
MILES


EXPLANATION
—50—
Line shows points of equal percentage. Number shows percentage of normal (1951–80) annual precipitation
0 200 400
MILES
HAWAII
0 100
MILES
ALASKA
0 400
MILES
PUERTO RICO
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0 40
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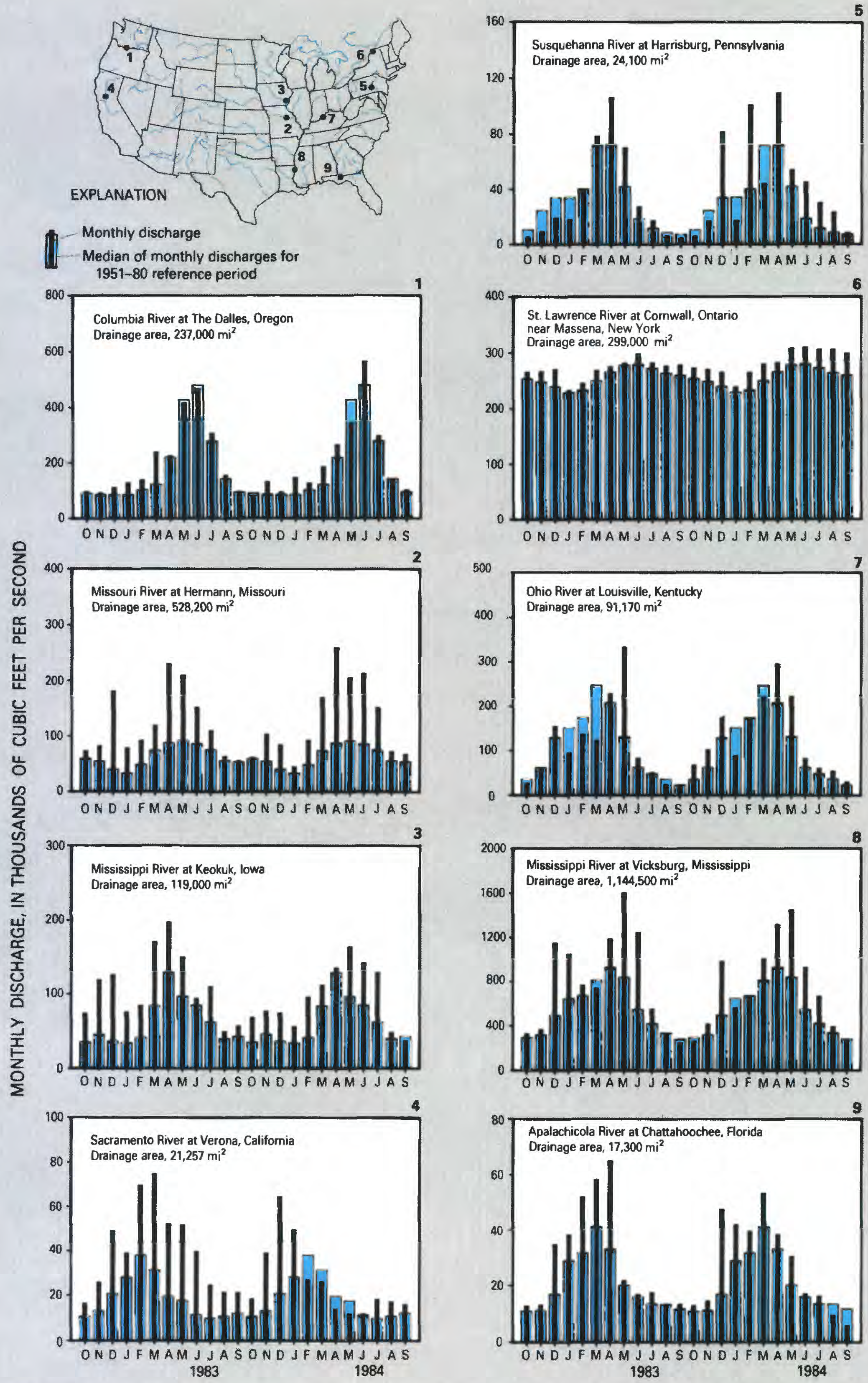

Figure 3. Monthly discharges for selected major rivers in the United States for water years 1983 and 1984 compared with monthly median discharges for the reference period 1951 to 1980. (Source: Compiled by H. C. Tang from U.S. Geological Survey data.)

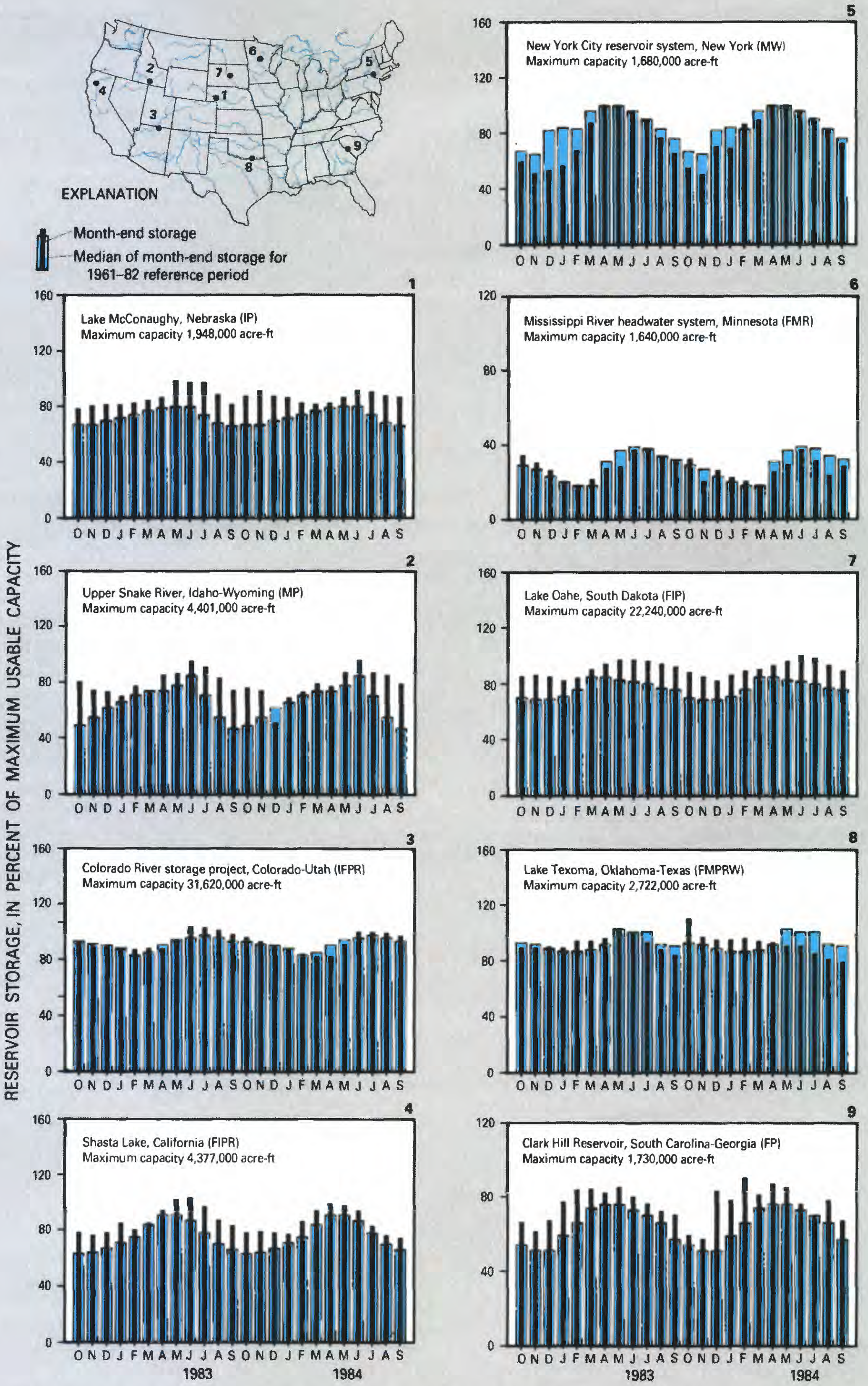

Figure 4. Month-end storage of selected reservoirs in the United States for water years 1983 and 1984 compared with median of month-end storage for reference period 1961 to 1982. Principal reservoir and water uses: F, flood control; I, irrigation; M, municipal; P, power; R, recreation; and W, industrial. (Source: Compiled by H. C. Tang from U.S. Geological Survey data.)

by considering the annual flow of the Nation's three largest rivers—the Mississippi, the St. Lawrence, and the Columbia. The combined average water year 1984 flow for these three rivers was more than 1.27 million cubic feet per second (ft^3/s), or 23 percent above the annual average. Moreover, the combined average flow of these rivers for each season in water year 1984 also exceeded its respective seasonal average.

Additional evidence for the nearly nationwide pattern of abundant surface-water resources (in water year 1983 as well as 1984) can be obtained from a check of the monthly flow and storage content of selected rivers and reservoirs across the country (fig. 3). The graphs indicate that, in at least 8 months of water year 1984, the nine rivers had flows in excess of the 30-year median value. Moreover, the Missouri River at Hermann, Mo., and the St. Lawrence River near Massena, N.Y., had discharges in excess of median flows in all 12 months. Graphs of monthly reservoir storage across the country show a basically similar pattern (fig. 4). Seven of the nine selected reservoirs had storage content in excess of a 21-year median value in at least 7 months of 1984. Two reservoirs exceeded the median values in 11 months and two reservoirs exceeded median values in all 12 months of water year 1984.

A tendency for most of the country to experience uniformly either excessive (as occurred in 1984) or deficient streamflow has been recognized for some time (Busby, 1963). The specific pattern of runoff in 1984 is the most common of several systematic and recurrent modes of nationwide streamflow variation (Lins, 1985). Moreover, the co-occurrence of opposing excessive and deficient flow departures in the middle Missouri River valley and in southern Texas also has been documented as a recurring pattern of variation on annual time scales (Lins, 1985). Thus, in a long-term context, the patterns characteristic of the 1984 water year are, in many ways, quite typical of annual streamflow variations in the United States.

Directly contributing to these general patterns of nationwide runoff were a series of significant and diverse hydrologic events. The geographic locations of these events are shown in figure 5, and a listing appears in table 1. Although many of these hydrologic events resulted from ephemeral meteorological conditions, others followed from more persistent atmospheric conditions. The flooding that occurred in the Great Basin and Central Rockies, for example, was primarily the result of the melting of a record snowpack that began accumulating in the Rockies in November 1983 (table 1, event 64). Similarly, a series of frontal systems brought showers and thunderstorms throughout the month of June 1984 to much of the Central Great Plains. As a result, peak flows along several streams within this region were the highest observed over a 50- to 80-year period of record (table 1, event 69). As for the low streamflows that occurred in parts of Texas, some areas had experienced more than 52 consecutive weeks of drought by the end of water year 1984. Such examples of hydrologic extremes emphasize the importance of climatic persistence in determining large-scale annual variations in streamflow.

Table 1. Chronology of significant hydrologic and water-related events, August 1983 to September 1984

[The events described below are representative examples of hydrologic and water-related events that occurred throughout water year 1984. However, to provide continuity with the 1983 *National Water Summary*, the chronology begins with the events of August 1983. 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 based on reports transmitted by State agencies. Meteorological data mostly are from reports of the National Oceanic and Atmospheric Administration (NOAA). Abbreviations used: mg/L = milligrams per liter, Mgal = million gallons, Mgal/d = million gallons per day, ft^3/s = cubic feet per second, mi = miles, mi^2 = square miles, gal = gallons, in. = inches, bbl = barrels, mi/hr = miles per hour]

Location number in figure 5	Event
	August 1983
1	Runoff from as much as 12 in. of rain on August 2 caused sharp rises and moderate flooding in southern Louisiana on the Amite River and nearby streams. The flow of the Amite was the highest in 45 years of record for August.
2	About 25,000 fish in a 1-mi reach of the Saline River near Equality in southern Illinois were killed by strip-mine effluent (sulfuric acid) on August 3. The Saline River is a tributary of the Ohio River, entering 40 mi southeast of Evansville, Ind.
3	Heavy thunderstorms on August 10 moved northward across Las Vegas Valley and caused flash flooding and major damage to more than 100 homes in the area. The heaviest rain occurred west of the city where the eastward- sloping Flamingo and Las Vegas washes became swollen beyond capacity.
4	In mid-August, Hurricane Alicia became the first hurricane to make landfall in the conterminous United States in 3 years. According to NOAA, the hurricane was one of of the costliest in Texas history. Alicia caused widespread damage to a large part of southeast Texas, including areas near Galveston and the entire Houston area. Rainfall amounts in coastal areas were 6 to 8 in.
5	In the Pacific Ocean, drought conditions on American Samoa, which had prevailed since October 1982, contributed to a sharp increase in chloride concentration in water from public-supply wells; some wells were shut down when the chloride concentration reached a level of 600 to 1,000 mg/L. On August 15, as a result of reduced water supplies due to terminated pumping of the wells, two tuna canneries, which normally use 1 Mgal/d, ceased production. On Guam, although drought conditions ended in August, the U.S. Navy's Fena Valley Reservoir had the lowest water level since the dam was completed in 1950.

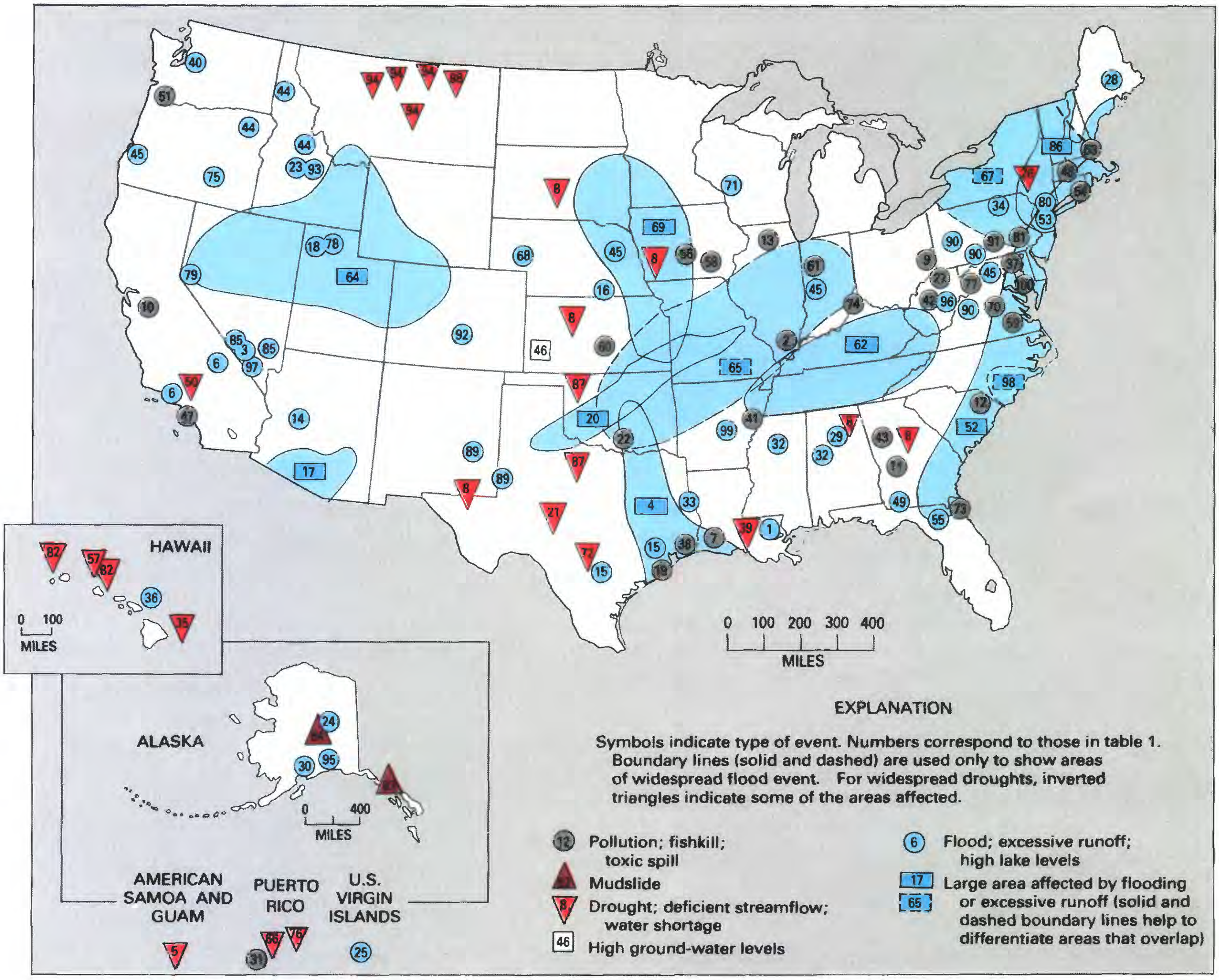

Figure 5. Location or extent of significant hydrologic and water-related events in the United States, Puerto Rico, U.S. Virgin Islands, Guam, and American Samoa, August 1983 to September 1984.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	August 1983—Continued
6	In southern California, runoff from unusually heavy rains on August 17 and 18, associated with the breakup of Hurricane Ishmael, produced moderate, but widespread, flooding in south-coastal areas and the desert areas of Imperial and San Bernardino Counties. Many secondary roads were washed out. On August 18, the stream gage on the Amargosa River at Tecopa Hot Springs, about 50 mi southeast of Death Valley, experienced a peak discharge of 10,800 ft^3/s; this was more than twice the previous all-time high flow in 23 years of record.
7	On August 23, a ruptured pipeline about 5 mi west of Lake Charles in southwestern Louisiana discharged more than 290,000 gal of crude oil into Bayou Verdine.
8	Drought conditions persisted in much of the Southeast and Midwest, although rains near the end of August relieved drought conditions in parts of the Southeast. Streamflows were the lowest of record for August in parts of Kansas and extreme southeast New Mexico. Some areas of west Texas received some relief from the severe drought during the latter part of the month from rains caused by Hurricane Alicia. Parts of north Texas received as much as 4 in. of rain. In Iowa, August was the driest and hottest on record.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	September 1983
9	On September 9, on the Ohio River near Wheeling, W. Va., about 1½ million fish were killed along 8 mi of the river by a discharge of cyanide into the river from a metals plant.
10	On September 14, at Los Banos, Calif., 70 mi southeast of San Francisco, a ruptured pipeline flooded Panoche Creek and a 1-acre marsh with 200,000 gal of medium- weight oil. Panoche Creek is a tributary of the San Joaquin River.
11	On September 15 and 16, in southwestern Georgia, a spill of toxaphene killed about 35,000 fish (mainly game species) in a 1½-mi reach of Muckaloochee Creek and in the 75-acre Wells Mill Pond near Smithville. The creek is a tributary of Flint River, which flows through Albany, Ga.
12	From September 16 to 18, near Effingham in southeastern South Carolina 70 mi east of Columbia, food-plant wastes discharging into the stream because of a lagoon-dike failure killed about 17,000 fish (70 percent game fish) in a 14-mi stretch of the Lynches River.
13	On September 17 and 18, in northern Illinois 55 mi west of Chicago, toxic materials from farming operations killed 46,000 fish along 4½ mi of Little Indian Creek near Leland. The creek is a tributary of the Illinois River.
14	On September 23, in the Prescott area of central Arizona, extreme amounts of precipitation from thunderstorms caused large flash floods. Measured amounts of rainfall at eight unofficial sites for the 36-hour storm period were 11 to 14.9 in. The peak discharge along Willow Creek was among the greatest measured in Arizona for streams with drainage areas of nearly the same size. Damage to public and private property was estimated to total nearly $2 million.
15	Flash floods occurred in several parts of south Texas as a result of thunderstorm rainfall of 3 to 7 in. or more on September 18 and 19. Flooding was widespread in Bexar County; one person was killed. In the Harris County-Houston area, three people drowned during the widespread flooding.
16	On September 28 and 29, flash flooding occurred in southeastern Nebraska and adjacent Kansas as a result of rains of 3 to 6 in. and as much as 8 in. in some local areas. The recurrence interval was estimated to be about 10 years. Considerable lowland flooding occurred along the Little Blue and Republican Rivers and their tributaries. Damage was primarily to farmlands and to county roads and bridges.
	September to October 1983
17	Heavy rains, from September 28 to October 3, deluged the southeastern quarter of Arizona with 3 to 11 in. of precipitation. Much of the moisture was supplied by Tropical Storm Octava. The largest floods of this century or the largest known floods occurred in places along the Santa Cruz, San Pedro, San Francisco, and Gila Rivers. Extreme floods also occurred on a few of the streams that are tributary to the major rivers in the area. The recurrence interval of the flood was greater than 100 years for the major rivers and several of the larger tributaries. This was Arizona's seventh major flood in 6 years. Preliminary estimates of damage to homes, agriculture, businesses, and public property totalled more than $175 million. More than 1,300 homes were damaged severely or destroyed. At least 10 storm-related deaths were reported. Flood damages along the Gila and San Francisco Rivers in New Mexico were reportedly more than $14 million. Damage to bridges and roadways on the secondary, primary, and interstate highways was severe with several major highways closed during and following the flooding. The President declared this to be a major disaster area as a result of the flood damage.
	October 1983
18	After the smallest seasonal decline ever recorded—0.5 ft between June 30 and September 25—Great Salt Lake began an unusually early rise. By mid-October, the level had risen 0.3 ft to an altitude of 4,204.55 ft above sea level.
19	On October 17, at an oil refinery at Clear Creek, Tex., in the Houston-Galveston area, more than 100,000 gal of light crude oil leaked from a tank, and much of the spill entered Clear Creek. The spill adversely affected fish and wildlife in the area. Clear Creek is a tributary of Galveston Bay. Cleanup was completed by October 31.
20	From October 19 to 21, torrential rains generated by northeastward-moving remnants of Hurricane Tico caused flooding in large areas from west Texas through Oklahoma to southern Missouri. Rainfall of more than 10 in. was common in parts of southwestern and central Oklahoma. As much as 13.8 in. of rain in 4 days caused flooding in Oklahoma City and many small communities. Amounts in southern Missouri generally were 4 to 7 in. In Oklahoma, at least five deaths resulted from the storm, and damage estimates were about $18 million for property and $77 million for agriculture. The President designated 16 counties as disaster areas. Peak flows of some tributaries of the Red River were the highest in 30 to 50 years of record, and estimated recurrence intervals were 50 to 100 years or more. Although the storm caused flash flooding, massive flooding generally was prevented by flood-control reservoirs that had been depleted by a summer-long drought. Guthrie, Okla., about 30 mi north of Oklahoma City, was one of the towns most severely affected by flash flooding from heavy rains. Nearby Cottonwood Creek crested at nearly 10 ft above flood stage.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	October 1983—Continued
21	The October rains brought long-term relief to the entire drought-stricken area of west Texas. As much as 4 in. fell on some counties where severe drought conditions had prevailed for many months.
22	On October 27, northwest of Lake Texoma in southern Oklahoma, a pipeline break leaked 42,000 gal of crude oil into the Washita River. High river waters prevented containment, and the oil was carried into the upper area of Lake Texoma.
23	The October 28 Borah Peak earthquake (magnitude 7.3 on the Richter scale), in Custer County, central Idaho, contributed to significant changes in flows of springs and to record-high surface runoff in the Big Lost River basin. The earthquake also is believed to have caused the erratic behavior of Old Faithful, a geyser in Yellowstone National Park 150 mi to the east, by altering ground-water flow patterns under the geyser.
	November 1983
24	On November 2 and 3, ice-jam floods occurred in the Tanana Valley of central Alaska as a result of the combination of sharply cooler temperatures in late October and of carryover of high streamflows. The ice jam of Salcha Slough, a tributary of the Tanana River about 33 mi east of Fairbanks, recurred on November 8. Wells and septic systems in the area were unusable for several days due to resultant high ground-water levels.
25	On November 4, heavy showers and thunderstorms caused local flooding in the Virgin Islands, especially over the eastern one-half of St. Croix, where 24-hour totals reached nearly 9.5 in. Major road damage occurred on St. Croix and St. John along with minor damages to some homes from overflowing creeks on parts of St. Croix.
26	On November 9, the Delaware River Basin Commission declared a drought warning for the Delaware River as a result of a dearth of rainfall in the reservoir storage areas (mainly in southeastern New York) of the Delaware, thereby putting restrictions and other conservation measures into effect. The Delaware River Master (a U.S. Geological Survey hydrologist designated in accordance with a U.S. Supreme Court decree) had advised interested parties on October 27 that restrictions on diversions of water from the basin by New York City were imminent.
27	On November 22 and 23, near Farmington in northwestern West Virginia, a tank truck spilled 4,000 gal of liquid sodium hydroxide into Little Dunkard Mill Run and killed 16,000 fish along a 2½-mi reach. The stream is a tributary of Buffalo Creek.
28	From November 24 to 27, local flooding was caused in many parts of Maine and Massachusetts by heavy rains and strong winds. Rainfall totals were commonly 2 to 4 in. in Maine, with as much as 5.4 in. at Bangor. About a dozen roads in Bangor alone were washed out or flooded to dangerous levels. More than 3 in. fell in much of eastern Massachusetts. Gale winds and high tides compounded the problems in coastal areas.
29	On November 27, in the Birmingham, Ala., area, a 24-hour rainfall of 5.2 in. triggered flash flooding of low areas.
30	On November 28 and 29, a combination of heavy rains and snowmelt caused by warm temperatures resulted in widespread flooding and mudslides in the southern Kenai Peninsula south of Anchorage, Alaska. The flood recurrence intervals may equal or exceed 100 years.
31	In late November, a ruptured pipeline near Barceloneta, Puerto Rico, spilled from 1 to 5 Mgal of mostly industrial wastes to the shallow ground-water bodies.
	December 1983
32	On December 2 and 3, heavy rains over the northern one-half of Mississippi and Alabama, exceeding 9 in. at Birmingham, caused widespread flash floods. Peak flows of several streams were as high as those likely to occur once in 50 to 100 years. One person died in Alabama as a result of the flood, and at least 2,700 dwellings in the two States were damaged. In west-central and northeast Mississippi, serious river flooding occurred in the Yazoo, Big Black, and Tombigbee River basins including flooding of homes mainly near the cities of Greenwood, Grenada, and Columbus. Rapidly rising water levels along the upper Black Warrior River above Tuscaloosa resulted in disruption of barge movement; many barges sank, and one lodged in the spillway gates of a control structure.
33	On December 10 and 11, heavy rains of 5 to 8 in. occurred across southern Louisiana and caused widespread flash flooding. Also, Sabine Parish in northwestern Louisiana received heavy rains of 5 in. or more. In east Texas, as much as 10 in. of rain caused local flooding, especially in San Augustine County.
34	From December 12 to 15, flooding in eastern Pennsylvania along such major rivers as the Susquehanna, Delaware, Lehigh, and Schuylkill was caused by 2.5 to 5.5 in. of rain. Some of the most extensive property damage occurred in Tioga and Bradford Counties. Two drownings were reported.
35, 36	On December 19, a drought emergency was declared for the Puna, Kau, and south Kona areas on the island of Hawaii. On December 25 and 26, heavy thunderstorm rains of 6 to 10 in. over Maui and northern parts of the adjacent island of Hawaii produced localized flash flooding that caused some damage to crops, roads, and construction projects. Despite the destructiveness, the rains brought temporary relief from the year-long drought. Nevertheless, 1983 was the driest year of record in many areas.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	December 1983—Continued
37	On December 24, a ruptured storage tank in the Baltimore, Md., area leaked 3,365 tons of sulfuric acid, of which about 90 percent entered the Cabin Branch of the Patapsco River. Cleanup included spreading soda ash to neutralize the acid in the soil and water.
38	On December 24, in Sea Rim State Park near Port Arthur, Tex., adjacent to the Louisiana border, 84,000 gal of crude oil discharged from an oil well because of failure to close the wellhead valve. Part of the oil flowed into Lost Lake and adjacent marshland before being recovered; the oil reportedly killed some birds in the State park.
39	The cold wave that gripped the midcontinent area of the country caused record cold for the month in Louisiana. On December 16, northern Louisiana received 8 in. of snow, an unusual occurrence. The Red River at Shreveport froze over for the first time in recorded history. On December 27, Baton Rouge pumpage was reported within about 3 percent of absolute capacity, owing to frozen and broken water pipes causing loss of pressure.
	January 1984
40	Intense precipitation in the State of Washington on January 4 and 5 caused flooding in the foothills on the western side of the Cascade Mountains. The floods had a recurrence interval of about 25 years and caused significant channel changes in small drainage areas.
41	On January 9, nearly 30,000 gal of jet fuel was spilled into the Mississippi River near Bruins, Ark., 25 mi south of Memphis, Tenn., when a tanker barge struck a river dike and sank. No cleanup of the spilled material was feasible because of the swift river current.
42	On January 9, chemical effluent, possibly highly concentrated sodium hydroxide or one or more aromatic hydrocarbons, killed about 10,000 fish along 2.6 mi of the Left Fork of Falls Run near Falls Mill, Braxton County, in central West Virginia. Falls Run is a tributary of the Little Kanawha River.
43	On January 12, more than 6,000 fish were killed by ammonium nitrate fertilizer in Tarver Branch near Woodbury, Ga., 50 mi south of Atlanta. The contaminant reached the stream as a result of firefighting operations at a bulk fertilizer warehouse. Tarver Branch is a tributary of the Flint River.
44	Moderating temperatures and rainfall near the end of January in the Northwestern States on both sides of the Continental Divide triggered ice-jam floods along several streams. In Union County, northeastern Oregon, overflow from several rivers caused loss of livestock and extensive damage to State parks. In eastern and northern Idaho, ice-jam floods along the Salmon and St. Joe Rivers damaged parts of Salmon and Calder, respectively. In the Missouri River basin, an ice jam nearly 500 mi long formed in the Missouri River above Jefferson City, Mo.
	February 1984
45	Between February 11 and 16, various combinations of thawing temperatures, rainfall, and ice jams caused lowland flooding in many parts of the Nation. In western Oregon, rains of 4.5 in. in 24 hours on February 12 and 13 caused floods, mudslides, and rockslides. Rainfall also was especially heavy in north-central Virginia, western Maryland, and Pennsylvania. Flows and flooding along the Potomac River were the greatest since Tropical Storm Agnes in 1972, but damage did not approach the severity of that storm. Ice-jam flooding was common in Illinois, Indiana, and New York State. Lowland flooding also affected the lower reaches of the Platte and Elkhorn Rivers in Nebraska.
46	The flow in the Arkansas River reached the Garden City, Kans., gaging station for the first time since 1975 on February 15. Ground-water levels in the adjacent alluvium rose 17.4 ft in 3 days to a level of 10.1 ft below land surface. The flow was due to high moisture conditions and subsequent abnormal ground-water seepage into tributaries entering the river downstream from John Martin Reservoir in eastern Colorado.
47	On February 17, at an oil facility in El Segundo, Calif., near the southeastern edge of Los Angeles, a ruptured tank discharged 42,000 gal of caustic phenol. The pollutant soaked into the ground.
48	During February, widespread ground-water contamination by the pesticide ethylene dibromide was discovered in north-central Connecticut and south-central Massachusetts. This chemical was used as a soil fumigant on tobacco fields from the mid-1950's to 1983.
	March 1984
49	During the period from March 6 to 10, moderate to severe flooding occurred in southern Georgia and parts of northern Florida, caused by runoff from heavy rains (as much as 9 in. in a 24-hour period) on March 5 and 6; totals of 5 to 6 in. were common. Floods on some Georgia streams had recurrence intervals of 50 years. The Suwannee River and its tributaries were reported to have experienced floods of 10- to 25-year recurrence intervals. The Withlacoochee River at Pinetta was within 1 ft of record high and nearly a 100-year-recurrence flood. With the Suwannee River in flood and many miles of developed property under water, the Suwannee River Water Management District established a policy of eventual acquisition of all property in the Suwannee River flood plain.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	March 1984—Continued
50	Very light rain on March 13 and 14 over most of coastal southern California broke a 10-week drought. Santa Barbara had its driest January (0.21 in.) and February (0.12 in.) of record since 1868. The city of Los Angeles had the second driest January and February of record since 1878 (0.18 in.). At San Bernardino County Flood Control headquarters, January rainfall was only 0.18 in. and February rainfall was 0.19 in.
51	On March 19, near St. Helens, Oreg. (20 mi north of Portland), an oil tanker ran aground on the rocky bottom of the Columbia River, spilling more than 150,000 gal of heating oil into the river.
52	A severe storm system from March 27 to 30, combining high winds, snow, ice, and thunderstorm rains, battered many parts of the Eastern United States. At least 80 deaths were attributed to the storm. Damage was greatest from tornadoes in the Southeast and from high winds, tides, and associated flooding along coastal areas from Massachusetts to the Carolinas. Moderate flooding occurred along many streams in the Carolinas and in southeastern Virginia.
	April 1984
53	On April 4 and 5, in northern New Jersey and southeastern New York, severe flooding resulted from intense rains, about 5 in. within 24 hours in some places, falling on frozen ground combined with melting of a residual snowpack. Two deaths were reported. Peak flows on the Wanaque and Ramapo Rivers were the highest in 68 and 66 years of record, respectively. In northern New Jersey, more than 9,000 people were forced to flee from their homes because of rising water.
54	On April 6, at Groton, Conn., a transformer leaked 30 gal of polychlorinated biphenyl (PCB), of which 10 gal entered the Thames River. The remainder, spilled on shore, was cleaned up within a few days.
55	A series of rains between April 9 and 15 caused moderate flooding in northern Florida. Peak discharge on the Suwannee River at Branford on April 13 and 14 had a recurrence interval of about 25 years.
56	Water samples taken in mid-April showed that the Des Moines, Iowa, water supply contained nitrate in excess of Federal recommended limits for drinking water. Des Moines obtains its water from infiltration galleries located adjacent to the Raccoon River. Low levels of trichloroethylene (TCE) also had been detected in Des Moines water samples.
57	On April 16, the Honolulu Board of Water Supply asked residents on Oahu to reduce usage of water by 10 percent because of a drop to "caution" water levels at five major sources. Three danger signals, "caution," "alert," and "critical," are used.
58	On April 24 and 25, in southeastern Iowa near Fairfield, nearly 20,000 fish were killed by ammonia (from fertilizers) in Crow Creek.
59	On April 29, near Hopewell, south of Richmond, Va., 650 gal of sulfuric acid was spilled into the James River from a defective heat exchanger at a chemical plant. The pH (hydrogen ion concentration) of the river water had returned to normal by May 2.
60	Samples of ground water withdrawn from a test well at a hazardous waste landfill near Furley, Kans., north of Wichita, contained more than 213,000 mg/L of organic compounds. Although specific chemicals were not identified, the organic compounds were determined to be solvents. The landfill has been closed since January 1982 when investigation revealed that hazardous chemicals had contaminated ground water beneath the site and were present in nearby Prairie Creek. The high concentration of organic solvents observed in April 1984 was almost 10 times greater than concentrations observed in January 1982 when the landfill was closed.
	May 1984
61	On May 2, in northwestern Indiana, drainage from an area spray-irrigated with swine waste, killed about 21,000 fish along 3.8 mi of Bridge Creek near Delphi. The creek flows into Deer Creek, a tributary of the Wabash River, 60 mi northwest of Indianapolis.
62	During the first 8 days of May, a series of storms moved eastward from northeast Texas to New Jersey, producing heavy downpours and flooding in many eastern and east- central parts of the United States. In central and southern Kentucky, for example, runoff from 4 to 8 in. of rain between May 5 and 7 caused most streams to reach flood stage; flows in Little River, Bacon Creek, and Russell Creek near Columbia, 60 mi southwest of Lexington, exceeded the 100-year flood. Widespread flooding occurred in the Big Sandy, the upper Kentucky, the Cumberland, and the Green River basins. In southwestern Virginia, extensive flooding occurred in Dickenson, Buchanan, and Washington Counties on May 7. In Tennessee, floods resulting from 4 to 9 in. of rainfall from May 5 to 8 had recurrence intervals ranging up to at least 50 years. Three deaths were reported. In southwestern West Virginia, the peak discharge of Tug Fork at Kermit on May 8 was equal to a 40-year-frequency flood; one death was reported, and thousands of people were evacuated because of rising water.
63	On May 10, during and following explosions and a fire at a manufacturing plant in Peabody in northeastern Massachusetts, 5 Mgal of runoff from firefighting at the plant entered the North River, which flows into Salem Harbor. The firefighting runoff contained low levels of cyanide, toluene, and benzene from 1,000 bbl of chemicals normally available for plant operations.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	May 1984—Continued
64	Warming temperatures in the Rockies, beginning about May 11, increased snowmelt from a record snowpack and caused severe flooding in addition to accompanying mudflows and mudslides. Extensive flooding and sustained high flows occurred in the Colorado River basin, the Snake River basin, the upper North Platte River basin, and also in the Great Basin. Peak discharges on many streams exceeded the 100-year-recurrence flood and, in many instances, were greater than the floods of the previous June. The flow of the Colorado River at the Colorado-Utah State line on May 27, 1984, for example, was the highest of the period of record since 1951. The Gunnison River in Colorado peaked on May 25, and peak discharges occurred again on June 7 and 8 as a result of rains in the North Fork of the Gunnison. On May 16 in Montana, a combination of heavy rains and melting snow caused flow of the Ruby River upstream of the Ruby River Reservoir near Alder to peak at 3,500 ft^3/s. This was 2.2 times the 100-year flood for the Ruby River at this site. In southern Wyoming, the flow of the Little Snake River near Dixon peaked at 12,000 ft^3/s, a rate which had a recurrence interval of greater than 100 years. This peak discharge included flow from Grieve Reservoir which the flood had breached. On May 15, 6 miles downstream, flooding started in the town of Baggs, which was inundated by as much as 4 ft of water on May 16. The town remained under water for several days as the result of continued snowmelt runoff. Flow in the upper North Platte River in Colorado and Wyoming remained high during this period and for much of the spring. Near-record discharge was recorded on the North Platte River near Northgate, Colo., on May 17, and a tributary stream, Pass Creek near Elk Mountain, Wyo., had a peak flow of 4,660 ft^3/s on May 12. This flow exceeded the 100-year flood and was four times the previously recorded maximum. The heat wave speeded the melting of Utah's record mountain snowpack on May 13 and triggered floods and mudslides that killed one person and injured at least three. Snowmelt from a record snowpack in northeastern Nevada led to extensive flooding along the Humboldt River from April to June. The peak flow of the Humboldt at Palisade, Nev., on May 18 had a recurrence interval of about 50 years.
	May to June 1984
65	Heavy showers on May 26 and 27 covered the eastern part of the Plains States and many of the Eastern States. By the end of the month, these storms and others caused widespread floods. Flooding, from as much as 13 in. of rain in less than 24 hours, was especially severe in the Tulsa, Okla., area, where damages were estimated to be $150 million and 14 lives were lost. Most of the widespread damage was in the eastern part of the city along Mingo Creek where homes and business properties are concentrated.
66	During May, severe drought conditions continued to affect most of Puerto Rico, where the 6-month drought resulted in water rationing in San Juan and 35 other towns. Precipitation over the north coast was the least in 70 years.
67	Heavy rains and flooding in New England continued from May into the beginning of June, producing flows on many streams that were the highest since the disastrous floods of 1955. About June 1, peak flows of some rivers in Maine were the highest for June in 60 years of record. In northern Vermont, damage estimates exceeded $1 million in Washington, Lamoille, and Franklin Counties. Peak flow of Lamoille River at Johnson on June 7 nearly equaled the peak flow of record in 56 years at that measurement site and well in excess of 100-year-recurrence interval. The peak flow of the Connecticut River at Montague City, Mass., 10 mi south of the Massachusetts-Vermont State line, was the fifth highest for 80 years of record. In Connecticut, the peak flow of the Connecticut River at Hartford on June 1 was the fourth highest flow in 79 years of record. (See article "Record Late Spring Floods of 1984 in New England.")
68	Lowland flooding occurred for the second consecutive year along the North Platte River in western Nebraska in late May and early June as a result of runoff from the snowpack in Wyoming and the need to release water from Wyoming reservoirs. Peak discharges of the North Platte River at gaging stations upstream from Lake McConaughy were greater than the peak flows of water year 1983 and had recurrence intervals of about 25 years. Because peak flow of the South Platte River was only about one-half of the 1983 peak discharge, extreme flooding did not occur on the Platte River below the confluence of the North and South Platte Rivers as it did in 1983. The 1984 peak discharges of the Platte River in central Nebraska had recurrence intervals of about 15 years.
69	Repeated and heavy rains during June caused severe flooding in the Central Plains, especially in eastern Nebraska and adjacent areas of southeastern South Dakota, south western Minnesota, southwestern Iowa, northwestern Missouri, and northeastern Kansas. Parts of South Dakota received more than 5.5 in. of rainfall, and rains of more than 4 in. caused extensive damage in parts of Iowa and Kansas. Flood damage to property and crops in Iowa was estimated to be $1 billion, and storm and flood damage in 44 counties in Nebraska was estimated to be $94 million. In Minnesota, these storms caused the worst soil and crop losses of recent years. Peak flows on many streams in the six-State area were highest of record for June. Extensive flooding occurred along the Missouri, the Big Sioux, and the Nishnabotna Rivers. The flows on a few streams were all-time highs for the past 50 to 80 years. In eastern Nebraska, for example, the peak discharges of the Little Blue River near Fairbury on June 13 and the Big Blue River at Beatrice on June 14

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	May to June 1984—Continued
	were the highest flows in 63 and 82 years of record, respectively. Turkey Creek, a tributary of the Big Blue River in eastern Nebraska, had a peak discharge on June 13 of about 4½ times the previous maximum in 24 years of record. The flood discharge was about three times the discharge for the 100-year recurrence interval. More than 600 residents of DeWitt, at the mouth of Turkey Creek, were evacuated. In southeastern South Dakota on June 23, the peak discharge of the James River near Scotland was at an all-time high in the 56 years of record and exceeded flows of the 100-year recurrence interval. (See article "June 1984 Floods on the Missouri River and Tributaries.") The greatest monthly volume of flow ever recorded in June during the past 50 to 75 years occurred on several streams in Minnesota, including the Minnesota, the Chippewa, and the Des Moines Rivers. Heavy flows of the Chippewa and Lac qui Parle Rivers into Lac qui Parle caused the Minnesota River (which flows through the lake) to flow upstream over the Marsh Lake Dam (the next dam upstream) as well as downstream out of the lake for several days during June.
	June 1984
70	On June 4, at Richmond, Va., 20 Mgal of sewage, which was discharged directly into the James River, bypassed the water-treatment plant. This was done to prevent possible plant damage from potentially dangerous and explosive chemicals in the runoff from a nine-alarm fire that destroyed a feed and seed warehouse.
71	Intense thunderstorms occurred over the southeastern tip of Minnesota and adjacent west-central Wisconsin on June 16. Seven inches of rain in 75 minutes was reported near Westby, Wis., 80 mi northwest of Madison. A flood with a recurrence interval greater than 100 years occurred on Spring Coulee Creek near Coon Valley, 5 mi northwest of Westby.
72	On June 25, water levels in the San Antonio area, Texas, "sole-source" Edwards aquifer declined to 625 ft above sea level and triggered Phase I, Voluntary Conservation, of the recently established water-conservation plan.
73	Two fishkills occurred in June along Trout Creek in northeastern Florida, about 25 miles south of Jacksonville, apparently caused by discharges from food-processing operations. Estimates of fish killed on June 15 were 80,000, and, on June 28 and 29, nearly 400,000 were killed. Trout Creek is a tributary of the St. Johns River.
74	In a 20-acre pond at Milan in southeastern Indiana, nearly 5,000 game fish died on June 29 and 30 from pollution by an insecticide.
75	In June, the level of Malheur Lake, Oreg., peaked at an altitude of 4,102.4 ft, highest in the 52-year period for which levels have been recorded or observed and exceeding the previous highest record level observed by 7 ft. Malheur and Harney Lakes, coalesced into a single body of water as a result of the rising water levels, covered nearly 150,000 acres. Eighteen ranch families were evacuated, and damages were estimated to be $13 million. Persistent flooding of lakeshore areas has been escalating since 1982.
76	In Puerto Rico, June rains, especially during the second one-half of the month, replenished the water resources of the island and thus ended a prolonged period of drought and water shortages.
77	In June in Frederick County in northwestern Virginia, a tire fire that had burned for 8 months following ignition on October 31, 1983, finally was quenched. The fire consumed a 4.5-acre mountain of 9 million used tires. At its peak, the fire generated more than 100,000 gal of residual oil per day. More than $1.25 million of Superfund money allocated by the U.S. Environmental Protection Agency assisted in the support of fire-suppression and pollution-control efforts. After containment of the surface contaminants, surface-water problems were minor, but long-range effects on ground water are uncertain.
	July 1984
78	On July 1, the level of Great Salt Lake peaked at 4,209.25 ft above sea level, the highest level in more than a century. The historical high level, about 4,211.5 ft above sea level, was in 1873, when the lake covered about 2,500 mi^2. The lowest recorded level was 4,191.35 ft in 1963, when the lake covered only 1,000 mi^2. (See article "Rise of Great Salt Lake, Utah.")
79	The largest terminal lakes in west-central Nevada reached their maximum water levels in many years in July. Pyramid Lake, the terminus of the Truckee River, peaked at 3,813 ft above sea level, the highest level since the 1940's. Walker Lake, the terminus of the Walker River, peaked at nearly 3,972 ft above sea level, the highest level since the mid-1960's. Carson Sink, the normally nearly dry terminus of the Carson and Humboldt Rivers, reached a peak of about 3,876 ft above sea level, which probably was the highest since the 1860's or the 1870's.
80	On July 7, intense thunderstorms caused significant flooding of several streams in Westchester County, in southeastern New York State. As a result of this storm, the highest peak discharge since 1972 was recorded for the Bronx River. In north-central New Jersey, also on July 7, severe thunderstorms caused record or near-record flooding in the 190 mi^2 drainage area of the North Branch Raritan River. At least 75 families

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	July 1984—Continued
	were evacuated from their homes. Rainfall of 8.92 in. in 24 hours at Pottersville on the Lamington River was reported by the National Weather Service. Peak flows on the Lamington River and parts of the North Branch Raritan River were higher than any in the last 89 years.
81	Along a 7-mi reach of the Susquehanna River near Marietta and west of Lancaster in southeastern Pennsylvania, herbicides and pesticides from agricultural operations killed about 3,000 fish between July 11 and 15.
82	Hawaii entered the 18th month of a drought that began in January 1983. Irrigated sugar-cane fields on leeward slopes on Oahu, which have received only 50 percent of normal rainfall since 1983, were depending heavily on ground water for irrigation. Honolulu received 5.03 in. of rain in 1983, less than one-quarter of its normal annual amount of 22 in. In July 1984, Kalihi Stream near Honolulu had its lowest July flow in 70 years of record. On July 12, Oahu residents and businesses were ordered to reduce water usage by 10 to 25 percent. Kauai residents have been under water conservation orders since April 1983.
83	On July 16, in Juneau, southeastern Alaska, a mud and debris slide from an old drainage chute off Thunder Mountain caused extensive personal property damage. The slide followed 10 days of rain, of which 1.5 in. fell within the 24-hour period before the slide.
84	Denali (Mount McKinley) National Park, in south-central Alaska, was closed on July 26 after a third mudslide in 3 days blocked the only road in the park. The park received about 1.56 in. of rain in one 24-hour period and about 3.76 in. for the month. July rainfall in the park usually amounts to only a trace.
85	During the last 10 days of July, Nevada had many heavy thunderstorms that caused moderate to intense flooding. In the Moapa Valley and at Las Vegas, many flash floods caused damage in the millions of dollars and the deaths of at least two persons.
86	Heavy rains in the Northeast during July, especially July 15 to 21, resulted in widespread flooding. A washout on a rail line caused a passenger-train accident in northern Vermont.
87	Extremely dry conditions persisted in much of Oklahoma and Texas. Flows of many streams in central and south Texas were near or at record low flows for the month.
88	At the end of July, nearly all the streams in north-central and northeastern Montana had very low flows or dry channels. Milk River at Nashua and Teton River were dry, the first zero-flow occurrence in the period of record. In contrast, streamflow elsewhere in the State, was average or near average, except in the southwestern part of the State where flow was higher than average.
	August 1984
89	Flash floods hit the Southwestern States on August 6 and 7. In New Mexico, six deaths and $2.5 million in property and roadway damage were reported.
90	From August 10 to 13, heavy rains caused local flooding on the eastern slopes of the Appalachians. Intense rains of 5 to 7 in. fell in a 3-hour period on August 13 on the headwaters of the Wills Creek basin in Somerset and Bedford Counties in southwestern Pennsylvania. Flooding occurred along a 28-mi reach of Wills Creek resulting in numerous evacuations and five deaths by drowning. The communities of Glencoe, Fairhope, and Hyndman suffered most of the devastation with total damage estimated in excess of $14 million. Peak discharge exceeded 100-year levels as far downstream as Hyndman. The flood was the highest observed at the Hyndman gage in the 34 years of record. In Maryland, peak discharge of a small stream west of Baltimore occurred on August 13 and had a recurrence interval of 75 years. In northwestern and west-central Virginia, intense local flooding occurred in parts of Loudoun and Nelson Counties; total rainfall from August 10 to 13, was as much as 6 in. in some locations.
91	About 4,400 fish died in a 1½-mi reach of Bargers Run, which is a tributary of the Susquehanna River, near Liverpool, Pa., 20 mi north of Harrisburg, on August 17. The cause was runoff from a hog-manure lot.
92	In southeastern Colorado, heavy rains between August 18 and 22, resulted in high flows in Fountain Creek and the Arkansas River upstream from John Martin Reservoir. Considerable hail damage occured (August 21) in and east of Pueblo during the storms. Insurance claims resulting from the hailstorm and associated wind and flooding in southeastern Colorado totalled more than $20 million.
93	In central Idaho, an earthquake of magnitude 5.2 occurred in the morning of August 22, 8 mi east of Challis, in the same general area as the earthquake of October 28, 1983. The hydrologic responses of both earthquakes were rising water levels in wells and increases in streamflow.
94	Lightning in dry forest and prairie areas of northern and central Montana triggered massive forest fires beginning about August 25. The fires were fanned by 70-mi/hr winds, strong enough to help the blazes jump the Missouri River and fire lines. Areas primarily affected were sparsely populated federally owned timber and grasslands. More than 300,000 acres were burned. Potential flood and sediment problems in the burned areas are of concern.

Table 1. Chronology of significant hydrologic and water-related events—Continued

Location number in figure 5	Event
	September 1984
95	In southern Alaska, record-high August rainfall preceded by above-normal temperatures caused excessive runoff in the area of Portage Glacier, 60 mi southeast of Anchorage. Flooding of Portage Creek, near Portage Lake, was in the vicinity of the National Park Service's new observatory, which is under construction.
96	Intense rainfall of 4 to 6 in. in a 2- to 4-hour period on August 30, produced major flash floods in eastern West Virginia. Several streams near Marlinton and Webster Springs had peak flows with a recurrence interval of 100 years. The Cranberry River near Richwood, W. Va., reached a stage that was the highest recorded in over 40 years.
97	A continuing series of moderate to severe flash floods that extended from the end of July to September in the Las Vegas Valley, Nev., culminated in the drowning death of a five-member family when their vehicle was washed off a roadway on September 10.
98	Hurricane Diana, after stalling off the North Carolina coast on the night of September 11, moved inland near Southport, N.C., at about 1 a.m. on the 13th with heavy rains and winds of about 100 miles per hour. Winds quickly decreased to 80 miles per hour, and, by the afternoon, Diana was downgraded by the National Weather Service to a tropical storm. The system moved slowly westward over New Hanover, Brunswick, and Craven Counties in southeastern North Carolina and then moved northwestward. Early on September 14, the storm circled northeastward across the central Coastal Plain and moved out to sea. Significant flooding occurred along headwater and intermediate-sized streams (less than 1,000 mi^2). Recurrence intervals of floods on smaller streams generally were 5 to 25 years. At Black River near Tomahawk, N.C., the highest flow of record (17,300-ft^3/s) contributed to a flood with a recurrence interval of greater than 100 years. Although the storm produced excessive rains, dry antecedent conditions and the sandy nature of Coastal Plain soils contributed to minimize surface runoff, and flood crests were considerably below predicted levels. Total damage estimates were over $90 million including more than $20 million in structural and agricultural damage in Brunswick and New Hanover Counties. The coastal towns of Southport, Long Beach, and Yaupon Beach (Brunswick County), reported the greatest damage. As much as 16 in. of rain fell in parts of New Hanover and Brunswick Counties. Elsewhere in the storm's path, rainfall generally was 3 to 10 in.
99	Four inches of rain that fell in about 2½ hours on September 23 resulted in flash flooding in Pine Bluff, Ark., southeast of Little Rock. Flood waters as deep as 6 ft on some city streets were reported. Sixty-nine buildings including residences, businesses, and public buildings were damaged, some seriously.
100	*Hydrilla verticillata*, the submersed aquatic plant from southeast Asia, that recently invaded the tidal Potomac River in the Washington, D.C., area, had become established on both sides of the river from Alexandria, Va., to Marshall Hall, Md., and also had been found in Chicamuxen Creek and Mallows Bay, south of Quantico, Va. Along most of the shoreline, *Hydrilla* was growing with many other submersed aquatic plants such as wildcelery, sago pondweed, coontail, and water-stargrass. It was most abundant from Hunting Creek to south of Dyke Marsh, the location where it was first discovered in 1982. The extremely rapid growth rate and reproductive capability of *Hydrilla* have made it a nuisance plant in California and Florida and in parts of the Southeastern United States. Although it has many of the same beneficial attributes as other submersed aquatic vegetation, concern is increasing that it may outcompete other, more desirable species and interfere with recreational use of the river.

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SEASONAL SUMMARIES OF HYDROLOGIC CONDITIONS, WATER YEAR 1984

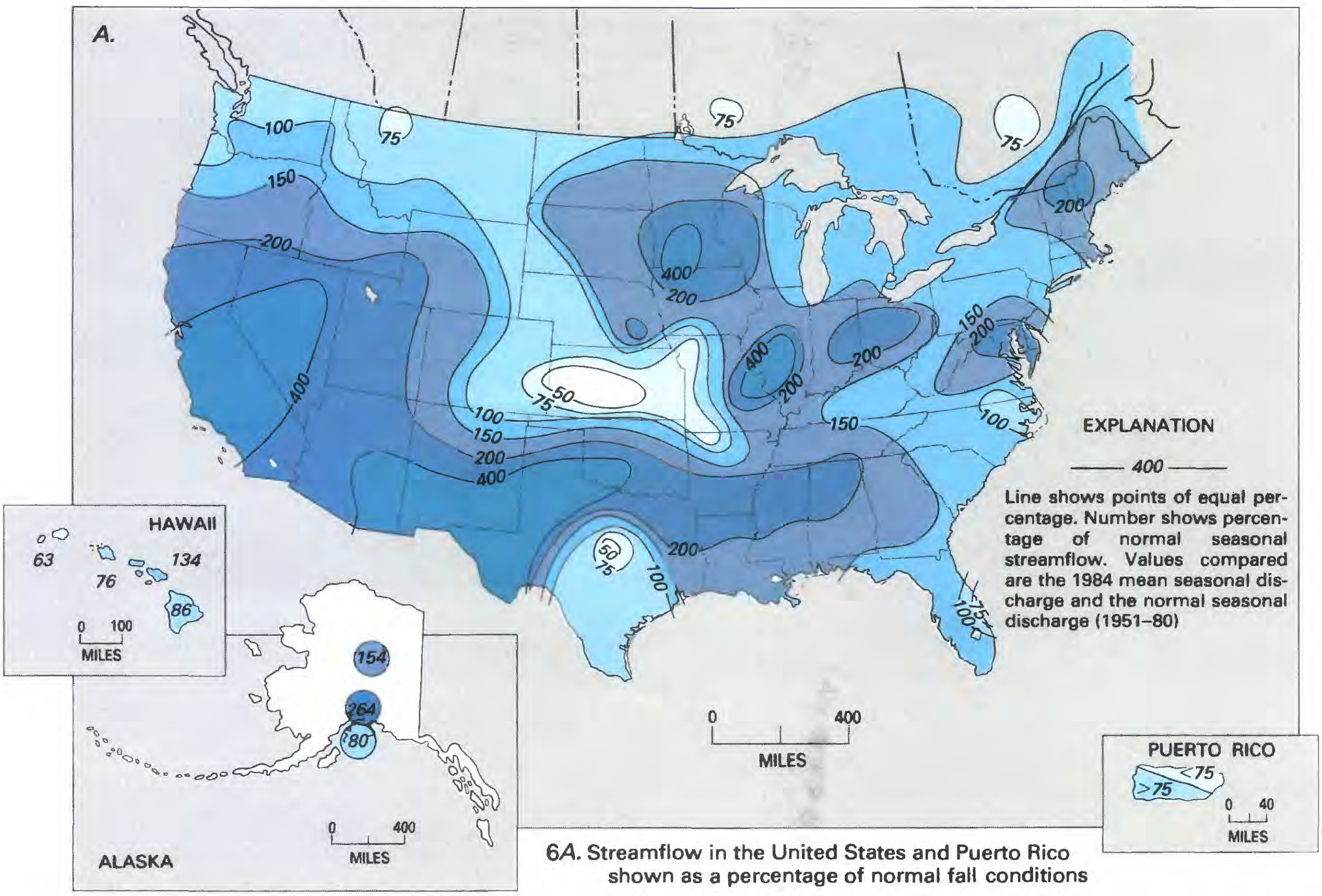
By Harry F. Lins

FALL SEASON—OCTOBER TO DECEMBER 1983

Above-normal streamflow dominated most of the conterminous United States during the fall season of water year 1984 (fig. 6*A*). Above-normal streamflow occurred in a broad band across the Southwest, in Oklahoma and western Texas, and throughout the Mississippi Valley. Below-normal streamflow was confined primarily to the High Plains region and south-central Texas. This largely nationwide pattern of above-normal flows appeared in conjunction with below-mean 700-millibar (mb) [about 10,000 feet (ft)] pressure surface heights over the Eastern Pacific Ocean and the Western United States and above-mean 700-mb heights in the Western Atlantic Ocean (dashed lines, fig. 6*B*). The principal effects of the resultant atmospheric circulation pattern were below-normal temperatures over the central two-thirds of the country (fig. 6*C*) and above-normal precipitation across most of the Nation (fig. 6*D*).

Although large positive departures of streamflow from normal were distributed widely across the Nation between October and December 1983, the climatic conditions and events giving rise to these flows were diverse. The very high flows occurring in the Southern Plains and middle Mississippi and Ohio River valleys resulted mostly from a single storm that moved northeastward across this region during a 7-day period in October. The storm, an extratropical cyclone, formed over Texas as warm moist air from the Gulf of Mexico mixed with the weakened remnants of the Pacific Hurricane Tico. Torrential rains, exceeding 10 inches (in.) in parts of Oklahoma, generated peak flows on some Red River tributaries in the 50- to 100-year-recurrence interval range. Cottonwood Creek, near Oklahoma City, crested at nearly 10 ft above flood level (table 1, event 20).

In contrast, the high flows observed in much of California and Nevada resulted from numerous frontal storms trailing from low-pressure systems that moved



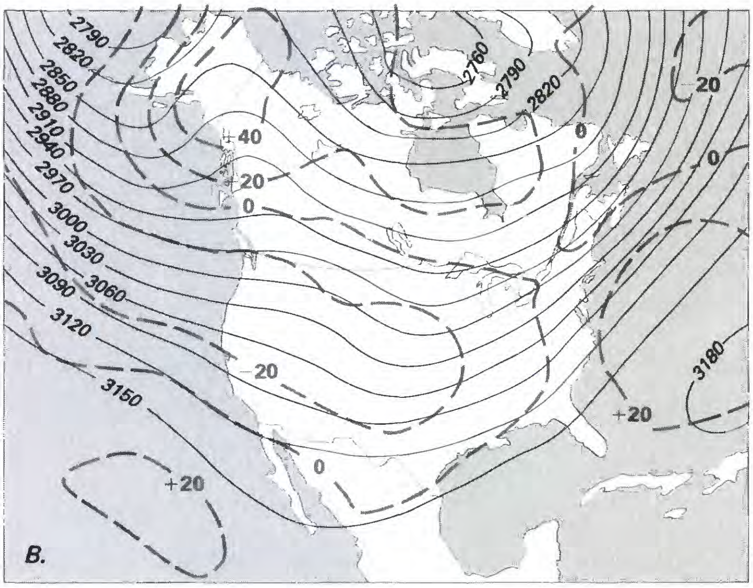
6*A*. Streamflow in the United States and Puerto Rico shown as a percentage of normal fall conditions

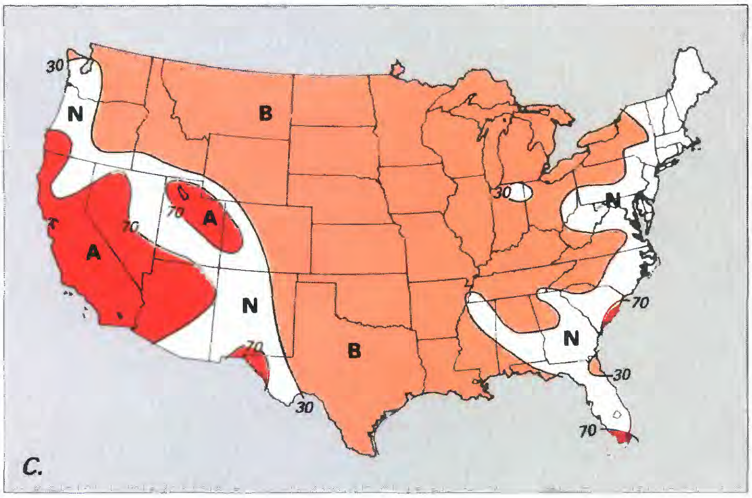
Figure 6. Hydrologic conditions during the fall season, October to December 1983. (Sources: Compiled by H. F. Lins and H. C. Tang from National Oceanic and Atmospheric Administration, National Weather Service, meteorological data and U.S. Geological Survey streamflow data.)

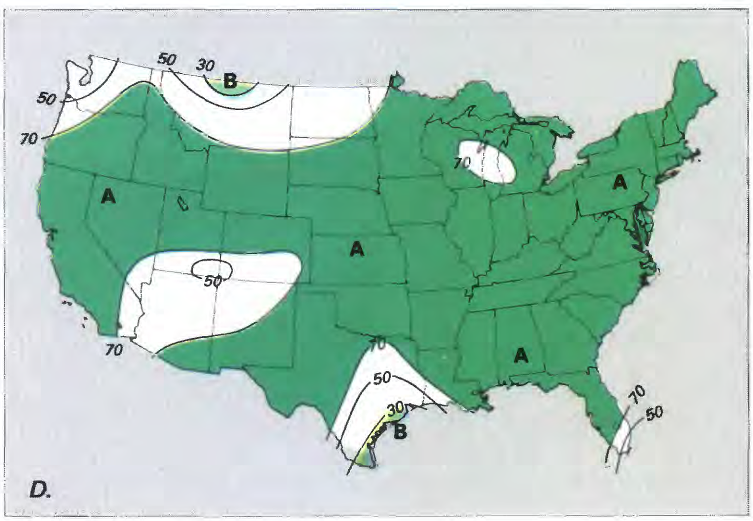
onshore between northern California and British Columbia during November and December. Similarly, above-mean flows along the east coast occurred in conjunction with the very regular movement of storms across the East and Southeastern United States during November and December. Local flooding was widespread in Maine and Massachusetts in late November after the fourth storm for the month swept through this region (table 1, event 28). Moreover, heavy rains in northern Mississippi and Alabama in early December produced severe flash flooding (table 1, event 32).

Outside the conterminous United States, extreme conditions also were noted. In Alaska, for example, heavy rains and snowmelt resulting from warm temperatures in late November led to widespread flooding and mudslides south of Anchorage on the lower Kenai Peninsula (table 1, event 30). On the island of Maui, in Hawaii, Christmas thunderstorms produced 6 to 10 in. of rainfall causing local floods while providing some relief from the drought that had persisted through the fall season (table 1, event 36).

Temperature also affected streamflow during the fall season. The below-normal temperature that covered much of the northern and central parts of the Nation during the fall season contributed to early and heavy snowfalls which kept the moisture from contributing immediately to streamflow. Nationally, temperatures during December were the coldest on record.







6*B*. Mean height of 700-millibar pressure surface (solid lines in meters) over North America and departures from normal fall conditions (dashed lines in meters).

6*C*. Temperature in the conterminous United States expressed as a departure from normal fall conditions. (**A** , above 70th percentile; **B** , below 30th percentile; **N** , between 70th and 30th percentiles).

6*D*. Precipitation in the conterminous United States expressed as a percentile for fall conditions. The 50th percentile represents the median precipitation (**A** , above the 70th percentile; **B** , below the 30th percentile)

Figure 6. Continued.

WINTER SEASON—JANUARY TO MARCH 1984

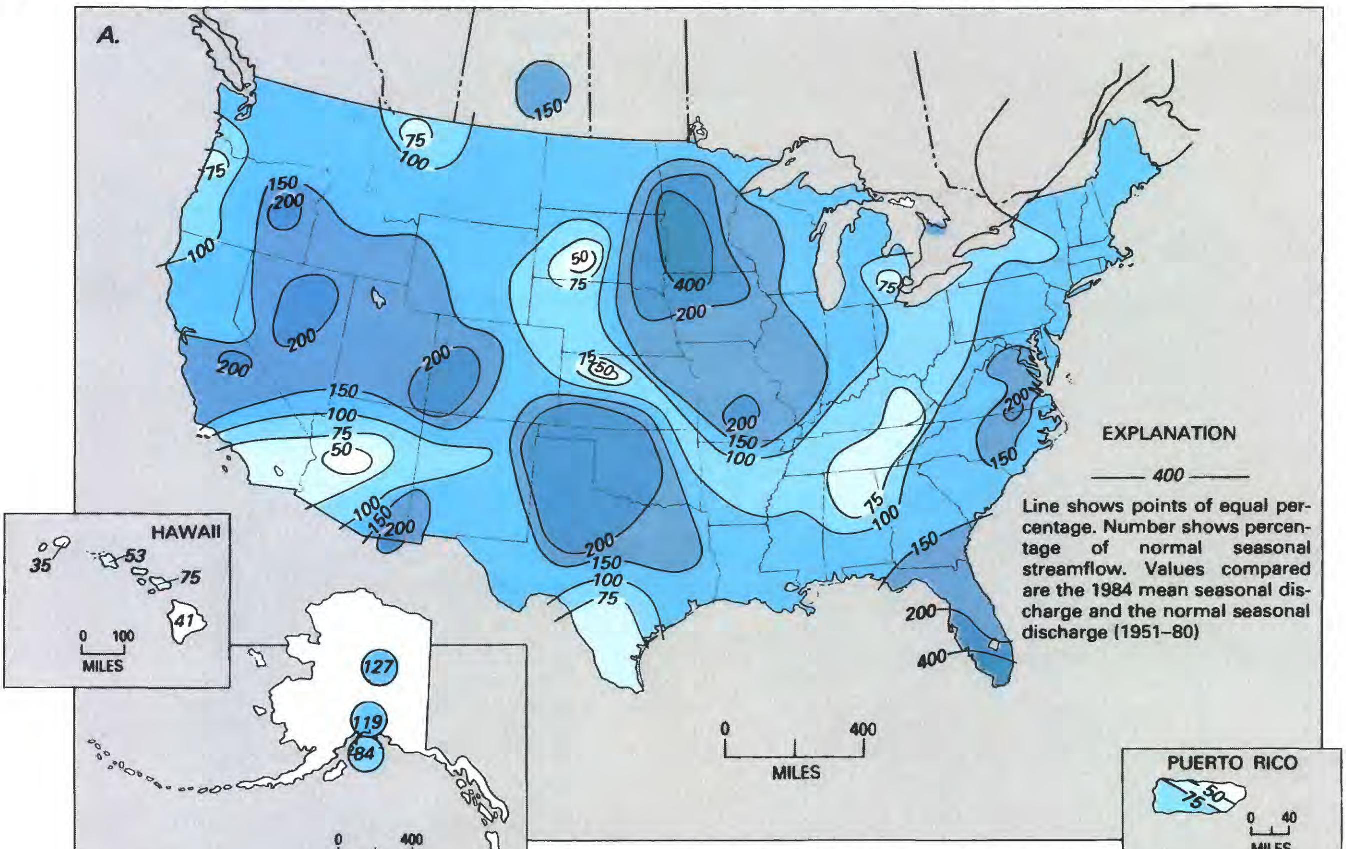
The national pattern of largely above-normal streamflow continued into the winter quarter (fig. 7*A*). The largest above-normal departures occurred in the upper Mississippi Valley and in southern Florida. High seasonal flows also were prevalent across the Great Basin and the western Rocky Mountains.

The continuation of above-normal streamflow across much of the Nation came in association with a 700-mb flow pattern similar to but more intensified than that which existed during the fall (fig. 7*B*). Principal features of this upper air pattern included a deep trough over the North Pacific Ocean, a moderate ridge over the west coast of the United States and Canada, and a trough over the eastern two-thirds of the United States.

Temperatures during the January-to-March period ranged from above normal along the Pacific coast and in the Northern Rockies and Northern Great Plains to below normal in the lower Great Lakes area, parts of the South, and sections of the Great Basin and the west-central Rockies (fig. 7*C*). Although severe cold engulfed the Nation in late December and persisted into January (the December-February period was the sixth coldest of record), the remainder of the winter quarter was quite mild over much of the country. February, in particular, was an unusually warm month from the Northern Great Plains to the Northeast.

Precipitation varied from below normal along the Appalachians, in the Southwest, and along the Pacific coast to above normal along the southeast Atlantic coast and in the Central Great Plains and the Central Rocky Mountain regions (fig. 7*D*). Notably, precipitation was below normal across much of the Nation during January but increased to normal amounts over most of the Nation during March.

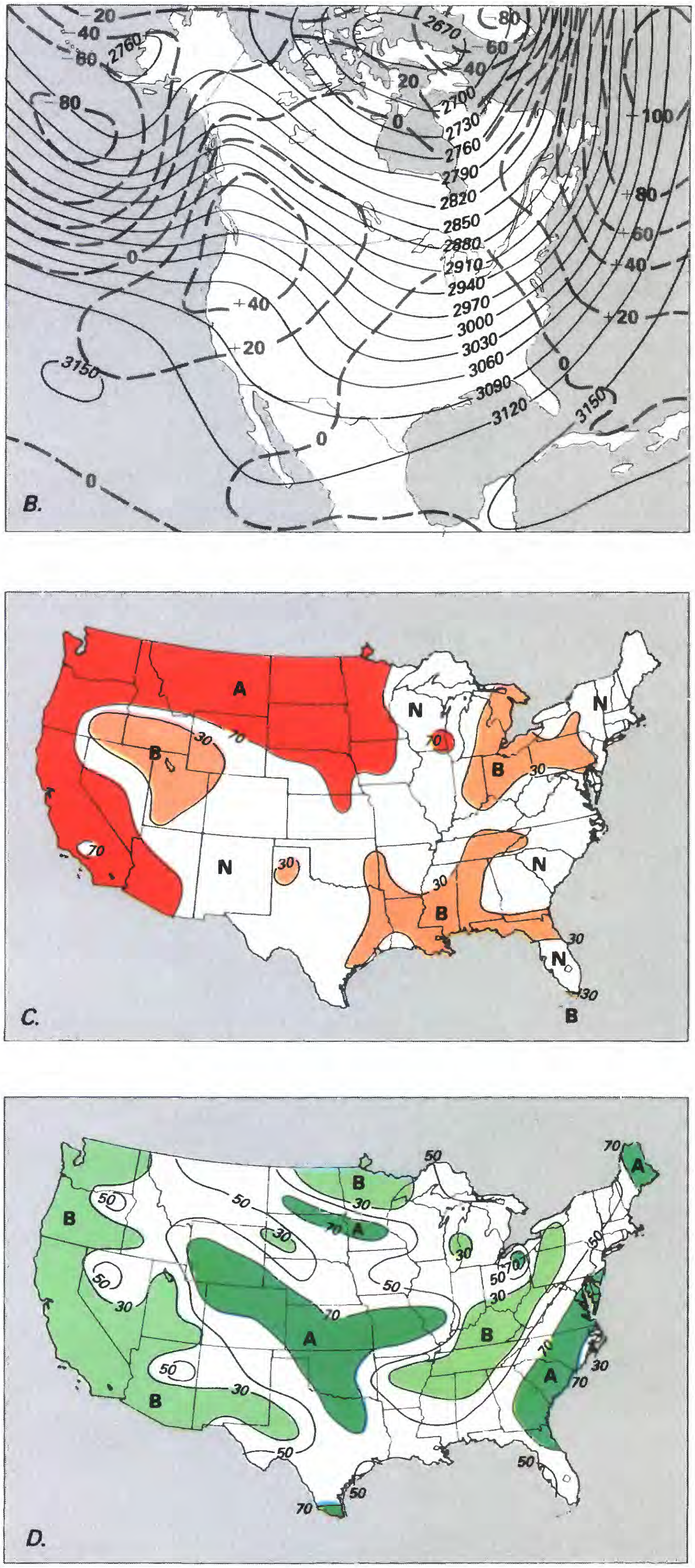
In general, the areas exhibiting excessive streamflow during the winter quarter also experienced above-normal flows during each month of the period; namely, the Great Basin-Central Rockies region, the Northern Great Plains–upper Mississippi River valley area, western Oklahoma-northern Texas, and Florida. Conditions giving rise to the flooding in each area varied considerably. The high flows in much of the upper Mississippi River valley resulted from snowmelt runoff and ice jams caused by the mild temperatures that began at the end of January and continued into March. In particular, moderating temperatures coupled with an ice jam nearly 500 miles long, which extended upstream along the Missouri River from Jefferson City, Mo., produced flooding along many streams near the end of



7A. Streamflow in the United States and Puerto Rico shown as a percentage of normal winter conditions

Figure 7. Hydrologic conditions during the winter season, January to March 1984. (Sources: Compiled by H. F. Lins and H. C. Tang from National Oceanic and Atmospheric Administration, National Weather Service, meteorological data and U.S. Geological Survey streamflow data.)

January (table 1, event 44). Similar conditions during the middle of February spawned lowland flooding in Illinois, Indiana, New York, Pennsylvania, Maryland, and Virginia (table 1, event 45). Moderate to severe flooding caused by 2 days of heavy rains affected southern Georgia and northern Florida. Flows on some Georgia streams had recurrence intervals of once in 50 years (table 1, event 49). High flows in the Great Basin–Western Rockies region, however, were associated primarily with storm-generated runoff and, toward the end of the quarter, with snowmelt.



7B. Mean height of 700-millibar pressure surface (solid lines in meters) over North America and departures from normal winter conditions (dashed lines in meters).

7C. Temperature in the conterminous United States expressed as a departure from normal winter conditions. (**A** , above 70th percentile; **B** , below 30th percentile; **N** , between 70th and 30th percentiles).

7D. Precipitation in the conterminous United States expressed as a percentile for winter conditions. The 50th percentile represents the median precipitation (**A**, above the 70th percentile; **B** , below the 30th percentile)

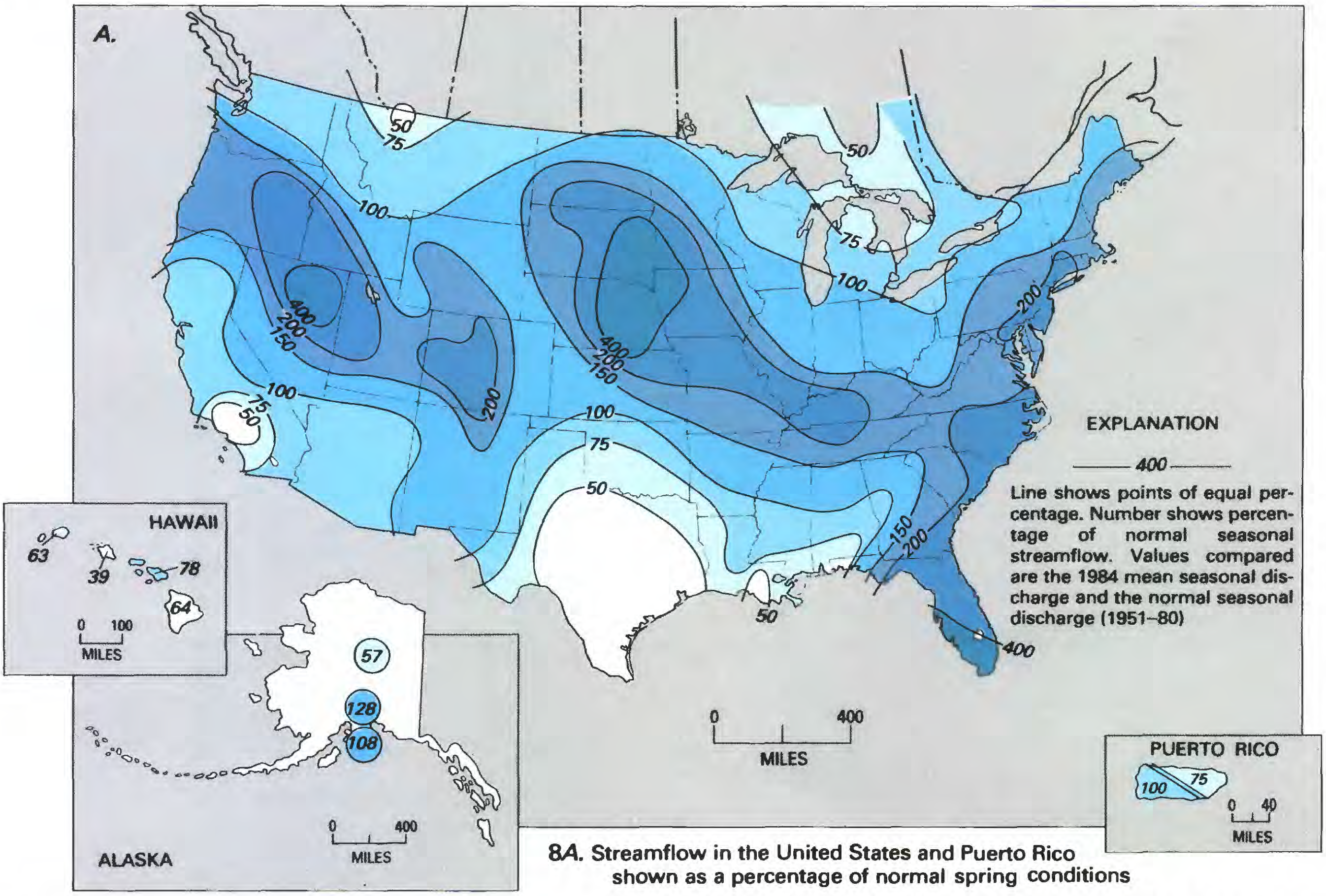
Figure 7. Continued.

SPRING SEASON—APRIL TO JUNE 1984

Nationwide, the pattern of above-normal streamflows persisted through the April to June period (fig. 8*A*). Spring patterns were similar to those of the winter, with high-flows occurring in the Great Basin and the Northern Great Plains, but they increased in both areal extent and magnitude. For example, the combined average flow of the Mississippi, the St. Lawrence, and the Columbia Rivers during the spring months increased 68 percent compared to the winter season. As during the winter, the areas with the greatest departures from long-term normal conditions were in the Great Basin–Central Rockies, Northern High Plains-middle Mississippi River valley, and southeast Atlantic coast. Again, as in the winter, streams in these areas had above-normal flows in each month of the season. The only large area of significantly below-normal streamflows was in Texas.

During the spring period, several notable events occurred. In northern New Jersey and southeastern New York, for example, severe flooding on April 4 and 5 resulted from intense rains falling on frozen ground and from melting of a residual snowpack. Peak flows of the Wanaque and Ramapo Rivers were the highest in nearly 70 years (table 1, event 53). Later, in early May, a series of storms moved eastward from northeast Texas to New Jersey and produced heavy downpours and flooding in many eastern and east-central parts of the United States. Extensive flooding between May 5 and 8 was reported along streams in central and southern Kentucky, southwestern Virginia, and Tennessee (table 1, event 62). In the Western United States, warming temperatures in the Rockies, beginning in mid-May, increased snowmelt from the record-high snowpack and caused severe flooding in addition to accompanying mudflows and mudslides. Extreme flooding occurred in the Colorado River basin, the Snake River basin, and also in the Great Basin. Peak discharges on many streams exceeded the 100-year flood (table 1, event 64). Finally, in June, rains replenished the water resources of Puerto Rico, ending a prolonged period of drought and water shortages (table 1, event 76).

Associated with these elevated flows nationwide was a greatly reduced gradient in the 700-mb height field over North America (fig. 8*B*). Such a reduction is typical in spring as the contrast in temperatures between high and low latitudes decreases. Specific aspects of the upper-air pressure field included intensification and northward extension of the North Pacific subtropical

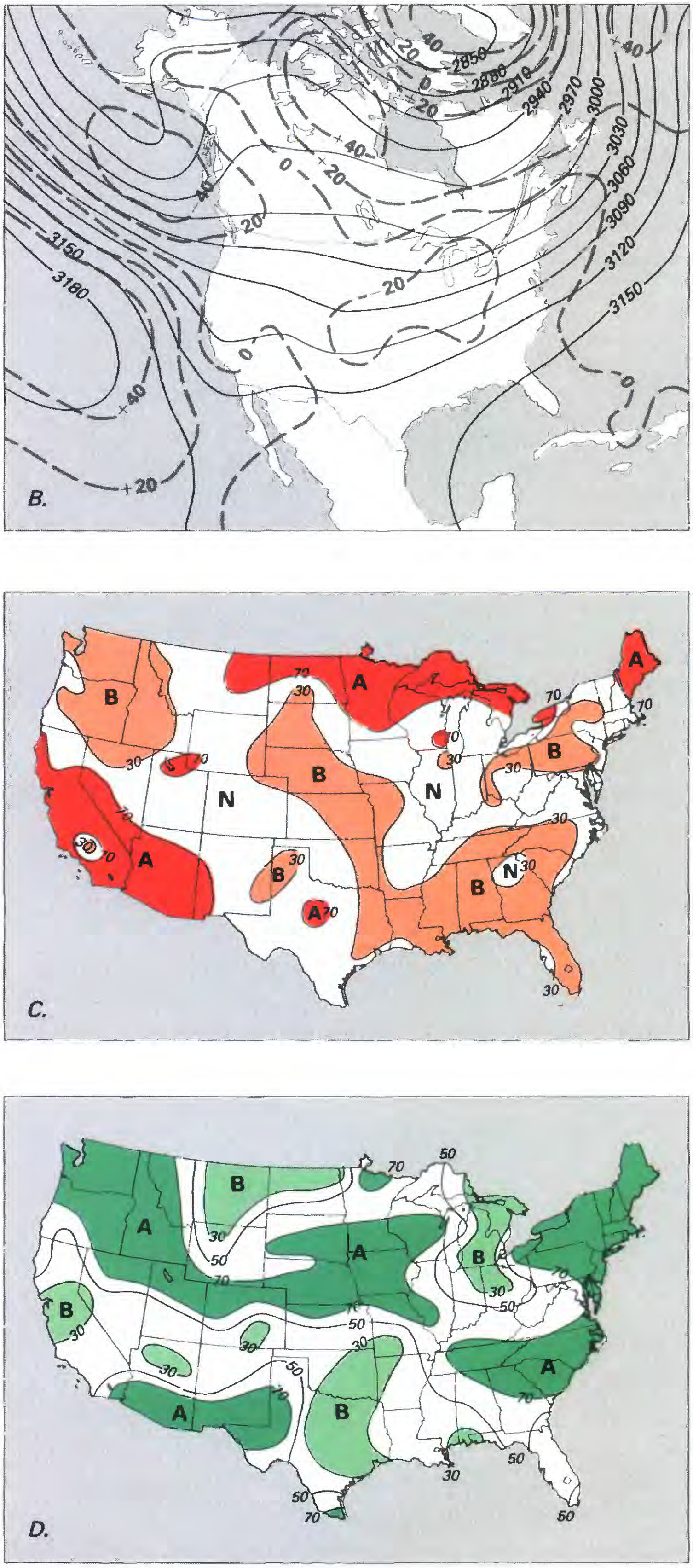


8*A*. Streamflow in the United States and Puerto Rico shown as a percentage of normal spring conditions

Figure 8. Hydrologic conditions during the spring season, April to June 1984. (Sources: Compiled by H. F. Lins and H. C. Tang from National Oceanic and Atmospheric Administration, National Weather Service, meteorological data and U.S. Geological Survey streamflow data.)

high-pressure area, a trough over the southern Pacific coast of the United States, and a relatively weak westerly upper-air flow over most of the conterminous United States.

Climatologically, these patterns were associated with above-normal temperatures in the Pacific Southwest, across the Northern Great Plains to the Great Lakes, and in Maine (fig. 8*C*). Below-mean temperatures dominated the Columbia Plateau-northern Rocky Mountain region, the middle Missouri and lower Mississippi River valleys, and most of the Southeast. Spring precipitation was normal to above normal over most of the Nation (fig. 8*D*). The notable dry areas (the Northern and Southern Great Plains, the central Great Lakes, and central California) generally were coincident with the areas of below-normal streamflow (fig. 8*A*). Much of the very high streamflow that occurred in the Northern and Central Great Plains came during June when, early in that month, an unusually cold air mass moved over the Rockies and the Northern Great Plains and generated severe weather and torrential rain over much of the region. Monthly mean flows were highest of record for June in parts of Iowa, Kansas, Nebraska, and South Dakota. In addition, peak flows on several streams in Kansas, Nebraska, and South Dakota were also highest of record (table 1, event 69).



8*B*. Mean height of 700-millibar pressure surface (solid lines in meters) over North America and departures from normal spring conditions (dashed lines in meters).

8*C*. Temperature in the conterminous United States expressed as a departure from normal spring conditions. (**A** , above 70th percentile; **B** , below 30th percentile; **N** , between 70th and 30th percentiles).

8*D*. Precipitation in the conterminous United States expressed as a percentile for spring conditions. The 50th percentile represents the median precipitation (**A**, above the 70th percentile; **B** , below the 30th percentile)

Figure 8. Continued.

SUMMER SEASON—JULY TO SEPTEMBER 1984

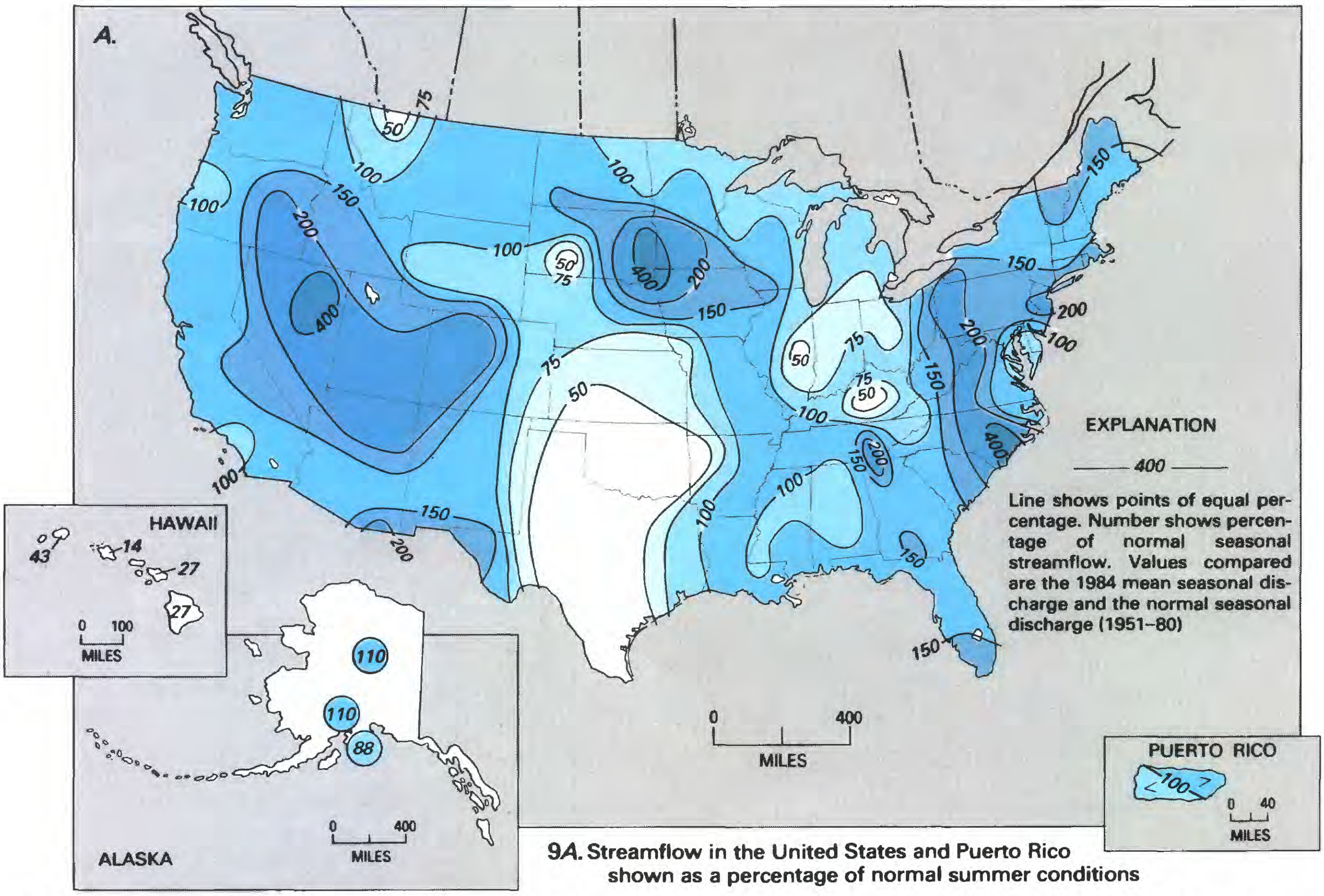
Streamflow patterns changed little during the summer season from those observed during the spring (fig. 9*A*). The core areas of above-average flows in the Great Basin-Central Rockies, Northern Great Plains, and across much of the Atlantic coast persisted, although some variations in their intensity and extent were observed. For example, large areas of above-average rainfall were observed in the West and, more locally, along the east coast during the July to September period. Across the Great Plains, however, the area of excessive flows in the northern and central sections of the Plains decreased considerably as very low streamflows carried over from the spring in the southern sections and spread northward into the central sections.

Another indication of the elevated state of summer season streamflows nationwide is evident in the combined average flow of the three largest rivers in the conterminous United States. Between July and September the Mississippi, the St. Lawrence, and the Columbia Rivers had a combined average monthly flow of 926,000 ft^3/s. Although this value represents a 52-percent decrease from the spring flow (a seasonal decline in flows during summer being normal), it was still 14 percent above the average summer combined flow for these rivers.

Specific events during the summer months included some record-setting flows. In July, for example, a slow-moving cold front moving eastward from the Northern Great Plains dropped locally heavy amounts of precipitation and produced record flooding on several streams in Connecticut and New Jersey. Several weeks later, a very similar frontal system produced rains which generated record flows on streams in Maine, Rhode Island, and New York (table 1, event 86).

Perhaps the most notable streamflow event of the summer quarter occurred during the middle of September in North Carolina. There, in response to several days of heavy rains associated with Hurricane Diana, severe flooding occurred on streams in the State's southeastern coastal plain region (table 1, event 98). Peak discharges on headwater streams had recurrence intervals in the 5- to 100-year range although only minor flooding occurred in the lowlands along the lower reaches of such major rivers as the Cape Fear and the Neuse. Porous, sandy soils coupled with locally dry antecedent conditions accounted for reduced flooding in the lowlands.

The broad similarity in streamflow anomalies between the spring and summer seasons can be associated with a notable persistence in the pattern of upper air circulation (fig. 9*B*). The maps of spring and summer mean 700-mb pressure surfaces (figs. 8*B*, 9*B*), do not show any apparent significant differences. Indeed, the only notable differences relate to the absolute height of the pressure contours and not to the



9*A*. Streamflow in the United States and Puerto Rico shown as a percentage of normal summer conditions

Figure 9. Hydrologic conditions during the summer season, July to September 1984. (Sources: Compiled by H. F. Lins and H. C. Tang from National Oceanic and Atmospheric Administration, National Weather Service, meteorological data and U.S. Geological Survey streamflow data.)

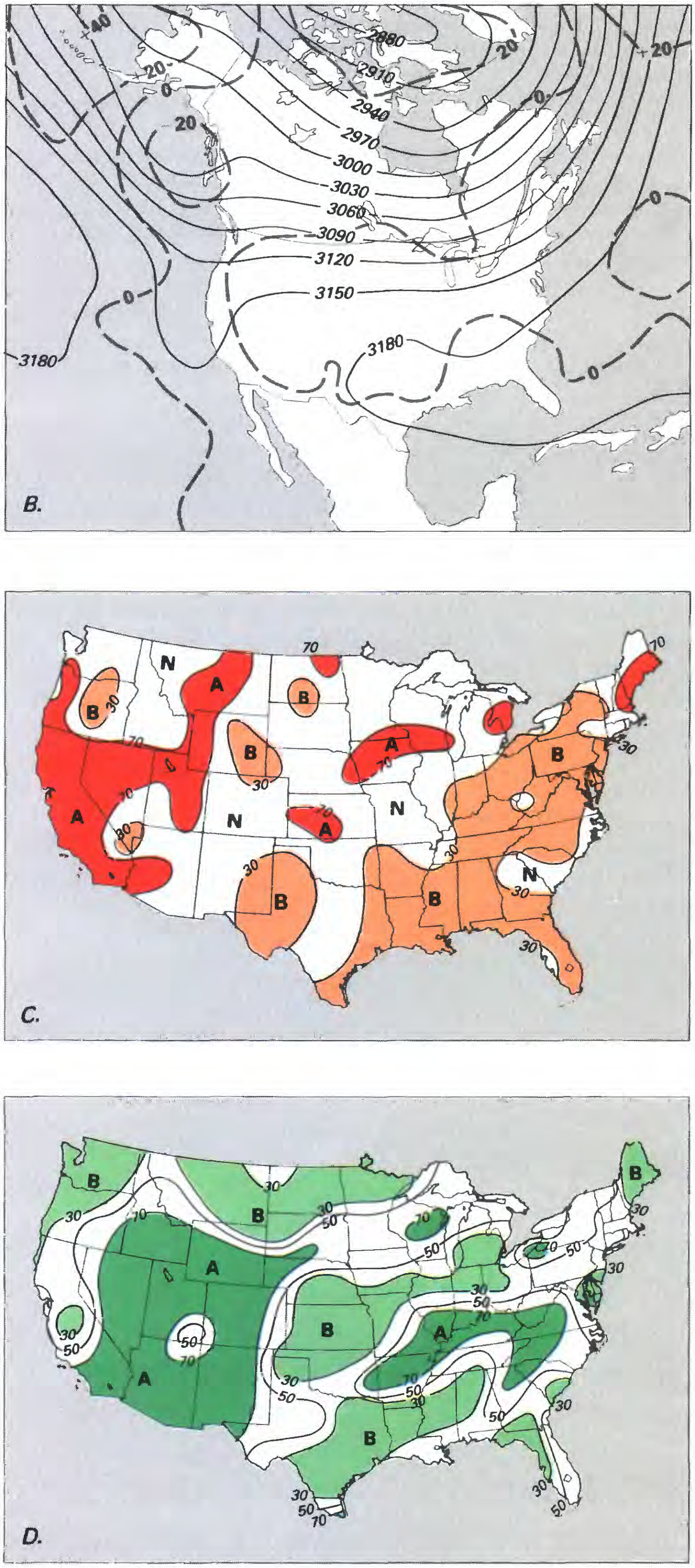


Figure 9. Continued

distribution or location of high- and low-pressure areas. The increase in the height of the contours across the map is associated with a "thickening" of the atmosphere that occurs every summer. This thickening, or expansion, of the atmosphere occurs in response to the warmer temperatures of the summer season. The most obvious associations between the summer 700-mb circulation and surface streamflow patterns occur in the Western and Central United States. The continued elevated flows in the Great Basin and Central Rockies resulted from the trough over coastal California, which deepened during the summer. Moreover, the intensification and expansion of the drought in the Southern and Central Great Plains was primarily caused by the westward and northward expansion of the "Bermuda High" into that region (note position of the 3,180-meter height contour over Texas and the Southeast in fig. 9*B*). With the position of this high-pressure area extending so far westward, moist tropical air from the Gulf of Mexico was not able to move northward into the Great Plains. Instead, the Gulf air moved into Mexico and, after taking on dry continental characteristics there, moved northward into the Great Plains.

Temperatures and precipitation nationwide varied considerably during the summer quarter (figs. 9*C*, 9*D*). Throughout California and in much of Nevada, Utah, and the Northern Rockies, temperatures averaged above normal. Across much of the Southwest, above-average precipitation resulted from the upper-air trough above the California coast. In north-central and northeastern Montana, high temperatures coupled with reduced rainfall led to exceedingly low flows in, or to the drying-up of, many streams (table 1, event 88).

In contrast, much of the northwest and central portions of the Nation experienced normal summer temperatures. Given the below-average precipitation over much of the Pacific Northwest and most of the Central and Southern Plains, these normal temperatures helped to keep the reduced summer streamflows from being even lower. This was especially true in north and west Texas where below-average temperatures prevailed. Finally, most of the eastern and southeastern parts of the country had normal or below-normal temperatures during the summer. Interestingly, despite the heavy rains along the southeast Atlantic coasts which accompanied Hurricane Diana, most of this region still remained below average in precipitation for the summer quarter.

9*B*. Mean height of 700-millibar pressure surface (solid lines in meters) over North America and departures from normal summer conditions (dashed lines in meters).

9*C*. Temperature in the conterminous United States expressed as a departure from normal summer conditions. (**A** , above 70th percentile; **B** , below 30th percentile; **N** , between 70th and 30th percentiles).

9*D*. Precipitation in the conterminous United States expressed as a percentile for summer conditions. The 50th percentile represents the median precipitation (**A**, above the 70th percentile; **B** , below the 30th percentile)

Selected Hydrologic Events, Water Year 1984

Rising Lake Levels

During the late 1970's and early 1980's, rising lake levels in the Central and Western United States created a host of flood problems affecting communities, highways, wetlands, recreational facilities, and agricultural lands adjacent to terminal or closed lakes.

These lakes occur in interior drainage basins that have no natural outlet to the oceans. Runoff within these basins creates the lakes found in the low-lying areas of these drainage systems. The altitudes of such lakes fluctuate in response to changes in climate and (or) other changes in the hydrology of the interior-drainage system. Interior-drainage basins comprise 5 percent of the drainage area in North America (de Martonne, 1927).

Within the past 2 years, high lake levels have caused flooding problems at the Great Salt Lake in Utah, Devils Lake in North Dakota, Big Marine Lake in Minnesota, Round and East Eightmile Lakes in Wisconsin, and the Malheur-Harney Lakes system in Oregon. In July 1984, the largest terminal lakes in west-central Nevada—Pyramid Lake, Walker Lake, and Carson Sink—reached their maximum water levels in many years (table 1, event 79). Because of the unusual nature of the rising lake-level phenomenon and the effects on neighboring communities, two of these lakes—Great Salt Lake and Devils Lake—are discussed in detail in this section.

Saltair, a huge dance and recreational pavillion, being submerged by the Great Salt Lake, Utah. Water covered the dance floor to a depth of more than 1 foot on April 11, 1984, as the lake level reached 4,207.7 feet. The lake peaked at 4,209.25 feet on July 1, 1984. (Photograph by Ted Arnow.)

RISE OF GREAT SALT LAKE, UTAH

By Ted Arnow

The Great Salt Lake (fig. 10) rose 5.0 feet (ft) from September 25, 1983, to July 1, 1984, the second largest seasonal rise for this lake since records began in 1847. The maximum seasonal rise was observed the previous year when the lake rose 5.1 ft from September 18, 1982, to June 30, 1983. The lake declined only 0.5 ft during the summer of 1983; therefore, the net rise from September 18, 1982, to July 1, 1984, was 9.6 ft. By comparison, the previously recorded maximum net rise during a 2-year period was 4.75 ft during 1970 and 1972.

Great Salt Lake is the modern remnant of a much larger water body, Lake Bonneville, which covered about 20,000 square miles (mi^2) in Utah, Nevada, and Idaho during the most recent ice age of the Pleistocene Epoch. Lake Bonneville reached its maximum level, approximately 1,000 ft above the present surface of Great Salt Lake, about 16,000 to 17,000 years ago. About 11,000 years ago, the lake declined to its current level of approximately 4,200 ft above sea level (Scott and others, 1982, p. 3).

The lake level has a yearly cycle (fig. 11). It begins to decline in the spring or summer when the weather is hot enough so that the loss of water by evaporation from the lake surface is greater than the combined inflow from surface streams, ground water, and precipitation directly on the lake. It begins to rise in the autumn when the temperature decreases and the loss of water by evaporation is exceeded by the inflow. According to past records, the rise can begin at any time between September and December and the decline any time between March and July.

Thus, the level and volume of the lake reflect a dynamic equilibrium between the inflow and evaporation. The surface area and brine concentration are the major aspects of the lake that affect the volume of evaporation. During dry years, the water level declines, causing a decrease in surface area; consequently, the volume of evaporation decreases. Moreover, as the lake level declines, the brine generally becomes more concentrated, which also decreases the rate of evaporation. During wet years, the water level rises, causing an increase of surface area; consequently, the volume of evaporation increases. As the lake rises, the brine generally becomes less concentrated, which also increases the rate of evaporation.

When the lake level peaked on July 1, 1984, it was at an altitude of 4,209.25 ft above sea level, and it covered an area of about 2,300 mi^2. This level was still below the historic high level in 1873 at approximately 4,211.5 ft above sea level. At that time, the lake surface covered about 2,500 mi^2. At the other extreme, the lowest lake level was recorded in 1963 at 4,191.35 ft, when the lake covered less than 1,000 mi^2.

During the summer of 1983, precipitation was above average, and evaporation was relatively small because of greater-than-usual cloud cover. These conditions resulted in an unusually small decline of lake level during the summer. By September 25, when the seasonal rise began, the lake level had declined only 0.5 ft. The excessive precipition continued throughout the fall and culminated in the wettest December ever recorded at Salt Lake City. By New Year's Day, Salt Lake City had received 24.26 in. of precipitation during calendar year 1983, about 1.6 times the average.

The cumulative precipitation from January to June 1984 also was above average. Much of the precipitation fell in the form of snow on the mountains in the drainage basin. The snowmelt began soon after May 1, at which time the snow cover ranged from about 1.2 to 1.5 times greater than the average amount for May 1 in the Bear River basin, about 1.5 times the average in the Weber River basin, and from about 1.3 to 1.8 times the average in the Jordan-Provo River basin (Whaley, 1984, p. 9–13).

The lake rose steadily from October 1983 through June 1984, primarily in response to the surface inflow that resulted from the excessive precipitation. The precipitation at the Salt Lake City Airport was about 1.5 times greater than average for the 9-month period, and the resultant inflow from the three major surface tributaries of the lake during that period greatly exceeded their average flows for this 9-month period: the Bear River flow was 2.7 times greater (3.12 million acre-ft), the Weber River flow was 2.1 times greater (923,000 acre-ft), and the Jordan River flow was 5.2 times greater (1.23 million acre-ft). The flow in the Bear River during water year 1984 was the greatest measured during 95 years of record, and the flow during water year 1983 was the second greatest on record. Similar annual records were observed for the Weber and Jordan Rivers based on the past 35 years of measurement.

Because of the shape of the lakebed, more water is needed to raise the level of the lake each additional foot as the water altitude increases. Thus, the 5.0-ft rise from September 25, 1983, to July 1, 1984, involved about 15 percent more water than did the 5.1-ft rise from September 18, 1982, to June 30, 1983. When the lake peaked on July 1, 1984, the net increase in volume represented by the 9.6 ft rise since September 18, 1982, was about 12 million acre-ft, and the increase in area was about 600 mi^2 (an increase of 35 percent).

This increase in the lake's area resulted in extensive damage to roads, railroads, wildfowl-management areas, recreational facilities (fig. 12), and industrial installations that had been established on the exposed lakebed. The capital damage at these facilities as the lake rose the 9.6 ft was approximately \$212 million (Utah Division of Water Resources, 1984, p. 3–41).

The salinity of the brine in Great Salt Lake before 1959 varied inversely with the lake level (fig. 11). During 1869, for example, when the lake was within a few feet of its historic high level, the concentration of

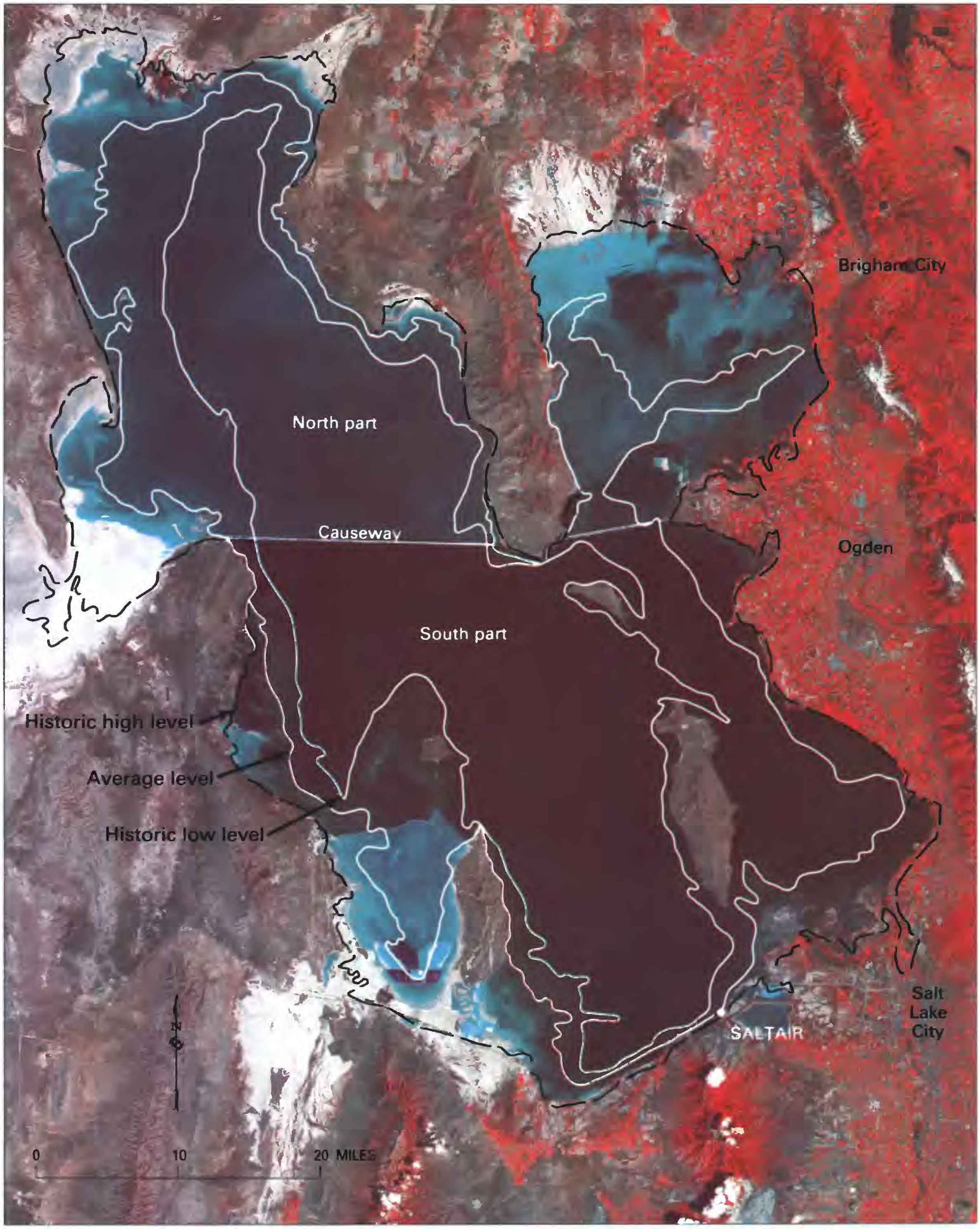


Figure 10. Landsat thematic mapper image of Great Salt Lake, Utah. The lake was imaged on June 25 and July 2, 1984, during two passes of the Landsat satellite. The southern part of the lake crested at 4,209.25 feet on July 1, 1984. The level is within 0.1 foot of the peak as shown on the image. The satellite image is capable of delineating the shoreline more completely than ground surveying or aerial photographic methods. The southern and northern parts of the lake are separated by a causeway, producing great differences in water quality in the two halves of the lake and thus differences in the color of the water.

dissolved minerals was 15 percent of the brine weight. During 1930, however, when the lake was about 10 ft lower, the mineral concentration was 21 percent.

Between 1957 and 1959, the Southern Pacific Transportation Co. built a railroad causeway, which divided the lake and restricted the movement of the brine. The southern part of the lake receives more than 90 percent of the freshwater inflow, whereas the inflow to the northern part is nearly all brine that moves through the causeway from the southern part. Thus,

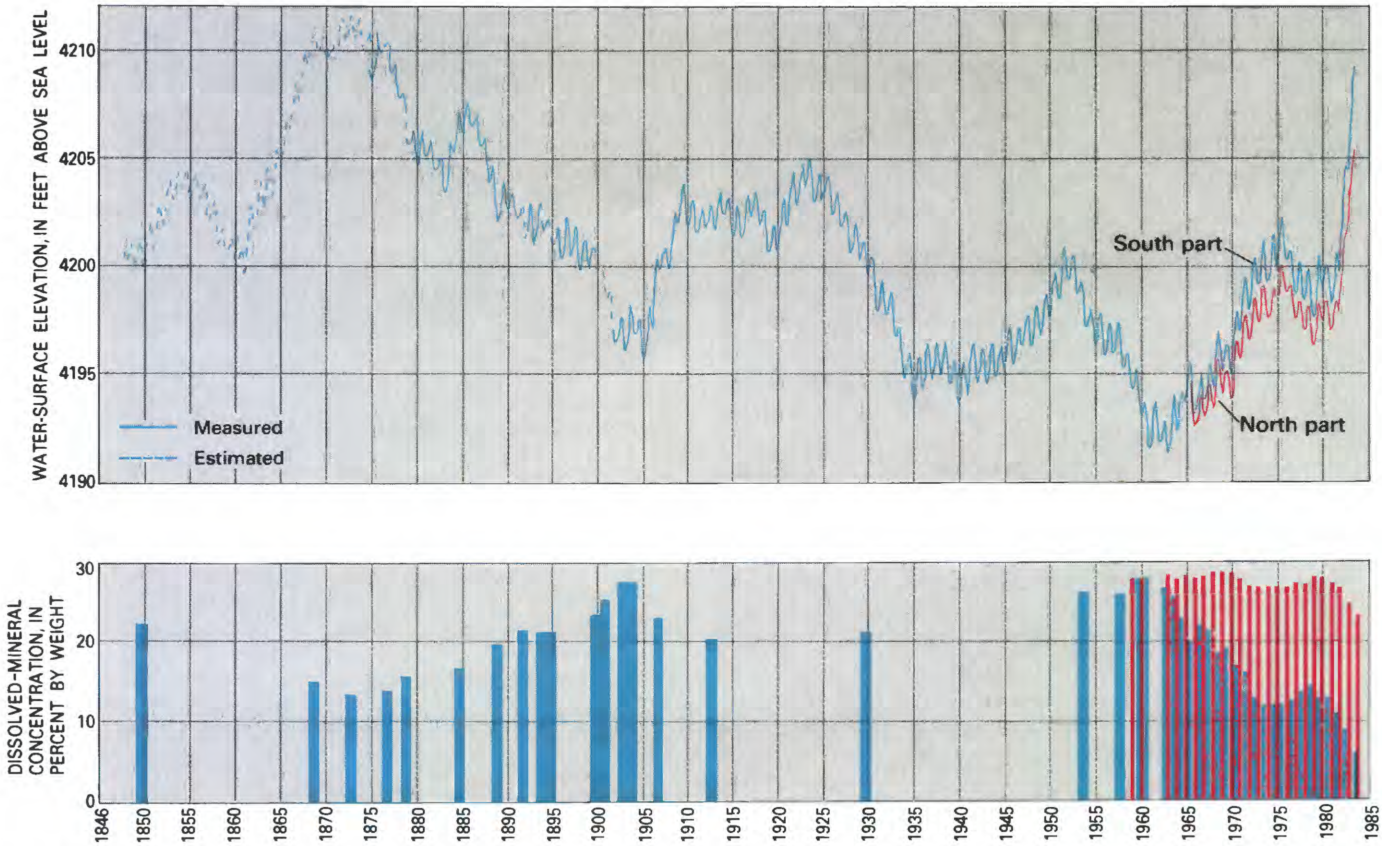


Figure 11. Changes of water level and dissolved-mineral concentrations of Great Salt Lake, Utah, 1847 to 1984. Since 1959, the northern and southern parts of the lake have differed in water level and mineralization, the data for which are shown in blue for the southern part and in red for the northern part. (Source: Compiled by Ted Arnow from U.S. Geological Survey and Utah Geological and Mineral Survey data.)

the water in the southern part always is higher and fresher than the water in the northern part of the lake.

From 1959 to 1982, the brine concentration north of the causeway remained relatively constant at or close to saturation regardless of changes in lake levels. The concentration decreased somewhat, however, during the large lake-level rises of 1983 and 1984. The brine south of the causeway was close to saturation during the historic low lake level in 1963. As the lake rose, the salinity of the brine south of the causeway continued to change inversely with the lake level, but the salinity was less than it would have been before the construction of the causeway. In 1977, for example, at a lake level of about 4,200 ft, the mineral concentration was approximately 12 percent, whereas before 1957 at the same level, it would have been more than 20 percent.

The maximum recorded difference in levels between the two parts of the lake was 3.7 ft on July 1, 1984, when the salinity in the northern part was about 23 percent, and in the southern part, only about 6 percent. At 6 percent, which is less than two times the salinity of ocean water, the famed flotation powers of Great Salt Lake are practically nonexistent.

The Utah legislature in 1984 approved an action to breach the railroad causeway to help equalize the water levels between the northern and southern parts of the lake. A 300-ft wide opening was completed on August 3. This will reduce the differences in level and salinity between the two parts of the lake, but it will not eliminate completely the differences. Given the uncertainty about future lake levels and the effects of increased flooding if lake levels continue to rise, the behavior of Great Salt Lake will continue to be the subject of intensive interest and study.

Figure 12. Entrance to Antelope Island Causeway, looking west, with the lake level at 4,209.15 feet on June 16, 1984. Note center line of the Causeway showing through the water. The causeway was completed in 1968 when the lake level was at 4,195 feet. (Photograph by Ted Arnow.)

Rise of Devils Lake, North Dakota

By Gregg J. Wiche

Another example of a lake with rising water levels is Devils Lake in northeastern North Dakota. The Devils Lake basin is a 3,900-square mile (mi^2) closed basin in the drainage of the Red River of the North (fig. 13). About 3,130 mi^2 of the closed basin drains into Devils Lake itself; the remaining 770 mi^2 are tributary to East Devils and Stump Lakes, which lie to the east. The topographic relief and surficial landforms of the basin are of glacial origin, which accounts for the large number of shallow depressions and potholes throughout the basin. Many of these depressions are connected by poorly defined channels and swales.

The rising levels of Devils Lake (fig. 14) pose a flood threat to the community of Devils Lake, a National Guard Camp, roads, and sewer and lagoon systems of several other communities. Rising ground-water levels probably caused by the rising lake levels also have flooded basements and septic systems in and near the city of Devils Lake. However, not all impacts of rising lake levels have been adverse; the water quality of the lake has improved, which, in turn, has increased fishing and other water recreation on the lake. An additional source of interest in Devils Lake is the fact that it is included as part of the Garrison Diversion Unit, a congressionally authorized water-development project. The primary reason for including Devils Lake in the proposed project is to stabilize the lake's level.

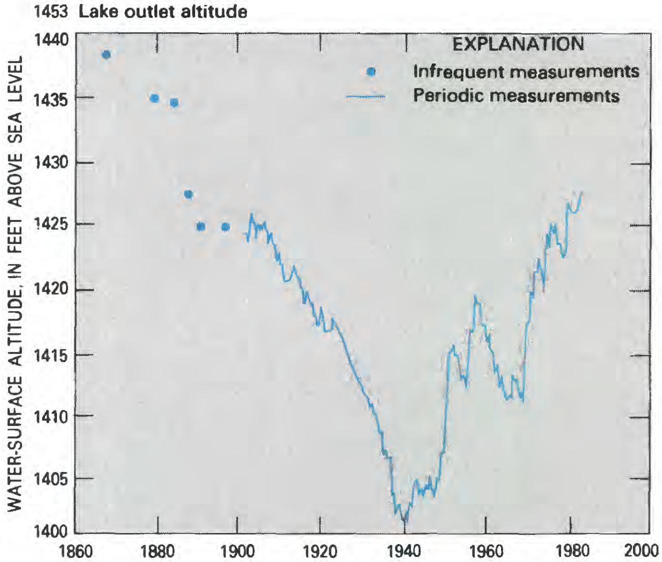


Figure 14. Water levels of Devils Lake, N. Dak., 1867 to 1983. The outlet of Devils Lake is 1,453 feet above sea level. (Source: Compiled by G. J. Wiche from U.S. Geological Survey data.)

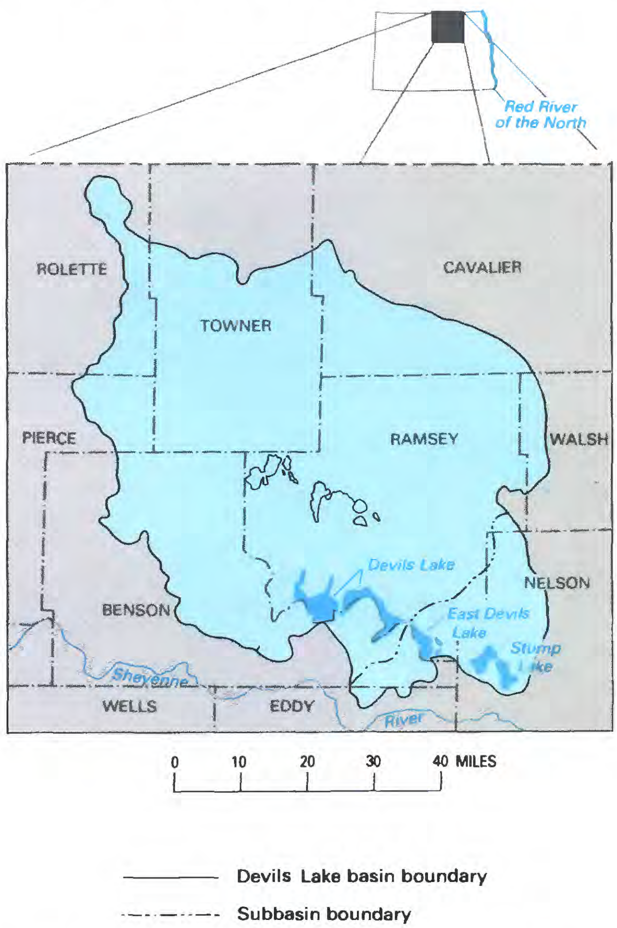


Figure 13. Drainage basin of Devils Lake, N. Dak. (Source: Compiled by G. J. Wiche from U.S. Geological Survey data.)

Water-surface altitudes of Devils Lake were recorded, albeit somewhat sporadically, from 1867 to 1901, and these records have been authenticated by the U.S. Geological Survey. In 1901, the U.S. Geological Survey established a gage on Devils Lake. The maximum water-surface altitude of 1,438 ft above sea level for the period of record of Devils Lake occurred in 1867, when the lake had a surface area of about 140 mi^2. From 1867, the water-surface altitude of Devils Lake fell almost continuously until 1940, when it reached a recorded low of 1,400.9 ft above sea level and was a shallow, brackish body of water covering 10.2 mi^2 (North Dakota State Engineer, 1944). From 1940 to 1956, Devils Lake rose; from 1956 to 1968, it declined again; and, in 1983, it rose to a modern maximum altitude of 1,428.1 feet. Lake levels have remained fairly stable during 1983 and 1984, and the surface area of the lake has been about 84 mi^2.

Swenson and Colby (1955) reported a dissolved-solids concentration of 25,000 mg/L in Devils Lake in November 1948 when the water level was only 3 ft above the recorded low level of 1940. Water samples collected in May 1979 indicated that, when the lake was at one of its peaks, dissolved solids were less than 2,000 mg/L (U.S. Geological Survey, 1980).

Knowledge of the fluctuations of Devils Lake before 1830 is based on studies by Aronow (1957) and Callender (1968). Aronow (1957) developed a postglacial chronology of lake-level fluctuations based on tree stumps uncovered as the water receded, lacustrine deposits containing buried soils, and bison skulls. Aronow indicated that Devils Lake rose to its outlet altitude of 1,453 ft above sea level (fig. 14) at least twice since the retreat of Pleistocene glaciers about 10,000 years ago.

Callender (1968) studied the postglacial sedimentology of Devils Lake and reconstructed the recession of the lake from the chemical contents of core samples. Callender's chronology which extends from about 6,000 years ago indicates that a substantial fluctuation in water-surface altitude of Devils Lake has occurred in response to climatic variations. His findings corroborate much of Aronow's research.

Numerous reasons for the lake-level fluctuations have been proposed and debated (Swenson and Colby, 1955, p. 8). In the early 1900's, the popular theory was that human settlement in the 1880's and subsequent breaking of the "impermeable" sod caused a reduction in runoff. According to this theory, the water table was lowered because of related increases in evapotranspiration (Horton and others, 1910; Simpson, 1912). However, as the water-surface altitude of Devils Lake rose in the 1940's, support for this theory declined. Swenson and Colby (1955) indicated that, based on limited climatic data, fluctuations in lake levels were caused by climatic change. Langbein (1961), however, stated that the decline in water-surface altitude from 1867 to 1940 was greater than can be accounted for by changes in climate and the negligible amount of irrigation that had occurred.

Although it is certain that both climatic variability and human modifications of the drainage basin of Devils Lake are affecting lake-level fluctuations, additional interpretation and analysis of data will be required before the relative importance of the various processes controlling lake levels can be completely understood. Currently, studies are underway to achieve this understanding.

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Floods

Floods were prominent hydrologic events throughout the Nation during water year 1984. (See "Overview of Water Year 1984 Hydrologic Conditions and Water-Related Events.") Damage caused by these floods was an estimated \$3.5 to \$4 billion—the third highest amount for the period 1975-84 (U.S. Army Corps of Engineers, 1985). This section describes, in some detail, two areas of major flooding, one in the East and the other in the Midwest. Also described is the unusually large spring runoff in the Colorado River basin.

Figure 15. Flooding along Route 7 in New Milford, Conn., caused by overflow of the Housatonic River, May 31, 1984. View is looking north along Route 7. (Photograph courtesy of Michael McAndrews and the *Hartford Courant*.)

RECORD LATE-SPRING 1984 FLOODS IN NEW ENGLAND

By Richard A. Fontaine

Springtime flooding as a result of snowmelt combined with moderate rainfall is a normal pattern that generally occurs from about mid-March through mid-May in New England. In late May 1984, however, a series of extratropical storms, associated with a deep, upper-level trough of low pressure, moved across New England. These storms brought eight consecutive days of rain to some parts of the region and caused extensive damage (figs. 15 and 16). From May 28 through June 3, precipitation ranged from 3 to 5 inches (in.) in the northern parts of Maine, New Hampshire, and Vermont to 9 in. or more in the hilly and mountainous areas of northern and western Connecticut and Massachusetts, in southwestern Maine, and in southern New Hampshire and Vermont.

In Maine, the May precipitation, as reported by the National Weather Service, averaged 235 percent of normal. At individual sites in Maine, totals ranged from 129 to 325 percent of normal. Precipitation at Portland, Maine, set a new record total for May of 9.64 in. The same pattern of record-breaking precipitation for May was noted throughout New England.

Runoff in response to this record rainfall varied widely throughout New England. Floods with recurrence intervals that ranged from 5 to 25 years occurred on most streams, although flooding on some streams was considerably more severe with recurrence intervals that ranged from 35 to 100 years (table 2). Locally intense rainfall contributed to record or near-record flooding on the Winnipesaukee and Ashuelot Rivers in New Hampshire. The Kennebec River basin in Maine and the Housatonic and Connecticut River basins in Massachusetts and Connecticut had record or near-record flooding that was primarily in response to the large areal extent of the intense rainfall. Peak discharges at selected sites (fig. 17) are summarized in table 2.

Figure 16. Aftermath of flooding in central Vermont, June 7, 1984. The remains of a home destroyed when floodwaters undercut 50 feet of embankment behind the structure located in the foreground. View is upstream on Great Brook in Plainfield, Vt. (Photograph courtesy of Toby Talbot, Associated Press photographer.)

Table 2. Peak discharge at selected stream sites caused by the New England storm, May 28 to June 3, 1984

[do = ditto, ft³/s = cubic feet per second. Data from U.S. Geological Survey files]

Site no. on fig. 17	River and station location	Date	Peak discharge (ft³/s)	Approximate recurrence interval (years)	Length of record (years)
1	Kennebec River:				
	Bingham, Maine	June 1	[1]68,000	100	56
2	The Forks, Maine	--do--	[2]30,000	100	83
3	Winnipesaukee River:				
	Tilton, N.H.	May 31	[1]4,500	100	47
4	Ashuelot River:				
	Hinsdale, N.H.	June 1	[2]14,000	100	74
5	Housatonic River:				
	Great Barrington, Mass.	May 31	10,200	60	71
6	Falls Village, Conn.	--do--	21,100	70	72
7	Gaylordsville, Conn.	--do--	34,000	35	44
8	Connecticut River:				
	Montague City, Mass.	--do--	140,000	50	80
9	Thompsonville, Conn.	June 1	186,000	50	56
10	Hartford, Conn.	--do--	192,000	65	80
11	Middletown, Conn.	June 2	186,000	75	20

[1] Highest peak discharge of record. [2] Second-highest peak discharge of record.

Figure 17. Areas of New England flooded in 1984 by late-spring floods. Numbers show location of stations listed in table 2.

The May 28 to June 3 storm caused extensive damage throughout New England. Several hundred people were forced to evacuate their homes, and agricultural losses were severe. An account published in the Springfield, Mass., *Morning Union* newspaper (June 1, 1984) estimated agricultural damage to be as much as $30 million in the Connecticut River Valley of Massachusetts alone. Flooding, such as that in New Milford, Conn., depicted by figure 15, was commonplace. New Milford is located on the Housatonic River, about 7 miles (mi) downstream from the U.S. Geological Survey stream gage at Gaylordsville (table 2).

Residents of central Vermont who did not experience the extreme flooding from the May 28 to June 3 storm were not as fortunate the following week. An intense band of thundershowers traversed Vermont from St. Albans in a southeasterly direction to Wells River near the New Hampshire border on the evening of June 6 and the morning of June 7. The storm dumped from 2 to 5 in. of rain in an area where soils were saturated from the rains of the previous week. Flash floods occurred throughout Franklin, Lamoille, and Washington Counties. Figure 16 depicts damage that was typical in this area. A peak discharge of 13,600 cubic feet per second (ft³/sec) was recorded on June 7 on the Lamoille River at Johnson, Vt. This peak had a recurrence interval greater than 100 years and was the second-highest peak discharge recorded at the site in 57 years of record.

The late-spring floods of 1984 in New England also were abnormal because of the unusually late time of the year in which they occurred. In New England, flooding in the early spring is much more common. It typically occurs in response to snowmelt that is accelerated by seasonally warm temperatures or rainfall or a combination of both. Spring floods may be intensified by several factors, mainly frozen or saturated soils that retard infiltration. The probability of flooding is decreased once the snow has melted, the soils have thawed and drained, and evapotranspiration has increased in response to plant growth and elevated temperatures. Thus, most annual peak discharges of New England streams occur in March and April each year.

Annual peak discharges, for example, on the Piscataquis River near Dover-Foxcroft, Maine (fig. 18), occurred during the spring months 63 percent of the time over the period from 1903 to 1983. Of these peaks, 88 percent occur in the first half of the spring season (March 20–May 8). In southern and coastal New England, 73 percent of the annual peak discharges on streams such as the Salmon River near East Hampton, Conn., occur from midwinter to early spring. Only twice in the 55-year period of record at the Salmon River station has an annual peak discharge occurred during the months of May or June.

In summary, the late-spring floods of 1984 in New England were unusual, not only because of their magnitude, but also because of their late occurrence in the year.

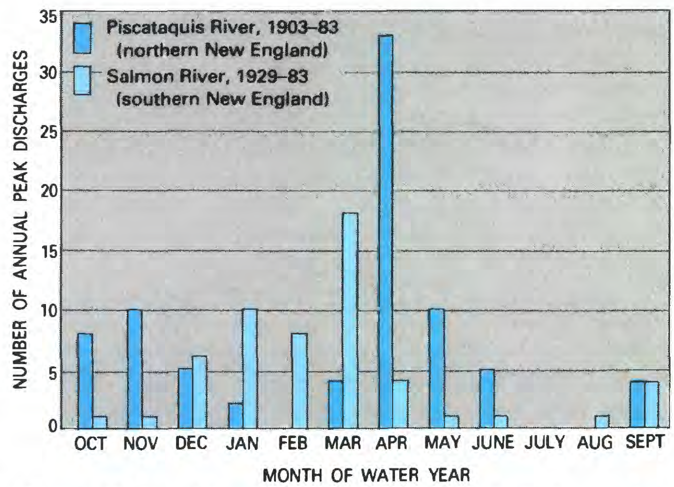

Figure 18. Monthly occurrence of annual peak discharges for the period of record of the Salmon River near East Hampton, Conn., and the Piscataquis River near Dover-Foxcroft, Maine. (Source: Compiled by Richard Fontaine from U.S. Geological Survey data.)

JUNE 1984 FLOODS ON THE MISSOURI RIVER AND TRIBUTARIES

By I. L. Burmeister

Heavy rains in South Dakota, Nebraska, and Iowa during a 3-week period in June 1984 caused extensive flooding on streams in those States and along the Missouri River from Sioux City, Iowa, to Rulo, Nebr. Although June floods are common in the Midwest, a persistent climatological pattern across the United States led to unusually serious flooding this year. At the surface and in the upper air, a nearly stationary ridge of high pressure was established over the Southeastern United States, while a similarly stationary trough of low pressure settled over the Western States. The western trough produced cool temperatures and numerous storm systems which moved eastward toward the Great Plains and intensified as they mixed with the warm moist Gulf air pushed north by the high pressure in the Southeast. The succession of cyclones and frontal passages produced many intense and widespread rainstorms. Nebraska and Iowa last experienced this type of weather pattern in 1967, when similar flooding occurred (Osugi, 1984).

Major Nebraska flood areas were Louisville and Plattsmouth along the Platte River and Nebraska City and Rulo along the Missouri River (fig. 19). On June 14, the Platte River at Louisville peaked at a flow of 144,000 cubic feet per second (ft^3/s) exceeding the previous record of 124,000 ft^3/s that occurred on March 30, 1960. The flow on June 14 was a combination of sustained high seasonal releases from upstream reservoirs (in anticipation of high runoff from later snowmelt) and flooding along tributaries to the Platte River (including Salt Creek, Loup River, and Elkhorn River). At Plattsmouth, downstream from Louisville, the water and waste-treatment plants, businesses, and homes were flooded for many days.

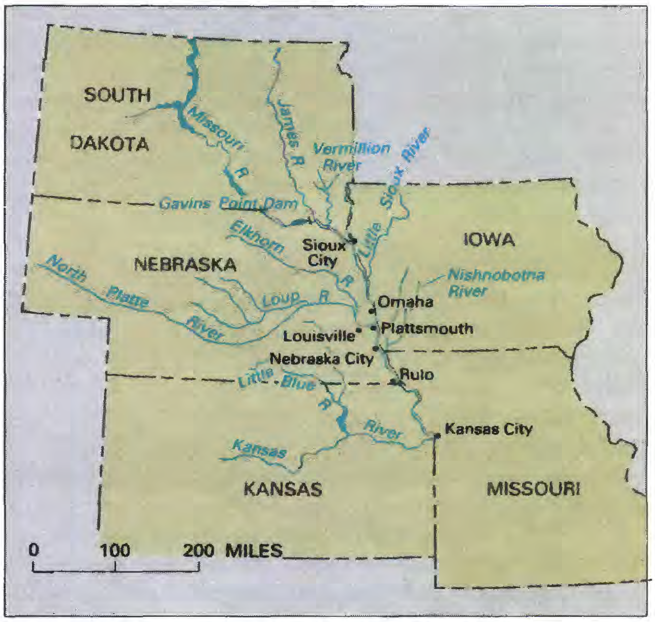

Figure 19. Area of June 1984 floods on the Missouri River and tributaries.

Although high flows on the Platte River were a major factor in the downstream flooding at Nebraska City and Rulo along the Missouri River, a combination of other factors also contributed to the flooding. Several intense thunderstorms in eastern Nebraska, eastern South Dakota, and western Iowa produced accumulative rainfall totals of 10 to 13 inches (in.). Amounts of 6 to 10 in. fell in several 24-hour periods. As a result, flood crests of major tributaries other than the Platte River significantly added to the Missouri River crest; for example, during this period, the Big Blue River had the second-highest discharge of record, the Little Blue River had a record discharge, Weeping Water Creek discharge was second highest of record, and the Nishnabotna River had a record water height. Another contributing factor was that upstream from Rulo, a levee was breached on the Missouri State side and caused flooding at Big Lake State Park and the surrounding area. Many homes, cabins, marinas, bridges, and highways suffered flood damage (fig. 20).

Another crest reached Nebraska City and Rulo on June 26 and 29, respectively. This flooding was caused by high runoff from thunderstorms in eastern South Dakota, northeastern Nebraska, and northwestern Iowa. Record flows were recorded on the James, Vermillion, and Little Sioux Rivers. The Missouri River at Sioux City, Iowa, even with controlled releases at the Missouri River dams at and above Gavins Point Dam (just upstream from James River), reached its second-highest stage of record with a discharge of 103,000 ft^3/s on June 25.

On June 27, the Missouri River crested at Omaha, Nebr., with a discharge of 114,000 ft^3/s. Although levees in the Omaha area held, most marinas, riverfront property, country highways, and cropland along the river were flooded for several days. This flooding still did not exceed the record flood at Sioux City, which occurred on April 14, 1952, when the Missouri crested with a discharge of 441,000 ft^3/s.

Damage from the 1984 floods was very high, particularly in terms of crop loss and soil erosion. The depth and duration of the flood waters on the low-lying cropland caused suffocation of the young plants in the fields. Moreover, because the plants were small and had immature root systems, they provided little protection against soil erosion. The heavy rains saturated the soil early in the 3-week period, resulting in high runoff rates from the rainfall that occurred later. Six counties in Iowa, five in Missouri, and several in Kansas and Nebraska were declared Federal disaster areas. Damages were extensive to croplands in Iowa, Nebraska, and Missouri. The U.S. Army Corps of Engineers halted barge traffic on the Missouri River during the 3-week period of flooding. Two swing-span bridges near Leavenworth, Mo. (upstream from Kansas City), were not opened to barge traffic from June 8 to July 9 because of high water. Consequently, in addition to erosion and crop losses, financial losses to the barge operators and to other businesses and industries dependent on barge transportation were substantial.

Figure 20. Aftermath of flooding of the Missouri River at Rulo, Nebr., June 18, 1984. High water marks for peak flow on June 16, 1984, were 0.9 foot higher on buildings. (Photograph by V. L. Spiers.)

Spring 1984 Runoff in the Colorado River Basin

By Dannie L. Collins

Runoff in the Colorado River during the 1984 runoff season (April-July) was much higher than normal for the second consecutive year. This unusually large runoff resulted from very heavy snows in November and December augmented by additional heavy snows in April and early May. Examples of the snowpack variation from the U.S. Soil Conservation Service (1984), for the 1983-84 winter season for the Colorado River watershed in Colorado are as follows:

1984	Average snowpack, in percent of 1961 to 1980 average
January 1	222
February 1	160
March 1	139
April 1	141
May 1	169

Heavy snowfall also occurred after May 1 just before the start of the major runoff season. Unseasonably warm temperatures followed the late-spring snowstorms, causing the near-record runoff that began about May 20, 1984.

The magnitude of peak flows for the 1984 runoff season varied somewhat but were generally 5 to 10 percent greater than those of 1983. The peak flow of the Colorado River near Cisco, Utah, for example, was 68,500 ft^3/s, the largest recorded peak flow since 1917 and 110 percent of the 1983 peak discharge. The estimated recurrence interval for this peak (using the station record for analysis after major storage structures were in place) was about 100 years. An extreme example was the flow of the Uncompahgre River at Delta, Colo. (fig. 21). The peak flow of 5,750 ft^3/s at that station was more than 1.5 times the estimated 100-year peak flow and 194 percent of the 1983 peak discharge. The Uncompahgre River basin has no major flood-control storage structures.

Another indicator of the unusually large runoff in the Colorado River basin during the 1984 runoff season is the inflow into Lake Powell. Flow volumes and their recurrence intervals were computed for the combined flows at the three Utah gaging stations that measure the major inflows into Lake Powell—Colorado River near Cisco, Green River at Green River, and San Juan River near Bluff.

From May 1 through July 31, 1984, the combined flow volume was 11.8 million acre-ft, which was equal to the flow volume for the same period in 1957, the largest since 1921. The estimated recurrence interval for this flow volume is approximately 35 years. For water year 1984, the combined flow volume was 20.6 million acre-ft; this flow exceeds the 1983 combined flow volume of 19.5 million acre-ft and is the largest annual volume since 1917. The estimated recurrence interval for this annual volume is 100 years. Peak inflow into Lake Powell, which occurred on May 28, 1984, was approximately 122,000 ft^3/s. Peak outflow from Lake Powell (42,800 ft^3/s) began on May 8, 1984, and continued until mid-July. Lake Powell crested at 3,702.5 ft on July 12, 2.5 ft above normal full-pool level. Downstream at the Hoover Dam outlet, the maximum flow peaked at about 37,500 ft^3/s on June 25, 1984. Further downstream, the maximum releases from Davis and Parker Dams were about 35,000 ft^3/s and 32,500 ft^3/s, respectively.

High releases over a period of 42 days through the Glen Canyon Dam spillways during the 1983 spring runoff resulted in extensive tunnel damage. Repairs, which began in July 1983, included excavation and removal of the tunnel's damaged concrete lining, the filling of cavities eroded in the sandstone, the installation of a new lining, and the construction of airslots in the inclined portions of the spillway tunnel to prevent

Figure 21. The Colorado River basin.

Figure 22. Flow being released from Glen Canyon Dam, Ariz., May 23, 1984. Rate of flow was approximately 42,800 cubic feet per second. (Photograph by U.S. Bureau of Reclamation.)

cavitation (or erosion) damage during future operations (U.S. Bureau of Reclamation, 1983, p. 1). Repairs were completed on both spillways during the summer of 1984 and one spillway was tested successfully in August 1984 (U.S. Bureau of Reclamation, 1984, p. 1-2).

Larger than normal releases from all major reservoirs within the basin were begun in late fall 1983 and continued through spring and summer 1984 in anticipation of runoff forecast to be higher than normal (fig. 22). These releases caused continued minor flooding in some downstream areas that had been flooded in 1983. Releases at Glen Canyon Dam were increased to 42,800 ft^3/s in May as inflows to Lake Powell were forecast to be 197 percent of normal. The sequence of operations throughout the year enabled the Colorado River Storage Project to accomodate the largest annual volume of runoff in the basin since 1917. Peak flows along the lower Colorado River downstream from Davis Dam were about 10,000 ft^3/s less than the damaging flows of 1983. If additional flood storage space had not been made available, peak flows would have been much higher and flooding would have been severe and widespread. Instead, flood damage in the basin during the 1984 runoff season was minor except in some areas adjacent to uncontrolled streams in the upstream part of the basin.

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Water Quality

The discovery of relatively high and toxic concentrations of selenium in irrigation return flows along the west side of the San Joaquin Valley of California is a matter of concern to many different groups. Although it is not a hydrologic event in the sense of a flood or drought, it is a notable example of how human activities can seriously affect water quality.

Figure 23. View of the Kesterson Reservoir, San Joaquin Valley, Calif., (looking west) showing the San Luis Drain (foreground) and evaporation ponds (background). (Photograph by S. J. Deverel.)

SELENIUM IN THE SAN JOAQUIN VALLEY OF CALIFORNIA

By Steven J. Deverel

In 1983, the U.S. Fish and Wildlife Service found deformities and a high mortality rate in newborn and embryonic coots, grebes, stilts, and ducks nesting at the Kesterson National Wildlife Refuge near Gustine, Calif. (fig. 23). Those symptoms matched embryonic and developmental deformities in chickens attributed to selenium poisoning described by the National Research Council (1977, p. 205–488). Selenium concentrations in fish and bird tissues from the Kesterson refuge were found to be considerably higher than those at nearby wetland wildlife areas not receiving agricultural drainage water (U.S. Bureau of Reclamation, 1984).

Selenium, a naturally occurring, nonmetallic element present in the soils and ground water of the west side of the San Joaquin Valley in California, is believed to be essential to human and animal nutrition in minute amounts but can be toxic at relatively low concentrations.

Agricultural drainage water from part of the west side of the San Joaquin Valley flows into the wetland wildlife refuge, which was developed as part of the San Luis Drain, a drainage canal constructed to aid agriculture in the area (fig. 24). The selenium present in the drainage water is believed to originate from sedimentary rocks of marine origin in the California Coast Range, which has been eroded to form the valley-fill deposits along the west side of the San Joaquin Valley. These valley soils are underlain by a shallow, impermeable clay layer that restricts the downward drainage of applied irrigation water. This irrigation water is essential to farming of about 1.2 million acres in this semiarid region.

Because the clay layer restricts downward movement of water, the water accumulates close to the land surface. When water levels rise to the point that the root zone becomes saturated, plant growth may be inhibited, and salts can accumulate near the soil surface. Salts present in the irrigation water and soil are left behind as the shallow water evaporates and as the plants extract water from the soil. This can create saline conditions in the crop-root zone to a degree that decreases agricultural productivity. The U.S. Bureau of Reclamation estimates that about 253,000 acres in the San Joaquin Valley are affected by inadequate drainage of salts and leaching water (U.S. Bureau of Reclamation, 1984). To remove the drainage water from the valley, the Bureau started construction of a discharge canal in 1968, the San Luis Drain (fig. 24), to carry the water from the west side of the valley ultimately to a proposed outlet in Suisun Bay in the Sacramento-San Joaquin Delta, where the two major rivers of California's Central Valley flow into the San Francisco Bay. The completed drain would provide a drainage outlet for about 493,000 acres of irrigated land.

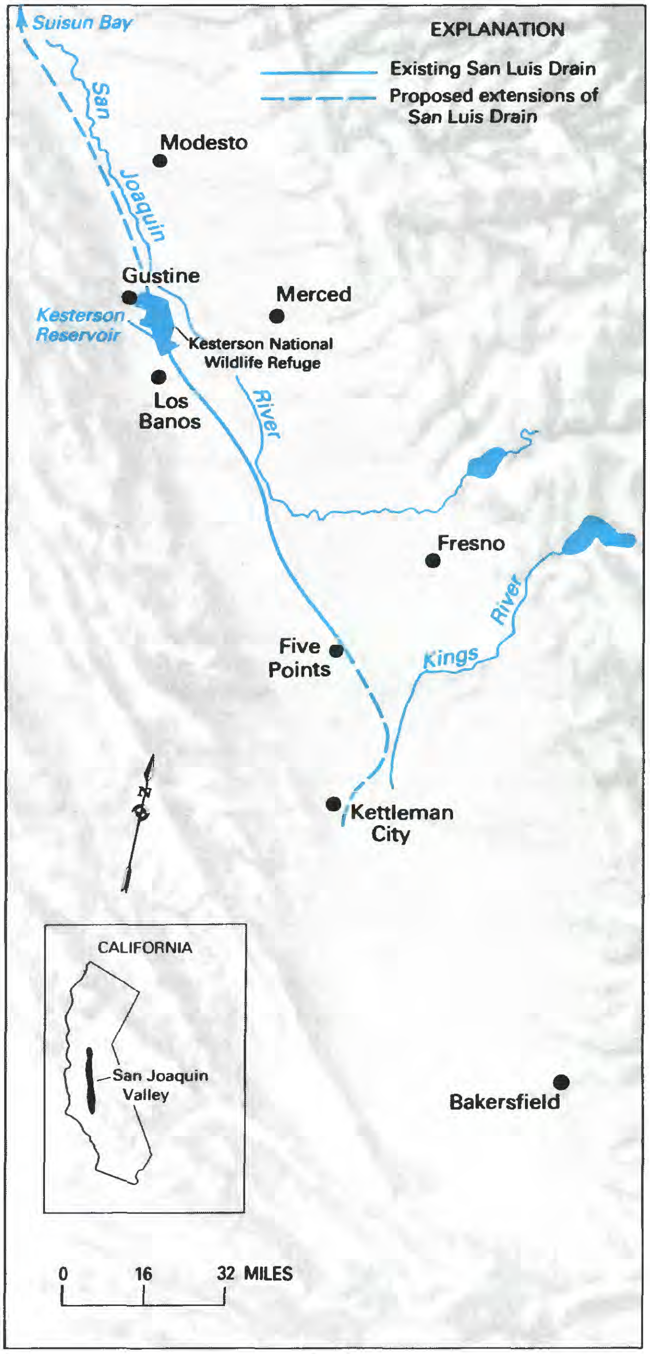

Figure 24. The existing and the proposed San Luis Drain, San Joaquin Valley, Calif.

In 1975, 85 miles (mi) of the proposed 207-mi-long San Luis Drain were completed from Five Points, Calif., to a temporary discharge point at Kesterson Reservoir which, by agreement between the U.S.

Bureau of Reclamation and the U.S. Fish and Wildlife Service, was designated Kesterson National Wildlife Refuge (fig. 24). In 1978, the U.S. Bureau of Reclamation began discharging water from the San Luis Drain into the wildlife refuge, which is managed cooperatively by the U.S. Fish and Wildlife Service and the U.S. Bureau of Reclamation. The drain presently (1984) provides a drainage outlet for about 8,000 acres.

In 1982, the U.S. Fish and Wildlife Service found that selenium levels in the fish at Kesterson Reservoir were 100 times the levels in fish from an adjacent State wildlife area that did not receive agricultural drainage water (U.S. Bureau of Reclamation, 1984). Total dissolved selenium concentrations in the drainage water flowing into the San Luis Drain and in the water in the Kesterson Reservoir subsequently were found to range from 0.1 to 1.4 milligrams per liter (mg/L) (Presser and Barnes, 1984, p. 8). Water taken from farm-drain systems to be serviced by the proposed completed drain was found to contain selenium concentrations as high as 4.2 mg/L. In a recently completed study of the areal distribution of selenium in the shallow ground water (Deverel and others, 1984), the proposed San Luis Drain service area was divided in three zones based on topography and soils. The alluvial fan zone, which includes the gently sloping deposits on the western edge of the service area, and the basin rim zone, which includes the level part of the valley between the alluvial fan and the San Joaquin River basin, had the highest selenium concentrations. The minimum limit for classification of dissolved selenium as a hazardous waste has been set at 1 mg/L by the U.S. Environmental Protection Agency (1980, p. 33122). In drinking water the criterion is 0.01 mg/L (U.S. Environmental Protection Agency, 1982); however, these farm-drain systems are not part of a domestic water supply.

Selenium toxicity has been observed in other parts of the world where livestock consume forage crops and grains that have high selenium contents. Chronic selenosis in cattle and sheep is manifested by weight loss and muscle dysfunction. At the other extreme, minute amounts of selenium are added to the diet of livestock in areas that lack selenium to prevent dietary deficiencies. According to Lakin (1973, p. 97), "Selenium is an essential nutrient for animals [and humans] and is required at a concentration level of about 40 ppb [parts per billion; 0.040 milligrams per liter (mg/L)] in their diet; at concentrations of 4,000 ppb [4.0 mg/L] and above, however, it becomes toxic to animals."

Additional work is needed to define the extent and severity of the water-quality problem in the San Joaquin Valley. Areas of concern include:

- The source and areal extent of selenium in the San Joaquin Valley,
- The geochemical processes controlling selenium mobility in the soil,
- The potential effects of discharging drainage water into the Sacramento–San Joaquin Delta and San Francisco Bay,
- Possible treatment for removal of selenium from drainage water, and
- The toxic effects of selenium on waterfowl and aquatic organisms.

A number of government agencies have ongoing studies or have proposed studies to address these topics.

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Hydrologic Perspectives on Water Issues

Introduction

The articles in this part of the 1984 *National Water Summary* are grouped under the headings "Water-Quality Issues" and "Water-Availability Issues." Each was selected because it provides a useful insight into an important aspect of water quality and supply. A synopsis of each article is given below. As in the foregoing description of significant hydrologic events, the authors of each article are identified.

Articles under the heading "Water-Quality Issues" examine variations in the concentrations, loads, and trends of five water-quality constituents (sediment, dissolved solids, phosphorus, nitrogen, and pesticides) commonly associated with nonpoint-source pollution of surface water. Progress in the control of point sources of pollution of surface water, such as discharges from industrial and municipal waste-treatment plants, has focused attention on the need to reduce nonpoint-source pollution in runoff from agricultural and urban areas to further improve surface-water quality (U.S. Environmental Protection Agency, 1984a); for example, the U.S. Environmental Protection Agency and the U.S. Fish and Wildlife Service estimate that nonpoint sources of pollution contribute to water-quality problems in 38 percent of all waters and are a major concern in 19 percent of those waters (Judy and others, 1984). The U.S. Environmental Protection Agency (1984b) found that, in about 20 percent of the States, nonpoint sources of pollution are considered the most important cause of water-quality problems.

Of the five constituents discussed here, suspended sediment is presented first ("Sediment in Rivers of the United States") because of the dual role sediment transported by rivers plays in determining water quality: the direct effects of sediment concentrations and loads and the transport of phosphorus and other contaminants, such as pesticides, radionuclides, and toxic metals, that can be adsorbed onto the sediment particles and travel with the sediment. Erosion has long been recognized as an agricultural problem and a potential threat to the continued productivity of the land but only recently has attention been given to the consequent offsite effects of sediment runoff. Not all sediment eroded from a field immediately makes its way into a stream, and the sediment that does reach a water course may be stored in the local stream basin or be trapped behind a dam for many years before moving downstream. An understanding of sediment-transport processes and changes in sediment concentrations and loads in streams is important in relating the phenomena to specific soil-erosion-control practices.

Following the discussion of sediment is a presentation of the distribution of dissolved solids and the nutrients, phosphorus and inorganic nitrogen ("Loads and Concentrations of Dissolved Solids, Phosphorus, and Inorganic Nitrogen at U.S. Geological Survey National Stream Quality Accounting Network Stations") and a brief discussion of trends and their possible causes and interpretation ("Trends in Concentrations of Dissolved Solids, Suspended Sediment, Phosphorus, and Inorganic Nitrogen at U.S. Geological Survey National Stream Quality Accounting Network Stations"). Both articles are based on continuing analyses of data from the U.S. Geological Survey's National Stream Quality Accounting Network (NASQAN). Two major rivers that have some of the highest dissolved-solids concentrations in the country, the Colorado and the Arkansas, are discussed as specific examples of problems that may be associated with this water-quality characteristic. An analysis of information collected by the U.S. Geological Survey and the U.S. Environmental Protection Agency's Pesticide Monitoring Network during water years 1975 to 1980 ("Pesticides in Rivers of the United States") concludes the discussion of surface-water quality.

Although information on the occurrence of synthetic organic substances and toxic chemicals in ground water is very sparse, information on a national scale can be assembled on the occurrence of some of the more common water-quality constituents. One of these constituents, nitrogen, is the subject of the article, "An Overview of the Occurrence of Nitrate in Ground Water of the United States."

Under the heading "Water-Availability Issues," the effects of water-resources development on ground-water levels in five areas of the country where water table or artesian water levels are more than 40 feet below predevelopment levels in at least one aquifer (U.S. Geological Survey, 1984, p. 40) are examined. The article is titled "Ground-Water-Level Changes in Five Areas of the United States." A related article, "Declining Ground-Water Levels and Increased Pumping Costs: Floyd County, Texas—A Case Study," presents detailed information on the cost of ground-water withdrawals in relation to increased energy prices and changes in water levels. These examples of the results of intensive ground-water development in different hydrogeologic settings provide a background for interpreting the hydrographs shown in each description of ground-water resources in the "State Summaries of Ground-Water Resources" part of this report.

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Water-Quality Issues

SEDIMENT IN RIVERS OF THE UNITED STATES

By Robert H. Meade and Randolph S. Parker

INTRODUCTION

Sediment ranks high among the substances that are supplied to rivers by nonpoint sources. Part of the sediment supplied to rivers is a natural consequence of the geologic processes that erode the continents and transport the eroded material as sediment to the oceans. The rest of the sediment in rivers, which may be most of the sediment in some heavily affected rivers, is a consequence of the accelerated erosion that follows such human activities as forest clearing, crop farming, surface mining, and construction. Because most of the sediments supplied to rivers come from diffuse sources, whether they are induced naturally or artificially, the sources are difficult to identify, predict, and control.

Adding to the difficulties of predicting sediment inputs to rivers is the complexity of estimating the rate of sediment delivery. Although onsite erosion of specific types of soils under specific conditions of cultivation or other land uses can be predicted by using such tools as the Universal Soil Loss Equation (Wischmeier and Smith, 1965), predicting how much of the eroded soil will be delivered eventually to the channel of a neighboring stream still remains difficult. Sediment that has been eroded off upland fields often is deposited on hillslopes or in the upper parts of stream valleys before it reaches a water course. The length of time during which the sediment is stored in this manner can range from a few days to hundreds of years. Consequently, the sediment that one observes in a river channel today may represent episodes of erosion that took place decades or even a century ago.

Once it reaches a stream channel, sediment may cause a number of problems. By raising the elevation of the channel bed, increased sedimentation can lead to increased flooding due to a decrease in the carrying capacity of the stream channel. Sediment affects the maintenance of in-channel structures, navigation systems, and other works in the river environment. Furthermore, sediment particles adsorb many contaminants, such as pesticides, radionuclides, and toxic metals, that are transported, deposited, and stored as part of the sedimentary component of the riverine system.

After first describing some general characteristics of sediment in rivers of the United States, this article will discuss some of the more prominent issues involving sediment. By way of introduction, figures 25 and 26 show suspended-sediment discharges at the mouths of selected rivers.

In the conterminous United States (fig. 25), the patterns of suspended-sediment concentration reflect such influencing factors as climate (especially rainfall) and the properties of the rocks and soils that are exposed to erosion. In the Eastern and Northwestern States, suspended-sediment concentrations generally are low, except in two areas: parts of western Mississippi, western and central Tennessee, Illinois, and Iowa that are underlain by loess (easily erodible windblown silt deposits) and southwestern Washington, where the recent eruption of Mount St. Helens has added large quantities of sediment to the lower Columbia River stream system.

On the High Plains of South Dakota, Colorado, Oklahoma, Texas, and New Mexico, consistently large concentrations of suspended sediment are the result of a combination of easily eroded sedimentary rocks and relatively little protective vegetation. Although intense rainfall events on the High Plains are frequent enough to cause significant erosion, the total amount of precipitation is too small to allow the development of the kind of vegetation that would protect the soil from erosion (Langbein and Schumm, 1958). Similar combinations of erodible soils and sporadic, but intense, rainfall also account for most of the large concentrations of suspended sediment in rivers in the Southwestern States.

Mean annual suspended-sediment loads discharged to the oceans, in millions of tons per year, are portrayed in figure 25 by half-circles at the mouths of selected rivers. These sediment loads, which are averages as of 1980, reflect a number of artificial influences, not the least of which is the interruption of the downriver flow of sediment by dams and reservoirs. The dominance of the Mississippi River as a mover of sediment is readily apparent. In spite of the large dams that have been built across its major tributaries, the Mississippi River still ranks sixth or seventh in the world in suspended

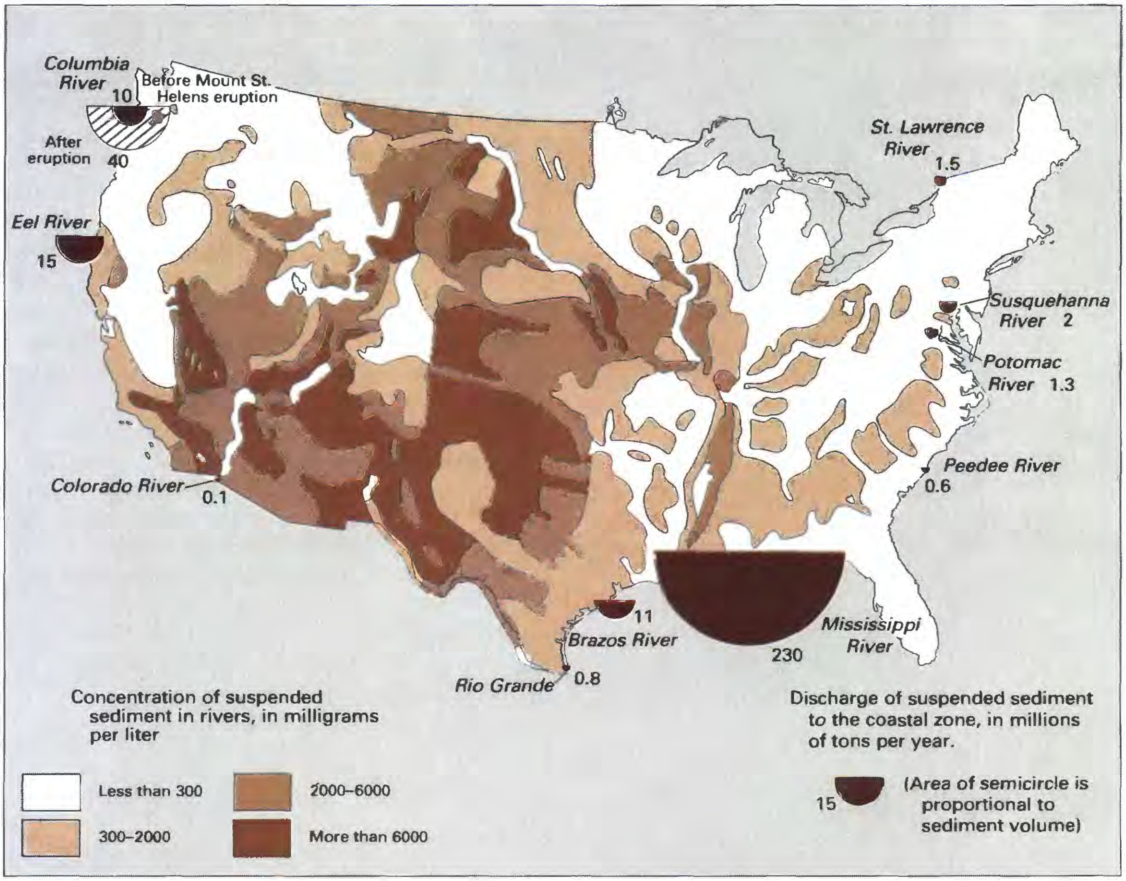

Figure 25. Average concentration of suspended sediment in rivers and average discharge of suspended sediment at the mouths of selected rivers of the conterminous United States. See table 3 for ranking of rivers. (Sources: Concentration map modified from Rainwater, 1962, plate 3; sediment-discharge data compiled by R. S. Parker and R. H. Meade from files of the U.S. Geological Survey, U.S. Army Corps of Engineers, and the International Boundary and Water Commission)

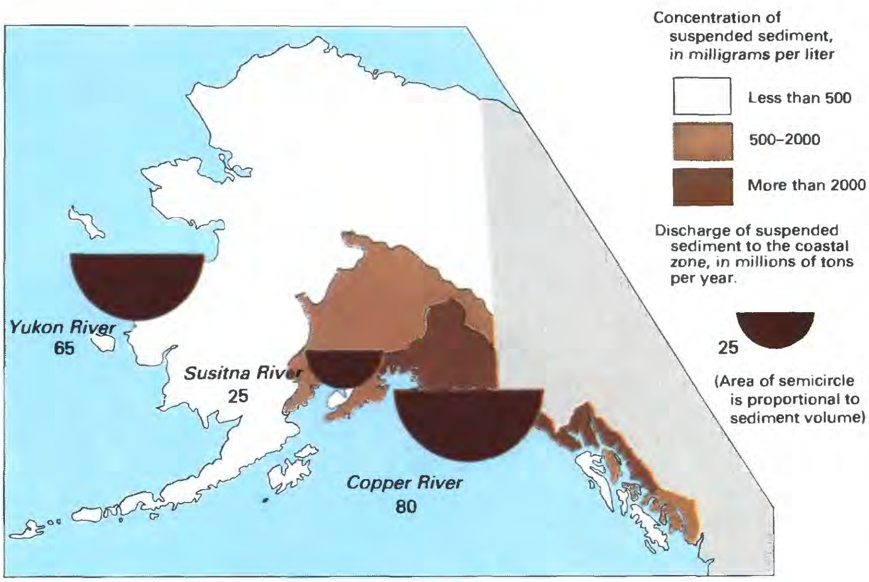

Figure 26. Average concentration of suspended sediment in rivers and average discharge of suspended sediment at the mouths of selected large rivers of Alaska. (Source: Compiled by R. H. Meade from U.S. Geological Survey data, including reports by Burrows and Harrold, 1983; Knott and Lipscomb, 1983; and Scott, 1982.)

sediment discharge to the oceans (Milliman and Meade, 1983, p. 2). Next in rank in the conterminous States is the Columbia River, which is shown in figure 25 with two different values of suspended sediment discharge: 10 million tons per year (ton/yr), the average load transported before the 1980 eruption of Mount St. Helens, and 40 million ton/yr, the estimated annual suspended sediment load transported after the eruption. Although over 140 million tons of suspended sediment from Mount St. Helens was discharged by the Cowlitz River into the Columbia River in the first 4 months after the eruption, this discharge has decreased considerably in the last few years. The additional sediment attributed to Mount St. Helens has declined to about 30 million ton/yr.

Less information is available on the concentration and discharge of suspended sediment in the rivers of Alaska (fig. 26). It is reasonably certain, however, that suspended sediment concentrations are low in the rivers of northern and western Alaska. Sediment concentrations are larger in south-central Alaska, where glaciers erode the mountain slopes and glacial meltwaters carry large sediment loads, but these concentrations still are not as large as those in the arid and semiarid parts of the western conterminous United States. The present-day sediment discharges of three rivers that drain the glaciated peaks of the Alaska Range, the Copper, the Yukon, and the Susitna, rank, respectively, second, third, and fourth, among the rivers of the United States.

Ten rivers of the United States that are important by virtue of their large sediment discharges or their large drainage areas are listed in table 3. The sediment discharges of the Mississippi River, the Rio Grande, and the Colorado River have been diminished by dams and reservoirs (discussed later in this article). Although it discharges three-quarters as much water to the ocean as the Mississippi River, the St. Lawrence River carries relatively little sediment because the Great Lakes act as natural sediment traps.

Table 3. Discharge of suspended sediment to the coastal zone by 10 major rivers of the United States, about 1980
[ton/yr = tons per year]

Rivers	Average annual sediment discharge (million ton/yr)
Rivers that discharge the largest sediment loads:	
Mississippi	[1]230
Copper	80
Yukon	65
Susitna	25
Eel	15
Brazos	11
Columbia:	
Before Mount St. Helens eruption	10
(Since Mount St. Helens eruption-approximate	40)
Rivers with large drainage areas:	
St. Lawrence	1.5
Rio Grande	.8
Colorado	.1

[1] Includes Atchafalaya River.

EFFECTS OF RESERVOIRS ON SEDIMENT LOADS

One of the most pervasive influences on sediment loads is exerted by the dams and reservoirs that have been built in large numbers across the rivers of the United States. Dams are built to impound water for various purposes, and the reservoirs they form interrupt the downriver flow of sediment. Although the river water that enters a reservoir is released eventually (through a powerplant, into a diversion canal, or over a spillway), much of the sediment is trapped permanently in the reservoir. Nearly all reservoirs on major rivers of the United States trap at least one-half of the river sediment that flows into them. Some of the largest reservoirs in the country, like Lake Powell and Lake Mead on the Colorado River, trap virtually all the sediment that flows into them.

The effects of reservoirs on sediment loads are apparent in rivers in all parts of the country; however, they are most obvious in the large western rivers where the original sediment loads were naturally large and where the construction of dams has been especially intense. Although dams cause a variety of downstream changes in the configurations of the river channels themselves (Williams and Wolman, 1984), only the effects of reservoirs on the quantities of the sediment loads transported by rivers are discussed in this article. These effects are well described by extensive collections of data from three large western river systems—the Missouri-Mississippi, the Rio Grande, and the Colorado—and a group of rivers in the Eastern United States (figs. 27, 28, 29, and 30).

MISSOURI-MISSISSIPPI RIVER SYSTEM

Annual discharges of suspended sediment measured at six gaging stations on the Missouri River and two stations on the Mississippi River over a period of about four decades are shown in figure 27. The Missouri River has always been the principal supplier of sediment to the lower Mississippi River; the other two large components of the Mississippi River system, the upper Mississippi River and the Ohio River, supply large quantities of water but comparatively small amounts of sediment. When five large dams were completed for irrigation and hydroelectric power above Yankton, S. Dak., between 1953 and 1963, the flow of sediment from the upper Missouri basin virtually was stopped (fig. 27). Following the closure of Fort Randall Dam and Gavins Point Dam in 1953, downstream sediment loads were diminished immediately, and the effect could be observed all the way down to the mouth of the Mississippi River. Sediment discharges to the Gulf of Mexico by the Mississippi River are now (1984) less than one-half of what they were before 1953. This decrease in the supply of river sediment is probably a strong contributory factor to a rapid recession of shorelines that is occurring in the subsiding Mississippi delta.

RIO GRANDE

Sediment loads in the Rio Grande, which flows through New Mexico and also forms the international boundary between Texas and Mexico, have been severely diminished by the

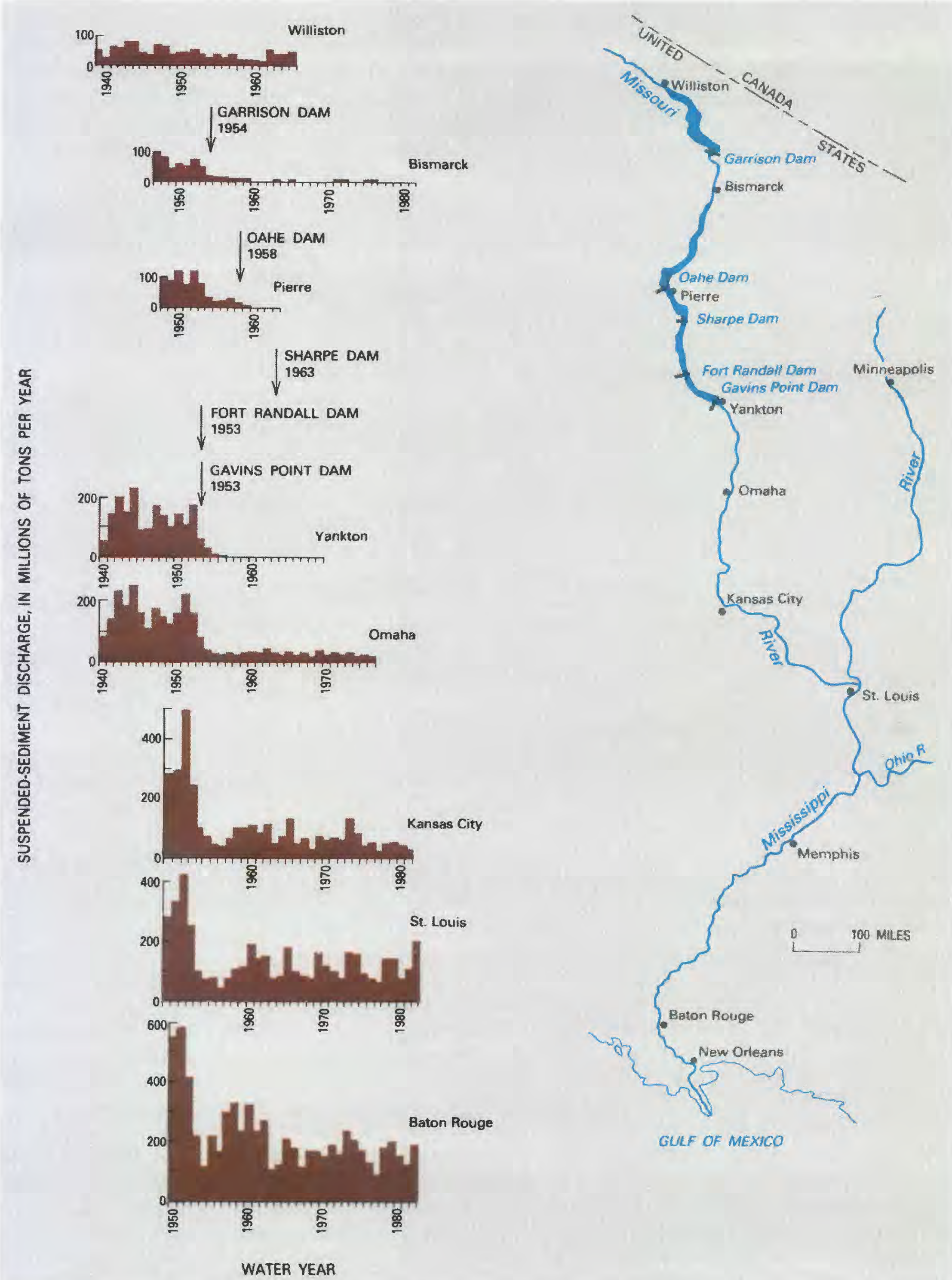

Figure 27. Annual discharge of suspended sediment at six stations on the Missouri River and two stations on the Mississippi River showing the effects of reservoirs on downstream sediment loads, 1939 to 1982. (Source: Compiled by R. H. Meade from U.S. Army Corps of Engineers and U.S. Geological Survey data.)

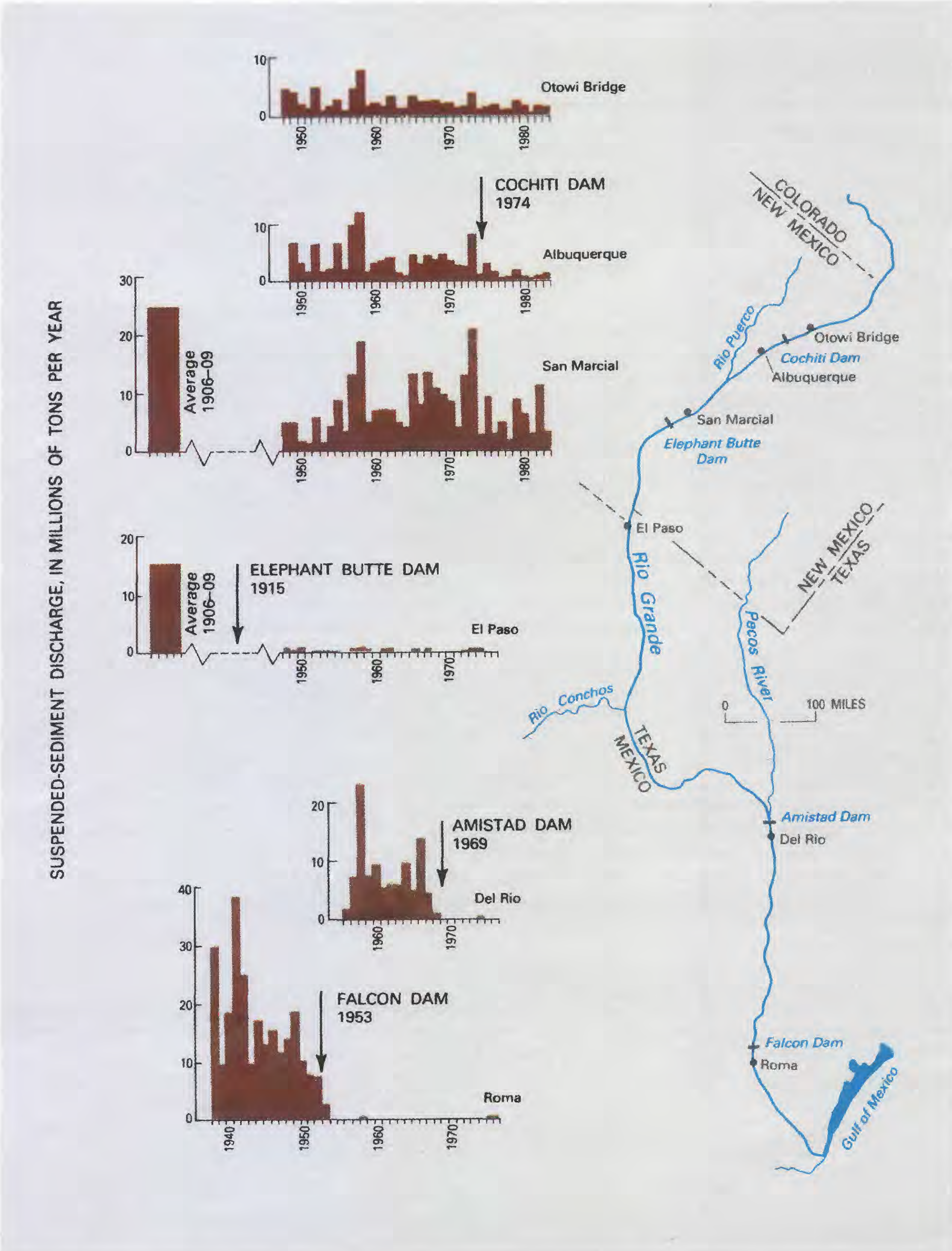

Figure 28. Annual discharge of suspended sediment at six stations on the Rio Grande showing the effects of reservoirs on downstream sediment loads, 1906 to 1983. Years are water years in upper three histograms and calendar years in lower three histograms. (Source: Compiled by D. W. Litke from U.S. Geological Survey and International Boundary and Water Commission data.)

dams and reservoirs that were built to divert water for irrigation. Records of annual sediment discharges at six gaging stations on the Rio Grande are summarized graphically in figure 28. These records clearly show the effects of reservoirs on the sediment loads in different parts of the river even though they indicate strong year-to-year fluctuations in sediment discharge that are typical of the irregular discharges of water and sediment in arid parts of the country.

The records from the uppermost two stations show the effects of the closure of Cochiti Dam in 1974. Before 1974, sediment discharges at Albuquerque were always greater than those recorded upriver at Otowi Bridge; since 1974, however, sediment discharges at Albuquerque generally have been smaller than those at Otowi Bridge. Between Albuquerque and San Marcial, the sediment discharge of the Rio Grande is increased markedly by additions from several important tributaries, most notably the Rio Puerco. Records of sediment discharge at San Marcial and El Paso dramatically show the effects of Elephant Butte Reservoir. (See fig. 28.) During the last several decades, suspended-sediment discharges at El Paso have averaged only about 200,000 ton/yr, or less than 5 percent of the average discharge at San Marcial during the same period. Below El Paso, the sediment discharge of the Rio Grande is increased again by contributions from two more tributaries, the Rio Conchos from the Mexican side and the Pecos River from the Texas side. These added contributions of sediment have been trapped, however, behind Falcon Dam, which closed in 1953, and Amistad Dam, which closed in 1969. The discharge of suspended sediment to the Gulf of Mexico by the Rio Grande, which was on the order of 20 million ton/yr as recently as 1940 and probably was even greater before Elephant Butte Dam was closed in 1915, now averages less than 1 million ton/yr.

Colorado River

Perhaps the classic example in the United States of the interruption of a large discharge of river sediment to the oceans is that of the Colorado River. Before about 1930, the Colorado River delivered an average of 125 to 150 million tons of suspended sediment per year to its delta at the head of the Gulf of California. Since the closure of Hoover Dam, which began in 1935, this rate of sediment delivery has declined, first precipitously and then more gradually, to an average annual amount today of about 100,000 tons. Figure 29 graphically shows this decline in sediment and also the more gradual decline of water flow in the lowermost Colorado River since the turn of the century. Aside from a period between 1934 and 1938, when 25 million acre-ft of the river water was appropriated for the initial filling of Lake Mead behind Hoover Dam, the quantity of water carried by the Colorado River past Yuma, Ariz., has declined more or less progressively. This decline has been in response to the increasing diversion of water from the Colorado River for irrigation of croplands and for municipal water supplies. The more abrupt decline in sediment discharge at Yuma clearly was related to a single event, the closing of Hoover Dam. The example of the Colorado River is altogether analogous to that of the Nile River of Egypt, which formerly carried more than 100 million ton/yr of sediment past Cairo to its delta in the Mediterranean Sea, and which now (since the completion of the high dam at Aswan) discharges virtually no sediment or water to the sea.

Southwestern Atlantic Seaboard

To avoid the impression that interruption of the seaward transport of sediment by dams and reservoirs is a phenomenon confined to the western part of the country, figure 30 is presented to show the effects of reservoirs on the sediment loads of rivers in Georgia and the Carolinas. Although continuous records of sediment discharge, such as those shown in figures 27 to 29, are not available for these rivers, enough data were available to compare measurements made about 1910 with data collected about 1980. During the years between the two World Wars, many dams were built across these rivers, mostly for hydroelectric power and flood control. A comparison of the sediment loads before (about 1910) and after (about 1980) shows the large influence of these reservoirs in trapping sediment. As shown in figure 30, five major rivers, which previously carried a total of 10 million ton/yr of sediment to the coastal zone, now carry only about one-third of that amount.

STORAGE OF SEDIMENT IN RIVER SYSTEMS

The 1983 *National Water Summary* (U.S. Geological Survey, 1984, p. 68–69) emphasized the importance of sediment storage in the overall picture of erosion and sedimentation. It points out that, on a national scale, the amount of sediment delivered to the oceans by rivers was only about 10 percent of the total amount eroded off the uplands of the country and that

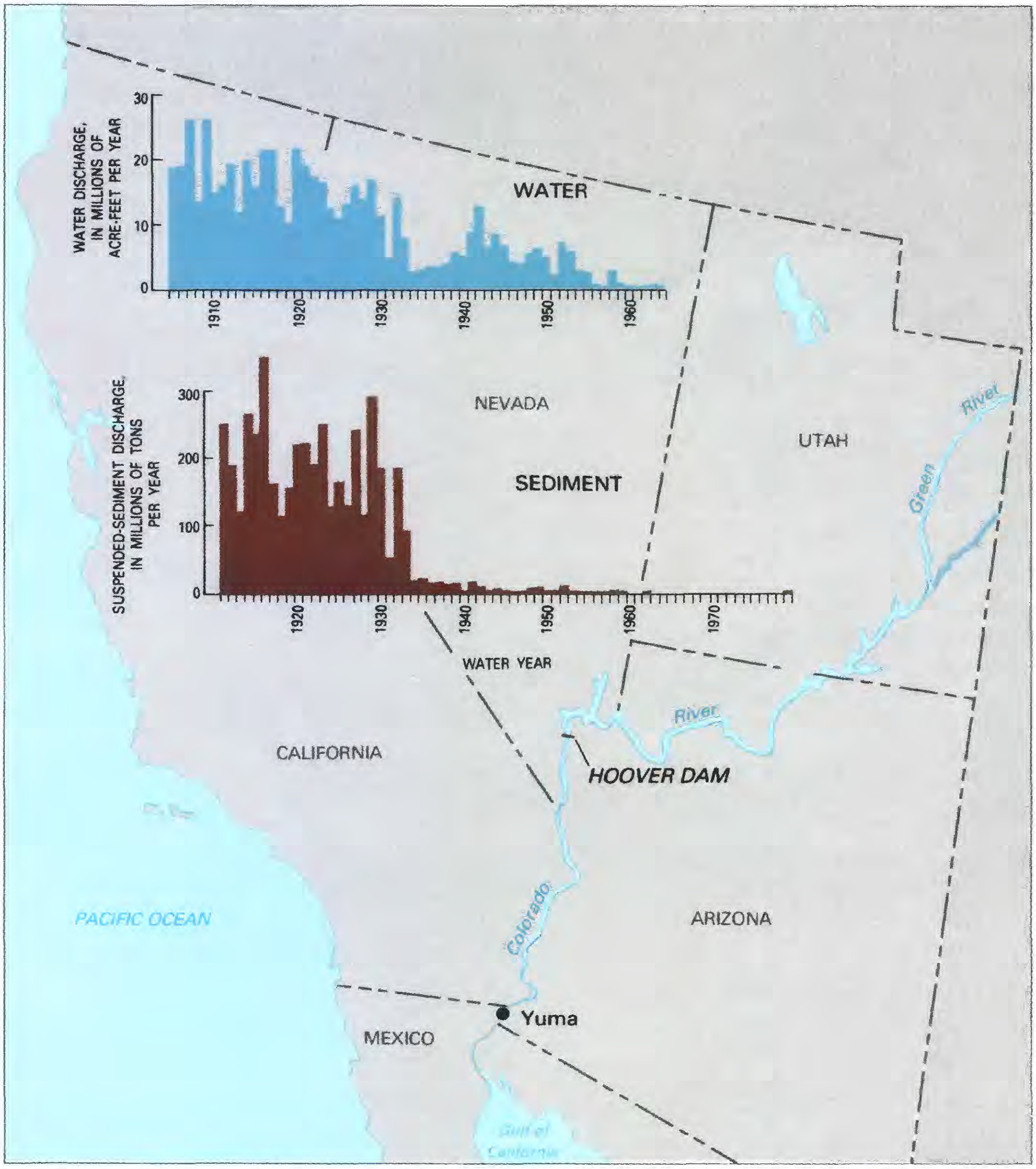

Figure 29. Annual discharge of water (1905–64) and suspended sediment (1911–79) in the Colorado River at Yuma, Ariz. Large sediment discharges shown for the years through 1940 may be somewhat exaggerated; these data were collected before modern sediment samplers and techniques were developed and standardized. However, this does not detract from the observation that the abrupt decrease in suspended-sediment discharge in the middle 1930's coincided with the closure of Hoover Dam. (Source: Compiled by R. S. Parker from U.S. Geological Survey water-discharge data and U.S. Bureau of Reclamation suspended-sediment data.)

90 percent of the soil eroded in the country was being stored somewhere between erosion sites and the sea. A fraction of this 90 percent is being stored in reservoirs, as discussed in the preceding paragraphs, but most of it is stored in other places, such as on hillslopes, flood plains, and other parts of stream valleys. The implications of the large amount of sediment storage are enormous; for example, because many of the toxic materials that travel in streams, such as metals, radionuclides, pesticides, and other organic substances, are adsorbed tightly onto sediment particles, any accurate prediction of the fate of toxic substances in a stream will require an understanding of what is happening to the sediment. Sediment storage is difficult to

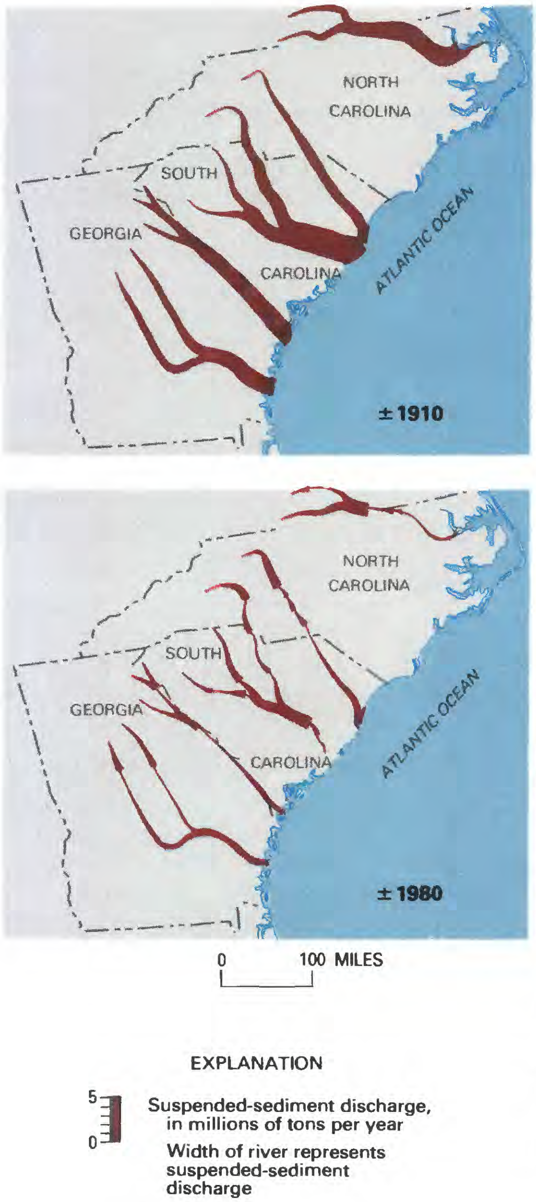

Figure 30. Average suspended-sediment discharges of major rivers in Georgia and the Carolinas during two periods, about 1910 and about 1980, that indicate the decrease in sediment loads caused by several reservoirs constructed during the intervening years. (Source: Compiled by R. H. Meade from U.S. Geological Survey data.)

predict, however, because it involves many different sedimentary processes, operating at a variety of different time scales (Walling, 1983). The following examples serve to illustrate some of these processes.

Short-Term Storage of Sediment—Lower Mississippi River

Short-term (seasonal) storage of sediment in river channels is probably easier to understand and predict than long-term storage in river systems. Some of the short-term changes in storage of suspended sediment in the lower reaches of the Mississippi River in Louisiana are shown in figure 31. No dams obstruct these reaches of the Mississippi, no tributaries bring in sediment, and no outlets drain sediment away until it reaches the mouth of the river. Any downriver changes that are observed in the discharges of suspended sediment represent deposition of material onto the riverbed or resuspension of material from the riverbed. At average water discharge, the sediment load remains the same through the entire 300-mile reach of the lower Mississippi; on a net basis, sediment is neither stored nor resuspended at average water discharge. At less-than-average water discharge, the suspended load decreases down the reach; sediment is being dropped by the flowing river and stored on the riverbed. At greater-than-average water discharge, the sediment load increases down the reach; at least part of the previously stored sediment is being resuspended from the riverbed. The short-term pattern, therefore, shows sediment being deposited and stored on the riverbed at lower flows and being resuspended and flushed out to the Gulf of Mexico on higher flows. Analogous patterns of seasonal storage and remobilization of sediment have been observed and described from rivers that range in size from small (Emmett and others, 1983; Meade and others, 1981) to the largest in the world (Meade and others, 1979, p. 482; 1983, p. 1139–1140).

Questions involving the seasonal storage and resuspension of sediment in the lower Mississippi River that need to be studied include the following: What is the long-term balance between storage and resuspension—in the long run, is more sediment being stored than resuspended, or vice versa?, and how does the seasonal storage affect the pollutants that are adsorbed on the sediment particles?

Long-Term (Decade-to-Century) Storage—Hydraulic-Mining Debris in California

A well-known case of long-term movement and storage of sediment in a river system is that of the hydraulic-mining debris in the Sacramento River valley of California (Gilbert, 1917; Kelley, 1959). Between 1855 and 1885, enormous quantities of sediment were washed into some of the tributaries of the Sacramento River during hydraulic mining for gold. The resulting problems that developed downstream (flooding, filling of navigation channels, destruction of flood-plain farms) became so serious that hydraulic mining was curtailed by a court decision in 1884. By that time, however, the large mass of sediment, characterized as a "wave" by G. K. Gilbert (1917), was already into the stream channels and was moving slowly down the tributaries and into the Sacramento River. As the mass of sediment advanced, it raised the levels of the channel beds, much as an ocean swell raises the level of the sea as it passes through. Bed levels rose 19 feet (ft) in the tributary Yuba River at Marysville and nearly 11 ft in the Sacramento River at Sacramento. The riverbeds at these towns reached their greatest elevations 10 to 20 years after the mining was stopped, and then they declined steadily to their previous elevations during the next 30 to 40 years. All in all, the great wave of hydraulic-mining debris took nearly a century to pass through the channels of the Sacramento River system and finally to reach San Francisco Bay.

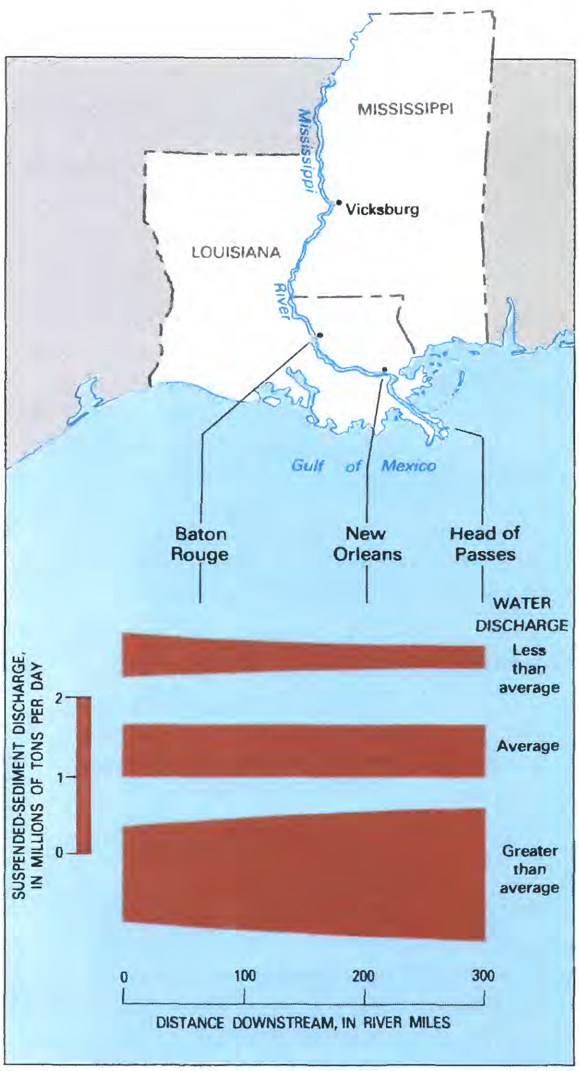

Figure 31. Suspended-sediment discharge in the lowermost 300 miles of the Mississippi River at three different stages of river flow—less than average, average, and greater than average. (Source: Compiled by R. H. Meade from U.S. Geological Survey data collected by Everett, 1971, p. 14; and Wells, 1980, p. 13.)

This pattern, however, applied only to the sediment in and near the river channels. It did not apply to the debris that had overflowed onto the flood plains. The hydraulic-mining debris that was carried out of the river channel during floods and deposited on the flood plains was sufficient in many places to cover entire houses and orchards (Kelley, 1959, p. 134–135, 203–204). Most of that debris still remains where it was deposited a century ago. The time required to remove sediment from storage on the flood plain is much longer than the century that was required to remove the debris from the main river channels. Flood-plain deposits are removed mainly by erosion of channel banks as streams slowly migrate laterally, a process that proceeds at a substantially slower pace than the vertical removal of material stored in the bottom of the river channel.

Longer Time Scales for Sediment Storage—Coon Creek Basin, Wisconsin

Many of the problems associated with the prediction of long-term sediment storage are demonstrated in a study carried out on Coon Creek, a small stream that drains 140 square miles of southwestern Wisconsin (Trimble and Lund, 1982). Originally covered by forests, Coon Creek basin was settled by European immigrants and cleared for farming about 1850. As the forests were cleared and the land was plowed, a cycle of erosion and sedimentation began, the consequences of which are still strongly in effect today. In 1933, after about 80 years of land-management practices that resulted in excessive erosion, soil-conservation efforts were begun in earnest. These efforts still continue. Two time periods (1853–1938 and 1938–1975) are described below. The year 1938 was selected as the transitional date because of an extensive sedimentation study that was carried out that year.

Figure 32*A* shows the accelerated erosion of sediment from the uplands and tributary areas and the transfer of sediment to the lower hillslopes and valleys of the Coon Creek basin between 1853 and 1938. Much less than 10 percent of the sediment eroded off the uplands during this period was exported out of the basin by the creek. More than 90 percent of the sediment was deposited along the way, on hillslopes and flood plains, where most of it still remains in storage.

From 1938 to 1975, improved soil conservation and land management reduced the rates of upland erosion. However, the quantity of sediment that passes out the mouth of Coon Creek is still less than 10 percent of the total

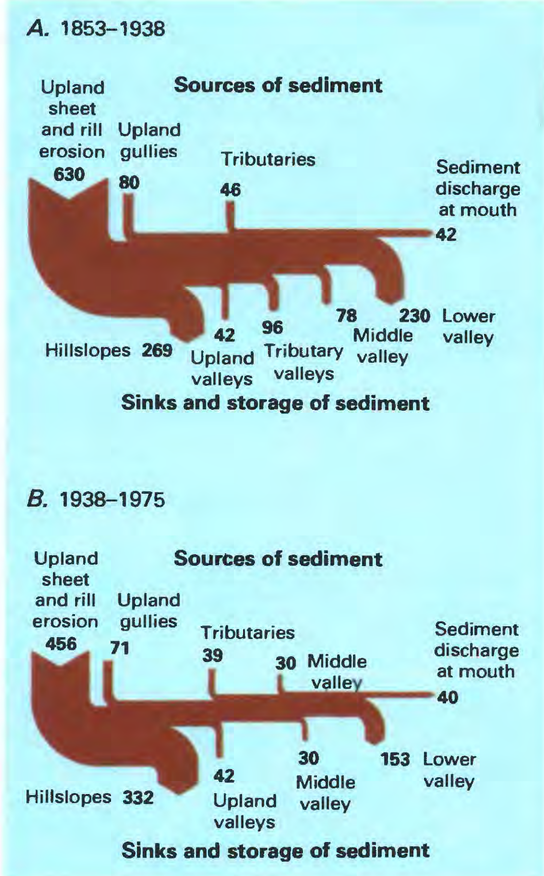

Figure 32. Sources, sinks, and storage of sediment in the drainage basin of Coon Creek, Wis., during two periods. *A*, 1853 to 1938. *B*, 1938 to 1975. Numbers on the diagram are annual averages for the period, in thousands of tons per year. During the 122-year period between 1853 and 1975, a total of 80 million tons of sediment were transferred from eroded upland sources to lowland storage sites within the Coon Creek basin. During that same period, only 5 million tons of sediment were carried out of the basin by the creek. (Source: Modified from Trimble, 1983.)

upland erosion (fig. 32*B*). The other 90 percent or more of the eroded sediment still is being stored within the creek basin. The only important difference in recent years is that some of the sediment formerly stored in the middle valley is now being remobilized and transported out of the basin.

Further details of the Coon Creek study can be found in two recent publications by Trimble and Lund (1982) and Trimble (1983). The study demonstrates the complexity of the sediment-storage problem. The time scales of storage are so long and the storage sites so diverse that it is difficult to even begin to construct mathematical models to predict the eventual rates of sediment movement. As outlined in a recent summary by Walling (1983), the problems of sediment delivery and long-term storage in river valleys are among the principal challenges for future studies of sediment.

EFFECTS OF INFREQUENT LARGE STORMS ON SEDIMENT TRANSPORT

In many rivers of the conterminous United States, a large proportion of the sediment load is transported in only a small proportion of the time; for example, within any individual year, more than one-half of the sediment load for the year is likely to be transported in only 5 or 10 days. Also, over a period of many years, a large proportion of the long-term sediment load may be transported in response to a few large, but infrequent, storms.

The frequencies of suspended-sediment discharge within individual years and the importance of infrequent large storms in producing large sediment loads are demonstrated by the daily suspended-sediment discharge records for three stations—Eel River at Scotia, Calif., Delaware River at Trenton, N.J., and Juniata River at Newport, Pa. (fig. 33). The storms whose effects are shown are of two types—Atlantic coast hurricanes and Pacific coast winter storms.

These three data sets were selected because each contained the effects of a large storm (whose recurrence interval was longer than the period of sediment record), and each contained sufficient data from years of more average sediment discharge to place the effects of the storm into a reasonably comparative context. Figure 33 shows for each year the quantities and proportions of suspended sediment discharged during 1, 10, and 100 percent of the year. Among the three rivers, nearly one-half of a year's sediment usually is discharged in 3.65 days, and nearly 90 percent usually is discharged in 36.5 days.

EFFECTS OF ATLANTIC COAST HURRICANES ON SUSPENDED-SEDIMENT DISCHARGE

The effects of hurricane-induced floods on the sediment discharges of two rivers that drain parts of the middle Atlantic seaboard are shown in figures 33*A* and *B*. In both rivers, the suspended-sediment discharges generated by the hurricanes (10 days' discharge on the Juniata River and 2 days' discharge on the Delaware River) were equivalent to the totals carried during 3 full years of average suspended-sediment discharge. Further, the record for the Delaware River shows that the quantity of suspended sediment carried past Trenton in 2 days following Hurricane Connie was more than the river carried during 5 full years (1962–66) of the mid-1960's drought. In the record for the Juniata River, it is noteworthy that the suspended-sediment discharge during the year of Hurricane Agnes stands alone; during none of the other 31 years in the period of record did the suspended-sediment discharge even approach that recorded during 1972.

EFFECTS OF PACIFIC COAST WINTER STORMS ON SUSPENDED-SEDIMENT DISCHARGE

The most spectacular single sediment-discharge event preserved in the daily sediment records of the United States is the storm that struck northwestern California a few days before Christmas 1964 (fig. 33*C*). In 3 days, the Eel River carried more sediment past Scotia, Calif., than it had carried during the previous 7 years. In 10 days, it carried a quantity of sediment equivalent to that transported in 10 average years. The total suspended-sediment discharge of 168 million tons that the Eel River carried past Scotia during water year 1965 was almost as great as the 184 million tons that the Mississippi River carried past St. Louis that same year. The storm of December 1964 brought about long-term changes in the sediment-transport characterisitics of many stream channels in northwestern California (Lisle, 1981, 1982).

The sediment loads generated by the large storms as shown in figure 33 seem to belong to different statistical populations than do the normal year-to-year sediment loads. The large loads seem to stand alone with no intermediate sediment loads to bridge the wide gaps between them and the more normal loads. This suggests that it may not be possible to predict accurately the large size of these sediment loads merely by extrapolating a sediment record that does not contain at least one of them. Because it is obviously impractical (and impossibly expensive) to continue collecting daily sediment records at each gaging station until one of these large events has been recorded, estimating their frequencies and magnitudes is extremely difficult.

CONCLUSIONS

Among the issues and problems that relate to the sediment in rivers of the United States are (1) the effects of dams and reservoirs on sediment transport, (2) importance of large, infrequent storms on the generation and transport of sediment, and (3) the implications of sediment storage on the downstream movement of sediment particles and their associated contaminants. Dams and reservoirs have diminished by one-half the amount of sediment that the Mississippi River formerly transported to its delta. They have almost completely stopped the seaward transport of sediment by two other great rivers of the country, the Colorado and the Rio Grande. Until the storage of sediment in river valleys at different time scales is understood more clearly, predicting the fate of many of the pollutant substances that are found in the Nation's rivers will continue to be problematical.

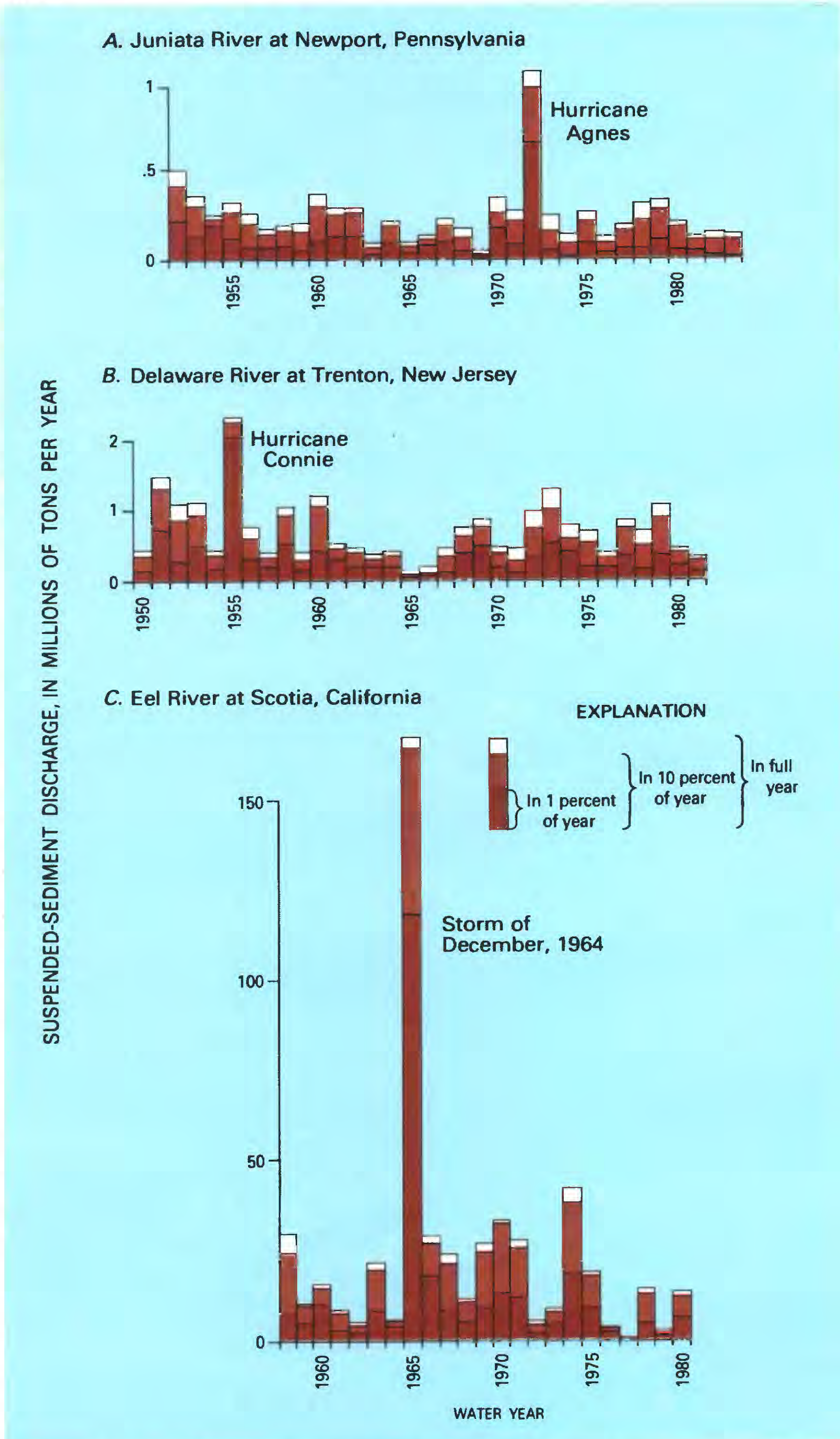

Figure 33. Annual suspended-sediment discharge of three rivers showing the frequencies of suspended-sediment discharges within individual years and the importance of infrequent heavy storms in producing large sediment loads. *A*, Juniata River at Newport, Pa. *B*, Delaware River at Trenton, N.J. *C*, Eel River at Scotia, Calif. (Source: Compiled by R. H. Meade from U.S. Geological Survey daily-sediment data.)

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LOADS AND CONCENTRATIONS OF DISSOLVED SOLIDS, PHOSPHORUS, AND INORGANIC NITROGEN AT U.S. GEOLOGICAL SURVEY NATIONAL STREAM QUALITY ACCOUNTING NETWORK STATIONS

By James E. Kircher, Robert J. Gilliom, and R. Edward Hickman

Dissolved solids, phosphorus, and nitrogen were identified as water-quality concerns in the 1983 *National Water Summary* (U.S. Geological Survey, 1984, p. 45–63). When present in high concentrations, they can restrict water use for many purposes. The following discussion provides a broad, national perspective of the loads (transport rates) and concentrations of dissolved solids, total phosphorus, and inorganic nitrogen (nitrate plus nitrite) in the Nation's major rivers and also serves as an introduction to subsequent discussions of water-quality trend analyses and case studies of dissolved solids in the Colorado and Arkansas Rivers.

DATA SOURCES AND METHODS

Data used in this discussion and in the following trend analyses are from the U.S. Geological Survey's National Stream Quality Accounting Network (NASQAN). This network was established in 1972 to account for the quantity and quality of streamflow within the United States, to depict the areal variability of water conditions, and to detect changes in stream quality with time (Britton and others, 1983, p. 5). Data collected include the quantity of streamflow, concentrations of major inorganic and trace constituents, presence or absence of bacterial indicators of pollution, and concentrations of selected pesticides. A standard set of water-quality characteristics is measured at each station using the same collecting procedures, sampling frequency, and analytical methods. These procedures provide uniform and consistent data upon which to base analyses. NASQAN is an "accounting network" in that it measures the amount of water and dissolved or suspended material that move from one hydrologic accounting unit to another or to the oceans. However, the data from NASQAN stations do not necessarily characterize water-quality conditions either upstream or downstream of the measuring points because many of the reported constituents undergo changes in concentrations as the water moves downstream.

Of 504 currently active NASQAN stations, the 298 stations with complete monthly data from October 1974 to September 1981 (water years 1975–81) were selected to depict national patterns of mean concentrations and transport. Concentration of a constituent usually is expressed as mass per unit volume of water and is reported here as milligrams per liter. Transport is characterized by the mean annual load of a constituent passing by a station. It is computed as the product of water discharge and concentration and is reported as tons per day or tons per year. In this report, mean annual loads and mean annual concentrations were calculated using methods described by Smith and Alexander (1983).

All results are shown on national maps (figs. 34, 35, and 36). The mean annual load at each station is shown by a circle that is proportional in size to the computed load, as indicated in the map explanations. All loads less than the minimum amount specified in the map explanations are depicted by the same-sized circle. Concentrations of each constituent are generalized in three classes and indicated by the color of the circle.

DISSOLVED SOLIDS

The major inorganic components of dissolved solids in rivers are sodium, potassium, calcium, magnesium, carbonate, bicarbonate, chloride, and sulfate ions (Rainwater, 1962). The main sources of these constituents are the dissolution of rock and soil, atmospheric deposition, and human activities. Human activities contribute dissolved solids through the discharge of wastewater from such point sources as municipal and industrial waste treatment plants and through runoff and drainage from such nonpoint sources as agricultural and urban areas. One of the most important sources of dissolved solids is irrigation return flow to streams by direct surface runoff or by subsurface drainage. Agricultural and natural sources of dissolved solids are addressed in more detail later in this report in the case studies of dissolved solids in the Colorado and Arkansas River basins. The importance of atmospheric sources, which include both human-induced and natural dissolved solids, was evaluated by Peters (1984).

The concentration of dissolved solids is used widely as a general indicator of water quality and of the suitability of water for various uses. High concentrations, for example, hamper municipal and industrial uses of water by increasing treatment costs, accelerating pipe corrosion, and increasing soap and detergent use. The U.S. Environmental Protection Agency (1982a) recommends that public water supplies contain no more than 500 milligrams per liter (mg/L) of dissolved solids. High dissolved solids also detract from the value of water for irrigation at levels greater than about 700 mg/L (U.S. Bureau of Reclamation, 1983) although higher concentrations can be tolerated by some crops grown on permeable soils with careful water irrigation management. Generally, water used for irrigation contains less than 2,000 mg/L (National Academy of Sciences and National Academy of Engineering, 1972, p. 335). The mass transport of dissolved solids by a river is sometimes used as a measure of how rapidly rock weathering is occurring in a watershed.

Mean dissolved-solids concentrations at NASQAN stations vary widely, reflecting the broad range of natural and human influences on dissolved solids in different parts of the country (fig. 34). Mean concentrations at NASQAN stations range from 26.0 mg/L in the Saco River in Maine to 32,900 mg/L in the Salt Fork Brazos River in Texas. These extremes are indicative of the general pattern of more high concentrations west of the Mississippi River than to the east. Of 71 stations with mean concentrations exceeding the drinking water criteria of 500 mg/L, 68 are west of the Mississippi River. The western part of the country contains vast arid and semiarid areas that favor concentration of dissolved solids through evapotranspiration, a process further stimulated by extensive irrigation. In areas with moderate to high annual precipitation—mainly the area east of the Mississippi River, mountain areas, and the Pacific Northwest—rivers generally have low dissolved-solids concentrations due to dilution.

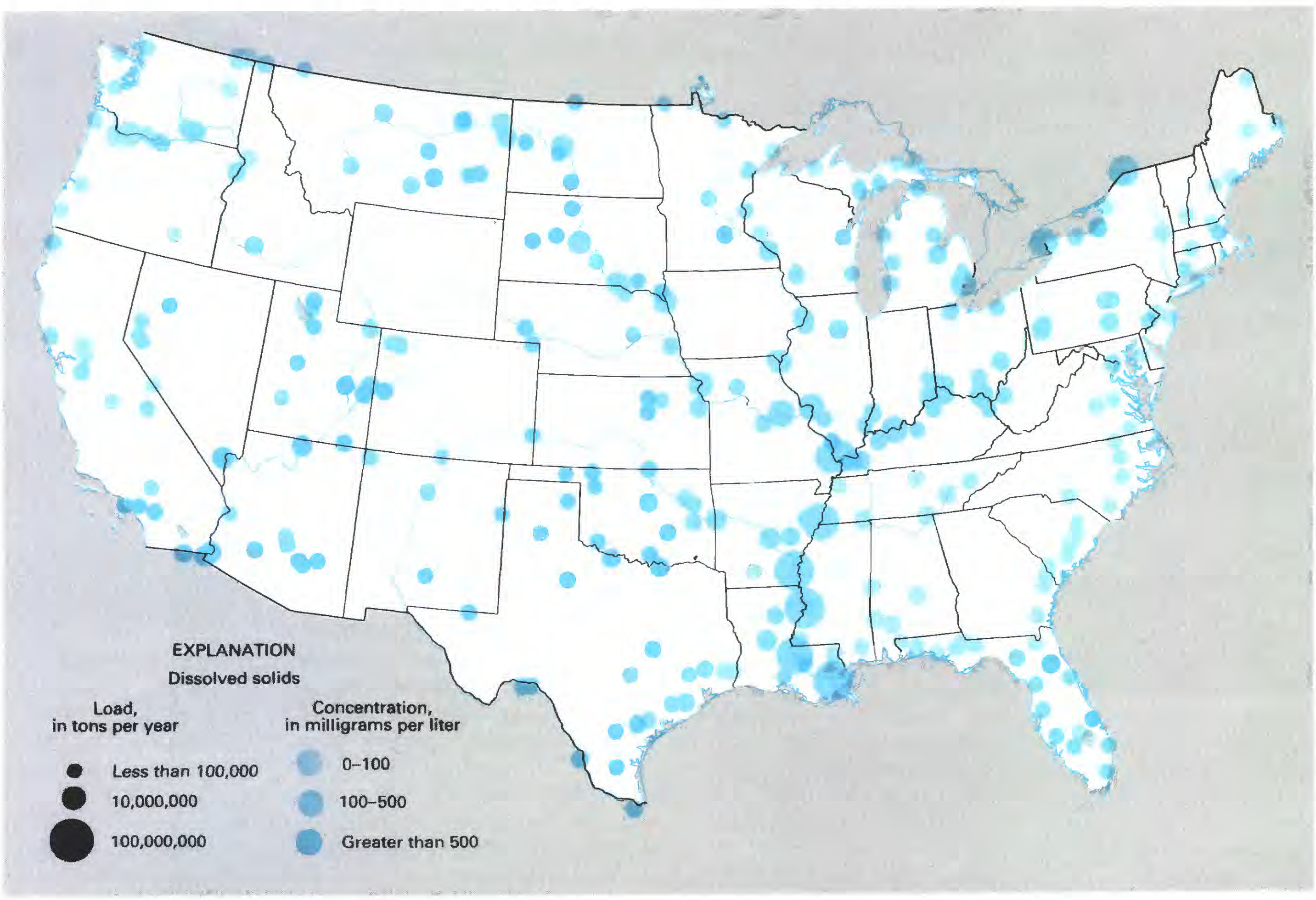

Figure 34. Dissolved-solids loads (tons per year) and mean annual concentrations (milligrams per liter) at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981. Color of the circle represents the concentration range and the size of the circle is proportional to the load. (Source: Compiled from data in Smith and Alexander, 1983.)

In contrast to dissolved-solids concentration, the greatest transport of dissolved solids occurs in rivers with the largest flows of water even though they contain fairly low concentrations (fig. 34). The prominent example is the Mississippi River, which transports an average of about 121 million tons per year into the Gulf of Mexico. The Mississippi and other large rivers carrying particularly high dissolved-solids loads—the St. Lawrence, the Ohio, and the lower Missouri—generally drain large humid areas of the Nation with relatively high rates of rock weathering, extensive agriculture, and high population densities. In most rivers, dissolved-solids loads generally increase downstream as the flow of the river increases.

PHOSPHORUS

Phosphorus is an essential and key plant nutrient derived from natural and human-induced sources. Most phosphorus in rivers is either dissolved as phosphate ions and organic phosphorus molecules or suspended in association with inorganic suspended sediment and organic particulate matter, such as algae. Natural sources of phosphorus include dissolution of phosphorus-bearing rocks (abundant in some parts of the country, such as Florida), decay of organic plant material, animal wastes, and atmospheric deposition. Important human-induced sources are human wastes and synthetic detergents in sewage effluent and runoff from feedlots and urban and fertilizer-rich agricultural areas.

The principal adverse effect of phosphorus on water quality is the stimulation of excessive growth of aquatic plants. Such growth may lead to murky water, floating scums of algae, dense mats of rooted and floating aquatic plants, depletion of dissolved oxygen associated with decaying plant material, and associated damage to fisheries. Recreation may be hampered and treatment costs may increase for municipal and industrial users. Such problems are more severe in lakes, reservoirs, and estuaries fed by rivers rather than within the rivers, where velocities of flow reduce the adverse effects. The U.S. Environmental Protection Agency (1976) has suggested that total phosphorus concentrations generally should not exceed 0.05 mg/L in rivers near where they enter a lake or reservoir or 0.10 mg/L elsewhere

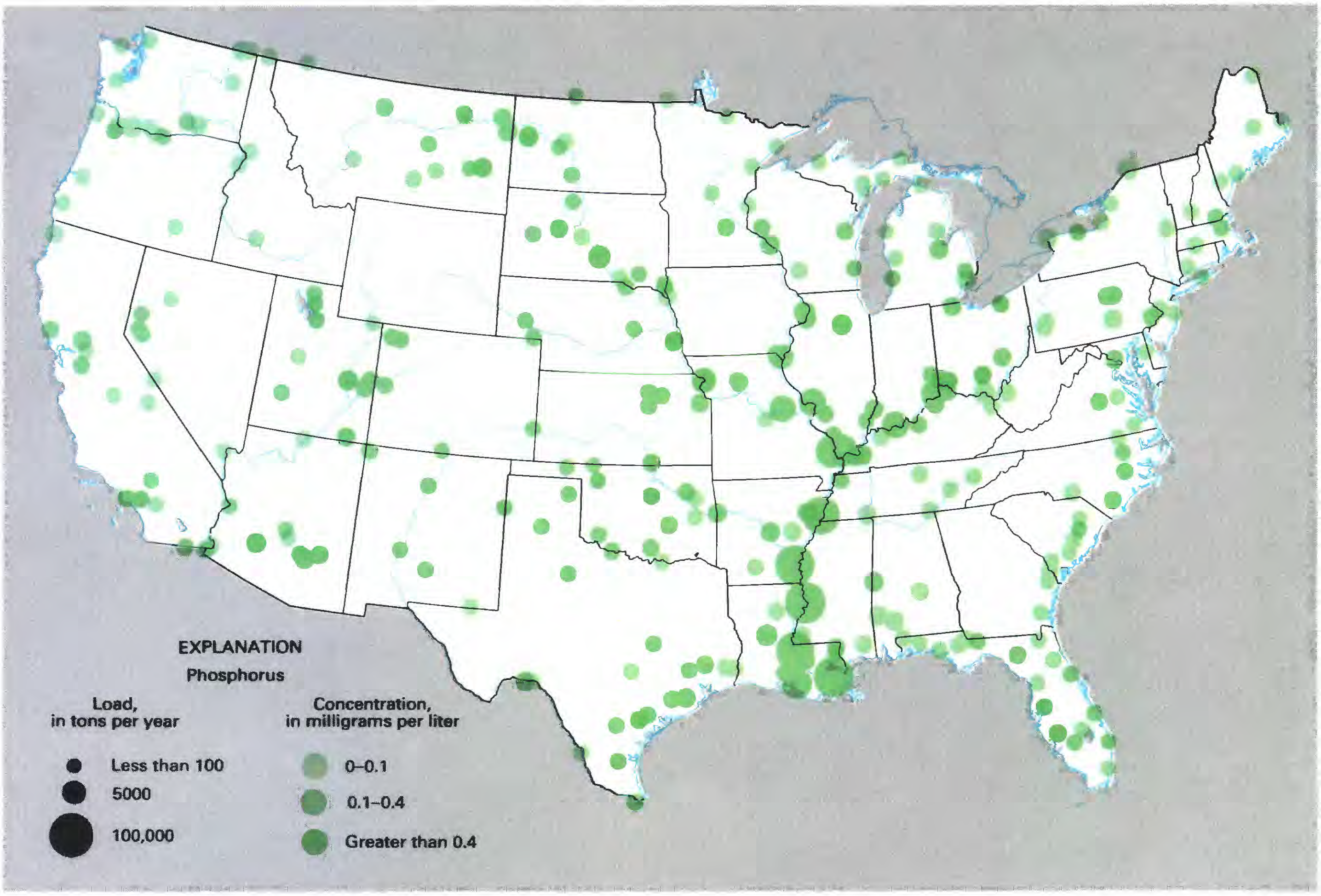

Figure 35. Phosphorus loads (tons per year) and mean annual concentrations (milligrams per liter) at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981. Color of the circle represents the concentration range and the size of the circle is proportional to the load. (Source: Compiled from data in Smith and Alexander, 1983.)

in rivers. However, the variability between rivers in terms of the biological availability of the phosphorus they contain is so large that uniform criteria are often not suitable or relevant, and, thus, there is no firm total phosphorus criterion.

The load of phosphorus carried by a river is particularly important where it enters a lake, reservoir, or estuary. Useful management criteria have been developed from relations between phosphorus loadings to lakes and reservoirs and phosphorus concentrations in the impoundments (for example, see Reckow, 1979). However, the applicability of such relations to river inflows carrying much of the phosphorus in association with inorganic particulate matter, rather than in more biologically available forms, is unclear.

Mean concentrations of total phosphorus at NASQAN stations vary widely across the country (fig. 35) and generally are similar in pattern to the suspended-sediment concentrations depicted in figure 25 (see "Sediment in the Rivers of the United States"). In many rivers, most of the phosphorus is associated with fine-grained sediment rather than with the dissolved state. Mean concentrations range from 0.015 mg/L in the Saco River in Maine to 5.7 mg/L in the Little Colorado River in Arizona. The general quality guideline of 0.05 mg/L for rivers entering lakes or reservoirs is exceeded by mean concentrations at 233 stations, and the guideline of 0.10 mg/L is exceeded at 165 stations. The high frequency at which the quality guidelines are exceeded may be somewhat misleading because a majority of the phosphorus in these large rivers probably is bound tightly with sediment particles and not readily available to biota.

As with dissolved solids, most phosphorus transport occurs where flow is greatest, even though concentrations are moderate. The greatest loads occur in the Mississippi River basin where flows are large and in which many of the tributaries drain agricultural land and, therefore, have high concentrations of the nutrient.

INORGANIC NITROGEN

Like phosphorus, nitrogen also is a key plant nutrient. The primary forms of nitrogen in rivers are nitrate, nitrite, ammonia, and

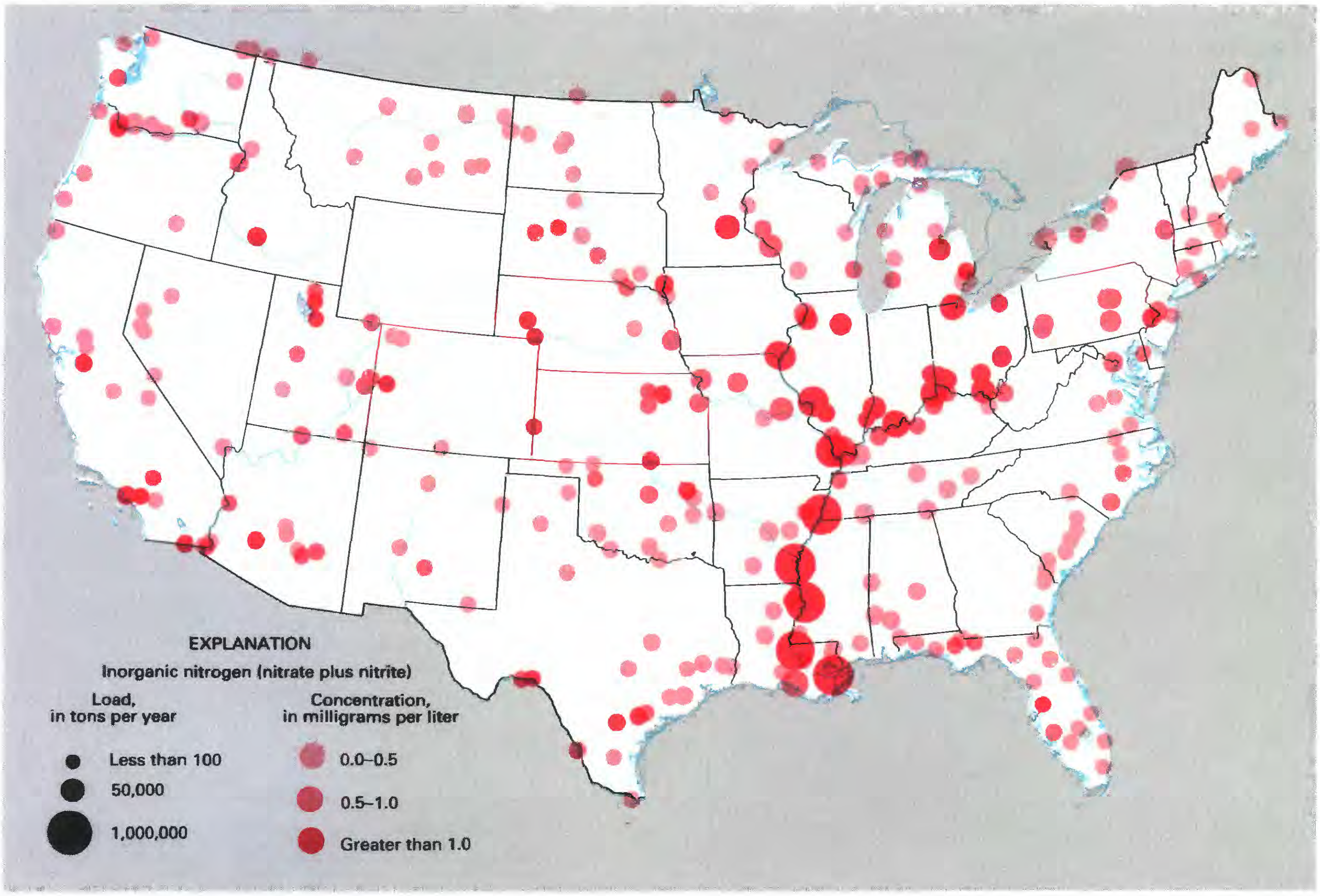

Figure 36. Inorganic nitrogen (nitrate plus nitrite) loads (tons per year) and mean annual concentrations (milligrams per liter) at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981. Color of the circle represents the concentration range and the size of the circle is proportional to the load. (Source: Compiled from data in Smith and Alexander, 1983.)

assorted organic compounds. This discussion focuses on inorganic nitrogen which primarily consists of nitrate with lesser amounts of nitrite. The principal natural sources of nitrogen are atmospheric deposition and soil nitrogen derived from the degradation of organic material and biological fixation of nitrogen gas from the atmosphere. Human sources include sewage effluent and agricultural and urban runoff. The various transformations of nitrogen compounds in the environment are discussed in detail in the article "Overview of the Occurrence of Nitrate in Ground Water of the United States." Nitrate is much more soluble than phosphorus, and all nitrate found in river water is biologically available.

Potential water-quality effects of nitrate include stimulation of excessive plant growth and toxicity to human infants. There are no water-quality criteria related to the role of nitrogen in stimulating plant growth. The human-health criterion for nitrate in drinking-water supplies is 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 1982b).

Nitrate concentrations follow a pattern that is distinctly different from that of dissolved solids and phosphorus (fig. 36). Many of the highest mean concentrations are in the Mississippi River and its tributaries where discharge and transport also are high. Much of that area is farmed intensely, receives heavy nitrogen fertilizer applications, and produces large quantities of nitrogen-rich livestock wastes. Nationwide, mean nitrate concentrations range from 0.025 mg/L nitrogen in the Pend Oreille River in Washington to 9.8 mg/L nitrogen in the Gila River in Arizona. Mean nitrate concentration did not exceed the human-health criterion of 10 mg/L at any station.

The foregoing national scale analysis of mean concentrations and loads of three key water-quality constituents provides an overview of recent average conditions in the Nation's larger rivers. This overview may be compared with the discussion of recent trends for the same constituents, which is covered in more detail in the following article.

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TRENDS IN CONCENTRATIONS OF DISSOLVED SOLIDS, SUSPENDED SEDIMENTS, PHOSPHORUS, AND INORGANIC NITROGEN AT U.S. GEOLOGICAL SURVEY NATIONAL STREAM QUALITY ACCOUNTING NETWORK STATIONS

By Richard A. Smith and Richard B. Alexander

The U.S. Geological Survey is analyzing and interpreting trends in data at its National Stream Quality Accounting Network (NASQAN) and National Hydrologic Bench-Mark Network of water-quality monitoring stations using statistical trend-testing procedures (Hirsch and others, 1982; Smith and others, 1982) and ancillary information from large environmental data bases such as the National Resource Inventory (U.S. Department of Agriculture, 1984). The 1983 *National Water Summary* (U.S. Geological Survey, 1984, p. 46) included preliminary results of these trend analyses for a group of 34 water-quality constituents. This article presents the national pattern of trends for dissolved solids, suspended sediment, total phosphorus, and inorganic nitrogen (nitrate plus nitrite) based on data collected at 298 NASQAN stations between October 1974 and September 1981 (water years 1975-81) and proposes possible explanations for their occurrence.

Because the purpose of these analyses is to define water-quality trends resulting from human activity rather than from natural causes such as changes in temperature and precipitation, the statistical trend testing procedures have been designed to remove variations in water quality resulting from changes in season and streamflow. Each trend was tested for significance at the 90-percent confidence level which implies that there is less than a 10-percent chance that the trend could have resulted from a random arrangement of the data. In the following maps, which are used to illustrate the trend patterns, triangles indicate the location of stations with trends that are statistically significant, and circles indicate the location of stations where trends are not significant (concentrations are interpreted to have not changed). Upward-pointing triangles indicate increasing concentrations, and downward-pointing triangles indicate decreasing concentrations.

TRENDS IN DISSOLVED SOLIDS

A large number of the Nation's rivers showed significant change in dissolved solids during water years 1975 to 1981 (fig. 37). Dissolved-solids concentrations increased at 59 percent of the stations that showed significant trends. Because the data were flow adjusted before applying the trend tests, the effects of wet and dry years largely were eliminated as explanations for these trends. Therefore, some form of human activity is the probable cause for most of the trends.

The geographic pattern of the trends and the location of irrigated farmlands suggests that irrigation return flows are important contributors of dissolved material to rivers, especially in semiarid basins of the West and Southwest. Increases in irrigated agriculture in some basins may lead to increases in dissolved solids. In basins where efforts to control the dissolved-solids content (salinity) of return flows have been made, dissolved-solids concentrations may decrease over time. River basins in which irrigated agriculture is thought to have a major influence on water quality include the Arkansas, Red, and Colorado to name a few. (See case study articles "Dissolved Solids in the Colorado River Basin" and "Dissolved Solids in the Arkansas River Basin.")

A second type of human activity that may influence dissolved-solids trends is the application of salt to highways for snow and ice control. Highway salt application has increased dramatically in quantity and geographic extent since the 1950's and is now a major source of dissolved salt in river basins in the Northeast and North-Central States as far south as Missouri and Virginia. Since 1974, however, the nationwide tonnage of applied salt has fluctuated considerably from year to year in response to the severity of winter weather (fig. 38). Moreover, changes in the use of highway salt may lead to either increasing or decreasing trends in dissolved solids, depending on the geographic region and the intensity of application in relation to station locations. Further insight into the interpretation of these trends in dissolved solids will require analyses of individual basins.

TRENDS IN SUSPENDED SEDIMENT

Suspended-sediment trends from 1975 to 1981 show nearly equal numbers of stations with increasing (44) and decreasing (43) concentrations, but some regional groupings of trends

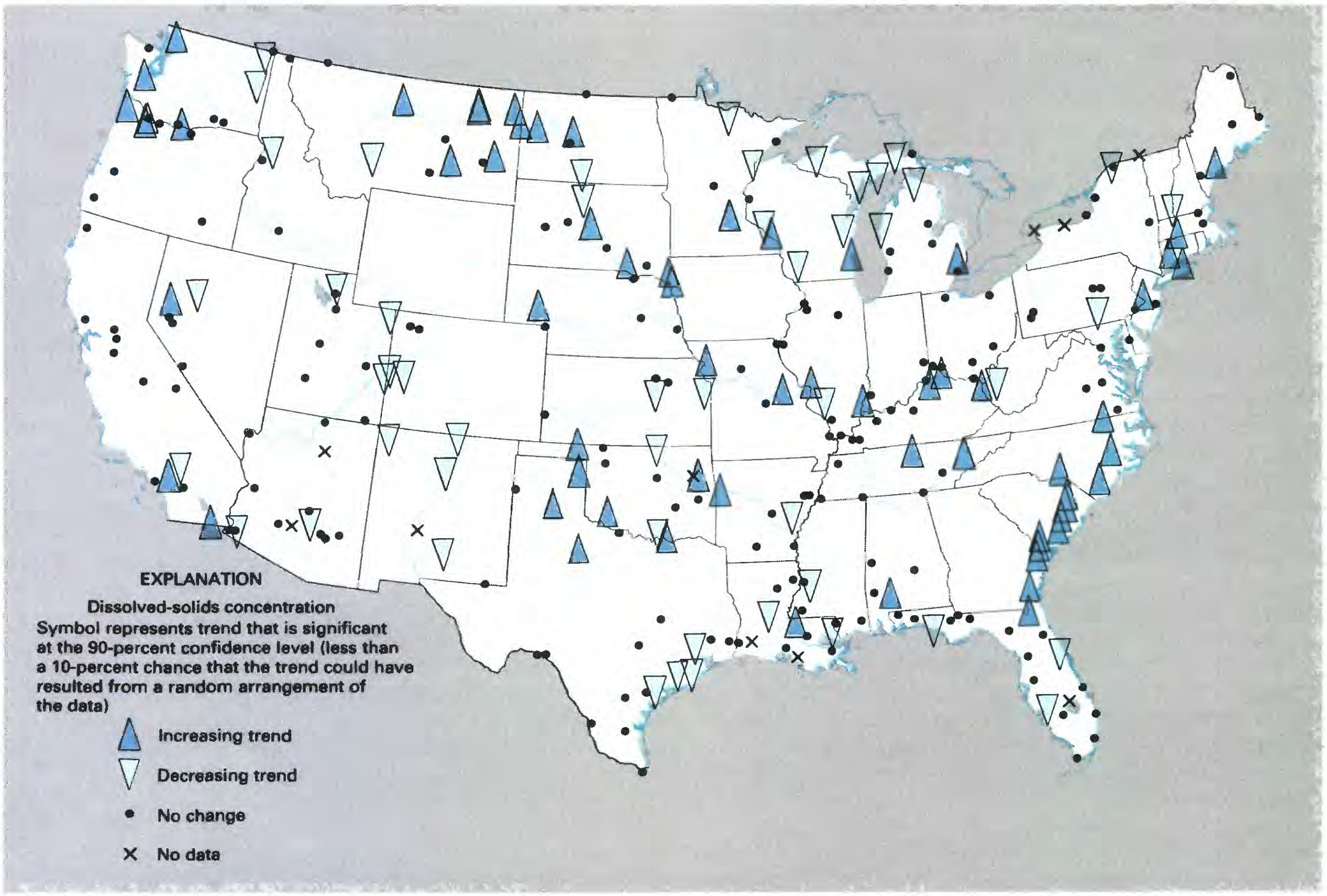

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Figure 37. Trends in dissolved-solids concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981 (Source: Compiled from data in Smith and Alexander, 1983.)

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Figure 38. Increase of salt application as a highway deicing chemical in the United States, 1947 to 1983. (Source: Compiled by I. C. James II, U.S. Geological Survey, from data supplied by the Salt Institute, 1984.)

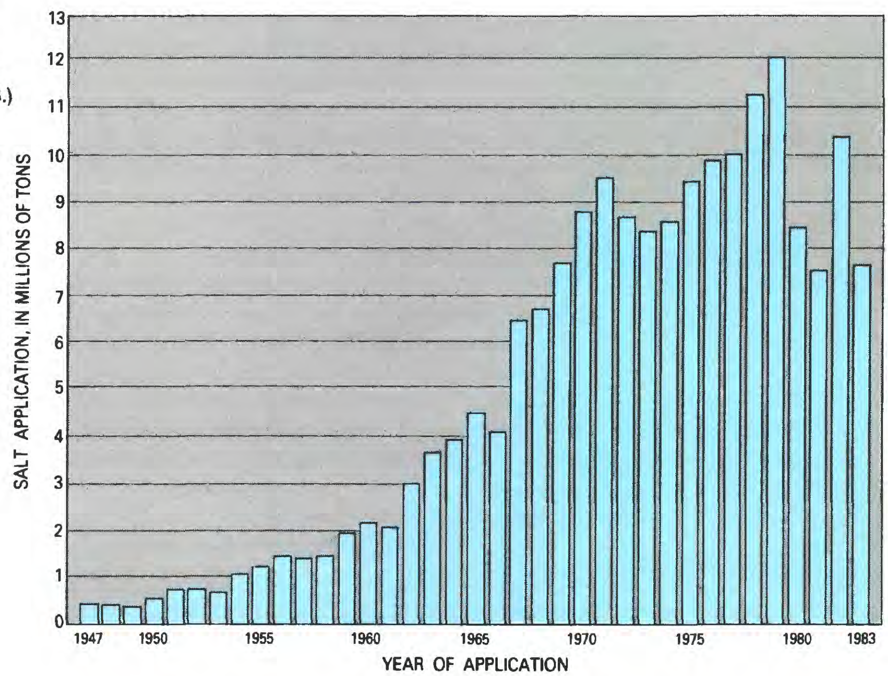


Figure 39. Trends in suspended-sediment concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981. (Source: Compiled from data in Smith and Alexander, 1983.)

are important (fig. 39); for example, a number of decreases in suspended-sediment concentrations occur on the Missouri River mainstem as well as on such tributaries as the Yellowstone, the Knife, the Cannonball, the Grand, the Bell Fourche, the White, and the James in Montana, North Dakota, and South Dakota. Declining concentrations have been reported previously for a number of locations in the Missouri River basin (Williams and Wolman, 1984) (see also article "Sediment in Rivers of the United States") and are attributed to the effects of reservoir construction throughout the basin during the 1950's and 1960's. Reservoirs act as a trap for sediment, and the effects of a reservoir on suspended-sediment concentrations downstream may be felt for an extended period of time after construction as a new equilibrium is established between those processes that carry sediment and those that result in sediment deposition in the river channel.

Regions in which the trends in suspended-sediment concentrations are mostly increasing include the Columbia River basin in Oregon and Washington, the Arkansas and Red River basins in Oklahoma, and the tributaries to the Mississippi River near the junctions of the Missouri and Ohio Rivers (fig. 39). In each instance, it appears likely that increased land use is an important cause of the trends; for example, in the Arkansas, Red, and Mississippi River basins, agricultural production increased during the late 1970's (U.S. Department of

Percentage of drainage area located upstream of reservoirs	Number of NASQAN stations showing trends in suspended-sediment concentrations		
	Increasing	Decreasing	No change
Less than 10	27	29	136
10 to 50	6	6	26
Greater than 50	10	4	32

Agriculture, 1983), and, in the Columbia River basin, logging increased during that period (U.S. Bureau of Census, 1984). In addition to the effects of land use, many streams in the Columbia River basin were transporting unusually large loads of sediment derived from volcanic ash and mudflow deposits resulting from eruptions of Mount St. Helens during 1980 and 1981 (Haeni, 1983).

In addition to recognizing the regional patterns of trends visible in figure 39, some general questions about the possible trends in suspended-sediment concentrations in rivers throughout the country should be posed. In view of the large number of decreasing concentrations in suspended sediment in the Missouri River basin, for example, it is logical to question the effect of reservoirs on sediment trends at NASQAN stations in general. The table to the left shows the number of stations with increasing, decreasing, and no significant change in concentrations as a function of the percentage of basin area located upstream of reservoirs.

From this tabulation, it does not appear that the presence of reservoirs in the basin strongly correlates with the occurrence of suspended-sediment concentration trends in general. However, where more than 50 percent of the basin is controlled by reservoirs, a slightly greater percentage of stations have increasing concentrations than those in less controlled basins.

The degree to which land use and related soil erosion affects trends in suspended-sediment concentrations at NASQAN stations also is an important question that has not yet been resolved. It is increasingly apparent that the off-site effects of soil erosion are extremely large in dollar terms, larger even than the effects of soil loss on agricultural production (Clark and others, 1985). It is of interest to know, therefore, whether NASQAN stations that show increasing concentrations in suspended sediment lie downstream of areas of intense soil erosion and whether erosion resulting from specific types of land use is associated with the trends.

The largest and most comprehensive collection of information about soil erosion nationwide is the Natural Resources Inventory (NRI) conducted by the U.S. Soil Conservation Service (U.S. Department of Agriculture, 1984). The 1982 NRI includes soil-erosion estimates and related land use information for nearly 1 million sample locations across the country. The erosion data for individual sample locations can be aggregated according to the boundaries of the NASQAN river basins (a median of 2,037 NRI sites per basin) and then used to characterize basins in which water-quality trends were observed during the same period. Some of the results of these comparisons appear below. Due to the possibility that intensive regulation by reservoirs may affect the trend results, the following analyses are based on NASQAN stations in basins with less than 50 percent of the drainage area controlled by reservoirs.

The table below gives the number of stations at which suspended-sediment concentration trends were detected in relation to cropland erosion rates in the basins. Where cropland erosion rate is low [less than 1 ton per acre per year (ton/acre/yr)], the number of decreasing trends is more than twice the number of increasing trends, and, where cropland erosion is high (greater than 5 ton/acre/yr), the ratio of decreases to increases is nearly reversed.

The statistical significance of the association between trends in suspended-sediment concentrations with erosion rates can be evaluated with the Chi-square test of independence. Chi-square tests can be performed on any relevant part of the tables presented in this section; for example, a Chi-square test comparing the numbers of stations with increases and decreases in sediment concentrations in basins that have erosion rates less than 1 ton/acre/yr with those in basins having erosion rates greater than 5 ton/acre/yr, shows that the results are significant at the 90-percent confidence level ($p = 0.07$). The probability, p, of incorrectly rejecting the null hypothesis that there is no association between concentration trends and erosion rates is equal to 0.07; therefore, the likelihood that the identified trend is real and does not result from a random arrangement of the data is 93 percent. This is above the 90-percent criterion, and, thus, the association is considered significant at that level. This tends to support the conclusion that the direction of trends in suspended-sediment concentration is

Cropland erosion rate (ton/acre/yr)	Number of NASQAN stations showing trends in suspended-sediment concentrations		
	Increasing	Decreasing	No change
Less than 1	5	11	38
1 to 2.5	8	10	43
2.5 to 5	11	9	33
Greater than 5	9	5	43

Erosion from rural land, as a percentage of total erosion	Number of NASQAN stations showing trends in suspended-sediment concentrations		
	Increasing	Decreasing	No change
Cropland:			
Less than 25	8	21	58
Greater than 25	25	14	99
Forest land:			
Less than 25	27	23	130
Greater than 25	6	12	27
Range and pasture land:			
Less than 25	22	21	88
Greater than 25	11	14	69

associated with the cropland erosion rate in the basin.

If cropland erosion is expressed as a percentage of total erosion in the basin, an even stronger relation is seen. As shown in the table above, decreases greatly outnumber increases where cropland erosion is a minor contributor to total erosion, but increases outnumber decreases where cropland erosion contributes more than 25 percent of total erosion. A Chi-square test of dependence for the above ratios of increases to decreases is highly significant ($p = 0.007$).

Trends in suspended-sediment concentrations vary in relation to erosion from other types of rural land, such as range and forest lands, in a fashion complementary to the pattern described above for cropland. As shown in the table above, decreases outnumber increases where either forest land or range and pasture land contribute more than 25 percent of total soil erosion in the basin; however, the results are not significant at the 90-percent level ($p = 0.13$ for forest land; $p = 0.56$ for range and pasture land).

Thus, despite certain regional exceptions to the pattern, evidence exists that, on a nationwide scale, the hydrologic effects of cropland erosion represent a worsening problem, and those of erosion from other types of land apparently do not. This result, if borne out in more focused types of sampling programs, would have important policy implications regarding the allocation of erosion control efforts. For the present, however, it remains a tentative finding with implications primarily for future sampling and analysis.

TRENDS IN PHOSPHORUS CONCENTRATIONS

Total phosphorus concentrations at NASQAN stations for water years 1975 to 1981 show roughly equal numbers of increasing (49) and decreasing (43) trends in phosphorus nationwide (fig. 40), but, as with suspended-sediment concentrations, certain regions exist in which the trends are predominantly in one or the other direction. In the Great Lakes and Upper Mississippi regions, phosphorus concentrations generally are declining possibly as a result of major phosphorus-control efforts in those areas during the late 1970's (Loehr and others, 1980). In Florida, along the Gulf Coast, and in the Arkansas and Red River basins, phosphorus concentrations are mostly increasing. Many of the increases in the South are in agricultural areas and, thus, may result from increased agricultural activity and fertilizer use.

The geographic distribution of trends in phosphorus and suspended-sediment concentrations are similar, a finding that is not suprising because of the tendency for phosphorus to adsorb to the surface of sediment particles. The relation between trends in phosphorus and suspended-sediment concentrations is summarized in the table below. The results of a Chi-square test are highly significant ($p = 0.001$).

Direction of trend in phosphorus concentrations	Number of NASQAN stations showing trends in suspended-sediment concentrations		
	Increasing	Decreasing	No change
Increasing	12	2	23
Decreasing	1	9	19
No change	31	30	161

Major source of soil erosion in river basins	Number of NASQAN stations showing trends in phosphorus concentrations		
	Increasing	Decreasing	No change
Cropland	13	14	73
Range and pasture land	11	3	62
Forest and other lands	6	7	46

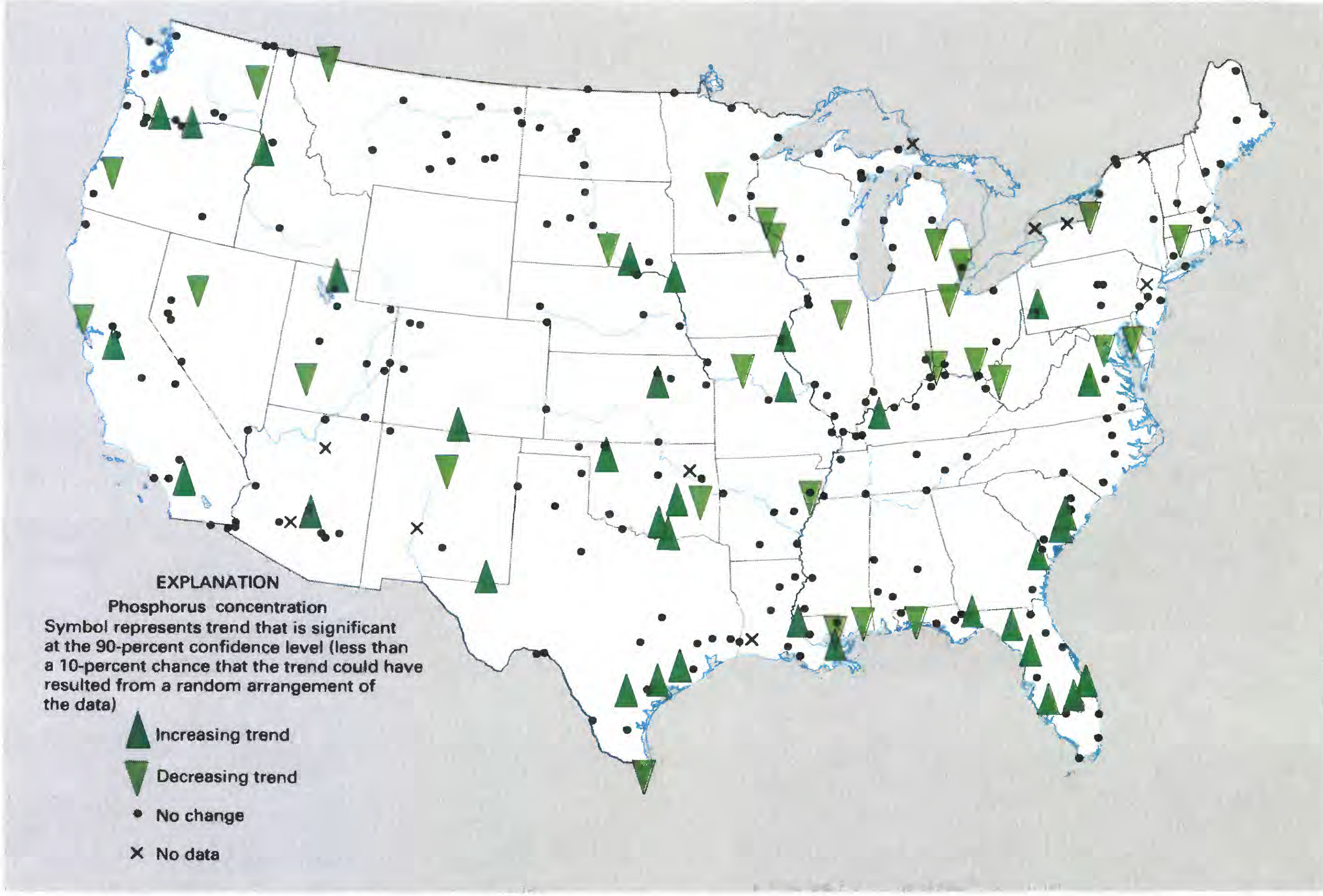


Figure 40. Trends in total phosphorus concentrations at U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981. (Source: Compiled from data in Smith and Alexander, 1983.)

Some apparent differences, however, exist between the trends in phosphorus and suspended-sediment concentrations in terms of their relation to land use and soil erosion within a basin. Basins where the total erosion is dominated by erosion from pasture and range land have a noticeably higher ratio of phosphorus increases to decreases than basins where total erosion is dominated by erosion from either cropland or forest and other nonagricultural lands (see table to the left). However, the association between concentration trends and major source of soil erosion is not quite significant at the 90-percent level (p = 0.13).

TRENDS IN INORGANIC NITROGEN (NITRATE PLUS NITRITE) CONCENTRATIONS

Inorganic nitrogen concentrations at NASQAN stations from 1975 to 1981 show a large number of increases nationwide, especially at stations in the eastern one-half of the country and in the Pacific coast basins of the Northwest. Only scattered locations in the western one-half of the country, especially the Colorado River basin, show decreases (fig. 41).

Although the ratio of increases to decreases for inorganic nitrogen is about 3 to 1 nationwide, the ratio varies greatly with the type of land and the erosion rate. This suggests that nonpoint sources of inorganic nitrogen are involved to some extent, which is not surprising in view of the importance of nitrogen fertilizers in agriculture generally. Trends in inorganic nitrogen in relation to the type of land contributing the largest percentage of total soil erosion in a basin are shown in the table below.

These trends show a much lower ratio of increases to decreases for basins dominated by

Major source of soil erosion in river basins	Number of NASQAN stations showing trends in inorganic nitrogen concentrations			Ratio of increases to decreases
	Increasing	Decreasing	No change	
Cropland	33	4	63	8.25
Range and pasture land	9	11	56	.82
Forest and other lands	19	3	39	6.00

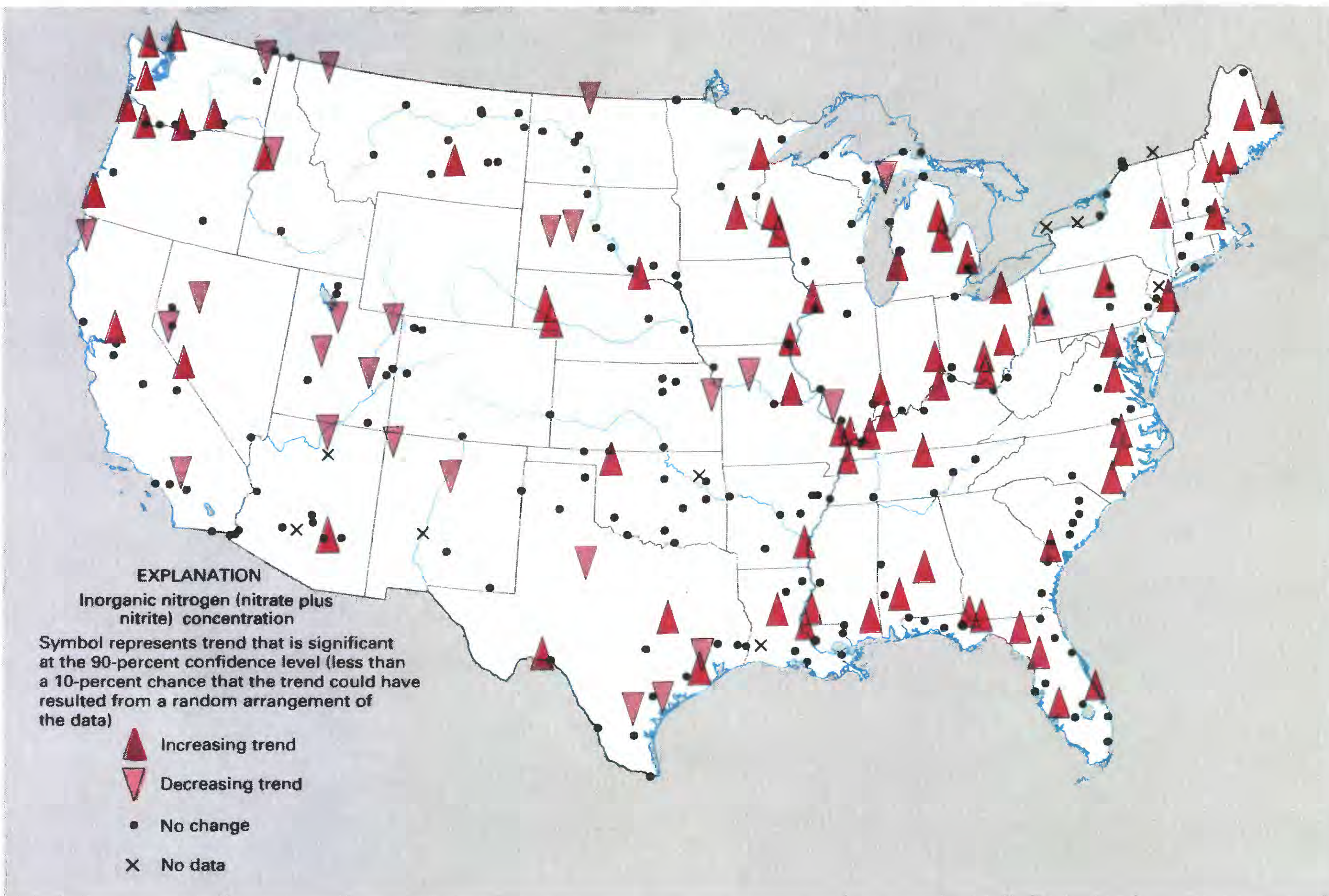
erosion from range and pasture land than for basins dominated by erosion from either cropland or forest and other nonagriculture lands. Differences in the trend ratios for the three types of land use are highly significant ($p = 0.0004$). From 1975 to 1981, the total quantity of nitrogen fertilizer applied nationally increased by about 38 percent (U.S. Bureau of Census, 1984), a change which would tend to explain the high number of increases for cropland-dominated basins.

The relatively large number of increases in inorganic nitrogen concentrations at NASQAN stations result, at least in part, from widespread increases in atmospheric deposition of nitrate rather than from changes in nitrogen sources directly from the land. The primary evidence for the important role of atmospheric sources consists of recently available nationwide measurements of nitrate in precipitation (J. H. Gibson and C. V. Baker, National Atmospheric Deposition Program, written commun., 1982), which correlate well with inorganic nitrogen levels at NASQAN stations and represent, in some instances, the largest known source of nitrogen in the basin. Moreover, emission rates of nitrogen to the atmosphere are known to have increased since 1975, especially in the Eastern States (National Research Council, 1983).

Median yields of inorganic nitrogen at NASQAN stations (quantity of inorganic nitrogen carried by a stream per year per unit area of drainage basin) in relation to the atmospheric deposition rate of nitrate in precipitation is shown in figure 42 for each of the 18 water-resources regions of the conterminous United States. In the eastern basins, nitrate deposition ranges from one to three times the basin yield of nitrate; and, in the western basins, with the exception of the California region, atmospheric deposition is as high as 10 times basin yield. By comparison, point sources of nitrogen amount to only about one-half to one-third of the measured yield in most of the water-resources regions (Leonard Gianessi, Resources for the Future, written commun., 1984). In regions dominated by cropland, nitrogen-fertilizer application equals from 5 to 10 times the basin yield of nitrate.

Because inorganic nitrogen is a plant nutrient and is biologically removable from soil and water, it is not surprising that the total of all

Figure 41. Trends in inorganic nitrogen (nitrate plus nitrite) concentrations at stations in the U.S. Geological Survey National Stream Quality Accounting Network stations in the conterminous United States, 1975 to 1981. (Source: Compiled from data in Smith and Alexander, 1983.)



sources of nitrogen is greater than the basin yield of inorganic nitrogen in these large regions. Given the data currently available, however, it is nearly impossible to develop a complete mass balance for nitrogen; that is, accurately quantify all inputs and outputs. For this reason, some uncertainty remains about the causes for trends in inorganic nitrogen in stream water.

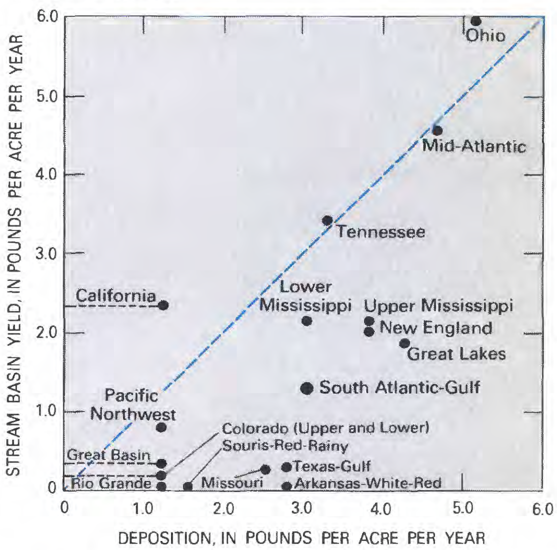


Figure 42. Median yield of inorganic nitrogen at U.S. Geological Survey National Stream Quality Accounting Network stations in relation to atmospheric deposition rate of nitrate in precipitation for the 18 water-resources regions of the conterminous United States. (Source: Compiled by R. A. Smith and R. B. Alexander from U.S. Geological Survey data.)

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Dissolved Solids—Case Studies

DISSOLVED SOLIDS IN THE COLORADO RIVER BASIN

By James E. Kircher

INTRODUCTION

The Colorado River is an important source of water for more than 14½ million people, many industrial users, and about 2½ million acres of irrigated agricultural land. As the Colorado River and its tributaries flow from their headwaters to their mouths, the concentrations of dissolved solids increase to undesirable levels, which result in millions of dollars of damage annually to agricultural, industrial, and municipal water users (U.S. Bureau of Reclamation, 1983a). The cost attributed to excessive dissolved solids in the Colorado River system was about $91 million in 1983 (D. H. Merritt, U.S. Bureau of Reclamation, written commun., 1984).

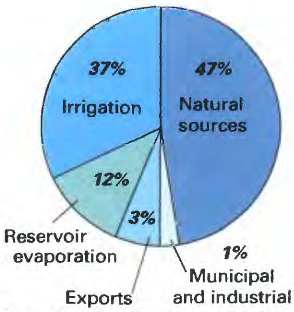

Figure 43. Source of dissolved solids in the Colorado River basin. (Source: Modified from Jonez, 1984, p. 338.)

The effects on municipal and industrial users occur primarily as increased water-treatment costs, accelerated pipe corrosion and appliance wear, increased usage of soap and detergent, and decreased water palatability. For irrigators, the greater dissolved-solids concentrations cause decreased crop yields, altered crop patterns, increased soil leaching and drainage requirements, and increased management costs. Depending on the soil conditions, the composition of dissolved solids in the water, and the type of crop, agricultural losses occur when dissolved-solids concentrations of applied irrigation water reach 700 to 850 milligrams per liter (mg/L).

The 1,400-mile (mi)-long Colorado River originates in the Rocky Mountains of Colorado and is joined by its principal tributary, the Green River, which originates in Wyoming. The Colorado River and its tributaries drain 242,000 square miles (mi^2), including parts of seven States—Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming, or one-twelfth of the conterminous United States—and 2,000 mi^2 in Mexico.

Precipitation in the Colorado River basin ranges from as much as 60 inches per year (in./yr) in the mountains to as little as 2 in./yr in the deserts adjacent to the middle and lower reaches. The range in precipitation and natural wet- and dry-climatic cycles have affected significantly the development of the Colorado River reservoir complex. Many dams and reservoirs exist along the Colorado River in order to store sufficient water to maintain flows of the Colorado River to meet downstream needs during dry periods. In fact, the many reservoirs in the Colorado River basin can store amounts of water equivalent to the average flow of the Colorado River for several years (U.S. Geological Survey, 1984, p. 32).

SOURCE OF DISSOLVED SOLIDS

The dissolved-solids concentration of the Colorado River at its headwaters in the mountains is about 50 mg/L. This amount increases progressively downstream as a result of water use and dissolved-solids contributions from a variety of sources and reaches an average concentration of about 850 mg/L at Imperial Dam, Ariz. About one-half of the dissolved-solids concentration in the Colorado River basin is attributed to natural sources (U.S. Bureau of Reclamation, 1983b). The remaining one-half of the concentration is caused by irrigation, reservoir evaporation, river-basin exports (mostly of headwater flows), and municipal and industrial use (fig. 43).

Increases in dissolved-solids concentrations are the result of two main processes—addition of dissolved solids to water from surface-water and ground-water tributary inflows and the concentration of dissolved solids through water losses by evaporation. The addition of dissolved solids to a given amount of water results primarily from surface water percolating into the ground and dissolving mineral substances, including fertilizers, from the soil and subsoil. When the water returns to the river system, the dissolved-solids load is increased. The concentration of dissolved solids in water involves the loss of water by reservoir evaporation, by exportation of fresher water from the basin, and by evapotranspiration from irrigated crops. As water is evaporated and transpired by plants, the residual dissolved solids concentrate in the soil and remaining water.

DISSOLVED-SOLIDS ANALYSIS

Water development has led to changes in the quantity and quality of water flowing in the Colorado River basin. Most water-development projects in the basin were complete by 1965. For this reason, the period from 1965 to 1983 was chosen for analysis of the variations in dissolved-solids loads and concentrations within the Colorado River basin. These analyses were made at 26 sites which had concurrent records of water discharge and dissolved-solids concentrations (table 4).

The maximum, mean, and minimum annual dissolved-solids load for the 26 sites in the Colorado River basin are summarized graphically in figure 44. In the upper Colorado River basin, the mean annual dissolved-solids loads increase in a downstream direction. The dissolved-solids loads also increase in a downstream direction in the lower Colorado River basin, except at site 24 below Hoover Dam. Downstream from Hoover Dam, the dissolved-solids load actually decreases, due largely to decreases of water discharge in the lower Colorado River basin as a result of increased diversions behind Parker (site 25) and Imperial (site 26) Dams. Although the dissolved-solids load and water discharge decrease progressively downstream in the lower Colorado River basin, the dissolved-solids concentrations increase (fig. 45; table 4).

The concentration of dissolved solids often is a better index for locating sources and regions of poor water quality than is the dissolved-solids load. Maximum, mean, and minimum annual dissolved-solids concentrations for the 26 stations are shown in figure 45. Mean dissolved-solids concentrations are greater than 2,500 mg/L at only 2 of the 26 stations in the Colorado River basin—site 16, the Price River at Woodside, Utah (2,720 mg/L), and site 18, the San Rafael River near the Green River, Utah (2,560 mg/L). These large concentrations are attributable primarily to dissolved solids gained as water flows through the irrigated areas of these drainage basins. A smaller contribution is due to overland flow from desert-rangeland areas in these basins.

TRENDS IN DISSOLVED-SOLIDS CONCENTRATIONS

Trends in dissolved-solids concentrations have been investigated at 26 stations in the Colorado River basin to determine if changes have occurred between 1965 and 1983 (fig. 46). Concentrations were adjusted for flow to minimize the impacts of changes in flow on concentrations and to give a more reliable indication of the actual changes in the processes that deliver dissolved solids to the streams (Crawford and others, 1983). The trends were statistically tested at the 90-percent confidence level. Data from 23 stations show a significant trend in the concentration of dissolved solids (fig. 46). Decreasing trends were detected at 20 stations on the main stem of the Colorado or on major tributaries. Increasing trends were detected for only three sites on tributary streams: site 5, on the Dolores River near Cisco, Utah; site 13, on the Little Snake River near Lily, Colo.; and site 23, on the Virgin River at Littlefield, Ariz. Only 3 of the 26 stations show no trends.

Table 4. Mean annual water discharge, dissolved-solids load, and dissolved-solids concentration for 26 stations in the Colorado River basin, water years 1965 to 1983 (October 1964–September 1983)

[ft^3/s = cubic feet per second; mg/L = milligrams per liter; ton/yr = tons per year]

Site number on fig. 44	Station name	Water discharge (ft^3/s)	Dissolved solids: Load (million ton/yr)	Dissolved solids: Concentration (mg/L)
1	Colorado River at Hot Sulphur Springs, Colo.	230	0.02	90
2	Colorado River near Glenwood Springs, Colo.	2,200	.56	330
3	Colorado River near Cameo, Colo.	3,700	1.45	540
4	Gunnison River near Grand Junction, Colo.	2,400	1.31	730
5	Dolores River near Cisco, Utah	900	.51	1,660
6	Colorado River near Cisco, Utah	6,700	3.75	770
7	Green River at Warren Bridge near Daniel, Wyo.	520	.07	250
8	Green River below Fontenelle Reservoir, Wyo.	1,700	.38	240
9	Green River near Green River, Wyo.	1,900	.57	390
10	Blacks Fork near Little America, Wyo.	370	.21	970
11	Green River near Greendale, Utah	2,200	1.08	500
12	Yampa River near Maybell, Colo.	1,600	.26	280
13	Little Snake River near Lily, Colo.	640	.13	360
14	Duchesne River near Randlett, Utah	570	.37	1,010
15	White River near Watson, Utah	660	.27	490
16	Price River at Woodside, Utah	140	.24	2,720
17	Green River at Green River, Utah	6,000	2.75	550
18	San Rafael River near Green River, Utah	130	.19	2,560
19	San Juan River near Archuleta, N. Mex.	1,200	.19	170
20	San Juan River near Bluff, Utah	2,200	1.00	550
21	Colorado River at Lees Ferry, Ariz.	12,800	7.06	560
22	Colorado River near Grand Canyon, Ariz.	13,300	8.00	620
23	Virgin River at Littlefield, Ariz.	270	.37	1,890
24	Colorado River below Hoover Dam, Ariz.-Nev.	12,000	8.11	700
25	Colorado River near Parker Dam, Ariz.-Calif.	10,000	7.21	720
26	Colorado River above Imperial Dam, Ariz.-Calif.	8,800	7.18	850

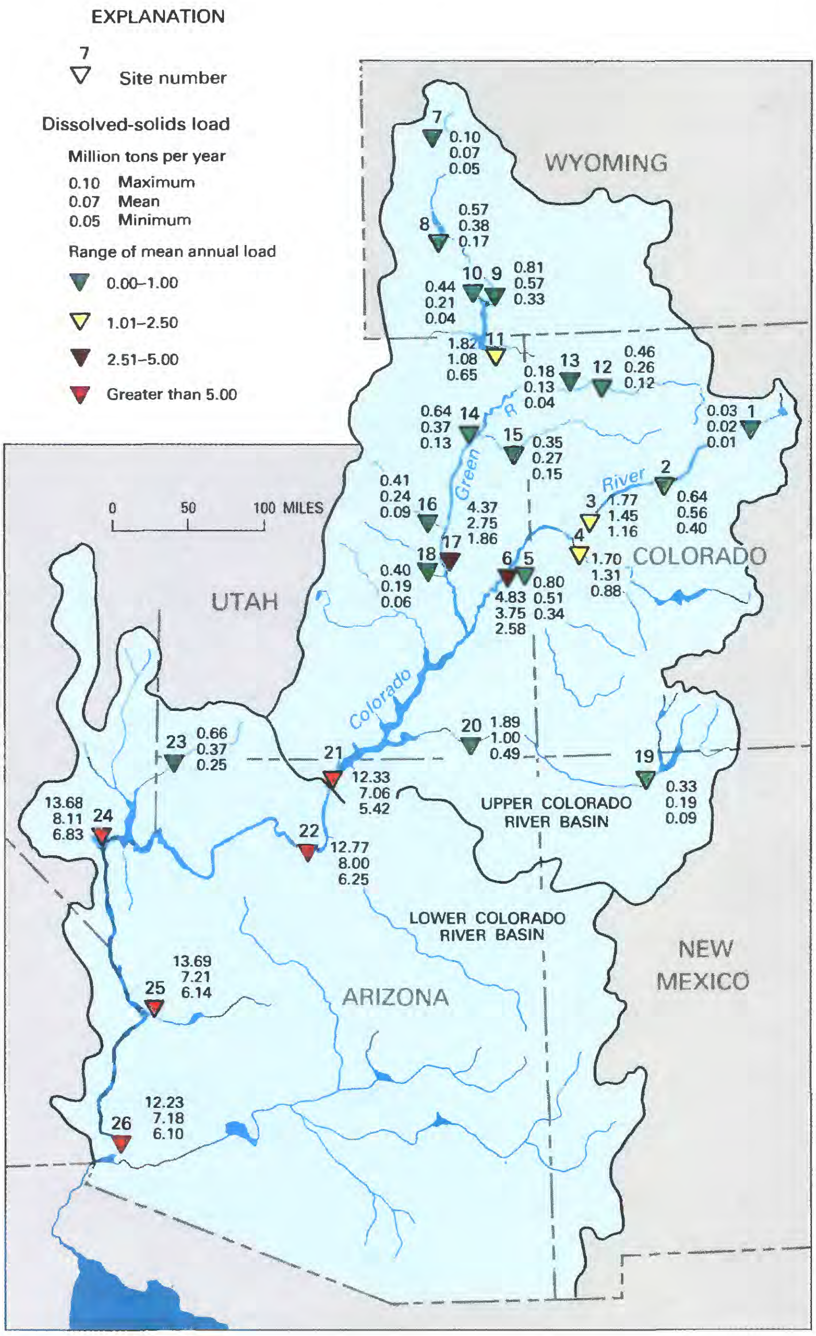

Figure 44. Maximum, mean, and minimum dissolved-solids loads for 26 stations in the Colorado River basin, 1965 to 1983. (Source: Compiled by J. E. Kircher from U.S. Geological Survey and U.S. Bureau of Reclamation data.)

Several factors may be influencing the generally decreasing trends in dissolved-solids concentration shown in figure 46. These factors include reservoir storage and operation, dissolved-solids control measures in the basin, and variations in natural runoff. The dissolved-solids concentration in rivers generally decreases with increased streamflow on an annual basis.

The period from 1963 to 1980 represents the most significant period of reservoir filling in the history of water development in the Colorado River basin. The amount of water stored in Flaming Gorge Reservoir, Lake Powell, and Lake Mead collectively increased from less than 20 million acre-feet (acre-ft) in 1963 to more than 50 million acre-ft in 1980. During the period of filling, it is possible that the more dense water (high dissolved-solids concentration) moved to the bottom of the reservoir and the less dense water (low dissolved-solids concentration) flowed out of the reservoir. Such a situation would cause a decrease in dissolved-solids concentrations downstream of the reservoir.

Another possible reason for the trends is changes in irrigation practices. Much of the farmland that had poor drainage and had excessive dissolved solids in the soil has been taken out of production. In addition, irrigation practices have changed significantly during the past 20 years, which should decrease return flows and decrease the dissolved solids input to streams.

Many aquifers in the region contain large concentrations of dissolved solids but are confined by hundreds of feet of impermeable shales and, therefore, yield relatively little saline ground water through springs to the streams under natural conditions. However, when the confining layers for the saline aquifers are disrupted by mining or drilling, the saline ground water can more readily flow to the surface or reach the streams. Many saline springs and flowing wells have been identified in the basin. Some of these flowing wells have been plugged as part of dissolved-solids-control projects, such as at Meeker Dome, near Meeker, Colo., and, therefore, could be causing a decreasing trend in some areas. The initiation of other dissolved-solids-control projects during this period also may contribute to the decline in dissolved-solids concentrations in parts of the basin. Each of these factors possibly contributes to the predominantly decreasing trends in dissolved-solids concentrations, but determining the relative importance of these major causes will require further study.

DISSOLVED-SOLIDS CONTROL MEASURES

In 1972, an amendment to the Federal Water Pollution Control Act (Public Law 92-500) set forth goals that included the restoration and maintenance of water quality, limitation of polluting effluent discharges, and eventual zero pollution discharge. Numerical criteria subsequently were established for three stations by the Colorado River Basin Salinity Control Forum, adopted by each of the seven basin States, and approved by the U.S. Environmental Protection Agency. The criteria are:

Colorado River locations	Annual flow-weighted average dissolved-solids concentration (mg/L)
Below Hoover Dam	723
Below Parker Dam	747
At Imperial Dam	879

The overall approach to meeting the criteria is to prevent dissolved solids from entering and mixing with the river's flow. A number of agricultural, point, and diffuse sources of dissolved solids have been identified throughout the basin for possible interception.

Another source of great interest in the dissolved-solids concentration of the Colorado River is the international treaty with Mexico concerning the river's water quality as it crosses the international border.

In June 1974, Congress enacted the Colorado River Basin Salinity Control Act (Public Law 93-320) which directed the Secretary of the Interior to expedite planning studies on 12 salinity-control projects of a basinwide program to control the dissolved solids of Colorado River water and to construct four select salinity-control projects. Title I of the Act authorized the construction of facilities and onfarm measures to enable the United States to comply with its obligations under Minute No. 242 of the International Boundary and Water Commission, United States, and Mexico. In brief, Minute 242 requires that water delivered to Mexico have an average annual dissolved-solids concentration that is no more than 115 mg/L (± 30 mg/L) greater than the concentration in Colorado River water arriving at Imperial Dam upstream of the United States–Mexican border.

At the State level, all seven Colorado River basin States have appointed representatives to the Colorado River Basin Salinity Control Forum and to the Colorado River Basin Salinity Control Advisory Council to coordinate State actions and to advise the Federal Government on the State views on issues affecting water-quality standards and ways to meet those standards. At the Federal level, dissolved-solids-control efforts of the U.S. Department of the Interior, the U.S. Environmental Protection Agency, and the U.S. Department of Agriculture are coordinated through an Interagency Salinity Control Committee to improve management of irrigated agriculture through research and onfarm improvements and to implement selected structural and nonstructural control measures (U.S. Bureau of Reclamation, 1983c).

Specific solutions to the dissolved-solids problem depend, in part, on the mechanisms by which the dissolved solids enter the river. Several dissolved-solids-control measures for the Colorado River basin currently are under evaluation:

1. Point-source controls are proposed to remove salt from such local areas as mineral springs, abandoned oil wells, and geysers. To date (1984), several abandoned oil wells have been plugged in the Meeker area, decreasing dissolved-solids loads locally by as much as 57,000 ton/yr. Proposals are being formulated for the control of

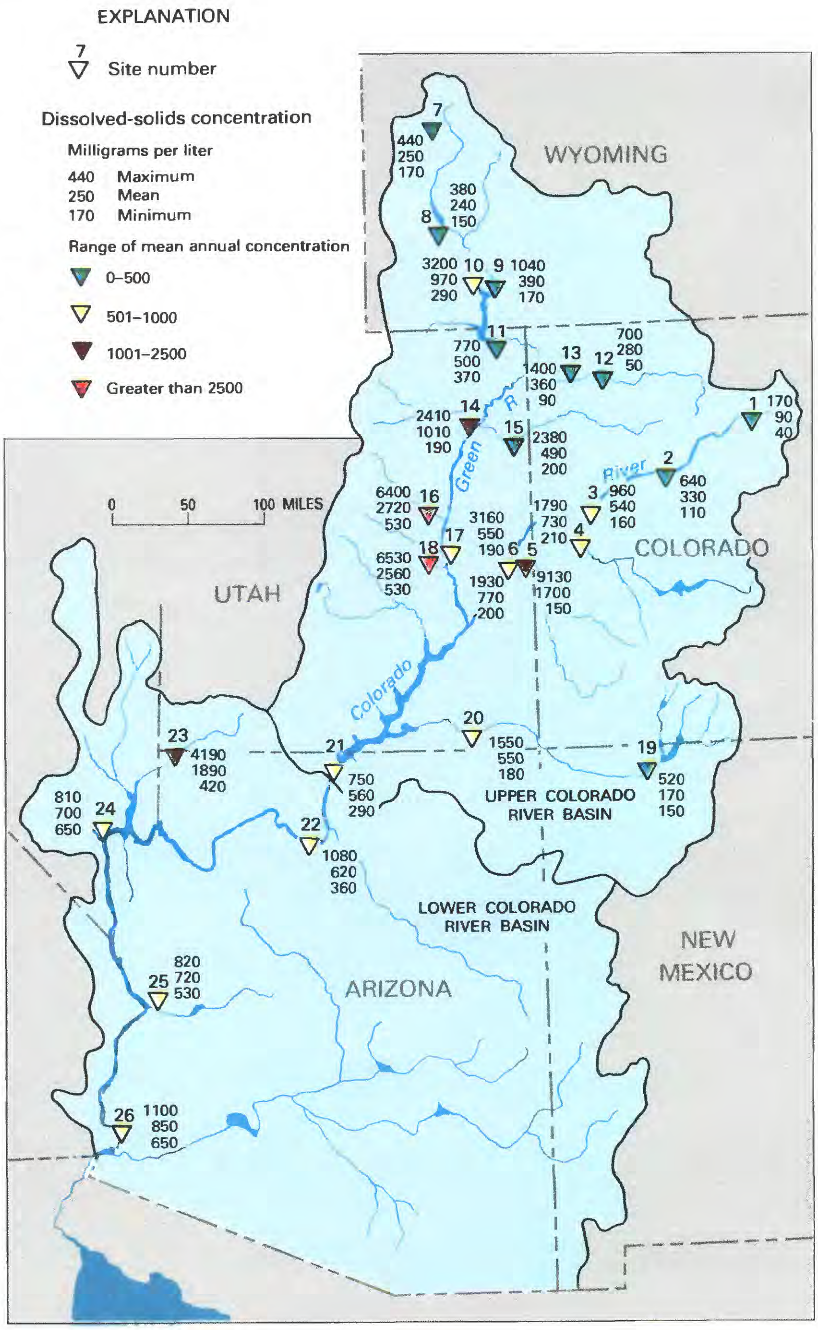

Figure 45. Maximum, mean, and minimum dissolved-solids concentrations for 26 stations in the Colorado River basin, 1965 to 1983. (Source: Compiled by J. E. Kircher from U.S. Geological Survey and U.S. Bureau of Reclamation data.)

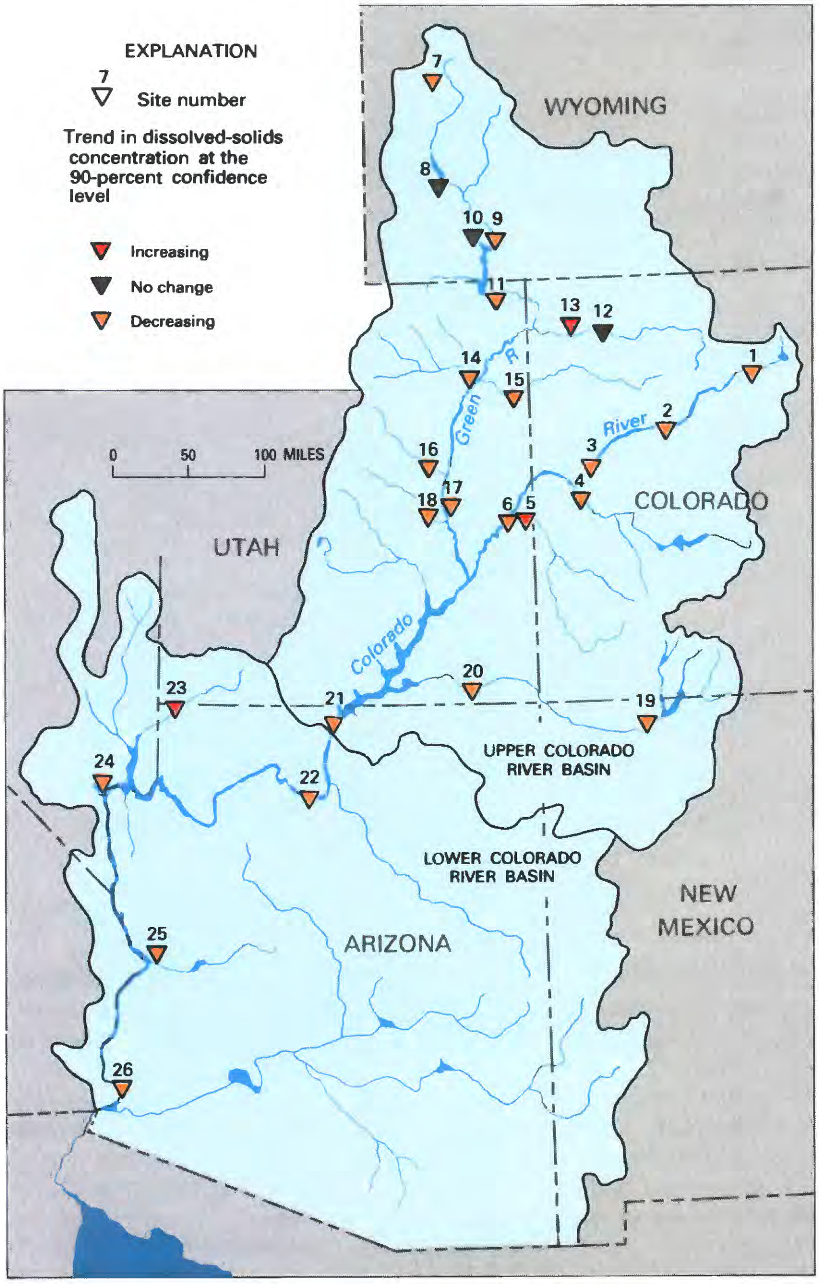

Figure 46. Trends in dissolved-solids concentrations at 26 stations in the Colorado River basin, 1965 to 1983. (Source: Compiled by J. E. Kircher from U.S. Geological Survey and U.S. Bureau of Reclamation data.)

other point sources within the basin, such as the Glenwood-Dotsero mineral springs.

2. Diffuse-source controls of dissolved solids being considered include watershed management, land treatment, and the collection and disposal of irrigation-return flows.
3. Irrigation controls are proposed to decrease salt loadings by improving onfarm irrigation systems and irrigation management practices that result in the leaching of salts from marine shales and other saline deposits.

Controlling the dissolved solids in the Colorado River basin has challenged and will continue to challenge state-of-the-art technology and water-management skills.

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Dissolved Solids in the Arkansas River Basin

By Jerry D. Stoner

INTRODUCTION

The Arkansas River originates in the heart of the Rocky Mountains and flows 1,459 miles (mi) to its confluence with the Mississippi River (fig. 47). It drains parts of seven States—Arkansas, Colorado, Kansas, Missouri, New Mexico, Oklahoma, and Texas. The drainage area of the Arkansas River basin is 160,576 square miles (mi^2), an area larger than the State of California. From the eastern slopes of the Rocky Mountains, the river flows across the Great Plains of Colorado and Kansas and into Oklahoma, where it flows through a transition zone from the Great Plains to the Ozark and Ouachita Mountains and then flows across the Mississippi River flood plain to its confluence with the Mississippi River.

Precipitation in the Arkansas River basin ranges from an annual average of 15 inches (in.) in eastern Colorado to an annual average of 49 in. in Arkansas. Because of the increase in precipitation from west to east, 80 percent of the total basin mean annual water discharge at the mouth of the river originates downstream from Tulsa, Okla., the lower one-third of the river's total length. Tributaries that contribute the most water enter the Arkansas River in Oklahoma and south-central Kansas. These tributaries are the Salt Fork Arkansas, Cimarron, Verdigris, Neosho, Illinois, Canadian, Walnut, and Ninnescah Rivers.

Throughout its length, the Arkansas River and most of the major tributaries are affected directly by human activities. Reservoirs, which have been constructed on the mainstem, as well as on many of the tributaries, are mostly in Oklahoma. The operation of these reservoirs affects the flow regime by decreasing the maximum flows somewhat and increasing the minimum flows.

In Colorado, upstream and downstream of the John Martin Reservoir, water is diverted often from the Arkansas River for irrigation, and the streamflow decreases through this area of diversions. The average annual water discharge near Coolidge, Kans., (table 5, site 3) is about 20 percent of the mean annual water discharge 217 mi upstream at Portland, Colo. (site 1), and about 50 percent of the mean annual water discharge 58 mi upstream just below John Martin Reservoir, Colo. (site 2). Diversion activities in the upper one-third of the length of the Arkansas River have altered drastically the water discharge.

Downstream from Tulsa, Okla. (site 11), the Arkansas River becomes the McClellan-

Figure 47. Maximum, mean, and minimum dissolved-solids loads for 18 stations in the Arkansas River basin, 1968 to 1982. (Source: Compiled by J. D. Stoner from U.S. Geological Survey data.)

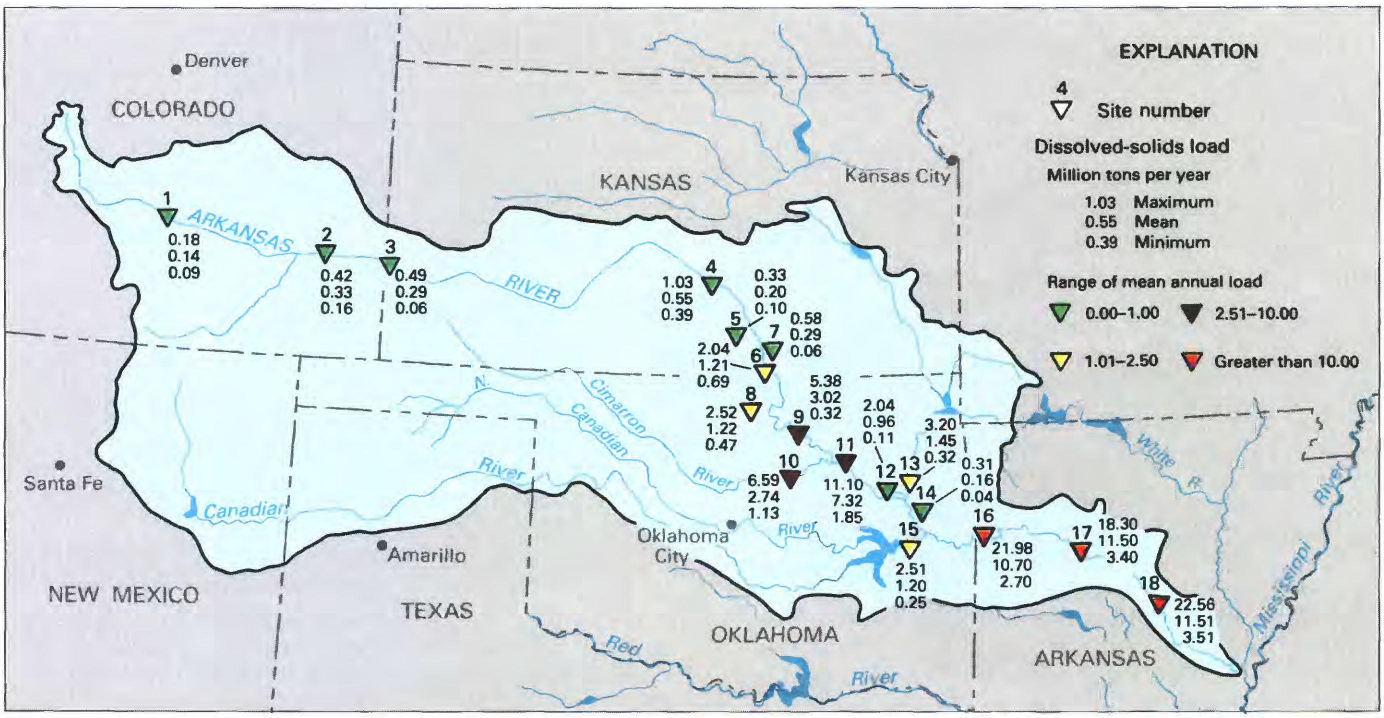


Table 5. Mean annual water discharge, dissolved-solids load, and dissolved-solids concentrations for 18 stations in the Arkansas River basin, water years 1968 to 1982 (October 1967–September 1982)

[ft^3/s = cubic feet per second; mg/L = milligrams per liter; ton/yr = tons per year]

Site number on fig. 47	Station name	Water discharge (ft^3/s)	Dissolved solids: Load (million ton/yr)	Dissolved solids: Concentration (mg/L)
1	Arkansas River at Portland, Colo.	[1]657	0.14	273
2	Arkansas River below John Martin Reservoir, Colo.	222	.33	2,632
3	Arkansas River near Coolidge, Kans.	89	.29	3,673
4	Arkansas River near Hutchinson, Kans.	576	.55	1,575
5	Ninnescah River near Peck, Kans.	488	.20	627
6	Arkansas River at Arkansas City, Kans.	1,995	1.21	954
7	Walnut River at Winfield, Kans.	887	.29	579
8	Salt Fork Arkansas River at Tonkawa, Okla.	754	1.22	3,127
9	Arkansas River at Ralston, Okla.	4,870	3.02	882
10	Cimarron River at Perkins, Okla.	1,197	2.74	5,077
11	Arkansas River at Tulsa, Okla.	7,449	7.32	1,101
12	Verdigris River near Inola, Okla.	4,700	.96	252
13	Neosho River near Fort Gibson, Okla.	9,311	1.45	165
14	Illinois River near Gore, Okla.	1,596	.16	112
15	Canadian River near Whitefield, Okla.	5,413	1.20	259
16	Arkansas River near Van Buren, Ark.	33,700	10.70	373
17	Arkansas River at Dardanelle, Ark.	36,310	11.50	397
18	Arkansas River below Little Rock, Ark.	44,340	11.51	301

[1] Period of record: 1975 to 1982.

Kerr Waterway and provides an inland waterway for barge traffic from Tulsa to the Mississippi River. This is the primary use of the lower one-third of the Arkansas River. The waterway begins as a navigation improvement on the Verdigris River at Catoosa, Okla., on the eastern edge of the Tulsa metropolitan area and continues to a point downstream from Inola, Okla. (site 12), where it joins the Arkansas River and follows it from there to the Mississippi River.

The primary use of Arkansas River water in the middle one-third of the river basin is for irrigation. The high dissolved-solids concentrations in this reach of the river limits its use for other purposes.

SOURCES OF DISSOLVED SOLIDS

Dissolved solids in the Arkansas River basin are from two major sources. In the upper reach of the river (eastern Colorado and western Kansas), the source is irrigation flow. Where water is diverted from the river for irrigation, some of the water applied to the cropland returns to the river. This return flow carries dissolved material from soil and rock. In the lower reach of the river (south-central Kansas and northwestern Oklahoma), the source is ground water discharging to the surface-water system from rocks of Permian age, which contain sodium chloride and other naturally occurring salts (Gogel, 1981; Leonard and Kleinschmidt, 1976; Reed, 1982). This water is quite saline, and, in many areas, the dissolved-solids concentrations exceed 35,900 milligrams per liter (mg/L) (Gogel, 1981). In Kansas, the saline-water discharge is to the Little Arkansas River and, through several minor tributaries, directly to the Arkansas River. In Oklahoma, the saline-water discharge is to the Salt Fork Arkansas and the Cimarron Rivers.

These dissolved-solids loadings, particularly chloride, make the water in the Arkansas River upstream of Tulsa, Okla., (site 11), unsuitable for many uses without pretreatment. The national drinking-water criterion for chloride is 250 mg/L (U.S. Environmental Protection Agency, 1982b), and this criterion generally is exceeded more than 50 percent of the time in the Oklahoma reach of the Arkansas River (Stoner, 1981a). For most of the upper two-thirds of its length, the Arkansas River is unsuitable for public water supply and for most commercial and industrial uses without treatment to reduce the chloride concentration. Within Oklahoma, the high dissolved-solids concentration in the Arkansas, Salt Fork Arkansas, and Cimarron Rivers decreases the use of these rivers as sources of water for irrigation (Stoner 1981a, b). Most of the time, the irrigation salinity hazard (Wilcox, 1955) of these streams ranges from high to very high.

DISSOLVED-SOLIDS ANALYSIS

In the Arkansas River basin, human activities such as construction and operation of diversion structures, dams, reservoirs, and waterways have continually changed the flow patterns in the basin. The rate of construction had slowed by 1968, and the flow patterns within the basin are now mostly the result of operational rather than construction activities. Therefore, the period from 1968 to 1982 was selected for an analysis of dissolved solids in the basin to minimize the effect of project construction. Eighteen sites within the Arkansas River basin had discharge and dissolved-solids data available for most of this period (see table 5).

DISSOLVED-SOLIDS LOADS

Within the Arkansas River basin the amount of dissolved solids transported increases in the downstream direction (fig. 47). This downstream increase in load is the cumulative result of the contributions of dissolved solids from tributaries and ground-water inflow. Of these inflow sources, the major increases in the load of the mainstem are due to irrigation return flow and natural brine inflow. Thus, although the mean annual water discharge in the Arkansas River near Coolidge, Kans. (site 3), is only about 20 percent of the mean annual water discharge upstream at Portland, Colo. (site 1), the mean annual dissolved-solids load near Coolidge is twice as great as the dissolved-solids load at Portland. Downstream from the irrigation diversion areas in Kansas, the water discharge in the Arkansas River again increases through tributary and ground-water inflow. The mean annual water discharge of the Arkansas River is about 19 times greater at Arkansas City, Kans. [(site 6; 1.45 million acre-feet per year (acre-ft/yr)], than it is at the site near Coolidge (76,000 acre-ft/yr). In this same reach of the river the mean annual dissolved-solids load increases about four times, from 290,000 tons per year (ton/yr) near Coolidge, Kans., to 1.21 million ton/yr at Arkansas City.

The Cimarron and the Salt Fork Arkansas Rivers enter the Arkansas River between Arkansas City, Kans., and Tulsa, Okla. The dissolved-solids input from these two rivers causes a dramatic increase in the load in the mainstem. The rivers contribute 34 percent of the mean annual dissolved-solids load for the entire basin while contributing only 4 percent of the basin's mean annual water discharge. Of these two streams, the Cimarron River is the major contributor. This stream contributes 24 percent of the basin's mean annual load while contributing only 3 percent of the basin's mean annual water discharge.

Four major tributaries enter the Arkansas River between Tulsa, Okla., and Van Buren, Ark. These tributaries (sites 12–15) contribute another 33 percent of the basin's mean annual dissolved-solids load, which is about the same as the combined contribution from the Cimarron and Salt Fork Arkansas Rivers. However, their combined mean annual water discharge, which is 15 million acre-ft, or 47 percent of the basin's mean annual water discharge, is more than 10 times the combined mean annual water discharge of the Salt Fork Arkansas and Cimarron Rivers (1.42 million acre-ft). As the Arkansas River flows through the State of Arkansas, its mean annual water discharge increases by about 30 percent, from 24.4 million acre-ft near Van Buren (site 16) to 32.1 million acre-ft below Little Rock (site 18). The mean annual dissolved-solids load, however, increases in this reach by only 6 percent, from 10.7 million to 11.5 million tons. Altogether, the major tributaries of the Arkansas River contributed 71 percent of the basin's mean annual dissolved-solids load. The remaining 29 percent is contributed by minor tributaries and undefined ground-water inflow.

DISSOLVED-SOLIDS CONCENTRATIONS

Information on dissolved-solids concentrations, which directly determine the suitability of the river water for various uses, often is overshadowed by information on dissolved-solids loads. It is important to know the volume of water being discharged. At sites 6, 8, and 15, for example, the mean loads are almost the same, but the mean concentrations vary considerably, which reflect the differences in the water discharges. Although the mean loads for two of these sites, Salt Fork Arkansas and Canadian Rivers, are nearly the same, the mean concentration for the Salt Fork Arkansas River (site 8) is 12 times greater than that of the Canadian River (site 15), which makes the Salt Fork Arkansas useless for most purposes.

At four sites in the basin (fig. 48), mean dissolved-solids concentrations were greater than 2,000 mg/L, the maximum limit for most irrigation (site 2, 2,632 mg/L; site 3, 3,673 mg/L; site 8, 3,127 mg/L; and site 10, 5,077 mg/L). These four sites correspond to the areas of irrigation return flow and natural brine inflow that were discussed above. Moving downstream from Tulsa (site 11), the dissolved-solids concentrations in the Arkansas River decrease in the downstream direction due to less-saline tributary inflow. This downstream decrease is shown in figure 48 by site 11, where

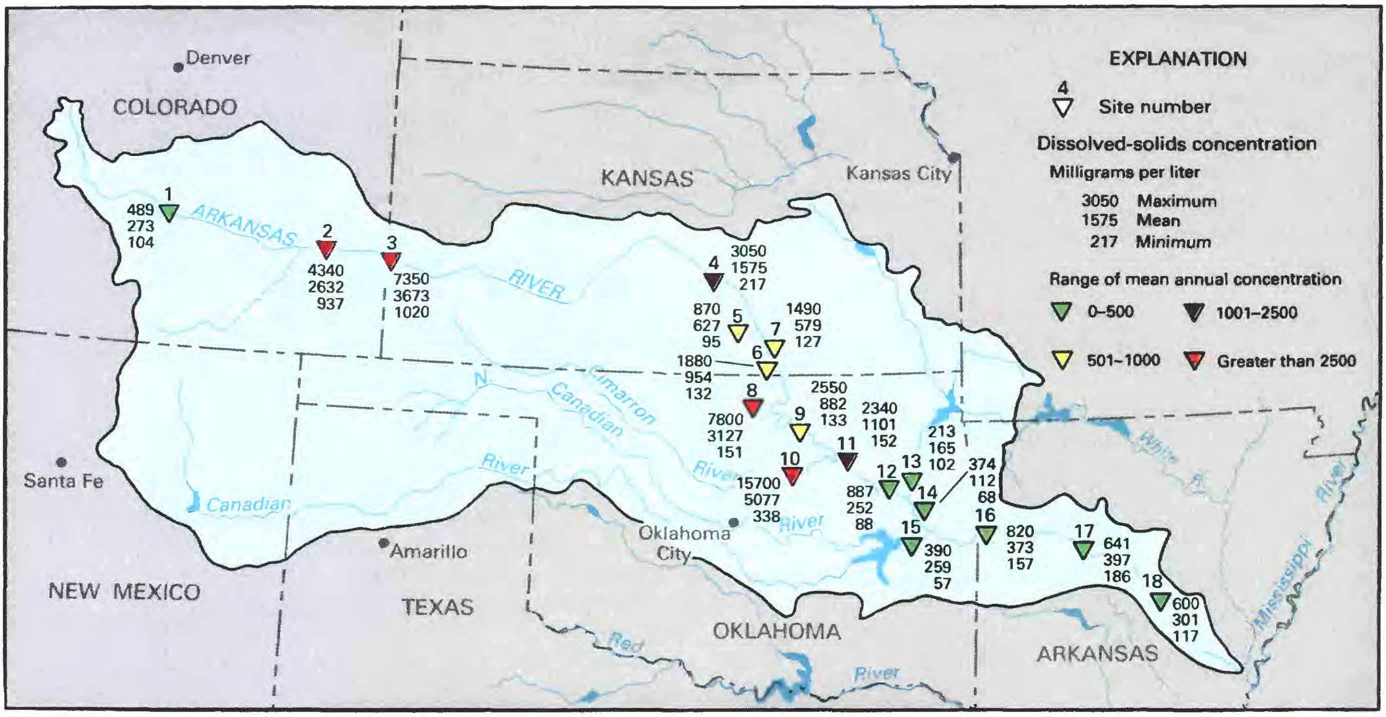


Figure 48. Maximum, mean, and minimum dissolved solids concentrations for 18 stations in the Arkansas River basin, 1968 to 1982. (Source: Compiled by J. D. Stoner from U.S. Geological Survey data.)

the mean concentration was 1,101 mg/L, and by site 18, where it was 301 mg/L.

The influence of irrigation activities in the upper part of the Arkansas River basin is reflected in the increase in dissolved-solids concentration (from 2,632 to 3,673 mg/L) between sites 2 and 3 (fig. 48). This increase in dissolved-solids concentration is accompanied by a slight decrease, 12 percent, in the mean annual water discharge. Downstream from Coolidge, Kans., for about 140 mi, water discharge in the Arkansas River continues to decrease due to human activities, predominantly irrigation diversion. However, adequate dissolved-solids concentration data from 1968 to 1982 are not available to determine the effects on concentration in this reach. Downstream from the major area of diversions, water discharge in the Arkansas River increases, and dissolved-solids concentration decreases. At site 4, mean annual water discharge is more than five times greater, than at site 3, and the mean dissolved-solids concentration is less than one-half of that at site 3.

The influence of the natural brine inflows into the Salt Fork Arkansas and Cimarron River basins is reflected in figure 48, where the mean dissolved-solids concentrations were 3,127 mg/L in the Salt Fork Arkansas River (site 8) and 5,077 mg/L in the Cimarron River (site 10); maximum concentrations at these sites were 7,800 and 15,700 mg/L, respectively. These high concentrations severely limit the suitability of these stream waters for most common uses. In these two basins within Oklahoma, more than 95 percent of the total water withdrawals is ground water. The surface water used is from impoundments on streams in the areas that have better water quality. The impact of these two streams on dissolved-solids concentration in the Arkansas river is not severe, however. The mean dissolved-solids concentration in the Arkansas River at site 6, which is above the confluences of the two streams with the Arkansas River, is 954 mg/L, whereas the mean concentration at site 11, below the confluences, is 1,101 mg/L. This change amounts to an increase of only 13 percent of the mean concentration. This small increase is due mostly to the dilution of the saline inflow by increased water discharge in the reach. Between sites 6 and 11, mean annual water discharge in the Arkansas River increases by 3.93 million acre-ft, of which only 1.40 million acre-ft can be attributed to the Salt Fork Arkansas and Cimarron Rivers.

Downstream from site 11, the Verdigris, the Neosho, the Illinois, and the Canadian Rivers flow into the Arkansas River. The dissolved-solids concentration of these tributaries is significantly less (fig. 48), and the mean dissolved-solids concentration in the Arkansas River at site 16, downstream from these tributaries, is 373 mg/L, or about one-third of that at site 11. In Arkansas, the dissolved-solids concentrations of the inflowing waters to the Arkansas River, generally are less than 100 mg/L and average about 70 mg/L.

TRENDS IN DISSOLVED-SOLIDS CONCENTRATIONS

Trend analyses for the dissolved-solids concentrations were performed for the 18 sites selected for this study to identify changes that might have occurred during the 1968 to 1982 period. Because dissolved-solids concentrations normally decrease as water discharge increases, the dissolved-solids concentrations were flow adjusted (Crawford and others, 1983) to minimize the effects of trends in water discharges during the period of record.

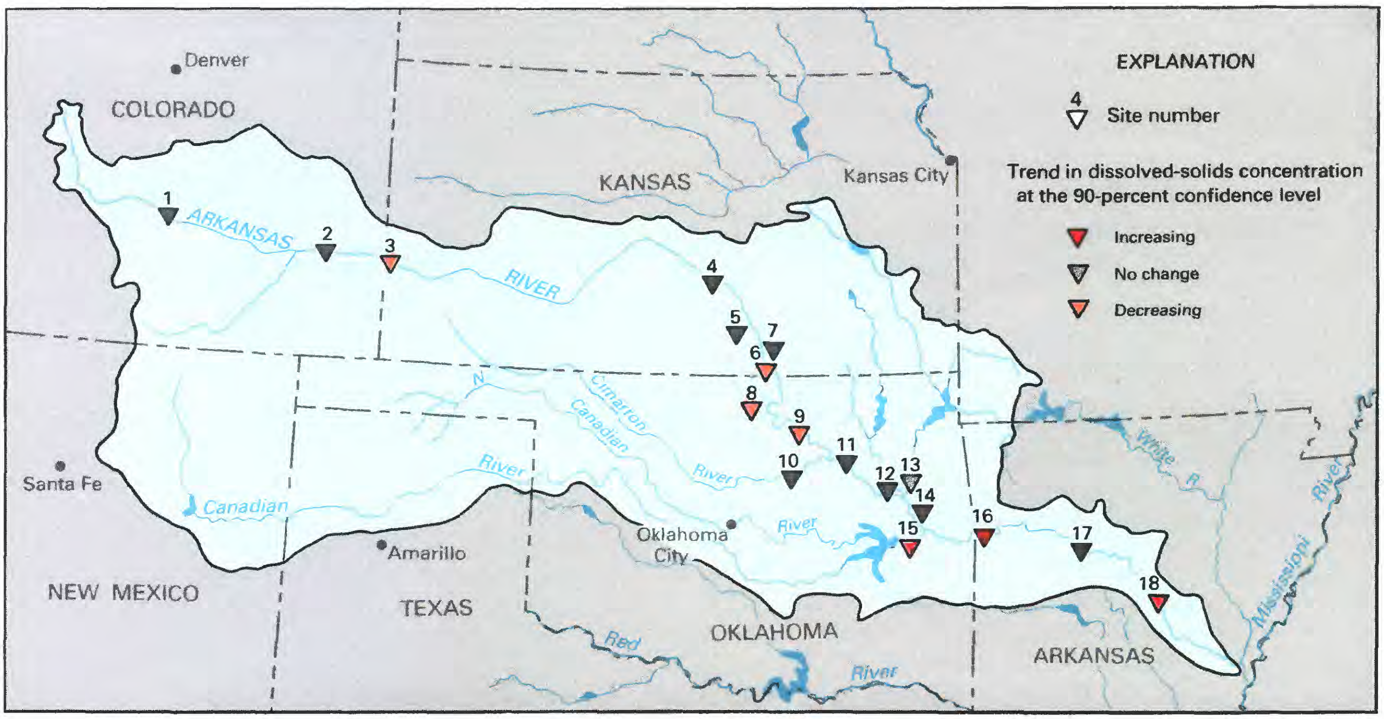
Of the 18 sites, 3 had increasing trends in concentration, 4 had decreasing trends, and 11 had no change (fig. 49). The decreases in concentration on the Arkansas River at sites 3 and 6 may be due to improved irrigation practices during the period. However, no mechanism was readily apparent to explain the indicated decreasing trends in concentration at these sites or at site 8 on Salt Fork Arkansas River. The decreasing trend indicated for the Arkansas River at site 9 probably is the downstream propogation of the trends at sites 6 and 8, whatever their causes. The increasing trends in dissolved-solids concentration on the Canadian River (site 15) may be due to evaporation or operational practices at Eufaula Reservoir just upstream of that site. The increases in concentration in the Arkansas River at sites 16 and 18 also may be due to reservoir effects; however, no change was indicated at site 17, which also is just downstream from a reservoir.

Other mechanisms affect the concentrations of dissolved solids, but their relative importance to the dissolved-solids loads of the Arkansas River is unknown. Increased ground-water pumping can decrease the ground-water gradients toward the streams and thereby diminish the natural brine inflows. Improved treatment practices can decrease point-source loading, whereas, increased population can increase point-source loadings. None of the mechanisms offered has been investigated or confirmed, and the trends indicated may be due to entirely different, unidentified causes.

SUMMARY

The large dissolved-solids load in the Arkansas River is due primarily to irrigation return flows and natural brine inflows. The mean dissolved-solids load transported out of the basin from 1968 to 1982 was 11.5 million ton/yr, of which 3.96 million tons, or 34 percent, was contributed by the Salt Fork Arkansas and Cimarron Rivers, although these two streams contributed only 4 percent of the mean annual water discharge from the basin. The major tributaries entering the Arkansas River between Tulsa, Okla., and Van Buren, Ark., contributed another 33 percent of the mean annual dissolved-solids load out of the basin; however, these tributaries also contributed 47 percent of the basin's mean annual water discharge. The natural brine inflow to the Arkansas River above the confluences of the

Figure 49. Trends in dissolved-solids concentrations at 18 stations in the Arkansas River basin, 1968 to 1982. (Source: Compiled by J. D. Stoner from U.S. Geological Survey data.)



Salt Fork Arkansas and Cimarron Rivers contributed about 5 percent of the basin's dissolved-solids load. In Colorado and Kansas, irrigation return flow contributed about 5 percent of the basin's dissolved-solids load.

The high dissolved-solids concentrations in the basin also are due to the two major sources of dissolved solids. Mean concentrations greater than 2,500 mg/L are associated with irrigation return flow in the upper reach of the Arkansas River and with the natural brine inflows in the Salt Fork Arkansas and Cimarron River basins. The high dissolved-solids concentrations are diluted by inflows of better water quality from the major tributaries, the Verdigris, the Neosho, the Illinois, and the Canadian Rivers, which enter the Arkansas River downstream from Tulsa, Okla.

Trend analyses show that dissolved-solids concentrations in the basin have remained for the most part unchanged although four stations had decreases in concentrations and three stations had increases in concentration from 1968 to 1982.

The two major sources of dissolved solids in the Arkansas River basin contributed almost one-half (49 percent) of the mean annual dissolved-solids load in the basin during the 1968 to 1982 period. The mean annual water discharges associated with these major sources was about 8 percent of the total basin mean annual discharge. Although irrigation return flow contributes to the total basin dissolved-solids load (5 percent), the natural brine inflow is the primary source (44 percent) of the total basin dissolved solids load. Therefore, the major dissolved-solids load problem in the Arkansas River basin is due much more to the natural brine inflow than to human activities. Studies of methods to control these brine inflows have been conducted by the U.S. Army Corps of Engineers (DeGeer, 1971; Rought, 1984). Construction of diversion dikes, evaporation ponds, and other control structures, however, has not been authorized.

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PESTICIDES IN RIVERS OF THE UNITED STATES

By Robert J. Gilliom

INTRODUCTION

Large-scale use of chemicals for pest control began as early as 1840, when sulfur dust was found to be effective for controlling powdery mildew on grapes. By 1890, at least 40 insecticides were patented, most containing arsenic or sulfur as the active ingredient (Dahm, 1970). Then, during the 1940's, the insecticidal properties of DDT and lindane were discovered, and, in the following years, numerous other synthetic organic pesticides were developed. Most pesticides are either insecticides for controlling insects or herbicides for controlling weeds. By 1964, the chemical industry had developed more than 10,000 commercial pesticide products that contained various combinations and formulations of over 250 basic active ingredients, mostly synthetic organic compounds (Eichers and others, 1968).

The synthetic organic pesticides that have come into use since World War II have been proven to be cost-effective against many pests. They have helped increase agricultural productivity by improving yields and reducing labor requirements. Pesticides also have been used widely for other purposes such as the control of roadside and right-of-way weeds and house and garden pests.

Along with the benefits of pesticides, however, come environmental costs such as damage to fish and wildlife and the potential health effects of human consumption of pesticides in food and water. Pesticides, for example, caused more than 1,000 fishkills in United States waters from 1961 to 1975 and accounted for about 18 percent of all reported fishkills (U.S. Environmental Protection Agency, 1979). Most of the pesticides discussed in this article have been shown to be potentially hazardous to human health if present in drinking water, and water-quality criteria on acceptable concentrations for both drinking water and aquatic biota have been established (U.S. Environmental Protection Agency, 1980). No similar criteria have been established for pesticides in the bed material (bottom sediment) of rivers or lakes because of a lack of sufficient knowledge about the interactions of contaminants in bed materials with water and aquatic organisms.

Although plants and soil are the recipients of most pesticides applied, water is the principal vehicle for movement after application. Water transports pesticides by eroding pesticide-laden soil or powders applied with the pesticide and by dissolving pesticides. The water and pesticides may seep through the soil to recharge ground water or may run off into urban or agricultural drains, ditches, and small streams to rivers and lakes. One of the national water-quality issues identified in the 1983 *National Water Summary* (U.S. Geological Survey, 1984, p. 75) was nonpoint-source pollution by pesticide residues in agricultural runoff.

To examine the extent and trends of pesticide contamination of major rivers of the United States, the U.S. Geological Survey and the U.S. Environmental Protection Agency cooperatively monitored levels of selected pesticides in the water and bed material at more than 150 river sites (fig. 50) during water years 1975 to 1980 (Feltz and others, 1971). The findings discussed below are based on a detailed analysis of data from the Pesticide Monitoring Network for the conterminous United States (Gilliom and others, 1985).

GENERAL CHARACTERISTICS OF PESTICIDES

The Pesticide Monitoring Network focused on 22 pesticides of particular environmental concern during the 1970's. These pesticides, which represent a wide range of chemical characteristics, toxicity, and uses, included organochlorine and organophosphate insecticides and chlorophenoxy and triazine herbicides (table 6).

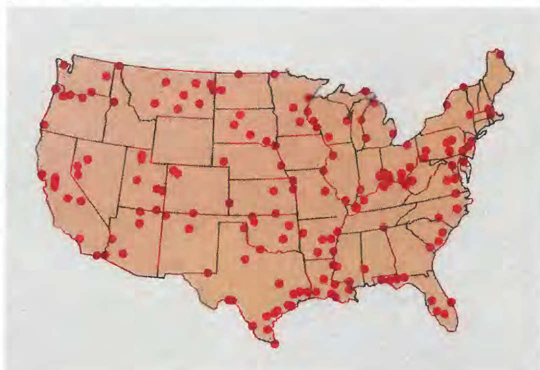

Figure 50. Location of stream-sampling stations of the U.S. Geological Survey-U.S. Environmental Protection Agency Pesticide Monitoring Network in the conterminous United States, 1975 to 1980.

An important aspect of some pesticides and other synthetic organic chemicals is that many are thought to be hazardous to aquatic life and human health at concentrations that are lower than the concentrations that can be reliably detected and measured by commonly applied analytical methods; for example, the aquatic-life criterion for DDT is 0.001 microgram per liter (µg/L), and the human-health criterion is 0.0002 µg/L, yet the limit of detection for analyses of DDT in Pesticide Monitoring Network samples was 0.05 µg/L (table 6). In other words, even though an analysis does not detect the presence of a pesticide, the pesticide still may be present in the sample at a concentration believed to be hazardous. Because pesticide concentrations are often diluted by river water to levels below detection limits, monitoring pesticide levels and interpreting pesticide data are difficult.

Two characteristics that account for variations in environmental behavior of different pesticides are solubility in water and persistence in the environment (table 6). Chemicals with low solubility and high persistence, such as many of the organochlorine insecticides, generally are found in association with particulate bed materials or suspended sediment and may not degrade for several years. These chemicals also tend to accumulate in aquatic organisms and their predators, and, over time, they can reach harmful concentrations in organisms even if concentrations in water and bed material are low. Conversely, other types of chemicals, such as the organophosphate insecticides, are highly soluble in water and usually last only days or weeks before degrading. Even though such chemicals usually degrade to a benign form and do not accumulate in organisms, most are more acutely toxic than the organochlorine insecticides. The herbicides monitored also are readily soluble in water, but they generally persist for weeks to months. In general terms, therefore, the organochlorine insecticides are the least soluble and most persistent, the organophosphate insecticides are highly soluble and the least persistent, and the herbicides are highly soluble and moderately persistent.

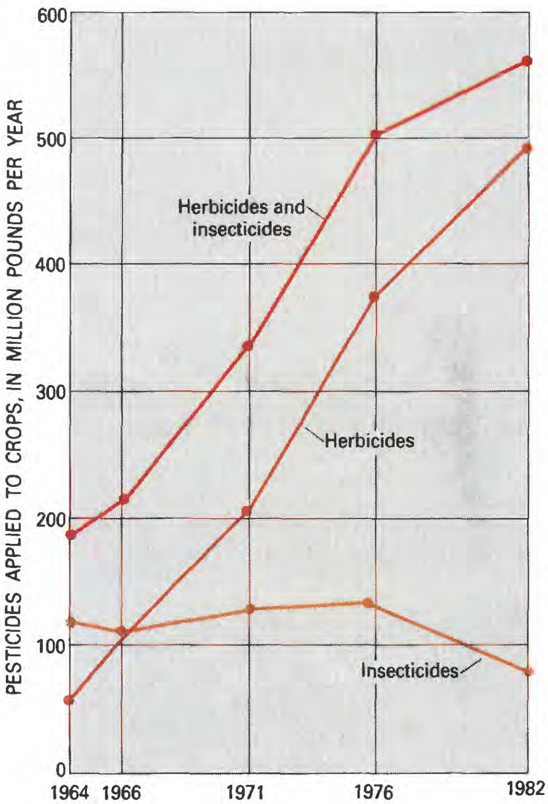

Figure 51. Trends in national use of herbicides and insecticides on major crops, 1964 to 1982. (Source: Compiled by R. J. Gilliom from data in Eichers and others, 1970; Andrilenas, 1974; Eichers and others, 1978; and U.S. Department of Agriculture, 1983. Reported use in 1982 was adjusted according to past use patterns to account for use in States for which there were no data.)

USE OF PESTICIDES

All the pesticides analyzed in the Pesticide Monitoring Network are synthetic organic chemicals and, thus, only appear in the environment as a result of their use, disposal, or manufacture. The greatest release of pesticides was on farms (Eichers and others, 1978), of which about 98 percent was applied to crops and 2 percent to livestock. Corn, cotton, wheat, sorghum, rice, other grains, soybeans, tobacco, peanuts, alfalfa, other hay and forage, and pasture and range land accounted for 85 percent of the pesticides used on crops.

Nationally, insecticide use on crops is declining gradually, whereas herbicide use is increasing (fig. 51). Much of the decline in amount of insecticide applied is due to the use of more potent new chemicals. Since 1976, for example, fenvalerate and permethrin, two new insecticides for use on cotton which require very low application rates, largely have replaced toxaphene and methyl parathion, which were routinely applied at much higher application rates (McDowell and others, 1982).

PATTERNS AND TRENDS IN PESTICIDE DETECTIONS

The percentage of samples that contained detectable concentrations of pesticides and the percentage of stations at which pesticides were detected are listed in table 7 for water and bed material, respectively. Relatively few water samples contained detectable pesticide concentrations; the most common pesticides in water were lindane, diazinon, and atrazine. In bed material, however, some organochlorine compounds were detected relatively frequently, although organophosphate insecticides and the herbicides were detected very rarely. Data from the Pesticide Monitoring Network indicate that less than 10 percent of almost 3,000 water samples and less than 20 percent of almost

1,000 bed-material samples contained detectable concentrations of any of the pesticides for which analyses were made.

Organochlorine Insecticides

Use and Occurrence

For most of the organochlorine insecticides, a combination of increasing regulatory restriction and decreasing effectiveness due to insect resistances has caused a dramatic decrease in use since the mid-1960's (table 6). Overall use of organochlorine insecticides on major crops has declined from a 63-percent share of all insecticide use in 1964 to a 40-percent share in 1971 to a 28-percent share in 1976 (Eichers and others, 1970, 1978). Data for 1982 show that this share has decreased further to less than 10 percent (U.S. Department of Agriculture, 1983). Only toxaphene retained a major share of total use through the 1970's though its use also had declined greatly by 1982. Despite these decreases in farm use, chlordane, heptachlor, methoxychlor, and toxaphene still are used heavily for other purposes, as indicated by the disparity between total use and farm use (table 6). Chlordane and heptachlor, for example, are used extensively for termite control.

Frequencies of detection of organochlorine insecticides (table 7) reflect the combined effects of different detection limits, amounts of use, persistence and solubility, and degradation products (table 6). A striking feature of table 7 is the contrast between the very low frequency of detection of organochlorine compounds in water samples and the relatively high frequency of detection in bed material. The low number of detections in water samples compared to bed material is consistent with the low solubility of these compounds and their tendency to associate with particulate matter.

A key factor that potentially affects the frequency of detection of a pesticide is the amount used. On the basis of historic use, toxaphene, methoxychlor, DDT, and aldrin should occur most frequently. However, the analytical methods for toxaphene and methoxychlor are the least sensitive of the organochlorine insecticides; consequently, they were seldom detected. DDT degrades over time into DDD and DDE. Though DDT was detected fairly often in bed material, its degradation products, DDD (low use) and DDE (not used), were detected even more often. Aldrin, which has a low detection limit but degrades fairly rapidly to dieldrin, was seldom detected in either water or bed material. Its more persistent degradation product, dieldrin, was detected in about 29 percent of bed-material samples despite substantially less direct use of dieldrin as a pesticide.

In contrast to these more heavily used compounds, lindane was used relatively little and yet was the most frequently detected organochlorine in water. The combination of lindane's relatively high solubility, high persistence, and a low detection limit probably explains this. Chlordane, used only slightly more than lindane, was almost never detected in water samples but was one of the most frequent pesticides detected in bed-material samples. Chlordane is one of the most persistent of the organochlorine insecticides and is only one-third as soluble as lindane. Thus, the patterns of detection that would be expected from use data alone do not occur because of varying chemical properties and analytical capabilities.

Trends Over Time

Concentrations of organochlorine insecticides in both water and bed material appear to have decreased erratically but gradually since about 1976 or 1977. Frequencies of detection for all stations and samples are shown in figure 52. Average numbers of detections per 100 samples were computed by summing the number of detections for all organochlorine compounds for a given year and dividing by the number of samples analyzed for organochlorines that year. The maximum possible number of detections per 100 samples is 1,100 because 11 organochlorine insecticides were monitored. Comparison of Pesticide Monitoring Network data for water samples to data from an earlier U.S. Geological Survey study of pesticides in western rivers (Schulze and others, 1973) indicate a marked reduction in concentrations since the late 1960's. For 16 stations identically or

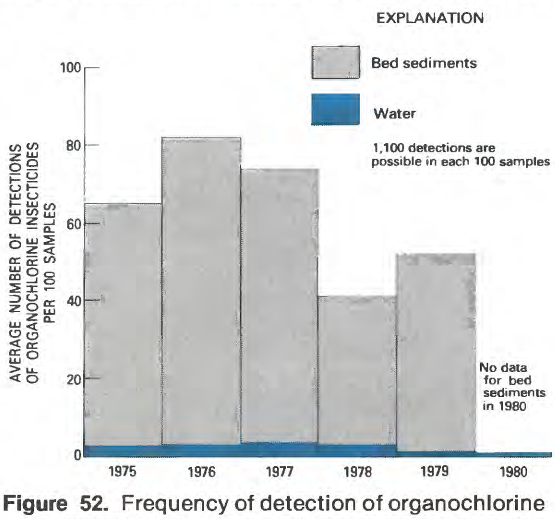

Figure 52. Frequency of detection of organochlorine insecticides in water and bed-material samples from stations in the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network, 1975 to 1980.

Table 6. Selected characteristics and uses of pesticides monitored by the U.S. Geological Survey-U.S. Environmental Protection Agency Pesticide Monitoring Network, 1975 to 1980

[μg/L, microgram per liter; lb/yr = pounds per year; nd, no available data; nr, none reported]

Chemical	Characteristics					Uses					
	Detection limit[1] (μg/L)	Water-quality criteria[2] (μg/L) Human health	Water-quality criteria[2] (μg/L) Aquatic life	Solubility[3] (μg/L)	Relative persistence within pesticide group[4]	Principal uses and sources	National use on farms[5] (million lb/yr) 1966	1971	1976	1982	Total use, 1981[6] (million lb/yr)
Organochlorine insecticides											
Aldrin	0.01	0.0007	0.002	13	Low	Corn	15	7.9	0.9	nr	0.8
							(Most farm uses cancelled 1974)				
Dieldrin	.03	.0007	.002	22	Medium	Termite control, degradation product of aldrin.	.7	.3	nr	nr	0
							(Most farm uses cancelled 1974)				
Chlordane	.15	.005	.004	56	High	Corn, termites, general purpose.	.5	1.9	nr	nr	9.6
							(Most farm uses cancelled 1974)				
DDD	.05	.0002	.001	5	--do--	Fruits and vegetables, degradation product of DDT.	2.9	.2	nr	nr	0
							(Cancelled 1972)				
DDE	.03	.0002	.001	10	--do--	Degradation product of DDT and DDD.	nr	nr	nr	nr	0
DDT	.05	.0002	.001	17	--do--	Cotton, fruits, vegetables, general purpose.	27	.1	nr	nr	0
							(Cancelled 1972)				
Endrin	.05	*1	.002	14	nd	Cotton, wheat	.6	1.4	.8	nr	.3
Heptachlor epoxide	.01	.003	.004	30	Low	Degradation product of heptachlor which is used on corn, and termite control.	1.5	1.2	.6	nr	2.0
Lindane	.01	*4	.08	150	Medium	Livestock, seed treatment, general purpose.	.7	.7	.2	nr	.8
Methoxychlor	.10	*100	*.03	3	nd	Livestock, alfalfa, general purpose.	2.6	3.0	3.8	.6	5.0
Toxaphene	.25	.007	.013	400	nd	Cotton, livestock	35	37	33	5.9	16
Organophosphate insecticides											
Diazinon	.10	nd	nd	40,000	High	Corn, general purpose.	5.6	3.2	1.6	.3	9.0
Ethion	.25	nd	nd	2,000	nd	Citrus fruits	2.0	2.3	nr	nr	2.0
Malathion	.25	nd	.1	145,000	Low	General purpose	5.2	3.6	2.8	1.6	28
Methyl parathion	.25	nd	nd	57,000	--do--	Cotton and wheat	8.0	28	23	11	20
Methyl trithion	.50	nd	nd	nd	nd	Not identified	nr	nr	nr	nr	.1
Parathion	.25	nd	.04	24,000	Low	Wheat, corn, sorghum.	8.5	9.5	6.6	4.0	5.0
Trithion	.50	nd	nd	340	nd	General purpose	nr	nr	nr	nr	.1
Chlorophenoxy and triazine herbicides											
Atrazine	.5	nd	nd	33,000	High	Corn	24	54	90	76	92
2,4-D	.5	*100	nd	900,000	Low	Wheat, rangeland, general purpose.	4	31	38	23	60
2,4,5-T	.5	*10	nd	240,000	Medium	Rice, rangeland, general purpose.	.8	nr	nr	.2	2.2
Silvex	.5	nd	nd	140,000	nd	Sugarcane, rice, rangeland.	nr	nr	nr	nr	.4

[1] Detection limits shown are for water samples. Bed-sediment reporting limits are 10 times greater and are expressed in units micrograms per kilogram (Lucas and others, 1980).

[2] All criteria are from U.S. Environmental Protection Agency (1980), except for values marked by asterisks, which are from U.S. Environmental Protection Agency (1976). The human-health criteria for all pesticides except endrin, lindane, methoxychlor, 2,4-D, and 2,4,5-T represent the estimated average concentrations associated with an incremental increase in cancer risk of 10^{-5} (one additional cancer per 100,000 people over a lifetime of exposure). The aquatic-life criteria are for freshwater and are 24-hour average concentrations.

[3] Data from Kenaga and Goring (1980).

[4] Relative persistence within each pesticide group as estimated from Hiltbold (1974) and Wauchope (1978).

[5] Data for 1966, from Eichers and others (1970); for 1971, Andrilenas (1974); for 1976, Eichers and others (1978); for 1982, U.S. Department of Agriculture (1983). Data for 1982 do not include use on livestock or use in California, Colorado, Connecticut, Maine, Massachusetts, Nevada, New Hampshire, New Jersey, New Mexico, Oregon, Rhode Island, Utah, Vermont, West Virginia, and Wyoming.

[6] Data from Mark H. Glaze (U.S. Environmental Protection Agency, written commun., 1983).

* See footnote 2.

Table 7. Summary of detections of pesticides in water and bed sediments at the U.S. Geological Survey-U.S. Environmental Protection Agency Pesticide Monitoring Network stations, 1975 to 1980

Chemical	Water				Bed material			
	Stations		Samples		Stations		Samples	
	Number monitored	Percentage with detections	Number collected	Percentage with detections	Number monitored	Percentage with detections	Number collected	Percentage with detections
Organochlorine insecticides								
Aldrin - - - -	177	2.3	2,946	0.2	171	2.9	1,015	0.6
Dieldrin - - -	177	2.3	2,945	.2	172	29	1,017	12
Chlordane - -	177	.6	2,943	.0	171	30	1,014	9.9
DDD- - - - -	177	4.0	2,720	.3	171	31	990	12
DDE- - - - -	177	.6	2,715	.0	172	42	989	17
DDT- - - - -	177	2.8	2,721	.4	171	26	992	8.5
Endrin - - - -	180	1.1	2,950	.1	171	2.3	1,015	.6
Heptachlor epoxide - - -	177	4.5	2,946	.3	171	5.3	1,017	1.0
Lindane - - -	177	8.5	2,945	1.1	171	.6	1,018	.1
Methoxychlor -	172	.0	2,761	.0	160	.6	941	.1
Toxaphene - -	177	2.8	2,946	.4	171	3.5	1,014	.6
Organophosphate insecticides								
Diazinon - - -	174	9.8	2,859	1.2	164	1.2	929	.2
Ethion - - - -	174	.6	2,823	.1	163	.6	928	.4
Malathion - -	174	.6	2,859	.1	163	.0	929	.0
Methyl parathion - -	174	2.7	2,861	.1	163	.0	929	.0
Methyl trithion - - -	174	.0	2,822	.0	163	.0	928	.0
Parathion- - -	174	.6	2,856	.0	163	.0	928	.0
Trithion - - -	174	1.1	2,819	.1	163	.0	925	.0
Chlorophenoxy and triazine herbicides								
Atrazine - - -	144	24	1,363	4.8	126	.0	347	.0
2,4-D - - - -	186	2.4	1,764	.2	142	1.4	487	.4
2,4,5-T - - - -	186	.6	1,765	.1	142	.7	486	.2
Silvex - - - -	167	.6	1,768	.1	142	1.4	488	.4

similarly located in both programs, the earlier data for the western rivers showed an average frequency of detection from 1968 to 1971 of about 12 detections per 100 water samples (using Pesticide Monitoring Network detection limits), compared to an average of less than 1 detection per 100 samples during the period from 1975 to 1980 in the Pesticide Monitoring Network.

Trends also were evaluated statistically for each chemical at every station where at least 2 water samples out of 10 or 2 bed-material samples out of 6 contained detectable amounts of pesticides. There were only enough detections in water samples to evaluate trends for 13 out of about 2,000 possible station-chemical combinations. Trends in bed-material levels, however, were testable for 123 station-chemical combinations. Statistically significant (α = 0.30) trends in pesticide concentrations in bed-material were found for 36 station-chemical combinations, with 7 increasing trends and 29 decreasing trends. These trends were concentrated at relatively few stations. Trends were most often apparent for the chemicals most frequently detected—DDD, DDE, DDT, chlordane, and dieldrin. Of the seven increasing trends nationwide, five occurred at the Black River at Kingstree, S.C., which had increasing trends in DDD, DDE, DDT, chlordane, and dieldrin. Of the 29 decreasing trends nationwide, 18 occurred at only 6 stations, and the remaining 11 were at 11 different stations.

ORGANOPHOSPHATE INSECTICIDES

Use and Occurrence

Farm use of the organophosphate insecticides that were monitored has declined steadily through the 1970's, though not as dramatically as the use of organochlorine insecticides (fig. 51, table 6). Only the total use of diazinon has been increasing. Methyl parathion was used most often, mainly on cotton. Some of the other chemicals monitored—ethion, methyl trithion, and trithion—were used very little on farms during the time the Pesticide Monitoring Network was in existence.

Frequencies of detections of organophosphate insecticides, as with the organochlorine insecticides, reflect the combined effects of variable detection limits, amount of use, solubility, and persistence. The low frequency of detections probably results primarily from the relatively high detection limits for these chemicals and their low persistence. Methyl parathion was the most heavily used organophosphate insecticide and yet was detected in only 3 of almost 2,900 water samples. Other chemicals in the group with detection limits equal to or higher than methyl parathion and with less use were detected in even fewer water samples. Diazinon was detected substantially more often than the other organophosphate chemicals in water, but there were only 34 detections in 2,859 samples (1.2 percent). The detection limit for diazinon is less than one-half of that of the other chemicals in this group, and it is more persistent than the other organophosphate compounds. In bed material, organophosphate chemicals were almost never detected due to their high solubility in water and low persistence.

Trends Over Time

No trends are evident in detections of organophosphate insecticides on a national scale (fig. 53) or regional scale or at any individual station for either water or bed material. Detections were too few to allow any analysis of trend in bed-material concentrations. Only six bed-material detections were made at a total of three stations. On a station-by-station basis for all organophosphate chemicals, sufficient numbers of detections in water samples were made to test trends for only seven station-chemical combinations, and no significant trends were evident.

CHLOROPHENOXY AND TRIAZINE HERBICIDES

Use and Occurrence

The use of herbicides has rapidly increased during the past 20 years (fig. 51), with atrazine and 2,4-D accounting for much of the increase. From 1971 to 1976, these two chemicals accounted for about 50 percent of all herbicide use, but the dominance of these chemicals had decreased somewhat by 1980; for example, atrazine fell from 41 percent of total herbicide application on corn in 1976 (Eichers and others, 1978) to 33 percent in 1980 (Hanthorn and others, 1982).

Data from the Pesticide Monitoring Network show virtually no detections of herbicides

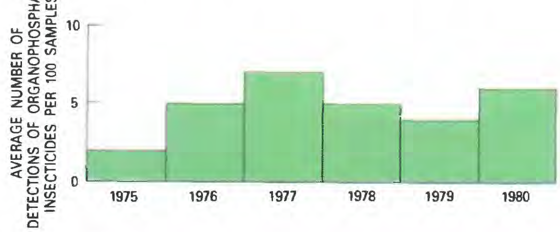

Figure 53. Frequency of detection of organophosphate insecticides in water samples from stations in the U.S. Geological Survey–U.S. Environmental Protection Agency Pesticide Monitoring Network, 1975 to 1980.

in bed material and, except for atrazine, few detections in water samples (table 7). For most stations, herbicides were measured for only 3 years (1976–78). The second most detected herbicide after atrazine was 2,4-D. These findings may be explained by the extremely heavy use of atrazine and 2,4-D, combined with the greater persistence of atrazine (table 6). All stations at which atrazine was detected more than two times are located downriver from major corn-growing areas where virtually all atrazine is applied.

Trends Over Time

The generally low rate of detections of herbicides, as well as the limited time span of data available for the triazine herbicides made it impossible to evaluate trends meaningfully in either bed sediments or water samples.

CONCLUSIONS

Concentrations of chlorinated hydrocarbon insecticides, including dieldrin, chlordane, and DDT, have decreased in both the water and bed material of major United States rivers since the mid-1970's, when their use was greatly curtailed. No clear trends are evident in concentrations of the organophosphate insecticides and herbicides that were monitored.

From 1975 to 1980, fewer than 10 percent of almost 3,000 water samples and fewer than 20 percent of nearly 1,000 bed-material samples contained detectable levels of any of the 22 common pesticides monitored. The small number of detections is due partly to the difficulties of sampling and measuring the very low concentrations of pesticides that generally are present. Although analytical detection limits were not sensitive enough to determine if concentrations exceeded established water-quality criteria, the low frequency of detections suggests that the 22 pesticides that were monitored do not occur in many rivers at concentrations that consistently far exceed water-quality criteria.

The low and variable frequency of detection of the pesticides, regional patterns of use, and the constantly changing array of available pesticides make national-scale monitoring of pesticides a very difficult undertaking. Pesticide use tends to be strongly regional, with most use of each chemical occurring in only one or two regions of the country; for example, most DDT and toxaphene were applied in cotton-growing areas, and most atrazine was applied in corn-growing areas. The types of pesticides used are changing constantly; new chemicals are being introduced each year, and others are being discontinued. Each different type of chemical presents unique sampling and analysis problems.

Future pesticide-monitoring efforts will need to respond to changes in the types of pesticides, methods of application, chemical characteristics, and geographic patterns of use. Analytical methods will need to be developed and improved, and different types of monitoring approaches will need to be applied. As our knowledge about pesticide chemicals and their behavior in the environment increases, efforts to monitor the levels, trends, and geographic distribution of pesticides gradually will become more sophisticated and effective.

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OVERVIEW OF THE OCCURRENCE OF NITRATE IN GROUND WATER OF THE UNITED STATES

By Robert J. Madison and Jilann O. Brunett

INTRODUCTION

Nitrate and other nitrogenous compounds are essential elements in the life processes of plants and animals. In spite of its importance, nitrate is a potentially hazardous pollutant when present in drinking water at sufficiently high concentrations (U.S. Environmental Protection Agency, 1982)[1]. Although nitrate in itself is relatively nontoxic, it can be reduced bacterially to nitrite in the intestines of newborn infants and may result in the disease methemoglobinemia. Infant mortality from methemoglobinemia is rare where nitrate-nitrogen concentrations in drinking water are less than 10 milligrams per liter (mg/L), but its incidence increases with increasing concentrations (Walton, 1951). Nitrite also can react with other substances, such as amines, in the stomach or lungs to form N-nitrosoamines, which have been found to induce tumors in laboratory animals. Although no human tumors have been linked directly to these compounds, exposure to the compounds may pose a risk of human cancer (National Research Council, 1978, p. 3).

Most natural waters that are unaffected by human-related activities contain less than 10 mg/L nitrate-nitrogen (Feth, 1966, p. 49) though, in some arid areas, natural concentrations may be greater. As discussed later in this article, nitrate-nitrogen concentrations greater than about 3 mg/L may be indicative of human sources. A survey of relevant publications indicates that in many areas of the Nation, human sources of nitrogen have resulted in concentrations of nitrate-nitrogen that are well above 3 mg/L in ground water, especially in shallow aquifers. Freeze and Cherry (1979, p. 413) stated that dissolved nitrogen in the form of nitrate is the most common contaminant of aquifer systems. The severity of nitrate contamination on a national scale, however, has not been well documented.

In a recent assessment of nitrate in the environment, the National Research Council (1978, p. 465) concluded that the present ambient levels of nitrate in the United States rarely have been reported to affect adversely the health of humans or livestock. However, rapid population growth and associated human activities may aggravate nitrate-pollution problems in the future.

In States where nitrate contamination of ground water has been identified, reconnaissance surveys and mass-balance studies that attempt to account for the total input and output of nitrogen in individual aquifers or areas have been accomplished. Many of these studies show qualitative relations between high nitrate concentration in ground water and known or suspected nitrogen sources. Several studies have used nitrogen-isotope analysis with some success to infer the sources of nitrate in ground water. In southern Delaware, for example, Ritter and Chirnside (1984) used nitrogen-isotope ratios in combination with land use information to distinguish between fertilizer nitrogen, animal- or human-waste nitrogen, and natural soil nitrogen. Similar results with isotope ratios have been reported for high-nitrate waters in Texas, Nebraska, and New York (Kreitler and others, 1978; Kreitler and Jones, 1975; Gormly and Spalding, 1979). However, a search of the current literature revealed no studies that summarized the occurrence and distribution of elevated concentrations of nitrate in ground water on a nationwide scale.

The purpose of this discussion is to provide a general overview of the occurrence of high-nitrate concentration; to delineate those areas of the country where nitrate contamination of ground water may be, or has the potential for becoming, a regional problem, and to discuss the major sources of nitrate in soils and ground water.

SOURCES AND TRANSPORT OF NITROGEN

Nitrate can enter the ground-water system from a variety of natural and human sources. The principal natural sources are soil nitrogen, nitrogen-rich geologic deposits, and atmospheric deposition. Principal human-related sources and contributory activities include fertilizers, septic tank drainage, feedlots, dairy and poultry farming, land disposal of municipal and industrial wastes, dry cultivation of mineralized soils, and the leaching of soil as the result of the

[1] In this discussion nitrate concentration is expressed in terms of its equivalent elemental nitrogen (N) content. Some investigators may report nitrate content in terms of nitrate ion (NO_3-). Nitrate content expressed as nitrate ion can be converted to its equivalent elemental nitrogen content by dividing by 4.43; for example, 44 mg/L nitrate ion is equivalent to about 10 mg/L nitrate-nitrogen.

application of irrigation water.

Regardless of the source, the amount of nitrate that enters the ground water is controlled by a complex set of hydrologic, chemical, and biological processes that take place in the subsurface environment (fig. 54). The simplified diagram in figure 55 illustrates the following major transformations of nitrogen that can take place (commonly referred to as the nitrogen cycle):

1. *Assimilation* of inorganic forms of nitrogen (ammonia and nitrate) by plants and microorganisms.
2. *Heterotrophic conversion* of organic nitrogen from one organism to another.
3. *Ammonification* of organic nitrogen to produce ammonia during the decomposition of organic matter.
4. *Nitrification* of ammonia to nitrite and nitrate by the chemical process of oxidation.
5. *Denitrification* (bacterial reduction) of nitrate to nitrous oxide (N_2O) and molecular nitrogen (N_2) under anoxic conditions.
6. *Fixation of nitrogen* (reduction of nitrogen gas to ammonia and organic nitrogen) by microorganisms.

The operation of the nitrogen cycle controls the amount of nitrate produced in the soil column, primarily as a result of nitrification, but the concentration at any one place can vary widely depending on environmental conditions. Most nitrogen compounds appear to move freely through aquifers without much change in their total concentrations. An exception is ammonium ions (NH_4^+) which may be adsorbed on clay minerals. The rate of movement of nitrate through the soil column and the amount that is ultimately "leached" to the ground water are controlled primarily by the soil type and its hydraulic conductivity. Other factors include soil moisture, temperature, vegetation or crop type, and precipitation.

In saturated soils, the main factors limiting water movement are the size and continuity of pores in the soil. Generally, as average interstitial pore size increases, the hydraulic conductivity and, thus, the potential for water movement increase. Hydraulic conductivity values for saturated uniform-grain size sandy soils can be several hundred times greater than corresponding values for clay soils or soils with heterogeneous mixtures of grain sizes. Thus, clean sandy soils will transmit more water and

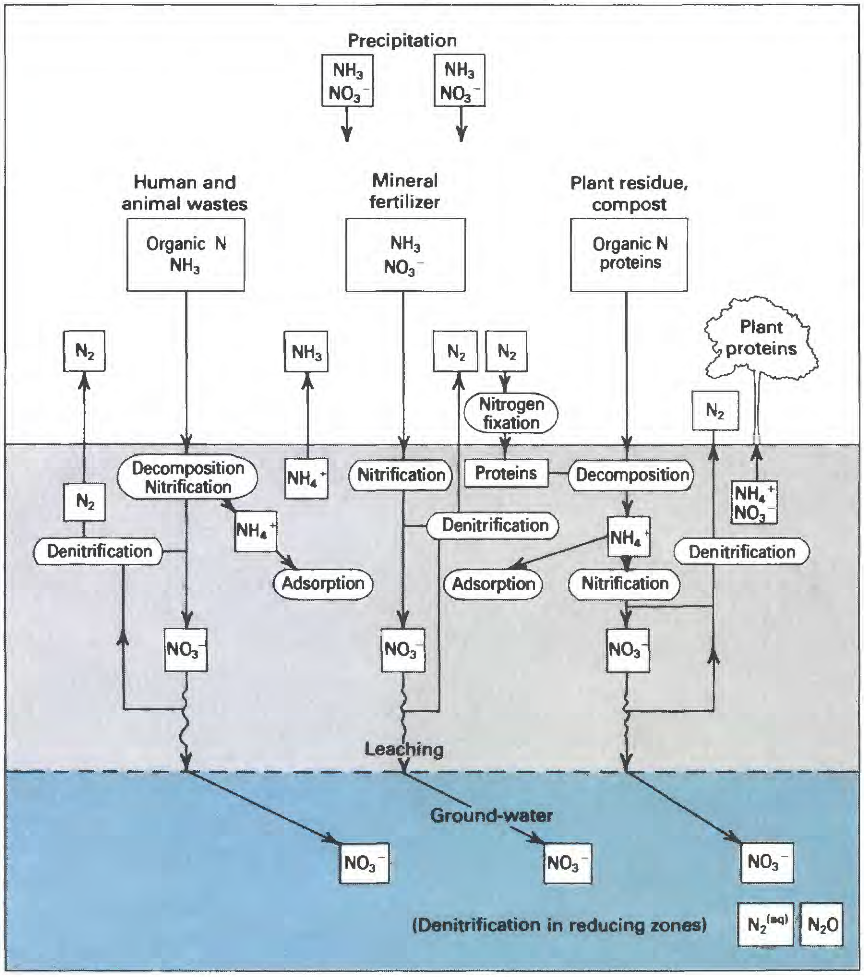

Figure 54. Sources, movement, and reaction of nitrogen in soils and ground water. (Chemical symbols: N, elemental nitrogen; N_2, nitrogen gas; N_2O, nitrous oxide; NO_2^-, nitrite; NO_3^-, nitrate; NH_3, ammonia, NH_4^+, ammonium; N_2(aq), nitrogen gas; dissolved in water. (Source: Modified from Freeze and Cherry, 1979, p. 414.)

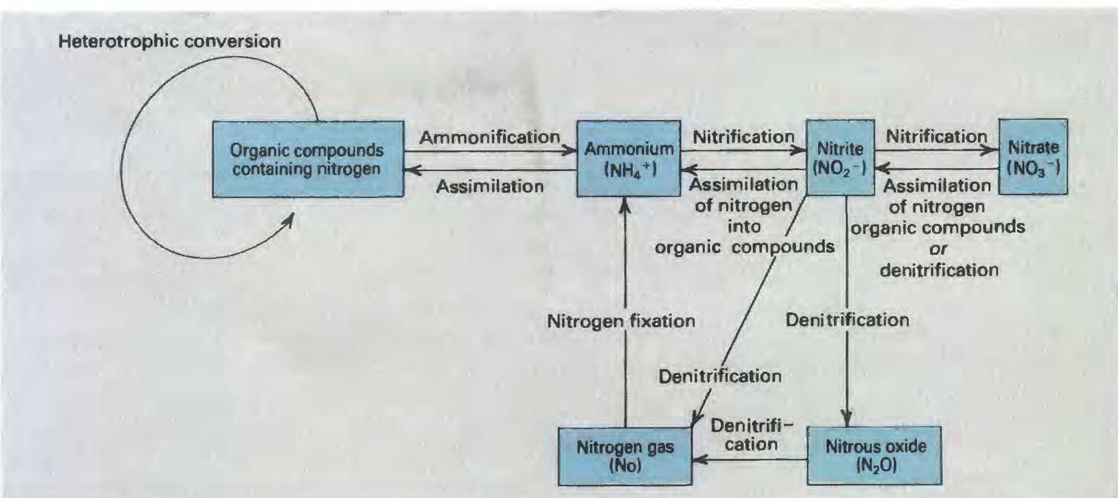

Figure 55. Simplified biological nitrogen cycle, showing some environmentally important reactions of nitrogen. Other biological reactions evolving nitrogen also occur. (Source: Modified from National Research Council, 1978, p. 23.)

more dissolved materials, but they provide less opportunity of the dissolution of nitrates than the fine-grain or organic-rich soils. As soils dry out, the hydraulic conductivity and, thus, the rate of soil-water movement decrease rapidly. At a pressure of 1 atmosphere, the hydraulic conductivity of an unsaturated soil can be as little as one hundred thousandth of the value for the same soil when saturated (National Research Council, 1978, p. 107). A detailed discussion of the rate of nitrate leaching in soils for various geographic areas of the United States can be found in Thomas (1970, p. 1-20).

NITRATE LEVELS IN GROUND WATER

The level of nitrate concentration that is considered to be above natural or background levels and, thus, the result of human activities, has not been clearly defined. Nitrate-nitrogen concentrations in most unpolluted ground waters seldom exceed 10 mg/L (Feth, 1966, p. 49). In a few isolated areas of naturally occurring nitrate-rich deposits, however, values on the order of several hundred milligrams per liter have been found (Hendry and others, 1984, p. 185). To obtain a national perspective on the extent of elevated nitrate concentrations in ground water for the *National Water Summary*, existing data were evaluated for human-related influences. Based on this evaluation, a concentration of more than 3 mg/L was arbitrarily defined as indicating possible human inputs.

The U.S. Geological Survey's National Water-Data Storage and Retrieval System (WATSTORE) contains nitrate analyses for about 87,000 wells throughout the United States. Nitrate data from this computerized data base represent samples collected and analyzed over a period of 25 years. The data, which were analyzed statistically to see if regional areas of elevated nitrate concentrations could be reasonably portrayed from existing data, were separated into four ranges of nitrate-nitrogen concentrations:

- Less than 0.2 mg/L—Assumed to represent natural background concentrations.
- 0.21 to 3.0 mg/L—Transitional; concentrations that may or may not represent human influence.
- 3.1 to 10 mg/L—May indicate elevated concentrations resulting from human activities.
- More than 10 mg/L—Exceeds maximum concentration in National Interim Primary Drinking-Water Regulations (U.S. Environmental Protection Agency, 1982).

Because few data for Texas were available in WATSTORE, the Texas Natural Resources Information System (TNRIS) of the Texas Department of Water Resources also was used in the analysis. This data base contains water analyses from more than 36,000 wells, including about 5,000 public-supply wells.

The frequency distribution of the data for the four categories defined above are shown in table 8. Those areas where more than 25 percent of the wells (for which nitrate data are available) had water with a maximum nitrate-nitrogen concentration exceeding 3.0 mg/L are outlined in figure 56. Figure 56 should be interpreted with caution. The data bases used to compile figure 56 do not necessarily represent a random or unbiased sample of all wells or aquifers in the United States inasmuch as the data were collected to meet many different objectives; thus, the types of wells sampled, the numbers of wells, the time period covered, and the areal coverage of sampling networks differ from State to State and within a State. In locations where problems related to nitrate in water are known to exist, the density of sampling may be higher than in nonproblem areas. Little information was available for areas in some States because existing data were not in a machine-readable form or because ground water is not yet important enough to warrant the expense of water analysis. For the rest of the country, the data base contained water analyses from at least five wells in most counties. Because of these biases in the data, figure 56 should not be used to imply that more than 25 percent of all unsampled wells in any shaded area also will have elevated nitrate values. The data do indicate, however, that human activities have elevated the nitrate-nitrogen levels in ground water above 3 mg/L in many areas of the United States.

Of the nearly 124,000 wells for which nitrate values are available, more than 24,000 (20 percent) had water with maximum nitrate-nitrogen concentrations higher than 3 mg/L. However, only about 8,200 of these wells (6 percent) had water with maximum nitrate-nitrogen concentrations that exceeded 10 mg/L, the criterion for drinking waters as established by the U.S. Environmental Protection Agency (1982).

In most instances, elevated nitrate concentrations were found in water from relatively shallow wells (less than 100 feet). The relations between nitrate concentrations and well depth for the data analyzed in this study are shown in figure 57. Water samples with more than 3 mg/L nitrate-nitrogen tended to be less common with increasing depth of the sampled wells. This inverse relation of nitrate concentration to well depth has been documented by many investigators (for example, see Spruill, 1983, p. 977-81). Wells that yielded water samples with less than 3 mg/L nitrate-nitrogen had a depth distribution similar to that of all the wells sampled, supporting the assumption of 3 mg/L as a break point between human-

Table 8. Summary of nitrate-nitrogen concentrations in ground water, by State

[Percentages for each State may not add to 100 percent because of independent rounding; mg/L = milligrams per liter. Source: Data from samples collected and analyzed by the U.S. Geological Survey and Texas Department of Natural Resources over a period of 25 years

State	Number of wells sampled	Percentage of wells for which maximum nitrate-nitrogen concentration fell within indicated range (mg/L)			
		0–0.2	0.21–3.0	3.1–10	More than 10
Alabama	244	47.1	45.5	7.4	0.0
Alaska	1,305	60.9	33.9	2.8	2.4
Arizona	4,164	12.1	49.7	24.4	13.9
Arkansas	2,436	49.1	38.5	8.5	3.9
California	2,732	21.9	45.4	22.5	10.1
Colorado	5,492	33.8	43.3	17.2	5.7
Connecticut	348	33.6	49.7	14.4	2.3
Delaware	165	34.5	30.9	25.5	9.1
Florida	3,140	71.5	24.2	2.3	2.0
Georgia	1,137	66.7	28.5	4.3	.5
Hawaii	164	15.9	75.0	9.1	.0
Idaho	1,806	33.3	52.0	12.9	1.7
Illinois	359	56.0	30.1	5.6	8.4
Indiana	650	55.4	33.4	9.7	1.4
Iowa	4,088	44.9	36.7	13.4	5.0
Kansas	1,140	17.0	28.8	34.2	20.0
Kentucky	3,227	36.5	46.2	13.0	4.2
Louisiana	3,177	78.3	19.4	1.8	.6
Maine	147	50.3	35.4	12.2	2.0
Maryland	1,521	40.9	30.4	22.0	6.8
Massachusetts	414	42.3	52.2	4.3	1.2
Michigan	1,108	79.1	17.1	2.8	1.1
Minnesota	1,655	39.1	40.7	10.9	9.3
Mississippi	1,701	76.5	21.7	1.6	.2
Missouri	2,165	64.2	27.2	6.6	2.1
Montana	2,821	43.4	45.1	7.7	3.8
Nebraska	2,326	18.0	49.3	23.4	9.3
Nevada	465	46.2	45.4	7.5	.9
New Hampshire	69	66.7	29.0	2.9	1.4
New Jersey	1,385	63.0	25.6	10.0	1.4
New Mexico	4,685	38.4	48.9	9.8	2.9
New York	2,491	28.9	30.8	29.3	11.0
North Carolina	908	72.1	22.0	5.1	.8
North Dakota	7,387	22.4	68.5	4.4	4.6
Ohio	339	61.7	29.8	5.9	2.6
Oklahoma	1,724	23.0	41.2	24.1	11.8
Oregon	685	57.1	36.4	5.4	1.2
Pennsylvania	4,326	31.1	38.7	24.4	5.9
Puerto Rico	79	16.5	48.1	32.9	2.5
Rhode Island	171	17.0	38.0	8.8	36.3
South Carolina	557	69.3	26.6	3.4	.7
South Dakota	1,996	49.2	35.9	8.2	6.7
Tennessee	109	65.1	29.4	4.6	.9
Texas	36,196	<--- 76.5--->		14.1	9.4
Utah	3,301	39.1	50.4	8.4	2.0
Vermont	73	52.1	41.1	5.5	1.4
Virginia	762	70.7	25.9	2.6	.8
Washington	1,158	38.3	38.9	18.6	4.3
West Virginia	954	68.6	25.9	5.0	.5
Wisconsin	2,727	40.1	41.3	15.1	3.6
Wyoming	1,477	47.9	40.7	7.6	3.8
Total or percentage	123,656	<---80.4--->		13.2	6.4

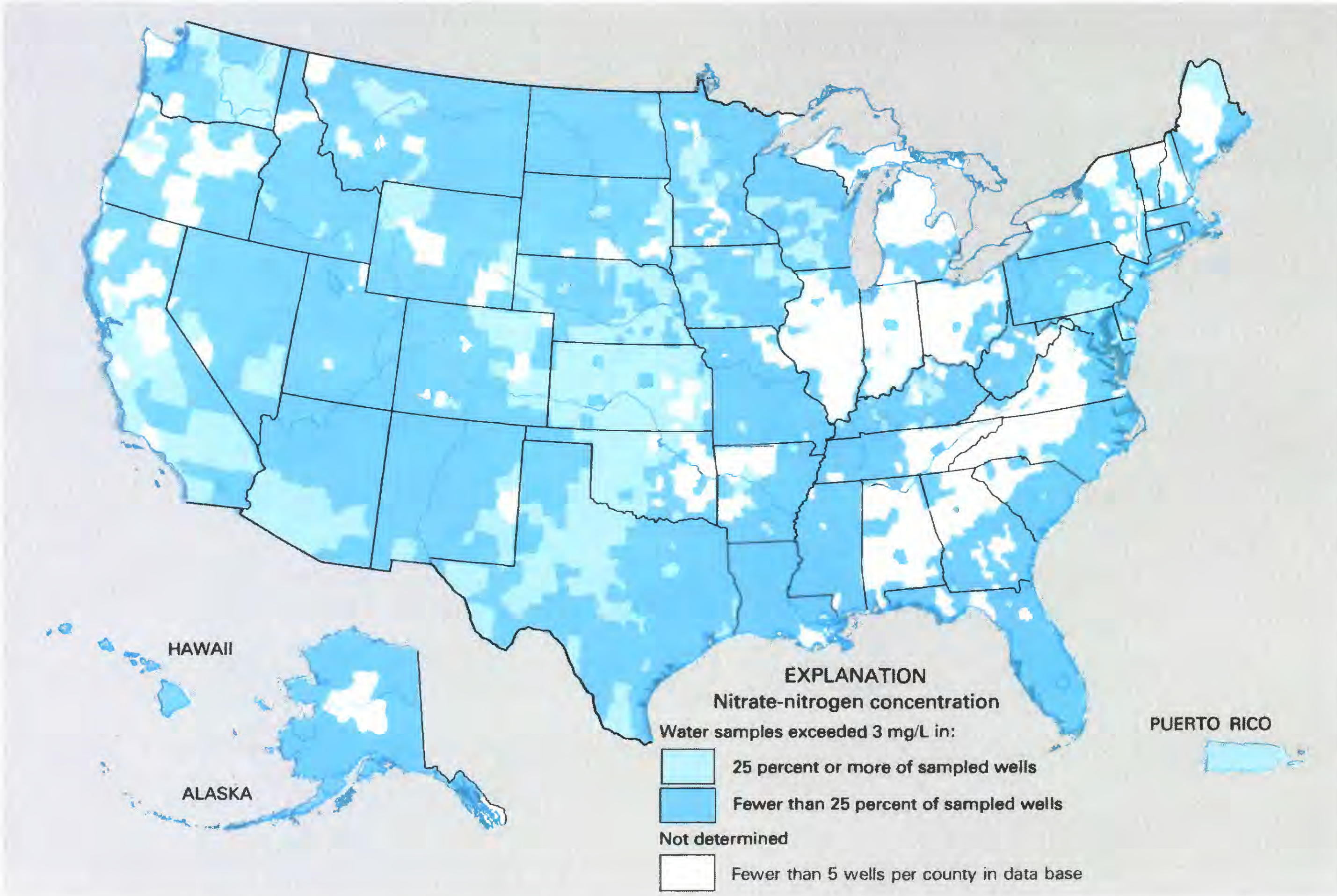

Figure 56. Nitrate-nitrogen distribution in ground water of the United States and Puerto Rico. Delineation is based on whether or not the concentration of nitrate-nitrogen in water exceeded 3 milligrams per liter (mg/L) in 25 percent of sampled wells in each county. The 3-mg/L concentration was selected for the purpose of the 1984 *National Water Summary* as the approximate concentration beyond which human activities could be contributing nitrogenous compounds to the ground water. It should be noted that concentrations of 3 mg/L or more also can occur naturally, especially in the semiarid West. In most of the area shown on the map, water with less than 3 mg/L nitrate-nitrogen may be available from different parts of the same aquifer. The data represent samples collected and analyzed over the past 25 years. See table 8 for number of wells sampled in each State and text for additional interpretation of map data. (Data were compiled by R. J. Madison and J. O. Brunett from U.S. Geological Survey and Texas Department of Water Resources data.)

and natural-nitrate influences. Because most nitrate sources are at the land surface or in the soil column, it would be expected that shallow aquifers would be more susceptible to contamination than deeper aquifers. Nitrate contamination of deeper ground water can occur, however, where a hydraulic connection and downward hydraulic gradient exist between shallow and deep aquifers and where sufficient time has elapsed for the contaminants from shallow sources to migrate to the deeper zones (Perlmutter and Koch, 1972, p. B22).

MAJOR SOURCES OF ELEVATED NITRATE CONCENTRATIONS

The major sources of potential nitrate contamination include septic systems, agricultural activities (fertilizers, irrigation, dryland farming, and livestock wastes), land disposal of wastes, industrial wastes, and a variety of natural sources. These sources are summarized below, and specific case studies are used to illustrate the present extent and possible regional significance of elevated nitrate concentrations.

Septic System Discharges

Septic tanks and shallow drain fields are the principal method for the disposal of domestic wastes from about 25 percent of the year-round housing units in the United States (U.S. Bureau of the Census, 1982, p. 754). The estimated nitrogen content of wastes delivered annually to septic tanks is about 6 percent of the total nonpoint-nitrogen-pollution load (National Research Council, 1978, p. 263). The effluent from a typical septic tank may contain

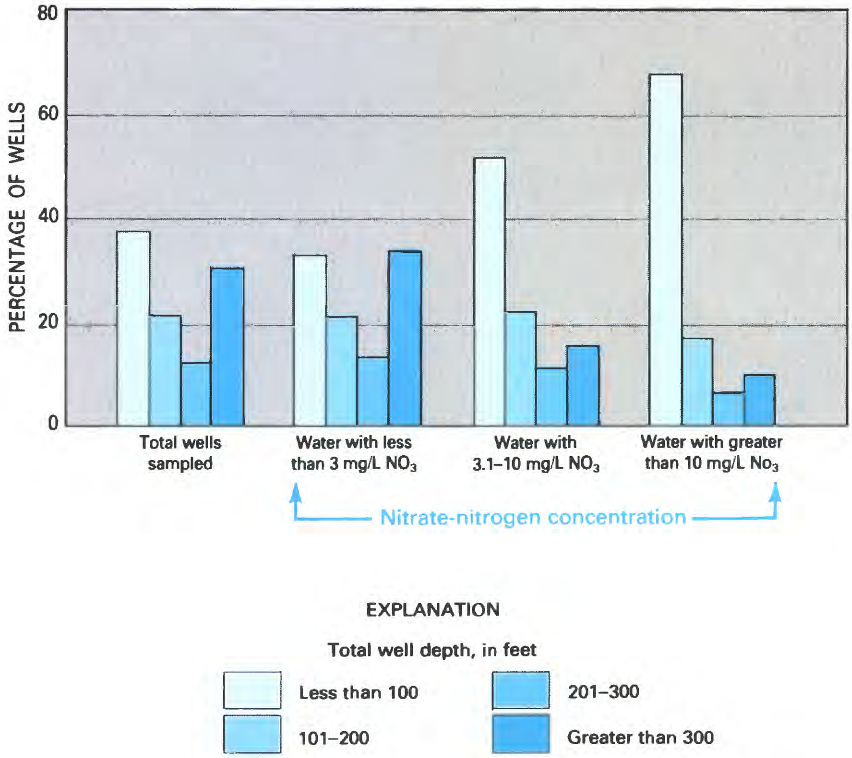

Figure 57. Distribution of three ranges of nitrate-nitrogen concentrations (milligrams per liter) in well water with well depth. About 124,000 wells were included in analysis. (Source: Compiled by R. J. Madison and J. O. Brunett from U.S. Geological Survey and Texas Department of Water Resources data.)

as much as 70 mg/L nitrogen, primarily in the form of ammonia and organic nitrogen, which is nitrified and moves into the ground water as nitrate.

Local nitrate contamination, such as that caused by effluent from a single disposal system entering a well in the immediate vicinity, can occur almost anywhere. More extensive problems occur in urban or suburban areas where a high density of individual septic systems contributes large quantities of wastes, with the potential to contaminate large parts of water-supply aquifers.

Discharge from septic tanks was identified as one of the more prevalent sources of ground-water contamination and elevated nitrate concentrations in the Northeastern United States (Miller and others, 1974). In the 11 States reported on in that study, 12 million people (23 percent of the total population) used septic systems that discharged as much as 0.5 to 1 billion gallons per day (bgd) of raw sewage to the subsurface. In addition to describing several regional ground-water quality problems, the report stated that cases of contamination from individual onsite disposal systems probably number in the thousands.

Several comprehensive studies of the effects of individual sewage-disposal systems on ground-water quality have been carried out on Long Island, N.Y. (Perlmutter and Koch, 1972; Katz and others, 1980; Porter, 1980). Perlmutter and Koch (1972, p. B225–B235) concluded that the two main sources of nitrate contamination of the aquifers in southern Nassau County were sewage from several hundred thousand active or abandoned septic systems and leachate from chemical fertilizers. Nitrate-nitrogen in ground water in many parts of the study area approached or exceeded the drinking water limit of 10 mg/L. Nitrate-nitrogen concentrations in the upper aquifer, based on 200 randomly located wells, averaged about 6.3 mg/L and, in several places, exceeded 22.5 mg/L. A major concern was that water from the upper aquifer had moved downward into the underlying Magothy aquifer, forming a body of nitrogen-enriched water that occupied nearly the full thickness of the aquifer in parts of the study area. The Magothy aquifer is a principal source of public water-supply wells. During the period from 1952 to 1969, 72 of 234 public-supply wells for which long-term records are available showed statistically significant increases in nitrate concentration. Perlmutter and Koch concluded that if the trend present in 1969 continues, the nitrate concentration of water from 40 to 50 public-supply wells may exceed the 10 mg/L drinking water limit within the next 50 years. From a comparison of sewered and unsewered areas, they also concluded that improvement in the quality of chemically deteriorated ground water after construction of sanitary sewers is a slow process. Several decades may be required for effective natural dilution and discharge of most of the residual nitrate. Other areas where regional problems from septic systems have been reported include the Boston, Mass., suburban area, Los Angeles, Calif., Dade County, Fla., and the States of Delaware and Connecticut (Miller, 1980, p. 196–198).

Agricultural Activities

Agricultural activities are the largest non-point sources of elevated nitrate concentrations in ground water. Nitrate in ground water under agricultural land results from a variety of land use practices and can originate from several sources. A search of the scientific publications revealed reports of investigations of nitrate contamination from agricultural activities for almost every State in the country.

Fertilizers

The use of chemical fertilizers has grown rapidly in the United States since the end of World War II. During the period from 1950 to 1970, fertilizer use in the United States doubled, from 20 million to 40 million tons per year (Miller, 1980, p. 431). During this same period, the percentage of nitrogen in all fertilizers used increased from 6.1 to 20.4 percent. The two areas of greatest fertilizer use in the United States are the Corn Belt (Iowa, Illinois, Indiana, and parts of adjacent States) and the Central Valley of California.

The application of nitrogen fertilizers does not necessarily cause an increase in nitrate levels in ground water. However, in many places, the amounts applied exceed that required by crops; this excess is available to be leached by natural precipitation or irrigation water. The actual amount of nitrate leached also depends on the types of crops grown; shallow-rooted crops such as potatoes require much heavier fertilization than do deep-rooted crops such as corn and must be irrigated more heavily.

Saffigna and Keeney (1977) evaluated the nitrate and chloride concentration of ground water in a 650-square-mile (mi^2) area of the central Wisconsin sand plains where about 25 percent of the irrigated cropland is planted in potatoes. Nitrate-nitrogen concentrations of ground water ranging from 4 to 23 mg/L were reported in the areas of cultivation, considerably above the values for well waters sampled in uncultivated areas. About 40 percent of the well waters sampled during this study had nitrate-nitrogen concentrations exceeding 10 mg/L. Measured chloride-nitrate ratios were relatively constant for all wells, suggesting that much of the nitrogen and chloride input to the ground water was from nitrogen and potassium (potassium chloride) fertilizers.

Ground water beneath large areas of the Central Platte region of Nebraska reportedly had nitrate concentrations greater than the drinking water limit. Gormly and Spalding (1979, p. 291) reported that 183 of 256 ground-water samples collected from parts of Buffalo, Hall, and Merrick Counties during 1976 and 1977 contained nitrate-nitrogen in excess of 10 mg/L. The authors concluded, on the basis of measured nitrogen-isotope values, that the primary source of contamination in most well waters was fertilizer. In various other surveys in Nebraska, 4,350 wells were sampled, 700 of which yielded water containing nitrogen concentrations in excess of 10 mg/L. Eighty-two percent of the contaminated wells were affected by nonpoint sources, such as nitrogen fertilizer contained in irrigation return flow (Pye and others, 1983, p. 140).

Irrigated Agriculture

The use of irrigation water to expand crop production has increased substantially in the last century. In 1890, about 4 million acres were irrigated. By 1980, 58 million acres were irrigated (Solley and others, 1983, p. 16). As irrigation water moves through the soil profile, residual nitrate is leached. Because the permeable soils that commonly are irrigated have high leaching rates and high nitrification rates, nitrate leaching can be a serious problem for many irrigated soils. As mentioned above, the source of the nitrate leached can be applied fertilizers. Naturally accumulated soil nitrate may be an equally important source, however, especially in the West.

Although irrigation usage has been increasing in the Eastern United States, most of the irrigated land is still in the West; for example, in the Northeastern United States less than 1 percent of total cropland is irrigated (Solley and others, 1983, p. 18). According to a summary of ground-water contamination in the Northeast, ground-water-quality problems resulting from irrigation practices are not as prevalent as those related to the application of fertilizers (Miller and others, 1974, p. 252).

In many parts of the arid West, the soils are highly saline and not conducive to crop growth. To leach out unwanted salts and thus maintain soil salinity at tolerable levels for crop production, water applications must exceed plant requirements. The amount of irrigation water reaching the subsurface commonly is estimated to be 20 to 40 percent of the applied water. Where natural soil nitrogen has accumulated or where large amounts of fertilizer are applied, nitrate leaching can and does occur.

California has the greatest percentage of cultivated land under irrigation in the United States; approximately 17 percent of the national total (Solley and others, 1983, p. 18). The impact of irrigated agriculture on nitrate levels in ground water has been studied extensively in that State, especially in the Central Valley region. Hull and others (1985) found well waters with elevated nitrate concentrations throughout the Sacramento Valley, which comprises the northern one-third of the Central Valley. They analyzed data from about 700 wells covering the period from 1912 to 1978. Under natural conditions, the maximum nitrate-nitrogen concentration in well water was about 3 mg/L. They defined nitrate-nitrogen concentrations greater than 5.5 mg/L as "excessive," which indicated contamination due to human activities. The percentage of wells with nitrate-nitrogen concentrations greater than 5.5 mg/L increased from 2.2 percent between 1912 and 1913 to 4.9 percent for the decade, 1960 to 1969. The long-term increase accelerated sharply from 1974 to 1978, when 10.5 percent of 671 wells sampled had nitrate-nitrogen concentrations exceeding 5.5 mg/L. Based on statistical analysis of 62 wells with long-term records, the authors concluded that water in nearly one-third of the wells in the Sacramento

Valley may be undergoing a significant increase in nitrate concentrations.

Except for urban areas in the Sacramento Valley, where the disposal of sewage wastes contributes to high nitrate concentrations, Hull and others (1985) found the major source of excessive nitrate in ground water throughout the Valley to be the leaching of fertilizers by irrigation water, primarily in orchard areas. The major physical factors contributing to the presence of excessive nitrate were good vertical flow in the soil profile, irrigation water derived primarily from ground-water pumping, and a water table that is moderately deep (more than 10 feet). Based on these factors, the areas identified as being susceptible to nitrate contamination cover roughly one-third of the Sacramento Valley. In the southern end of the Central Valley, especially in the San Joaquin Valley, the problem of high nitrate in irrigation drainage waters has prompted several intensive studies to determine the source of nitrate and methods of removing it (Federal Water Quality Administration, 1969).

Dryland Farming

Dryland farming, especially in the Northern Great Plains, can lead to nitrate contamination on a regional level. The crop-fallow rotation system of farming has reduced evapotranspiration, allowing excess moisture to move down through the soil profile beneath the root zone. The region is underlain by geologic formations deposited in a marine environment, and the subsoil has a large supply of natural soluble salts, including nitrate.

The shallow ground-water system is underlain in many areas by poorly permeable shale. In the overlying glacial till above the shale, the percolating water forms a mound and moves downslope. As the ground water migrates from upland recharge areas to nearby discharge areas, it leaches the soluble salts and can accumulate large quantities of dissolved solids in relatively short distances. The ground water eventually discharges at some stream channel or depression as a seep. The discharge water commonly has a dissolved-solids concentration in excess of 25,000 mg/L (Miller, 1980, p. 431). Significant concentrations of trace metals as well as high nitrate levels have been found in ground water in seep-prone areas, and nitrate poisoning of livestock from salinized ponds has been reported in a number of areas (Miller and Bergantino, 1983). Seep-affected areas in Montana cover more than 200,000 acres; however, no reports were found that deal directly with nitrate contamination of ground water from these areas. The areas of saline seeps mapped by Miller and Bergantino (1983, p. 2) coincide closely with the areas of elevated nitrate concentrations shown in figure 56. The leaching of natural soil nitrate after dryland farming also has been identified as one cause of excessive nitrate contamination of the ground water in Runnels County, Tex. (Kreitler and Jones, 1975, p. 53).

Livestock and Poultry Wastes

An increasing population and consequent increase in demands for meat and poultry products have resulted in a trend toward confined feeding of livestock. The largest areas of cattle feedlot operations are in southern California and Arizona, the Texas-Oklahoma Panhandles, the central Corn Belt, and from eastern Colorado through Nebraska to the North Dakota State line (National Research Council, 1978, p. 253). The major poultry-raising regions are in the Southern States and in the Delaware-Maryland area. In 1975, approximately 10 million cattle were fed in operations with more than a 1,000-head capacity (Miller, 1980, p. 390). The National Research Council (1972, p. 20) estimated that animal wastes containing 6 million tons of nitrogen are produced annually in the United States. In Delaware, one of the largest poultry-producing areas, about 140 million chickens are raised annually. The amount of waste they produce is estimated to be greater than the amount of solid waste produced by New York City (Liebhardt, 1972, p. 1).

Miller (1980, p. 389) listed several primary mechanisms of ground-water contamination from animal feedlots and their associated treatment and disposal facilities: runoff and infiltration from the feedlots themselves, runoff and infiltration from waste products collected and disposed of on land, and seepage or infiltration through the bottoms of waste lagoons. The rate of nitrate percolation to the ground-water table will depend on the quantity of nitrate formed, the hydraulic conductivity of the soil, and the amount of denitrification that takes place. Active feedlots reportedly have relatively low infiltration rates because of the puddled condition of the soil, but, when the feedlot is taken out of use, the soil surface dries, nitrification is rapid, and significant leaching and downward percolation of nitrate may occur. Rapid leaching and infiltration also can occur when feedlots are established on coarse-textured soil or if manure is removed frequently.

Because confined feeding of livestock is a relatively new practice, few case histories of actual contamination of ground water are available. Stewart and others (1968) evaluated ammonium and nitrate concentrations in ground water under feedlots and adjacent irrigated fields in Colorado and concluded that the feedlots were a significant source of nitrate and ammonium in the ground waters. Mink and others (1976, p. 415) in a study of the land disposal of animal waste in the Boise Valley, Idaho, found that, due to denitrification, nitrate-nitrogen concentrations in the soil profile beneath two feedlots decreased rapidly from about 60 mg/L near the surface to 20 mg/L at the 6- to 7-ft depth. Where ground-water levels were less than 5 ft from the surface, the water was found to be affected by the feedlot.

In a survey of high-nitrate ground water in Missouri, Keller and Smith (1967) analyzed water from more than 5,000 wells and springs. About 42 percent of the samples (12–75 percent for individual counties) contained more than 5 mg/L nitrate-nitrogen. They found the dominant source of nitrate in Missouri ground water to be nitrogenous waste from livestock feedlots.

Chicken farms can present special problems because of the high concentration of nitrogen in the waste. Data from more than 800 well samples collected during a study of ground-water quality in Sussex County, Del., where millions of broilers are raised annually, revealed that the shallow water-table aquifer contains excessively high concentrations of nitrate in several areas (Robertson, 1979). More than 20 percent of the wells sampled yielded water that exceeded the drinking water limit of 10 mg/L. The greatest incidence of high nitrate concentrations was associated with confined poultry-feeding operations. The average nitrate-nitrogen concentration in ground water sampled at chicken farms was 14 mg/L.

Land Disposal of Municipal Wastes

In 1972, 571 communities in the United States with a total population of 6.6 million used land-disposal methods for municipal effluents. Most were crop-irrigation systems located in the arid Southwest and in the East primarily in North and South Carolina (National Research Council, 1978, p. 259). Also, many municipalities in the West discharge effluents to infiltration basins in dry river beds. If the rates of application exceed the rate at which the soil or plants can assimilate nitrogenous compounds, nitrate contamination is a risk. Miller (1980, p. 230) estimated that approximately 2.3 bgd of effluent, some of which has received only primary treatment, is discharged onto the land.

In a report on ground-water contamination in Arizona, California, Nevada, and Utah, Fuhriman and Barton (1971, p. 105) reported ground-water pollution problems in the vicinity of several municipal disposal facilities. In the Santa Cruz and Salt-Gila River basins of Arizona, waste water has been discharged to ephemeral stream channels or used for irrigation for many years. The possibility of ground-water contamination from these disposal practices created a need for several monitoring programs to evaluate and trace the movement of the effluent (Schultz and others, 1976, p. 463). Nitrate-nitrogen concentrations in excess of 10 mg/L and as high as 28 mg/L were found in water from many wells. Maps of the water-quality data indicated that the ground-water areas with the highest chloride and nitrate concentrations tended to be associated with areas irrigated with sewage effluent.

Because of a paucity of available data or reports, the actual local and regional extent of ground-water contamination that has occurred as the result of the land disposal of municipal wastes is difficult to evaluate. If the wastes receive effective secondary treatment before disposal, the potential for water-quality degradation, with the exception of nitrate contamination, probably is minimal (Miller, 1980, p. 227). Existing Federal and State regulations require that effluents discharged to land not degrade ground-water quality below nonpotable conditions. Where these regulations are followed or enforced, problems probably will not occur. However, Miller (1980, p. 230) concluded that only a part of the 2.3 bgd of effluent applied to the land has received primary treatment or less-than-effective secondary treatment.

Industrial Wastes

Although the contribution of nitrate to ground-water systems from industrial wastes is minimal compared to nonpoint sources such as agriculture, local impacts can be severe. The industrial process with the greatest potential for producing nitrogenous wastes is the synthesis of ammonia which is then used to produce other nitrogenous products such as fertilizers, nitric acid, urea, and paper products. Ammonia-nitrogen concentrations of more than 200 mg/L can occur in the waste streams of a typical ammonium-nitrate fertilizer plant (National Research Council, 1978, p. 270–273), and it has been estimated that a pulp mill with a capacity of 100 tons per day could produce wastes equivalent to the nitrogen load in the sewage from a city of more than 100,000 people.

An example of the severity of contamination that can occur in the vicinity of fertilizer plants is shown in a study by Naymik and Barcelona (1981). Chemical constituents leached from an uncovered chemical fertilizer bin at a plant in Illinois were drawn into the cone of depression of production wells and thus contaminated the underlying aquifer. The ground water in the interior of the contaminated plume had ammonia concentrations as high as 2,100 mg/L and nitrate-nitrogen concentrations greater than 1,800 mg/L. As the plume moved downgradient, most of the ammonia was oxidized to nitrate rather than being lost by volatilization. This particular event involved a nitrate source not directly related to wastes from the production facility, but it does point out the potential for localized pollution where large quantities of nitrogenous materials are produced or concentrated.

NATURAL SOURCES

In addition to soil nitrogen, the major potential sources of natural nitrate in ground water are the accumulation of nitrate in caves (from bat guano and nitrogen-fixing bacteria) and in playas. Cave deposits have been reported in Indiana, Kentucky, Virginia, and Missouri (Viets and Hageman, 1971, p. 8), but their contribution to nitrate in ground water has not been well documented. The source that may be of most regional significance is the natural accumulation of nitrate by evaporation during the formation of playas in alluvial valleys in arid and semiarid parts of the country. This accumulation of nitrate in playas, along with high concentration of other dissolved salts, has been found in most of the drier parts of the Western States.

In most areas unaffected by human activities, playas probably do not contribute a large amount of nitrate to the ground water. Playas occur in areas where precipitation is low, surface drainage is impeded, and the land surface is underlain by materials that retard the downward movement of water. However, where conditions have been altered, such as the burial of ancient playa deposits, so that they are now in the zone of saturation, high nitrate ground water can result (Feth, 1966, p. 46). The occurrence or severity of elevated nitrate in ground water resulting from these natural deposits is difficult to evaluate. They have been postulated as a source of high nitrate in several studies, but their relative impact is difficult to assess because human sources also generally are present in the same areas.

A recent investigation of ground-water quality in Paradise Valley, Ariz., indicated that high nitrate levels within specific areas of the valley may be of natural origin (Silver and Fielden, 1980, p. 244). Historical records indicate that nitrate-rich ground water (more than 100 mg/L nitrogen) occurred in the early 1900's before extensive development of the area. Moreover, high nitrate levels were found in ground water from fine-grained strata at depths as much as 1,000 ft, probably too deep to be affected by modern human activities. One possible source may have been ammonium chloride leached from volcanic tuffs in the nearby Superstition Mountains, subsequently oxidized to nitrate, and deposited in abandoned channels of an ancient braided-stream complex.

Ground water with naturally occurring high nitrate concentrations also has been identified in the Great Plains area of southern Alberta, Canada, just north of Montana. Hendry and others (1984, p. 185) found nitrate-nitrogen concentrations exceeding 300 mg/L in ground water from isolated enclaves below the water table in weathered glacial till. Cultivation of native soil (as discussed earlier for Montana) was not considered a reason for these high nitrate values. Through geochemical studies, environmental isotope studies, microbial analyses, and laboratory experiments, they showed that the high nitrate is the result of the oxidation of ammonium present within the tills. It is postulated that the oxidation occurred when water tables were much lower than present-day levels.

Naturally occurring nitrate, either in geologic deposits or in soils, existed in a general equilibrium with soil water and underlying ground water before human development. However, the potential for leaching and downward migration of natural nitrates with significant contamination of ground water, is considerable in some areas as the land is disturbed or as land use practices change. Research into the relation between fertilizer use and water quality in Nebraska has resulted in the discovery of large quantities of naturally occurring nitrate within the deep loess mantle of the southwestern and central parts of the State (Boyce and others, 1976, p. 93). The loess region includes more than 9,000 mi^2, and the authors estimated that several million tons of nitrate in the loess is vulnerable to leaching. Data from soil cores in areas that previously had been irrigated showed that the nitrate had been leached. Because irrigation is expanding rapidly in the region, the potential for increased leaching and downward migration of nitrate from the soil, with resultant nitrate contamination of aquifers, is of concern.

PRESENT KNOWLEDGE AND FUTURE TRENDS

The examples discussed above of increased nitrate levels in ground water and their potential sources are but a few of the many cases reported in the hydrologic literature. In almost all cases, investigators have documented site-specific instances of ground-water contamination and have postulated sources. At the present time, few data are available to quantify the amounts of nitrate contributed by a particular source, even at site-specific locations.

A comprehensive review of nitrate in the environment, published by the National Research Council in 1978, contains detailed and well-documented evaluations of the present knowledge of the sources, transport, and fate of nitrate in air, water, and soil. The authors of that review concluded that the general qualitative relations between inputs, such as nitrogen fertilizer application rates, and crop yields are well known. However, the growth of a crop in a given location and the efficiency of its use of available nitrogen depend on soil properties, weather, climate, and cultivation and management practices. The interaction of these factors makes it difficult to predict how much nitrogen fertilizer a given crop needs at a given location or to determine the amount of residual nitrogen lost to the environment. The Council also concluded that, even at intensively studied sites, the complexities of soil, water, and nitrogen cycles have frustrated attempts to determine the quantitative contributions of specific sources of nitrate pollution. In an analysis of nitrogen-mass-balance models for two watersheds and for two statewide models, the Council found that a lack of adequate data, especially on nitrogen-cycle processes and leaching to the substrata was a major constraint to predictive modeling. Furthermore, soil characteristics, climatic factors, and agricultural practices are so heterogeneous that no quantitative general conclusions about the regional impact on water quality of a single factor, such as fertilizer application, could be supported.

Current trends suggest that nitrate accumulations in ground water of the United States will continue to increase in the future. Several investigators have used historical data to document increasing nitrate levels in shallow aquifer systems. McDonald and Splinter (1982, p. 439), for example, evaluated data from 4,597 water samples from municipal ground-water supplies from all parts of Iowa. They showed that nitrate levels in ground water from wells less than 100 ft deep increased slowly, but steadily, between 1950 and 1979. Agricultural activities (including the disposal of animal wastes) and the disposal of human wastes are the two largest sources of nitrate contamination of ground water throughout the United States. Agricultural activities will increase as population increases and, thus, the potential for a continuation of these trends is present. Although future septic system discharges may decrease with increasing urbanization and the construction of public sewer systems, the nitrate accumulated in the soil may be available for leaching for a significant period of time. In addition, natural dilution and discharge of human-induced nitrate in the affected ground water may take several decades (Perlmutter and Koch, 1972, p. 235).

Although elevated concentrations of nitrate are now most noticeable at shallow depths, long-term increases of nitrate levels in deeper wells are a possibility where the deeper aquifers are recharged by nitrogen-rich water from the shallow aquifers. The movement of drainage water through the unsaturated zone of many soils can be very slow, and the time required for present inputs of nitrogen to reach the ground-water reservoir may be many years. Because of this slow movement of recharge waters, contamination of deeper wells could continue for long periods, even if input sources of nitrogen decrease or are eliminated.

At the present time, situations in which contaminated drinking water is the chief source of ingested nitrate generally are localized and the total population likely to be affected by nitrate-enriched water supplies probably is small (National Research Council, 1978, p. 598). However, the major human inputs of nitrate have occurred over the last 40 to 50 years. This is a short period of time in terms of ground-water movement in some aquifers, and one must consider that the total effects of existing inputs may not yet have occurred in many areas.

TECHNIQUES FOR CONTROL

The severity of future environmental impacts from nitrate accumulation in ground water will depend to a great extent on the development of cost-effective methodologies either to control the input sources of nitrates or to collect and treat wastes before they are discharged. Advanced treatment systems presently are available that can remove most of the nitrate and other nitrogen species from waste waters. However, they are costly, and their economic feasibility for treating large volumes of waste water has not been proved.

Several cropland-management practices can reduce the amount of nitrate leaving the root zone and, thus, the amount available for leaching to the ground water. These include:

- Controlling use of irrigation water so that the amount of water applied is the minimum that is consistent with efficient crop production;
- Rotating crops that require high fertilization rates with those that require little fertilization or those that can utilize residual nitrogen from previous plantings;

- Adjusting the amount and timing of fertilizer applications to match the nitrogen uptake of plants and, thus, minimize the leaching and migration of fertilizer products below the root zone; and
- Using fertilizers that contain nitrification inhibitors, which reduce the rate of conversion of ammonia in fertilizers to nitrate.

Although a range of techniques is available for the control of specific nitrate problems, their long-term effectiveness is difficult to predict. Control measures that limit or reduce nitrate in one part of the nitrogen cycle may increase it in another; for example, treatment processes that remove nitrate from waste waters also have the potential for increasing the release of ammonia or nitrous oxide to the atmosphere. Commonly, the scientific data are inadequate for defining accurate relations among specific nitrate sources, best management or treatment practices, and their associated environmental or economic impacts. Many of the source-control techniques for nitrate-related problems, especially for agriculture lands, are cost- or labor-intensive. Moreover, agricultural practices today require large inputs of energy and capital with relatively low returns. Given these scientific and economic constraints, the reduction of nitrate concentrations in ground waters under intensively irrigated and fertilized croplands to levels compatible with drinking-water criterion may be difficult to achieve.

Additional research is needed before an accurate determination can be made of the ultimate health risks involved on a national scale or the most feasible methods of controlling nitrate contamination of ground water. Important areas of research related to water-quality impacts of human manipulation of the nitrogen cycle have been summarized in considerable detail by the National Research Council (1978, p. 721) and by Schaller and Bailey (1983, p. 455). Research needs relative to ground-water nitrate problems include:

- Site-specific (as opposed to State or regional) information on crop-yield response to nitrogen fertilizers under varying management conditions and weather patterns;
- More precise data on actual rates of nitrogen fertilizer consumption at the watershed level;
- Additional studies of the fate of nitrogenous compounds in soils based on actual field conditions;
- More precise information on the effectiveness and the economic and social impact of various best management practices to control potential nitrate pollution;
- Better information on the long-term influences of changing land use patterns on the transport of nitrogen into subsurface and ground waters;
- Improved models of the rate of movement, fate, and storage of nitrogen in managed ecosystems on local and regional scales;
- Further evaluation of the health hazards posed by nitrate in water; and
- Design of alternative, regionally specific control strategies.

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Water-Availability Issues

GROUND-WATER-LEVEL CHANGES IN FIVE AREAS OF THE UNITED STATES

By Larry J. Mann

An assessment of State water issues in the 1983 *National Water Summary* (U.S. Geological Survey, 1984) revealed that ground-water availability is a significant issue in almost every State. The development of the ground-water resources has led to declining ground-water levels in a number of areas of the country. Such declines may lead to streamflow depletion, land subsidence, saltwater intrusion, and increased pumping costs for water producers.

Under natural conditions, ground water moves from areas of recharge to areas of discharge. The water may be discharged to springs or streams, lost to the atmosphere by evapotranspiration, or directly discharged to the ocean in coastal areas. Generally, an equilibrium prevails in which the long-term recharge of the ground-water system is balanced by the long-term discharge from it.

Ground-water levels in an aquifer fluctuate in response to changes in the rate of recharge and discharge. When recharge exceeds discharge, water accumulates in storage and water levels rise. When discharge exceeds recharge, water is released from storage, and water levels fall. The intergranular pores, fractures, or solution openings in an unconfined aquifer are saturated with water below a free surface, termed the water table. The water table rises or falls as the volume of water in storage changes. In a confined or artesian aquifer, water completely fills the pores, fractures, and solution openings within the aquifer and is confined under pressure by an overlying confined bed of low hydraulic conductivity. Changes in storage occur through elastic expansion and contraction of the porous material and of the water in response to changes in pressure and, in some instances, through the inelastic compaction of fine-grained sediments with associated subsidence of the land surface. The water level in an artesian well stands above the top of the aquifer and, in some instances, may stand above the land surface, so that the well will flow if left open. For equal changes in water level, the changes in the volume of water stored in confined aquifers are much smaller than those in unconfined aquifers.

Confining beds vary in their ability to retard water movement, and virtually all are capable of transmitting flow in response to a sufficient difference in water level. Those which transmit measurable flows are often termed semiconfining, or leaky confining, beds, and the associated water-bearing units are termed semiconfined aquifers. Their behavior generally falls between that described above for confined and unconfined aquifers.

Under natural conditions, the largest fluctuations in ground-water levels for unconfined aquifers are seasonal. Short-term fluctuations in confined aquifers commonly occur due to such factors as changes in barometric pressure. In aquifers where long-term recharge balances discharge, including well withdrawals, ground-water levels may fluctuate from a few feet to a few tens of feet from one season of high levels to the next. However, in ground-water aquifers where large withdrawals from wells have caused discharge to exceed recharge over long periods of time, net declines may amount to tens or even hundreds of feet. These year-to-year declines may stop or even be reversed if pumpage is reduced, so that discharge is equal to or less than recharge.

In the State-by-State summaries of ground-water resources, which occur later in this report, information on ground-water withdrawals also is included, and water-level declines in principal aquifers are discussed for some States. A number of areas of the United States exist, however, where ground-water level declines have been substantial (40 feet or more) in at least one aquifer since development began (fig. 58). The historical behavior of water levels in aquifers in five important areas of ground-water use in which such declines have occurred are described below. These areas, which are in California, Illinois, Louisiana, Virginia, and South Dakota, illustrate the range of hydrologic conditions and water-use practices that cause changes in water levels in several regions of the country and identify some related effects, such as land subsidence, that may cause problems for ground-water users. Another related effect is the increased cost of ground-

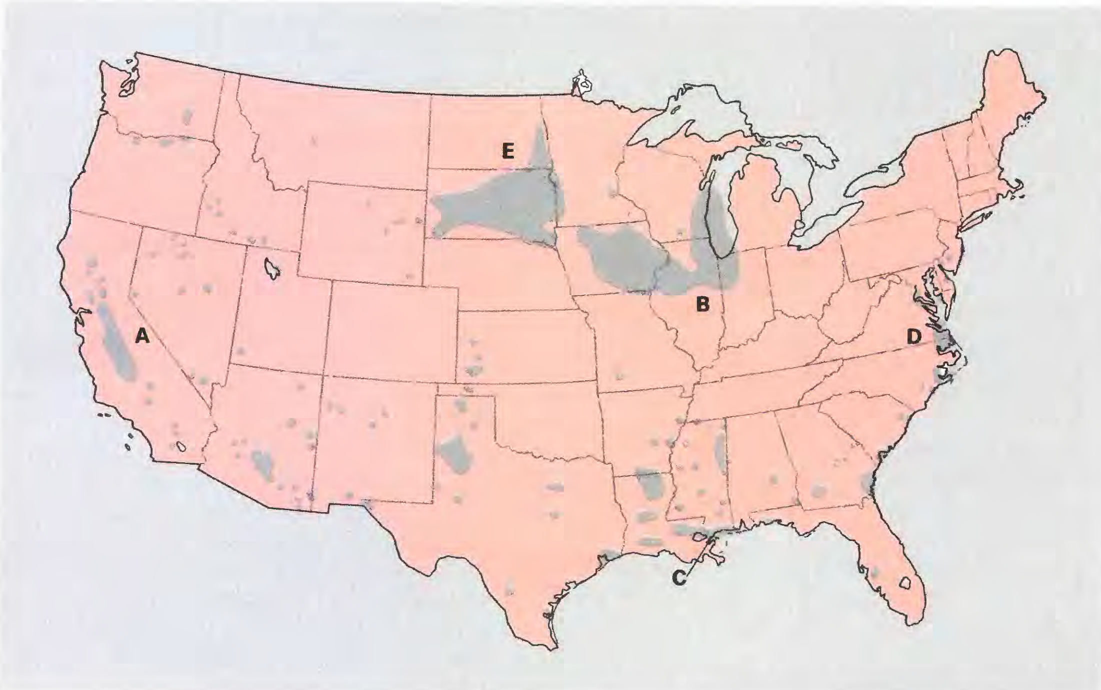


Figure 58. Areas of the conterminous United States where water-table decline or artesian water-level decline in excess of 40 feet in at least one aquifer has occurred since development began. Areas described in the text are San Joaquin Valley, Calif. (A), Chicago, Ill., area (B), Baton Rouge, La. (C), Franklin, Va., area (D), and the Dakota aquifer of South Dakota (E). (Source: U.S. Geological Survey, 1984, p. 40.)

water withdrawals as as result of increased energy prices and changes in water levels. A case study of this effect in Floyd County, Tex., completes the "Water-Availability Issues" section.

SAN JOAQUIN VALLEY, CALIFORNIA

The San Joaquin Valley (fig. 58) occupies the southern two-thirds of the Central Valley of California. It is a broad structural trough bounded by mountains in the west, east, and south and by the Sacramento-San Joaquin River Delta on the north. The valley is about 250 miles (mi) long and 25 to 55 mi wide and is underlain by unconsolidated sediments derived from erosion of the surrounding mountains. These sediments form a large alluvial basin aquifer.

The climate in the San Joaquin Valley is characterized by hot, dry summers and moderate, wet winters. The mean annual precipitation ranges from about 5 to 16 inches. The climate allows for a long growing season during which two or three crops commonly are harvested in some areas. Due to the favorable climate, fertile soils, and the availability of water for irrigation, the San Joaquin Valley has developed into one of the more productive agricultural areas in the world.

Significant development of ground-water resources to satisfy the need for irrigation water began in the early 1900's. As ground-water withdrawals increased to the point that discharge from the ground-water system exceeded recharge, perennial decline of water levels in the aquifer began. Water levels near Mendota, Calif., declined about 260 feet (ft) between 1940 and 1963 (fig. 59). The extraction of water in this part of the Central Valley resulted in the compaction of fine-grained sediments, which, in turn, caused subsidence of the land surface. During the period from 1940 to 1977, the area near Mendota subsided 29 ft (Ireland and others, 1984). By 1977, land subsidence in this area had ceased for the most part.

In response to the problem of declining water levels, rising pumping costs, and land subsidence, the Federal Central Valley Project and the California State Water Project developed a series of canals to bring surface water from northern California to the San Joaquin Valley. The Delta-Mendota Canal and the California aqueduct, major components of the two projects, began delivering water to the western part of the San Joaquin Valley, including the Mendota area, in the late 1960's. In 1968, when ground-water withdrawals were replaced by the surface water delivered by the aqueduct, the water level in the aquifer began to rise (fig. 59), although some land subsidence continued as a result of earlier withdrawals. By 1976, water levels had recovered about 200 ft, only to decline again in 1977 when California was struck by a 2-year drought. Old wells were reactivated, and new wells were drilled to meet the irrigation needs that the aqueduct could not provide. During this period of renewed pumpage, little or no renewal of compaction occurred. Thus, water was supplied largely from elastic storage release, rather than from com-

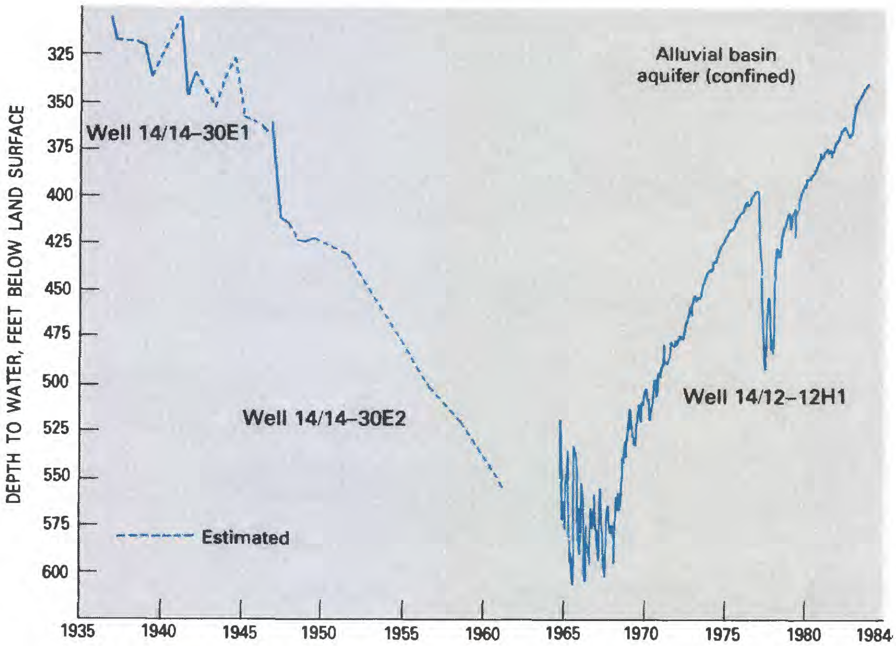


Figure 59. Water levels in three observation wells in an alluvial basin aquifer near Mendota, Calif., 1935 to 1983. (Source: Compiled by R. P. Fogelman from U.S. Geological Survey data.)

paction; as a result, water levels declined rapidly, falling nearly 100 ft during the drought. By the end of 1978, however, pumpage had decreased, and a rapid rise of water level had begun. Since the importation of surface water began, the total rise of water level has been nearly 240 ft in the western part of the San Joaquin Valley.

Ground-water withdrawals calculated for the period from 1961 to 1977 for the Mendota area, which is about 100 square miles (mi^2), show the dramatic reduction in withdrawals beginning in 1968 when imported surface water became available. As explained above, the increase in withdrawals in 1977 occurred as a result of the drought and resultant decrease in imported surface water. The relation between withdrawals and water-level decline and recovery can be seen by comparing the water withdrawals shown in the table below with the water levels shown in figure 59.

Annual withdrawals in the Mendota area, San Joaquin Valley, Calif., 1961 to 1977

[Source: Diamond and Williamson, 1983]

Year	Withdrawals (billion gallons per year)
1961	32.3
1962	31.6
1963	29.9
1964	30.9
1965	27.4
1966	31.0
1967	29.3
1968	9.7
1969	9.8
1970	7.6
1971	6.2
1972	4.0
1973	4.4
1974	3.7
1975	3.1
1976	3.1
1977	17.3

In the past few years, water levels have stabilized in the San Joaquin Valley and in some areas have risen, reflecting both the replacement of pumpage by surface water and the effects of above-average precipitation during the winters of 1981-82 and 1982-83.

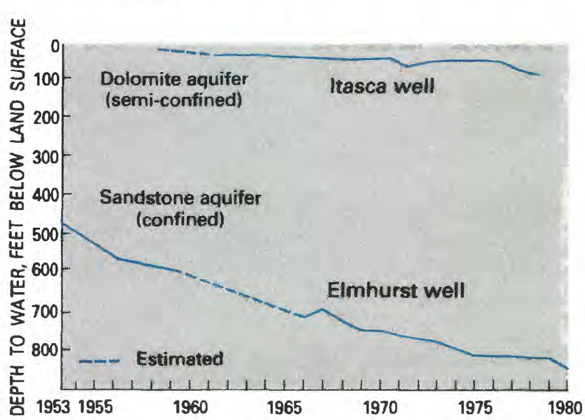
CHICAGO, ILLINOIS, AREA

In the Chicago, Ill., area (fig. 58), two aquifers supply most ground water—a deep sandstone aquifer, the Cambrian-Ordovician aquifer, in which ground water occurs under confined conditions, and a shallow dolomite aquifer in which conditions trend from unconfined to semiconfined with increasing depth. Water from both aquifers is used mainly for municipal supplies.

From 1864 to 1980, the six-county area of metropolitan Chicago had experienced water-level declines of more than 850 ft in the sandstone aquifer (Sasman and others, 1981). Ground-water levels in a well at Elmhurst, Ill., are characteristic of water-level trends in the deep sandstone aquifer (fig. 60). From 1953 to 1980, the water level declined about 370 ft in response to an increase in the annual withdrawal; for example, from 1959 to 1980, withdrawals increased from 10.7 million gallons per day (Mgal/d) to 20.6 Mgal/d.

Ground-water levels in a well at Itasca, Ill., are representative of water-level trends in the shallow dolomite aquifer (fig. 60). Water levels declined about 50 ft from 1958 to 1978. The dolomite aquifer, like the deep sandstone aquifer, has been intensively used for municipal water supply. From 1960 to 1979, the withdrawals increased from 0.40 to 5.3 Mgal/d. The water-level decline in the shallow aquifer, although much smaller than the decline in the deeper aquifer, has reduced the saturated thickness of the dolomite aquifer by 57 percent at

Figure 60. Water levels in observation wells in the sandstone aquifer at Elmhurst, Ill., and the dolomite aquifer at Itasca, Ill., 1953 to 1980. (Source: Compiled by M. G. Sherrill from U.S. Geological Survey data.)



Itasca, and the percentage may be much greater in more heavily pumped areas.

The amount of water-level decline in the semiconfined dolomite aquifer is much smaller per unit volume of water pumped than in the confined sandstone aquifer. For example, a 4.9-Mgal/d increase in withdrawals from the dolomite aquifer between 1960 and 1979 resulted in about 50 ft of water-level decline; however, an increase of nearly 10 Mgal/d from the sandstone aquifer between 1959 and 1980 resulted in about 250 ft of decline. Although the withdrawal from the sandstone aquifer was double that from the dolomite aquifer, the water-level decline was five times greater in the sandstone aquifer. The difference in the response of the two aquifers to a unit withdrawal of water reflects differences in storage properties, in water-transmitting properties, and in the influence of hydrologic boundaries.

No major land subsidence has been reported in the Chicago area as a result of the large ground-water withdrawals. This is because the rocks in the area are consolidated and resist compaction as water is withdrawn.

The declining water level in the Elmhurst, Ill., well that taps the sandstone aquifer is a source of concern to water users and managers in the Chicago area (Schicht and Moench, 1971). Artificial recharge of fresh water to the aquifer has been proposed as a solution, but reallocation of Lake Michigan water to replace part of the ground-water demand has been the principal management technique employed thus far.

BATON ROUGE, LOUISIANA

In the Baton Rouge, La., area (fig. 58), the "2,000-foot" sand is one of nine aquifers that occur at depths between about 400 and 2,800 ft below the land surface and is one of the principal sources of freshwater for local industry. The aquifer, which is confined by overlying silt and clay, ranges in thickness from 150 to 300 ft and its top is about 2,000 ft below the land surface. It extends at least 30 mi to the east, north, and west of Baton Rouge and is bounded on the south by the Baton Rouge fault, which inhibits water movement and is the southern limit of freshwater in the aquifer. Before 1940, withdrawals from the "2,000-foot" sand generally were less than 4 Mgal/d. By the early 1970's, however, withdrawals had increased to slightly more than 38 Mgal/d and, since 1974, have averaged about 37 Mgal/d.

Before development, water levels in this confined aquifer were reported to be as much as 60 ft above the land surface, but, by the late 1940's, they were 30 feet below the land surface (fig. 61). In about 1950, water levels began declining at a rate of about 10 feet per year (ft/yr). Development accelerated about 1965, and water levels declined at a rate of 15 to 25 ft/yr until 1973. At that time a combination of events, which included a business recession and the implementation of Government regulations concerning treatment of industrial effluents, caused a sharp cutback in industrial pumping. This resulted in the beginning of a general recovery of water levels (fig. 61). Although public-supply pumping in the Baton Rouge area continued to increase slowly, water-level recovery occurred in the aquifer in the industrial district. About 1981, water demand was reduced by industrial cutbacks resulting in additional water-level rises. Today (1984), seasonal water-level fluctuations caused by pumping are 10 to 40 ft at pumping centers and 1 to 5 ft in outlying areas; otherwise, levels generally are stabilized or are rising gradually.

Saltwater encroachment from the south in the "2,000-foot" sand as a result of the large

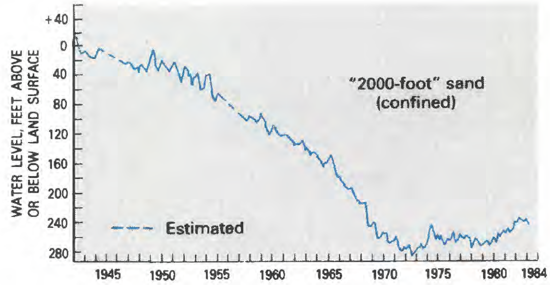


Figure 61. Water levels in an observation well in the "2,000-foot" sand in Baton Rouge, La., 1943 to 1983. (Source: Compiled by George Cardwell from U.S. Geological Survey data.)

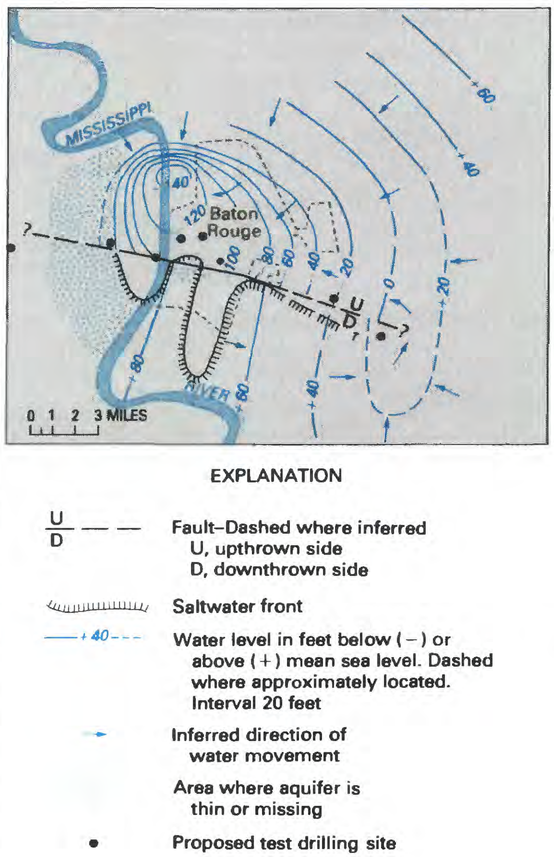


Figure 62. Saltwater front, water-level contours, and location of fault in the "2,000-foot" sand as determined during the 1965 test-drilling program in the Baton Rouge, La., area. (Source: Terry and others, 1979, p. N38.)

water-level declines is a major concern and has been monitored for about 20 years. Water-level differentials across the Baton Rouge fault zone near the industrial district pumping center are as much as 200 ft (fig. 62). The hydraulic conductivity of the fault zone is low, retarding the northward movement of saltwater (Whiteman, 1979; Torak and Whiteman, 1982); nevertheless, a small amount of saltwater apparently has leaked through the fault zone and may be moving slowly northward toward the pumping center (Terry and others, 1979, p. N36).

Land subsidence of about 1.3 ft has occurred locally in the Baton Rouge area as a result of pumpage from 1930 to 1940. Most of the early subsidence was attributed to decline in pressure in the shallower "400- and 600-foot" sands, but pressure declines in the deeper aquifers, especially the "2,000-foot" sand, are believed to have been a significant factor in later years. Instruments installed in 1975 to monitor compaction indicate that land subsidence has essentially halted coincidental with the rising water levels (Whiteman, 1980).

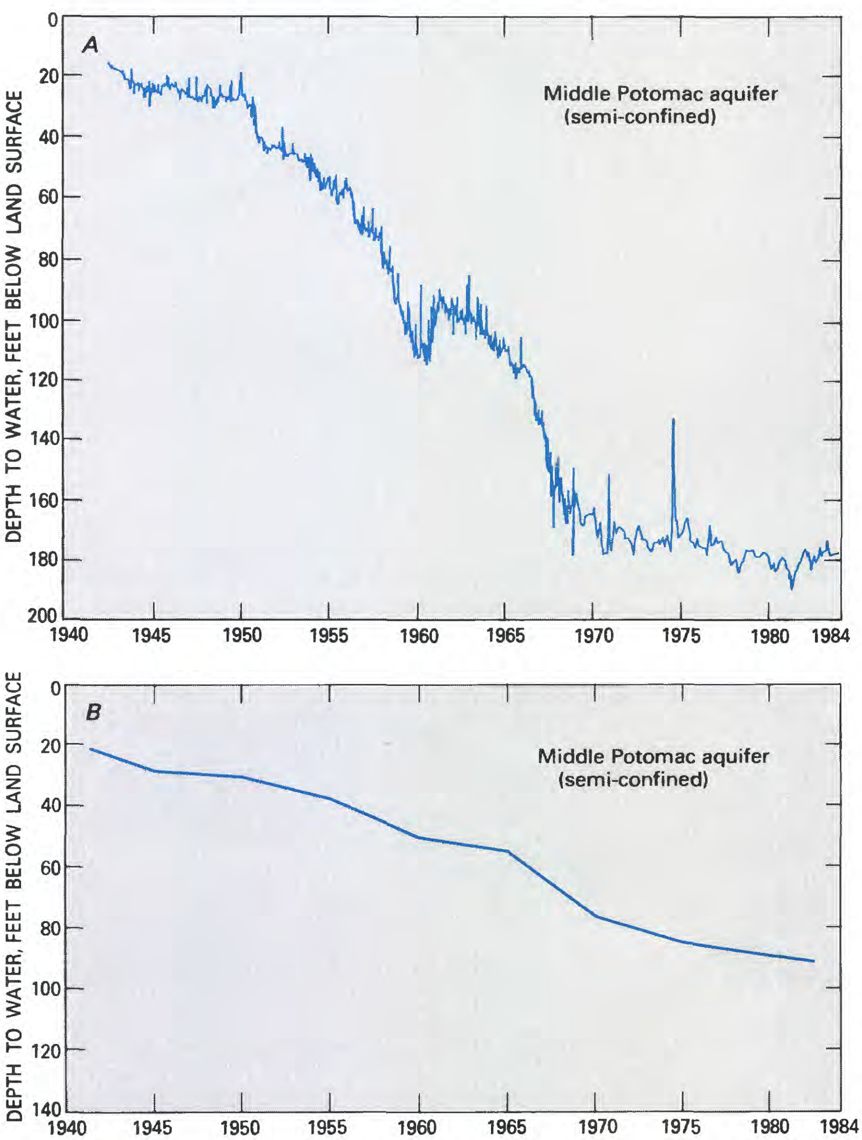


Figure 63. Water levels in observation wells in the middle Potomac aquifer, 1943 to 1984. *A*, Franklin, Va. *B*, Sebrell, Va. (Source: Compiled by J. F. Harsh from U.S. Geological Survey data.)

FRANKLIN, VIRGINIA, AREA

The most extensive and productive aquifers in the Virginia Coastal Plain are the lower, middle, and upper Potomac aquifers. The Potomac aquifers consist mainly of beds of sand locally separated by lenticular beds of silt and clay. The movement of water from one aquifer to another is impeded by the silt and clay beds, which locally confine the ground water in the beds of sand. The aquifers are part of a semiconfined, or leaky confined, multilayered aquifer system that extends from Long Island, N.Y., to South Carolina. The largest withdrawals of ground water from the lower and middle Potomac aquifers occur in the Franklin area of southeastern Virginia (fig. 58). Before the start of pumping, flowing wells were the source of water supply (Cederstrom, 1945). About 1940, water was beginning to be withdrawn from large-capacity industrial and municipal wells in the Franklin area. Withdrawals increased steadily until 1967 (fig. 63), but, since then, generally have stabilized. Withdrawals at present are about 41 Mgal/d compared to about 5 Mgal/d in 1940. These withdrawals have caused water levels in the aquifers to decline over an area of more than 5,000 mi^2 (Cosner, 1975). Hydrographs for observation wells show that the decline of water levels in the middle Potomac aquifer since the 1940's ranges from about 80 ft near the town of Sebrell to about 160 ft near Franklin (fig. 63).

Water-level declines in the middle Potomac aquifer are about 30 ft in the vicinity of the Atlantic coast. Declines of this magnitude could cause saltwater to move inland in the aquifer, perhaps threatening freshwater supplies. However, computed flow velocities for water in the coastal area suggest the landward movement of salty water could not exceed a few feet per hundred years (P. P. Leahy, U.S. Geological Survey, oral commun., August 1983).

In the lower and middle Potomac aquifers, water levels are not affected greatly by seasonal water-level changes in overlying aquifers because of the low hydraulic conductivity of overlying and intervening confining beds. Data collected since 1979 show that aquifer compaction due to the decline of water levels is only a few hundredths of a foot at present (H. T. Hopkins, U.S. Geological Survey, written commun., August 1983).

DAKOTA AQUIFER OF SOUTH DAKOTA

The Dakota aquifer (fig. 58), also referred to as the Dakota-Newcastle aquifer, is made up of water-yielding sandstones of the Dakota Formation. The Dakota Formation ranges in thickness from more than 400 ft in east-central and southeastern South Dakota to less than 40 ft near the northern Black Hills and in the northwest-central part of the State (Hedges, 1968; Schoon, 1971; Howells, 1982).

Water in the Dakota aquifer is confined except at the outcrop of the Dakota Formation near the Black Hills and possibly in the southeastern part of South Dakota. In much of the eastern one-half of the State and before extensive development began, water levels in wells drilled into the aquifer rose above the land surface. According to available records, ground-water development began in 1881, principally for irrigation, water power, and municipal supplies (Nettleton, 1892; Darton, 1896).

Development occurred because the wells provided large volumes of water, as much as 4,000 gallons per minute, and they did not have to be pumped; that is, the water flowed freely from the wells at the land surface. In some counties, township boards used tax money to drill two wells per township for irrigation. Where artesian pressure was adequate, wells were drilled to power flour mills, machine shops, and other industries. Many cities and towns tapped the Dakota aquifer to save both the cost of pumps and of pumping. By 1895, about 400 wells had been drilled, and the estimated flow was 150 Mgal/d (Darton, 1896). In 1916, the State Engineer estimated that at least 10,000 wells had been drilled. In 1983, at least 10,000, and possibly more than 15,000, wells were in use or flowed unused. Estimated discharge from the Dakota aquifer through wells was 160 Mgal/d and may have ranged from 150 and 200 Mgal/d between 1895 and 1983 (Bradford, 1981). A generalized reconstruction of the approximate area in which wells flowed at the land surface in 1881 and, for contrast, the approximate area in which wells flowed at the land surface in 1983 are shown in figure 64.

The pressures in flowing wells that tapped the aquifer declined rapidly after development began. An example of the pressure decline that occurred in the aquifer can be seen in the following data from a well near Woonsocket,

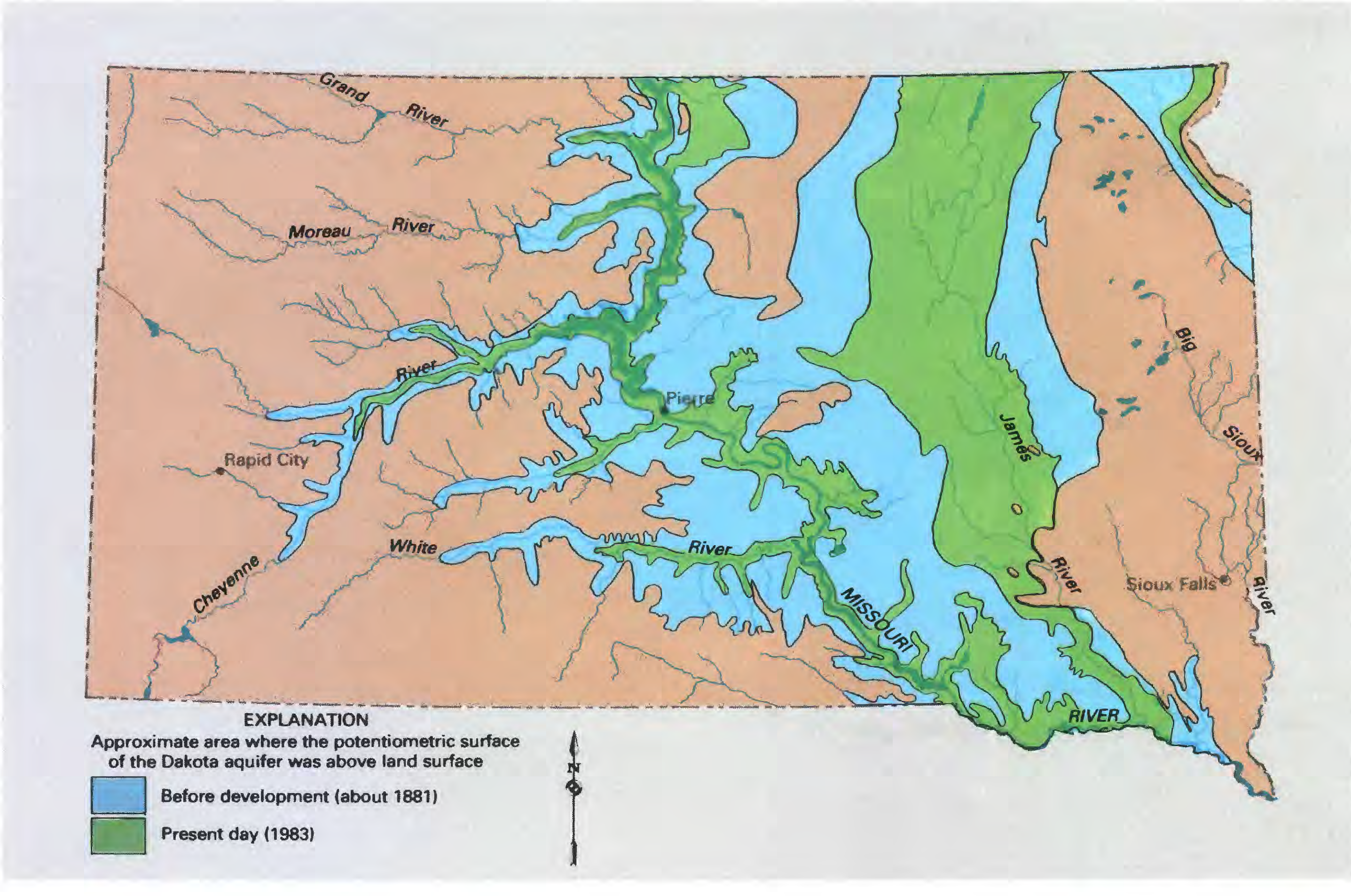


Figure 64. Approximate area in South Dakota where wells in the Dakota aquifer flowed freely at the land surface before development (about 1881) and at the present time (1983). (Source: Compiled by L. W. Howells from U.S. Geological Survey data.)

S. Dak., in the James River valley (L. W. Howells, U.S. Geological Survey, written commun., April 1984).

Year	Shut-in pressure (pounds per square inch)
1888	250
1890	155
1892	130
1915	45
1961	23

Use of the well in which these pressures were recorded was discontinued in 1961. Pressures in other wells at Woonsocket have not decreased significantly since that time (N. C. Koch, U.S. Geological Survey, oral commun., August 1984).

The 227-pounds-per-square-inch reduction in the shut-in pressure between 1888 and 1961 is equivalent to about 520 ft of water-level decline; more than 90 percent of this decline occurred between 1888 and 1915. By 1910, almost all use of water from the Dakota aquifer for power had ceased. Irrigation use of the more saline ground water, which also is often high in sodium, resulted in both sodium and salt poisoning of soils after 4 to 6 years of irrigation. For this reason, much of the use of the water from the Dakota aquifer for irrigation had ended by 1900. For several decades thereafter, the major uses of ground water from the Dakota aquifer were for livestock, domestic, and municipal water supplies.

In general, water from the Dakota aquifer contains 100 to 5,000 milligrams per liter (mg/L) of sodium, 600 to 1,300 mg/L of sulfate, and 1,200 to 2,500 mg/L of dissolved solids. In some areas, the water may have fluoride concentrations of as much as 6 mg/L. In the northwestern part of South Dakota, however, the water contains 6,000 to 12,000 mg/L of dissolved solids, mainly sodium and chloride (U.S. Geological Survey and U.S. Bureau of Reclamation, 1975). These values are very high relative to most municipal supplies and to the National Interim Drinking-Water Regulations (U.S. Environmental Protection Agency, 1982a, b). Consequently, use of water from the Dakota aquifer has decreased since 1970, and rural and municipal water systems have been constructed or developed from other sources.

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Declining Ground-Water Levels and Increasing Pumping Costs: Floyd County, Texas—A Case Study

By John E. Schefter

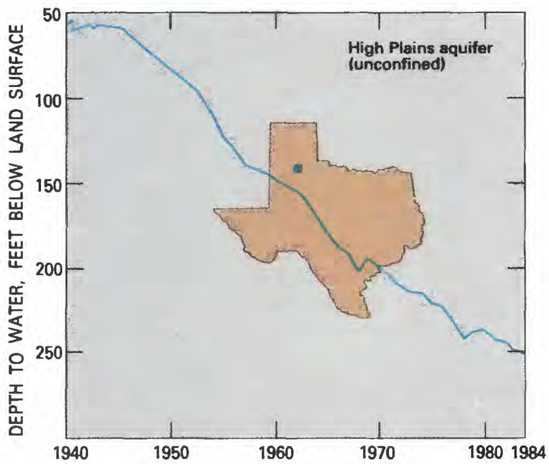

Figure 65. Water levels in a well in the High Plains aquifer, Floyd County, Tex., 1940 to 1984. (Source: Compiled by E. D. Gutentag from U.S. Geological Survey data.)

Irrigated agriculture in Floyd County, Tex., provides an extreme example of the effect that declining water levels and increased energy prices may have on the cost of ground-water withdrawals. Floyd County, which is in the northern part of the State, is underlain by the High Plains aquifer. Although ground-water levels have declined throughout much of the High Plains aquifer, the declines in northern Texas, in general, have been greater than anywhere else (Luckey and others, 1981). The aquifer, which consists mainly of sand and gravel, commonly yields from 100 to 500 gallons per minute (gal/min) of water to wells and is the main source of water for irrigation. Ground-water withdrawals from the aquifer for irrigation began in the early 1940's. In 1958, the annual irrigation withdrawal in Floyd County was 61.5 billion gallons (gal), and by 1969 it had increased to 103.5 billion gal. However, by 1979, withdrawals had decreased to 57.7 billion gal (Texas Department of Water Resources, 1981). Some of the causes of this sharp decrease in withdrawals are explained below.

Between 1945 and 1984, the water level in an observation well in Floyd County decreased from 60 to 245 feet (ft) below the land surface (fig. 65), mainly in response to the withdrawal of water for irrigation. The saturated thickness of the aquifer at that well was reduced from about 300 ft in the early 1940's to about 100 ft in 1980, a decrease in saturated thickness of about 67 percent (Luckey and others, 1981). The observation well is representative of conditions in about 400 square miles of Floyd County, where ground-water levels have declined 100 ft or more since development began.

The cost per acre-foot of pumping water between 1952 and 1981 from the observation well using different assumptions (constant energy cost and constant pressure head) is shown in figure 66. This cost is only that for electrical energy to lift water from the well; it does not include other operating and capital costs. Changes in pumping costs are summarized in the table.

In terms of nominal (unadjusted for inflation) dollars, the cost of pumping water to the surface increased 594 percent from 1952 to 1981. The change in the nominal cost is due to the following factors: changes in the depth to water and changes in the price of electrical energy. Had electricity remained at its 1952 price, the cost of pumping water would have increased only 172 percent due to declining water levels alone. However, electricity prices did not remain constant; they declined slightly between 1952 and 1973, and increased 233 percent between 1973 and 1981 (Stevens and Cumming, 1977; Sam Thomas, Southwest Public Service, oral commun., 1982). Had the water level remained at the 1952 level, the cost of pumping would have declined until 1973 and then increased in subsequent years for an average increase of 155 percent due solely to increased energy prices from 1952 to 1981.

Over the entire 30-year period (1952–81), declining water levels contributed more to increased pumping costs than did increased energy prices. However, between 1973 and 1981, increased energy prices contributed more to increased pumping costs than did declining water levels. In that period, pumping costs increased 302 percent. Had the water level remained constant at the 1973 level, pumping costs would have increased 233 percent due to the increase in energy price alone, and had the energy price remained at its 1973 level, pumping costs would have increased only 21 percent due solely to declining water levels.

Although the cost of pumping water increased 594 percent between 1952 and 1981, the index of prices received by farmers for their crops increased 116 percent over the same period. It cost about $3.82 to lift 1 acre-foot of water to the surface in 1952 and about $26.47 in 1981. But, in 1952 the index of prices received by farmers for their crops stood at 62 (1977 = 100), whereas it was equal to 134 in 1982 (Council of Economic Advisors, 1983). Thus, pumping cost, relative to the crop price index, increased 221 percent over the 30-year period.

The decrease in annual ground-water withdrawals, from 103.5 billion gal in 1969 to 57.7 billion gal in 1979 can be attributed partially to increased pumping costs, declining well yields, and resulting changes in irrigation practices. Between 1969 and 1979, 22,000 acres were taken out of irrigation, a decline of about 7 percent. During this same period, the volume of irrigation water applied decreased from 1.0 acre-foot per acre (acre-ft/acre) in 1969 to 0.6 acre-ft/acre in 1979. Total irrigated acreage in the southern High Plains of Texas, which includes Floyd County, dropped 10 percent during that period and the average rate of application of water dropped 15 percent, from 1.2 to 1.0 acre-ft/acre (Texas Department of Water Resources, 1981). These changes undoubtedly are related to pumping costs, but changes in other production costs also played a role, as have changes in the prices received by farmers for their crops (Sloggett and Mapp, 1984).

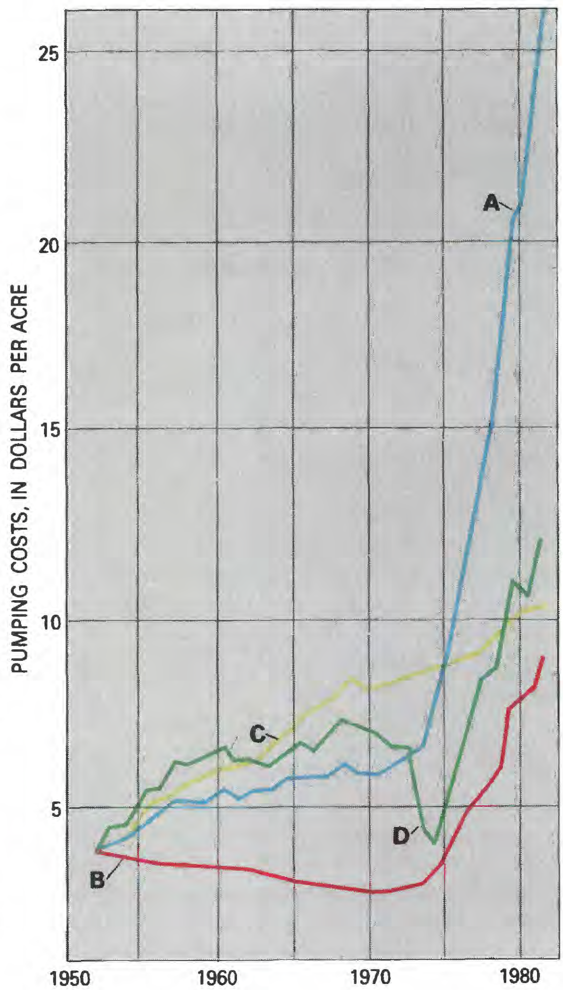

Figure 66. Estimated pumping costs at an observation well in Floyd County, Tex., 1952 to 1981, based on four scenarios: A, observed (historic) changes in water levels and energy prices; B, changes in energy prices with constant water levels; C, changes in water levels with constant energy prices; and D, relative to index of crop prices received by farmers. (Source: Compiled by J. E. Schefter.)

Percentage changes in pumping costs due to changes in energy prices and ground-water levels, for three time periods

[Percentages in rows do not add because base year used for calculation of first column (1952) differs from that used in second (1973)]

Factors affecting changes in pumping costs	Percentage change in pumping costs		
	1952 to 1973	1973 to 1981	1952 to 1981
Observed (historic changes in energy prices and water levels	73	302	594
Changes attributable to water-level decline; no change in energy price	125	21	172
Changes attributable to energy price; no change in water levels	-23	233	155

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Aerial infrared view of center pivot irrigated field patterns near Imperial, Neb., September 1979. The dark-red fields are primarily irrigated corn; the center pivot in the northeastern part of the photograph is in fallow. (Photograph by U.S. Environmental Protection Agency for U.S. Geological Survey Regional Aquifer System Analysis study of the High Plains aquifer.)

State Summaries of Ground-Water Resources

INTRODUCTION TO STATE SUMMARIES OF GROUND-WATER RESOURCES

By Ralph C. Heath

The "State Summaries of Ground-Water Resources" part of the 1984 *National Water Summary* contains descriptions of the occurrence, use, and general quality of the ground-water resources of each State, the District of Columbia (combined with Maryland), Puerto Rico, the U.S. Virgin Islands, and the Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. (Hereafter, the term "State" is used for all geographic areas.) Each summary contains the following components:

- General setting—Highlights of the physiographic, hydrologic, and geologic framework of the ground-water system.
- Principal aquifers—A description of location, geology, and use of the aquifers.
- Ground-water withdrawals and water-level trends—A description of the location and purpose of major ground-water withdrawals and the trends in water levels.
- Ground-water management—A description of ground-water related laws and regulations and an identification of management agencies.
- Selected references—A listing of relevant reports on ground-water resources.
- Table 1, Ground-water facts—A tabulation of ground-water withdrawals for various uses in relation to total water withdrawals. (Not included with the Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa.)
- Table 2, Aquifer and well characteristics—A listing of important characteristics of the principal aquifers and of the water-supply wells drilled in the aquifers. (Table 1 in Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa.)
- Figure 1, Principal aquifers—A map showing geographic distribution of the principal aquifers.
- Figure 2, Areal distribution of major ground-water withdrawals and trends in ground-water levels—A map showing areas of withdrawals, hydrographs showing the long-term water level trends of aquifers, and a tabulation of areas of withdrawals and use of the water.

In the State summaries, common ground-water terms are used, and reference is made, without explanation, to basic ground-water principles. Some of those terms and principles are described briefly in the glossary at the end of the report. Additional discussions of basic ground-water terms and principles and of the general features of ground-water occurrence in the United States are found in Heath (1983, 1984).

IMPORTANCE OF GROUND WATER TO THE NATION

Ground water is available in at least small amounts at nearly every point on the Earth's surface, making it one of the most widely available of all natural resources. It serves as the only, or the dominant, source of drinking water for most rural areas, as the largest source of water for irrigation and other purposes in arid and most semiarid regions, and as an important source of water for urban, industrial, and supplemental irrigation purposes in humid areas. The importance of ground water in the United States is shown graphically in figure 67. Nationwide, ground-water withdrawals in 1980 (excluding those for thermoelectric power) range from less than 1 percent of the total water withdrawal in the District of Columbia to 85 percent of that in Kansas. In 10 States, ground water represents more than one-half of the total withdrawal.

By far the largest use of ground water is for irrigation. States with the largest ground-water use are those in the western part of the conterminous United States—Arizona, California, Idaho, Kansas, Nebraska, and Texas—where irrigated agriculture is a major activity. In the eastern part of the country, States that use large amounts of ground water for irrigation include Arkansas, Florida, Louisiana, and Mississippi.

The importance of fresh ground water to the different States readily can be seen by comparing ground-water withdrawals to total fresh surface-and ground-water withdrawals (table 9). Total withdrawals, as given in water use reports, usually include thermoelectric power withdrawals mainly for condenser and reactor cooling and related purposes. Because water used for thermoelectric power must be available in very large quantities, 99 percent of it is obtained from surface-water sources, of which 30 percent is from saline surface-water bodies. Thus, the inclusion of thermoelectric power in total withdrawals tends to obscure the relative importance of ground and surface water for other uses, such as for public supplies, irrigation, and industrial usage (exclusive of thermoelectric power). For this reason, the ground-water facts table in each State summary shows total withdrawals including and excluding thermoelectric power.

DELINEATION OF PRINCIPAL AQUIFERS IN THE STATE SUMMARIES

In each State summary, the aquifers that are developed most intensively for water supplies are identified, and their areal extents are shown on a map (fig. 1 in each summary). Areas in many of the States, and especially those that occupy parts of the Atlantic and Gulf Coastal Plains, are underlain by two or more aquifers separated by confining beds. In most instances, the maps show the uppermost of these multiple aquifers, although the maps for some States delineate the most-used aquifers. The relative vertical positions of the aquifers and of the intervening confining beds are indicated on cross sections or in block diagrams which show schematically the arrangement of the aquifers and confining beds along vertical slices through the Earth's

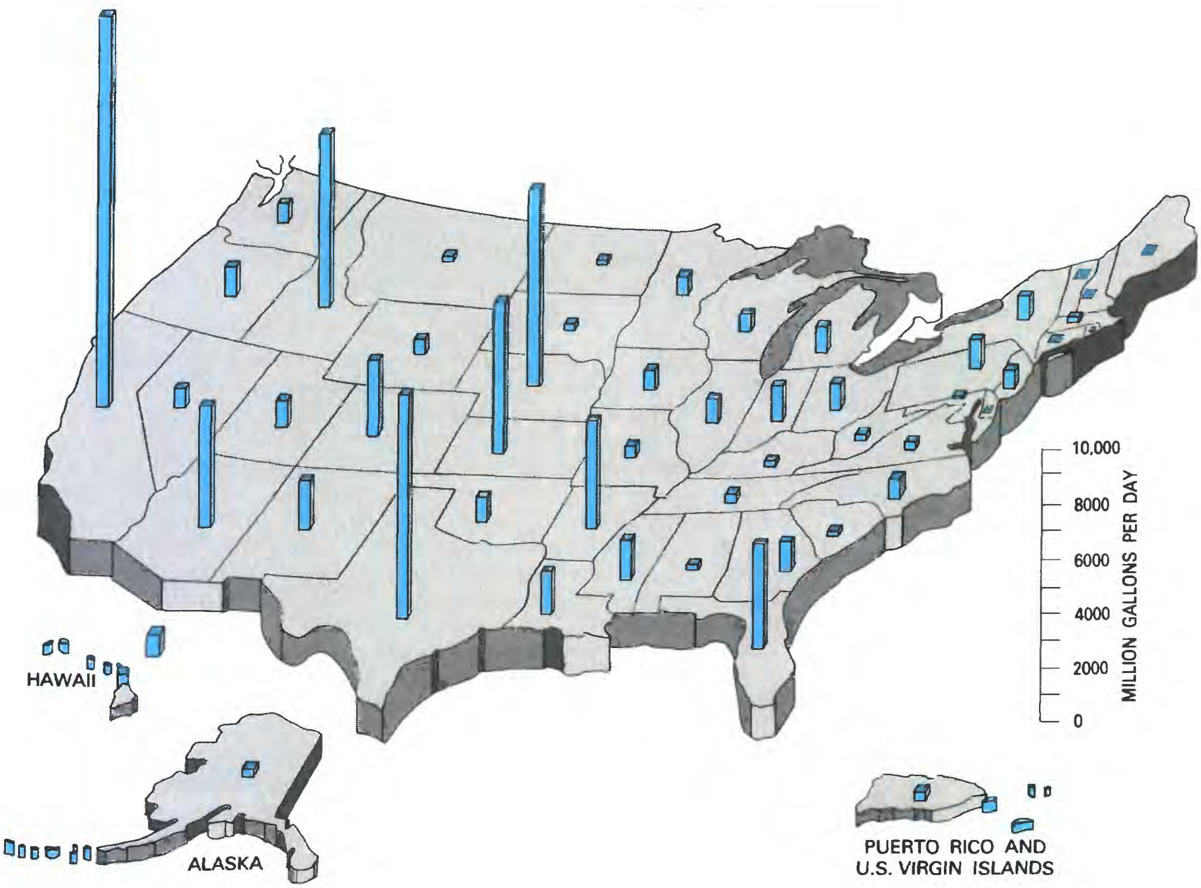

Figure 67. Ground-water withdrawals in 1980 for the United States, Puerto Rico, and U.S. Virgin Islands. (Source: Modified from Solley and others, 1983.)

crust. To help the reader visualize the aquifer distribution in relation to land forms, figure 1 also has a small map showing the physiographic divisions of the State.

The relative vertical positions of the aquifers in each State also are indicated in a table of aquifer and well characteristics (table 2 in each summary). Thus, it will be useful to refer to this table while scanning the aquifer map and the cross section or block diagram.

In some areas, an aquifer occurring in the same geologic formation is identified by one name in one State and by another in an adjacent State. In preparing this report, attempts were made to resolve these differences in names; however, several remain. Where appropriate, the corresponding name(s) of the aquifer in the adjacent State is given in the table 2 "Remarks" column to aid in understanding aquifer nomenclature.

The importance of an aquifer as a source of water may change from one State to another because of changes in demands for freshwater, variations in ground-water quality, and differences in the hydrogeologic characteristics of the aquifer. The differences may be of such magnitude that an aquifer that serves as a principal source of supply in one State may not be intensively developed in a neighboring State. For these reasons, the aquifer boundaries depicted in figure 1 of each State summary may not match at State boundaries.

RESPONSE OF AQUIFERS TO WITHDRAWALS

A map showing the location of major withdrawals and, through the use of symbols, the magnitude of the withdrawals, is given for each State (fig. 2 in each summary). Also included in this figure are hydrographs that show, in some cases, the effects of climatic changes and, in others, the long-term effect of withdrawals on ground-water levels; the hydrograph data are the annual greatest depth to water. A list of the withdrawal points, the name of the aquifer, and the principal uses of withdrawals also is provided.

Changes in the position of the water level in wells reflect changes in the amount of ground water in storage in aquifers, and, where these changes are due to withdrawals, they also may reflect changes in flow direction. Thus, the measurement of the position of the water levels in wells is an important part of most ground-water investigative programs. These water-level measurements are most readily understandable in the form of hydrographs as given in the State summaries and in the form of water-level maps, which can be used to determine directions of flow. The hydrographs included in the State summaries were selected, in most instances, to show the effect of withdrawing ground water from the most intensively developed aquifers.

Table 9. Summary of fresh ground-water withdrawals as a percentage of total fresh surface- and ground-water withdrawals for all categories of use and for specific categories of use, by State

[Data rounded to two significant figures. Data not included for Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. Mgal = million gallons. Sources: State data from table 1 in respective State summary, *National Water Summary 1984*; total data from Solley, Chase, and Mann, 1983]

State	Total surface- and ground-water withdrawals per day (Mgal)	Percentage of population served by ground water	Ground-water withdrawals per day (Mgal)	Ground-water withdrawals as a percentage of total fresh surface- and ground-water withdrawals for— All categories of use[1]	Specific categories of use: Public supply	Rural supply: Domestic	Rural supply: Livestock	Industrial self-supplied[1]	Irrigation
Alabama	8,700	52	290	3 (14)	28	100	34	0.6 (4)	30
Alaska	220	69	49	22 (26)	43	99	0	9 (11)	0
Arizona	7,300	65	4,200	58 (57)	54	100	82	72 (88)	58
Arkansas	33,000	50	4,300	13 (81)	42	100	36	1 (55)	86
California	38,000	46	14,600	39 (38)	46	93	41	54 (89)	39
Colorado	16,000	15	2,800	18 (18)	8	36	18	2 (1)	19
Connecticut	1,300	32	150	11 (20)	17	100	18	3 (10)	8
Delaware	140	60	82	59 (57)	38	100	100	68 (73)	63
District of Columbia	340	0	.8	.2 (.4)	0	0	0	.6 (57)	0
Florida	7,300	90	3,800	52 (69)	86	100	66	27 (82)	53
Georgia	6,700	48	1,200	18 (52)	29	100	61	8 (57)	66
Hawaii	1,700	95	710	41 (37)	90	90	96	73 (20)	93
Idaho	18,000	88	6,300	35 (35)	94	96	42	95 (95)	25
Illinois	18,000	49	980	5 (24)	27	97	100	1 (10)	100
Indiana	14,000	32	1,200	11 (30)	41	90	18	8 (18)	98
Iowa	3,200	82	900	28 (81)	81	100	100	13 (71)	84
Kansas	6,600	49	5,600	85 (89)	48	86	43	35 (77)	92
Kentucky	4,600	31	180	4 (22)	13	91	5	2 (25)	6
Louisiana	12,000	69	1,800	14 (27)	44	100	70	5 (12)	47
Maine	850	57	80	9 (10)	19	98	59	5 (5)	3
Maryland	1,400	30	175	13 (17)	9	100	54	6 (18)	54
Massachusetts	2,500	33	320	13 (28)	24	100	58	6 (30)	28
Michigan	15,000	43	530	4 (18)	17	100	77	1 (3)	37
Minnesota	3,100	75	670	22 (48)	52	100	85	5 (20)	88
Mississippi	2,900	93	1,500	54 (82)	18	100	77	21 (61)	35
Missouri	6,900	34	470	7 (34)	22	74	26	2 (39)	75
Montana	11,000	54	200	2 (2)	39	94	38	20 (52)	1
Nebraska	12,000	82	7,100	59 (73)	77	100	80	3 (85)	67
Nevada	3,600	50	710	20 (20)	40	94	31	30 (45)	17
New Hampshire	380	60	65	17 (21)	48	98	25	5 (6)	0
New Jersey	2,900	45	730	25 (37)	40	100	67	10 (20)	73
New Mexico	3,900	89	1,800	47 (47)	90	97	50	25 (98)	44
New York	7,900	35	970	12 (28)	23	89	65	4 (11)	46
North Carolina	8,100	55	770	10 (20)	12	100	85	6 (17)	30
North Dakota	1,000	62	110	11 (11)	54	100	40	.3 (25)	37
Ohio	13,000	42	740	6 (32)	27	90	60	2 (16)	36
Oklahoma	1,700	41	960	56 (61)	28	83	12	23 (35)	84
Oregon	6,800	61	1,100	17 (17)	29	87	27	15 (16)	14
Pennsylvania	16,000	44	1,000	6 (16)	16	100	88	4 (15)	14
Puerto Rico	1,100	26	246	22 (35)	22	42	50	3 (21)	34
Rhode Island	170	24	37	22 (21)	15	100	50	36 (36)	9
South Carolina	5,800	42	210	4 (21)	22	100	55	1 (5)	27
South Dakota	690	77	330	48 (48)	68	94	88	54 (55)	33
Tennessee	10,000	51	460	5 (21)	40	100	17	2 (11)	51
Texas	16,000	47	9,700	61 (62)	46	84	49	23 (24)	70
Utah	4,300	63	770	18 (18)	66	90	80	14 (16)	10
U.S. Virgin Islands	6	42	1.1	18 (18)	12	100	0	0 (0)	0
Vermont	340	54	45	13 (50)	35	85	62	2 (35)	19
Virginia	5,600	41	370	7 (30)	17	100	10	2 (24)	29
Washington	8,200	71	750	9 (9)	37	78	67	15 (15)	4
West Virginia	5,600	53	220	4 (22)	27	95	13	3 (18)	8
Wisconsin	5,900	70	580	10 (46)	48	100	96	1 (15)	97
Wyoming	5,300	54	540	10 (11)	33	92	21	34 (76)	8
Total or percentage	380,000	51	88,000	23 (38)	35	97	55	6 (26)	40

[1]Number in parentheses was calculated excluding thermoelectric power.

These hydrographs represent only a small sample of those available from the U.S. Geological Survey and State ground-water agencies. The response of water levels in aquifers to ground-water withdrawals is described in detail in the 1983 *National Water Summary* (U.S. Geological Survey, 1984, p. 36–45).

Estimates of well yields for each aquifer are given in table 2 of each State summary. These yields are the amounts of water per minute that can be obtained when an effort is made to design and construct wells to obtain large supplies of water, such as are needed for agricultural, public supply, or industrial uses. For most aquifers, they do not represent the average yield of all wells, which may include many small-yield rural domestic wells. A range of yields reflects the effect of areal differences in aquifer thickness or composition. The yields listed in the "May exceed" column are obtainable where conditions are especially favorable; for example, where an aquifer has its greatest thickness or is most permeable. All yields represent the rates at which individual wells can be pumped continuously for long periods. They do not, however, include the possible influence of interference from nearby wells and do not indicate the "safe" or sustained yields of the aquifer.

GROUND-WATER MANAGEMENT

The Nation's freshwater needs are met by withdrawals from streams, lakes, reservoirs, and ground-water systems. Trends in water developments over the last 30 years show that the use of ground water for all purposes, exclusive of thermoelectric power, has been increasing at a faster rate than has the use of surface water for the same purposes. Several factors may cause this trend to continue or accelerate in the future. First, the most cost-effective surface reservoir sites already have been developed (U.S. Geological Survey, 1984, p. 33) and the sustained yields of existing reservoirs are decreasing due to sedimentation. Second, the cost of storage at the remaining reservoir sites is becoming increasingly expensive. And third, public opposition is increasing to reservoir construction because of potential environmental damages. Thus, the development of alternative ground-water supplies and the protection of ground-water quality are management issues of critical importance.

Discussion of the quality of ground water is limited in this report to identifying the natural condition of the water in those instances where it influences the use of the water. For the most part, data are available to assess the common constituents that influence the quality of the Nation's ground water. However, much less is known about ground-water constituents that occur naturally in trace concentrations and about the degree and extent of contamination by human activities. Investigations by Federal and State agencies, universities, and other groups are underway to address these technical aspects of ground-water management.

To ensure that the Nation's future water demands are met, it is important that an infrastructure exists within each State to utilize the technical information and manage the ground-water resources. To achieve these ends, many States have enacted ground-water laws and regulations and have established organizations to implement them. A description of these management initiatives constitutes the final section of each State summary.

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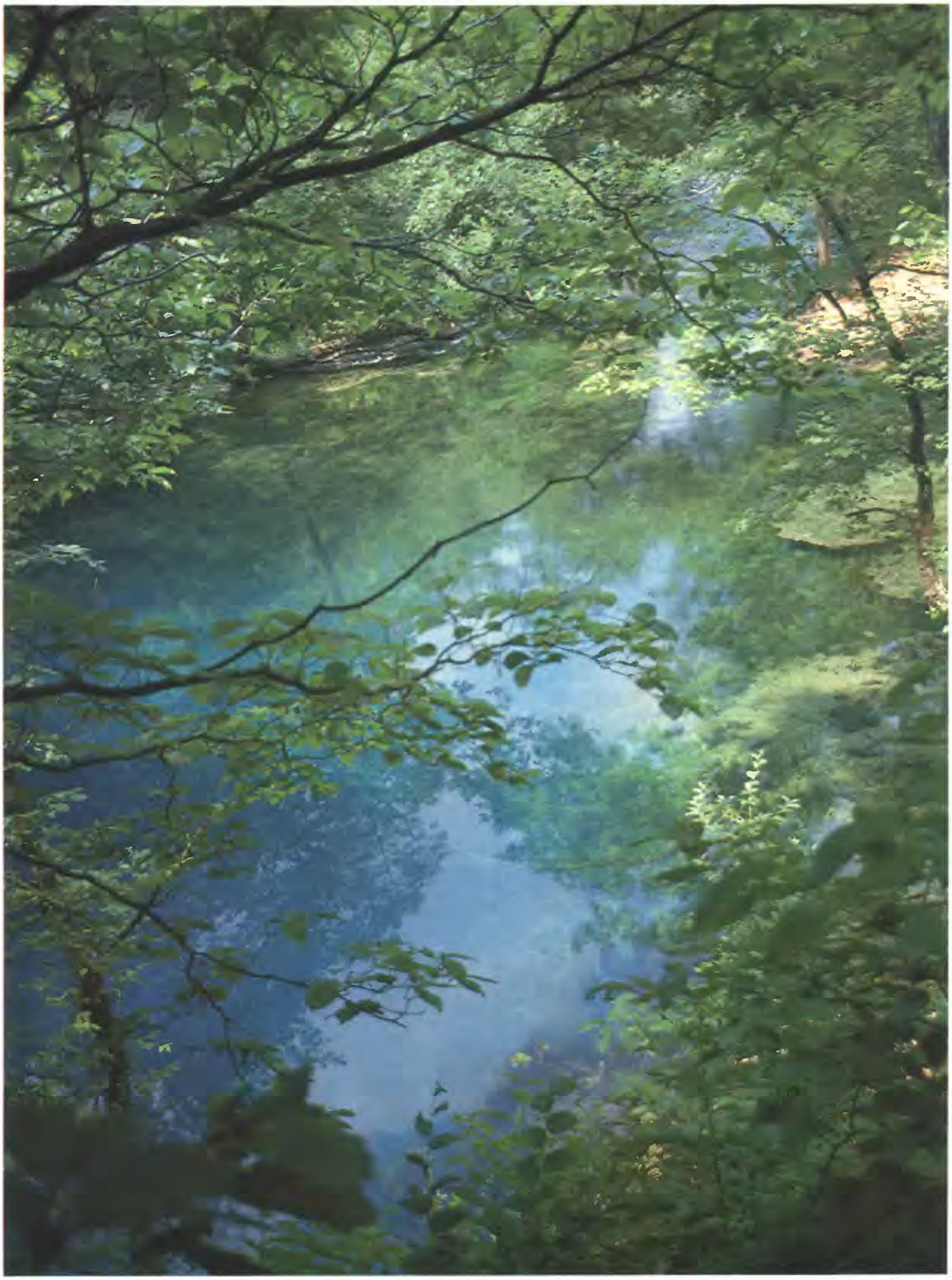


Ground water rises to form Blue Spring beneath a bluff of Eminence Dolomite near Owls Bend, Mo. (Photograph by J. H. Barks.)

ALABAMA
Ground-Water Resources

Ground water is used by 52 percent of the population of Alabama, even though it constitutes only 14 percent of the total freshwater used in the State, excluding thermoelectric use (Baker, 1983; Solley and others, 1983). Ground water also is used extensively for irrigation, livestock, and industrial-commercial supplies. Ground-water withdrawals in 1982 totaled 290 million gallons per day (Mgal/d); withdrawals for various uses and related statistics are given in table 1.

GENERAL SETTING

Alabama comprises an area of about 51,705 square miles (mi^2) and has a population of about 4.1 million (1982 projection, University of Alabama, Center for Business and Economic Research, 1983). The State contains parts of five physiographic divisions (fig. 1)—the Coastal Plain, Piedmont, Valley and Ridge, Appalachian Plateaus, and Interior Low Plateaus provinces (Fenneman, 1938). The Coastal Plain province is underlain predominantly by unconsolidated sediments that dip gently toward the south and southwest. Underlying the Piedmont province are complexly folded and faulted metamorphic rocks and massive igneous rocks. The Valley and Ridge province is underlain by folded and faulted carbonate rocks, sandstone, and shale. The Appalachian Plateau consists of plateaus underlain by sandstone, shale, siltstone, and coal. The Interior Low Plateau is underlain by beds of carbonate rocks, sandstone, and shale that dip generally southward. The differing geologic features and land forms of Alabama cause significant differences in ground-water quality and availability.

Recharge to the ground-water system in Alabama is derived from precipitation. Normal annual precipitation ranges from about 49 inches (in.) in Montgomery County to about 66 in. in southern Baldwin County, according to National Weather Service records for 1951 to 1980. Most of the precipitation runs off to streams or is returned to the atmosphere by evaporation and transpiration; however, a small part (about 3-6 in.) recharges the ground-water system and supplies base flow to streams.

Table 1. Ground-water facts for Alabama

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Baker, 1983]

Population served by ground water, 1982	
Number (thousands)	2,092
Percentage of total population	52
From public water-supply systems:	
Number (thousands)	1,481
Percentage of total population	37
From rural self-supplied systems:	
Number (thousands)	611
Percentage of total population	15
Freshwater withdrawals, 1982	
Surface water and ground water, total (Mgal/d)	8,700
Ground water only (Mgal/d)	290
Percentage of total	3
Percentage of total excluding withdrawals for thermoelectric power	14
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	160
Percentage of total ground water	55
Percentage of total public supply	28
Per capita (gal/d)	108
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	46
Percentage of total ground water	16
Percentage of total rural domestic	100
Per capita (gal/d)	75
Livestock:	
Ground water (Mgal/d)	30
Percentage of total ground water	10
Percentage of total livestock	34
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	51
Percentage of total ground water	18
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	0.6
Excluding withdrawals for thermoelectric power	4
Irrigation withdrawals:	
Ground water (Mgal/d)	12
Percentage of total ground water	4
Percentage of total irrigation	30

PRINCIPAL AQUIFERS

Principal aquifers in Alabama consist of a sequence of unconsolidated sediments that underlie the Coastal Plain and consolidated sediments, carbonate rocks, and igneous and metamorphic rocks that underlie the other four physiographic provinces in the State. The aquifers, which are grouped into the Coastal Plain aquifers and non-Coastal Plain aquifers, are described below and in table 2; their areal distribution is shown in figure 1.

COASTAL PLAIN AQUIFERS

Many of the principal aquifers in Alabama are in the Coastal Plain, and consist of, from youngest to oldest, the Citronelle-Miocene aquifer, the Floridan aquifer, the Tertiary sedimentary aquifer system, and the Cretaceous aquifer system. Relatively impermeable sediments (chalk and clay) are present between the aquifers.

The Citronelle-Miocene aquifer consists of sand beds in the Citronelle Formation of Pliocene age and in the undifferentiated Miocene Series (Copeland, 1968; Barksdale and Moore, 1976). This aquifer is used primarily in Baldwin, Mobile, Washington, and Escambia Counties in southwestern Alabama; wells commonly yield as much as 500 gallons per minute (gal/min). Water quality is generally suitable for municipal, industrial, and irrigation uses but may be acidic and corrosive locally.

The Floridan aquifer system consists of porous limestone in formations of Oligocene age and in the Ocala Limestone (Copeland, 1968; Barksdale and Moore, 1976). Yields from this system may exceed 700 gal/min per well in southeastern Alabama.

Table 2. Aquifer and well characteristics in Alabama

[Gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Alabama State agencies]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Coastal Plain aquifers:				
Citronelle-Miocene aquifer: Sand, sandy gravel, sandy clay, gravel, and sandstone. Unconfined to confined.	100 - 500	200 - 500	700	Principal aquifer in southwest Alabama. Water may be acidic and corrosive locally.
Floridan aquifer: Limestone and sand. Unconfined to confined.	75 - 400	100 - 500	700	Includes Oligocene Series (undifferentiated) and Ocala Limestone. Principal shallow aquifer in extreme southeast Alabama.
Tertiary sedimentary aquifer system: Sand, sandy clay, gravelly sand, and limestone. Unconfined to confined.	200 - 1,200	350 - 700	1,000	Principal aquifer system in south-central and southeast Alabama. Water-level declines of 100 ft in Dothan.
Cretaceous aquifer system: Sand, gravelly sand, sandy clay, sandy limestone, and calcareous clay. Unconfined to confined.	200 - 1,500	300 - 1,000	1,400	Principal aquifer system in northern and central parts of the Coastal Plain. Water may contain chloride in excess of 250 mg/L locally, especially near major rivers, downdip at depths greater than 2,500 ft, and in areas where no principal aquifers are present.
Non-Coastal Plain aquifers:				
Paleozoic carbonate aquifer system: Limestone and dolomite. Unconfined to confined.	75 - 500	100 - 500	1,000	Includes carbonate formations of Mississippian through Cambrian age. Important source of ground water from wells and springs in Valley and Ridge and Interior Low Plateaus physiographic provinces.
Pennsylvanian sandstone aquifer: Sandstone, shale, siltstone, and coal. Unconfined to confined.	75 - 200	1 - 10	100	Primarily Pottsville Formation. Water may contain iron in excess of 0.3 mg/L locally.
Igneous-metamorphic aquifer: Schist, phyllite, and quartzite saprolite. Unconfined to confined.	75 - 300	1 - 10	100	Generally unproductive aquifer. Water may contain iron in excess of 0.3 mg/L locally.

The Tertiary sedimentary aquifer system consists of sand beds in the Lisbon, the Tallahatta, the Hatchetigbee, and the Nanafalia Formations and limestone and sand beds in the Clayton Formation; this aquifer system is used extensively across southern Alabama, and wells generally yield 350 to 700 gal/min.

The Cretaceous aquifer system consists of sand beds in the Providence Sand and the Ripley and Eutaw Formations and Tuscaloosa Group (Carlston, 1944; Barksdale and Moore, 1976); this aquifer system is used in a large part of the Coastal Plain of Alabama (fig. 1). The Providence-Ripley aquifer yields as much as 700 gal/min. Wells in the Eutaw aquifer generally yield between 700 and 1,000 gal/min. Wells in the Tuscaloosa aquifer, the lowermost of the Cretaceous aquifer system in Alabama, yield between 700 and 1,400 gal/min. Water quality in both the Tertiary sedimentary and Cretaceous aquifer systems generally is suitable for municipal, industrial, and irrigation uses. However, chloride concentrations, downdip from outcrops, exceed 250 milligrams per liter (mg/L) in many areas; chloride concentrations are also high at depths of less than 200 feet in west-central Alabama. The iron concentration may exceed 0.3 mg/L locally with no geographic pattern evident.

Non-Coastal Plain Aquifers

The principal non-Coastal Plain aquifer is the Paleozoic carbonate aquifer system in the central and northern parts of the State. Two additional aquifers, the Pennsylvanian sandstone and the igneous-metamorphic, are significant, even though well yields are small, because they are the only aquifers available over a large part of northern and eastern Alabama.

The Paleozoic carbonate aquifer system consists of cavernous limestone and dolomite that range in geologic age from Mississippian to Cambrian (Johnston, 1933; Barksdale and Moore, 1976). These aquifers are used in the Valley and Ridge province and in the Interior Low Plateaus province (primarily the Tennessee Valley). Although well yields differ greatly in carbonate terranes, wells in these aquifers generally yield 100 gal/min and may yield 1,000 gal/min or more in some areas.

The Pennsylvanian sandstone aquifer consists of sandstone of the Pottsville Formation. Water in this aquifer is present in joints, fractures, and bedding-plane partings (Johnston, 1933; Barksdale and Moore, 1976). Wells in the Pottsville generally produce less than 10 gal/min but may yield more than 100 gal/min. Water quality generally is acceptable for domestic and municipal uses; however, the iron concentration commonly exceeds 0.3 mg/L.

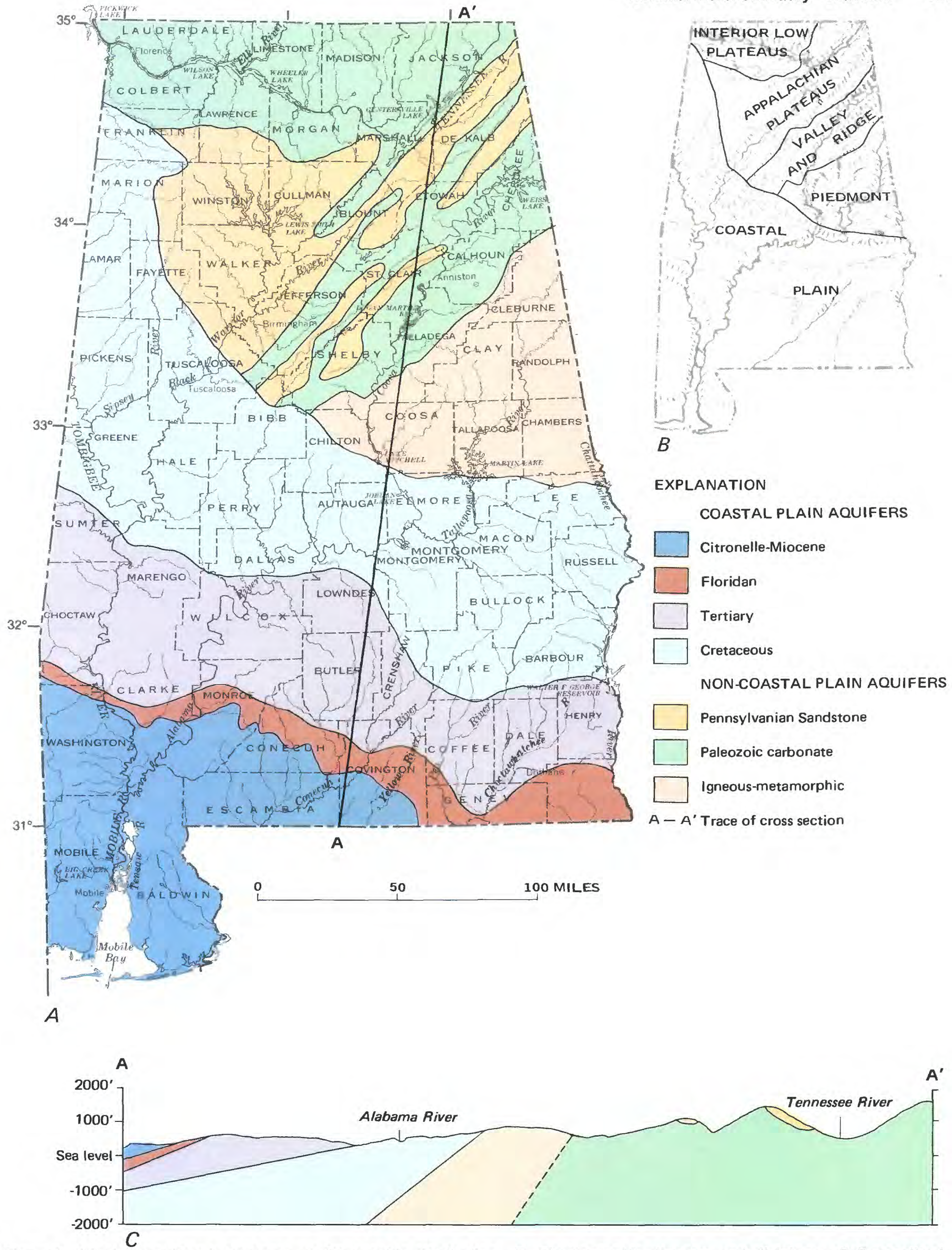


Figure 1. Principal aquifers in Alabama. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Johnston, 1933; Carlston, 1944. *B*, Fenneman, 1938; Raisz, 1954. *C*, Copeland, 1968; Barksdale and Moore, 1976.)

The igneous-metamorphic aquifer consists of schist, phyllite, quartzite, marble, granitic rocks, and saprolite (inplace decomposed rock in the Piedmont). Ground water is present in fault zones, joints, and other fractures in the bedrock and pore spaces in the saprolite. Wells in the Piedmont generally yield from 1 to 10 gal/min, but yields can exceed 100 gal/min. Water having an iron concentration greater than 0.3 mg/L is a common local problem.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Most cities and towns in the Coastal Plain of Alabama depend solely on ground water for water supplies. Exceptions are Mobile, Tuscaloosa, and Phenix City, which have surface-water supplies, and Montgomery, which uses ground and surface water. Most rural public water-supply systems in the Coastal Plain use ground water, as do almost all self-supplied homes and farms. Non-Coastal Plain areas that use ground water extensively include Madison County, Anniston, and Jefferson County (locations 1, 3, 5, fig. 2). These metropolitan centers have surface-water supplies, but ground water constitutes a significant part of the total water used.

The distribution of major ground-water withdrawals and trends of ground-water levels near selected pumping centers are shown in figure 2. The largest concentrations of ground-water pumpage are in Madison, Calhoun, Montgomery, Mobile, and Houston Counties (locations 1, 3, 7, 9, 11, fig. 2).

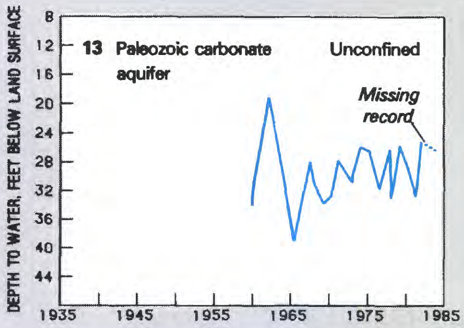
Water levels generally decline in response to increased pumping and recover when pumping is reduced. The hydrograph for the well in Hale County (location 14, fig. 2) shows that the water level has been declining since 1961, as does the hydrograph for the well in Dale County (location 16, fig. 2). These declines are typical of Coastal Plain aquifers where pumpage has steadily increased during the past 40 years. The hydrograph for the well in Montgomery County (location 15, fig. 2) shows a general decline from 1958 to 1966, recovery from 1966 to 1976, and a decline from 1976 to 1981. The city of Montgomery pumped extensively from the Tuscaloosa aquifer until a surface-water plant was built in 1966. In 1976, the demand for water became greater than the capacity of the surface-water plant, and Montgomery resumed pumping from the Tuscaloosa aquifer. The hydrograph for the well in the Citronelle–Miocene aquifer in southern Baldwin County (location 17, fig. 2) shows an initial decline due to pumping, but it soon stabilizes and shows only seasonal fluctuations because pumping rates have not dramatically increased in the area. The hydrograph for the well in Madison County (location 13, fig. 2), which is used to monitor a Paleozoic carbonate aquifer, shows seasonal declines and recoveries; no long-term decline has occurred. This aquifer is recharged locally from precipitation and by the Tennessee River, and pumpage is small in relation to the amount of available recharge. Also, the observation well is not near any large pumping wells.

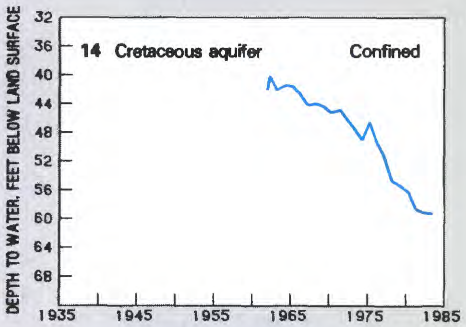
In summary, trends in water levels are not consistent throughout the State. Long-term water-level declines in the Coastal Plain aquifers of Alabama are common where pumpage has increased during the past 40 years. Significant declines are not common in the non-Coastal Plain Paleozoic carbonate aquifers.

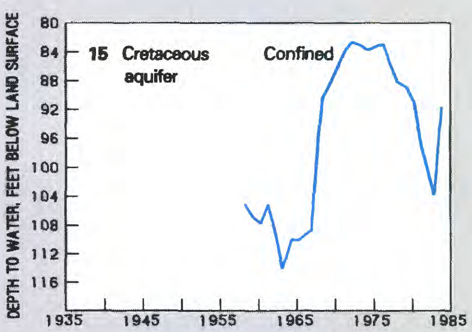
GROUND-WATER MANAGEMENT

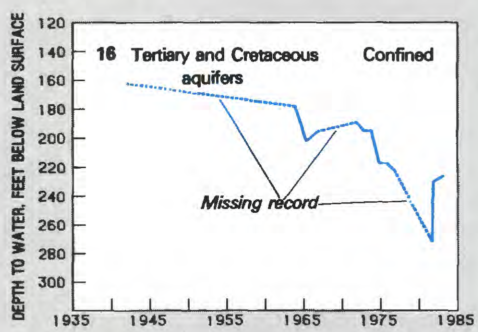
Alabama has very little legislation pertaining to ground-water management. The Public Water Supply Section of the Water Division of the Alabama Department of Environmental Management (ADEM) regulates public-water supplies. Their regulation, however, mainly concerns the potability of the water and the adequacy of a water-supply system to meet demands. The ADEM certifies well drillers and develops well standards but generally does not participate in the selection of well sites or regulate the spacing of wells. Permits are required by the ADEM for any well within the Coastal Area Zone that produces 50 gal/min or more. The ADEM investigates reports of ground-water contamination and has the authority to close wells that produce water that is hazardous for human consumption. Self-supplied industrial, commercial, irrigation, and other agricultural users of ground water are not regulated in Alabama.

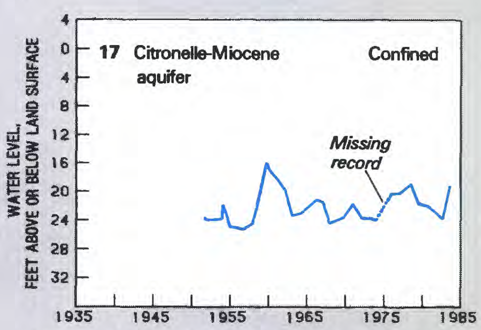
The Geological Survey of Alabama and the ADEM, in cooperation with the U.S. Geological Survey, maintain a statewide water-data network and conduct investigations of Alabama's water resources. The research, data collection, and analyses provided by this cooperative program form an information base upon which ground-water management decisions can be made.

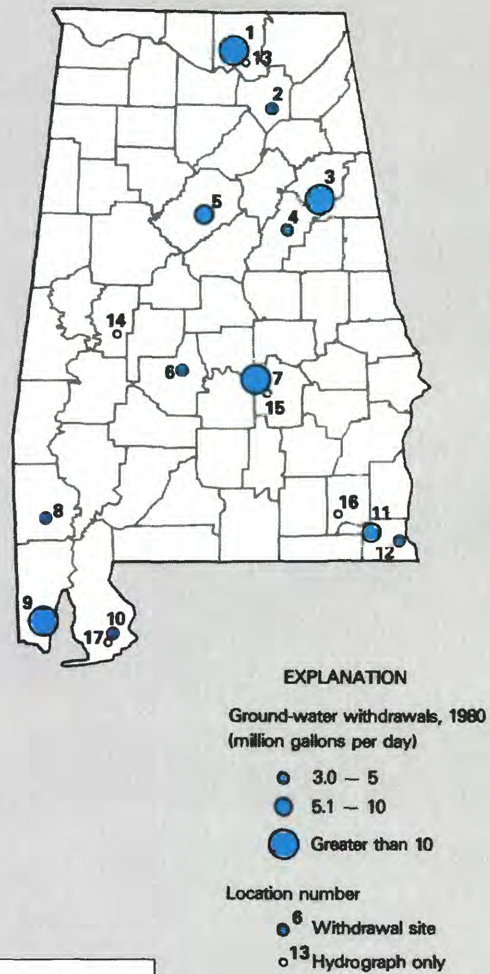












WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Huntsville	Paleozoic carbonate. . . .	Public supply.
2	Marshall County.	. . . .do	Industrial.
3	Anniston	. . . .do	Public supply.
4	Talladega.	. . . .do	Do.
5	Jefferson County	. . . .do	Industrial.
6	Selma.	Cretaceous	Public supply.
7	Montgomery.	. . . .do	Do.
8	Washington County. . .	Citronelle-Miocene	Industrial.
9	Mobile County	. . . .do	Do.
10	Baldwin County.	. . . .do	Agriculture.
11	Dothan.	Tertiery, Cretaceous . . .	Public supply.
12	Houston County	Floridan, Tertiary.	Agriculture.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Alabama. (Sources: Withdrawal data from Baker, 1983; water-level data from U.S. Geological Survey files.)

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Prepared by John C. Scott, John S. Williams, and Ann K. Sparkes

For further information contact District Chief, U.S. Geological Survey, 520 19th Avenue, Tuscaloosa, AL 35401

ALASKA
Ground-Water Resources

Alaska has abundant surface-water resources, but many of the streams and lakes are frozen for most of the year and most of the larger streams transport glacial silt that makes the water unacceptable for many uses. These factors lend special significance to ground water as a source of supply, even though permafrost (perennially frozen ground) profoundly affects the occurrence and availability of ground water in all but the south coastal regions (Williams, 1970; fig. 1). Permafrost forms a virtually impermeable layer that restricts recharge, discharge, and movement of ground water, functions as a confining layer, and decreases the volume of unconsolidated deposits and bedrock in which water may be stored (Zenone and Anderson, 1978, p. 1).

Ground water constitutes 22 percent of total water use in the State. Aquifers provide water to 276,000 people (69 percent of the population), of which 172,000 rely on public water-supply systems and 104,000 on rural (private) systems. Ground-water withdrawals for various uses in 1980 and related statistics are given in table 1.

GENERAL SETTING

Major landforms of Alaska include three great mountain ranges—the Coastal, the Alaskan, and the Brooks—from south to north; a broad interior lowland that is drained by large rivers and contains scattered highlands and plateaus; and large coastal plains, valleys, and river deltas (Wahrhaftig, 1965). The principal mountain ranges have cores of igneous and metamorphic rocks, which are overlain by younger sedimentary and igneous rocks. In most of the State, the bedrock is covered by unconsolidated deposits of glacial and alluvial origin.

Because of its large geographic area, climatic conditions differ considerably across the State. Average annual temperatures range from 10°F in northern Alaska to 45°F in the southeastern coastal areas; extremes range from -80° to 100°F, which occur in the interior lowland. Recorded annual precipitation ranges from about 5 inches (in.) on the north slope of the Brooks Range to 300 in. along the southeastern coast. A large amount of precipitation and relatively low temperatures in the coastal mountains of southeastern and south-central Alaska favor the formation and persistence of glaciers and perennial snowfields, which now cover nearly 30,000 square miles (mi^2), or about 5 percent of the State. Melting snow and ice in glaciated areas provide a water source not directly related in time to local precipitation. The meltwater has a regulatory or moderating effect on streamflow variability and, in turn, on ground-water recharge along alluvium-filled glacial valleys (Zenone and Anderson, 1978, p. 2).

Table 1. Ground-water facts for Alaska

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	276
Percentage of total population	69
From public water-supply systems:	
Number (thousands)	172
Percentage of total population	43
From rural self-supplied systems:	
Number (thousands)	104
Percentage of total population	26
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	220
Ground water only (Mgal/d)	49
Percentage of total	22
Percentage of total excluding withdrawals for thermoelectric power	26
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	23
Percentage of total ground water	47
Percentage of total public supply	43
Per capita (gal/d)	134
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	11
Percentage of total ground water	22
Percentage of total rural domestic	99
Per capita (gal/d)	105
Livestock:	
Ground water (Mgal/d)	0
Percentage of total ground water	0
Percentage of total livestock	0
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	14
Percentage of total ground water	31
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	9
Excluding withdrawals for thermoelectric power	11
Irrigation withdrawals:	
Ground water (Mgal/d)	0
Percentage of total ground water	0
Percentage of total irrigation	0

PRINCIPAL AQUIFERS

Principal aquifers in Alaska consist of unconsolidated alluvium and glacial deposits, and consolidated clastic and carbonate sedimentary rocks. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics in Alaska

[Mgal/d = million gallons per day; gal/min = gallons per minute; ft = feet. Note: Permafrost restricts availability of ground water, especially in rocks of little permeability. Sources: Reports of the U.S. Geological Survey, Alaska Department of Environmental Conservation, and the Alaska Department of Natural Resources]

Aquifer name and description	Water withdrawals (Mgal/d)	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Unconsolidated aquifers: Alluvial and glacial outwash deposits. Confined to unconfined.	48	50 - 200	5 - 10	20	Individual private-supply wells in thin alluvium or mixed glacial deposits.
		100 - 400	50 - 1,000	3,000	Major supply wells in thick alluvium, glacial outwash deposits. Provides public supply at Anchorage and Fairbanks, industrial supply for Kenai Peninsula.
Bedrock aquifers: Igneous metamorphic, and sedimentary rocks. Generally unconfined.	1	50 - 500	1 - 10	25	Source for most private wells in upland areas, particularly near Anchorage and Fairbanks.

Unconsolidated Aquifers

The greatest volume of ground water in Alaska is stored in alluvium of river valleys, including flood plains, terraces, and alluvial fans of major valleys and smaller mountain and upland valleys. Alluvial deposits in the valleys of the Yukon, the Tanana, the Kuskokwim, the Kobuk, and the Susitna Rivers have a large recharge potential because they are connected hydraulically to the extensive surface-water system. In the lower Tanana River basin, for example, the maximum known thickness of alluvium is 2,000 feet (ft) (Anderson, 1970), and wells less than 200 ft deep may yield as much as 3,000 gallons per minute (gal/min).

Coastal basins and valleys are filled by glacial till and fine-grained glaciolacustrine materials that are interbedded with more permeable, water-worked deposits of sand and gravel. The largest and best-known ground-water system of this type is that of the Cook Inlet lowland, particularly in the Kenai and Anchorage areas, where alluvium of glacial outwash origin that is confined by glacial, lacustrine, and estuarine deposits yields as much as 1,500 gal/min to wells.

Alluvium-filled coastal valleys along the Gulf of Alaska (such as those in the Seward area) and in mountainous southeastern Alaska (such as that of the Mendenhall River near Juneau) probably contain large, but as yet not fully explored ground-water supplies. However, freshwater aquifers in these areas may be connected hydraulically to the ocean, and extensive ground-water development potentially could cause saltwater intrusion.

Because most ground-water development in Alaska is from unconsolidated aquifers, virtually all available water-quality data are for those aquifers. Known dissolved-solids concentrations of water from unconsolidated aquifers range from about 25 milligrams per liter (mg/L) in shallow stream-channel alluvium to 64,000 mg/L in shallow coastal wells, but most sampled ground water contains less than 250 mg/L of dissolved solids and is suitable for most uses (Feulner, Childers, and Norman, 1971, p. 39). Very mineralized ground water occurs in the Copper River basin (reported dissolved-solids concentrations of 2,400 mg/L in a well and 14,500 mg/L in a spring, both near Glennallen) and in many parts of the continuous permafrost zone (fig. 1). Iron is present in objectionable concentrations (more than about 0.3 mg/L of iron causes staining of laundry and plumbing fixtures) in a large percentage of shallow wells in most areas of the State. Other constituents that are present locally in undesirable concentrations include nitrate as nitrogen (as much as 60 mg/L) and arsenic (as much as 10 mg/L) at Fairbanks (Johnson and others, 1978).

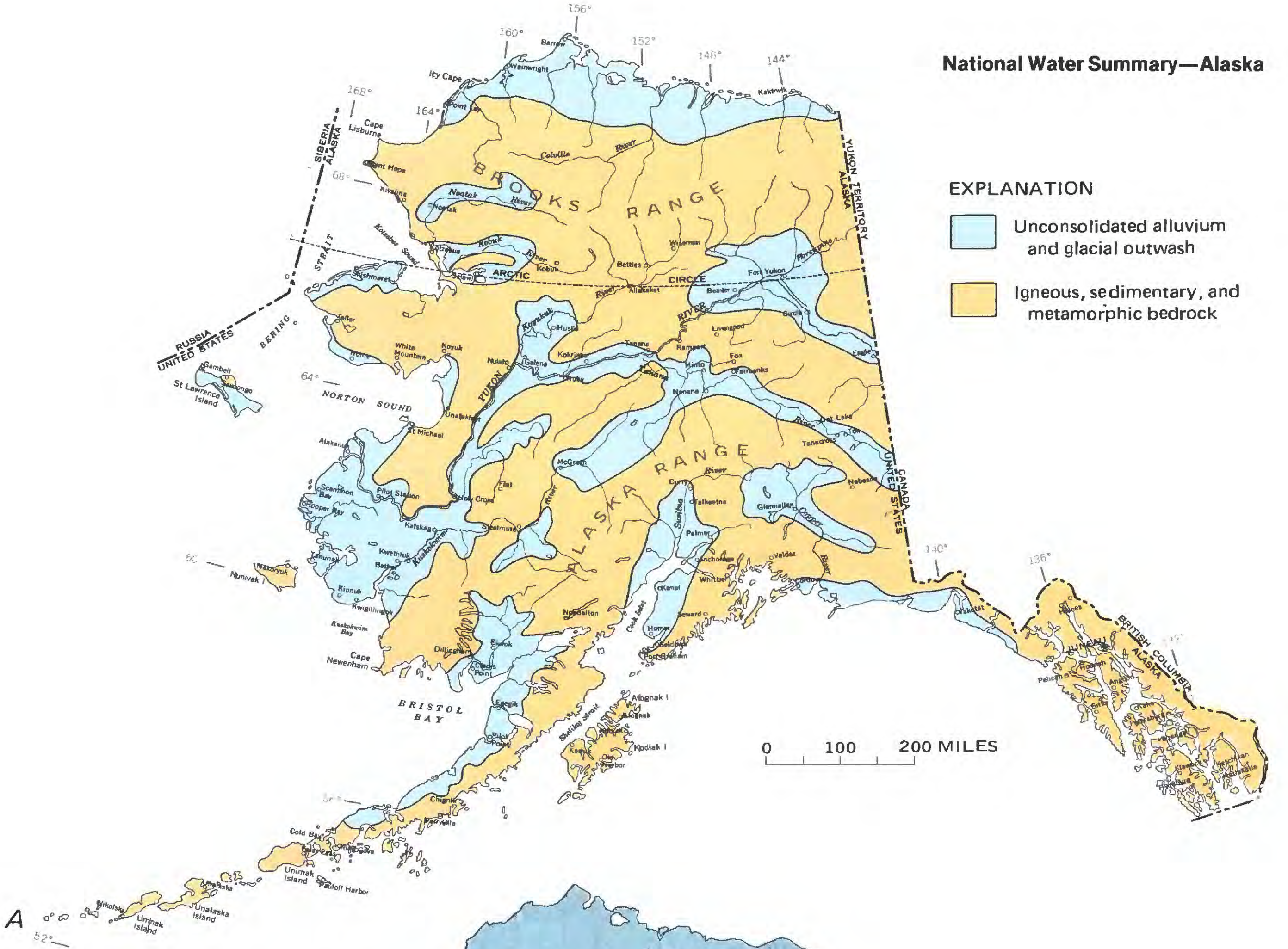
Bedrock Aquifers

Glacial and alluvial deposits are either very low in permeability, thin, or absent in approximately 75 percent of Alaska. In such areas, appreciable amounts of ground water are present only in consolidated rocks. Carbonate rocks in the northeastern Brooks Range in northern Alaska provide extensive reservoirs for ground water. Individual springs in these rocks discharge as much as 16,000 gal/min. Sandstone and alternating strata of sand, silt, and clay are widespread throughout the State, but such rocks have been explored for water only in the western Kenai Peninsula where they are poor aquifers because of low permeability. Probably the most intensive development of bedrock aquifers is in the uplands near Fairbanks (fractured schist) and in a few places in southeastern Alaska. These rocks generally provide only modest amounts of water (well yields of 10 gal/min or less) that are adequate for single household needs.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Much of the ground-water withdrawal in Alaska occurs within the municipality of Anchorage (location 4, fig. 2), where more than one-half of the State's population resides. About 50 other communities rely solely on ground water for their supply. The only areas outside Anchorage with large-scale ground-water use are the Tanana River valley in interior Alaska (locations 1, 2, fig. 2), and the industrial complex on the Kenai Peninsula (location 5, fig. 2).

The withdrawal and use of ground water are increasing with the growth of population and continuing industrial and commercial development. Analysis of observation-well data from the Anchorage, Fairbanks, and Kenai areas, however, indicates that past and present pumping has not resulted in such adverse effects as saltwater encroachment in coastal areas or excessive drawdown.



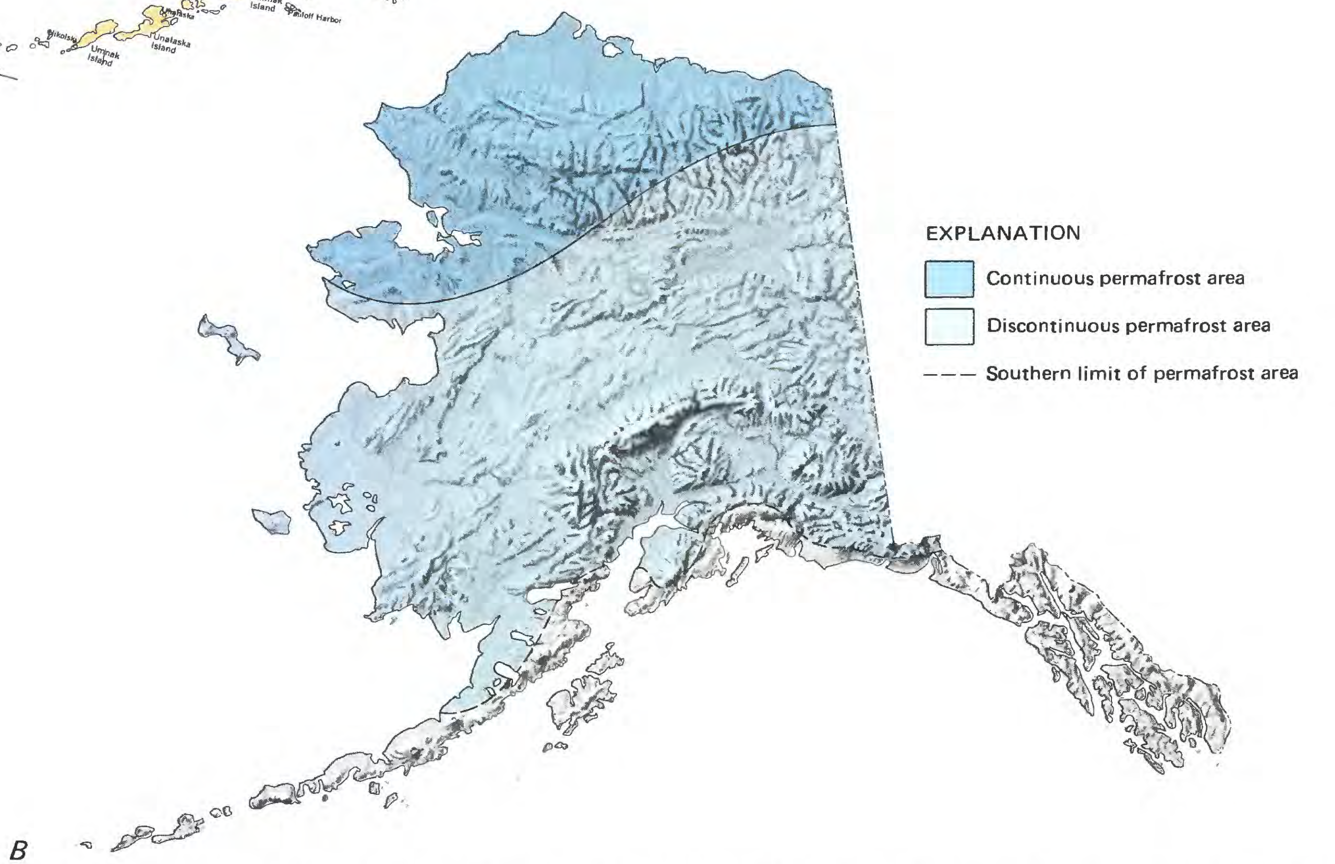


Figure 1. Principal aquifers in Alaska. *A*, Geographic distribution. *B*, Geographic distribution of permafrost areas. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Wahrhaftig, 1965. *B*, Williams, 1970.)

GROUND-WATER MANAGEMENT

The Alaska Water Use Act, Alaska Statutes 46.15.010-270, was enacted in 1966 to regulate appropriation and use of water in the State. This Act gave statutory definition to the doctrine of prior appropriation (first in time, first in right) authorized by the State Constitution. The Act also established a procedure for maintaining existing rights and providing new rights to ground and surface waters of Alaska. The original regulations implementing the Water Use Act were amended extensively on December 29, 1979, and incorporated as 11 AAC 93, Water Management. Those of particular interest relate to the appropriation of water, water-well standards, and temporary water use. The latest amendments to the Alaska Water Use Act include legislation relating to geothermal development and reservation of water (Alaska Department of Natural Resources, 1981).

Alaska's Water Quality Standards, established in Title 18, Chapter 70 of Alaska Administrative Code, identify the uses of the State's waters and set criteria, which limit man-induced pollution, to protect these water uses. Procedures and criteria for changing the identified uses of a water body are included in the standards (Alaska Department of Environmental Conservation, 1979).

The Alaska Department of Natural Resources (ADNR), Division of Geological and Geophysical Surveys (DGGS) is the designated State agency responsible for water-data collection. The DGGS, in cooperation with the U.S. Geological Survey and other State and Federal agencies, has developed and implemented an Alaskan Water Resources Evaluation (AWARE) Plan to coordinate water-data collection and water resource study activities in the State (U.S. Geological Survey and Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys, 1984).

The ADNR's Division of Forest, Land and Water Management, Water Management Section, is responsible for planning and administering the appropriation of water in the State, and the Department of Environmental Conservation is responsible for implementation of the provisions of Alaska's Water Quality Standards. Future development, protection, and conservation of the State's water resources depend on these important functions.

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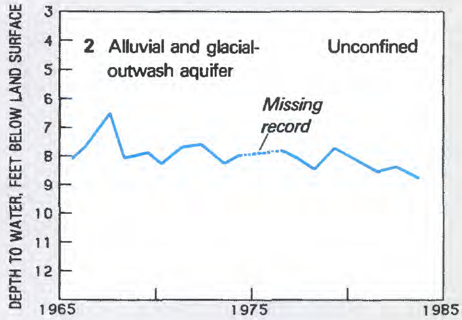
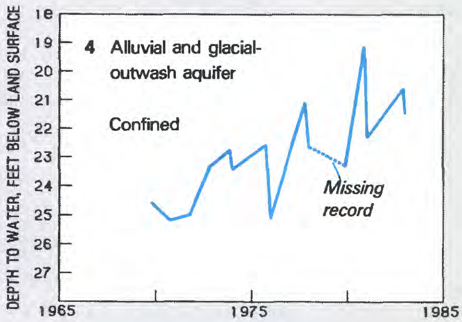
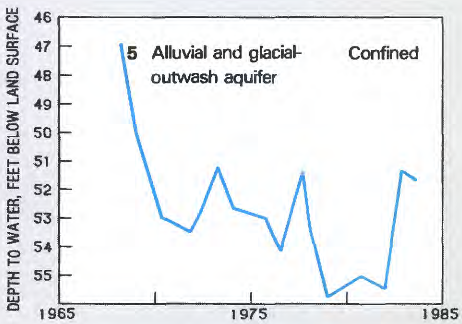
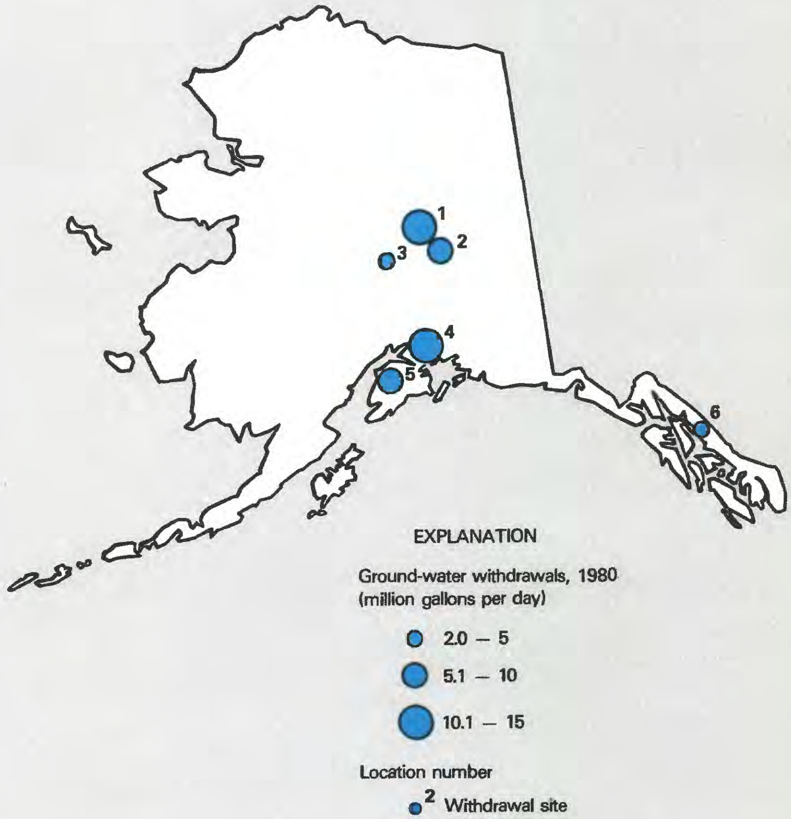
Prepared by Charles E. Sloan, Philip A. Emery, and Chester Zenone

For additional information contact District Chief, U.S. Geological Survey, 4230 University Drive, Anchorage, AK 99508-4664









WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Fairbanks	Alluvial and glacial-outwash	Public supply.
2	Eielson	....do	Industrial.
3	Clear	....do	Do.
4	Anchorage	....do	Public supply.
5	Kenai	....do	Industrial.
6	Juneau	....do	Rural supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Alaska. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

ARIZONA
Ground-Water Resources

The availability of adequate and potable water supplies in Arizona has had a great effect on the location of cities and croplands. Agriculture depends almost entirely on irrigation because annual rainfall is low. The amount of surface water available is not sufficient to meet continually increasing demands, thus, ground-water reservoirs are of prime importance as a source of water. Many towns and cities—including the second largest in the State, Tucson, depend entirely on wells for water supply. Except during infrequent periods of greater than normal streamflow, all available surface water is appropriated, and any increased water demand must be supplied by ground water. In 1980, about 58 percent of the total water supply in the State came from its ground-water reservoirs (table 1).

The principal use of ground water is for irrigation of crops, although municipal and industrial uses are increasing steadily. Arizona ranks second in the Nation in population growth; population increased about 53 percent from 1970 to 1980 (Valley National Bank of Arizona, 1981, p. 3). As population increases, some cropland is being retired in favor of housing developments, and ground-water withdrawals for public supply are increasing. More industrial enterprises also are being developed in the State. In 1975, less than 9 percent of the ground water withdrawn was used for public supply, rural, and industrial purposes (Babcock, 1977), whereas in 1980 about 12 percent was used for these purposes (table 1).

Table 1. Ground-water facts for Arizona

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	1,770
Percentage of total population	65
From public water-supply systems:	
Number (thousands)	1,490
Percentage of total population	55
From rural systems:	
Number (thousands)	280
Percentage of total population	10
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	[1]7,300
Ground water only (Mgal/d)	4,200
Percentage of total	58
Percentage of total excluding withdrawals for thermoelectric power	57
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	300
Percentage of total ground water	7
Percentage of total public supply	54
Per capita (gal/d)	201
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	32
Percentage of total ground water	0.8
Percentage of total rural domestic	100
Per capita (gal/d)	114
Livestock:	
Ground water (Mgal/d)	9.8
Percentage of total ground water	0.2
Percentage of total livestock	82
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	180
Percentage of total ground water	4
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	72
Excluding withdrawals for thermoelectric power	88
Irrigation withdrawals:	
Ground water (Mgal/d)	3,700
Percentage of total ground water	88
Percentage of total irrigation	58

[1] The total freshwater withdrawal (as published in Solley and others, 1983) has been reduced by the amount of surface water that is returned to the Colorado River. For additional information, see U.S. Geological Survey, 1982b.

PRINCIPAL AQUIFERS

The principal aquifers in Arizona consist of unconsolidated alluvium, consolidated sedimentary rocks, and crystalline igneous and metamorphic rocks. Arizona is divided into three water provinces, which are essentially synonomous with physiography—the Plateau uplands province in the northern part of the State, the Basin and Range lowlands province in the southern part of the State, and the Central highlands province, which is transitional between the other two provinces (fig. 1). The occurrence of ground water differs greatly in each of the provinces. The aquifers in Arizona are described according to the water province in which they occur. The aquifers also are described in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

PLATEAU UPLANDS

In the Plateau uplands province, the principal aquifers are beds of fine-grained permeable sandstone interbedded with relatively impermeable siltstone and claystone (fig. 1, table 2). The Navajo and Coconino Sandstones are two of the most important units in the province. The sandstones provide large reservoirs for the storage of ground water, but well yields are small except where the rocks have been fractured and faulted. In places, the claystone and siltstone layers confine the water in the underlying aquifers under artesian pressure.

Dissolved-solids concentrations in the ground water in the Plateau uplands range from 90 to about 60,000 milligrams per liter (mg/L). Wells that tap the sandstone aquifers in the northeastern part of the area yield water that contains from about 200 to 25,000 mg/L of dissolved solids. In some areas, water from the sandstone aquifers contains too much dissolved solids for most uses (Kister, 1973).

Table 2. Aquifer and well characteristics in Arizona

[Gal/min = gallons per minute; ft = feet. Source: Reports of the U.S. Geological Survey and the Arizona Department of Water Resources]

Aquifer name and description	Well characteristics			Remarks
	Depth, common range (ft)	Yield (gal/min) Common range	Yield (gal/min) May exceed	
Alluvial aquifers: Generally sand, gravel, silt, and clay. Occur in the Basin and Range lowlands and parts of the Central highlands. Confined and unconfined	100 - 2,000	1,000	2,500	Thickness from a few hundred to about 10,000 ft. Deposits grade in texture from large boulders near mountains to fine-grained sediments along axis of valleys. In places, dense clay beds form confining layers for permeable sand and gravel beds beneath. Provides water for most cities and extensive irrigated areas in southern part of State.
Sandstone aquifers: Mostly fine-grained sandstone units; fracturing and faulting increases permeability; in places, siltstone and claystone layers function as confining beds. Occur in parts of the Central highlands and in the Plateau uplands. Confined and unconfined.	50 - 2,000	0 - 50	500	Thickness from about 200 to 500 ft. Aquifers may be as much as 1,000 ft below land surface and are separated by thick, relatively impervious layers. Coconino and Navajo Sandstones provide largest supply of water for all uses in central and northern parts of State.
Low-yielding bedrock aquifers: Crystalline and sedimentary rocks. Permeable only where extensively fractured and faulted. Confined and unconfined.	50 - 1,000	0.5 - 2	200	These rocks are generally not considered to be aquifers but do supply usable quantities of water to individual sources for domestic supply in rural areas.

Basin and Range Lowlands

The Basin and Range lowlands province is characterized by rugged mountain ranges separated by broad alluvium-filled basins. The mountains consist of crystalline and consolidated sedimentary rocks that contain usable amounts of water only where extensively fractured or faulted. The thick alluvial deposits in the basins are the major aquifers and provide storage for large amounts of ground water (fig. 1; table 2). The deposits, which consist of sand, gravel, silt, clay, evaporites, and volcanic rocks range in thickness from a few hundred to about 10,000 feet (ft). The capacity of the materials to store and transmit water differs widely among the various basins and in different parts of the same basin. Thick clay and silt beds at various depths can restrict the movement of ground water and decrease well yields. In places, these clay or silt beds form confining layers, and water in the underlying permeable beds may locally be under artesian pressure. The block diagram in figure 1 shows a typical configuration of these aquifers.

The chemical quality of the ground water in the Basin and Range lowlands generally is suitable for all uses. Dissolved-solids concentrations of water in the alluvial basins generally are less than 1,000 mg/L. Brackish water—that which contains between 1,000 and 10,000 mg/L of dissolved solids —is present mainly in areas along and near the Gila River, along the southernmost reach of the Colorado River, and near the towns of Willcox (Willcox basin), Casa Grande (lower Santa Cruz basin), and Tucson (upper Santa Cruz basin) (Kister, 1973).

Recharge to the aquifers in the Basin and Range lowlands is limited by small amounts of precipitation and large evaporation rates. Recharge from direct infiltration of precipitation is negligible. Infiltration of runoff from the adjacent mountain areas, at mountain fronts, and in stream channels probably is the most important source of recharge to the aquifers in the alluvial basins (Halpenny and others, 1952, p. 16). In a few basins, the ground-water reservoir is recharged from perennial reaches of through-flowing streams; for the most part, streams in the area are ephemeral and recharge takes place only during times of flow. Some water is recharged by seepage from irrigated fields and from unlined canals.

Central Highlands

The Central highlands province is a mountainous area that separates the Plateau uplands from the Basin and Range lowlands. The province consists principally of rugged, sharply pinnacled ranges and volcanic mountains. The igneous, metamorphic, and consolidated sedimentary rocks that form the core of the province contain usable amounts of water only where fractured or faulted. A few valleys in the province are filled with alluvium that provides minor amounts of water. Available data indicate the ground water in the Central highlands generally contains less than 1,000 mg/L of dissolved solids, although some springs yield saline water to streams (Kister, 1973).

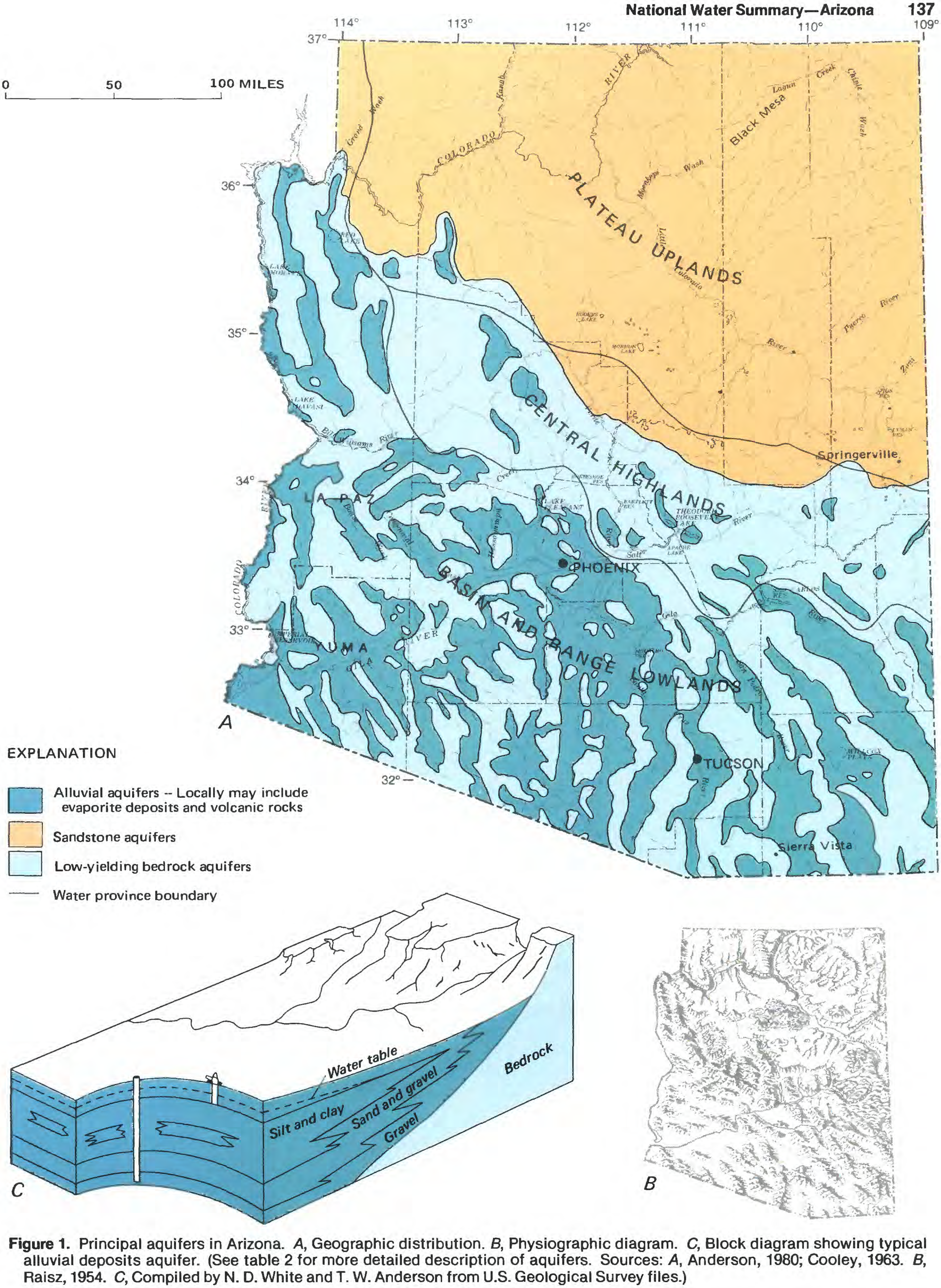


Figure 1. Principal aquifers in Arizona. *A*, Geographic distribution. *B*, Physiographic diagram. *C*, Block diagram showing typical alluvial deposits aquifer. (See table 2 for more detailed description of aquifers. Sources: *A*, Anderson, 1980; Cooley, 1963. *B*, Raisz, 1954. *C*, Compiled by N. D. White and T. W. Anderson from U.S. Geological Survey files.)

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The Basin and Range lowlands province is the most developed of the three water provinces. In 1980, nearly 96 percent of the total ground water withdrawn in the State was withdrawn in this province, and about 84 percent of the water was used for the irrigation of crops (U.S. Geological Survey, 1982a).

The Salt River Valley and the lower Santa Cruz basin are, and have been for many years, the areas of largest use (fig. 2). The other areas for which ground-water withdrawal is shown in figure 2 also use large amounts of ground water principally for irrigation. Through 1980, nearly 180 million acre-feet of water had been withdrawn from the ground-water reservoirs in the province (U.S. Geological Survey, 1982b). The withdrawal is balanced only partly by recharge. In nearly all the areas shown in figure 2, and in other areas as well, water levels generally are declining in response to the withdrawal of ground water at a rate in excess of the rate of replenishment. In part of the Salt River Valley, a water-level decline of 400 ft occurred from 1923 to 1976; most of the decline has occurred since the 1940's when intense ground-water development began (Laney and others, 1978). From 1923 to 1977, declines of nearly 500 ft occurred in part of the lower Santa Cruz basin (Konieczki and English, 1979).

Land subsidence and earth fissures have occurred in some areas of large water-level decline. In an area of about 120 square miles in the lower Santa Cruz basin, the land subsided more than 7 ft from 1952 to 1977 (Laney, Raymond, and Winikka, 1978).

Hydrographs for the Willcox and lower Santa Cruz basins and west Salt River Valley (location 7, 2, and 1A, respectively, fig. 2) show water-level changes since 1950 that are the result of the removal of water from storage in the alluvial deposits, although the rate of decline has decreased in some areas since about 1965 to 1970 as a result of increased recharge or a reduction in pumpage. The hydrograph for a well near east Salt River Valley (location 1B, fig. 2) shows the effect of unusually high flows in the Salt River in recent years (Mann and Rohne, 1983) that have recharged the aquifer.

In the Plateau uplands and the Central highlands provinces, ground-water development is small compared to that in the Basin and Range lowlands province. The use of ground water is limited to irrigation of a few thousand acres, scattered industrial and utility sites, and a few small population centers. For the most part, the small amount of ground water withdrawn has not resulted in any discernible pattern of rise or decline in water levels. However, some decline has occurred in places such as Little Chino Valley in the Central highlands. In the irrigated part of this valley, water levels in a few wells declined as much as 75 ft from 1940 to 1982 (Remick, 1983). Elsewhere in the two provinces, water levels have declined only a few feet.

GROUND-WATER MANAGEMENT

As much of the foregoing material indicates, Arizona's major water problem is the imbalance between the water needed for various uses and the available supply. The Arizona Ground-Water Management Act, enacted on June 12, 1980, is the first comprehensive legislative framework for managing the ground-water resources of the State (Arizona Department of Water Resources, 1982). The ground-water code is found in the Arizona Revised Statutes, Sections 45-401 through 45-637. Before this Act, only the Critical Ground-Water Code of 1948 had attempted to alleviate the problem of overdraft. That code provided for the establishment of critical ground-water areas in which the cultivation of new irrigated acreage was prohibited; however, the ground-water overdraft problem was not reduced by the code. The 1980 Act created the Department of Water Resources and made it responsible for administering the law's complex provisions. The Act established four Active Management Areas (AMA's)—areas in which intensive ground-water management is needed because of the large and continuous ground-water overdraft. Within the AMA's, the law requires a 45-year water-conservation and water-management program. The management goal is "safe yield" by the year 2025. Safe yield is the concept whereby long-term ground-water discharge is equal to ground-water recharge. Further details of the ground-water code for Arizona may be obtained from the Arizona Department of Water Resources.

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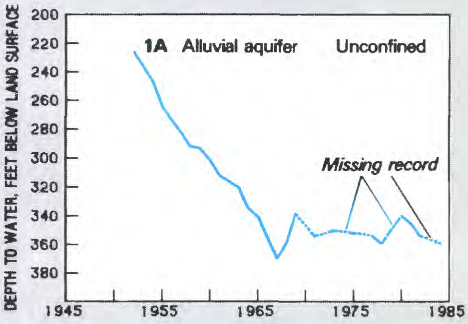

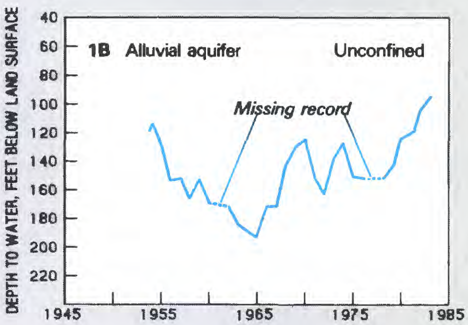

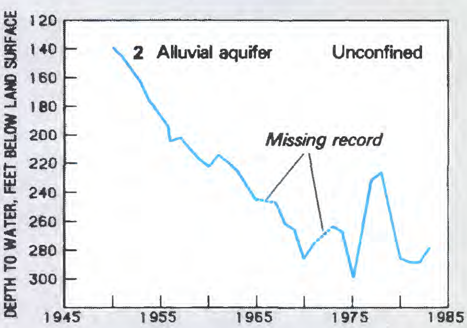

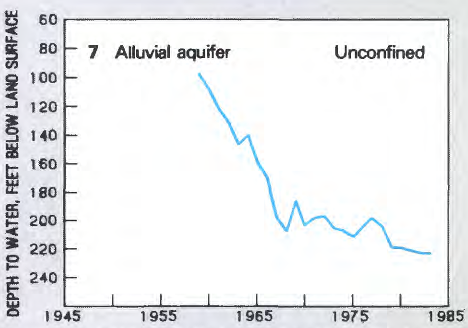

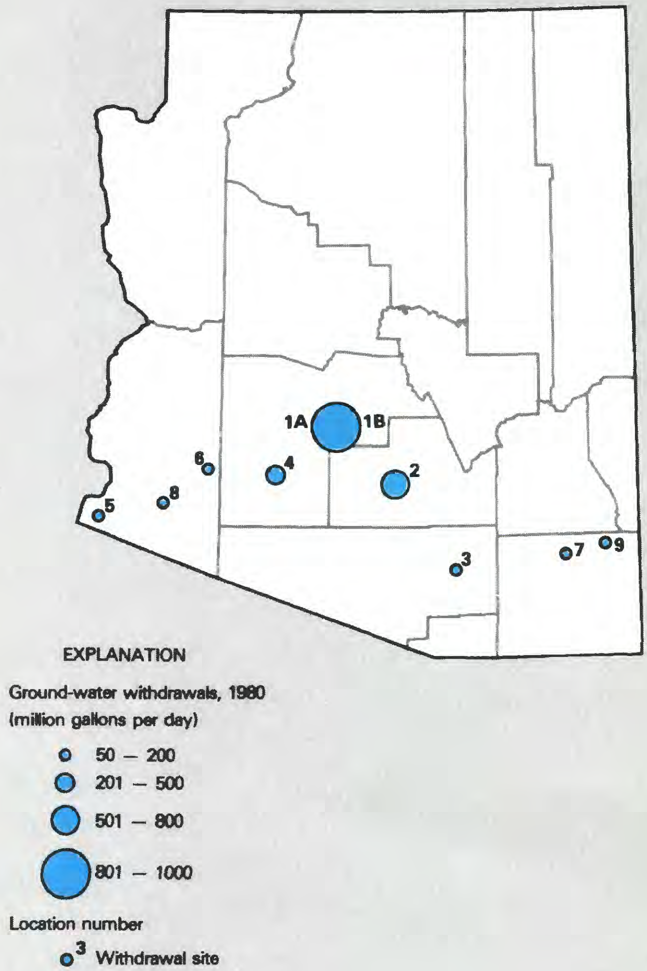

WITHDRAWAL SITES

[Aquifers are all in alluvial deposits]

No. on map	Geographic area	Principal uses
1A	West Salt River Valley . . .	Irrigation, public supply.
1B	East Salt River Valley . . .	Do.
2	Lower Santa Cruz basin . .	Irrigation.
3	Upper Santa Cruz basin . .	Irrigation, public supply.
4	Gila Bend basin	Irrigation.
5	Yuma.	Do.
6	Gila River, Painted Rock to Texas Hill.	Do.
7	Willcox basin	Do.
8	Gila River, Texas Hill to Dome.	Do.
9	San Simon basin.	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Arizona. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

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Prepared by Natalie D. White and Thomas W. Anderson

For further information contact District Chief, U.S. Geological Survey, 300 W. Congress Street, Tucson, AZ 85701-1393

ARKANSAS
Ground-Water Resources

Ground water plays a major role in satisfying the water-supply needs in Arkansas. Ground-water sources provide 81 percent of the State's water for irrigation, public and rural supplies, and industrial uses (table 1). The largest withdrawal of ground water [3,800 million gallons per day (Mgal/d)] is for irrigation, mostly in the eastern part of the State. Nearly all municipal and industrial supplies in the southeastern one-half of the State are obtained from ground-water sources. Ground water provides 330 Mgal/d for self-supplied industries and 155 Mgal/d for public and rural domestic supplies. One-half of the population of the State depends on ground water as a source of drinking water. Between 1975 and 1980, the use of ground water in the State increased 56 percent (Holland and Ludwig, 1981, p. 25). Most of the ground water withdrawn (88 percent) is used for irrigation.

GENERAL SETTING

Arkansas is divided physiographically into two almost equal areas—the Gulf Coastal Plain and the Interior Highlands (fig. 1). The occurrence of ground water is associated closely with the types of rocks that underlie each physiographic area. Ground water is abundant in the Gulf Coastal Plain but is relatively scarce in the Interior Highlands.

The Gulf Coastal Plain, which encompasses approximately 27,000 square miles (mi^2) in the southeastern one-half of Arkansas, is underlain by thick alluvial deposits and by gently dipping unconsolidated and semiconsolidated sediments. The sediments that comprise the Gulf Coastal Plain are of marine and continental origin and consist of alternating sequences of gravel, sand, silt, and clay, with lenses of limestone and lignite. In general, the marine deposits are composed of clays that confine water in the aquifers.

The Interior Highlands, which encompasses about 31,000 mi^2 in the northwestern one-half of the State, is underlain by thick sequences of consolidated rocks that consist mostly of limestone, dolomite, sandstone, and shale. The rocks are extremely folded and faulted, and their primary porosity has been reduced greatly by compaction and cementation (Cordova, 1963). Water occurs primarily in fractures in the sandstone and in solution openings in the carbonates.

Precipitation is the source of recharge to the ground-water system in Arkansas. Precipitation averages 49 inches (in.) (1951–80) annually and ranges from 39 in. near Fort Smith to 59 in. in the higher elevations in west-central Arkansas. Of the 49 in. of precipitation that falls on the land surface, an average of about 2 in. recharges the ground-water system. The recharge rate differs from place to place, depending on the permeability of the surficial material. In the eastern part of the State, where the alluvial aquifer is covered by thick clay, the recharge rate is only about 0.4 in. per year (Broom and Lyford, 1981).

Table 1. Ground-water facts for Arkansas

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Population data from Arkansas Industrial Development Foundation, 1981 (unpublished data); withdrawal data from Hall and Holland, 1984]

Population served by ground water, 1981	
Number (thousands)	1,440
Percentage of total population	50
From public water-supply systems:	
Number (thousands)	819
Percentage of total population	28
From rural self-supplied systems:	
Number (thousands)	621
Percentage of total population	22
Freshwater withdrawals, 1981	
Surface water and ground water, total (Mgal/d)	33,000
Ground water only (Mgal/d)	4,300
Percentage of total	13
Percentage of total excluding withdrawals for thermoelectric power	81
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	100
Percentage of total ground water	2
Percentage of total public supply	42
Per capita (gal/d)	127
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	55
Percentage of total ground water	1
Percentage of total rural domestic	100
Per capita (gal/d)	89
Livestock:	
Ground water (Mgal/d)	23
Percentage of total ground water	1
Percentage of total livestock	36
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	330
Percentage of total ground water	8
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	1
Excluding withdrawals for thermoelectric power	55
Irrigation withdrawals:	
Ground water (Mgal/d)	3,800
Percentage of total ground water	88
Percentage of total irrigation	86

PRINCIPAL AQUIFERS

Most of the ground-water supplies in the State are obtained from six aquifers or aquifer systems—the alluvial, the Cockfield, the Sparta Sand, the Wilcox, the Nacatoch Sand, and the Ozark. Although other ground-water sources may be important locally, these six aquifers are regionally significant, and, except for rural domestic supplies, they constitute the source of nearly all ground-water withdrawals in the State. The aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

ALLUVIAL AQUIFER

Alluvium is the principal source of water for irrigation. Alluvial deposits blanket much of eastern Arkansas, the Red River Valley in southwestern Arkansas, and isolated areas along the Arkansas River in the Interior Highlands (fig. 1). The alluvium is as much as 250 feet (ft) thick in parts of

Table 2. Aquifer and well characteristics in Arkansas

[Gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Arkansas Geological Commission]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Alluvial aquifer: Sand and gravel at the base grades upward to silt and clay near the surface. Confined to unconfined.	100 - 150	200	1,000 - 2,000	5,000	Water used primarily for irrigation. Generally hard and contains much iron. Intruded by saline water in places. Water-level declines of as much as 80 ft in Arkansas, Cross, and Poinsett Counties.
Cockfield aquifer: Interbedded fine to medium sand, clay, and lignite. Confined except in the outcrop.	350 - 500	700	100 - 350	500	Used mostly for domestic purposes and for municipal supplies in Chicot and Desha Counties. Water is soft, sodium bicarbonate or sodium chloride type. Contains as much as 1,800 mg/L of chloride in parts of extreme southeastern Arkansas.
Sparta Sand aquifer: Massive fine to medium sand with interbedded clay and lignite. Generally confined.	500 - 1,000	1,200	500 - 1,500	3,000	Equivalent to Memphis Sand ("500-foot sand") in northeastern Arkansas. Principal source of water for municipal and industrial uses in much of the Gulf Coastal Plain south of latitude 35°N. Water-level declines of as much as 320 ft in Columbia, Union, and Jefferson Counties. Declines have induced localized saline-water contamination in places. Saline downdip in southeastern Arkansas.
Wilcox aquifer: Fine to medium sand, silt, clay, and lignite. Generally confined.	750 - 1,100	1,500	50 - 500	2,000	Greatest yields in eastern and northeastern Arkansas. Known as "1,400-foot sand" near Memphis, Tenn. Water a soft, sodium bicarbonate type. Saline in downdip areas. Equivalent to Fort Pillow Sand in Tennessee.
Nacatoch Sand aquifer: Massive cross-bedded sand, limestone lenses, and calcareous clay. Confined.	500 - 800	1,100	150 - 300	500	Equivalent to the McNairy aquifer in Missouri. Contains freshwater in parts of southwestern and northeastern Arkansas. Used mostly for municipal and industrial supplies. Water is a soft, sodium bicarbonate type. Saline in downdip areas.
Ozark aquifer: Sandstone and sandy dolomite. Confined.	600 - 2,400	3,000	150 - 300	500	Includes the Roubidoux Formation and Gunter Sandstone Member of the Van Buren Formation. Principal source of water for municipal and industrial wells in northern Arkansas. Yields hard or very hard calcium-bicarbonate-type water.

eastern Arkansas and is composed of coarse sand and gravel at the base that grades upward to silt and clay near the surface. Wells in the alluvium generally yield from 1,000 to 2,000 gallons per minute (gal/min) but may yield as much as 5,000 gal/min. Water in the alluvium generally is hard, averaging 246 mg/L of hardness as calcium carbonate, and contains iron in excess of 1.0 mg/L (Boswell and others, 1968). In parts of Chicot, Desha, Lincoln, Monroe, and White Counties, the water contains as much as 3,750 mg/L of dissolved solids, which makes it unsuitable for irrigation. The saline water is believed to have migrated upward from underlying, saline-water-bearing beds through faults or abandoned oil test wells. A similar problem exists in the Red River alluvium in parts of Miller and Lafayette Counties (Ludwig, 1972).

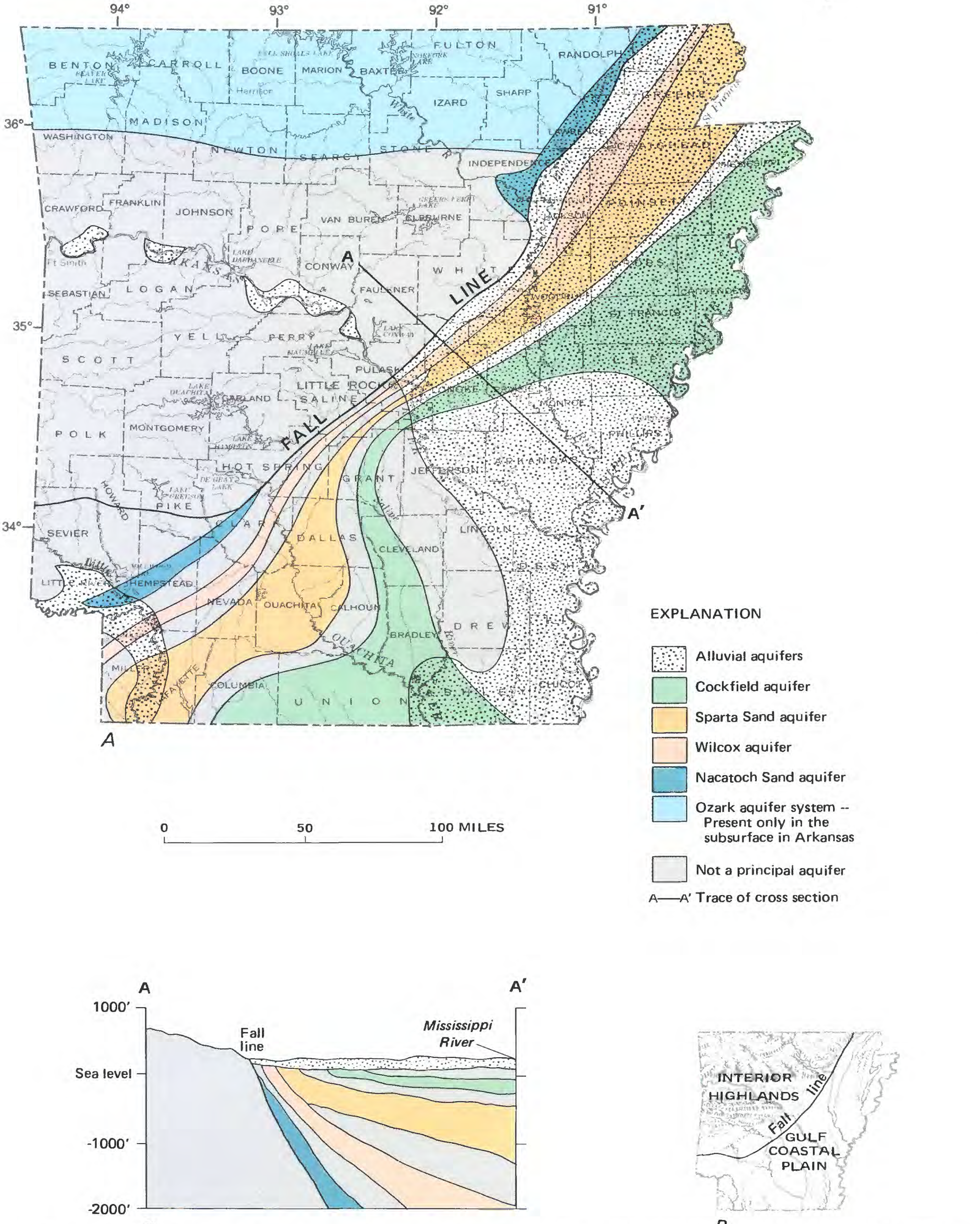


Figure 1. Principal aquifers in Arkansas. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A,C*, Ludwig, 1972 and compiled by A. H. Ludwig from U. S. Geological Survey files. *B*, Raisz, 1954.)

COCKFIELD AQUIFER

The Cockfield aquifer is at or near the surface of the Coastal Plain of southeastern Arkansas. The aquifer, which consists of interbedded fine to medium sand, clay, and lignite, is as much as 400 ft thick in Chicot and Desha Counties. The water generally is suitable for most municipal and industrial uses but, in places, contains iron in excess of 0.3 mg/L, the criterion established by the national drinking-water regulations (U.S. Environmental Protection Agency, 1982). Yields from wells in the Cockfield may exceed 500 gal/min.

SPARTA SAND AQUIFER

The Sparta Sand aquifer is the principal source of water for public and industrial supplies in much of southern and southeastern Arkansas. The aquifer also is being tapped increasingly for irrigation in Arkansas County. The Sparta, which is composed of massive fine to medium sands that contain interbedded clay lenses, is as much as 800 ft thick. Wells that tap the Sparta generally yield from 500 to 1,500 gal/min but may yield as much as 3,000 gal/min. North of about latitude 35°N, the Sparta Sand becomes part of a thick sand sequence known as the Memphis Sand (Hosman and others, 1968). The Memphis Sand is used as a source of water for Memphis, Tenn., but commonly is not used in Arkansas because the water generally contains concentrations of iron greater than 0.9 mg/L.

WILCOX AQUIFER

The Wilcox aquifer occurs throughout most of the Coastal Plain in Arkansas but is a major source of water only in northeastern Arkansas where it is known as the "1,400-foot sand." Wells that tap the Wilcox aquifer in Crittenden and Mississippi Counties yield as much as 2,000 gal/min. Withdrawals are primarily for public and industrial supplies. In southwestern Arkansas, the unit is composed of fine sand and silt and does not yield significant amounts of water. The Wilcox aquifer contains freshwater (less than 1,000 mg/L of dissolved solids) to a depth of 1,500 ft below land surface in Crittenden County.

NACATOCH SAND AQUIFER

The Nacatoch Sand aquifer underlies the Gulf Coastal Plain part of the State but contains freshwater only in parts of the northeast and southwest. It is used primarily for public and industrial supplies in Clay, Greene, Randolph, and Lawrence Counties in the northeast and in Nevada, Hempstead, and Little River Counties in the southwest. The Nacatoch Sand aquifer yields as much as 500 gal/min of water to wells in Clay and Greene Counties (Hines and others, 1972). However, water-level declines of more than 40 ft have been noted at Prescott in Nevada County as a result of large municipal withdrawals (Ludwig, 1972). Water in the Nacatoch Sand aquifer generally is soft (less than 30 mg/L of hardness as calcium carbonate) and contains less than 500 mg/L dissolved solids in the freshwater areas.

OZARK AQUIFER

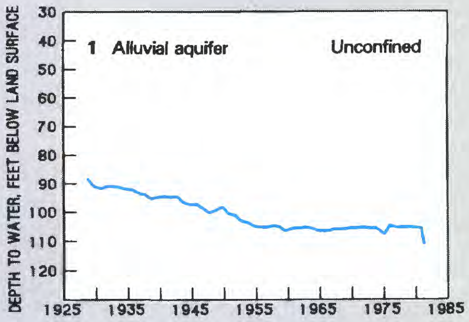
The Ozark aquifer consists primarily of dolomite, sandy dolomite, and sandstone and is the only significant aquifer system, except for the Arkansas River alluvium in the Interior Highlands. It is used in northern Arkansas in an area from Benton and Washington Counties to Randolph and Lawrence Counties (fig. 1). The system includes the Roubidoux Formation and the Gunter Sandstone Member of the Van Buren Formation, which do not crop out in Arkansas. These strata are the principal source of ground water in the northern part of the State. The Roubidoux is 100 to 250 ft thick and is present at depths ranging from 600 ft at the Arkansas–Missouri State line to about 2,300 ft at the southern limits of the area of use. The Gunter Sandstone Member is about 50 ft thick and is 300 to 600 ft below the Roubidoux Formation. The massive dolomites between these aquifers do not yield water. Together, the Roubidoux and Gunter aquifers yield as much as 500 gal/min to wells, but generally yield 150 to 300 gal/min (Lamonds, 1972). Water in the Ozark aquifer system contains less than 1,000 mg/L of dissolved solids throughout the area shown in figure 1.

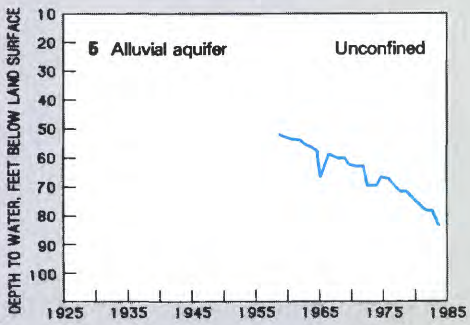
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

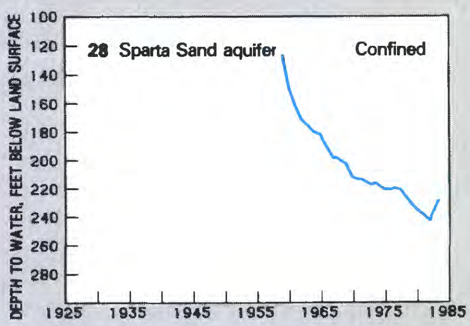
Areas of major ground water withdrawals are shown in figure 2. Most of the ground water used in the State (88 percent) is for irrigation, primarily irrigation of rice. Irrigation is practiced extensively in the Mississippi River alluvial plain, which encompasses all or parts of 27 counties in eastern Arkansas. Irrigation also is important in parts in the Red River Valley in southwestern Arkansas and in the Arkansas River Valley between Little Rock and Fort Smith. Irrigation withdrawals for the 27 counties in eastern Arkansas (locations 1–27, fig. 2) were 3,718 Mgal/d in 1981, or about 99 percent of the total irrigation withdrawals in the State. Irrigation withdrawals for the Grand Prairie, a very productive rice-growing area, are represented by locations 1 to 3. The largest single withdrawal rate was 356 Mgal/d, mostly in western Poinsett County (location 16, fig. 2). Irrigation in western Poinsett and adjacent counties has increased significantly in recent years.

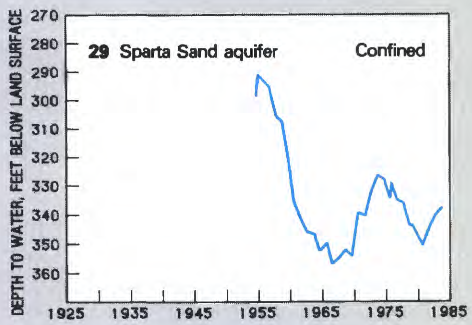
Large sustained ground-water withdrawals for irrigation have caused significant water-level declines in some areas. Water levels in the Grand Prairie and in western Cross, Poinsett, and Craighead Counties are as much as 115 ft below land surface. Only about 20 to 50 ft of saturated thickness remains in some places, and irrigators either are drilling deeper and more costly wells into underlying formations or are developing surface-water sources. Water levels in wells throughout much of the alluvial aquifer have declined at the annual rate of 0.3 to 0.5 ft. Water levels in wells in western Craighead County have declined at the annual rate of 0.75 feet (location 5, fig. 2) as the result of large irrigation withdrawals in the area (Hines and others, 1972).

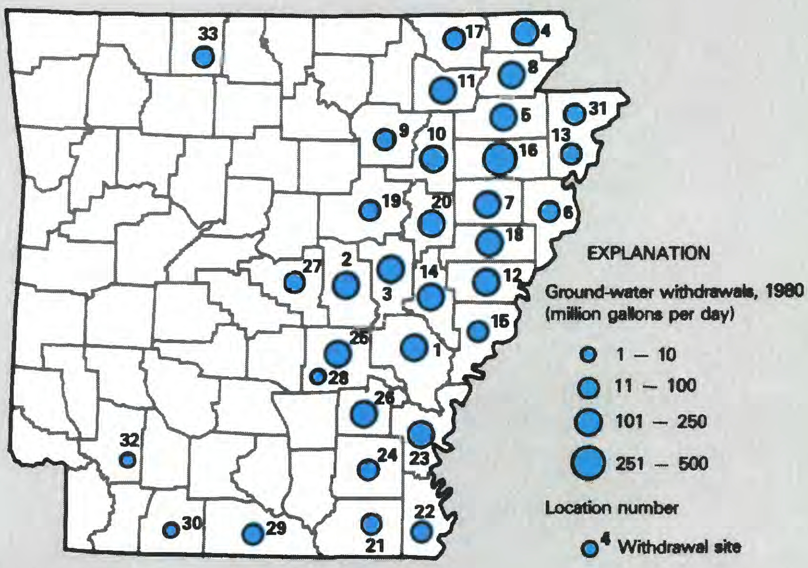
Water levels in wells in the Sparta Sand aquifer have declined substantially in several areas as a result of large municipal and industrial withdrawals. At El Dorado in Union County (location 29, fig. 2), water levels, which have declined about 60 ft since 1955 and about 320 ft since pumping began in that area, are at or near the top of the aquifer. Continued concentrated withdrawals in the intensively pumped areas may result in dewatering of the aquifer and in a reduction of well yield. Similar conditions exist at Magnolia in Columbia County (location 30, fig. 2) and at Pine Bluff in Jefferson County (location 28, fig. 2). The cone of depression at Pine Bluff has extended northeastward, toward the Grand Prairie, as a result of large withdrawals in recent years from the Sparta Sand aquifer for irrigation in Arkansas County. The decline in freshwater hydraulic head of the aquifer at El Dorado has allowed the movement of saline water into several industrial wells in the area.











WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Arkansas County	Alluvial, Sparta Sand	Irrigation.
2	Lonoke County	Alluvial	Do.
3	Prairie County	do	Do.
4	Clay County	do	Do.
5	Craighead County	do	Do.
6	Crittenden County	do	Do.
7	Cross County	do	Do.
8	Greene County	do	Do.
9	Independence County	do	Do.
10	Jackson County	do	Do.
11	Lawrence County	do	Do.
12	Lee County	do	Do.
13	Mississippi County	do	Do.
14	Monroe County	do	Do.
15	Phillips County	do	Do.
16	Poinsett County	do	Do.
17	Randolph County	do	Do.
18	St. Francis County	do	Do.
19	White County	do	Do.
20	Woodruff County	do	Do.
21	Ashley County	do	Do.
22	Chicot County	do	Do.
23	Desha County	do	Do.
24	Drew County	do	Do.
25	Jefferson County	do	Do.
26	Lincoln County	do	Do.
27	Pulaski County	do	Do.
28	Jefferson County	Sparta Sand	Municipal-industrial.
29	El Dorado area	do	Do.
30	Magnolia area	do	Do.
31	Northeastern Arkansas area	Wilcox, Nacatoch Sand	Do.
32	Southwestern Arkansas area	Nacatoch Sand	Do.
33	Northern Arkansas area	Ozark	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Arkansas. (Sources: Withdrawal data from Hall and Holland, 1984; water-level data from U.S. Geological Survey files.)

GROUND-WATER MANAGEMENT

Ground-water management in Arkansas is currently in the data-collection and planning stages. Several State and local agencies have limited or inferred jurisdiction over ground water. The Arkansas Department of Health is responsible for the protection of municipal and rural drinking supplies and regulates the construction and use of septic tanks. The Arkansas Soil and Water Conservation Commission is responsible for the Arkansas State Water Plan, which evaluates surface- and ground-water resources, problems, and management strategies. The Commission also is the leading proponent of the Arkansas Water Code Bill, which, if enacted, will require registration of ground-water withdrawals. The Arkansas Geological Commission provides the geologic and hydrologic data for the State's water-resources planning. The Arkansas Department of Pollution Control and Ecology is responsible for control of ground-water quality and execution of federally delegated programs, such as the Underground Injection Control Program, the Resource Conservation and Recovery Act, the Clean Water Act, and construction-grant programs. The Arkansas Oil and Gas Commission shares responsibility with the Arkansas Department of Pollution Control and Ecology over the Underground Injection Control Program. The Water Well Committee regulates a well-driller licensing program and maintains well-construction standards and files on well-completion reports. The Arkansas Plant Board, the Forestry Commission, and the Cooperative Extension Service also have responsibilities that indirectly affect ground water.

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Prepared by Augustine H. Ludwig with exception of section on "Ground-Water Management" written by Randy Young, Arkansas Soil and Water Conservation Commission, Little Rock, Arkansas.

For further information contact District Chief, Water Resources Division, U.S. Geological Survey, 700 West Capitol Avenue, Little Rock, AR 72201

CALIFORNIA
Ground-Water Resources

Ground water is an abundant natural resource in California and accounts for 39 percent of all freshwater withdrawals—more than 14 billion gallons per day (bgd) (table 1). More than 10 million people, 46 percent of the total population, are served by ground-water supplies. Even more significantly, 12.5 bgd of ground water is withdrawn for irrigation, 39 percent of the total amount of water withdrawn for irrigation. The geography and climate of California are the dominant factors controlling the State's water development. Generally, rainfall exceeds potential evapotranspiration in the north but is less than potential evapotranspiration in the south. The principal centers of population and agriculture are mostly in the water-deficient areas. Many of the valleys and plains of the water-deficient areas, however, are underlain by productive aquifers. Historically, ground water was the dominant source of supply, and the prevailing opinion was that these supplies were unlimited. The eventual realization that they were not unlimited was an important factor in the decisions that led to the large-scale importation from the water-abundant areas of the north to the water-deficient areas of the south.

The quality of water from the major aquifers of California generally is good. In many places, however, dissolved-solids concentrations exceed the U.S. Environmental Protection Agency criterion of 500 milligrams per liter (mg/L) for drinking water, but, nevertheless, the water is suitable for irrigation or industrial use. Many aquifers are adjacent to the ocean or deposits containing saline water, where pumping may cause saline-water intrusion.

GENERAL SETTING

Precipitation in California is extremely variable. Mean annual precipitation ranges from more than 40 inches (in.) in much of the mountainous areas of central and northern California to less than 5 in. in the desert areas. In the populated areas of the coastal valleys and southern California, annual precipitation generally ranges from 10 to 20 in. (California Department of Water Resources, 1983, p. 8-9). Natural recharge of ground water, from precipitation and stream infiltration, averages about 5.2 bgd statewide. Ground water also is recharged by an estimated 6.6 bgd of applied irrigation water that percolates through the root zone to the water table (California Department of Water Resources, 1983, p. 88).

California is one of the most physiographically and geologically diverse States in the United States. The terrain is characterized by the massive, rugged glaciated mountains of the Sierra Nevada and Cascade Ranges, the rugged Coast Ranges with their interspersed valleys, the broad and flat Central Valley, and the alternating basins and ranges of the desert areas (fig. 1). The mountains are formed of consolidated sedimentary, metamorphic, and igneous rocks. Geologic structures are complex, with abundant folds and faults, many of which are active. Earthquakes are common, particularly in the Coast Ranges. The valleys of California are filled with alluvium and other sedimentary materials that comprise most of the principal aquifers.

Table 1. Ground-water facts for California

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Total withdrawals from California Department of Water Resources (1983). Category of use numbers revised and extrapolated from Solley, Chase, and Mann (1983) to be consistent with California Department of Water Resources total]

Population served by ground water, 1980	
Number (thousands)	10,950
Percentage of total population	46
From public water-supply systems:	
Number (thousands)	9,580
Percentage of total population	40
From rural self-supplied systems:	
Number (thousands)	1,370
Percentage of total population	6
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	38,000
Ground water only (Mgal/d)	14,600
Percentage of total	39
Percentage of total excluding withdrawals for thermoelectric power	38
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	1,300
Percentage of total ground water	9
Percentage of total public supply	46
Per capita (gal/d)	120
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	90
Percentage of total ground water	0.6
Percentage of total rural domestic	93
Per capita (gal/d)	70
Livestock:	
Ground water (Mgal/d)	25
Percentage of total ground water	0.2
Percentage of total livestock	41
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	910
Percentage of total ground water	6
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	54
Excluding withdrawals for thermoelectric power	89
Irrigation withdrawals:	
Ground water (Mgal/d)	12,500
Percentage of total ground water	85
Percentage of total irrigation	39

PRINCIPAL AQUIFERS

About 40 percent of the land in California is underlain by aquifers (California Department of Water Resources, 1975a, p. 7). These aquifers are composed of alluvium and older sediments, mostly of continental origin, and volcanic rock. The sedimentary aquifers underlie the major valleys, coastal plains, and desert basins (fig. 1).

Alluvial and other sedimentary aquifers in California are divided into four geographic areas: coastal basins, Central Valley, southern California, and desert areas. A simplified summary of aquifer and well characteristics is given in table 2;

Table 2. Aquifer and well characteristics in California

[Mgal/d = millions of gallons per day; gal/min = gallons per minute; ft = feet. Sources: Reports of the U.S. Geological Survey and California Department of Water Resources, 1975a, 1980]

Aquifer name and description	Water withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Alluvium and older sedimentary aquifers:						
Coastal basins: Sand, gravel, silt, and clay; continental and marine origin. Unconfined and confined.	1,630	50 - 500	1,000	500 - 1,000	3,000	Aquifers consist of alluvium and older sediments that fill valleys which are tributary to the Pacific Ocean. Multiple aquifer systems are common. Most intensively developed areas are in Santa Clara, Salinas, and Santa Maria Valleys and Santa Rosa area.
Southern California: Sand, gravel, silt, and clay; continental and marine origin. Unconfined and confined.	1,720	50 - 1,000	1,500	500 - 1,500	4,000	Productive aquifers in coastal plains and inland valleys of Ventura, Los Angeles, Orange, and San Bernardino Counties. Seawater intrusion, once a problem in coastal areas, now under control.
Central Valley: Sand, gravel, silt, and clay; continental and marine origin. Unconfined and confined.	10,000	50 - 500	1,000	50 - 1,500	3,000	Largest aquifer system and greatest concentration of ground-water pumpage in California. Corcoran Clay Member, an extensive confining layer, exists in much of San Joaquin Valley.
Basin-fill, desert areas: Sand, gravel, silt, and clay, mostly of continental origin. Unconfined and confined.	700	20 - 400	1,000	200 - 1,500	4,000	Aquifers in some basins deep, and some wells have large yields. Recharge limited by little rainfall. Some aquifers recharged by runoff from streams that originate in high mountains.
Volcanic rocks: Andesite, rhyolite, and basalt. Mostly unconfined; confined locally.	unknown	75 - 200	300	100 - 1,000	4,000	Water occurs in rubble zones, pipes, and fractures. Well yields extremely variable, with a few exceptionally productive wells and many dry holes. Potential yield far exceeds present use.

the areal distribution of the aquifers is shown in figure 1. However, the geology can be locally complex, and multiple-aquifer systems are common. Numerous faults, folds, and uplifts may function as local hydraulic barriers.

Alluvium and Older Sedimentary Aquifers

Aquifers of the coastal basins consist mainly of alluvium and older sediments that underlie the valleys that drain into the Pacific Ocean from the Oregon border to Santa Barbara County. The largest valleys are the Santa Clara, the Salinas, and the Santa Maria Valleys and the Santa Rosa area (valleys tributary to the Russian River). The most intensively developed areas are the Santa Clara and Salinas Valleys.

The Central Valley of California (fig. 1) is one of its most intensively developed areas of irrigated agriculture. The Central Valley is about 500 miles (mi) long and 20 to 50 mi wide, with a total area of about 16,000 square miles. The northern part is known as the Sacramento Valley, whereas the southern part is known as the San Joaquin Valley. The alluvium and older sediments that underlie the Central Valley constitute one of the world's most extensive aquifer systems. Sediments extend to depths of more than 25,000 feet (ft). Freshwater (dissolved solids less than 2,000 mg/L) is present to depths of as much as 4,000 ft (Page, 1973), but most wells are less than 1,000 ft deep. An extensive confining layer known as the Corcoran Clay Member of the Tulare Formation underlies much of the San Joaquin Valley at depths ranging from 200 to 500 ft.

The principal aquifers of southern California are in the coastal plains of Ventura, Los Angeles, and Orange Counties and in adjacent inland valleys. The productive aquifers consist of alluvium and other continental sediments in the inland

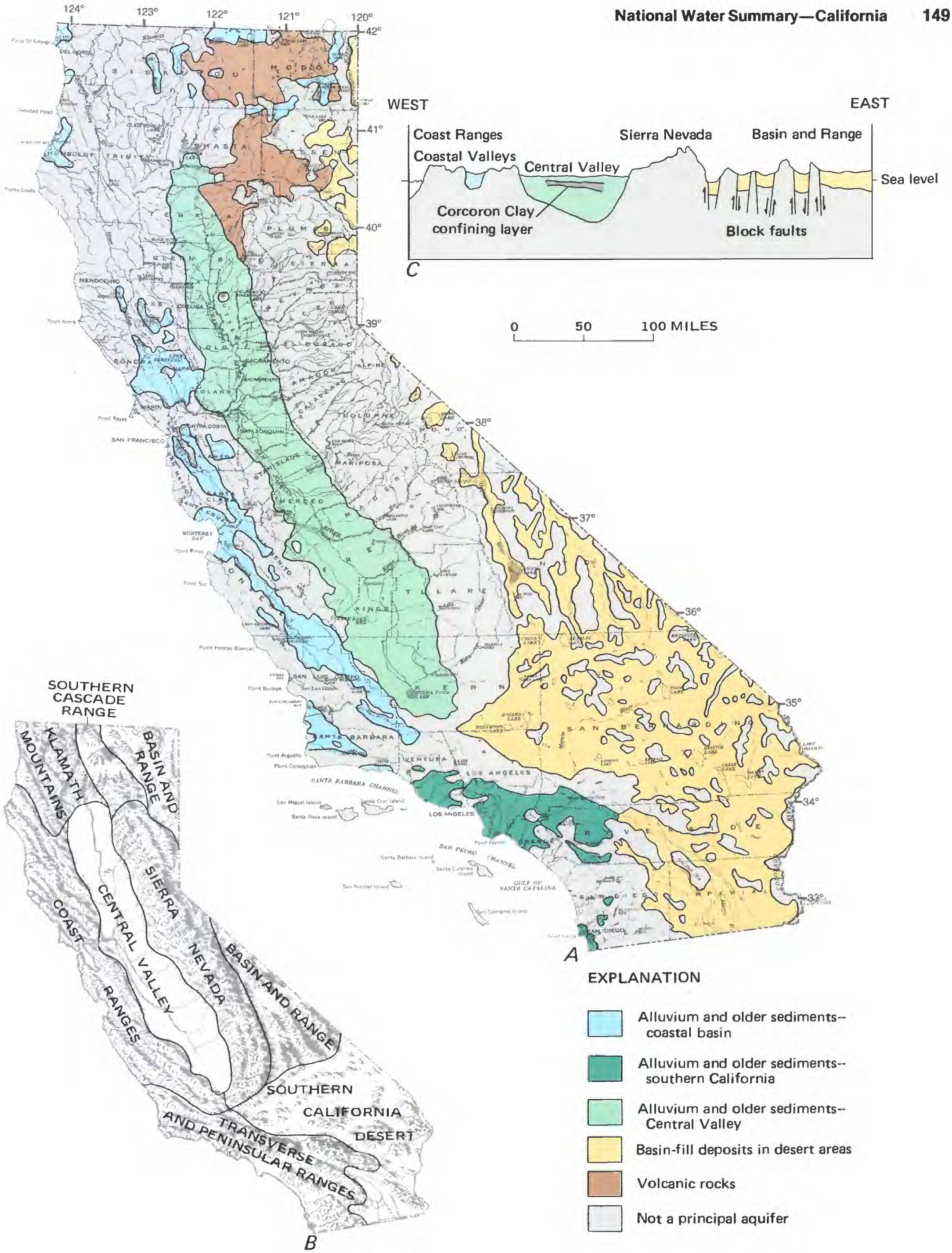


Figure 1. Principal aquifers in California. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section. (See table 2 for a more detailed description of the aquifers. Sources: *A*, California Department of Water Resources, 1975a, 1980. *B*, Raisz, 1954. *C*, Compiled by A. M. Spieker from U.S. Geological Survey files.)

areas that interfinger with deltaic and marine sediments in the coastal areas.

BASIN-FILL AQUIFERS

The desert areas comprise much of southeastern California (fig. 1). The topography consists of alternating basins and block-faulted mountain ranges. The basins are typically underlain by basin-fill deposits. The principal aquifers are alluvium, with interbedded lacustrine deposits. Many basins are deep, but well yields are variable.

The desert areas are the driest parts of California. Consequently, recharge is not abundant. What does occur is largely from streams, such as the Mojave River, that originate in the higher mountain areas, where rainfall is more abundant.

VOLCANIC ROCK AQUIFERS

Volcanic rock aquifers are mainly in northern California, on the flanks of the Cascade and Siskiyou Ranges and along the east side of the Sacramento Valley. The most common rock types are andesite, rhyolite, and basalt. Some volcanic rocks are excellent aquifers, but most water is found in fractures, rubble zones, and sand and gravel layers interbedded between lava flows. A few wells are extremely productive, but dry holes abound. Except in Butte and Shasta Valleys, which contain areas with numerous production wells, the volcanic rock aquifers are not used extensively.

OTHER AQUIFERS

Consolidated rock aquifers in the mountains and foothills—crystalline rock in the Sierra Nevada and bedded sandstones in the Coast Ranges—supply thousands of rural domestic wells. A regional carbonate rock aquifer system near Fish Lake and Death and Ivanpah Valleys, that underlies much of eastern and southern Nevada, barely extends into California.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

California had a ground-water withdrawal of 14.6 bgd in 1980, by far the largest of any State (California Department of Water Resources, 1983, p. 88). The location of the major pumping centers and representative hydrographs indicating long-term water-level trends are shown in figure 2. Information on population served and categories of use is given in table 1. The most striking feature of figure 2 is the concentration of ground-water pumpage in the Central Valley. More than 10 bgd (about 70 percent of the 1980 withdrawals) were from this area (California Department of Water Resources, 1983, p. 111-127). Irrigation accounts for 85 percent of all ground-water withdrawals in California (table 1). Thus, the withdrawals, here stated in million gallons per day over the entire year, actually occur largely during 4 to 5 months—generally May through September.

Apart from the Central Valley, the greatest concentrations of ground-water withdrawals are in southern California and in the Santa Clara and Salinas Valleys. Most cities in the San Joaquin Valley are supplied entirely by ground water, and ground water is a significant part of the public supplies in southern California and the Santa Clara Valley.

The six hydrographs in figure 2 show water-level trends in representative areas affected by pumping. Steady water-level declines are observed in areas where imported water is not available, such as Antelope Valley (location 17, fig. 2). Less severe declines have occurred in the Salinas Valley (location 3, fig. 2). Imported water became available to many areas, such as Santa Clara Valley, the Central Valley, and Orange County, in the mid- to late 1960's. Hydrographs from Santa Clara Valley, Orange County, and Mendota wells, (location 2, 10, and 18, fig. 2, respectively) show that water levels, which previously had been declining, began to rise at that time. Climatic trends are illustrated by generally declining levels during droughts in the 1930's and the late 1970's.

The Fresno and Mendota wells in the Central Valley, which are only about 25 mi apart, show strikingly different trends. Imported water is available in both areas. The Fresno well (location 19, fig. 2) is in an unconfined aquifer and the Mendota well (location 18, fig. 2) is in a confined one. Despite the availability of imported water, overdraft has continued in the Fresno area in response to increased pumping. The hydrograph from the Mendota well shows a water-level recovery beginning about 1968 when pumping was reduced as imported water became available. A dramatic decline of the water level during the drought of 1977 and 1978 also is apparent on the hydrograph.

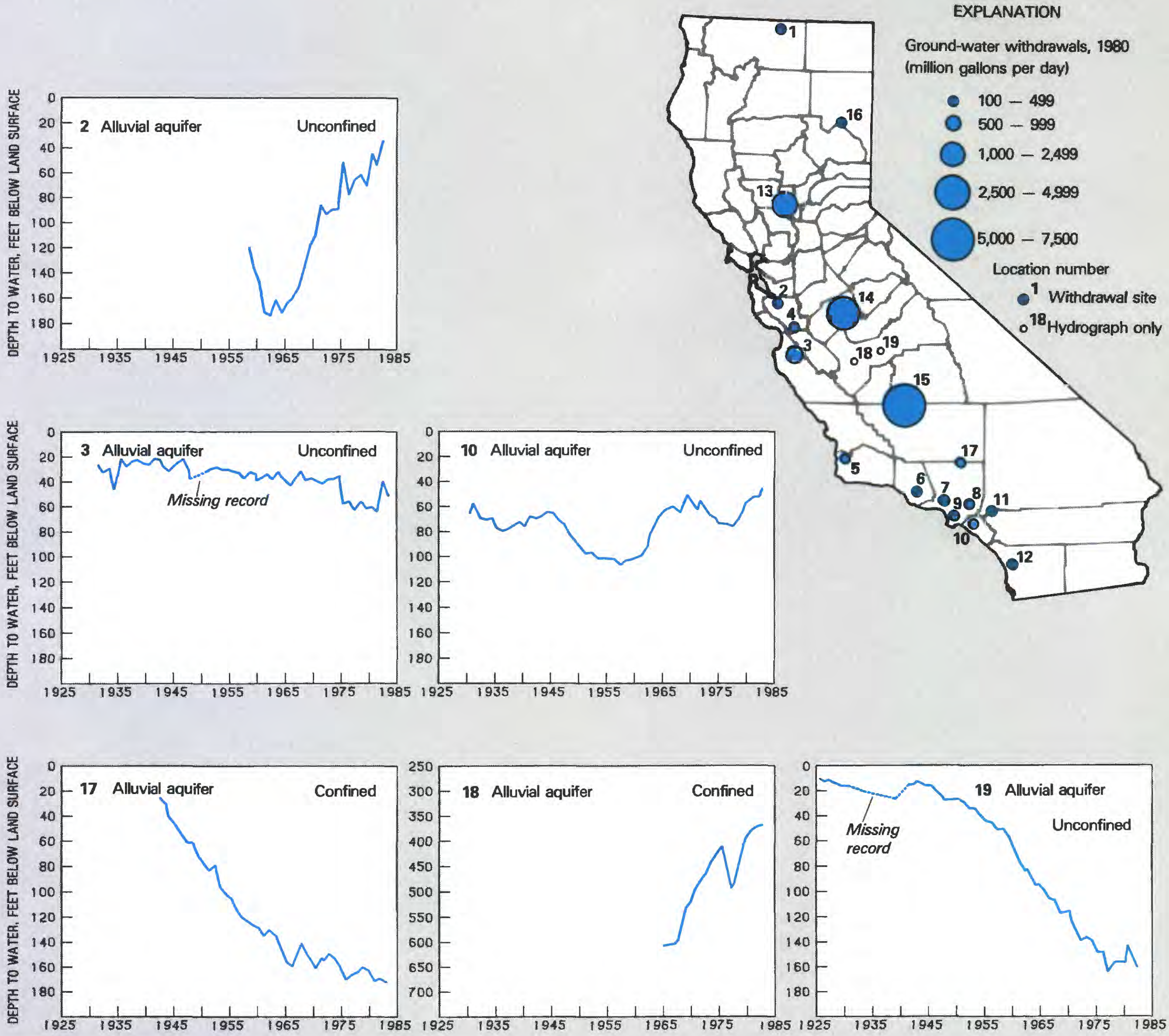
GROUND-WATER MANAGEMENT

California does not have statewide comprehensive ground-water-management laws. Management is practiced largely by local agencies. The California Department of Water Resources is the State's principal water agency. Its role in ground water is one of providing advice and technical support to local agencies, collecting data, and conducting investigations. The State Water Resources Control Board and nine Regional Boards establish and enforce standards for ground-water quality. The Department of Health Services monitors the quality of drinking-water supplies. The U.S. Geological Survey maintains a cooperative program for data collection and hydrologic investigations with several State and numerous local agencies.

Water rights have been adjudicated in eight ground-water basins where conflicts among users have arisen (Peters, 1982). Seven of these basins are in southern California. The Orange County and Santa Clara Valley Water Districts have been granted authority to regulate and tax pumpage and to import water. Several counties have enacted ordinances regulating the export of ground water. One such ordinance, in Inyo County, where the Los Angeles Department of Water and Power is exporting water from Owens Valley, was struck down by the Superior Court of Inyo County, but the appeal was delayed for the duration of a proposed 5-year cooperative study by Inyo County and the city of Los Angeles to develop a water-management plan.

The California State Water Resources Control Board has the authority to file an action in the Superior Court to restrict pumping or to impose physical solutions, or both, to the extent necessary to prevent degradation of the quality of ground water. Under the threat of such action concerning seawater intrusion in the Oxnard Plain of Ventura County, the Fox Canyon Water Management District was organized in 1983 to regulate pumping and to obtain water from the Santa Clara River for artificial recharge.

Major ground-water issues include ground-water overdraft, seawater intrusion, land subsidence, and artificial recharge and conjunctive use of ground water (Peters, 1982). The California Department of Water Resources (1980, p. 3) has identified 42 ground-water basins in overdraft, 11 of them in a "critical condition of overdraft," defined as a situation where "***continuation of present water management practices would probably result in significant adverse overdraft-related environmental, social, or economic impacts." Eight of



WITHDRAWAL SITES					
[Aquifers are all alluvium and older sediments or basin-fill deposits except for Butte and Honey Lake Valleys, which are volcanic rocks]					
No. on map	**Geographic area**	**Principal uses**	**No. on map**	**Geographic area**	**Principal uses**
1	Butte Valley	Irrigation, domestic, livestock.	11	San Bernardino-Riverside area.	Irrigation, public supply, industrial.
2	Santa Clara Valley	Public supply, industrial.	12	San Diego County basins.	Do.
3	Salinas Valley	Irrigation, domestic, livestock, Industrial.	13	Sacramento Valley	Irrigation, domestic, livestock, industrial.
4	Gilroy-Hollister area	Do.	14	Northern San Joaquin Valley.	Irrigation, drainage, domestic, industrial, public supply, livestock.
5	Santa Maria River Valley	Irrigation, public supply, industrial.			
6	Ventura County basins	Irrigation, public supply.			
7	San Fernando Valley	Public supply, domestic, industrial.	15	Southern San Joaquin Valley.	Irrigation, domestic, industrial, public supply, livestock.
8	San Gabriel Valley	Public supply, industrial.			
9	Los Angeles Coastal area	Do.	16	Honey Lake Valley and Susanville area.	Irrigation, domestic, livestock.
10	Orange County Coastal Plain.	Irrigation, public supply, industrial.	17	Antelope Valley	Irrigation, public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in California. (Sources: Withdrawal data from California Department of Water Resource, 1983; water-level data from U.S. Geological Survey files.)

the 11 basins are in the Central Valley; one each is in Santa Cruz, Santa Barbara, and Ventura Counties. Statewide overdraft in 1980 was estimated at 1.6 bgd (California Department of Water Resources, 1983, p. 88).

Seawater intrusion was most intense in the coastal basins of Los Angeles, Orange, and Ventura Counties, the Pajaro and Salinas Valleys, and the Fremont area of Alameda County from 1945 to 1965. It is now under control in most of these areas as a result of management programs that include injection-well barriers, controls on withdrawals, artificial recharge, and imported water (California Department of Water Resources, 1975b, 1980).

Intensive pumping of aquifers in the San Joaquin and Santa Clara Valleys has caused land subsidence over large areas, as much as 29 ft in the Los Banos–Kettleman City area (Ireland and others, 1984, p. 17). Little subsidence has occurred since imported water became available in the late 1960's, except for a slight resumption during the drought of 1977–78.

Artificial recharge and conjunctive use of surface and ground water are major elements of ground-water management in California. Artificial recharge was first used in southern California in the 1920's; it is widely used there now and in the Central and Santa Clara Valleys as well. Imported water is available in all these areas. An interesting variation on artificial recharge is "in-lieu replenishment," whereby imported water is delivered directly to users in return for reduction of ground-water withdrawals by an equivalent amount.

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Prepared by Andrew M. Spieker

For further information contact District Chief, U.S. Geological Survey, Room W-2235, Federal Building, 2800 Cottage Way, Sacramento, CA 95825

COLORADO
Ground-Water Resources

Ground water constitutes 18 percent of the total water used in Colorado, and, in some areas, is the main source for domestic and irrigation supply. Fifteen percent of the total population get their drinking-water supply from ground water. Public supplies provide ground water to 320,000 people, and private wells provide ground water to 125,000 people, mostly in rural areas. Ground-water withdrawals for irrigation are 96 percent of total ground-water withdrawals. Of the total 2.7 million acres irrigated in Colorado, 2.1 million acres are irrigated with ground water—1.6 million acres are irrigated with a combination of ground water and surface water, and 0.5 million acres are irrigated only with ground water. Ground-water withdrawals in 1980 for various uses are given in table 1, along with related statistics.

GENERAL SETTING

Annual precipitation ranges from about 7 in. (inches) in the San Luis Valley to about 40 in. in the Rocky Mountains. Eastern Colorado, where most crops are grown, receives less than 20 in., so that irrigation is required. Only a small percentage of rainfall recharges the aquifers; for example, annual recharge to the High Plains aquifer in Colorado is only about 0.18 to 1.7 in.

Geologic and topographic features cause significant differences in ground-water availability and conditions from one part of the State to another. Major descriptive areas of the State, based on geology, topography, drainage, and physiography, are the South Platte River basin, the Arkansas River basin, and the High Plains in eastern Colorado; the Rocky Mountain area in central Colorado; and western Colorado (fig. 1).

PRINCIPAL AQUIFERS

The most productive and easily developed aquifers in Colorado are those in unconsolidated sand and gravel deposits. However, where these aquifers are not present, adequate supplies generally can be obtained from aquifers in deeper, consolidated rock.

Colorado has seven principal aquifers or aquifer systems (fig. 1, table 2). Four of the principal aquifers consist of unconsolidated deposits and include the alluvial aquifer along the South Platte River and its tributaries, the alluvial aquifer along the Arkansas River and its tributaries, the High Plains aquifer underlying the High Plains, and the San Luis Valley aquifer system in the Rocky Mountain area. Most withdrawals, which in Colorado are primarily for irrigation, are from the aquifers in the unconsolidated deposits. The remaining three principal aquifers consist of consolidated rock and include the Denver Basin aquifer system in the South Platte River basin and part of the Arkansas River basin, the Piceance basin aquifer system in western Colorado, and the Leadville limestone aquifer in the Rocky Mountain area. Also shown in figure 1 are several other aquifers (including the Dakota, Morrison, and Entrada aquifers in southwestern Colorado) that are not principal aquifers, in Colorado, but are included because of their significance in adjacent States. The aquifers in Colorado are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

Table 1. Ground-water facts for Colorado

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	445
Percentage of total population	15
From public water-supply systems:	
Number (thousands)	320
Percentage of total population	11
From rural self-supplied systems:	
Number (thousands)	125
Percentage of total population	4
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	16,000
Ground water only (Mgal/d)	2,800
Percentage of total	18
Percentage of total excluding withdrawals for thermoelectric power	18
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	48
Percentage of total ground water	2
Percentage of total public supply	8
Per capita (gal/d)	150
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	35
Percentage of total ground water	1
Percentage of total rural domestic	36
Per capita (gal/d)	280
Livestock:	
Ground water (Mgal/d)	19
Percentage of total ground water	0.7
Percentage of total livestock	18
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	16
Percentage of total ground water	0.6
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2
Excluding withdrawals for thermoelectric power	1
Irrigation withdrawals:	
Ground water (Mgal/d)	2,700
Percentage of total ground water	96
Percentage of total irrigation	19

UNCONSOLIDATED SEDIMENTARY ROCK AQUIFERS

South Platte Alluvial Aquifer

The South Platte alluvial aquifer is an extensive system consisting of unconsolidated sand and gravel and minor beds of clay and silt that were deposited in broad valleys eroded into underlying consolidated sedimentary rock. This unconfined aquifer is in hydraulic connnection with the South Platte River along its mainstem and major perennial tributaries. Other tributaries flow only in response to intense thunderstorms or rapid snowmelt. The principal use of water is for irrigation, although some water is used for public supply. Significant ground-water development began in 1934 (Hurr and others, 1975), and by 1980 more than 7,500 wells tapped the aquifer for irrigation.

Table 2. Aquifer and well characteristics in Colorado

[Ft = feet; gal/min = gallons per minute; ft^2/d = feet squared per day; mg/L = milligrams per liter; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey, Colorado Water Conservation Board, and Colorado Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Principal Aquifers					
Unconsolidated sedimentary rock aquifers:					
South Platte alluvial aquifer: Interbedded gravel, sand, silt, and clay; contains some cobbles and boulders; unconsolidated. Generally unconfined.	30 – 150	250	100 – 1,500	3,000	Provides water for public supplies and supplemental irrigation. Transmissivity ranges from 2,000 to 200,000 ft^2/d. Dissolved-solids concentration ranges from 100 mg/L in areas overlain by dune sand to about 4,000 mg/L in some downstream areas. Water hard to extremely hard. Local areas show significant water-level declines.
Arkansas alluvial aquifer: Boulders, cobbles, gravel, sand, and clay. Generally grades from fine sand near the surface to coarse sand and gravel at the base. Generally unconfined.	25 – 100	200	100 – 1,200	1,500	Principal source of water for irrigation, public supply, and industrial wells. Transmissivity ranges from 1,000 to 150,000 ft^2/d. Dissolved-solids concentration ranges from about 800 to 5,000 mg/L. Water hard to extremely hard.
High Plains aquifer: Gravel, sand, silt, and clay; contains some caliche. Poorly to moderately consolidated. Generally unconfined.	200 – 400	450	350 – 2,000	2,500	Primary source for irrigation, public supply, and domestic use. Transmissivity ranges from 3,000 to 30,000 ft^2/d. Dissolved-solids concentration generally ranges from 200 to 500 mg/L. Widespread water-level declines affecting well production and increasing irrigation costs.
San Luis Valley aquifer system:					
Unconfined aquifer: Clay, silt, sand, and gravel; unconsolidated. Alluvial and lacustrine. 0 to 200 ft thick.	50 – 150	150	500 – 1,200	2,000	Provides supplemental irrigation water. Withdrawals greatest in Rio Grande and western Alamosa Counties. Transmissivity ranges from 100 to 34,000 ft^2/d. Dissolved-solids concentration ranges from 72 to 31,200 mg/L. Local areas show water-level declines.
Confined aquifer: Clay, silt, sand, and gravel, unconsolidated, interbedded with lava flows and tuffs. As much as 19,000 ft thick.	300 – 800	2,000	500 – 1,200	2,000	Provides supplemental irrigation water. Withdrawals greatest in Conejos and western Saguache Counties. Transmissivity ranges from 200 to 200,000 ft^2/d. Dissolved-solids concentration ranges from 60 to 2,440 mg/L.
Consolidated sedimentary rock aquifers:					
Denver Basin aquifer system:					
Dawson aquifer: sandstone and conglomerate with interbedded shale, siltstone. Confined except near outcrop area.	200 – 1,000	1,400	5 – 150	300	Sandstone thickness ranges from 100 to 400 ft. Dawson is uppermost aquifer in group. Primarily used for rural and public supply. Potential for local contamination from Lowry landfill in Arapahoe County. Less than 200 mg/L dissolved solids.
Denver aquifer: Sandstone with interbedded shale, siltstone, and coal. Confined except near outcrop area.	200 – 1,500	2,100	5 – 100	300	Sandstone thickness ranges from 100 to 300 ft. Denver contains more shale than other aquifers in group. Used primarily for domestic supply. Generally less than 200 mg/L dissolved solids.
Arapahoe aquifer: Sandstone and conglomerate with interbedded shale, siltstone. Confined except near outcrop area.	200 – 2,000	2,600	10 – 600	800	Sandstone thickness ranges from 100 to 350 ft. Arapahoe most permeable aquifer in group. Used extensively for public, commercial, and domestic supply. Less than 500 mg/L dissolved solids.

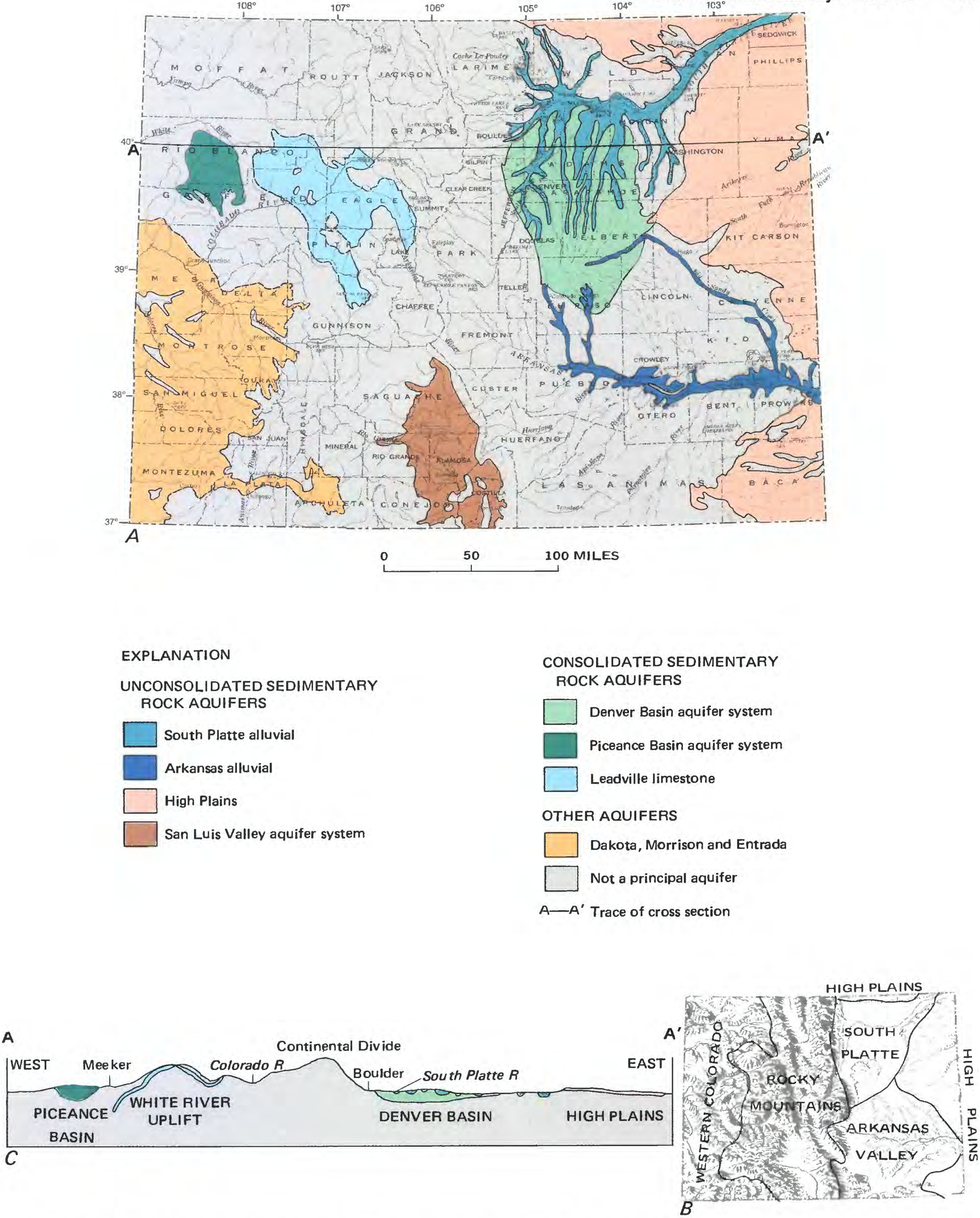


Figure 1. Principal aquifers in Colorado. *A*, Geographic distributions. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for more detailed description of the aquifers. Source: *A*, *C*, Compiled by R. T. Hurr from U.S. Geological Survey files. *B*, Fenneman, 1931; Raisz, 1954.)

Table 2. Aquifer and well characteristics in Colorado—Continued

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Principal Aquifers—Continued					
Laramie–Fox Hills aquifer: Sandstone and conglomerate with interbedded shale, siltstone, and coal. Confined except near outcrop areas.	200 - 2,500	3,200	2 - 300	400	Sandstone thickness ranges from 100 to 200 ft. Laramie-Fox Hills is deepest aquifer in group. Permeability small along western margin of basin. Potential for local contamination from the Marshall landfill in Boulder County. About 500 to 2,000 mg/L of dissolved solids.
Piceance basin aquifer system:					
Upper aquifer: Coarse- to fine-grained silty sandstone and siltstone of the Uinta Formation and fractured dolomite marlstone of the Parachute Creek Member of the Green River Formation above the Mahogany zone. Generally confined.	500 - 1,000	1,400	10 - 500	2,000	Potential of aquifer not developed. Water almost exclusively in fractures. Transmissivity ranges from 10 to 600 ft^2/d. Dissolved-solids concentration generally ranges from 400 to 2,000 mg/L.
Lower aquifer: Fractured dolomitic marlstone of the Parachute Creek Member of the Green River Formation below the Mahogany zone. Generally confined.	600 - 2,000	2,800	2 - 50	100	Potential of aquifer not developed. Transmissivity ranges from 10 to 600 ft^2/d. Water commonly contains dissolved gas. Dissolved-solids concentration ranges from about 500 to 40,000 mg/L.
Leadville limestone aquifer: Gray dolomitic limestone with some sandstone and chert. Confined.	-	2,000	-	500	Potential of aquifer not developed. Some exploratory wells drilled in Eagle County. Spring on Rifle Creek, north of Rifle, Colorado, discharges 11 ft^3/s.
Other Aquifers					
Western Colorado alluvial aquifers: Boulders, cobbles, gravel, sand, silt, and clay; unconsolidated and only moderately sorted. Generally unconfined.	20 - 40	140	5 - 100	500	Alluvial aquifers along Yampa, White, Colorado, and Uncompahgre Rivers provide some water for irrigation, public supply, and industrial use. Capability of aquifer in terms of yield and quality not determined. Measured transmissivity values as much as 75,000 ft^2/d.
San Juan basin aquifers:					
San Jose aquifer: Alternating sandstones commonly are conglomerate, rich in feldspar. Confined.	50 - 300	1,400	5 - 1,000	1,500	In southern part of western Colorado, principally in La Plata County and western part of Archuleta County. Potential of aquifer not developed in Colorado.
Animas aquifer: Sandstone and varicolored shale with interbedded breccia and volcanic conglomerate. Confined.	50 - 200	300	1 - 15	800	Hydraulic conductivity of fractured shale ranges from 0.2 to 0.3 ft/d. Dissolved-solids concentration ranges from 300 to 450 mg/L.
Mesaverde Group aquifer: Marine sandstone with interbedded siltstone and shale; coal-bearing in middle part of group. Confined, except near outcrop areas.	1,000 - 1,500	5,000	1 - 10	500	In western Colorado (Routt, Moffat, Montezuma, La Plata, and Archuleta counties). Water ranges from sodium bicarbonate type to calcium sulfate type, depending on presence or absence of shales. Dissolved-solids concentration ranges from 180 to 1,200 mg/L. May contain dissolved iron in excess of national drinking-water regulations.

Table 2. Aquifer and well characteristics in Colorado—Continued

Aquifer name and description	Well characteristics: Depth (ft), Common range	Depth (ft), May exceed	Yield (gal/min), Common range	Yield (gal/min), May exceed	Remarks
			Other Aquifers—Continued		
Mancos Shale unit: Silty and sandy marine shale; contains some interbedded sandstones and limestones. Unconfined.	20 - 50	200	1 - 10	25	In Pitkin County and throughout western Colorado. Commonly used for stock and domestic water where other aquifers are too deep or have poorer quality water. Water generally contained in fractures or weathered zones. Water is predominantly sodium bicarbonate type. Dissolved-solids concentration ranges from 200 to 4,800 mg/L.
Dakota aquifer: Sandstone with interbedded siltstone and carbonaceous shale; contains many conglomerate lenses near base. Confined.	200 - 1,000	2,000	1 - 25	500	Includes the Cheyenne Sandstone in the Arkansas River basin; also in southern one-half of western Colorado. Many wells flow at surface. Water ranges from sodium bicarbonate to calcium bicarbonate type. Dissolved-solids concentration ranges from 300 to 3,500 mg/L.
Morrison aquifer: Fine- to medium-grained, thin-bedded sandstone, and varicolored red and green shale.	250 - 600	1,000	1 - 10	15	In the southern one-half of western Colorado. Water is calcium bicarbonate type. Dissolved-solids concentration ranges from 200 to 300 mg/L.
Entrada aquifer: Medium- to very fine grained sandstone with some silt and clay. Confined.	500 - 700	1,200	1 - 25	35	In the southern one-half of western Colorado. Water generally sodium bicarbonate type. Some water contains dissolved hydrogen sulfide gas. Average value for transmissivity in Grand Junction area 20 ft^2/d.
Precambrian crystalline unit: Quartz-biotite gneiss and schist with some hornblende gueiss and quartzite; intruded by granite and quartz monzonite batholiths and other intrusives. Unconfined.	100 - 250	350	0.5 - 5	15	In the Rocky Mountain area. Used extensively along the Front Range between Fort Collins and Colorado Springs. Water available only from fractures. Transmissivity typically less than 10 ft^2/d. Dissolved-solids concentration ranges from 20 to 1,600 mg/L.

Recharge to the aquifer occurs mostly as leakage from reservoirs and ditches and as deep percolation of applied irrigation water diverted from the South Platte River and its major tributaries. Since about 1863, the recharge has increased water levels to the extent that ground water discharges to streams, augmenting their flow and providing more water for diversion downstream. Withdrawals by wells have reduced the flow of ground water to some streams (Hurr and others, 1975).

Arkansas Alluvial Aquifer

The Arkansas alluvial aquifer is similar to, but not as extensive as, the South Platte alluvial aquifer. In many areas, clay or sandy clay in the upper part of the alluvium confines the aquifer. Otherwise, the aquifer generally is unconfined. In general, the aquifer is in hydraulic connection with the Arkansas River and its major tributaries. The principal use of water is for irrigation, although some water is used for public supply and powerplant cooling. Significant development began about 1950 (Major and others, 1970), and, by 1980, about 2,900 wells tapped the aquifer for irrigation.

As in the South Platte River basin, recharge is mostly from leakage and percolation of water diverted from streams, but the rate of recharge is less. In general, the ground water moves toward and discharges to the principal streams. Withdrawals by wells have reduced the flow of ground water to some streams and, in a few areas, have induced flow from the streams to the aquifer.

High Plains Aquifer

The High Plains area is underlain by the High Plains aquifer, which consists principally of the Ogallala Formation but includes overlying alluvium and dune sand and the underlying Arikaree Formation and White River Group. The Ogallala Formation is comprised of unconsolidated to partly consolidated sand and gravel with minor beds of clay and silt and a hard caliche layer, known as the "mortar beds," several feet thick near the top. The formation dips gently eastward.

Although the aquifer generally is unconfined, wells completed in less than the full saturated thickness may respond to leaky artesian conditions because lenses and layers of silt and clay function as semipermeable, leaky confining beds. Although the principal use of ground water is for irrigation (Luckey and others, 1981), ground water also is used to meet public supply and nearly all stock and rural domestic water needs. By 1980, the High Plains aquifer was tapped by approximately 4,100 irrigation wells, 83 municipal wells, and 3,990 wells for stock and domestic use. Inasmuch as the only source of recharge to the High Plain aquifer is precipitation, which averages from 14 to 18 in. per year, these wells are withdrawing water from storage and, consequently, reducing ground-water flow into Kansas and Nebraska.

San Luis Valley Aquifer System

The San Luis Valley aquifer system is comprised of several thousand feet of sand and gravel that contain lava flows and lenses and layers of clay and silt (Emery and others, 1975). The system is subdivided into confined and unconfined aquifers. The shallow aquifer generally is unconfined and in hydraulic connection with the Rio Grande and the Conejos River. Deeper aquifers within the system are confined by clay layers or lava flows. The principal use of the ground water is for irrigation, although some is used to meet public supply, rural domestic, and stock needs. Also, some deep wells provide hot water that is used for heating. In 1887, when the discovery was made that flowing water could be obtained from the artesian aquifer system, numerous wells were drilled for stock and domestic use and allowed to flow freely. In the early 1950's, withdrawal of ground water for irrigation had become significant, and by 1980, approximately 3,720 irrigation wells had been drilled in the San Luis Valley.

Recharge to the San Luis Valley aquifer system is by leakage from canals and ditches, percolation of applied surface water, and subsurface flow from adjacent mountains. The ground water moves from the margins of the valley toward the interior and discharges as evapotranspiration or to springs and streams. As a result of the large ground-water withdrawals, water levels have declined and evapotranspiration and discharge to springs and streams have been reduced.

Consolidated Sedimentary Rock Aquifers

Denver Basin Aquifer System

The Denver Basin aquifer system, which consists of the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers, is recharged in its outcrop areas by rainfall, snowmelt, and, in topographically high areas, loss of streamflow. In areas where the Denver aquifer is covered by the Dawson aquifer or the Arapahoe aquifer is covered by the Denver aquifer, the underlying aquifer also may be recharged by downward leakage from the overlying aquifer. In general, the thick sequence of shale that overlies the Laramie-Fox Hills aquifer prevents significant vertical movement to or from this aquifer. Discharge from the aquifers is through wells, by seeps and springs in low areas around the perimeter of the aquifers, as discharge to streams, or by evapotranspiration. The principal use of water from the Denver Basin aquifers is for public supply and individual domestic use. Some ground water also is withdrawn for commercial and industrial use. The total annual production for all uses is about 30 Mgal/d (million gallons per day) (Robson, 1984).

Piceance Basin Aquifer System

The Piceance basin aquifer system consists of an upper, generally confined aquifer in the Uinta Formation and the upper part of the Green River Formation, and a lower, generally confined aquifer in the middle and lower parts of the Green River Formation. The aquifers are separated by the petroleum-bearing Mahogany zone (Weeks and others, 1974). The Green River Formation, of primary interest for oil-shale development, has little interstitial porosity, so that ground-water flow and well yields are controlled by fracture permeability. Wells yielding several hundred gallons per minute have been drilled and tested as part of the program to develop the oil-shale resources, but use of the ground-water resources in the basin has been extremely limited.

Leadville Limestone Aquifer

The Leadville limestone aquifer crops out in the west-central part of the Rocky Mountain area and underlies much of the northern part of western Colorado. However, it is generally shallow enough to be considered a principal aquifer only in the Rocky Mountain area. Recharge to the aquifer generally is in the higher outcrop areas, and discharge commonly is by springs along fracture zones and in lower outcrop areas. At present, ground-water withdrawals are small, but the potential of the aquifer to serve as a dependable source of water as indicated by a few exploratory wells (Hampton, 1974) and discharge from numerous springs is significant.

OTHER AQUIFERS

In the Arkansas River basin (fig. 1), the Dakota aquifer—principally the sandstones in the Dakota Formation and Cheyenne Sandstone—provides water for some public supplies and for domestic use. Some wells also have been used to provide ground water for irrigation.

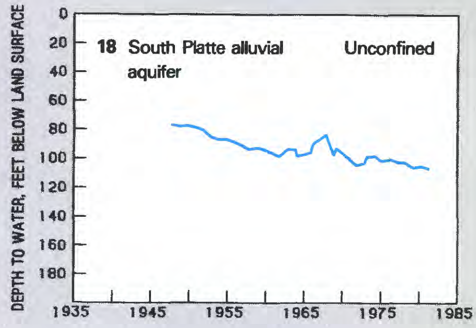
The Rocky Mountain area consists primarily of exposed Precambrian igneous and metamorphic rocks, Tertiary volcanic rocks, and folded and faulted sedimentary rocks. Numerous domestic wells obtain water from the fractured igneous and metamorphic rocks in the Precambrian crystalline unit. These rocks are the principal source of water for people living in the mountains west of Denver and other areas along the Front Range.

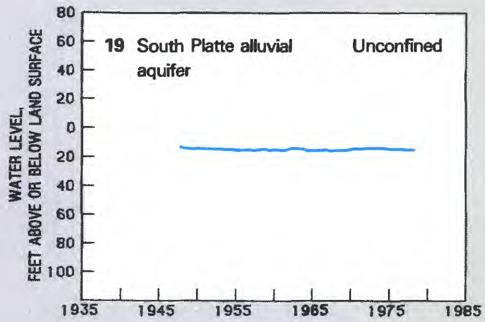
Western Colorado contains diverse geologic and hydrologic conditions. Alluvial aquifers along the major rivers have the potential for supplying water to wells in moderate quantities. Throughout much of western Colorado, the Mesaverde Group aquifer supplies water to domestic wells. Development of coal resources in the Mesaverde Group may have significant impact on these water resources. In the central and southern parts of western Colorado, domestic water supplies have been obtained from fractures in the weathered part of the Mancos Shale unit. The Dakota, the Morrison, and the Entrada Formations contain sandstone aquifers that supply water to domestic wells and a few public-supply wells. These sandstone aquifers are considered principal aquifers in New Mexico and Utah. The extreme southern part of the area, the San Juan Basin, which extends southward into New Mexico, contains several aquifers, principally the San Jose and Animas that supply water to domestic wells.

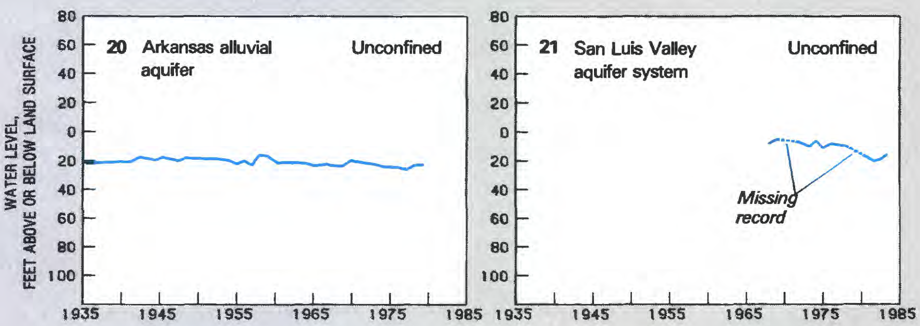
In many areas of the State, wells tap other aquifers, including sandstones in lower consolidated sedimentary rocks and in volcanic rocks. These aquifers, however, do not provide a significant volume of water compared to the total volume used.

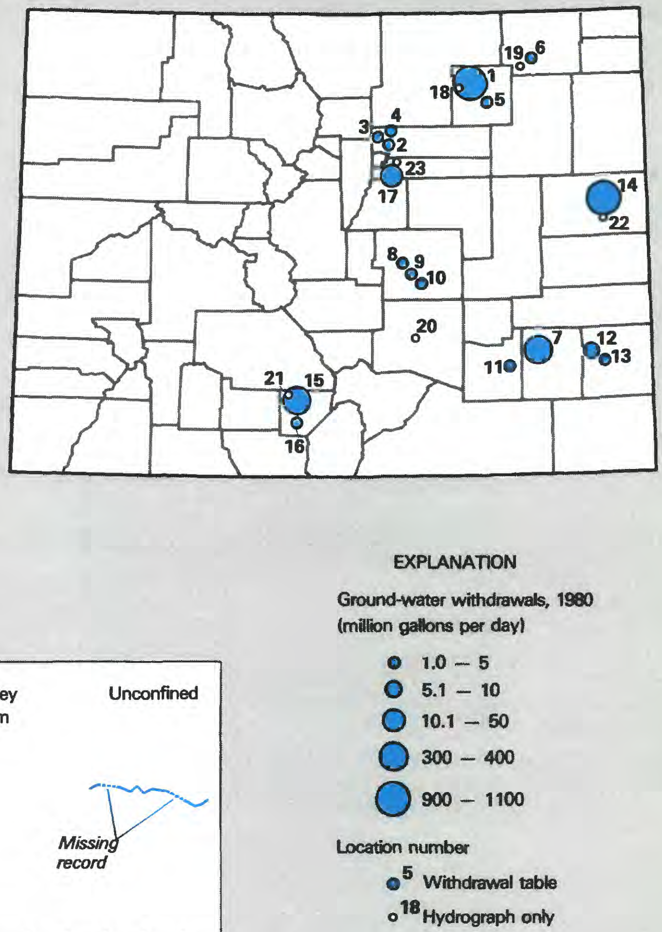
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Water-supply systems that produce from 0.1 to 1 Mgal/d are distributed throughout the State. Withdrawals of more









WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	South Platte River Valley.	South Platte alluvial	Irrigation.
2	South Adams	. . . .do	Public supply.
3	Thornton.	. . . .do	Do.
4	Brighton	. . . .do	Do.
5	Fort Morgan.	. . . .do	Do.
6	Sterling.	. . . .do	Do.
7	Arkansas River Valley.	Arkansas alluvial	Irrigation.
8	Widefield.	. . . .do	Public supply.
9	Security	. . . .do	Do.
10	Fountain.	. . . .do	Do.
11	La Junta	. . . .do	Do.
12	Lamar Light and Power.	. . . .do	Power plant, cooling.
13	Lamar	. . . .do	Public supply.
14	Eastern Colorado . . .	High Plains.	Irrigation.
15	South Central Colorado.	San Luis Valley . . .	Do.
16	Alamosa	. . . .do	Public supply.
17	East Central Colorado.	Denver Basin.	Public supply, irrigation, industrial.

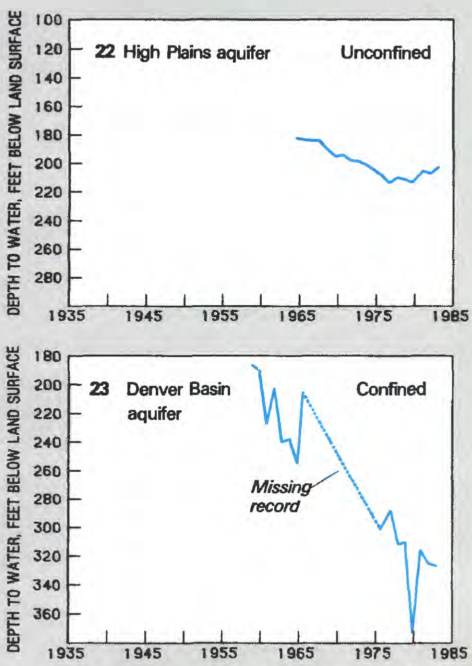


Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Colorado. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

than 1 Mgal/d are associated only with the principal unconsolidated aquifers and the Denver Basin aquifer system. The hydrographs shown in figure 2 reflect typical responses to ground-water withdrawals. Water levels in alluvial aquifers show seasonal fluctuations, but show no significant long-term changes in areas where surface water and ground water are used conjunctively for irrigation such as the South Platte River valley (location 19, fig. 2) and the Arkansas River valley (location 20, fig. 2). However, in areas where surface water is not used for irrigation, some long-term water-level declines have occurred. In the High Plains aquifer, ground water is being mined, as indicated by the large decline of ground water shown near location 22 (fig. 2). In the Denver basin (location 23, fig. 2) much of the water-level decline is from loss of artesian head rather than dewatering of the aquifer.

GROUND-WATER MANAGEMENT

Colorado water law for surface-water diversion is based on the right of prior appropriation. Before 1965, ground-water use was barely regulated, if at all, although well permits were required by the Colorado Division of Water Resources, Office of the State Engineer. In 1965 and 1969, the Ground Water Management Act (C.R.S. 37–90–101 to 104), commonly referred to as H.B. 1066, and the Water Rights Determination and Administration Act of 1969 (C.R.S. 37–92–101 to 602) were enacted. The latter Act controlled well drilling more effectively and, particularly, the effect that pumping ground water would be allowed to have on surface water hydraulically connected to the aquifer. Ground water that is part of a stream-aquifer system is classified as tributary ground water. Withdrawals of this class of ground water are administered within the priority system by the State Engineer to minimize the effect of withdrawals on surface-water supplies. Water in some aquifers, principally the High Plains aquifer and alluvial aquifers along intermittent or seasonal tributaries to the South Platte and Arkansas Rivers, is considered "designated ground water" and, as such, is controlled by the Colorado Ground Water Commission and local management districts. Water in consolidated "bedrock" aquifers underlying a management district also is managed by the district. Outside of the designated basins and in areas where ground water is considered not tributary to surface water, the ground water is classified as nontributary ground water and is administered by the State Engineer. In these areas, ground water cannot be withdrawn at an annual rate of greater than 1 percent of the volume of water stored beneath the property boundaries of the well owner. Much of the water in the Denver Basin aquifers is classified as nontributary.

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Prepared by R. Theodore Hurr and Glenn A. Hearne

For further information contact District Chief, U.S. Geological Survey, Building 53, Denver Federal Center, Mail Stop 415, Box 25046, Lakewood, CO 80225.

CONNECTICUT
Ground-Water Resources

Ground water is a valuable natural resource that presently supplies about one-third of Connecticut's approximately 3.1 million people. It is becoming an increasingly important resource because of several factors: land for additional surface reservoirs is scarce, cost of developing and operating surface-water sources are large, and State policy favors development of aquifers for future supplies. In 1980, ground water provided 17 percent of the total public supply and almost all self-supplied domestic, commercial, and industrial uses. Withdrawals for public supply ranged from 1.8 million gallons per day (Mgal/d) in Tolland County to 20.1 Mgal/d in Hartford County (Prisloe and Sternberg, 1983). Additional information on ground-water uses is given in table 1. The quality of the ground water generally is good to excellent and is suitable for most uses. However, principal aquifers are susceptible to contamination because of their shallow depth and thin or very permeable overburden, and numerous localized instances of ground-water contamination have been reported.

GENERAL SETTING

Geology and physiography are largely responsible for differences in ground-water conditions within the State. Subdivisions of the New England physiographic province (Fenneman, 1938) in Connecticut are shown in figure 1; they include the New England Upland, the Seaboard Lowland, the Taconic, and the Connecticut Valley Lowland. The first three subdivisions have moderate relief and are underlain by crystalline rocks that have been extensively folded and faulted. The Connecticut Valley Lowland is underlain by a sequence of interbedded sedimentary and igneous rocks that may be as thick as 16,500 feet (ft) (W. J. Wenk, University of Connecticut, written commun., 1984). These rock units dip to the east and are faulted extensively. Relief generally is low except where erosion-resistant igneous rocks form a series of north-trending ridges. Unconsolidated glacial sediments of differing thickness discontinuously mantle the bedrock throughout the State and are most common in the northern part of the Connecticut Valley Lowland.

Ground-water recharge in Connecticut is mainly from precipitation that percolates from the land surface to the water table. Although recharge rates are variable, the long-term average ranges from about 7 to 20 inches annually. Recharge from precipitation occurs mainly during the nongrowing season from fall to late spring. Locally, pumping centers near streams or lakes induce significant additional recharge from these surface-water bodies. Ground-water flow is concentrated in the upper part of the saturated zone (generally within 300 ft of land surface). Because of the relatively shallow depth of the flow system and moderate topographic relief, ground-water circulation in most parts of Connecticut is localized within each basin drained by a perennial stream. Larger regional flow systems may be present in the sedimentary rocks of the Connecticut Valley Lowland (Weiss and others, 1982, p. 26). Most ground-water discharge is to nearby streams, lakes and estuaries, although some ground water is evapotranspired or withdrawn by wells. In streams where flows have not been altered by human activities, ground-water discharge provides an estimated 30 percent or more of mean streamflow (Mazzaferro and others, 1979, p. 45) and all flow during periods where no surface runoff occurs.

Table 1. Ground-water facts for Connecticut

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day]

Population served by ground water, 1980[1]	
Number (thousands)	984
Percentage of total population	32
From public water-supply systems:	
Number (thousands)	440
Percentage of total population	14
From rural self-supplied systems:	
Number (thousands)	544
Percentage of total population	18
Freshwater withdrawals, 1980[2]	
Surface water and ground water, total (Mgal/d)	1,300
Ground water only (Mgal/d)	150
Percentage of total	11
Percentage of total excluding withdrawals for thermoelectric power	20
Category of use	
Public-supply withdrawals[3]:	
Ground water (Mgal/d)	65
Percentage of total ground water	44
Percentage of total public supply	17
Per capita (gal/d)	148
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	53
Percentage of total ground water	36
Percentage of total rural domestic	100
Per capita (gal/d)	97
Livestock:	
Ground water (Mgal/d)	0.4
Percentage of total ground water	0.3
Percentage of total livestock	18
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	27
Percentage of total ground water	18
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	3
Excluding withdrawals for thermoelectric power	10
Irrigation withdrawals:	
Ground water (Mgal/d)	1.6
Percentage of total ground water	1
Percentage of total irrigation	8

[1] Data from Sternberg, 1983.

[2] Data from Solley, Chase, and Mann, 1983; values for total freshwater withdrawals, fresh ground-water withdrawals and public supply withdrawals adjusted based on data from Sternberg, 1983.

[3] Includes all community water supplies that serve at least two residences or 25 residents.

PRINCIPAL AQUIFERS

Two principal types of aquifers underlie Connecticut-unconsolidated stratified-drift aquifers composed of sand and gravel and bedrock aquifers composed of sedimentary, igneous, and metamorphic rocks. Stratified-drift aquifers overlie

Table 2. Aquifer and well characteristics in Connecticut

[Gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Connecticut Department of Environmental Protection]

Aquifer name and description	Well characteristics: Depth (ft), Common range	Depth (ft), May exceed	Yield (gal/min), Common range	Yield (gal/min), May exceed	Remarks
Stratified-drift aquifers: Sand and gravel, commonly with interbedded layers or lenses of silt and clay. Generally unconfined.	50 - 100	150	50 - 500	2,000	Largest yields from wells near major rivers. Iron and manganese concentrations commonly exceed 0.3 and 0.05 mg/L, respectively. Dissolved-solids concentrations range from 31 to 1,270 mg/L. Salty ground water present locally in coastal areas. Aquifers susceptible to contamination.
Sedimentary-aquifer system: Sandstone, shale, siltstone, and conglomerate; some interbedded basalt flows and dikes. Unconfined to partly confined in upper 200 ft, may be confined at depth.	100 - 300	500	2 - 50	500	Hydrologic characteristics poorly defined, particularly in zones deeper than 300 ft. Generally overlain by variable thicknesses of unconsolidated deposits. Moderately hard to hard water, and large concentrations of dissolved chloride sodium, and sulfate occur locally.
Crystalline bedrock aquifer (noncarbonate rocks): Gneiss and schist with minor amounts of other metamorphic and igneous rock types. Generally unconfined in upper 200 ft, may be confined at depth.	100 - 300	500	1 - 25	200	Hydrologic characteristics poorly defined, particularly in zones deeper than 300 ft. Generally overlain by variable thicknesses of unconsolidated deposits. Iron and manganese concentrations may exceed 0.3 and 0.05 mg/L, respectively. Dissolved-solids concentrations range from 20 to 1,590 mg/L.
Carbonate rock aquifer: Marble; some schist and quartzite zones. Generally unconfined in upper 200 ft, may be confined at depth.	100 - 300	500	1 - 50	200	Hydrologic characteristics poorly defined, particularly in zones deeper than 300 ft. Generally overlain by variable thicknesses of unconsolidated deposits. Generally hard to very hard water; large iron and manganese concentrations are local problems.

the bedrock and store and transmit water through interconnected pore spaces. Bedrock aquifers store and transmit water primarily through fracture networks. The characteristics of the stratified-drift and bedrock aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

Stratified-Drift Aquifers

Stratified-drift aquifers are the most productive sources of ground water in the State. They were formed during the deglaciation of southern New England when interbedded layers of sand, gravel, silt, and clay were deposited in river valleys or in temporary glacial lakes. Stratified-drift aquifers are not distributed evenly (fig. 1) and differ significantly in their ability to yield water. They are most common in the Quinebaug River basin in eastern Connecticut and in the Farmington, the Quinnipiac and the upper Connecticut River basins in the Connecticut Valley Lowland. Because of generally low topographic relief and the history of deglaciation in this area, stratified-drift aquifers are widespread and commonly extend across surface-water drainage divides in the Connecticut Valley Lowland. Elsewhere in the State, these aquifers generally are less widespread and are confined to valleys. Several stratified-drift aquifers may be present in a single valley, and development of aquifers upstream can affect the yield of aquifers downstream by reducing the amount of streamflow available for induced recharge. Factors that effect well yields include thickness, extent, and permeability of aquifer materials and proximity and flow of adjacent streams that are sources of induced recharge. Where conditions are favorable, well fields can produce several million gallons of water per day.

Ground water in stratified-drift aquifers generally is of good to excellent quality, suitable for human consumption and most industrial uses. Constituents that may be present in concentrations excessive for some uses include iron [as much as 40 milligrams per liter (mg/L)], manganese (as much as 5.9 mg/L), silica (as much as 30 mg/L), sulfate (as much as 292 mg/L), and sodium (as much as 314 mg/L). Hard to very hard water (greater than 120 mg/L as calcium carbonate) is common in western Connecticut (Cervione and others, 1972; Ryder and others, 1970) because of dissolution of marble fragments in the stratified drift.

Stratified-drift aquifers are susceptible to contamination, and water quality has been affected locally in almost all regions of the State (Rolston and others, 1979). Where stratified-drift aquifers are adjacent to saltwater bodies, excessive pumping and coastal flooding have caused saltwater contamination. Major sources of ground-water contamination, which include waste-disposal facilities, accidental spills,

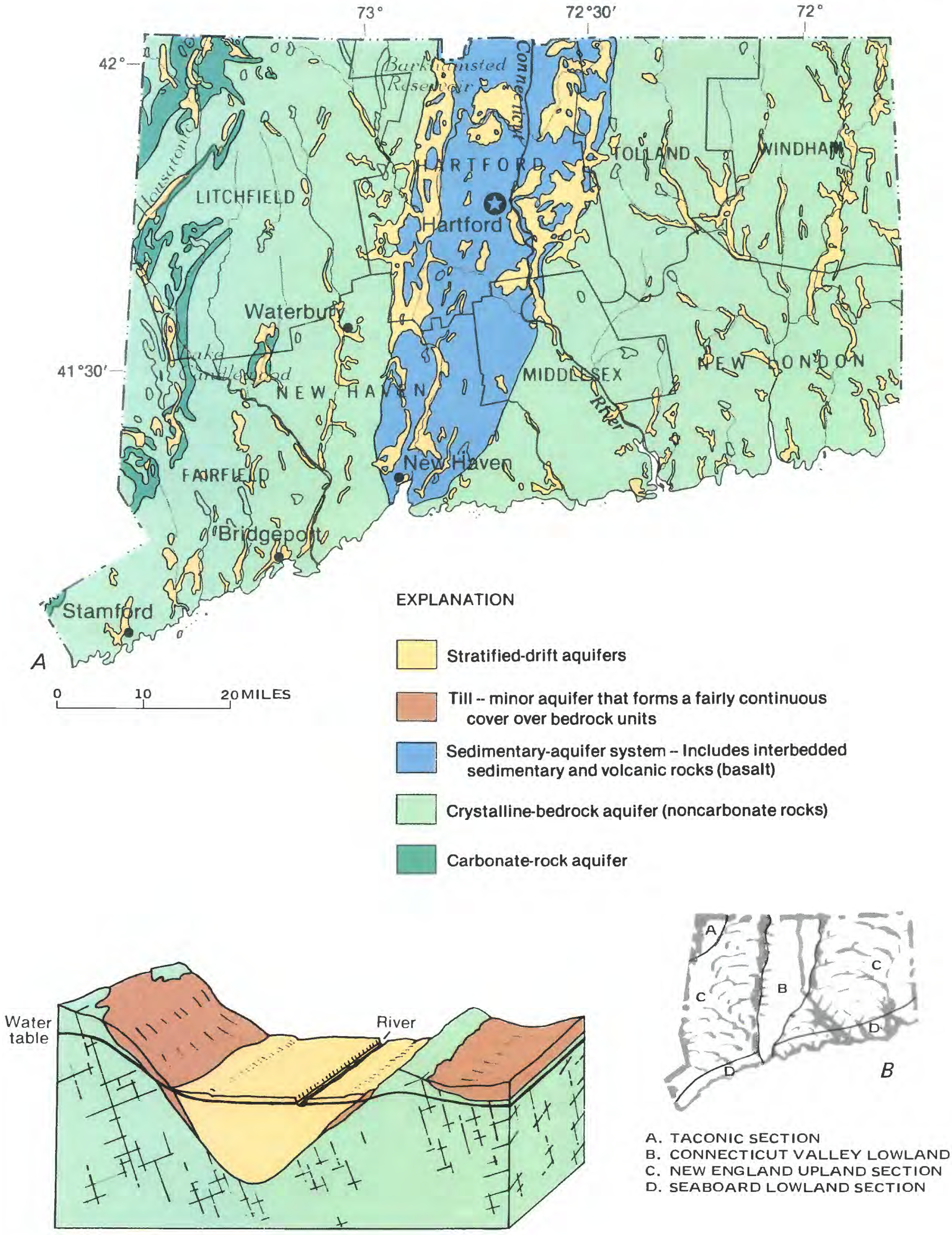


Figure 1. Principal aquifers in Connecticut. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Typical relationship between stratified-drift and bedrock aquifers. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Meade, 1978. *B*, Fenneman, 1938; Raisz, 1954. *C*, Compiled by R. L. Melvin from U.S. Geological Survey files.)

chemical storage, and pesticide and fertilizer application, are summarized in Handman and others (1979).

SEDIMENTARY, CRYSTALLINE BEDROCK, AND CARBONATE ROCK AQUIFERS

Bedrock aquifers underlie the entire State and are the principal source of water for self-supplied homes and small public-supply systems, commercial establishments, and industries. The bedrock aquifers can be subdivided broadly into a sedimentary-aquifer system, which is composed predominantly of sandstone, shale, siltstone, and conglomerate, and a crystalline bedrock aquifer, which is composed predominantly of gneiss, schist, and marble. Metamorphosed carbonate rocks (marble), although crystalline, are delineated separately in figure 1 and are described separately in table 2 because they produce a distinctive water quality and slightly larger well yields.

The sedimentary-aquifer system is composed of a thick sequence of Triassic and Jurassic sandstone, siltstone, shale, and conglomerate that underlies the Connecticut Valley Lowland and a small area in western Connecticut. Three basalt flows (igneous rocks) about 200 to 330 ft thick (Hubert and others, 1978) are interbedded with the sedimentary rocks. The hydrologic characteristics of this aquifer are defined poorly with respect to degree of confinement, permeability, and ground-water circulation, particularly in zones deeper than 300 ft. Well yields depend primarily on the number, size, and degree of interconnection of water-bearing fractures, especially in the upper 300 ft of this aquifer. Analyses of the records of several hundred wells that tap the sedimentary-aquifer system indicate larger median and maximum yields than in the crystalline bedrock (Mazzaferro and others, 1979; Ryder and others, 1981; and Weiss and others, 1982). Relatively large yields, ranging from 100 to 600 gallons per minute at several locations in the Connecticut Valley Lowland, may be associated with major fault zones.

Crystalline bedrock aquifers underlie eastern and western Connecticut (fig. 1). Well yields depend upon the number, size, and degree of interconnection of the water-bearing fractures intercepted. Analyses conducted for regional studies indicate little areal variation in the water-yielding characteristics of crystalline bedrock (Cervione and others, 1972; Randall and others, 1966; Mazzaferro and others, 1979; Weiss and others, 1982). Carbonate rocks (marble) and the more structurally competent granular rocks (gneiss and granite gneiss) generally are more productive than schists. Large yields have been associated with major fault zones and with areas where the bedrock is overlain by saturated stratified drift.

Water quality in the bedrock aquifers generally is suitable for most uses. Large concentrations of iron (as much as 8.6 mg/L) and manganese (as much as 6.4 mg/L) are common statewide, and hard to very hard water is widespread in the carbonate rocks in western Connecticut and in the sedimentary-aquifer system. Large concentrations of chloride (as much as 830 mg/L), sulfate (as much as 1,600 mg/L), and sodium (as much as 3,800 mg/L) are present in some parts of the sedimentary-aquifer system, particularly in deeper wells. The bedrock aquifers also have been contaminated locally by inorganic and organic substances (Rolston and others, 1979); the major sources of contamination are summarized in Handman and others (1979).

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Areas of major ground-water withdrawals are concentrated in Hartford, Fairfield, Middlesex and New Haven Counties (fig. 2). Most of the water is used for public supply. Pumping centers are located in stratified-drift aquifers with the exception of one that taps the sedimentary aquifer system north of Hartford (location 4, fig. 2).

Natural trends of ground-water levels in major aquifers are shown in the hydrographs of figure 2 (locations 26 and 27). The lowest water levels occurred during the drought period of the 1960's; high water levels in the early 1970's reflect higher than average rainfall. Water-level measurements near pumping centers are not available. Widespread, progressive water-level declines are unlikely because most pumping centers are located in unconfined stratified-drift aquifers near large streams and derive much of their water from induced recharge rather than aquifer storage. Records of discontinued U.S. Geological Survey observation wells in the New Haven area show progressive water-level declines that have been accompanied by saltwater intrusion in a coastal stratified-drift aquifer. Water levels in this aquifer began to recover after withdrawals were reduced in the 1950's.

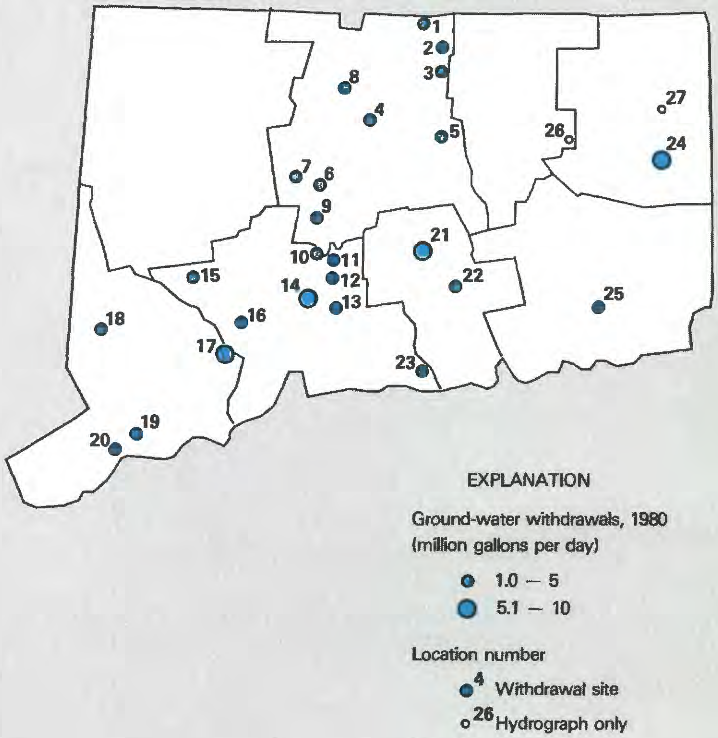
Because of the widespread dependence on induced recharge to sustain withdrawals from stratified-drift aquifers, the most significant impact of development is the depletion of streamflow. Withdrawal rates generally are greater in the summer when ground-water levels and streamflow are relatively low. A larger proportion of total streamflow may infiltrate the aquifer during this period and parts of small streams may become completely dry.

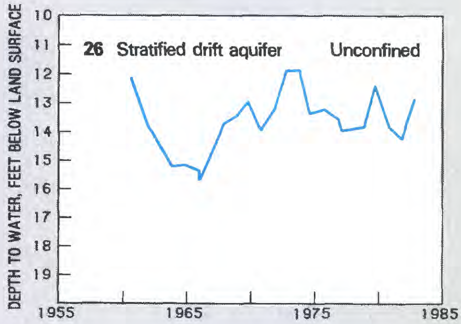
GROUND-WATER MANAGEMENT

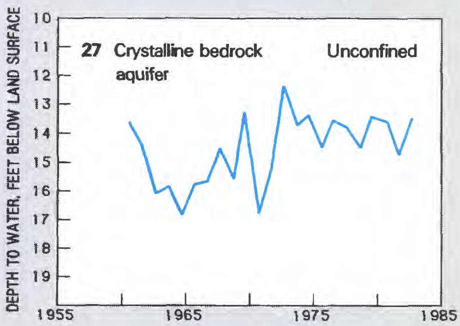
Connecticut has a comprehensive program for managing ground-water resources that originated with passage of the Clean Water Act of 1967 (Connecticut Public Act 57) and that has been strengthened by subsequent passage of Federal clean water legislation. Joint management planning by the Connecticut Departments of Environmental Protection (DEP) and of Health Services (DOHS) and the Office of Policy and Management is a continual process.

Water-quality management is an important State activity. The Connecticut DEP is responsible for establishing quality goals for ground water and for planning regulatory programs to ensure that these goals are met. Water-quality standards for ground water, which were adopted in 1980 (Connecticut Department of Environmental Protection, 1980), provide the framework for basin-wide plans that specify actions to eliminate water-quality problems and for such regulatory programs such as waste-discharge permits and enforcement actions.

Permits for drilling wells and submission of well records have been required by the State since 1955. The Connecticut Water Policy Diversion Act (Connecticut General Statutes, Sec. 22a-365) gives the DEP the authority to regulate ground-water withdrawals that exceed 50,000 gallons per day. The process for permitting withdrawals addresses issues of water quantity and quality. The DEP also is responsible for investigating pollution incidents, for providing technical assistance to municipalities, and for conducting inventories and investigations of the State's water resources. The inventories and investigations, done principally as part of a cooperative program with the U.S. Geological Survey, provide the scientific information base for the State's ground-water planning and management. Information needs for ground-water management that have been identified by the DEP (H. F. Thomas, Connecticut Department of Environmental Protection, oral commun., 1984) include definition of the flow system and water quality in principal stratified-drift aquifers, relations between land use and ground-water quality, and affects of induced recharge from waste-receiving streams.







WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Enfield	Stratified drift. . . .	Public supply.
2	Enfield	. . . .do	Do.
3	East Windsor.	. . . .do	Do.
4	Bloomfield.	Sedimentary rock . .	Commercial.
5	Manchester.	Stratified drift. . . .	Public supply.
6	Plainville	. . . .do	Do.
7	Bristol	. . . .do	Do.
8	Simsbury.	. . . .do	Do.
9	Southington	. . . .do	Do.
10	Cheshire	. . . .do	Do.
11	Meriden	. . . .do	Do.
12	Wallingford	. . . .do	Do.
13	North Haven.	. . . .do	Industrial.
14	Cheshire, Hamden. . .	. . . .do	Public supply.
15	Southbury	. . . .do	Do.
16	Seymour	. . . .do	Do.
17	Seymour, Derby, Shelton.	. . . .do	Do.
18	Danbury	. . . .do	Do.
19	Westport	. . . .do	Do.
20	Norwalk	. . . .do	Do.
21	Middletown	. . . .do	Public supply, industrial.
22	Haddam	. . . .do	Industrial.
23	Clinton, Guilford, Madison.	. . . .do	Public supply.
24	Plainfield.	. . . .do	Aquaculture.
25	Montville.	. . . .do	Industrial.

Figure 2. Area distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Connecticut. (Sources: Withdrawal data from Sternberg, 1983, and Connecticut Department of Environmental Protection files; water-level data from U.S. Geological Survey files.)

The Connecticut DOHS, under Section 19-13 of the Connecticut General Statutes, has the major role in managing ground-water resources used for drinking water. Responsibilities include protection and location of private and public-supply wells, well-construction requirements, and development and enforcement of standards for the quality of drinking water. Public water-supply utilities are required by Connecticut Public Act 84-502 to submit long-range water-supply plans to DOHS to aid in identifying aquifers to be protected for future public supply. Programs designed to protect aquifers as sources of public supply were instituted by 25 municipalities through 1983 using either local planning and zoning or municipal ordinances. Most of these programs include regulations that prohibit uses or activities that could adversely affect ground-water quality.

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Prepared by Robert L. Melvin

For further information contact Chief, Connecticut Office, U.S. Geological Survey, Abraham A. Ribicoff Federal Building, Room 525, 450 Main Street, Hartford, CT 06103

DELAWARE
Ground-Water Resources

Ground water is the primary source of public, rural, and industrial water supply in 94 percent of the State of Delaware. Only the northernmost 6 percent of the State is supplied predominantly by surface water. Most of Delaware's population is concentrated in the northern part of the State; consequently, about 60 percent of the statewide population is served by ground water and 40 percent by surface water. Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

GENERAL SETTING

Delaware is situated in two physiographic provinces that are separated by the Fall Line (fig. 1). The Piedmont province lies north of the Fall Line and comprises about 6 percent of the State. Ground water in the Piedmont occurs in crystalline rocks. The Coastal Plain province, south of the Fall Line, includes the remaining 94 percent of Delaware. The Coastal Plain province is composed of a wedge-shaped deposit of alternating layers of sand and clay that overlies the crystalline basement rocks and increases in thickness to the southeast, attaining a thickness of 15,000 feet (ft) in southeastern Delaware (Woodruff, 1977).

Most of the 43 inches (in.) of average annual precipitation in the Coastal Plain either evaporates, is transpired by plants, or runs off to streams and rivers. Johnston (1973) estimated that only about 14 in. of precipitation actually enters the ground-water system annually. Although abundant freshwater recharges the Coastal Plain aquifers, water 600 ft or more below land surface is generally saline.

PRINCIPAL AQUIFERS

Two types of aquifers underlie Delaware: unconsolidated sedimentary deposits of the Coastal Plain and crystalline bedrock of the Piedmont. The unconsolidated deposits are the most important aquifers in the State. These deposits store and transmit water through interconnected pore spaces. The bedrock aquifer stores and transmits water primarily through fracture networks and weathered surfaces of the bedrock. The characteristics of the aquifers are described, from youngest to oldest, below and in table 2; their areal distribution is shown in figure 1.

Ground-water quality generally is suitable for human consumption and most other uses. Saline water occurs, however, in downdip parts of most Coastal Plain aquifers and at shallow depths in some aquifers that subcrop along Delaware Bay and the Atlantic Ocean. Water in the confined Coastal Plain aquifer ranges in chemical character from calcium bicarbonate water containing less than 100 milligrams per liter (mg/L) dissolved solids to sodium chloride-bicarbonate water containing more than 1,000 mg/L dissolved solids. Some brackish water has been induced into the Potomac aquifer by pumping near Delaware Bay. Locally large concentrations of iron (more than 0.3 mg/L) and nitrate (more than 10 mg/L) may limit the use of water from some of the unconsolidated aquifers. Pollution from human activities has caused local contamination of both crystalline rock and unconfined aquifers.

Table 1. Ground-water facts for Delaware

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	354
Percentage of total population	60
From public water-supply systems:	
Number (thousands)	254
Percentage of total population	43
From rural self-supplied systems:	
Number (thousands)	100
Percentage of total population	17
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	140
Ground water only (Mgal/d)	82
Percentage of total	59
Percentage of total excluding withdrawals for thermoelectric power	57
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	30
Percentage of total ground water	37
Percentage of total public supply	38
Per capita (gal/d)	118
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	25
Percentage of total ground water	30
Percentage of total rural domestic	100
Per capita (gal/d)	250
Livestock:	
Ground water (Mgal/d)	2.0
Percentage of total ground water	2
Percentage of total livestock	100
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	21
Percentage of total ground water	26
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	68
Excluding withdrawals for thermoelectric power	73
Irrigation withdrawals:	
Ground water (Mgal/d)	4.1
Percentage of total ground water	5
Percentage of total irrigation	63

UNCONFINED AQUIFER

The unconfined aquifer consists of channel-fill sands in northern Delaware south of the Piedmont Province and of a broad sheet of sand across central and southern Delaware. The saturated thickness of the aquifer ranges from a few feet in much of northern Delaware to more than 180 ft in southern Delaware (Johnston, 1973). The northern limit of the areally continuous unconfined aquifer, which has a saturated thickness of 25 ft or more, is shown in figure 1. This aquifer supplies large quantities of water for public supply and irriga-

Table 2. Aquifer and well characteristics in Delaware

[Gal/min = gallons per minute, ft = feet. Sources: Reports of the U.S. Geological Survey and Delaware Geological Survey]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Unconfined aquifer: sand and gravel, some silt and clay.	25 - 100	125	100 - 500	1,000	Concentrations of iron, nitrate, or chloride may exceed national drinking-water regulations in local areas.
Chesapeake Group aquifers: Fine to coarse sand; layers of lignite and shells are common. Generally confined.	50 - 300	400	100 - 500	1,000	Includes the Pocomoke, the Manokin, the Ocean City, and the Cheswold aquifers. In some areas, chloride or iron concentrations exceed national drinking-water regulations.
Piney Point aquifer: Fine to medium glauconite sand. Confined.	200 - 600	700	100 - 500	1,000	Important source of water for Dover.
Rancocas aquifer: Fine to medium silty glauconite sand. Confined south of subcrop.	50 - 400	400	50 - 100	300	Equivalent to Aquia aquifer in Maryland.
Magothy aquifer: Clean quartz sand with layers of clayey silt. Confined south of subcrop area.	50 - 300	400	10 - 25	50	Minor aquifer, used in southern New Castle County.
Potomac aquifer: Silt and clay containing channel-fill deposits of sand and gravel. Confined south of subcrop area.	40 - 600	600	100 - 400	1,000	Major source of public and industrial water supply in central New Castle County.
Crystalline rock aquifer: Granodiorite, gabbro, schist, and marble. Unconfined.	40 - 100	100	5 - 20	200	Supplements surface-water supplies in the Piedmont.

tion and also serves as a recharge area for the underlying aquifers of the Coastal Plain. Nitrate may exceed 10 mg/L as nitrogen in areas affected by agriculture or domestic sewage, and iron may exceed 30 mg/L in some areas of the unconfined aquifer.

Aquifers in Chesapeake Group

Aquifers in the Chesapeake Group generally are confined except where they subcrop beneath the unconfined aquifer. The Pocomoke, the Ocean City, and the Manokin aquifers are used in southern Delaware for public and industrial water supplies. The lowermost aquifer of the Chesapeake Group, the Cheswold aquifer, is an important source of water in Kent County.

Piney Point Aquifer

The Piney Point aquifer is confined completely in Delaware. Recharge to this aquifer is derived from leakage of water through adjacent confining beds composed of silt and clay. The Piney Point aquifer, in conjunction with the Cheswold aquifer described above, supplies about 80 percent of the total municipal and industrial water used in Kent County (Leahy, 1982).

Rancocas Aquifer

The Rancocas aquifer supplies small to moderate amounts of water for public-supply, industrial, and agricultural use in southern New Castle County. Sundstrom and Pickett (1971) estimated that 650,000 gallons per day (gal/d) were withdrawn from this aquifer in 1966.

Magothy Aquifer

The Magothy aquifer receives recharge from the unconfined aquifer in central New Castle County. South of the recharge area the aquifer is confined and provides water for domestic, agricultural, and minor public-supply use. Water in the Magothy aquifer becomes salty about 6 miles (mi) southeast of Middletown (Sundstrom and Pickett, 1971).

Potomac Aquifer

The Potomac aquifer is composed of several sandy zones within the Potomac Formation. These sandy zones are interbedded with variegated clay and differ considerably in lateral extent. Martin and Denver (1982) estimated that the Potomac aquifer provided 19.9 million gallons per day (Mgal/d) for industrial and public-water supply. This aquifer is the primary source of ground water in central New Castle County.

Crystalline Rock Aquifer

The Piedmont crystalline rocks of northern Delaware are composed of granodiorite, gabbro, schist, and marble. Rasmussen and others (1957) found that of 165 wells in the granodiorite, gabbro, and schist, and their weathering products, those that produce water from the gabbro had the greatest average yield [28 gallons per minute (gal/min)]. Two wells subsequently completed in marble, however, produce an average of 600,000 gal/d. Well yields in this part of Delaware usually are small, averaging about 20 gal/min (Sundstrom and Pickett, 1971).

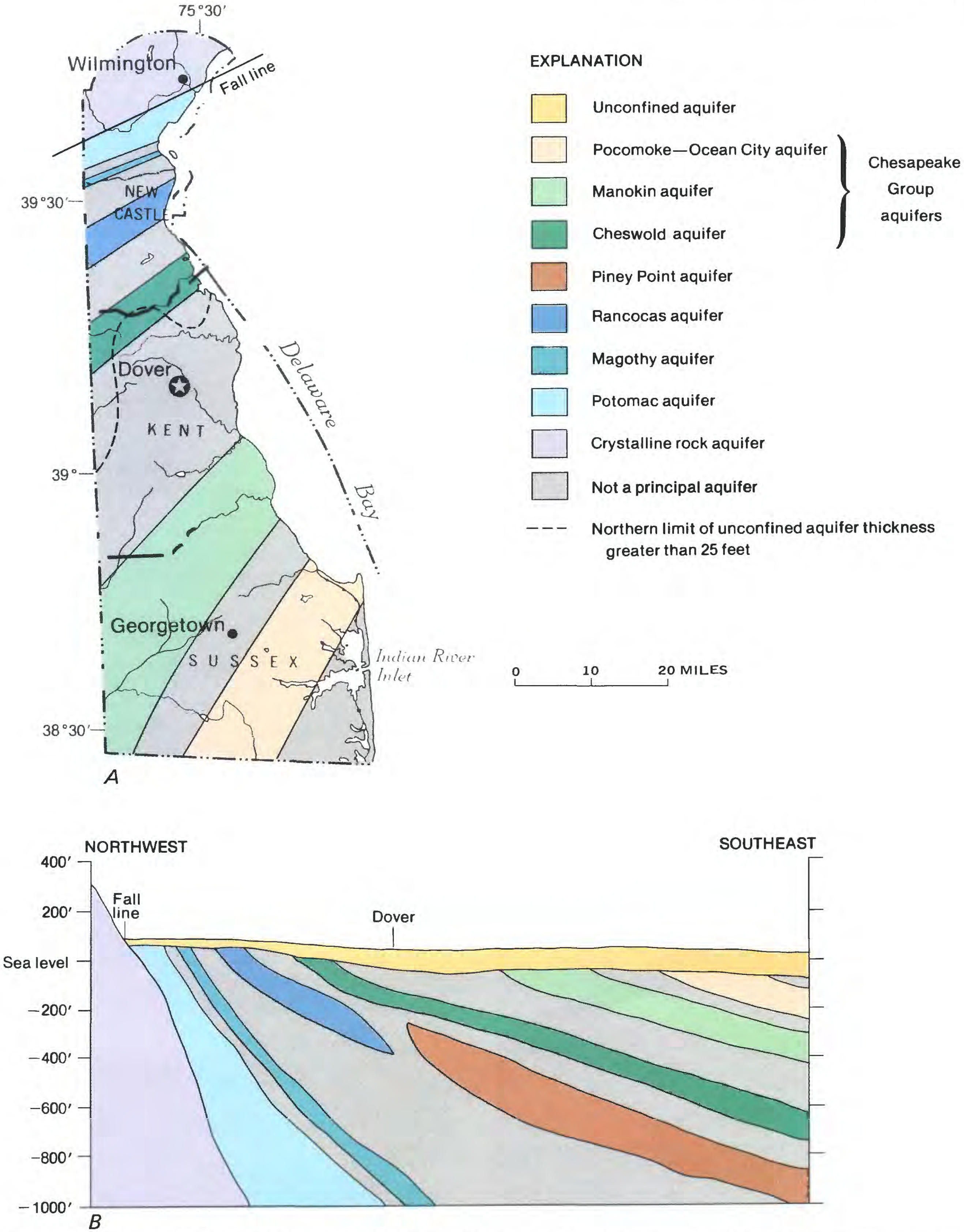


Figure 1. Principal aquifers in Delaware. *A*, Geographic distribution. *B*, Generalized cross section. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Cushing and others, 1973; Sundstrom and Pickett, 1971; Hodges, 1984. *B*, Cushing and others, 1973; Sundstrom and Pickett, 1971; Hodges, 1984.)

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals and trends in ground-water levels are shown in figure 2. The largest concentration of pumping is in central New Castle County where almost 20 Mgal/d is pumped for public-supply and industrial use. In Kent County, the city of Dover and Dover Air Force Base (location 4, fig. 2) withdraw a total of more than 6 Mgal/d. The largest use of water in Sussex County is for irrigation (location 8, fig. 2). Irrigation wells normally operate for only 4 months each year. Average daily use during the growing season is, therefore, about three times the annual average value shown in the explanation.

The hydrographs shown in figure 2 represent water-level trends near the major withdrawal centers of the Coastal Plain aquifers of Delaware. Increased growth of population and heavy industry in central New Castle County (location 1, fig. 2) caused a rapid decline of water levels in the Potomac aquifer during the late 1950's. A slight decrease in withdrawals during the late 1960's and early 1970's allowed water levels to recover somewhat, but increased demand during the past 10 years has caused water levels to resume their decline. Development of the Piney Point aquifer as a source of public, industrial, and military water supply in the Dover area (location 4, fig. 2) began in 1957. Since that time, water levels in the aquifer have declined steadily. The unconfined aquifer, however, receives abundant recharge from precipitation. Water levels in this aquifer normally decline as much as 5 ft during the summer growing season and then recover during the winter and spring.

GROUND-WATER MANAGEMENT

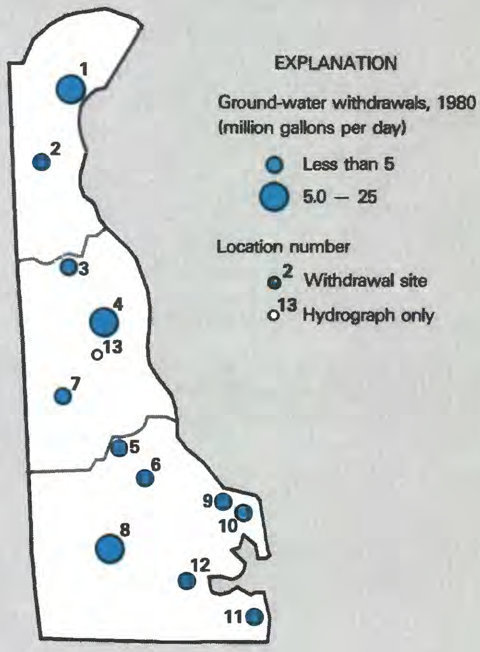
Delaware ground-water use is regulated by the Department of Natural Resources and Environmental Control (DNREC) under the terms of the Delaware Environmental Protection Act (7 Delaware Code, chapter 60). The Water Supply Section of DNREC licenses well drillers, issues permits for the construction of all water wells, requires reports on the completion of these wells, and issues allocations for the use of ground and surface water. The DNREC also issues permits for onsite wastewater treatment installations, and monitors National Pollution Discharge Elimination System wastewater return-flow data.

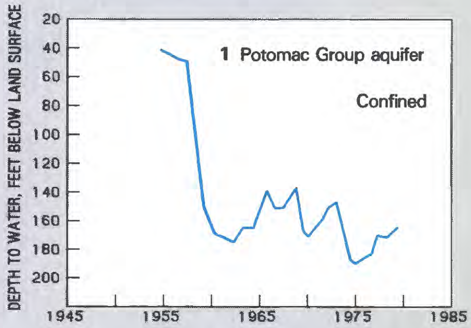
The Delaware Department of Health and Social Services, Division of Public Health (DPH) regulates the quality and adequacy of public water-supply systems (16 Delaware Code, 122) that provide service to three or more dwelling units, public or semipublic buildings, or to establishments that use water to prepare food or drink. Under this law, the DPH has the power to regulate the adequacy of source water as well as the adequacy of treated water and, under 16 Delaware Code, 1244, can regulate any activity within 1 mi of a source of public-water supply.

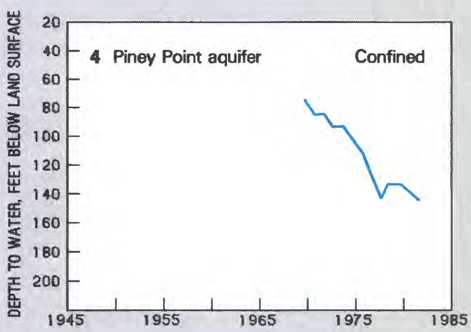
Public-water supplies also are regulated by the Public Service Commission (PSC). The PSC, in addition to requiring adequacy of service, can function as an enforcement arm of the Department of Health, or of other State agencies.

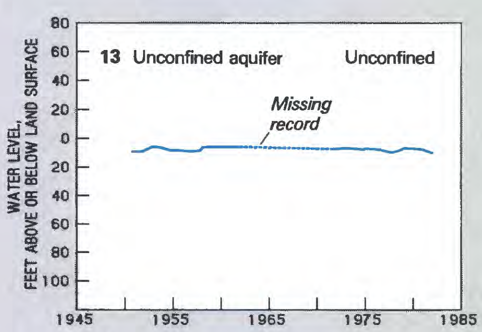
The Delaware River Basin Commission (DRBC), by agreement between the various States in the Delaware River basin, regulates the use of surface and ground water in that part of Delaware within the basin boundary. All projects within the basin that will have a "substantial impact" on water resources are subject to DRBC permit procedures. These projects include wells that withdraw an average of 100,000 gal/d or more during any calendar month, discharge or inject pollutants into ground water, or change land cover on major aquifer-recharge areas.

Nonregulatory agencies involved in Delaware ground-water issues include the Water Resources Agency for New Castle County (WRANCC) and the Delaware Geological Survey (DGS). At present, the WRANCC is presently developing a plan titled "Water 2000," which is a management strategy for developing adequate present and future water supplies in New Castle County. In addition to other hydrologic and geologic responsibilities, the DGS, in cooperation with the U.S. Geological Survey, maintains a statewide water-data network and investigates the ground-water resources of the State.









WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	New Castle County . . .	Unconfined, Potomac Group.	Public supply, industrial.
2	Middletown	Unconfined, Rancocas, Magothy.	Public supply.
3	Smyrna area	Unconfined, Rancocas . . .	Public supply industrial, institutional.
4	Dover area	Cheswold, Piney Point . . .	Public supply, industrial, thermoelectric power.
5	Milford	Unconfined, Chesapeake Group.	Public supply.
6	Milton	Chesapeake Group	Public supply, industrial.
7	Kent County.	Unconfined	Irrigation.
8	Sussex County.	. . . .do	Do.
9	Lewes.	Unconfined, Chesapeake Group.	Public supply, industrial.
10	Rehoboth area.	Unconfined	Public supply.
11	Bethany Beach area. . .	Unconfined, Chesapeake Group.	Public supply, industrial.
12	Millsboro.	. . . .do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Delaware. (Sources: Withdrawal data from Delaware Department of Natural Resources and Environmental Control; water-level data from U.S. Geological Survey files.)

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Prepared by Arthur L. Hodges, Jr.

For further information contact Chief, Delaware Office, U.S. Geological Survey, Federal Building, Room 1201, 300 S. New Street, Dover, DE 19901

FLORIDA
Ground-Water Resources

Florida contains abundant ground-water resources. Large quantities of water are obtainable from each of the principal aquifers in most areas of the State. The State also contains 27 of the 78 first-magnitude springs in the United States (Heath and Conover, 1981, p. 131). Because of its abundance and availability, ground water is the principal source of freshwater for public-supply, rural, and industrial uses, and is the source for about half of the water used for irrigation. More than one-half of the 7,300 million gallons per day (Mgal/d) of freshwater used in Florida for all purposes comes from ground-water sources (Leach, 1983), and about 90 percent of Florida's population depends on ground water for its drinking water (table 1). Nationally, Florida ranks eighth among States in total fresh ground-water withdrawals for all uses, second for public supply, first for rural domestic and livestock, third for industrial uses, and ninth for irrigation withdrawals (Solley and others, 1983). Ground water is one of Florida's most valuable natural resources.

GENERAL SETTING

The entire State is in the Coastal Plain physiographic province, which is a region that has generally low relief and is underlain by unconsolidated to poorly consolidated sediments and indurated carbonate rocks. Florida is mantled nearly everywhere by surficial sands that overlie a thick sequence of bedded limestone and dolomite. Together, the surficial sands and the limestone and dolomite form an enormous ground-water reservoir that provides proportionally larger quantities of ground water in Florida than in any other State (McGuinness, 1963, p. 244). Nearly all of Florida's ground water originates from precipitation. Relatively small amounts also are supplied by subsurface inflow from adjacent areas of Alabama and Georgia and by leakage from streams that enter Florida.

Average annual precipitation (1951-80) exceeds 50 inches (in.) over most of the State. Part of this precipitation percolates to the water table and recharges the ground-water reservoir. Annual recharge rates range from near zero in perennially wet, lowland areas to as much as 20 in. or more in well-drained upland areas. In much of the State, most of this recharge moves through the surficial aquifers and discharges to nearby streams; only a small fraction, ranging from nearly 0 to 5 in. (Bush, 1982), percolates downward to recharge deeper aquifers.

PRINCIPAL AQUIFERS

Principal aquifers of Florida are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

BISCAYNE AQUIFER

The Biscayne aquifer is the most intensively developed of all the Florida aquifers. It supplies the densely populated Miami-Palm Beach coastal area with virtually all of its water needs. The Biscayne aquifer underlies all of Dade and Broward Counties and adjoining parts of Palm Beach and Monroe Counties. It is primarily highly permeable limestone in south and west Dade County but becomes increasingly sandy and less permeable to the north and east. The high permeability is caused largely by extensive carbonate dissolution. Large-diameter public-supply wells in Dade County produce as much as 7,000 gallons per minute (gal/min), with little water-level drawdown. Water in the Biscayne aquifer is unconfined and in hydraulic continuity with the many canals that cross the area. Induced recharge from the canals occurs where the water table is depressed below canal stage near well fields. Water-level stages in the canals are controlled by structures near their mouths to prevent saltwater from flowing inland to the well fields and, there, infiltrating the aquifer.

Because the Biscayne aquifer is very permeable and very vulnerable to contamination and is the sole source of drinking water for more than 3 million people in southeast Florida, the U.S. Environmental Protection Agency has designated it as a

Table 1. Ground-water facts for Florida

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	8,750
Percentage of total population	90
From public water-supply systems:	
Number (thousands)	6,800
Percentage of total population	70
From rural self-supplied systems:	
Number (thousands)	1,950
Percentage of total population	20
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	7,300
Ground water only (Mgal/d)	3,800
Percentage of total	52
Percentage of total excluding withdrawals for thermoelectric power	69
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	1,200
Percentage of total ground water	31
Percentage of total public supply	86
Per capita (gal/d)	176
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	250
Percentage of total ground water	7
Percentage of total rural domestic	100
Per capita (gal/d)	128
Livestock:	
Ground water (Mgal/d)	39
Percentage of total ground water	1
Percentage of total livestock	66
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	710
Percentage of total ground water	19
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	27
Excluding withdrawals for thermoelectric power	82
Irrigation withdrawals:	
Ground water (Mgal/d)	1,600
Percentage of total ground water	42
Percentage of total irrigation	53

Table 2. Aquifer and well characteristics in Florida

[Mgal/d = millions of gallons per day; gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Florida State agencies; water withdrawals from Healy, 1981, data for public supply only]

Aquifer name and description	Water withdrawals (Mgal/d)	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Surficial aquifers:					
Biscayne aquifer: Limestone, sandstone, and sand. Unconfined.	461	40 - 150	500 - 1,000	7,000	Supplies all public-supply water systems in southern Palm Beach, Broward, and Dade Counties. Designated by U.S. Environmental Protection Agency as "sole-source" drinking-water supply. Aquifer managed carefully to control saltwater intrusion into coastal well fields. Water generally very hard.
Sand-and-gravel aquifer: Sand and gravel interbedded with discontinuous clay layers. Unconfined in upper part to locally confined in deeper part.	34	100 - 300	500 - 1,000	2,000	Primary water source for Pensacola and other public-supply and private pumpage in Escambia and Santa Rosa Counties. Water soft; little dissolved solids (less than 50 mg/L), but locally iron exceeds 0.3 mg/L. Known as Pliocene–Miocene aquifer in Alabama.
Unnamed surficial aquifers: Sand, shell, and clayey sand; locally contains thin discontinuous limestone layers. Unconfined to locally confined.	104 (with intermediate aquifer(s))	50 - 400	<100	1,000	Locally important as water sources where deeper aquifers contain saline water, especially along east coast and in southwest Florida. Hardness and dissolved-solids concentrations vary widely. Saltwater intrusion a local problem.
Intermediate aquifer(s): Limestone and shell beds with discontinuous clay layers and some interbedded sand. Confined.		100 - 600	<200	1,000	Important public-supply source along west coast from Sarasota to Lee County. Elsewhere tapped generally for small to moderate supplies. Flowing wells common in coastal areas. Some parts in and around Sarasota County yield water containing sulfate and radionuclide concentrations exceeding National drinking-water regulations. Also called "secondary artesian aquifer(s)."
Floridan aquifer system: Limestone and dolomite. Unconfined in outcrop areas, confined where deeply buried.	460	100 - 1,800	500 - 1,000	20,000	Occurs throughout Florida and extends into parts of Alabama, Georgia, and South Carolina. Contains nonpotable, saline water in south Florida, westernmost Florida panhandle, and locally along the west coast where unconfined. Elsewhere water is hard. Locally sulfate concentrations exceed National drinking-water regulations. Principal source of water for all uses where water is fresh. Also called "principal artesian aquifer" and "Floridan aquifer."

"sole-source aquifer" under provisions of the Safe Drinking Water Act of 1974 (Public Law 93-523). Locally, the aquifer has been contaminated by industrial discharges, landfill leachate, and fuel spills.

SAND-AND-GRAVEL AQUIFER

The sand-and-gravel aquifer is the major source of water supply in the western part of the Florida Panhandle. The aquifer consists of surficial sediments that exceed 700 feet (ft) in thickness in northwestern Escambia County. The aquifer thins to the south and east and pinches out in central Walton County. Water in the sand-and-gravel aquifer is under both unconfined and confined conditions, depending on the presence of discontinuous clay lenses of little permeability that are interbedded with the more permeable sand-and-gravel layers. The deep production zone of the aquifer, which is

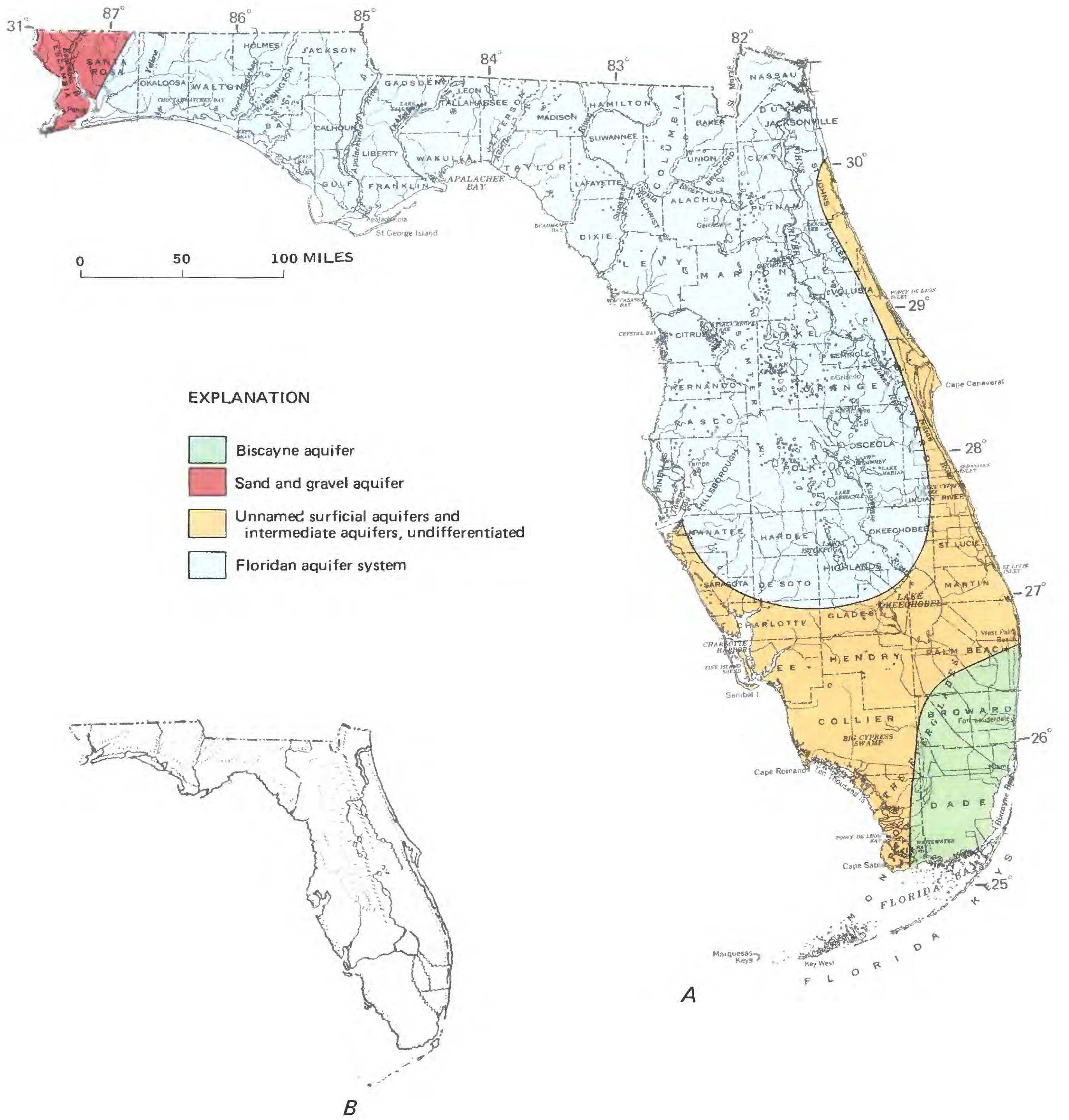


Figure 1. Principal aquifers in Florida. *A*, Approximate areal extent over which principal aquifers are the primary source of supply. *B*, Physiographic diagram. (See table 2 for a more detailed description of the aquifers. Source: *A*, Modified from Franks, 1982. *B*, Raisz, 1954.)

tapped by most large-capacity wells, generally is semiconfined. Wells capable of producing several hundred gallons per minute are common. Industrial operations in and around Pensacola have caused local contamination of the aquifer's water; a noteworthy example is contamination by phenol and pentachlorophenol from a wood-preserving plant during the past several decades (Mattraw and Franks, 1984).

Unnamed Surficial and Intermediate Aquifers

Unnamed surficial aquifers are present over much of the remainder of the State but they are little used where more plentiful supplies are obtained from deeper aquifers that contain potable water. Where the deeper aquifers contain nonpotable water, these surficial aquifers are important sources of supply. The surficial deposits consist of sand and shell with minor limestone beds. These aquifers are used most intensively for public supply in the area southwest of Lake Okeechobee and in scattered towns along the east coast from Palm Beach County northward. Elsewhere, these aquifers are used mainly for rural supplies. The aquifers have been contaminated locally with saline water from uncontrolled flowing artesian wells that tap deeper aquifers.

In south Florida and along the eastern part of peninsular Florida, one or more aquifers are present between the local surficial aquifer and the underlying Floridan aquifer system; these are informally referred to as intermediate aquifers. The rocks that contain the intermediate aquifers are mainly limestone and shell beds interbedded with sand and clay. Intermediate aquifers are an important source of water for public supply and irrigation in coastal southwestern Florida from about Sarasota County to Lee County where the underlying Floridan aquifer system contains nonpotable water. Well yields differ widely depending on the amount of permeable limestone available; however, yields of 1,000 gal/min or more can be obtained. Elsewhere, these aquifers generally are used only for rural or small-community supplies. Water in the intermediate aquifers is confined. The intermediate aquifers contain water too saline for human consumption in most of the area south of Lake Okeechobee. Parts of the aquifers in and around Sarasota County contain water having concentrations of naturally-occurring radium 226 that exceed national drinking-water standards (U.S. Environmental Protection Agency, 1982).

Floridan Aquifer System

The Floridan aquifer system, one of the most productive sources of ground water in the United States, extends across the entire State of Florida, southern Georgia, and adjoining small parts of Alabama and South Carolina. The Floridan is the lowermost part of the ground-water reservoir in Florida. It consists of as much as 3,500 ft of limestone and dolomite beds that are interconnected hydraulically to differing degrees. The Floridan is at or near land surface in the western part of the peninsula that extends from Wakulla to Pasco County and in most of Holmes and Jackson and a small part of Walton Counties in the panhandle area bordering Alabama. Elsewhere, it is buried to depths as much as 1,100 ft below sea level in southern Florida and 1,500 ft below sea level in the westernmost part of the Florida Panhandle. Water in the Floridan is unconfined in about one-quarter of the State, where the aquifer system is at or near land surface, and is confined elsewhere.

Many public-supply systems tap the Floridan aquifer system including those serving Jacksonville, Orlando, Clearwater (Pinellas County), St. Petersburg (Pinellas County), and Tallahassee. The Floridan also is a major source of water for industrial, irrigation, and rural uses. Total pumpage from the aquifer system in Florida exceeds 2 billion gallons per day (Peter W. Bush, U.S. Geological Survey, written commun., 1984). Yields vary considerably, but yields of several hundred to a thousand gallons per minute commonly are attainable by large-diameter wells, and yields of as much as 20,000 gal/min have been reported (Heath and Conover, 1981, p. 159). Flowing artesian wells that tap the Floridan are common over much of the lower lying areas of the State. The entire aquifer system contains nonpotable water in the southern one-third of the peninsula. Contamination by aldicarb and ethylene dibromide from agricultural activities has been noted recently in parts of the State (J. E. McNeal, Florida Department of Environmental Regulation, written commun., 1983; S. H. King, Florida Department of Health and Rehabilitative Services, written commun., 1983). Where the aquifer is at or near land surface, it is susceptible to contamination by leachate from landfills and other waste-disposal facilities.

Besides its wide use as a water-supply source, the Floridan aquifer system also is used as a repository for wastewaters. Stormwaters enter the upper part of the aquifer system through hundreds of drainage wells, mostly in central peninsular Florida (Kimrey and Fayard, 1984). Industrial and municipal wastewaters are injected into saline parts of the aquifer system mainly in the Pensacola area, in Pinellas County, and along the southeastern coast from Miami to Indian River County (Vecchioli, 1981).

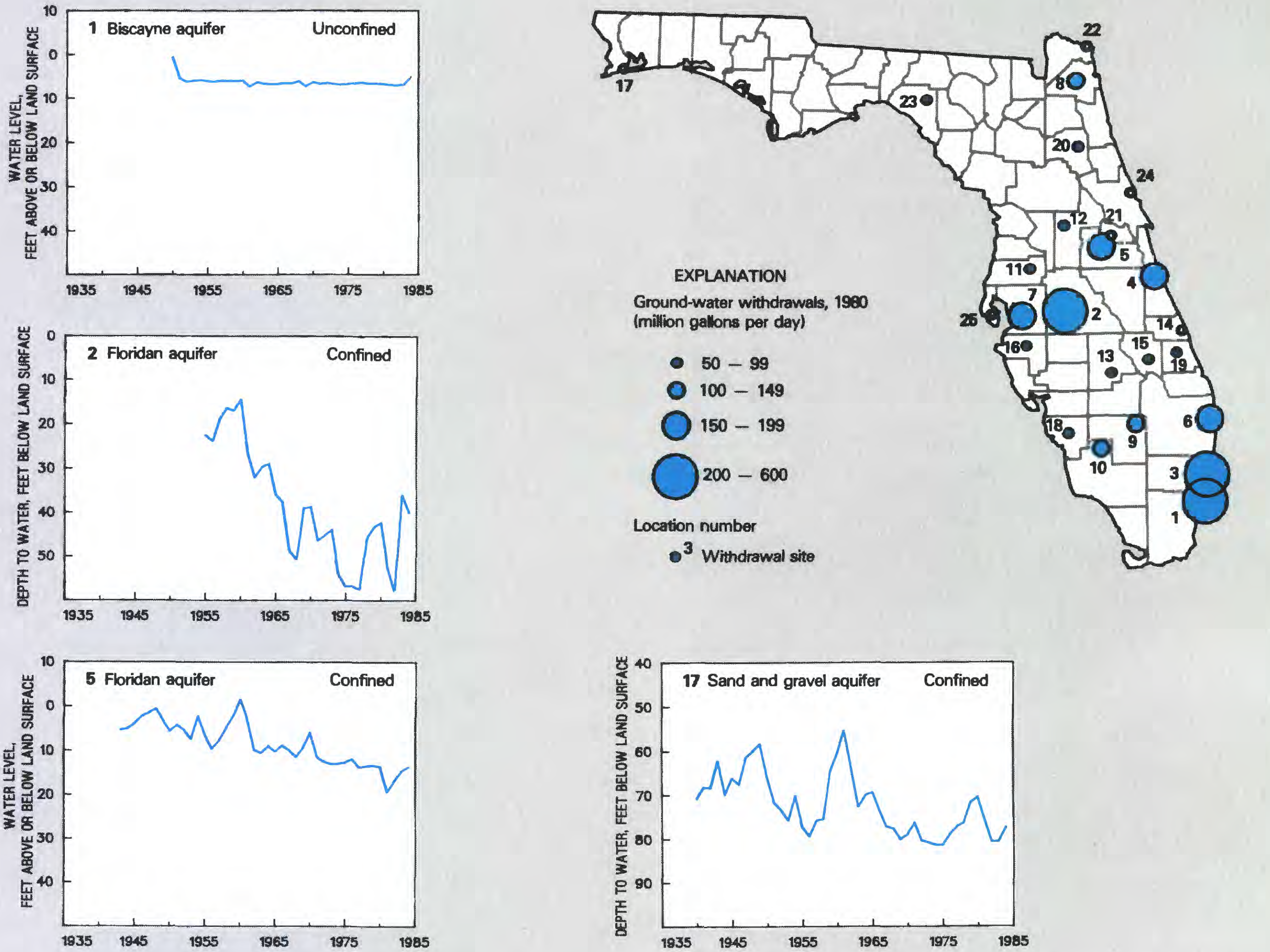
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The distribution of major ground-water withdrawals and trends of ground-water levels near selected pumping centers are shown in figure 2. Fresh ground-water withdrawals in 1980 exceeded 1 Mgal/d in every county but Liberty (Leach, 1983). Withdrawals were greatest in Dade and Polk Counties (433 and 312 Mgal/d, respectively). The hydrographs in figure 2 show the response of the principal aquifers to pumping at selected withdrawal centers.

Water levels in the Biscayne aquifer respond to the large amount of pumpage in the Miami area (location 1, fig. 2) for public supply, but, because the Biscayne is unconfined and readily recharged by infiltration of canal water and precipitation, the response is seasonal and small in magnitude. However, these small declines are of concern because of the potential for saltwater intrusion into the coastal well fields.

Withdrawals in the Pensacola area (location 17, fig. 2) from the sand-and-gravel aquifer have caused water levels to decline somewhat, but the trend has stabilized over the last decade. The production zone in the aquifer is semiconfined to confined.

Water levels in the confined Floridan aquifer system in Polk County (location 2, fig. 2) have declined since the early 1950's in response to large withdrawals, primarily for the phosphate-mining industry and secondarily for irrigation. Water levels have recovered somewhat since the mid-1970's because of artificial recharge practices implemented by the phosphate industry and a reduction in pumpage due to water recycling. In the Orlando area of Orange County (location 5, fig. 2), water levels in the confined Floridan also have declined in response to large withdrawals for irrigation and public supply. The magnitude of these water-level declines has been reduced by the recharge of stormwater through more than 400 drainage wells. Where unconfined, water levels in the Floridan have been little affected by withdrawals on a long-term basis. Overall, only four areas in Florida have experienced water-level declines of more than 10 ft in the Floridan aquifer



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Miami area	Biscayne	Public supply.
2	Bartow area	Floridan	Mining.
3	Broward County coastal area	Biscayne	Public supply.
4	Brevard County	Floridan	Irrigation.
5	Orlando area	....do	Irrigation, public supply.
6	Palm Beach County coastal area	Surficial	Public supply.
7	Hillsborough County	Floridan	Irrigation, public supply.
8	Jacksonville	....do	Public supply, industrial.
9	Hendry County	Surficial	Irrigation.
10	Collier County	....do	Do.
11	Pasco County	Floridan	Public supply.
12	Lake County	....do	Irrigation.
13	Highlands	....do	Do.
14	Indian River County	....do	Do.
15	Okeechobee County	....do	Do.
16	Manatee County	....do	Do.
17	Pensacola area	Sand and gravel	Industrial, public supply.
18	Lee County	Intermediate	Irrigation.
19	St. Lucie County	Floridan	Do.
20	Putnam County	....do	Irrigation, industrial.
21	Seminole County	....do	Irrigation, public supply.
22	Fernandina Beach area	....do	Industrial.
23	Taylor County	....do	Do.
24	Volusia County	....do	Public supply, irrigation.
25	Pinellas County	....do	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Florida. (Sources: Withdrawal data from Leach, 1983; water-level data from U.S. Geological Survey files.)

system from 1961 through 1980 (Healy, 1982); in addition to the two areas mentioned above, the Jacksonville (Duval County) and Fort Walton Beach (Okaloosa County) areas also have been affected.

GROUND-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 Florida Department of Natural Resources. The five districts, which encompass the entire State, include the Northwest Florida Water Management District, the Suwannee River Water Management District, the St. Johns River Water Management District, the Southwest Florida Water Management District, and the South Florida Water Management District. The Act, among other things, empowered the districts to permit well drilling and the withdrawal of ground water for consumptive use that is shown to be reasonable or beneficial. Later, the Florida Environmental Reorganization Act of 1975 created the Department of Environmental Regulation and transferred to it all powers and functions of the Department of Natural Resources relating to water management. Since 1975, the five water-management districts have functioned within the Department of Environmental Regulation and generally have been delegated the primary responsibility for quantity-related aspects of water management; the Department of Environmental Regulation is concerned primarily with quality-related aspects of water management.

Permitting regulations, which differ from district to district, control the construction of wells 2 inches or more in diameter and the withdrawal of ground water for all uses except private domestic use and minor other uses through consumptive-use permitting. Two of the districts have set threshold values (greater than 100,000 gallons per day average use, greater than 1 Mgal/d maximum capacity, or greater than 6-in. diameter well) below which users are not required to obtain a consumptive-use permit, and a third includes zones with differing requirements. Permitting regulations pertaining to waste disposal or other activities that impact on ground-water quality are administered directly by the Department of Environmental Regulation. Recently, the Florida Water Quality Assurance Act of 1983 made the 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 and the individual water management districts each have a cooperative water-resources program of study with the U.S. Geological Survey. Through these cooperative programs, much of the hydrologic data and interpretive information needed to manage the quality and quantity of Florida's ground water are made available.

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Prepared by John Vecchioli and Donald W. Foose

For further information contact District Chief, U.S. Geological Survey, 227 North Bronough Street, Suite 3015, Tallahassee, FL 32301

GEORGIA
Ground-Water Resources

Ground water is an abundant natural resource in Georgia and comprises 18 percent of the total freshwater used (including thermoelectric) in the State. Georgia's aquifers provide water for more than 2.6 million people, or almost one-half of the total population of the State. Of this number, about one-half are served by public water-supply systems and one-half by rural water-supply systems. Most ground-water withdrawals are in the southern one-half of the State where the aquifers are very productive. Ground-water withdrawals in 1980 for various uses, and related statistics, are given in table 1.

Table 1. Ground-water facts for Georgia

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	2,604
Percentage of total population	48
From public water-supply systems:	
Number (thousands)	1,320
Percentage of total population	24
From rural self-supplied systems:	
Number (thousands)	1,284
Percentage of total population	23
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	6,700
Ground water only (Mgal/d)	1,200
Percentage of total	18
Percentage of total excluding withdrawals for thermoelectric power	52
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	230
Percentage of total ground water	19
Percentage of total public supply	29
Per capita (gal/d)	174
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	140
Percentage of total ground water	12
Percentage of total rural domestic	100
Per capita (gal/d)	109
Livestock:	
Ground water (Mgal/d)	17
Percentage of total ground water	1
Percentage of total livestock	61
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	400
Percentage of total ground water	34
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	8
Excluding withdrawals for thermoelectric power	57
Irrigation withdrawals:	
Ground water (Mgal/d)	380
Percentage of total ground water	32
Percentage of total irrigation	66

GENERAL SETTING

Differing geologic features and landforms of the several physiographic provinces of Georgia cause significant differences in ground-water conditions from one part of the State to another (fig. 1). The most productive aquifers in the State are located in the Coastal Plain province in the southern one-half of Georgia; the province is underlain by alternating layers of sand, clay, and limestone that dip and thicken to the southeast. Aquifers generally are confined in the Coastal Plain, except near their northern limit where the formations are exposed or are near land surface. Principal aquifers of the Coastal Plain include the Floridan aquifer system, the Claiborne aquifer, the Clayton aquifer, and the Cretaceous aquifer system (table 2). The Piedmont and Blue Ridge provinces, which include most of the northern one-half of Georgia, are underlain by massive igneous and metamorphic rocks that form aquifers of very low permeability. The Valley and Ridge and Appalachian Plateaus provinces, which are in the northwestern corner of Georgia, are underlain by layers of sandstone, limestone, dolostone, and shale of Paleozoic age.

Recharge to the ground-water system in Georgia is derived almost entirely from precipitation. Average annual precipitation based on the 30-year period of record (1941–70) is about 50 inches (in.) statewide and ranges from about 44 in. in the east-central part of the State to about 76 in. in the northeastern corner of the State. Of this amount, about 88 percent is discharged to streams or is lost to evapotranspiration, and about 12 percent enters the ground-water system as recharge (Carter and Stiles, 1983).

PRINCIPAL AQUIFERS

FLORIDAN AQUIFER SYSTEM

The Floridan aquifer system is one of the most productive ground-water reservoirs in the United States. More than 600 million gallons per day (Mgal/d) is withdrawn from the aquifer system in Georgia (1980), making it the principal source of ground water in the State. The aquifer system generally is confined but is semiconfined to unconfined near its northern limit and near areas of karst topography in the Dougherty Plain and near Valdosta. In parts of the area where the Floridan aquifer system is exposed or is near land surface, intensive pumping can contribute to the formation of sinkholes. Although water suitable for most uses can be obtained from the aquifer system throughout most of the Coastal Plain, water-quality problems have occurred in some areas. The following examples serve to illustrate the problem: (1) at Brunswick, the intrusion of brackish water into the aquifer system resulted in chloride concentrations of as much as 1,000 milligrams per liter (mg/L) in some wells (Wait and Gregg, 1973), (2) in the area of Wheeler and Montgomery Counties in central-south Georgia, naturally occurring radioactivity exceeds 25 picocuries per liter (S. S. McFadden, Georgia Geologic Survey, oral commun., September 1984), (3) in nearby Ben Hill County, barium concentrations of as much as 2.1 mg/L are present in some wells (S. S. McFadden, Georgia Geologic Survey, oral commun., September 1984), (4) at Valdosta, naturally occurring organic substances, color, and hydrogen sulfide gas have been a cause of concern (Krause, 1979), and (5) in the Dougherty Plain area, small concentrations of commonly used pesticides have been detected in some farm wells (Hayes and others, 1983).

Table 2. Aquifer and well characteristics in Georgia

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey and Georgia Geologic Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Floridan aquifer system: Limestone, dolomite, and calcareous sand. Generally confined.	40 - 900	1,000 - 5,000	11,000	Supplies 50 percent of ground water in State. Major users include the Savannah, the Brunswick, the Jesup, the St. Marys, the Albany, and the Dougherty Plain areas. Water-level declines at Savannah and Brunswick. Intrusion of brackish water from deeper zones at Brunswick. In some areas, water has natural radioactivity that exceeds State and national drinking-water regulations. Formerly called principal artesian aquifer.
Claiborne aquifer: Sand and sandy limestone. Generally confined.	20 - 450	150 - 600	1,500	Major source of water in southwestern Georgia. Supplies industrial and municipal users at Dougherty, Crisp and Dooly Counties and provides irrigation water north of Dougherty Plain. Called Tertiary sands aquifer in South Carolina and Tennessee. Part of Tertiary sedimentary aquifer system in Alabama.
Clayton aquifer: Limestone and sand. Generally confined.	40 - 800	250 - 600	2,150	Major source of water in southwestern Georgia. Supplies industrial and municipal users at Albany and provides irrigation water northwest of Albany. Water-level declines exceed 100 ft at Albany. Iron concentrations in Randolph County exceed national drinking-water regulations. Part of Tertiary sedimentary aquifer system in Alabama.
Cretaceous aquifer system: Sand and gravel. Generally confined.	30 - 750	50 - 1,200	3,300	Major source of water in east-central Georgia. Supplies water for kaolin mining and processing. Includes Providence aquifer in southwestern Georgia. Water-level declines greater than 50 ft at kaolin mining centers and 100 ft near Albany. Iron concentrations exceed national drinking-water regulations in some areas. Called Black Creek and Middendorf aquifers in South Carolina.
Paleozoic aquifers: Sandstone, limestone, and dolomite; storage is in regolith and fractures and solution openings in rock. Generally unconfined.	15 - 2,100	1 - 50	3,500	Not laterally extensive. Limestone and dolomite aquifers most productive. Springs in limestone and dolostone aquifers discharge at rates of as much as 5,000 gal/min. Sinkholes can form in areas of intensive pumping. Water is generally of good quality, although contamination from septic tanks and farm waste reported in some areas. Laterally equivalent to Paleozoic carbonate aquifers in Alabama and Pennsylvanian sandstone aquifers in Alabama and Tennessee.
Crystalline rock aquifers: Granite, gneiss, schist, and quartzite; storage is in fractures in rock and in regolith. Generally unconfined.	40 - 600	1 - 25	500	Not laterally extensive. Water of good quality with exception of large concentrations of iron and manganese in some areas and contamination from septic tank effluent in densely populated areas.

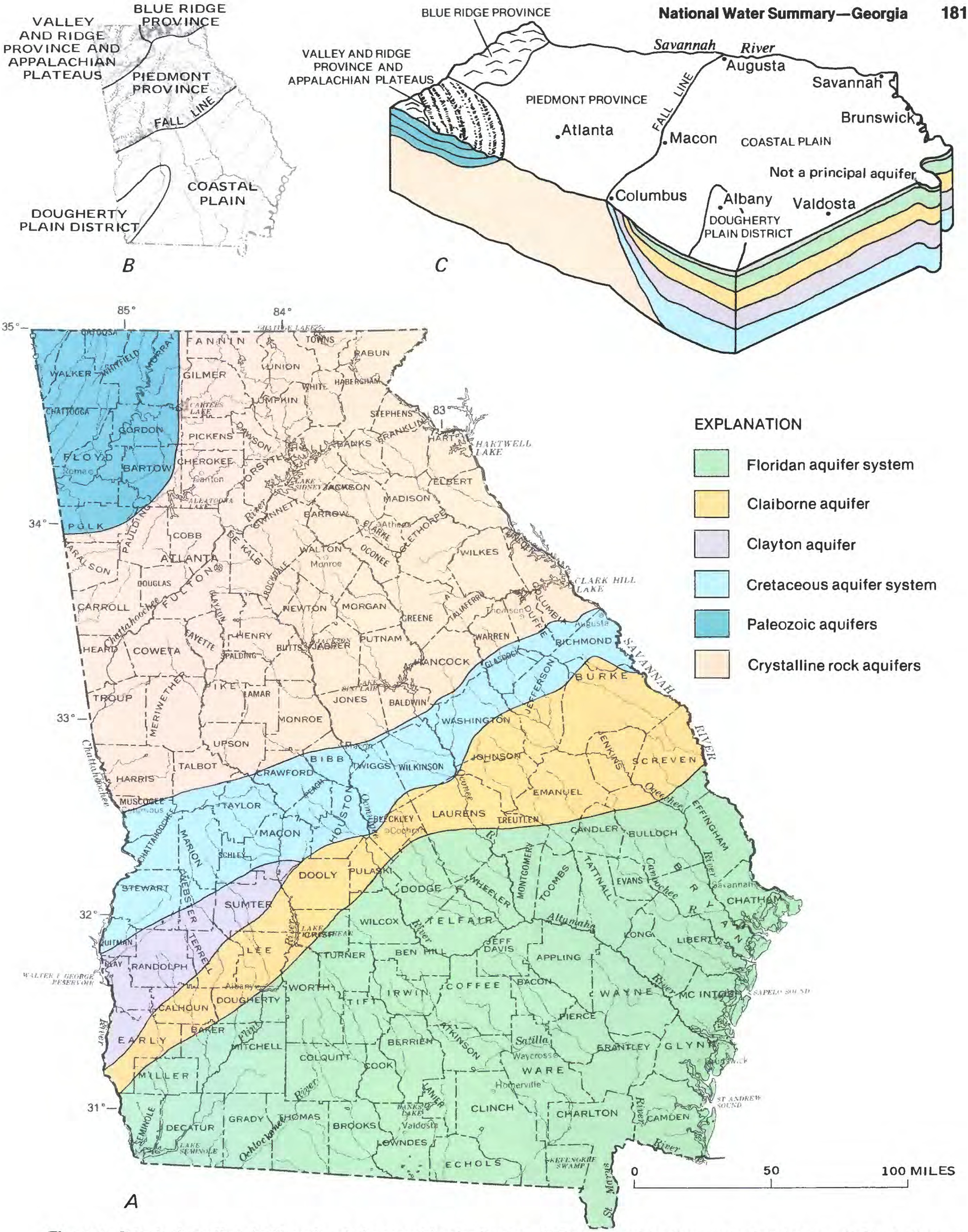


Figure 1. Principal aquifers in Georgia. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Block diagram showing principal aquifers and physiographic divisions. (See table 2 for a more detailed description of the aquifers. Sources: *A*, J. S. Clarke, U.S. Geological Survey, written commun., 1984. *B*, Fenneman, 1938; Raisz, 1954. *C*, Modified from Pierce and others, 1984.)

CLAIBORNE AQUIFER

The Claiborne aquifer is an important source of water in part of southwestern Georgia (fig. 1) and supplied an estimated 36 Mgal/d in 1980, primarily for irrigation (McFadden and Perriello, 1983). Although the Claiborne aquifer yields water suitable for most uses over most of its extent, naturally occurring concentrations of dissolved solids and chloride in the south-central part of the State have been reported as 22,200 and 11,900 mg/L, respectively (Wait, 1960).

CLAYTON AQUIFER

The Clayton aquifer is an important source of water in southwestern Georgia (fig. 1), where it supplied an estimated 20 Mgal/d in 1980. Most of the withdrawals were for public supply (58 percent) and irrigation (35 percent). With the exception of large concentrations of iron (greater than 0.3 mg/L) in Randolph County, water from the aquifer is suitable for most uses (Clarke and others, 1984).

CRETACEOUS AQUIFER SYSTEM

The Cretaceous aquifer system is a major source of water in the northern one-third of the Coastal Plain (fig. 1). During 1980, the aquifer system yielded an estimated 128 Mgal/d, primarily for industrial and public-supply use. The aquifer system consists of sand and gravel that locally contain layers of clay and silt which function as confining beds. These confining beds locally separate the aquifer system into two or more aquifers. In southwestern Georgia, the Providence aquifer is part of the Cretaceous aquifer system. Water from the aquifer system is soft (less than 60 mg/L as calcium carbonate), has little dissolved solids (generally less than 100 mg/L), and is of a sodium bicarbonate type that is suitable for most uses. In the center of the area of usage (fig. 1), the iron concentration may be as much as 6.7 mg/L.

PALEOZOIC AQUIFERS

Water in the Paleozoic aquifers generally is unconfined, and storage is limited mainly to joints, fractures, and solution openings in the bedrock. During 1980, an estimated 33 Mgal/d was withdrawn from the Paleozoic aquifers, primarily for industrial supply. Wells that tap the Paleozoic aquifers yield differing amounts of water, depending on the aquifer used. Dolostone aquifers typically yield 5 to 50 gallons per minute (gal/min), whereas limestone and sandstone aquifers typically yield 1 to 20 gal/min; maximum reported yields from these aquifers are 3,500 and 300 gal/min, respectively. Springs discharge from the limestone and dolostone aquifers at rates of as much as 5,000 gal/min. Where the limestone and dolostone aquifers are near land surface, pumping can contribute to the formation of sinkholes. Water from wells and springs in the Paleozoic aquifers generally is suitable for most uses, although contamination from septic tanks and farm waste has been reported (Cressler and others, 1976).

CRYSTALLINE ROCK AQUIFERS

Although individual crystalline rock aquifers are not laterally extensive, collectively they yielded an estimated 99 Mgal/d in 1980, primarily for rural supply. Ground-water storage occurs in the regolith and where the rocks have joints, fractures, and other types of secondary openings (Cressler and others, 1983). Crystalline rock aquifers in these areas generally are unconfined and show a pronounced response to rainfall, although deep fracture systems commonly are confined. Water from the aquifers generally is suitable for most uses, and, with the exception of iron (as much as 14 mg/L) and manganese (as much as 1.5 mg/L), constituent concentrations rarely exceed national drinking-water regulations (U.S. Environmental Protection Agency, 1982a,b). In some densely populated areas, septic-tank effluent has contaminated the aquifers (Cressler and others, 1983).

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals and trends in ground-water levels near selected pumping centers are shown in figure 2. With the exception of one center in the Valley and Ridge province (location 1, fig. 2), all major pumping centers are in the Coastal Plain, where aquifers are very productive. The largest pumping center is the Dougherty Plain area where ground-water withdrawal for irrigation exceeds 200 Mgal/d.

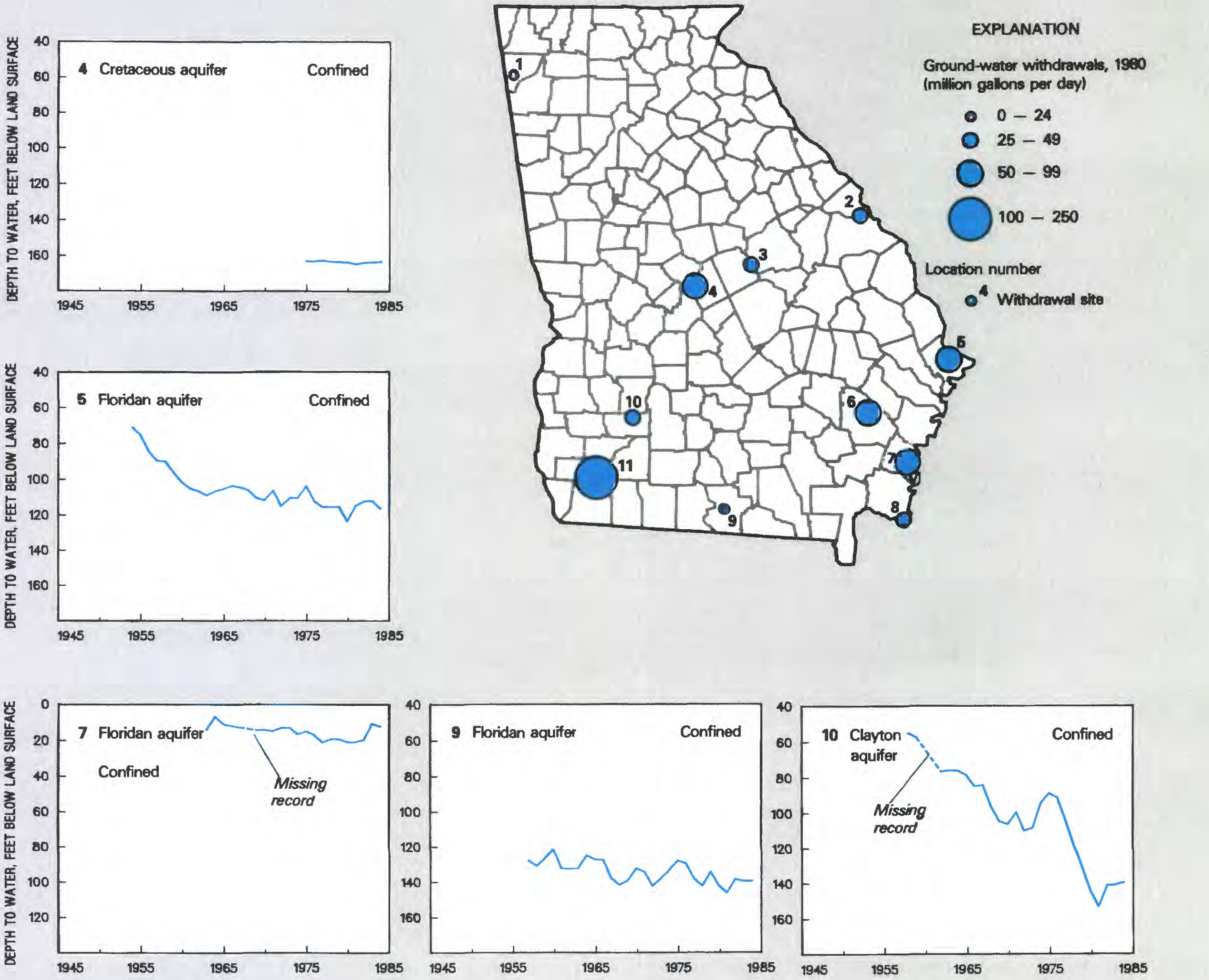
The hydrographs shown in figure 2 reflect the responses of aquifers to pumping at selected pumping centers under a variety of hydrologic conditions. In the Floridan aquifer system, large cones of depression have formed at Savannah, Brunswick, Jesup, and St. Marys as a result of pumping for industrial and public supply. At Savannah (location 5, fig 2.), the water level has declined at least 160 feet (ft) since pumping began in the late 1800's (McCollum and Counts, 1964). The hydrograph shows that the water level declined 45 ft from 1954 to 1961 and less than 10 ft from 1961 to 1984. These changes reflect pumping patterns in the area. At Brunswick, the water level in the aquifer system declined 65 ft from predevelopment to 1964 (Wait and Gregg, 1973). The decline continued until 1982 (location 7, fig. 2), then rose about 10 ft as the result of a significant decrease in pumping by a major water user. Near Valdosta (location 9, fig. 2), the water level in the Floridan aquifer system responds to changes in recharge derived from streamflow and to local pumping. The hydrograph shows a moderate long-term response to changing recharge rates and to pumping. Pumpage from the Floridan aquifer system in the Dougherty Plain area (location 11, fig. 2) is primarily for seasonal irrigation which, averaged over the year, exceeded 200 Mgal/d in 1980. In this area, pumpage is scattered widely. Some recharge to the Floridan aquifer system occurs locally. As a result, water-levels recover annually.

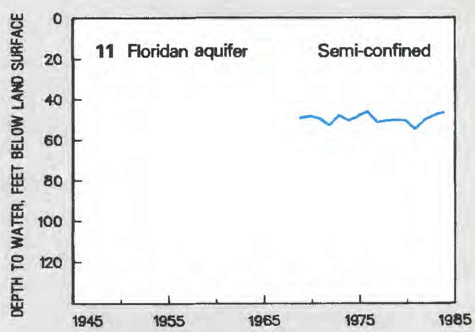
In the Albany area (location 10, fig. 2), water is withdrawn from the Tertiary Floridan aquifer system, the Claiborne aquifer, and the Clayton aquifer and the Cretaceous Providence aquifer. Water-level declines of more than 100 ft have occurred in the Clayton and Providence aquifers (Clarke and others, 1983, 1984). The water level in the Clayton aquifer near withdrawal location 10 (fig. 2) generally declined from 1958 to 1984 in response to increased pumping for public supply and agriculture.

The water level in the Cretaceous aquifer system has declined more than 50 ft since 1950 in areas of heavy pumping for public supply and industrial use. However, in the Huber–Warner Robins area (location 4, fig. 2), the water level has not declined significantly from 1975 to 1984 despite a slight increase in ground-water withdrawals during that period.

GROUND-WATER MANAGEMENT

Georgia has a comprehensive set of laws governing the quality and use of ground water. The Ground-Water Use Act of 1972 provided for the permitting of withdrawals for industrial and municipal use that exceed 100,000 gallons per day (gal/d) and authorized the Georgia Environmental Protection Division to issue regulations about reporting, timing of withdrawals, abatement of saltwater encroachment, well depth and spacing, and pumping levels or rates. Amendments to the





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Valley and Ridge . . .	Paleozoic.	Carpet mill industry.
2	Richmond-Burke . . .	Cretaceous. . . .	Public supply, industrial, irrigation.
3	Kaolin Belt.	. . . .do	Clay mining and processing.
4	Huber-Warner Robins.	. . . .do	Clay mining and processing, public supply.
5	Savannah.	Floridan	Public supply, chemical industry, pulp and paper industry.
6	Jesup	. . . .do	Pulp and paper industry.
7	Brunswick	. . . .do	Pulp and paper industry, public supply.
8	St. Marys.	. . . .do	Pulp and paper industry.
9	Valdosta	. . . .do	Public supply, industrial.
10	Albany	Floridan, Clayton, Claiborne, Providence.	Public supply, industrial, irrigation.
11	Dougherty Plain. . . .	Floridan	Irrigation.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Georgia. (Sources: Withdrawal data from Pierce and others, 1982; water-level data from U.S. Geological Survey files.)

Act in 1982 required that irrigation withdrawals in excess of 100,000 gal/d be reported to the State, although permits for that use still are not required. The Oil and Gas Deep Drilling Act of 1975 authorized the Board of Natural Resources to regulate drilling and use of oil, gas, and other types of wells for the purpose of protecting fresh ground-water supplies. The Georgia Safe Drinking Water Act of 1977 provides for regulation of water quality in public-water systems.

The Georgia Environmental Protection Division (EPD) and its branches are responsible for enforcing all surface-water, ground-water, and water-quality laws. In 1984, a ground-water management plan for Georgia was implemented to identify key activities performed by EPD management, to control and regulate potential pollution sources, and to develop a monitoring program to provide water-quality and water-quantity data on the State's principal aquifers. The Water Resources Management Branch issues permits for ground-water withdrawals that exceed 100,000 gal/d by industrial and municipal users and oversees the reporting of ground-water use for irrigation in excess of 100,000 gal/d. The Ground-Water Program of the Water Protection Branch provides for the permitting of operators of public water-supply systems that use ground water and monitors water quality for compliance with drinking-water standards. The Industrial and Hazardous Waste Management Program of the Land Protection Branch monitors ground water at hazardous waste sites. The Geologic Survey Branch provides technical support for the other branches and has a cooperative program with the U.S. Geological Survey that provides much of the basic data and interpretive information needed to manage the quality and quantity of ground water in the State.

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Prepared by John S. Clarke and Robert R. Pierce

For further information contact District Chief, U.S. Geological Survey, 6481 Peachtree Industrial Blvd., Suite B, Doraville, GA 30360

HAWAII
Ground-Water Resources

Hawaii has an abundant water supply, and ground water is an important natural resource that contributes significantly to the economic growth of the State. The total amount of water withdrawn in Hawaii in 1980 was 1.7 billion gallons per day of which 710 million gallons per day (Mgal/d) or 41 percent was from ground-water sources. Statewide, Maui was the largest user of fresh ground and surface water, with a total of 586 Mgal/d. Oahu was the principal user of ground water with 193 Mgal/d. For domestic use, Oahu led in ground-water usage with 173 Mgal/d (Nakahara, 1984). Ground-water withdrawals in 1980 for various uses in the State are given in table 1.

GENERAL SETTING

The islands of the Hawaiian Archipelago occupy a 6,450 square-mile land area. The Hawaiian Islands are the tops of shield volcanoes that rise from the ocean floor; the oldest is Kauai and the youngest is the island of Hawaii.

Rainfall is the sole source of freshwater and its quantity and spatial distribution govern the volume and quality of the ground water. Mean annual rainfall in Hawaii is about 73 inches (in.) and ranges from about 20 to 300 in. Ground-water recharge is estimated to be 30 percent of rainfall (Takasaki, 1978). Fresh ground water in Hawaii is present as basal water in unconfined aquifers or in aquifers confined by coastal caprock under artesian pressure. Smaller amounts of water are impounded by impermeable dike systems at higher elevations and occur in isolated ground-water bodies perched on top of impermeable lava beds. Basal ground water is developed by vertical drilled wells, by inclined shafts that intersect the basal water, and by dug wells along coasts.

PRINCIPAL AQUIFERS

Hydrographic areas established in 1959 by the Hawaii Water Authority (now the State Department of Land and Natural Resources, Division of Water and Land Management) are used to describe the principal aquifers on four of the major islands—Kauai, Oahu, Maui, and Hawaii (Hawaii State Water Authority, 1959). The boundaries of these areas are based on surface topography and outline the major surface drainage basins (fig. 1). Aquifers of the six principal islands (including Molokai and Lanai) are listed in table 2.

Table 1. Ground-water facts for Hawaii

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	920
Percentage of total population	95
From public water-supply systems:	
Number (thousands)	890
Percentage of total population	92
From rural self-supplied systems:	
Number (thousands)	30
Percentage of total population	3
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	1,700
Ground water only (Mgal/d)	710
Percentage of total	41
Percentage of total excluding withdrawals for thermoelectric power	37
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	180
Percentage of total ground water	25
Percentage of total public supply	90
Per capita (gal/d)	202
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	3.5
Percentage of total ground water	0.5
Percentage of total rural domestic	90
Per capita (gal/d)	117
Livestock:	
Ground water (Mgal/d)	5.3
Percentage of total ground water	0.7
Percentage of total livestock	96
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	140
Percentage of total ground water	20
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	73
Excluding withdrawals for thermoelectric power	20
Irrigation withdrawals:	
Ground water (Mgal/d)	370
Percentage of total ground water	53
Percentage of total irrigation	93

ISLAND OF KAUAI

Ground-water sources in hydrographic areas I through IV (fig. 1*A*) on Kauai are used primarily for public supply and irrigation of sugarcane. Posterosional lavas of the Koloa, Olokele, and Makaweli Volcanics overlie lavas of the Napali Formation in these areas. The coastal sediments are of limited extent and are composed of poorly sorted alluvium mixed with clay and calcareous material. Ground water occurs as basal and perched water in the Koloa lavas and generally is unconfined except where the lavas are overlain by sediments (Macdonald and others, 1960).

Area V, located in the western part of Kauai (fig. 1*A*), is the most prominent basal water body underlying the Kekaha–Mana coastal plain and is composed mostly of the Napali lavas. The coastal plain is composed of lagoon deposits, calcareous beach and dune sand, and alluvium. Coastal sediments are about 500 feet (ft) thick at the coast. Recharge to the basalt aquifer is from rainfall, and recharge to the caprock aquifer is mainly from rainfall and return irrigation water. Individual wells or shafts yield as much as 22 Mgal/d.

Table 2. Aquifer and well characteristics in Hawaii

[Ft = feet; gal/min = gallons per minute; Mgal/d = million gallons per day. Sources: Reports of the U.S. Geological Survey and various agencies of the State of Hawaii]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Kauai:				
Koloa Volcanics: Massive posterosional lava flows and breccia mixed with sediments. Unconfined.	100 - 1,100	100 - 400	2,000	Low to moderate permeability. Discontinuous perched water body at high levels, basal water below sea level.
Olokele, Makaweli, and Napali Volcanics: Basalt, alluvium, and calcareous dune sands in broad sedimentary coastal plains. Partly confined.	100 - 500	200 - 1,900	8,000	Moderate to high permeability. Important source for domestic and irrigation water. Brackish water in coastal plains.
Oahu:				
Alluvium: Consolidated deposits of conglomerate and breccia. Partly confined.	30 - 900	400 - 2,300	9,000	Low to moderate permeability. Found in stream channels and marine sediments.
Honolulu Group: Basalt, post-erosional lava flows; coral, reef and beach-sand deposits along coastal margins. Alluvium in stream channels. Partly confined.	100 - 1,100	700 - 6,000	13,000	Low to high permeability. Important source of domestic supply for city of Honolulu. Withdrawal of ground water managed under Ground-Water Use Act.
Koolau Volcanics: Basalt and sediment deposits of coralline limestone and sand along coast areas and alluvium. Partly confined.	100 - 1,100	600 - 4,000	12,000	Moderate to high permeability. Area IV is commonly called the Pearl Harbor aquifer. Principal source of ground water for domestic and irrigation supply. Aquifer managed under Ground-Water Use Act.
Waianae Volcanics: Basalt, breccia, and intercalated soils. Sediments consist of coralline limestone; terrestial material is alluvium. Partly confined.	40 - 600	70 - 2,300	9,000	Low to moderate permeability. Water confined near sea level and at high levels in dike complex. Withdrawal of ground water in Area VI managed under Ground-Water Use Act.
Maui:				
Hana Group: Posterosional lava flows primarily olivine basalt and rare feldspar phenocrysts. Unconfined.	90 - 500	40 - 60	80	Moderate to high permeability. Primary source of domestic and irrigation supply.
Kula Formation: Overlies the Honomanu Volcanics; large part of isthmus consists of sedimentary deposits of coralline limestone, sand dunes, and alluvium. Partly confined.	200 - 500	500 - 6,000	8,000	High permeability in dike-free area. Low to moderate permeability in sediment deposits. Important water source for domestic supply and irrigation of sugarcane.
Honolua and Wailuku Volcanics: Mainly thin bedded basaltic lava flows; andesite and sedimentary material of coralline limestone, sand, and alluvium near southern shorelines. Unconfined.	200 - 500	120 - 1,600	8,000	Moderate permeability; yields water to wells freely. Waikapu Shaft has yielded an average of 23 Mgal/d (1957–81). Important water source for irrigation of sugarcane and domestic supply.
Hawaii:				
Puna Volcanics: Basaltic lava flows overlying the Hilina Volcanic; vitric ash and tuff beds intrastratified with the lava. Unconfined.	20 - 800	500 - 2,500	7,000	Lava flows highly permeable. Important source of domestic supply for City of Hilo.
Laupahoehoe Volcanics: Posterosional andesitic lava flows. Unconfined.	—	—	—	Poor to moderate permeability. No data available.
Hualalai Volcanics: Volcanic posterosional trachyte and basalt with vitric ash overlying lava flows. Unconfined.	100 - 900	150 - 600	3,000	Basalt is highly permeable. Important source of domestic water for tourist industry in Kona.

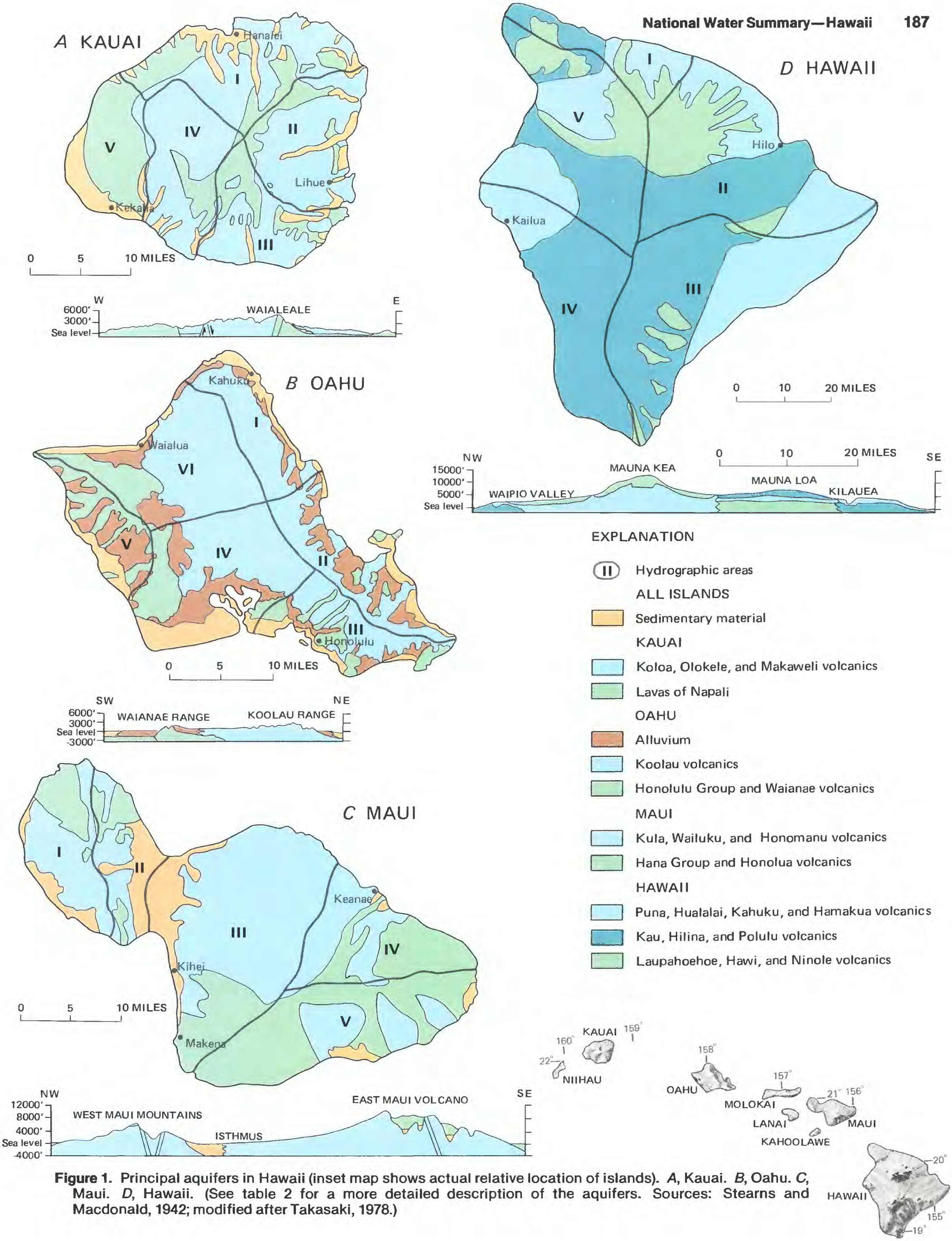


Figure 1. Principal aquifers in Hawaii (inset map shows actual relative location of islands). *A*, Kauai. *B*, Oahu. *C*, Maui. *D*, Hawaii. (See table 2 for a more detailed description of the aquifers. Sources: Stearns and Macdonald, 1942; modified after Takasaki, 1978.)

Table 2. Aquifer and well characteristics in Hawaii—Continued

Aquifer name and description	Well characteristics: Depth (ft), Common range	Yield (gal/min), Common range	Yield (gal/min), May exceed	Remarks
Kau Volcanics: Basaltic lava flows overlying the Kahuka and Ninole Volcanics; vitric ash and tuff beds interstratified with the lava. Unconfined.	300 - 1,000	400 - 1,500	2,500	Basalts are highly permeable. Brackish water along coast. Water mainly used for irrigation and processing of sugarcane.
Hamakua Volcanics: Primarily basaltic lava flows capped by Pahala ash. Unconfined.	200 - 800	200 - 1,300	3,800	Moderate to high permeability. Yields basal water freely to wells and springs.
Hawi Volcanics: Posterosional lava flows of oligoclase andesites. Unconfined.	--	--	--	Poor permeability. No well data available.
Pololu Volcanics: Primarily thin-bedded olivine basalt interbedded with a few vitric tuff beds. Unconfined.	30 - 800	100 - 900	4,100	High permeability. Yields water to wells freely.
Molokai:				
East Molokai Volcanics, upper member: Lava flows composed chiefly of dense andesites and trachyte. Unconfined.	80 - 1,100	50 - 200	500	Low to moderate permeability. Primary source of domestic supply.
Lanai:				
Lanai Volcanics: Primarily basaltic lava flows with small amounts of pyroclastic material. Unconfined.	60 - 1,200	80 - 150	200	Moderate to high permeability. Primary source of domestic and irrigation supply.

Island of Oahu

The island of Oahu is the weathered and eroded remnant of two major coalescing shield volcanoes—the Waianae and Koolau. The Koolau volcanics are highly permeable and yield water to wells freely. The Waianae Volcanics have low to moderate permeability. Hydrographic areas II to IV and VI on Oahu (fig. 1*B*) are important sources of ground water; the chemical quality of ground water in these areas is discussed by Swain (1973).

Areas I and II include the northeastern and southeastern parts of windward Oahu and are composed almost entirely of the dike complex of the Koolau Range with thick alluvium and caprock. Ground water is primarily dike impounded. Basal water is present in calcareous sedimentary materials at the southern end. Where ground water is confined by caprock or alluvium, water flows in the upper aquifer and discharges to streams (Takasaki and others, 1969).

The city of Honolulu and a part of southeastern Oahu are included in Area III. The area is underlain primarily by thin-bedded basalts of the Koolau Volcanics and posterosional flows of the Honolulu Group. Near the coast, an extensive caprock confines the basal aquifers. Ground water is present as thick basal lenses in the highly permeable Koolau lavas, and dike-impounded water is present at high elevations (Stearns, 1939). The aquifer in this area commonly is called the Honolulu aquifer.

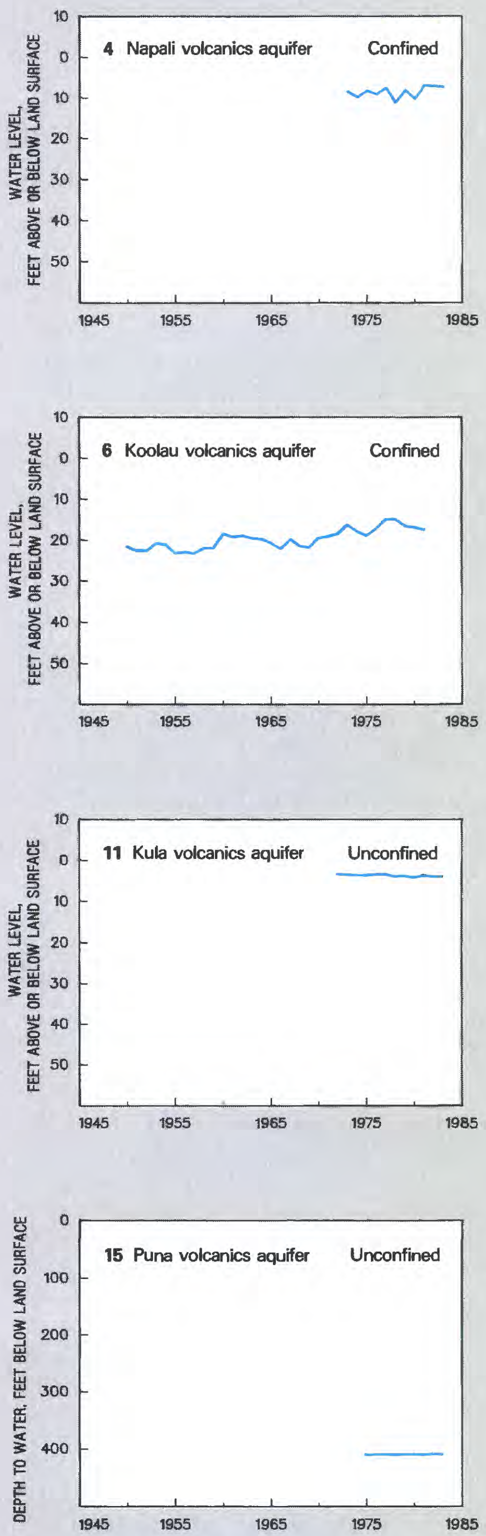
Area IV of central Oahu, includes large rainfall zones of the Koolau Range. Koolau lavas predominate in the area. The coastal plain in the southern section of the area is underlain by thick caprock that confines basal ground water. Basal ground water is present in caprock, alluvium, and dikes near the Koolau Crest and in much of the Waianae Volcanics (Visher and Mink, 1964). These rocks are known as the Pearl Harbor aquifer, which is the principal and most productive aquifer on Oahu. Recharge to the aquifer is by direct infiltration of rainfall and irrigation return water and by underflow from the Koolau dike compartments, the Schofield high-level water body, and the Honolulu area (Hawaii State Department of Land and Natural Resources, 1979).

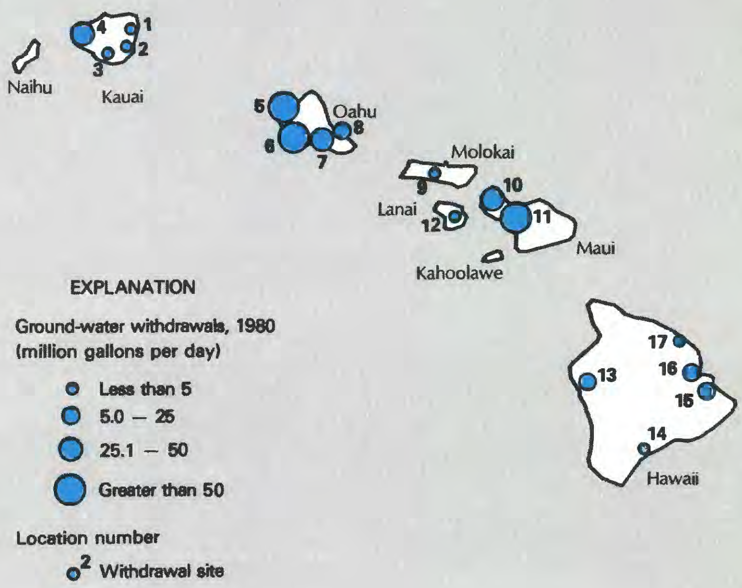
Area V, in the western part of the Waianae Range, is comprised chiefly of dike-intruded basalt of the Waianae Volcanic Series. Dike impoundments are the principal source of ground water.

Area VI, in the northwestern section of Oahu, includes part of the Schofield Plateau and the mountainous parts of the Waianae and Koolau Ranges. The principal basal aquifer is in the thin-bedded basalts of the Koolau Volcanics. A thick wedge of caprock occurs at the northern part of the area and confines water at hydraulic heads of 2 to 20 ft above sea level. Ground water in the Schofield Plateau contributes large volumes of underflow to this area and to Area IV to the south (Rosenau and others, 1971).

Islands of Molokai and Lanai

The upper member of the East Molokai Volcanics is the principal source of ground water on Molokai. It covers most of the island and is composed of dense andesites and trachytes (Stearns, 1947). Concentrations of chloride in basal water underlying coastal areas range from 600 to 1,000 milligrams per liter (mg/L).





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Wailua, Kapaa areas, Kauai.	Koloa volcanics	Public supply.
2	Lihue area, Kauai . . .	. . . .do	Public supply, industrial.
3	Koloa, Lawai areas, Kauai.	. . . .do	Public supply.
4	Mana, Kekaha areas, Kauai.	Napali volcanics. . . .	Irrigation, public supply.
5	Waialua area, Oahu . .	Waianae volcanics. . .	Irrigation, public supply, industrial.
6	Central Oahu area. . .	Koolau volcanics . . .	Do.
7	Honolulu area, Oahu.	. . . .do	Public supply, industrial.
8	Koolaupoko area, Oahu.	. . . .do	Public supply.
9	Island of Molokai . . .	East Molokai volcanics, upper member.	Irrigation, public supply.
10	West Maui area	Honolua volcanics. . .	Do.
11	Central Maui area . . .	Kula volcanics.	Do.
12	Island of Lanai	Lanai volcanics	Do.
13	Kona area, Hawaii. . .	Hualalai volcanics. . .	Public supply.
14	Pahala area, Hawaii . .	Kau volcanics	Irrigation, industrial.
15	Olaa, Puna, Kapoho areas, Hawaii.	Puna volcanics.	Public supply, irrigation.
16	Hilo area, Hawaii . . .	Kau volcanics	Public supply, industrial.
17	Laupahoehoe area, Hawaii.	Hamahua volcanics . .	Public supply, irrigation.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Hawaii. (Sources: Withdrawal data from Nakahara, 1984; water-level data from U.S. Geological Survey files.)

Lanai is composed primarily of basaltic lava flows from the Lanai Volcanics. The basal water along the coast is brackish. Ground water in the basaltic lava is confined by intrusive rocks and is the main source of potable water for the island. The water is of excellent quality with an average chloride content of 22 mg/L (Stearns, 1940b).

ISLAND OF MAUI

The island of Maui is formed by two volcanoes, Haleakala (East Maui) and West Maui. The isthmus connecting the two volcanoes is covered by terrestrial sediments, dune sands, and beach deposits. The bulk of the two volcanoes consists of very permeable basaltic lava flows. Hydrographic areas I through III (fig. 1C) are significant sources of ground water.

The western one-half of West Maui forms Area I. The thin-bedded, very permeable primary basalts of the Wailuku Volcanics and the massive and less permeable basalts of the Honolua volcanics comprise most of the aquifer. Basal ground water that exists along the coastal area extends inland from 1 to 3 miles (mi) and is the principal source of ground water. The principal source of drinking water is a narrow strip 1 to 2 mi inland at elevations of 700 to 900 ft. The chloride concentration of water in wells that tap the basal aquifer ranges from 100 to 2,000 mg/L for irrigation wells and 50 to 200 mg/L for domestic wells (M. E. Ikehara, U.S. Geological Survey, written commun., 1984).

Area II includes the eastern one-half of West Maui. Except for a large wedge of sedimentary material across the isthmus, it is similar geologically to Area I. Large basal water bodies are present in lava flows of the Kula Formation that underlie the isthmus. Water quality is excellent in the major basal water body and chloride concentration ranges from 10 to 50 mg/L. Water in the thin basal ground-water lens near the shoreline generally is brackish.

Area III is the western slope of Haleakala and the eastern one-half of the isthmus. The surface rocks are mostly massive, poorly permeable lava flows of the Kula Formation which overlies the Honomanu Volcanics. In the isthmus, the Kula lavas are overlain by alluvium and dune sands. In the northern part of the area, basal ground water is pumped intensively for irrigation of sugarcane. The chloride concentration of water in the basal wells ranges from 100 to 900 mg/L. Areas IV and V cover the northeastern and southern parts of Maui. The areas are geologically similar to the Hana Volcanics which veneer most of the surface. Ground water occurs mainly as basal water; chloride concentrations range from 10 to 200 mg/L in both areas.

ISLAND OF HAWAII

The island of Hawaii, which includes the mountains of Mauna Kea, Mauna Loa, Kohala, Hualalai and Kilauea, is formed predominantly of thin-bedded permeable basaltic lava flows. Sedimentary materials are sparse and generally are poorly permeable (Stearns and Macdonald, 1942b).

Currently, areas I through IV (fig. 1*D*) are important ground-water sources for public supply. Area I includes the northern part of the island. The principal basal aquifer consists of thin-bedded flows of the Pololu Volcanic Series occurring in coastal areas and capped by the Hawi Volcanics at higher elevations. The water quality is excellent in inland areas, but chloride concentrations near the coastline range from 1,000 to 2,000 mg/L. Area II includes the eastern part of the island and is composed of the basaltic lava flows of the Hamakua, the Ninole, and the Hilina Volcanic Series, and the posterosional lava flows of the Laupahoehoe, the Kau, and the Puna Volcanic Series. Numerous springs discharge water from perched water bodies near the surface along coastal areas. Ground water is fresh in inland areas and probably contains less than 1,000 mg/L of chloride near the shoreline.

Area III is the southeastern section of the island of Hawaii. The area contains no perennial streams despite an annual average rainfall that exceeds 125 in. Basal ground water in the Kau Volcanics discharges to the sea as spring flow. Chloride concentration of water pumped from inland wells ranges from 100 to 2,000 mg/L.

Area IV is the southwestern section of the island. The principal source of fresh water is basal ground water occurring in the Hualalai Volcanic Series, which is underlain by saline water. Because of an absence of sediments at the coast, basal water discharges freely at sea level along most of the shoreline. Where water levels are more than 3 ft above sea level, chloride concentrations range from 30 to 1,200 mg/L.

Area V is the driest of the hydrographic areas; no perennial streams exist in this area. The principal source of ground water is basal water that occurs in the Kau Volcanic Series along the coastal areas. It is used mainly for small domestic supplies.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Principal areas of ground-water withdrawal and trends in ground-water levels at selected wells on four major islands are shown in figure 2. Based on long-term pumpage records, the largest concentration of ground-water pumpage for irrigation is in hydrographic areas V on Kauai; IV and VI on Oahu, and areas I through III on Maui. The largest areas of pumping for public supply are areas II through IV on Oahu. In general, hydrographs for wells that produce water for irrigation of sugarcane reflect a slight rise in water level because of reduced pumping caused by urbanization of agricultural lands, replacement of furrow irrigation by the more efficient overhead spray, and use of drip-irrigation methods. In contrast, increased withdrawals for public supplies on Kauai and Oahu have contributed to steadily declining levels since 1973.

On the island of Hawaii, water levels in selected wells shown in figure 2 have been steady or risen slightly despite the dramatic growth of the population and tourist industry in the Hilo and Kona areas. The increase in water levels was due to above-average precipitation from 1973 to 1983, resulting in increased recharge.

GROUND-WATER MANAGEMENT

Comprehensive management of Hawaii's water resources is required by law under the 1978 amendment to the State Constitution (Article XI, Section 7). Two State organizations, the State Department Land and of Natural Resources (DLNR) and the State Department of Health (DOH), implement most of the regulatory and planning requirements mandated by this legislation.

The DLNR administers the overall water resources development and regulates all withdrawals of water from ground-water sources. Under the 1959 Ground-Water Use Act, Hawaii Revised Statutes (HRS 177, Title 13, Chapter 166), and Regulation 9, ground-water within designated areas is subject to control by the DLNR. Ground-water control designations have been established in areas III, IV, and VI on Oahu to prevent depletion, waste, pollution, or deterioration by saltwater encroachment. Permits for drilling of wells on Oahu are required by the DLNR or the Honolulu Board of Water Supply.

The DOH administers programs designed to protect the quality of ground water. The 1972 Federal Water Pollution Control Act Amendments (Public Law 92-500) are administered by the DOH in the State of Hawaii. In response to the specific requirements contained in Section 208 of the Act, the DOH developed plans for Hawaii in cooperation with other State and county departments to achieve the national, State, and county goals of preservation, restoration, and maintenance of water quality.

The 1974 Safe Drinking Water Act (Public Law 93-523) requires the U.S. Environmental Protection Agency (USEPA) to develop minimum programs for the State to protect underground drinking-water sources. In response to a request from USEPA, the DOH has compiled and adopted an Underground Waste Injection Control program to meet specific hydrogeologic settings.

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Prepared by Santos Valenciano

For further information contact District Chief, U.S. Geological Survey, P. O. Box 50166, Honolulu, HI 96850

IDAHO
Ground-Water Resources

Although intensive use of ground water for agriculture has lowered water levels significantly in some areas of Idaho, the State's overall ground-water resources barely have been tapped (Idaho State, 1972). In 1980, about 88 percent of the people in Idaho depended on ground water for domestic supply; however, withdrawals for public and rural domestic supplies amounted to only about 3 percent of the 6.3 billion gallons per day (bgd) of total ground-water withdrawals. Ground-water withdrawals in 1980 for major use categories are given in table 1.

By far the largest use of ground water in the State is irrigated agriculture. In 1980, about 4.1 bgd of ground water, or about 65 percent of total ground-water withdrawals, was pumped for irrigation. In 1980, about 2.1 bgd of ground water was used for industrial purposes; included in this total is ground water discharged from springs and used in the many aquaculture operations along the Snake River in southern Idaho.

GENERAL SETTING

Idaho encompasses parts of four physiographic provinces (fig. 1). The Columbia Plateaus province is located primarily in Oregon and Washington but extends into southern Idaho. Most of the Columbia Plateaus in Idaho consists of the 15,600-square mile Snake River Plain, which extends across southern Idaho and is underlain in part by one of the most productive aquifers in the United States—the Snake Plain aquifer. Most of the State north of the Snake River Plain is in the Northern Rocky Mountains province, which is underlain principally by granitic rocks. In general, the granitic rocks yield only small quantities of water to wells. The Middle Rocky Mountains province includes the mountains of eastern Idaho, the southernmost of which form the northern drainage of the Bear River, which flows into Utah. A small part of the Basin and Range province extends northward into southern Idaho and drains to the Bear River and Great Salt Lake in Utah.

Precipitation is affected by topography and varies widely throughout the State; the annual range is from about 10 inches (in.) on most of the Snake River Plain to 20 or 30 in. in the surrounding highlands. Ground-water recharge from precipitation on the Snake River Plain is 2 to 5 percent of the total precipitation (Kjelstrom, 1984). Over most of the central mountains, annual precipitation commonly is 40 to 50 in. but may exceed 60 in. in some areas. Most precipitation falls in the winter as snow.

Table 1. Ground-water facts for Idaho

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	827
Percentage of total population	88
From public water-supply systems:	
Number (thousands)	592
Percentage of total population	63
From rural self-supplied systems:	
Number (thousands)	235
Percentage of total population	25
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	18,000
Ground water only (Mgal/d)	6,300
Percentage of total	35
Percentage of total excluding withdrawals for thermoelectric power	35
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	150
Percentage of total ground water	2
Percentage of total public supply	94
Per capita (gal/d)	253
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	44
Percentage of total ground water	0.7
Percentage of total rural domestic	96
Per capita (gal/d)	187
Livestock:	
Ground water (Mgal/d)	9.3
Percentage of total ground water	0.1
Percentage of total livestock	42
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	2,100
Percentage of total ground water	33
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	95
Excluding withdrawals for thermoelectric power	95
Irrigation withdrawals:	
Ground water (Mgal/d)	4,100
Percentage of total ground water	65
Percentage of total irrigation	25

PRINCIPAL AQUIFERS

Although 70 aquifers have been identified in Idaho (Graham and Campbell, 1981), many are limited in extent and yield insignificant amounts of water. Three principal aquifers or groups of aquifers in Idaho are identified in figure 1 and are described below and in table 2.

Table 2. Aquifer and well characteristics in Idaho

[Gal/min = gallons per minute; ft = feet; °F = degrees Fahrenheit. Sources: Reports of the U. S. Geological Survey and Idaho state agencies]

Aquifer name and description	Well characteristics: Depth, common range (ft)	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Valley-fill aquifers: Intermontane valley fill and alluvium. Chiefly unconsolidated gravel, sand, silt, and clay. Primarily glacial outwash, locally interbedded with basalt and rhyolite in north Idaho. Generally unconfined.	20 - 700	2 - 2,000	3,500	Sedimentary rocks of Salt Lake Formation are important aquifers in some southeastern river valleys. Spokane Valley–Rathdrum Prairie aquifer in north Idaho supplies some water to city of Coeur d'Alene. Locally, concentrations of dissolved solids, nitrate plus nitrite, iron and cadmium may exceed national drinking-water regulations.
Basalt aquifers: Mostly olivine basalt with thin, interbedded layers of gravel, sand, silt, and clay. Confined and unconfined.	100 - 1,000	300 - 3,300	7,000	Chiefly basalts of the Snake River Group in southeast Idaho and basalts of the Columbia River Basalt Group in east-central and north Idaho. Snake Plain aquifer is principal aquifer in State and supplies water for irrigation and most domestic and industrial uses in eastern Snake River Plain. Well yields variable. Concentrations of nitrate plus nitrite and dissolved solids may exceed national drinking-water regulations. In northern Idaho, wells in basalt aquifers supply water to cities of Lewiston, Moscow, and Grangeville. Thermal ground water near 100°F is pervasive in Twin Falls County.
Sedimentary and volcanic aquifers: Unconsolidated fine sand, silt, and clay with basalt and felsic rocks and interbedded shale and sandstone. Confined and unconfined.	50 - 3,000	100 - 2,500	3,000	Most important aquifers in Boise Valley are in alluvial sands and gravels; depth to water commonly less than 25 ft in many areas, and drainage a problem locally. Aquifers in sediments and basalts of Idaho Group supply water to cities of Boise, Nampa, and Caldwell. Deep wells completed in silicic rocks of Idavada Volcanics and Banbury Basalt in Elmore and Owyhee Counties yield water between 100° and 180°F under pressures greater than atmospheric; these waters commonly have large concentrations of fluoride and sodium. Quality of water generally suitable for most agricultural and domestic uses.

Valley-Fill Aquifers

Unconsolidated sedimentary aquifers in intermontane valleys are grouped as valley-fill aquifers (fig. 1), which yield sufficient water to wells for most rural-domestic use and may sustain farming operations of considerable magnitude. Included in this group are aquifers in drainage basins tributary to the Snake, Boise, and Bear Rivers.

In the Idaho Panhandle area (northern Idaho), valley-fill aquifers consist primarily of glacial outwash—unconsolidated gravel, sand, silt, and clay—and some recent alluvium. Wells completed in these aquifers generally yield quantities of water suitable for domestic supplies. Dissolved-solids concentrations ranged from 250 to 500 milligrams per liter (mg/L), nitrate plus nitrite concentrations ranged from 0 to 25 mg/L, and iron concentrations exceeded 1.7 mg/L in one-half of the wells sampled (Parliman and others, 1980).

The Spokane Valley-Rathdrum Prairie aquifer, a valley-fill aquifer in Washington and Idaho (not specifically identified in fig. 1) is the main source of supply for the cities of Spokane, Wash., and Coeur d'Alene, Idaho. In Idaho, the aquifer consists chiefly of glacial outwash—a mixture of unconsolidated silt, sand, gravel, and boulders. Wells completed in this aquifer generally are less than 200 feet (ft) deep and are used primarily for irrigation supply. They commonly yield large quantities of water with little drawdown because of exceptionally large aquifer transmissivity. Locally, concentrations of dissolved iron in the water may exceed 0.2 mg/L (Parliman and others, 1980).

Basalt Aquifers

Numerous basalt flows and thin, interbedded sediments of the Snake River Group comprise the Snake Plain aquifer, which is the principal aquifer in Idaho. The aquifer supplies water for most domestic and industrial uses on the Snake River Plain upstream from King Hill. The greatest use of the water, however, is for irrigation (fig. 2); in 1980, about 1,720 Mgal/d of water was withdrawn from the Snake Plain aquifer to irrigate about 900,000 acres of farmland. The aquifer discharges about 6,000 cubic feet per second (ft^3/sec) to the Snake River, largely from a series of springs between Milner and King Hill that issue from the northern wall of the Snake River canyon (Kjelstrom, 1984). Spring flow accounts for

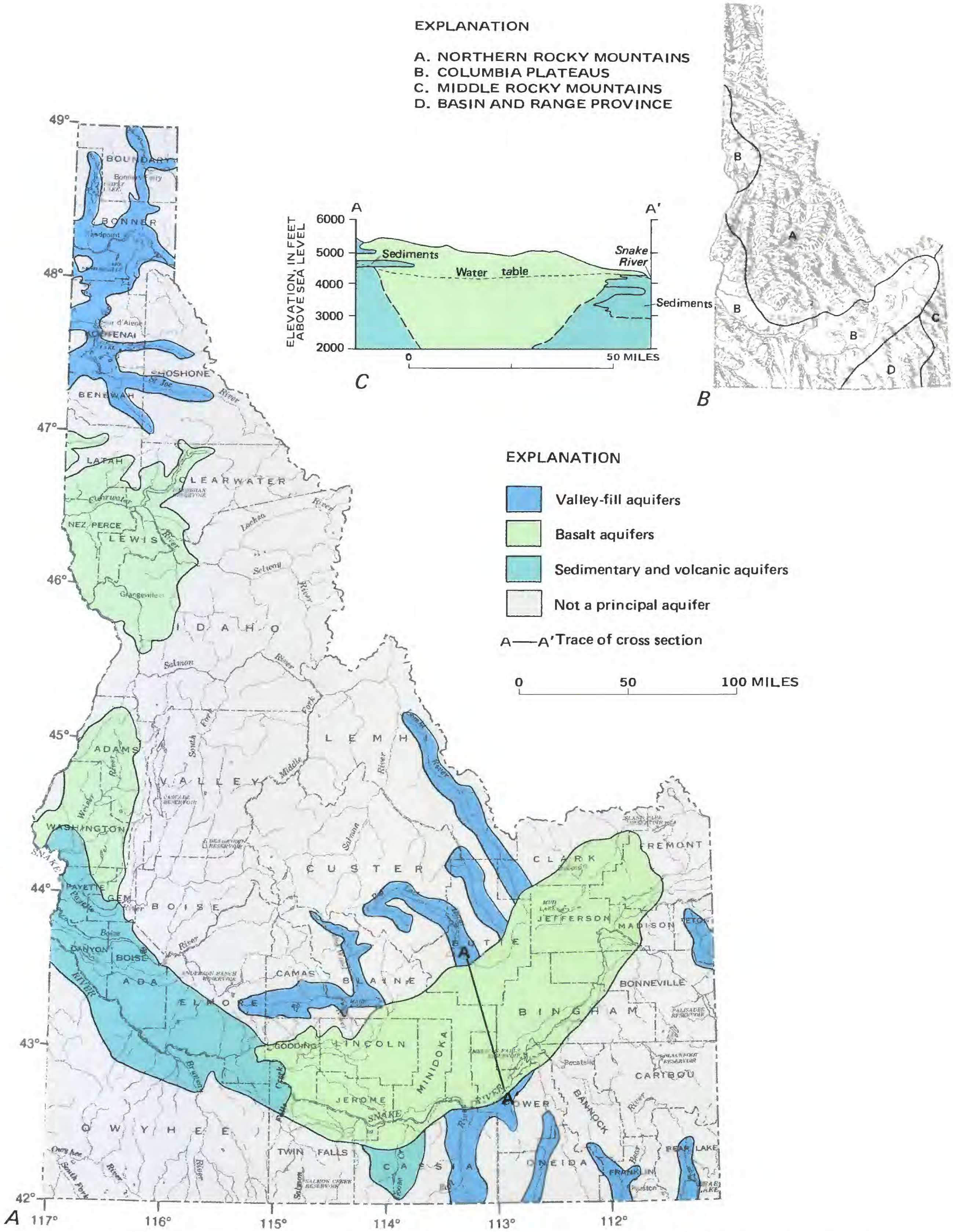


Figure 1. Principal aquifers in Idaho. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of aquifers. Sources: *A*, Graham and Campbell, 1981. *B*, Fenneman, 1931; Raisz, 1954. *C*, Whitehead, 1984.)

nearly 56 percent of mean annual flow in the Snake River at King Hill and for about 75 percent of the flow at that site during July and August when flows are at a minimum because of upstream diversions for irrigation. Urbanization, return of excess irrigation water to the aquifer through drain wells, and infiltration of industrial effluents have caused local deterioration of water quality in the aquifer. Generally, however, the quality of water is suitable for most agricultural and domestic uses. Locally in Twin Falls County, some wells completed in basalt yield geothermal water having temperatures of 86° to 160°F; the heated water is used for space heating, greenhouse operation, and agriculture.

In the Moscow-Lewiston area, basalt aquifers are intercalated with gravel, sand, and clay. Principal aquifers are in volcanic rocks of the Columbia River Basalt Group and fine-grained sediments of the Latah Formation. These aquifers supply the cities of Lewiston, Moscow, and Grangeville and, although well yields are mostly small to moderate, wells are pumped extensively for irrigation of wheat and barley.

In the Weiser River basin in western Idaho, aquifers in basalts of the Columbia River Basalt Group supply water for irrigation and rural domestic use and for the cities of Council, Cambridge, and Midvale.

Sedimentary and Volcanic Aquifers

Sedimentary and volcanic aquifers of the western Snake River Plain are composed of gravel, sand, silt, and clay interbedded with basalt, shale, and sandstone; water from these aquifers is used chiefly for irrigation. South of the Snake River in Owyhee County, wells as deep as 3,600 ft that tap interbedded volcanic and sedimentary rocks produce geothermal water at temperatures ranging from 90° to 183°F with artesian heads above land surface. Although the concentrations are typically large in fluoride (as much as 27 mg/L), and in sodium (as much as 140 mg/L), the geothermal water, when cooled, is used for irrigation of alfalfa.

Sedimentary and volcanic aquifers in the Mountain Home area are composed of basalt interbedded with poorly consolidated to unconsolidated gravel, sand, silt, and clay. Well yields are extremely variable. Water levels in some wells have declined markedly in the last 15 years in response to pumping for irrigation (location 6, fig. 2). Consequently, part of the area has been designated a Critical Ground-Water Area (see Ground-Water Management section). These aquifers are the principal source of water for the city of Mountain Home and for the Mountain Home Air Force Base. Locally, concentrations of nitrate and dissolved solids in ground water may exceed national drinking-water regulations established for public water supplies.

In the Boise Valley area, sedimentary and volcanic aquifers are composed chiefly of unconsolidated clay, silt, sand, and gravel with interbedded basalt. Most shallow aquifers are alluvial sands and gravels; deep aquifers are sediments and basalts of the older Idaho Group. These aquifers are used extensively for irrigation and for domestic and industrial supply for the cities of Boise, Nampa, and Caldwell. The quality of the water generally is suitable for most agricultural and domestic uses.

Aquifers in the Cottonwood-Oakley Fan area are composed of rhyolite, basalt, limestone, and unconsolidated sand and gravel. Water from the aquifers is used primarily for irrigation. Extensive pumping, particularly from volcanic rock aquifers, has lowered water levels as much as 50 ft between 1973 and 1983 (location 12, fig. 2). As a result, several Critical Ground-Water Areas have been designated in this area. Limited water-quality data indicate that the ground water is suitable for irrigation and domestic use.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

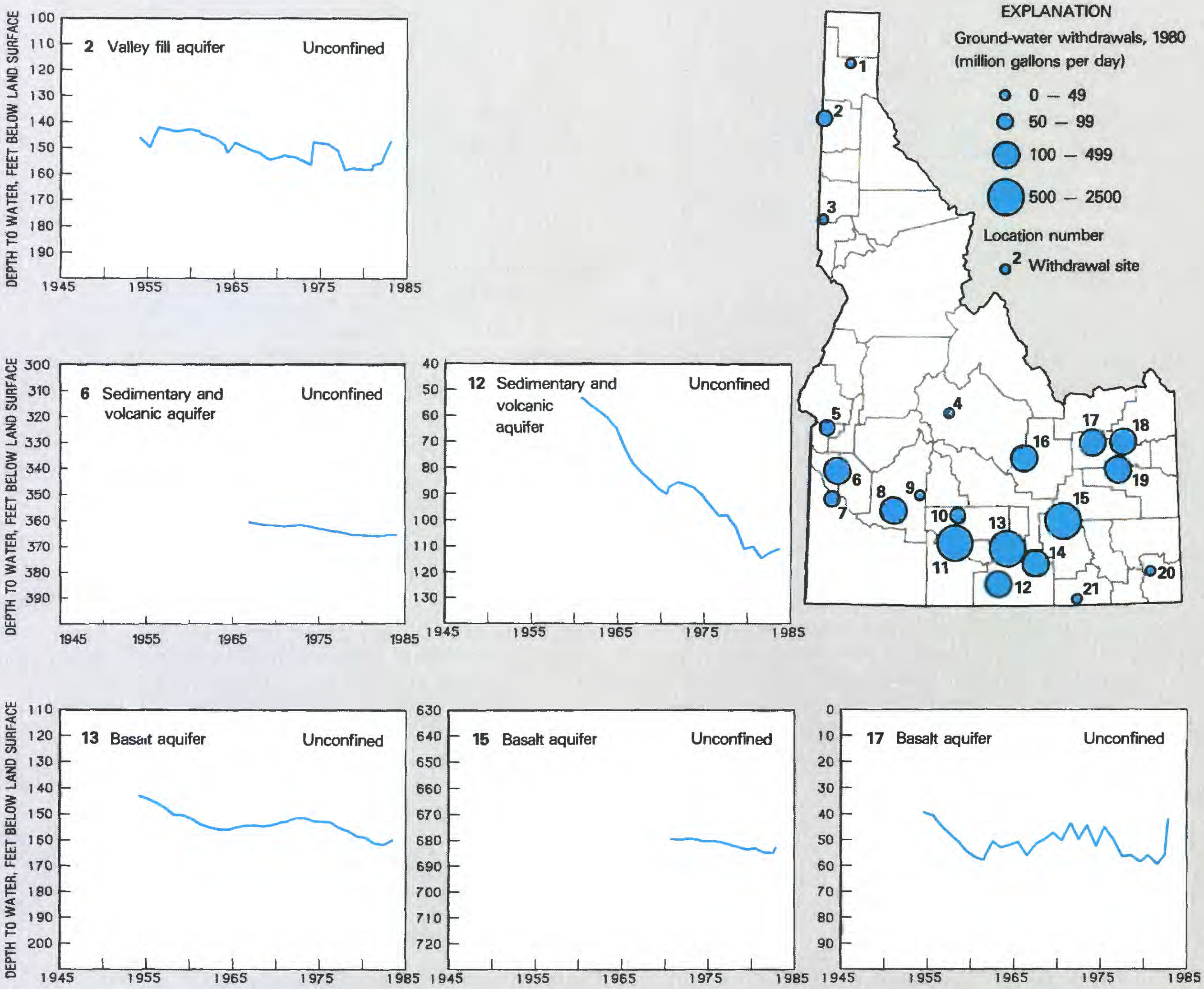
Distribution of ground-water withdrawals and water-level trends in the State are shown in figure 2. Nearly three-fourths of the State's population is located in southern Idaho on the Snake River Plain, and about 3.1 million acres of farmland were irrigated on the plain in 1980 (Bigelow and others, 1984). Consequently, most of the water use and associated water-level declines are in the southern part of the State.

Use of water from the Snake River and its tributaries for irrigation on the plain began in about 1840 and increased considerably in the 1880's. By 1899, about 550,000 acres on the Snake River Plain were irrigated (Lindholm and Goodell, 1984). After 1900, dams constructed on the Snake River supplied additional water for irrigation and, by 1929, irrigated acreage on the plain had expanded to 2.2 million acres (Lindholm and Goodell, 1984). Since the late 1940's, most surface-water supplies have been appropriated, and use of ground water for irrigation has increased.

In 1980, about 2.1 million acres on the Snake River Plain were irrigated with surface water, largely by gravity diversions from the Snake and Boise Rivers. One million acres were irrigated with about 2 bgd of ground water withdrawn from about 5,300 wells (Bigelow and others, 1984). With virtually all surface water on the Snake River Plain already appropriated, water for irrigation will be withdrawn from ground-water supplies if additional lands are developed for farming.

Water levels in wells on the Snake River Plain have been greatly affected by changes in irrigation practices over the years which include decreased use of surface water, increased use of ground water, and conversion to more efficient sprinkler irrigation systems. Recharge resulting from the application of large quantities of surface water for irrigation raised ground-water levels a few to several tens of feet over wide areas of the Snake River Plain. The rise in water levels resulted in increased spring discharge, particularly between 1910 and 1950, during which time spring discharge increased by about 1.9 bgd. Since 1950, ground-water levels and spring discharges generally have declined, partly because of increased use of ground water for irrigation (fig. 2).

Net water-level declines between 1971 and 1982 were observed in 75 percent of 361 observation wells; declines ranged from about 1 to 53 ft. Declines from 5 to 10 ft were common across most of the Snake River Plain. Declines of more than 10 ft were most common in or near areas of intensive agricultural development, such as northern Owyhee, southern Elmore, southern Canyon, and Camas Counties.



WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Idaho Panhandle	Valley fill	Public supply, irrigation.
2	Rathdrum Prairie	. . . .do	Public supply, industrial, rural domestic.
3	Moscow-Lewiston area	Basalt.	Industrial, public supply, irrigation.
4	Salmon River basin	Valley fill	Public supply, irrigation.
5	Payette-Weiser River Valleys. . . .	Valley fill, basalt	Do.
6	Boise Valley	Sedimentary and volcanic . . .	Irrigation, public supply, industrial, rural domestic.
7	Murphy area	. . . .do	Irrigation.
8	Mountain Home-Bruneau area. . .	. . . .do	Do.
9	Camas Prairie	Valley fill	Do.
10	Big-Little Wood River Valleys. . .	. . . .do	Irrigation, public supply.
11	Central Snake River Plain	Basalt.	Aquaculture, irrigation.
12	Cottonwood-Oakley Fan area . . .	Sedimentary and volcanic . . .	Irrigation.
13	Rupert-Burley area	Basalt.	Do.
14	Raft River Valley	Valley fill	Do.
15	American Falls-Blackfoot area. . .	Basalt.	Irrigation, aquaculture.
16	Big-Little Lost River Valleys. . . .	Valley fill	Irrigation, public supply, industrial.
17	Mud Lake area.	Basalt.	Irrigation.
18	Henrys Fork-Teton Valleys	Valley fill	Irrigation, public supply.
19	Upper Snake River Valley	Basalt.	Do.
20	Bear River Basin.	Valley fill	Do.
21	Curlew Valley	. . . .do	Irrigation.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Idaho. (Sources: Withdrawal data from Solley and others, 1983; water-level data from U.S. Geological Survey files.)

GROUND-WATER MANAGEMENT

Management of ground-water resources and protection of the resource from waste and contamination are the responsibilities of the Idaho Department of Water Resources (IDWR) and the Idaho Water Resource Board. Protection of ground-water quality in the State is the responsibility of the Idaho Department of Health and Welfare, Division of Environment.

Extensive pumping of ground water for irrigation has prompted the State to curtail additional agricultural development in some areas. Where declining ground-water levels become a concern to local water users, the State can declare an area a Ground-Water Management Area (GWMA) under Idaho Code 42-233b. In those areas, permits for new well construction must be approved by the IDWR to ensure that rights of existing water users are not affected adversely. If water levels decline at a rate that will threaten a reasonably safe supply for existing users, the State can declare the area a Critical Ground-Water Area (CGWA) under Idaho Code 42–233a. In those areas, no new well permits are issued, and ground-water withdrawals are reduced to levels determined by the IDWR. Presently, five GWMA's and eight CGWA's have been designated in the State.

The Idaho Department of Water Resources and the Idaho Department of Health and Welfare are engaged in cooperative data-collection programs and interpretive studies with the U.S. Geological Survey. Data collected and results of the studies provided by this cooperative program form an information base upon which ground-water management decisions in Idaho are made.

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Prepared by Robert E. Lewis and Sally A. Goodell

For further information contact District Chief, U.S. Geological Survey, 230 Collins Road, Boise, ID 83702

ILLINOIS
Ground-Water Resources

Ground water is the source of water for almost 49 percent of the State's more than 11 million population. More than 980 million gallons per day (Mgal/d) of ground water was withdrawn in Illinois during 1980; about 49 percent was used for public supply and about 22 and 19 percent for industrial and rural supplies, respectively. In the northern part of the State, especially in the metropolitan areas of Chicago and Rockford, large quantities of water are withdrawn from glacial drift and bedrock for municipal, industrial, and domestic use. Water use in rural areas, including much of the southern two-thirds of the State, is mostly from ground-water sources. Ground-water withdrawals and related statistics for 1980 are given in table 1.

Although Chicago and its suburbs in Cook County depend largely on water from Lake Michigan, this area also uses more than 106 Mgal/d of ground water. Many industries within the area served by Lake Michigan have private wells and use ground water for processing, cooling, and standby purposes. In addition to Cook County, the counties of Du Page, Grundy, Kane, Kendall, Lake, McHenry, and Will in northeastern Illinois historically have been very dependent on ground water. Pumpage in these counties has increased steadily from 9.2 Mgal/d in 1880 to more than 340 Mgal/d in 1980.

The ground-water quality in the State generally is good for most uses, although some water in the deeper aquifers has deteriorated. Ground-water contamination is a threat in the northwestern corner where aquifers lie at or near the land surface.

Table 1. Ground-water facts for Illinois

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Kirk and others, 1982; Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	5,592
Percentage of total population	49
From public water-supply systems:	
Number (thousands)	4,187
Percentage of total population	37
From rural self-supplied systems:	
Number (thousands)	1,405
Percentage of total population	12
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	18,000
Ground water only (Mgal/d)	980
Percentage of total	5
Percentage of total excluding withdrawals for thermoelectric power	24
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	480
Percentage of total ground water	49
Percentage of total public supply	27
Per capita (gal/d)	114
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	120
Percentage of total ground water	12
Percentage of total rural domestic	97
Per capita (gal/d)	85
Livestock:	
Ground water (Mgal/d)	67
Percentage of total ground water	7
Percentage of total livestock	100
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	220
Percentage of total ground water	22
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	1
Excluding withdrawals for thermoelectric power	10
Irrigation withdrawals:	
Ground water (Mgal/d)	97
Percentage of total ground water	10
Percentage of total irrigation	100

GENERAL SETTING

Most of Illinois lies within the Central Lowland physiographic province (fig. 1). Small parts of southern and southwestern Illinois lie within the Coastal Plain, Interior Low Plateaus, and Ozark Plateaus provinces. Differing physiography and geologic conditions cause significant differences in ground-water conditions.

Large areas in western, south-central, and southern Illinois are underlain by relatively thin glacial drift that is rarely more than 75 feet (ft) thick. In northern and east-central Illinois, the glacial drift is much thicker, exceeding 600 ft in some places. Large deposits of water-yielding sand and gravel are present in the drift, mostly in stream valleys or in buried bedrock valleys as outwash deposits.

The major sources of recharge to aquifers in Illinois are infiltration of precipitation on outcrop areas and percolation of ground water through confining units. Most recharge occurs during the spring when evapotranspiration is low and precipitation is frequent. Average annual precipitation (1931–60) ranged from 32 inches (in.) in the north to 48 in. in the southern tip of the State. Annual ground-water recharge rates differ across the State, but generally ranges from about 1 in. in material with little permeability to about 8 in. in permeable materials (Walton, 1965, p. 40–41).

PRINCIPAL AQUIFERS

Ground water in Illinois is obtained from unconsolidated sand-and-gravel aquifers (largely glacial drift) and from underlying sedimentary bedrock aquifers, including sandstone, limestone, and dolomite. Extensive areas of sand and gravel and bedrock in the northern one-third and extreme southern parts of the State yield large quantities of water. Elsewhere, yields generally are less, except where preglacial stream valleys are filled with sand and gravel or where Ordovician, Mississippian, and Pennsylvanian bedrock provide small supplies. The principal aquifers in Illinois are described below and in table 2; their areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics in Illinois

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey and State agencies]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Sand-and-gravel aquifers: Unconsolidated clay, silt, sand, gravel, and boulders deposited as till, outwash, lake deposits, and loess. Unconfined and confined.	50 - 500	10 - 1,000	3,000	Probabilities for ground-water development range from poor to excellent. Outwash sand and gravel yield more than 1,000 gal/min to wells at places; large supplies generally obtained from permeable outwash in major valleys. Glacial aquifers used for many small water supplies.
Pennsylvanian-Mississippian aquifer: Limestone and shale, cherty. Sandstone and coal beds. Confined.	40 - 700	5 - 25	1,000	Mississippian rocks generally creviced and water yielding; dependable aquifer for small supplies in western Illinois. Pennsylvanian rocks generally unfavorable for large yields; locally, domestic and farm supplies obtained from thin limestone and sandstone beds.
Shallow dolomite aquifer: Dolomite, fractured, silty at base; locally cherty. Unconfined and confined.	50 - 500	25 - 1,000	1,500	Some wells yield more than 1,000 gal/min; crevices and solution channels more abundant near surface.
Cambrian-Ordovician aquifer: Sandstone, fine- to coarse-grained; dolomite, fine grained, sandy. Confined.	100 - 2,000	150 - 1,000	2,500	St. Peter, Ironton, and Galesville Sandstones most productive. Crevices in other dolomite and sandstone units generally yield small to large quantities of water. Generally, wells in this aquifer also open to Mount Simon aquifer.
Mount Simon aquifer: Sandstone, coarse-grained, white, red in lower half; lenses of shale and and siltstone. Confined.	>1,500 - 2,000	150 - 1,000	2,500	Moderate amounts of potable water obtained from upper 100 to 300 ft; total dissolved solids also increase with depth and may exceed 2,000 mg/L. Water becomes saline with depth. Permeability intermediate between that of St. Peter and Galesville Sandstones. Generally, wells in this aquifer also open to Cambrian-Ordovician aquifer.

Sand-and-Gravel Aquifers

Glacial drift of Quaternary age covers about 80 percent of Illinois and ranges in thickness from about 1 to 600 ft. The only areas of the State not covered by glacial deposits are the extreme northwestern corner, a small area in the west, and the southern tip. The drift is more than 200 ft thick regionally in northeastern Illinois and as much as 600 ft thick in some of the major bedrock valleys. Sand and gravel of Tertiary and Cretaceous age form thick deposits in the southernmost counties in Illinois and usually are included as unconsolidated deposits with the Quaternary sand and gravel.

Well yields from sand-and-gravel aquifers range from about 10 to 1,000 gallons per minute (gal/min), depending on aquifer thickness, continuity, and permeability. The largest yields generally are obtained from glacial outwash sand and gravel in major valleys.

The quality of the water from the sand-and-gravel aquifers is satisfactory for most uses. The dissolved-solids concentration generally ranges from 400 to 600 milligrams per liter (mg/L), and the chloride concentration is generally less than 20 mg/L.

Pennsylvanian-Mississippian Aquifer

Sedimentary rocks of Pennsylvanian and Mississippian age form the bedrock surface in about four-fifths of Illinois and constitute the Pennsylvanian-Mississippian aquifer. These rocks include limestone, sandstone, and shale that generally have small porosity and permeability. Most wells developed in these units yield less than 20 gal/min, which is enough to satisfy most domestic, farm, and very small municipal needs with water of acceptable quality.

Shallow Dolomite Aquifer

The shallow dolomite aquifer includes carbonate rocks of Silurian and Late Ordovician age. The aquifer may be very productive where it is unconfined. Ground water is present in joints, fissures, and solution channels, and well yields may be as much as 1,500 gal/min. The water quality is acceptable for most uses. Dissolved-solids concentrations commonly range from about 350 to 450 mg/L and consist primarily of hardness-forming minerals. Median chloride concentrations range from about 5 to 30 mg/L, based on 40 years of record.

Cambrian-Ordovician Aquifer

The Cambrian-Ordovician aquifer consists of two primary producing units—the St. Peter Sandstone of Ordovician age and the Ironton and Galesville Sandstones of Cambrian age. On a regional basis, the entire sequence of Cambrian and Ordovician strata older than the Maquoketa Shale (which is a major confining unit) seems to function hydraulically as a single aquifer unit.

The St. Peter Sandstone is used widely for domestic, small municipal, and small industrial water supplies. It commonly yields as much as 100 gal/min.

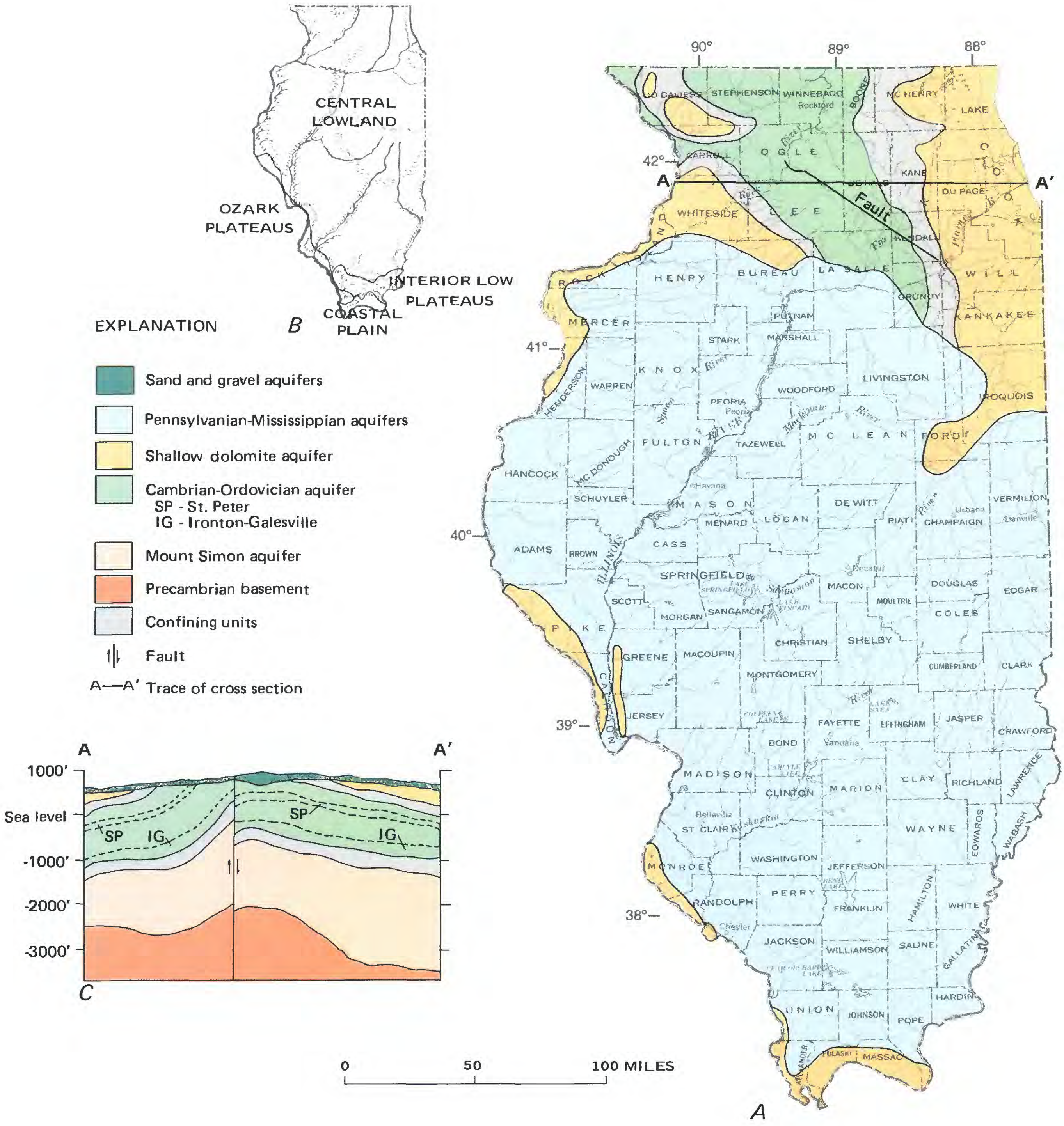


Figure 1. Principal aquifers in Illinois. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Willman and others, 1967. *B*, Leighton and others, 1948; Raisz, 1954. *C*, Compiled by M. G. Sherrill from U.S. Geological Survey files.)

The Ironton and Galesville Sandstones form the most productive unit in the Cambrian-Ordovician aquifer and yield nearly 50 percent of the aquifer's total production. Yields of more than 500 gal/min are common in northern Illinois. Water quality in this aquifer generally is suitable for most uses. The dissolved-solids concentration ranges from less than 400 mg/L in the north to more than 1,000 mg/L in the south, where these units are overlain by progressively thicker and younger bedrock units.

Mount Simon Aquifer

The Mount Simon aquifer collectively includes Cambrian sandstone of the lower Eau Claire Sandstone and the Mount Simon Sandstone, which are hydraulically connected. The medium- to coarse-grained parts of this aquifer yield moderate to large quantities of water with a quality similar to that of the overlying Cambrian-Ordovician aquifer. Commonly, wells are constructed to penetrate only the upper few hundred feet because water is highly mineralized below that depth. Because of the confining nature of the Eau Claire Sandstone and heavy pumpage in the Ironton and Galesville Sandstones, hydrostatic heads are usually higher in the Mount Simon aquifer than in the shallower bedrock aquifers.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Kirk and others (1982, p. 6–7) described nine water-use regions in Illinois. These regions are shown in figure 2. The distribution of major ground-water withdrawal areas and trends of ground-water levels near selected pumping centers are shown in figure 2. The largest total withdrawals are near the city of Rockford (locations 1 and 2, fig. 2) in Region A and in the Chicago metropolitan area (Region B, locations 3, 4, and 5, fig. 2). Pumpage exceeds 50 Mgal/d from the sand-and-gravel and the Cambrian-Ordovician aquifers in both these areas.

Water levels generally decline in response to increases in pumping and they recover as pumping is reduced. The hydrographs in figure 2 show the response of aquifers to pumpage and are representative of conditions in the principal aquifers at selected pumping centers in Illinois. Increased pumping in the Chicago region has created a corresponding decline in water levels in the shallow dolomite aquifer and especially in the Cambrian-Ordovician aquifer. As a result, water levels in some wells that tap the Cambrian-Ordovician aquifer have declined more than 850 ft.

In the East St. Louis area, withdrawals are primarily from the sand-and-gravel aquifer, and water levels are affected greatly by changes in pumpage, precipitation, and Mississippi River stage (location 11, fig. 2). Increased withdrawals for industrial and public-supply use through about 1956 lowered water levels in the area. Since the mid-1960's, many water users have shifted to the Mississippi River for water supply. The resulting rise in ground-water levels has caused problems such as flooding of basements and highway underpasses.

GROUND-WATER MANAGEMENT

At present, no State agency in Illinois has authority to regulate directly the withdrawal of ground water statewide and withdrawal permits are not required. The Illinois Water Use Act of 1983 (Public Act 83-700) established a mechanism for identifying areas of underground water-withdrawal conflicts; procedures for resolving conflicts currently are being developed.

Supplementing ground-water withdrawals with surface-water sources affects ground-water consumption in the counties of Lake, Cook, and Du Page. These counties must comply with Lake Michigan Order 80-4 (LMO #80-4), which was issued by the Illinois Department of Transportation, Division of Water Resources. This order sets allotments of Lake Michigan water to specific water users (Illinois Department of Transportation, 1980). Water users presently pumping from the Cambrian-Ordovician aquifer that begin to use an allotment of water from Lake Michigan must, under terms of the order, discontinue pumping from the aquifer within 5 years.

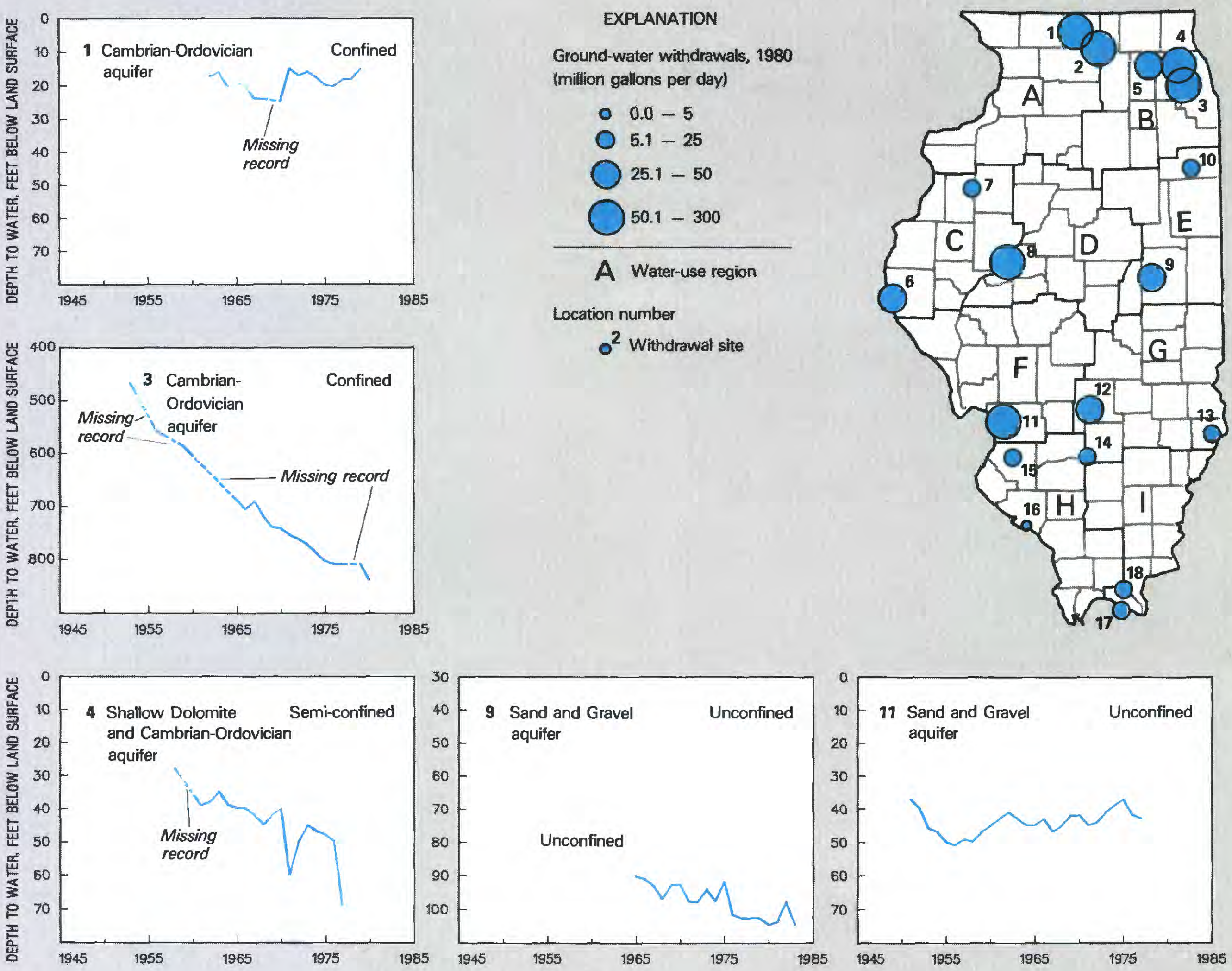
Several State agencies have regulatory authority over activities that affect ground-water quality. The Illinois Environmental Protection Act (IEP Act) grants extensive regulatory powers to the Illinois Pollution Control Board. The Board is authorized to promulgate regulations to prevent groundwater pollution and has the authority to act for the State with regard to establishing standards for Federal laws concerning environmental protection.

The Illinois Environmental Protection Agency (IEPA) is charged with enforcing regulations of the IEP Act. The charge includes evaluation, surveillance, and inspection of discharges from contaminant sources, monitoring of environmental quality of public-water supplies and waste-disposal sites, some classes of subsurface waste injection, and investigations of violations of the regulations or permits issued thereunder.

The Illinois Department of Public Health has regulatory authority over a variety of activities that can affect ground-water quality. These activities include sanitation investigations and inspections of public recreational and tourist facilities and licensing of private sewage-disposal contractors, water-well contractors, and pump installers.

The Illinois Department of Mines and Minerals has responsibilities for permitting and regulating those activities in coal mining, oil and gas exploration, and subsurface waste injection of oil and wastes, some of which might adversely affect ground-water quality.

Two branches of the Illinois Department of Energy and Natural Resources are nonregulatory but have authority to study ground water; these are the Illinois State Water Survey and the Illinois State Geological Survey. These agencies are authorized to collect facts and data concerning the volume, flow, and quality of underground and surface waters of the State and to publish results of these investigations. The U.S. Geological Survey works cooperatively with these two agencies and with the IEPA to maintain a statewide, water-data network and to investigate the State's water resources.



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
Water-use region A			
1	Rockford area	Cambrian-Ordovician	Public supply, rural-domestic, industrial.
2	Rockford area	Sand and gravel	Do.
Water-use region B			
3	Chicago area	Cambrian-Ordovicien	Public supply.
4	Chicago area	Shallow dolomite and Cambrain-Ordovician.	Do.
5	Elgin area	Sand and gravel	Do.
Water-use region C			
6	Quincy area	. . . .do	Rural-irrigation, industrial.
7	Monmouth-Galesburg area	Cambrain-Ordovician	Rural-livestock, industrial.
Water-use region D			
8	Havana area	Sand and gravel	Rural-irrigation.
Water-use region E			
9	Champaign area	. . . .do	Public supply, rural-domestic.
10	Kankakee area.	Shallow dolomite	Public supply, rural-irrigation.
Water-use region F			
11	East St. Louis area (Wood River) . . .	Sand and gravel	Industrial, rural-domestic.
Water-use region G			
12	Vandalia area	Pennsylvanian-Mississippian	Industrial, rural-livestock.
13	Lawrenceville area	Sand and gravel	Industrial, rural-irrigation.
14	Centralia area	Shallow dolomite	Industrial.
Water-use region H			
15	Belleville area	Sand and gravel	Industrial, rural-domestic.
16	Chester area	Pennsylvanian-Mississippian	Rural-livestock, public supply.
Water-use region I			
17	Metropolis area	. . . .do	Industrial, public supply.
18	Millstone area (Pope County)	Sand and gravel	Industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Illinois. (Sources: Withdrawal data from Kirk and others, 1982; water-level data from U. S. Geological Survey files.)

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Prepared by Marvin G. Sherrill, Timothy R. Lazaro, and Laura L. Harbison

For further information contact District Chief,U.S. Geological Survey, Champaign County Bank Plaza, 102 E. Main Street, Urbana, IL 61801

INDIANA
Ground-Water Resources

Ground water provides drinking water to about one-third of the people in Indiana. Virtually all water used by industry, excluding the steel and petrochemical withdrawals from Lake Michigan and cooling water for electric power generation, is ground water. Irrigation also is a major use of ground water in the State, withdrawals being roughly equal to the quantity of ground water withdrawn for public supply. Ground-water withdrawals in 1980 for various uses and other related statistics for Indiana are given in table 1.

Table 1. Ground-water facts for Indiana

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Clark, 1980; Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	1,732
Percentage of total population	32
From public water-supply systems:	
Number (thousands)	1,548
Percentage of total population	28
From rural self-supplied systems:	
Number (thousands)	184
Percentage of total population	4
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	14,000
Ground water only (Mgal/d)	1,100
Percentage of total	8
Percentage of total excluding withdrawals for thermoelectric power	27
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	240
Percentage of total ground water	22
Percentage of total public supply	41
Per capita (gal/d)	152
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	12
Percentage of total ground water	1
Percentage of total rural domestic	11
Per capita (gal/d)	63
Livestock:	
Ground water (Mgal/d)	8.0
Percentage of total ground water	1
Percentage of total livestock	18
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	600
Percentage of total ground water	55
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	8
Excluding withdrawals for thermoelectric power	18
Irrigation withdrawals:	
Ground water (Mgal/d)	230
Percentage of total ground water	21
Percentage of total irrigation	98

GENERAL SETTING

The most important geologic and physiographic feature in Indiana is the boundary of Wisconsinan glaciation (fig. 1). North of this boundary, drift ranges in thickness from 50 to about 200 feet (ft). In the area covered only by pre-Wisconsinan glaciations, the drift ranges in thickness from 0 to 50 ft. The bedrock, which is exposed in a small area of Indiana and underlies the glacial debris, generally dips gently from the structural high of the Cincinnati-Kankakee arch northeast into the Michigan basin and southwest into the Illinois basin. The bedrock ranges in age from Ordovician to Pennsylvanian and is generally a carbonate clastic sequence typical of the midcontinent. The most prolific water producers in the bedrock are Silurian and Devonian carbonate rocks. In the glacial mantle, the most prolific production is associated with glacial outwash and glaciofluvial channel deposits, although some isolated sand and gravel lenses within the till also can yield large quantities of water.

Recharge to the ground-water system in Indiana is derived mainly from precipitation. Annual precipitation ranges from 36 to 44 inches (in.) and averages 38 in. An annual average of 26 in. is returned to the atmosphere by evapotranspiration, 8.5 to 9 in. is surface runoff to major streams, and 3 to 3.5 in. recharges the ground-water system (Clark, 1980).

PRINCIPAL AQUIFERS

The principal types of aquifers in Indiana are glacial outwash and glaciofluvial deposits and carbonate bedrock. Water is stored and transmitted through interconnected pores in the glacial outwash and glaciofluvial deposits and through fractures and solution features in the carbonate bedrock. The quality of ground water generally is good and is of the same quality in the two principal types of aquifers. However, the ground water is very hard [200 to 400 milligrams per liter (mg/L) as $CaCO^3$] and, in places, contains as much as 3 mg/L of iron and from 0.01 - 1.0 mg/L of manganese (Clark, 1980, p. 80). Local ground-water quality problems exist (U.S. Geological Survey, 1984, p. 123) but no widespread problems have been documented. The principal aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

GLACIAL AND GLACIOFLUVIAL AQUIFERS

Glaciofluvial Deposits and Glacial Outwash Aquifers

The major aquifers in Indiana are of glacial origin. The most prolific of these are the glaciofluvial sands and gravels associated with glacial channels and modern river systems and the outwash sands and gravels in the northeastern part of the State (see fig. 1; table 2). The largest cities that rely primarily on ground water for public supplies are South Bend and Elkhart (locations 3, 4, fig. 2); both obtain water from glacial outwash. In general, the glaciofluvial and glacial outwash

Table 2. Aquifer and well characteristics in Indiana

[Gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and the Indiana Department of Natural Resources]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Glacial and glaciofluvial aquifers:					
Glaciofluvial aquifer: Sand gravel, some clay, and silt. Generally unconfined.	20 - 60	80	100 - 500	1,500	Water calcium-magnesium bicarbonate type. Generally very hard. commonly exceeding 400 mg/L. hardness as calcium carbonate.
Glacial outwash aquifers: Mostly sand and silt, some gravel, some clay. Generally unconfined.	20 - 100	150	100 - 500	1,000	Areally extensive in northern Indiana. Water hard (exceeds 120 mg/L as calcium carbonate).
Wisconsinan till aquifer: isolated lenses of sand, gravel, and some silt. Generally surrounded in all three dimensions by silty clay and clay tills. Generally confined or at least semiconfined.	20 - 100	150	10 - 100	400	Aquifers of very local extent and not dependably present over entire area mapped in figure 1. Some isolated channels covered by till. As in other glacial and glaciofluvial aquifers in Indiana, water hard.
Carbonate bedrock aquifers:					
Mississippian aquifers: Fractured limestones. Generally unconfined.	20 - 150	175	2 - 25	100	Limestones in middle of section are most productive rocks. Section has extensively developed karst.
Silurian-Devonian aquifers: Fractured limestone of very irregular distribution. Generally confined, especially where overlain by fine-grained glacial material.	50 - 250	300	10 - 100	600	Water quality generally hard. Sulfur may be problem. Well yields generally decrease toward southeastern part of State and brines occur in northwestern corner.

aquifers are unconfined, but confining and semiconfining units, such as flowtills, commonly are located within these aquifers. The aquifers tend to be laterally discontinuous and limited in areal extent.

Wisconsinan Till Aquifer

Some isolated sand and gravel lenses within the Wisconsinan till are good aquifers, commonly producing 100 gallons per minute (gal/min). These aquifers are of very local extent.

CARBONATE BEDROCK AQUIFERS

Bedrock units in Indiana also serve as sources of water in some areas. Looking at these by geological period, certain generalities can be made.

Mississippian Aquifers

The Mississippian rocks contain a zone of limestone, in which an extensive karst terrane has developed. This limestone can produce significant quantities of water if wells intercept major solution-channel systems (Aten and others, 1982).

Silurian-Devonian Aquifers

The Silurian carbonate rocks and the overlying Devonian carbonate rocks commonly are used for small supplies but, in some areas, are capable of producing relatively large supplies of water. In Newton and Jasper Counties, these units provide water for irrigation. The water in these limestones generally is confined by overlying, fine-grained glacial material.

OTHER AQUIFERS

Pre-Wisconsinan till and loess deposits also are used locally but are not productive enough to support large withdrawals. Pennsylvanian coal-bearing rocks, Mississippian clastic rocks, and Devonian shales are poor aquifers, capable of sustaining only domestic household needs. Where local alternative ground- or surface-water supplies are not available, these rocks can yield as much as 10 gal/min of water of extremely variable quality.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The distribution of major ground-water withdrawals and trends of ground-water levels are shown in figure 2. In general, water levels in observation wells have a seasonal variation of 3 to 5 ft, with the high levels in spring and the lows in the fall. In most parts of Indiana, water levels change little from year to year.

The biggest single use of ground water in the State is for self-supplied industry, which comprises 55 percent of fresh ground-water withdrawal. Public- water supply and irrigation account for 22 and 21 percent, respectively, of the total ground-water withdrawal. In the South Bend area (St. Joseph County), 53 million gallons per day (Mgal/d) is withdrawn, of which 31 Mgal/d is for public supply. In Indianapolis (Marion County), 52 Mgal/d is withdrawn, of which 40 Mgal/d is for industrial use. Most large withdrawals are either from

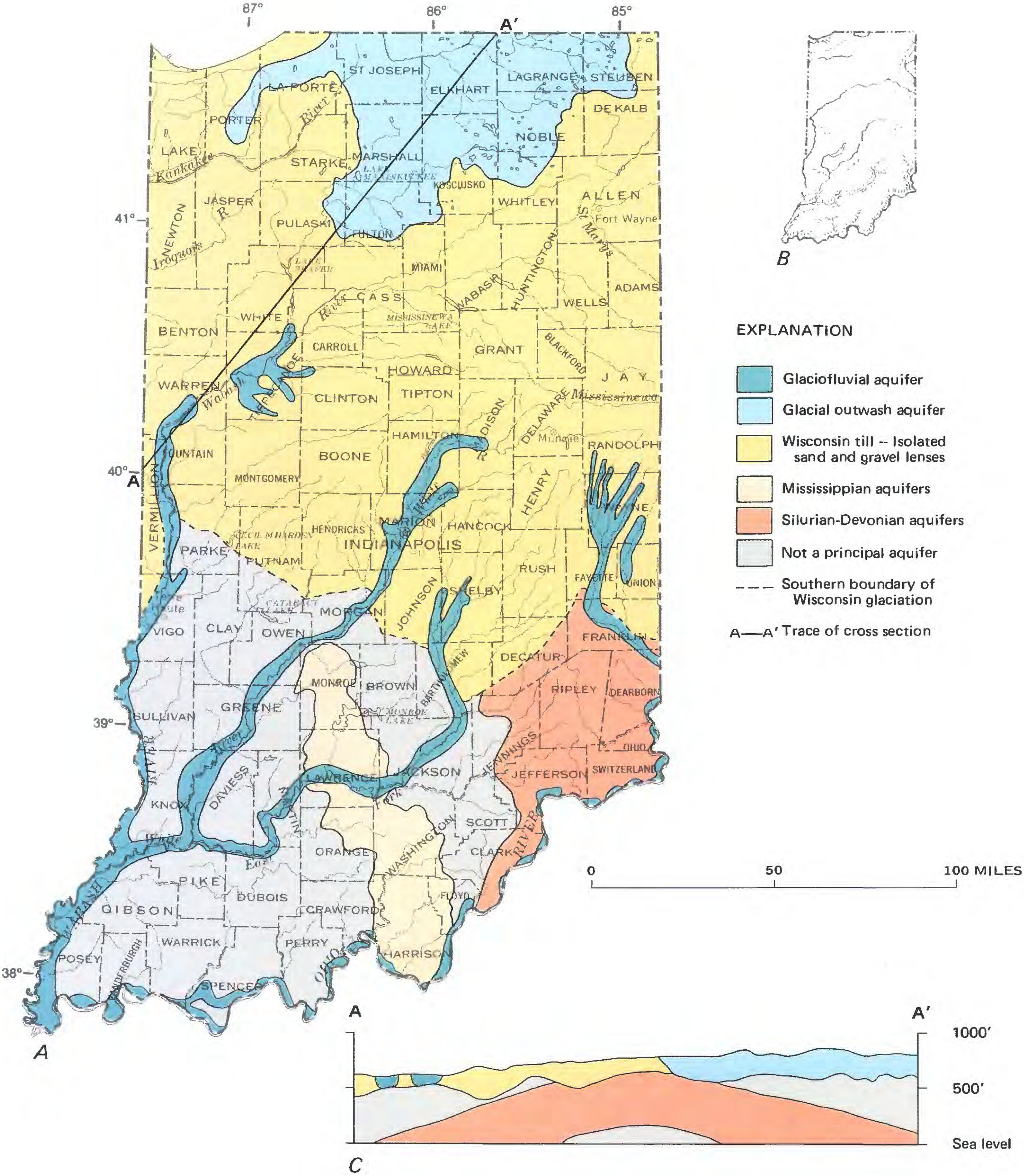


Figure 1. Principal aquifers in Indiana. *A*, Geographic distribution. *B*, Physiographic diagram. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Compiled by K. J. Banaszak from U.S. Geological Survey files. *B*, Raisz, 1954. *C*, Compiled by K. J. Banaszak from U.S. Geological Survey files.)

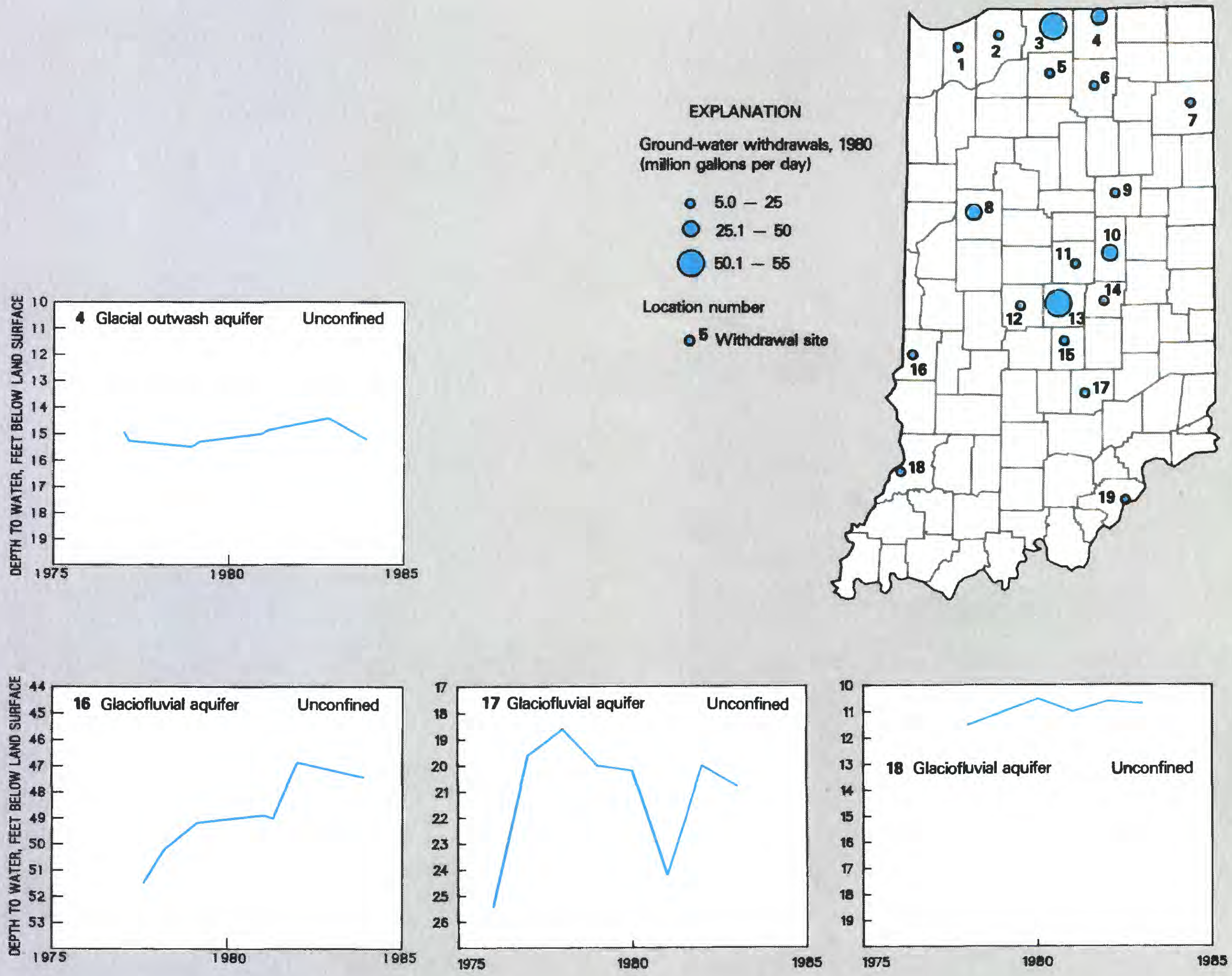
glacial outwash or glaciofluvial deposits. Heavy pumping has led to extensive cones of depression (a few square miles) locally, but, because of the very high permeability of these deposits and the amount of water available in storage, ground-water levels in most of these pumping centers have not been affected noticeably. (See hydrographs for locations 4 and 18, fig. 2.) When water levels do decline in response to pumping, as occurred in the central business district at Indianapolis, recovery is swift when pumping ceases (Meyer and others, 1975).

The trend of the annual greatest depth to ground water near location 16 (fig. 2) has been upward, probably due to a reduction in ground-water withdrawals. The graph of annual greatest depth to water near location 17 (fig. 2) shows a marked water-level decline and recovery for the period 1980–82. The decline in the yearly minimum water level probably resulted from a short period of intense pumping from nearby wells and does not indicate a long-term decline in aquifer storage. This conclusion is substantiated by the fact that yearly maximum water levels for the period 1980–82 increased 0.5 ft, and, for the period of record, yearly maximum water levels fluctuate only in a range of 2 ft.

The most severe competition for water currently has developed for withdrawals that are less than those that appear in figure 2. These withdrawals, principally for irrigation, are made from the confined Silurian–Devonian aquifer along the border of Newton and Jasper Counties. Of 7 Mgal/d withdrawn in the two counties, 4 Mgal/d is withdrawn for irrigation. Water levels in U.S. Geological Survey observation wells in the area have dropped as much as 29 ft in two months because of stress from intensive seasonal withdrawals for irrigation. The recovery of these water levels occurs more slowly, but by January recovery is apparently complete. The history of irrigation and its study in this area has not been long enough nor is the data areally comprehensive enough to make deductions about the long-term effect of irrigation withdrawals on the ground-water system. The issue, however, has been partially responsible for enactment of the Water-Resource Management Act discussed in the following section of the report.

GROUND-WATER MANAGEMENT

In 1983, Indiana enacted the Water-Resource Management Act, which established a Water Management Branch within the Division of Water in the Indiana Department of Natural Resources (Bruns, 1984). According to the Act, the most pressing and immediate need in Indiana is to establish registration for water-withdrawal facilities capable of removing more than 100,000 gallons per day (gal/d). These facilities make withdrawals from ground or surface-water sources or both. Additionally, the Branch assesses the availability of water, maintains an inventory of the significant uses of water withdrawn, and plans for development, conservation, and use of the water for beneficial uses. The assessment, for which the inventory was begun, is to be accomplished by river basin. The Water-Resource Management Act considers Indiana's water resource as unitary; that is, no distinction is made in the Act between ground and surface water. The Act has been codified as IC 13-2-6.1. Partial implementation of the Act occurred on January 1, 1984, and the Act was fully implemented on July 1, 1984.



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Porter County	Glacial outwash	Public supply, domestic, self supply.
2	LaPorte County	....do	Public supply, industrial.
3	St. Joseph County	....do	Public supply.
4	Elkhart County	....do	Do.
5	Marshall County	....do	Industrial.
6	Kosciusko County	....do	Industrial, irrigation.
7	Allen County	Silurian-Devonian	Industrial, domestic, self-supply.
8	Tippecanoe County	Glaciofluvial	Industrial, public supply.
9	Grant County	Silurian-Devonian	Public supply.
10	Madison County	Glaciofluvial	Industrial, public supply.
11	Hamilton County	....do	Industrial.
12	Hendricks County	Wisconsinan till	Do.
13	Marion County	Glaciofluvial	Do.
14	Hancock County	Silurian-Davonian	Do.
15	Johnson County	Glaciofluvial	Do.
16	Vigo County	....do	Do.
17	Bartholomew County	....do	Public supply.
18	Knox County	....do	Industrial.
19	Clark County	....do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Indiana. (Sources: Withdrawal data from Clark, 1980; water-level data from U.S. Geological Survey files.)

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Prepared by Konrad J. Banaszak

For further information contact District Chief, U.S. Geological Survey, 6023 Guion Road, Indianapolis, IN 46254

IOWA
Ground-Water Resources

Iowa has many aquifers that provide reliable sources of water for a variety of uses. In many areas of the State, ground water for rural domestic and livestock purposes can be obtained from shallow wells. Deeper and more productive aquifers, which are available under about 80 percent of the State, are used for large commercial, industrial, and public supplies.

Total water use in Iowa for 1980 was approximately 3.2 billion gallons per day (bgd). Of this total, about 2.1 bgd or 65 percent, was surface water used for thermoelectric power generation (Buchmiller and Karsten, 1983). Of the remaining 1.1 bgd, 900 million gallons per day (Mgal/d) was ground-water withdrawal, which comprised 81 percent of the total water use, excluding that used for the generation of thermoelectric power. Ground water provides water for 82 percent of the population in Iowa, 100 percent of the water used for domestic purposes in rural areas (except in some rural water districts), 71 percent of the water used by self-supplied industries, and 83 percent of the water used in irrigation projects (Buchmiller and Karsten, 1983). Ground-water withdrawals for various uses in 1980 and related statistics are given in table 1.

Table 1. Ground-water facts for Iowa

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Buchmiller and Karsten, 1983]

Population served by ground water, 1980	
Number (thousands)	2,392
Percentage of total population	82
From public water-supply systems:	
Number (thousands)	1,641
Percentage of total population	56
From rural self-supplied systems:	
Number (thousands)	751
Percentage of total population	26
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	3,200
Ground water only (Mgal/d)	900
Percentage of total	28
Percentage of total excluding withdrawals for thermoelectric power	81
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	246
Percentage of total ground water	27
Percentage of total public supply	81
Per capita (gal/d)	150
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	65
Percentage of total ground water	7
Percentage of total rural domestic	100
Per capita (gal/d)	85
Livestock:	
Ground water (Mgal/d)	193
Percentage of total ground water	22
Percentage of total livestock	100
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	320
Percentage of total ground water	36
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	13
Excluding withdrawals for thermoelectric power	71
Irrigation withdrawals:	
Ground water (Mgal/d)	76
Percentage of total ground water	8
Percentage of total irrigation	83

GENERAL SETTING

The landscape of Iowa has been shaped by successive Pleistocene glacial advances and retreats that have produced moderate relief and low elevations (fig. 1). Glaciation in north-central Iowa has produced landforms that have been relatively unmodified by stream erosion. The Des Moines Lobe is bordered by rolling hills of relatively low relief (Iowan Surface) in the northeast and by the loess-mantled Northwest Iowa Plains (Prior, 1976). South of the lobe are the flat divides and wide alluvial lowlands of the Southern Iowa Drift Plain. The Western Loess Hills, which border the Missouri River, are characterized by a narrow band of very unusual topography that developed on loess more than 200 feet (ft) thick. The only area of extensive bedrock exposure is in the Paleozoic Plateau in extreme northeastern Iowa. This region is relatively free of glacial drift and is characterized by deep valleys, high bluffs, and karst features.

A sequence of mostly sandstone, limestone, and dolomite ranging in age from Upper Cambrian through Cretaceous underlies the drift. The Paleozoic rocks have been folded to form a trough that dips gently toward the south and southwest. The Cretaceous rocks unconformably overlie the Paleozoic rocks in the west and northwest. A network of stream channels was incised into the bedrock before being buried by Pleistocene glacial drift.

The principal aquifers in Iowa are recharged by infiltration of precipitation. Normal annual precipitation (1951-80) ranges from 26 inches (in.) in the northwest to 35 in. in the southeast (P. J. Waite, State Climatologist, Des Moines, oral commun., 1984). Recharge to the water table is about 10 to 20 percent of precipitation. Some direct recharge to bedrock aquifers occurs in the Paleozoic Plateau of northeastern Iowa, although local flow systems may discharge nearly equivalent amounts, leaving a small balance for regional recharge.

PRINCIPAL AQUIFERS

The principal aquifers in Iowa are divided into two categories based on water-yielding and recharge characteristics. The first category consists of aquifers in bedrock very near the land surface and alluvial aquifers associated with major streams. The second category consists of the very productive parts of deep, artesian aquifers that are distant from their outcrop and subcrop recharge areas and are buried deeply beneath glacial drift and bedrock. Five principal aquifers are identified. They are described below and in table 2; their areal distribution is shown in figure 1. (Surficial aquifers are shown only on the cross section of figure 1 to provide more information on the plan view.)

Table 2. Aquifer and well characteristics in Iowa

[Gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Steinhilber and Horick, 1970; Horick and Steinhilber, 1973, 1978; Burkart, 1982; Horick, 1984]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Depth (ft) May exceed	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Surficial aquifers:					
Alluvial aquifers: Fine to coarse sand and gravel. Unconfined.	30 - 100	150	200 - 1,000	2,000	Alluvium along streams near State borders may yield from 1,000 to 2,000 gal/min, whereas interior stream valleys commonly yield only 200 to 300 gal/min with maximum about 2,000 gal/min. Very important source of water for public supply and industrial use. Water quality generally good; however, nitrate concentrations can exceed 10 mg/L (as nitrogen) in numerous locales. Bacteria and organic chemicals problems in selected areas.
Buried-channel aquifers: Coarse gravels. Confined.	50 - 100	200	10 - 100	500	Only of local importance in central and eastern parts of State where most productive.
Glacial-drift aquifer: Pebbly and sandy drift, sand lenses, and poorly sorted sand and gravel. Unconfined.	15 - 400	600	5 - 10	20	Important for farms and rural homes, especially in western and southern Iowa. Greatest yields in glacial outwash in north-central Iowa. Water quality is generally good; however, nitrate concentrations can be greater than 10 mg/L (as nitrogen). Bacteria and organic chemicals problems in selected areas.
Dakota aquifer: Fine to very coarse grained and poorly cemented sandstone. Confined.	100 - 600	600	100 - 250	1,000	Source of water for rural and public supply requirements in northwest and west-central Iowa. Yields of 1,500 gal/min have been obtained at Sioux City where aquifer recharged by overlying alluvium. Large concentrations of sulfate and dissolved solids present in numerous locals.
Mississippian aquifer: Limestone and dolomites. Confined.	100 - 300	500	50 - 100	900	Source of water for rural and public supply needs in north-central part of State. Smaller yields and poor quality water found in central and southeast Iowa. Water very mineralized.
Silurian-Devonian aquifer: Limestone and dolomite. Confined.	100 - 800	1,000	150 - 400	4,000	Important aquifer for meeting rural, public supply and industrial needs. In central and southern parts of State, water contains large concentrations solids.
Jordan aquifer: Dolomite and sandstone. Confined.	300 - 2,000	3,000	100 - 1,000	1,000	One of most dependable sources of water for large-capacity wells in State. Water contains in excess of 1,500 mg/L dissolved solids in southern and western parts of Iowa, but suitable for most uses in most of remainder of State.
Other aquifers:					
Dresbach aquifer: Sandstone. Confined.	400 - 1,000	2,000	50 - 1,000	2,000	Aquifer only of local importance in a few counties in eastern Iowa. However, at these locales, a very important source of water for public supply and industrial use.

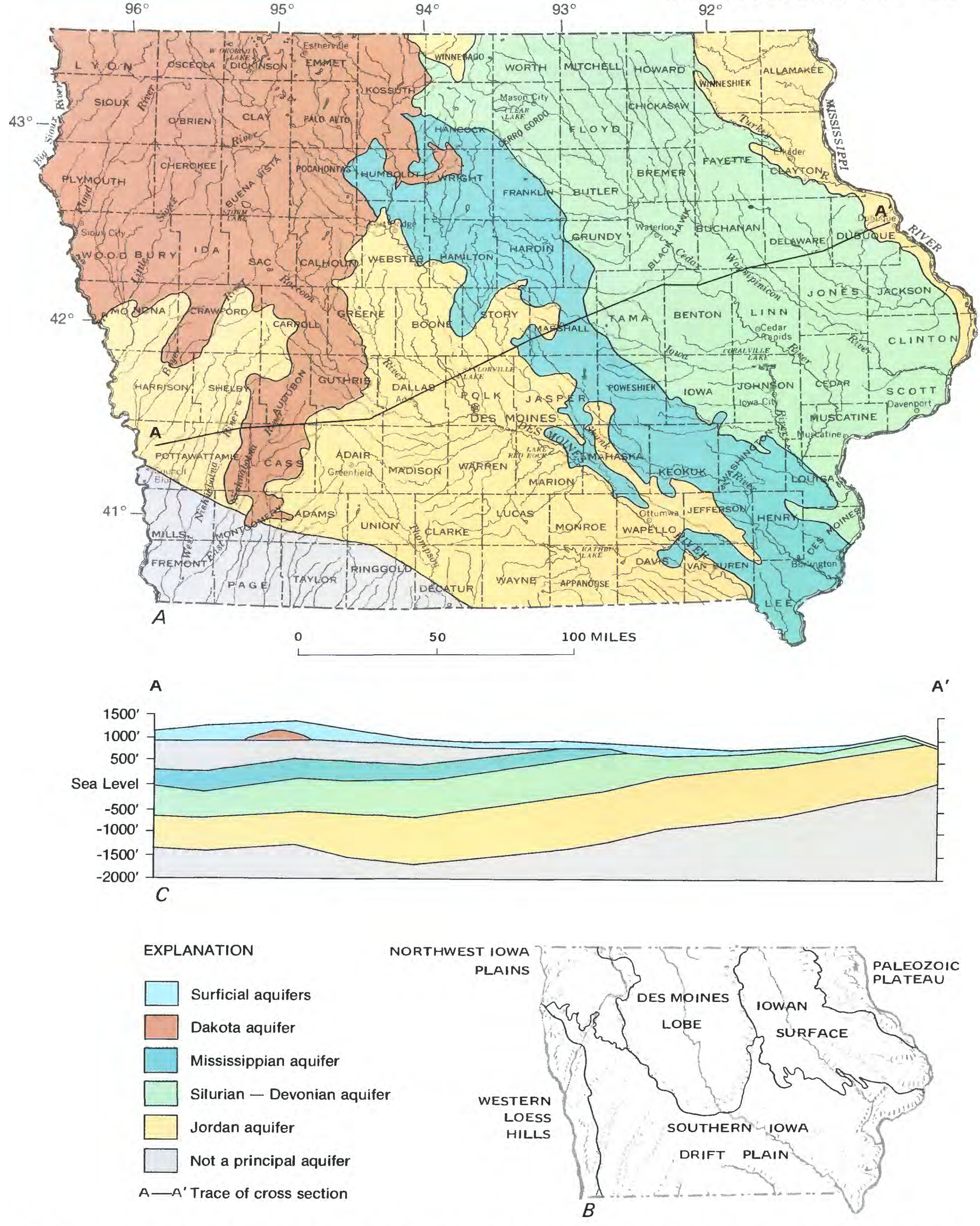


Figure 1. Principal aquifers in Iowa. *A*, Geographic distribution of most used aquifers. *B*, Physiographic diagram and divisions. *C*, Generalized cross section. (See table 2 for a more detailed detailed description of the aquifers. Sources: *A*, Hershey, 1969; Horick and Steinhilber, 1978. *B*, Raisz, 1954; Prior, 1976. *C*, Horick and Steinhilber, 1978.)

SURFICIAL AQUIFERS

The surficial aquifers are the alluvial aquifers that consist of fluvial and glaciofluvial deposits of Quaternary age beneath and adjacent to streams, the buried-channel aquifers that consist of glacial-outwash sand and gravel in bedrock channels, and the glacial-drift aquifer, a term applied to thin and discontinuous sand and gravel lenses in the glacial drift. Aquifers of this type are present throughout Iowa; consequently, their distribution is not shown in figure 1.

The alluvial flood plains and terraces of Iowa's major streams are important sources of water. These deposits are 100 to 160 ft thick along the Mississippi and Missouri Rivers and 30 to 70 ft thick along the principal interior streams. Yields from the Mississippi River alluvium range from 1,000 to 2,000 gallons per minute (gal/min). Those from the Missouri River alluvium range from 1,000 to 1,500 gal/min. Yields from the alluvium associated with major interior streams can be as much as 600 gal/min and, in some isolated instances, 2,000 gal/min has been obtained (Steinhilber and Horick, 1970).

The buried-channel aquifers occupy bedrock valleys and underlie glacial drift in the State. Although relatively unexplored, some of these valleys are known to be filled with outwash and alluvial sand-and-gravel deposits that yield from 10 to 100 gal/min. Where the buried channels are connected hydraulically to present-day streams, yields of 500 gal/min are obtainable. The buried-channel aquifers are most productive in the eastern and central parts of the State (Steinhilber and Horick, 1970).

The glacial-drift aquifer consists of lenses of sand and gravel in a till matrix. The thickness of glacial drift in Iowa ranges from 0 to 600 ft and averages about 200 ft. Yields from some wells are less than 5 gal/min. Under favorable conditions, yields of 20 gal/min can be obtained (Steinhilber and Horick, 1970).

The water quality in the alluvial and glacial-drift aquifers generally is suitable for most uses. However, concentrations of nitrate [greater than 10 milligrams per liter (mg/L)] exceed national drinking-water regulations (U.S. Environmental Protection Agency, 1982a,b) in some wells.

DAKOTA AQUIFER

The Dakota aquifer consists of sandstone of Cretaceous age. It is the primary bedrock aquifer in northwestern Iowa and is of local importance in west-central Iowa. The sandstone is fine to very coarse grained, is usually poorly cemented, and is from 10 to about 300 ft thick. Yields of more than 100 gal/min are common, but some wells can yield from 250 to 1,000 gal/min. The water is a calcium-magnesium sulfate type. In a relatively large area of northwestern Iowa, the water from the Dakota aquifer contains more than 1,500 mg/L of dissolved solids and 1,000 mg/L of sulfate. In some areas of northwestern Iowa, the Dakota aquifer contains naturally occurring concentrations of radium-226 and radium-228 in excess of 5 picocuries per liter (pCi/L). In these areas, the water may not be acceptable for domestic use, but has the potential for irrigation use, particularly on well-drained soils (Burkart, 1982).

MISSISSIPPIAN AQUIFER

The Mississippian aquifer consists mainly of limestone and dolomite and underlies about 60 percent of the State. Where it is overlain by glacial drift, the aquifer ranges in thickness from 100 to 300 ft; in the area where it is overlain by a thick sequence of Pennsylvanian and younger rocks, it has a maximum thickness of 600 ft. Yields range from 5 to 15 gal/min in domestic wells, from 25 to 50 gal/min in municipal wells in southeastern Iowa, and from 400 to 900 gal/min in municipal wells in north-central Iowa. In general, the water from the Mississippian aquifer contains more than 1,500 mg/L of dissolved solids. The dissolved-solids concentration of the water meets the recommended standard of 500 mg/L for drinking water (U.S. Environmental Protection Agency, 1982b) in a limited zone in the subcrop area. Water from Mississippian rocks may be of acceptable quality for most other uses in an additional zone of limited dimension southwest of the subcrop area (Steinhilber and Horick, 1970; Horick and Steinhilber, 1973).

SILURIAN-DEVONIAN AQUIFER

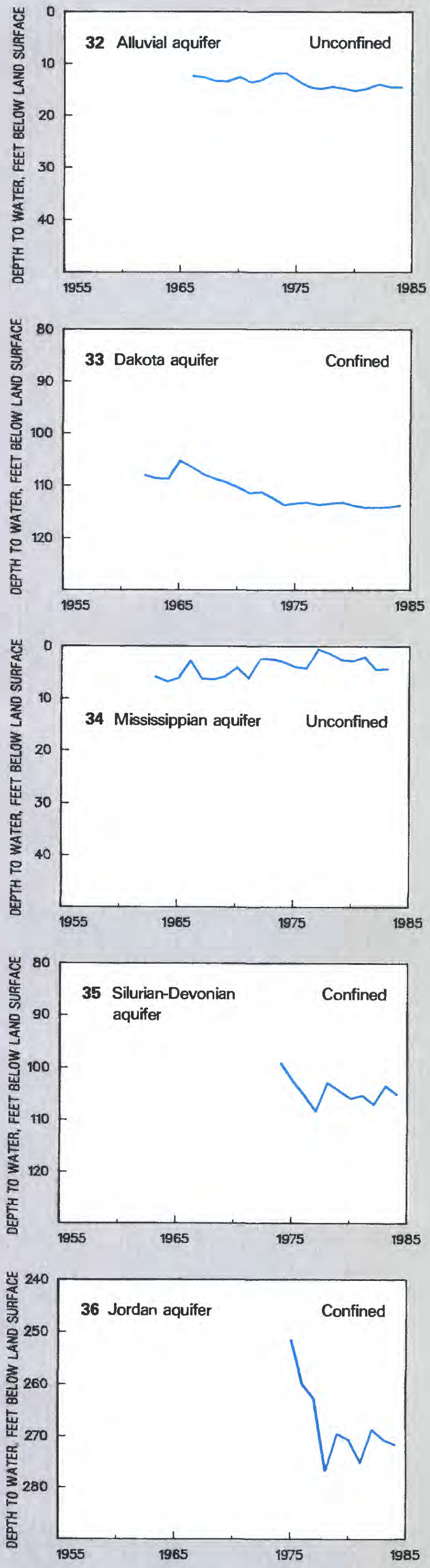
The Silurian-Devonian aquifer underlies about 90 percent of the State. Generally, this aquifer is 500 to 600 ft thick in the southwestern part of the State and 200 to 400 ft thick in the eastern and northern parts. The aquifer consists of dense limestone and dolomite and is very permeable as a result of extensive fracturing and enlargement of rock opening by solution. Most domestic wells yield at least 10 to 30 gal/min, whereas yields of 150 to 400 gal/min are common from public-supply wells. The aquifer is not used south and west of a line from Muscatine County northwest to Calhoun County and north to the Minnesota border. In the central and southern parts of the State, the water contains sulfate in excess of 500 mg/L, and dissolved-solids concentration exceeds 1,000 mg/L (Steinhilber and Horick, 1970; Horick, 1984). A sinkhole topography has developed where the aquifer material is exposed at or near land surface in northeast Iowa. The aquifer is particularly susceptible to surface contamination in this area.

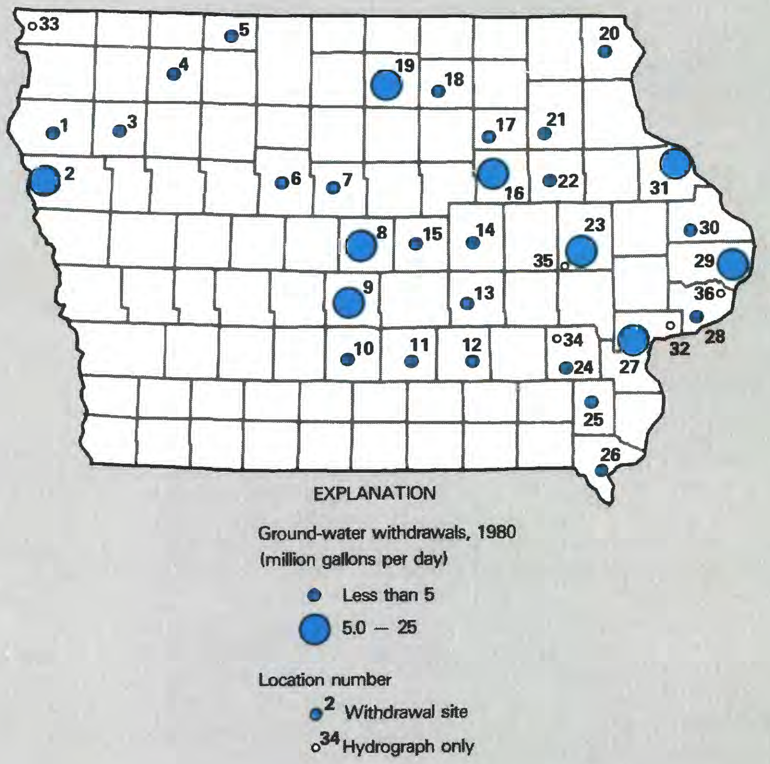
JORDAN AQUIFER

The Jordan aquifer consists of the Jordan Sandstone of Late Cambrian age and dolomite and sandstone of the Prairie du Chien Group of Early Ordovician age. The aquifer generally is 400 to 500 ft thick. It increases in thickness from 250 ft in northwestern Iowa to more than 800 ft in the southwestern part of the State. Extensive use is made of the aquifer by municipalities and industries in the eastern three-fourths of the State. Yields from wells range from 100 to 300 gal/min in the southwest to about 1,000 gal/min in the northeastern and central parts of the State. The water in the aquifer in northwestern Iowa is a calcium-magnesium bicarbonate type. In north-central, central, and southeastern Iowa, the water contains about equal quantities of the major ions. In western Iowa, the water in the Jordan aquifer contains greater proportions of chloride and sulfate than in other areas. Some water supplies from the Jordan contain naturally occurring radium-226 and radium-228 in excess of 5 pCi/L (Steinhilber and Horick, 1970; Horick and Steinhilber, 1978). Several communities in southern Iowa use the Jordan as an auxiliary supply of water. This aquifer, however, is not used in Missouri, just south of Iowa.

DRESBACH AQUIFER

The Dresbach aquifer, of Cambrian age, overlies rocks of Precambrian age and consists of a sequence of fine- to coarse-grained sandstone. This aquifer is only of local importance in a few counties in northeast and east-central Iowa where it yields 2,000 to 3,000 gal/min. It is not used elsewhere in Iowa because of small yields (50 gal/min) and concentrations of dissolved solids exceeding 1,500 mg/L (Steinhilber and Horick, 1970). The area where this aquifer is used is too small to be included in figure 1.





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Le Mars.	Dakota	Municipal.
2	Metropolitan Sioux City.	Dakota, alluvial	Do.
3	Cherokee.	Dakota	Do.
4	Spencer.	Jordan	Industrial.
5	Esterville	. . . .do	Municipal.
6	Fort Dodge-Duncombe.	. . . .do	Municipal, industrial.
7	Webster City. . . .	. . . .do	Municipal.
8	Ames	Alluvial.	Do.
9	Metropolitan Des Moines.	Alluvial, Jordan	Do.
10	Indianola.	Jordan	Do.
11	Knoxville.	. . . .do	Do.
12	Oskaloosa	Alluvial.	Do.
13	Grinnell	Jordan	Do.
14	Tama-Toledo . . .	. . . .do	Municipal, industrial.
15	Marshalltown . . .	Alluvial.	Municipal.
16	Waterloo-Cedar Falls.	Silurian-Devonian	Do.
17	Waverly.	Jordan, Silurian-Devonian.	Do.
18	Charles City	Silurian-Devonian	Do.
19	Mason City.	Jordan	Municipal, industrial.
20	Waukon-Postville.	. . . .do	Do.
21	Oelwein	Jordan, Silurian-Devonian.	Municipal.
22	Independence . . .	Silurian-Devonian	Do.
23	Cedar Rapids-Marion.	Alluvial, Jordan, Silurian-Devonian.	Municipal, industrial.
24	Washington	Jordan	Municipal.
25	Mt. Pleasant	. . . .do	Do.
26	Fort Madison . . .	Alluvial.	Do.
27	Muscatine	. . . .do	Municipal, industrial.
28	Davenport	Jordan	Industrial.
29	Clinton	Dresbach	Municipal, industrial.
30	Maquoketa-Preston.	Dresbach, Jordan	Do.
31	Dubuque	Dresbach, alluvial	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Iowa. (Sources: Withdrawal data from Buchmiller and Karsten, 1983; Horick, 1984; water-level data from U.S. Geological Survey files.)

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The distribution of principal ground-water withdrawals is shown in figure 2. The major areas of pumpage are in north-central, central, and east-central Iowa. In the alluvial aquifers that are hydraulically connected to streams, only small, long-term water-level declines have been recorded. To date, large withdrawals from the Mississippi River alluvium have not caused a general decline in water levels (Hansen and Steinhilber, 1977). An annual long-term regional water-level decline of about 0.3 ft in the Dakota aquifer in northwestern Iowa was noted by Burkart (1982). Periodically, larger water-level declines may occur in the Dakota aquifer, as shown by the hydrograph from location 33. Most wells in the Mississippian aquifer are located in areas where the aquifer underlies drift. Water levels away from pumping centers reflect changes in local recharge over time. Figure 2 includes a hydrograph from a water-table well in the Mississippian aquifer (location 34) and water-level changes in the Silurian-Devonian aquifer (location 35). Water-level changes due to pumping depend, in part, on aquifer permeability; for example, the water level in a well in Webster County that yields only 75,000 gallons per day (gal/d) from the Silurian-Devonian aquifer declined 61 ft in a little more than 30 years. In Linn County (location 23), however, water levels in industrial wells that pump large quantities of water from a more permeable part of the aquifer have declined only 27 to 30 ft since 1940 (Horick, 1984). Since the late 1800's, the potentiometric surface of the Jordan aquifer has declined from 50 to 100 ft regionally and from 175 to 200 ft at the major pumping centers (location 6, 19) (Horick and Steinhilber, 1978). The hydrograph (location 36) shown in figure 2 represents regional water-level declines for the Jordan aquifer.

GROUND-WATER MANAGEMENT

Laws regarding ground-water management in Iowa are found in the Code of Iowa, Chapter 455B; rules regarding ground-water management are in Chapter 900, Iowa Administration Code. These laws and rules are administered by the Iowa Department of Water, Air, and Waste Management. Under the authority of this agency, ground-water-withdrawal permits are granted, restrictions on withdrawals are enforced, and ground-water injection is regulated. The Iowa Geological Survey is the State's manager of water-resource information and supports various activities that assess the ground-water conditions in the State. The University of Iowa Hygienic Laboratory system is responsible for analysis of the quality of community supplies.

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Prepared by Richard A. Karsten and Michael R. Burkart

For further information contact District Chief, U.S. Geological Survey, P.O. Box 1230, Iowa City, IA 52244

KANSAS
Ground-Water Resources

Kansans rely on ground-water resources for public, rural, industrial, and irrigation water supplies. In the western two-thirds of the State, abundant ground-water resources provide most of the water supplies. Ground-water resources are limited in the eastern one-third of the State and surface-water resources provide most of the water supplies in that area.

Ground water supplies about 5.6 billion gallons per day (bgd), or 85 percent of the water used in Kansas. Public and rural systems provide ground water to almost 1.2 million people (about 49 percent of the State's population). Approximately 93 percent of the ground water withdrawn (5.2 bgd) is used for irrigation. Ground-water withdrawals during 1980 for selected uses and related statistics are given in table 1. Additional water-use data are available from the Kansas Water Office.

GENERAL SETTING

Ground-water conditions differ with physiography and geology. Physiographic provinces in Kansas (fig. 1) are the Osage Plains and Dissected Till Plains sections of the Central Lowlands province, the Ozark Plateaus province, and the Great Plains province (Fenneman, 1946).

The Osage and Dissected Till Plains and the Ozark Plateaus annually receive from 30 to 45 inches (in.) of precipitation. Although rain provides an abundant source of recharge, geology determines the availability of ground water. Pennsylvanian and Permian rocks (shale, limestone, and sandstone) crop out in the Osage Plains and dip toward the northwest. Glacial drift (clay, silt, sand, gravel, and boulders) of Pleistocene age mantles large areas of Pennsylvanian and Permian rocks in the Dissected Till Plains. Weathered and sandy dolomite of Cambrian and Ordovician age underlie the Ozark Plateaus at depths of 300 feet (ft) or more and dip towards the northwest.

The Great Plains receives from 15 to 30 in. of rainfall annually, and recharge is limited in the western part. Cretaceous rocks (shale, sandstone, limestone, and chalk) crop out in the northeast one-quarter of the area and dip toward the northwest. Cenozoic deposits (clay, silt, sand, and gravel) as much as 500 ft thick overlie Cretaceous rocks in the remainder of the area. Alluvial deposits (clay, silt, sand, and gravel) of Quaternary age are present in major river valleys throughout the State.

PRINCIPAL AQUIFERS

Principal aquifers in Kansas consist of two types—unconsolidated gravel, sand, silt, and clay, and consolidated sandstone, limestone, and dolomite. The principal aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

ALLUVIAL AQUIFERS

The Kansas River alluvial aquifer is an important source of water along the common border of the Osage and Dissected Till Plains. The aquifer consists of unconsolidated fluvial deposits of Quaternary age and is unconfined. Wells typically yield more than 500 gallons per minute (gal/min). The water generally is a calcium bicarbonate type that is suitable for most uses. Concentrations of iron commonly exceed 0.3 milligrams per liter (mg/L), and concentrations of manganese can exceed 0.05 mg/L.

In the Great Plains, wells developed in unconfined alluvial aquifers of the Arkansas, Republican, and Pawnee River valleys generally yield more than 500 gal/min. The water generally is a calcium bicarbonate type that is suitable for most uses. Locally, concentrations of dissolved solids greater than 500 mg/L, chloride greater than 250 mg/L, and nitrate greater than 10 mg/L can result from discharge of saline water from underlying bedrock, contamination from oilfields, and agricultural practices. Naturally occurring concentrations of selenium greater than 0.01 mg/L and gross-alpha radioactivity

Table 1. Ground-water facts for Kansas

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day]

Population served by ground water, 1980[1]	
Number (thousands)	1,153
Percentage of total population	49
From public water-supply systems:	
Number (thousands)	903
Percentage of total population	38
From rural self-supplied systems:	
Number (thousands)	250
Percentage of total population	11
Freshwater withdrawals, 1980[2]	
Surface water and ground water, total (Mgal/d)	6,600
Ground water only (Mgal/d)	5,600
Percentage of total	85
Percentage of total excluding withdrawals for thermoelectric power	89
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	140
Percentage of total ground water	3
Percentage of total public supply	48
Per capita (gal/d)	155
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	25
Percentage of total ground water	0.4
Percentage of total rural domestic	86
Per capita (gal/d)	100
Livestock:	
Ground water (Mgal/d)	35
Percentage of total ground water	0.6
Percentage of total livestock	43
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	190
Percentage of total ground water	3
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	35
Excluding withdrawals for thermoelectric power	77
Irrigation withdrawals:	
Ground water (Mgal/d)	5,200
Percentage of total ground water	93
Percentage of total irrigation	92

[1] Total population from Murray (1982); population served by public water-supply systems from Solley, Chase, and Mann (1983); population served by rural water-supply systems from U.S. Bureau of the Census (1983).
[2] Data from Solley, Chase, and Mann (1983). Rural domestic supplies estimated from data in U.S. Bureau of the Census (1983).

Table 2. Aquifer and well characteristics in Kansas

[Gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Kansas agencies]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Alluvial aquifers: Quaternary fluvial deposits of clay, silt, sand, and gravel. Generally unconfined.	10 - 150	10 - 500	1,000	Well yields in Kansas, Arkansas, Republican, and Pawnee River valleys exceed 500 gal/min. Wells in other valleys usually yield less than 100 gal/min. Locally, water from alluvial aquifers can have large concentrations of dissolved solids, chloride, sulfate, nitrate, iron, and manganese. Large concentrations of selenium and naturally occurring gross-alpha radioactivity sometimes occur in water from northern part of Great Plains.
Glacial-drift aquifer: Pleistocene glacial deposits of clay, silt, sand, and gravel. Generally unconfined.	10 - 300	10 - 100	500	Water from shallow wells generally a calcium bicarbonate type with less than 500 mg/L dissolved solids, but large concentrations of nitrate can occur. Water from deep wells can have large concentrations of dissolved solids, chloride, sulfate, iron, or manganese.
High Plains aquifer: Fluvial and eolian deposits of clay, silt, sand, and gravel of Cenozoic age. Generally unconfined.	10 - 450	500 - 1,000	1,500	Water generally a calcium bicarbonate type with concentrations of dissolved solids less than 500 mg/L, but large concentrations of fluoride and selenium can occur in northern Great Plains. Provides water supplies for Dodge City, Garden City, Great Bend, Pratt, Hutchinson, McPherson, Wichita, and most other towns in Great Plains.
Great Plains aquifer: Dakota and Cheyenne Sandstones of Cretaceous age. Generally unconfined.	20 - 200	10 - 100	1,000	Water quality variable. Calcium bicarbonate type water with less than 500 mg/L of dissolved solids produced where the aquifer is exposed. Sodium bicarbonate or sodium chloride type water with large concentrations of dissolved solids is produced west and north of the surface exposure. Large concentrations of iron occur in water from some wells. Some wells in Finney, Ford, and Hodgeman Counties can yield more than 1,000 gal/min.
Chase and Council Grove aquifer: Limestones of Chase and Council Grove Groups of Permian age. Generally unconfined.	20 - 200	10 - 20	200	Water generally a calcium bicarbonate type with concentrations of dissolved solids less than 500 mg/L. Water from some wells can have large concentrations of sulfate. Wells in Butler and Cowley Counties can produce water with large concentrations of dissolved solids. Concentrations of dissolved solids and chloride large west of the surface exposure, and water is not used.
Douglas aquifer: Channel sandstone of Pennsylvanian age. Generally unconfined.	5 - 400	10 - 40	100	Water ranges from a calcium bicarbonate type, with less than 500 mg/L of dissolved solids where aquifer is exposed, to a sodium bicarbonate or sodium chloride type, with large concentrations of dissolved solids at depth or west of surface exposure. Concentrations of fluoride may be large. Equivalent to Vamoosa-Ada aquifer in Oklahoma.
Ozark aquifer: Weathered and sandy dolomites of Arbuckle Group. Cambrian and Ordovician age. Confined.	500 - 1,800	30 - 150	500	Water generally a calcium bicarbonate type with less than 500 mg/L of dissolved solids in the Ozark Plateaus and in extreme southeast corner of the Osage Plains. Sodium bicarbonate chloride or sodium chloride type water with large concentrations of dissolved solids is produced in rest of Osage Plains. Hydrogen sulfide gas, or large concentrations of gross-alpha radioactivity or iron, can occur in water from some wells. Equivalent to Roubidoux aquifer in Oklahoma.

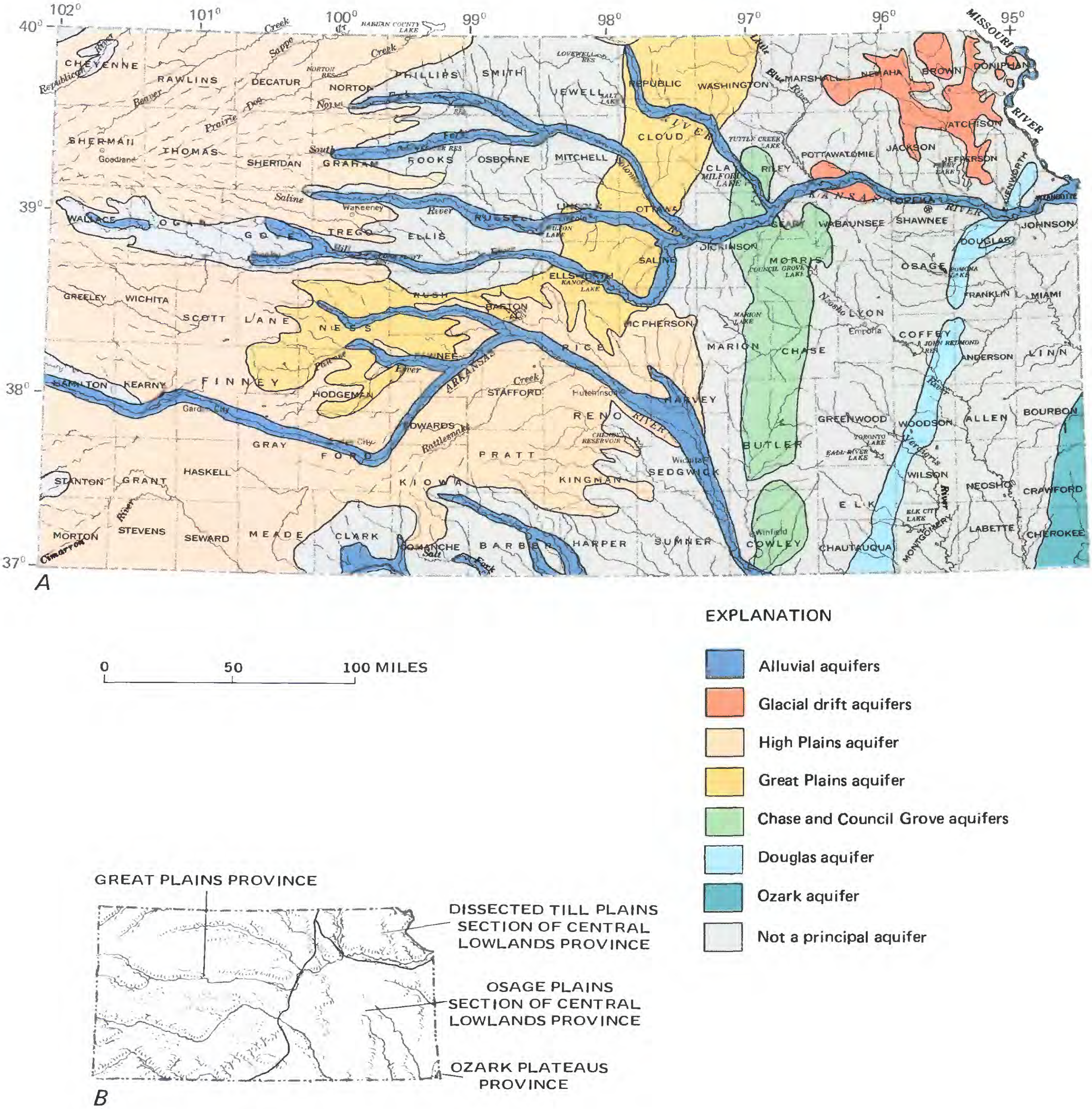


Figure 1. Principal aquifers in Kansas. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. (See table 2 for more detailed descriptions of the aquifers. Sources: *A*, Bayne, 1975; Luckey and others, 1981. *B*, Fenneman, 1946; Raisz, 1954.)

greater than 15 picocuries per liter (pCi/L) commonly are present in water from alluvial aquifers in the northern Great Plains.

Glacial-Drift Aquifer

The glacial-drift aquifer is a major source of water in the Dissected Till Plains. The aquifer consists of unconsolidated glacial deposits of Pleistocene age and generally is unconfined. Wells yield from 10 to about 500 gal/min. Shallow wells generally produce a calcium bicarbonate water that is suitable for most uses, but nitrate concentrations can exceed 10 mg/L. Deep wells can produce very mineralized water with concentrations of dissolved solids greater than 500 mg/L, sulfate and chloride greater than 250 mg/L, and iron exceeding 0.3 mg/L.

High Plains Aquifer

The High Plains aquifer is the most important and extensively used aquifer in Kansas. The aquifer consists of thick unconsolidated fluvial and eolian deposits of Cenozoic age and generally is unconfined. The aquifer is present in nearly three-fourths of the Great Plains. Wells yield from 500 to about 1,500 gal/min. The water generally is a calcium bicarbonate type that is suitable for most uses. Concentrations of fluoride greater than 1.4 mg/L and selenium greater than 0.01 mg/L are present in some water from northern parts of the High Plains aquifer.

Great Plains Aquifer

The Great Plains aquifer is a major source of water in the northeastern quarter of the Great Plains, where the aquifer material is exposed at the land surface, and in the southern part of the Great Plains, where it is exposed or is directly overlain by Cenozoic deposits. The aquifer consists of the Dakota and Cheyenne Sandstones of Cretaceous age and generally is unconfined. Wells yield from 10 to 100 gal/min in the northeast to more than 1,000 gal/min in the south. The water generally is a calcium bicarbonate type in areas where the aquifer is unconfined. However, sodium and chloride concentrations increase with depth, and the water is not used northwest of the area shown in figure 1. Some wells yield water with concentrations of iron exceeding 0.3 mg/L.

Chase and Council Grove Aquifer

The Chase and Council Grove aquifer is a major source of water where it is exposed in the Osage Plains. The aquifer consists of limestones of the Chase and Council Grove Groups of Permian age. Well yields range from 10 to about 200 gal/min. The water generally is a calcium bicarbonate type that is suitable for most uses, although concentrations of sulfate exceed 250 mg/L locally. The water is very mineralized (dissolved-solids and chloride concentrations exceed 500 mg/L and 250 mg/L, respectively) west of the area shown in figure 1 and is not used.

Douglas Aquifer

The Douglas aquifer is a source of water where it is exposed in the Osage and Dissected Till Plains. The aquifer consists of channel sandstone of the Douglas Group of Pennsylvanian age. In these areas, the aquifer generally is unconfined, and wells yield from 10 to about 100 gal/min. The water generally is a calcium bicarbonate type that is suitable for most uses. Some wells produce water with fluoride concentrations that exceed 1.4 mg/L. As in the case of the Chase and Council Grove aquifer, west of the area shown in figure 1, the water is not used because of its high mineral content.

Ozark Aquifer

The Ozark aquifer is the major source of ground water in the Ozark Plateaus. The aquifer consists of weathered and sandy dolomites of the Arbuckle Group of Cambrian and Ordovician age and is confined. The aquifer does not crop out in Kansas; at the shallowest point, it is 300 ft below land surface. Wells yield from 30 to about 500 gal/min. The water generally is a calcium bicarbonate type that is suitable for most uses. Water in some wells contains excessive concentrations of iron (greater than 0.3 mg/L) and naturally occurring gross-alpha radioactivity (greater than 15 pCi/L) (Spruill, 1983). In the Osage Plains, water from the Ozark aquifer becomes very mineralized with depth and toward the northwest, and hydrogen sulfide gas may be present. The water is not used west of the area shown in figure 1.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

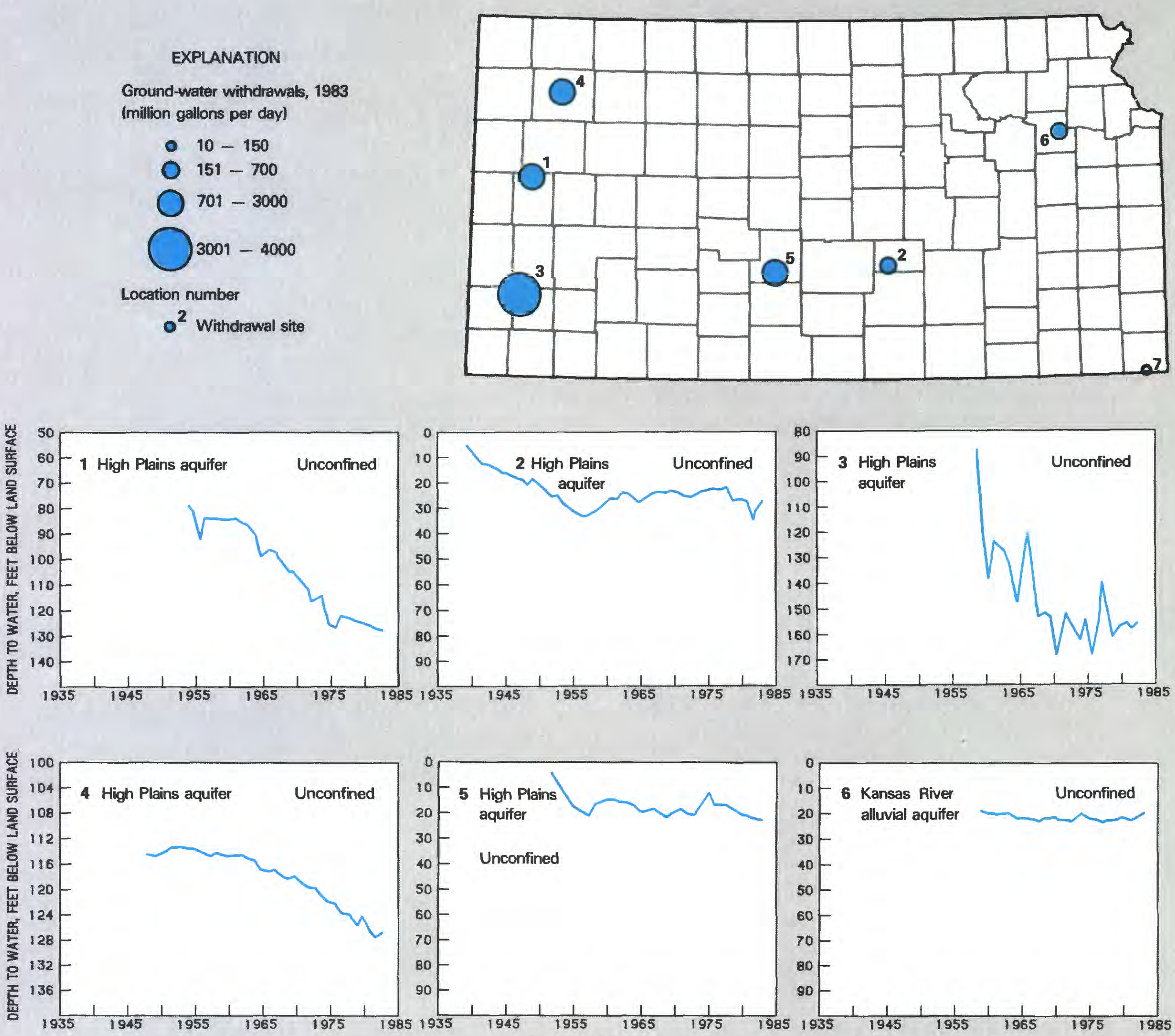
Although ground water is withdrawn throughout the State, seven major pumping centers produce most of the water. At locations 1 to 5 (fig. 2), water is withdrawn from the High Plains aquifer. These five pumping centers are Ground-water Management Districts (GMD's), which are political subdivisions of the State government locally organized to manage ground-water resources. Location 6 is the Kansas River valley in northeast Kansas. At location 7, water is withdrawn from the Ozark aquifer in southeast Kansas. Ground-water withdrawals are estimated from water rights granted by the Kansas State Board of Agriculture, Division of Water Resources. Estimates for pumping centers at locations 1 to 5 were provided by the GMD's. Estimates for pumping centers at locations 6 and 7 were obtained from unpublished data of the Kansas Division of Water Resources.

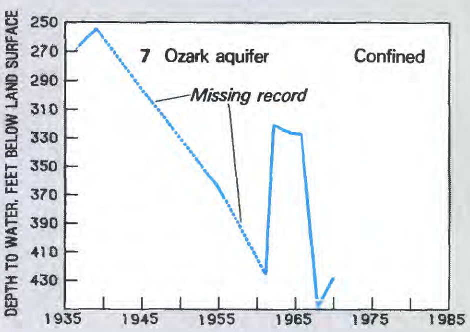
Approximately 710 million gallons per day (Mgal/d) of water is withdrawn from the High Plains aquifer at location 1 (fig. 2) which includes parts of Wallace, Greeley, Wichita, Scott, and Lane Counties. Because recharge is insufficient to replenish ground water withdrawn for irrigation, water levels had declined from 10 to 100 ft by 1980 (Luckey and others, 1981). The hydrograph shows that the greatest rate of water level decline occurred from about 1962 through 1975.

At location 2 (fig. 2), which includes parts of McPherson, Harvey, Reno, and Sedgwick Counties, approximately 190 Mgal/d of water is withdrawn from the High Plains aquifer. Although ground water is used extensively for irrigation and public supplies, recharge from precipitation generally had prevented water levels from declining more than 10 ft by 1980 (Luckey and others, 1981). The largest decline, about 30 ft, has occurred in the well field of the city of Wichita. The hydrograph from the Wichita well field (location 2, fig. 2) shows that the water level declined rather sharply from 1939 until 1957. The relative stability of water levels since about 1960 is primarily the result of decreased pumpage due to the increased use of surface water for public supplies.

Approximately 3.3 bgd of water is withdrawn from the High Plains aquifer at location 3 (fig. 2) which includes Stanton, Morton, Grant, Stevens, Haskell, Seward, Gray, Ford, and parts of Hamilton, Kearny, Finney, Hodgeman, and Meade Counties. Because precipitation is insufficient to replenish ground water withdrawn for irrigation, water levels had declined more than 150 ft in parts of the area by 1980 (Luckey and others, 1981). The hydrograph (location 3, fig. 2) shows that the greatest rate of decline occurred from about 1955 through 1970.

Approximately 920 Mgal/d of water is withdrawn from the High Plains aquifer at location 4 (fig. 2), which includes





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Western Kansas, Ground-water Managemant District 1.	High Plains. . . .	Irrigation, public supply.
2	Equus Beds, Groundwater Managament District 2.	. . . .do	Do.
3	Southwest Kansas, Ground-water Management District 3.	. . . .do	Do.
4	Northwest Kansas, Ground-watar Management District 4.	. . . .do	Do.
5	Big Bend, Groundwater Management District 5.	. . . .do	Do.
6	Kansas River valley, northeast Kansas.	Kansas River alluvial.	Irrigation, industrial.
7	Southeast Kansas	Ozark.	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Kansas. (Sources: Withdrawal data from Groundwater Management Districts 1-5 and Kansas State Board of Agriculture, Division of Water Resources; water-level data from U.S. Geological Survey.)

Sherman, Thomas, Sheridan, and parts of Cheyenne, Rawlins, Decatur, Graham, Wallace, Logan, and Gove Counties. Although ground water is withdrawn for irrigation in this area and precipitation provides little recharge, irrigation began later and is not developed as extensively as in other High Plains pumping centers. Ground-water levels in this area had declined generally less than 50 ft by 1980 (Luckey and others, 1981). The hydrograph (location 4, fig. 2) shows that the greatest rate of water-level decline occurred from about 1970 through 1983.

Approximately 910 Mgal/d of water is withdrawn from the High Plains aquifer at location 5 (fig. 2), which includes Stafford, Pratt, and parts of Kiowa, Edwards, Pawnee, Barton, Rice, and Reno Counties. Ground water is used extensively for irrigation, but increased recharge and decreased pumping during wet years can raise water levels significantly, as indicated by the well hydrograph (location 5, fig. 2). Ground-water levels in this area had declined generally less than 10 ft by 1980 (Luckey and others, 1981). However, declines of 25 ft have been observed locally.

Approximately 230 Mgal/d of water is withdrawn from the Kansas River alluvial aquifer at location 6 (fig. 2), which includes the Kansas River valley in Geary, Riley, Wabaunsee, Pottawatomie, Shawnee, Douglas, Jefferson, Johnson, Leavenworth, and Wyandotte Counties. Although ground water is used for irrigation and industrial supplies, increased recharge from precipitation and streamflow has kept water levels from declining significantly (location 6, fig. 2).

Approximately 14 Mgal/d of water is withdrawn from the Ozark aquifer in location 7 (fig. 2), which includes parts of Cherokee, Crawford, and Bourbon Counties. Although the quantity of ground water withdrawn from this area is considerably less than that from other areas, recharge has not increased because of confined conditions, and water levels have declined locally as much as 200 ft, based on predevelopment and 1980 potentiometric-surface maps (MacFarlane and others, 1981).

GROUND-WATER MANAGEMENT

Kansas has five State agencies and one type of local State government unit with major responsibilities for managing ground water. The Kansas Water Office is the water planning, policy, and coordination agency for the State (Kansas Statutes Annotated (K.S.A.) 74-2605 et seq.). It prepares State plans for water-resource management, conservation, and development. The Kansas Water Authority, a part of the Kansas Water Office (K.S.A. 74-2605 et seq.), is responsible for advising the Governor, Legislature, and Director of the Kansas Water Office on water-policy issues.

The Kansas State Board of Agriculture, Division of Water Resources, administers laws (K.S.A. 82a-701 et seq.) related to the conservation and use of water resources, including appropriation of ground water and assisting with the organization of Groundwater Management Districts.

The Kansas Department of Health and Environment, Division of Environment, has regulatory authority over matters dealing with water pollution (K.S.A. 65-161 et seq., K.S.A. 55-1003 et seq., K.S.A. 82a-1035 through 1038, and K.S.A. 82a-1201 et seq.). This agency is responsible for collecting, analyzing, and interpreting ground-water-quality data; developing water-quality-management plans; and responding to emergency water-pollution problems.

The Kansas Corporation Commission has a mandate (K.S.A. 55-115 et seq.) to protect fresh ground-water supplies from adverse effects of mineral-development activities.

The Kansas Geological Survey conducts ground-water research, including the collection, analysis, and interpretation of ground-water-quantity and quality data (K.S.A. 76-322, 76-2610, 82a-903, 55-128).

Groundwater Management Districts (GMD), locally managed political subdivisions of the State, have been formed as a result of the Groundwater Management District Act of 1972 (K.S.A. 82a-1020, et seq.). There are currently five GMD's in Kansas: District 1, western Kansas; District 2, Equus beds; District 3, southwest Kansas; District 4, northwest Kansas; and District 5, Big Bend. Each District is charged with managing ground-water resources within its boundaries.

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Prepared by Hugh E. Bevans, Timothy B. Spruill, and Joan F. Kenny

For further information contact District Chief, U.S. Geological Survey, 1950 Constant Avenue, Campus West, Lawrence, KS 66046

KENTUCKY
Ground-Water Resources

Ground water is an important resource in Kentucky. Excluding water used for power generation, about 22 percent of the water use in the State is from ground-water sources. About 31 percent of the population is served by ground water. In large karst areas in the central part of the State where streams are sparse, ground water is the only source of supply. In rugged areas in the coal fields, residents depend on ground water because surface flows generally are not reliable. Ground-water withdrawals for various uses in 1980 and related statistics are given in table 1.

Kentucky is located in three physiographic provinces—the Coastal Plain, Interior Low Plateaus, and Appalachian Plateaus. The Coastal Plain province and the major river valleys are underlain by unconsolidated deposits. The rest of the State is underlain by consolidated sedimentary rocks.

Recharge to the ground-water system in Kentucky is derived mostly from precipitation. Average annual precipitation (1948–77) ranges from about 40 inches (in.) in the northern part of the State to about 52 in. in the south-central and southeastern parts. Recharge rates differ according to geology and land forms but average about 9 percent of the precipitation.

Table 1. Ground-water facts for Kentucky

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Mull and Lee, 1984]

Population served by ground water, 1980	
Number (thousands)	1,145
Percentage of total population	31
From public water-supply systems:	
Number (thousands)	363
Percentage of total population	10
From rural self-supplied systems:	
Number (thousands)	782
Percentage of total population	21
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	4,600
Ground water only (Mgal/d)	180
Percentage of total	4
Percentage of total excluding withdrawals for thermoelectric power	22
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	48
Percentage of total ground water	26
Percentage of total public supply	13
Per capita (gal/d)	132
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	39
Percentage of total ground water	21
Percentage of total rural domestic	91
Per capita (gal/d)	50
Livestock:	
Ground water (Mgal/d)	2
Percentage of total ground water	1
Percentage of total livestock	5
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	93
Percentage of total ground water	51
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2
Excluding withdrawals for thermoelectric power	25
Irrigation withdrawals:	
Ground water (Mgal/d)	0.3
Percentage of total ground water	.2
Percentage of total irrigation	6

PRINCIPAL AQUIFERS

Aquifers consist mostly of unconsolidated sand, gravel, silt, and clay in the Coastal Plain province and in the alluvial aquifer along the rivers and of sandstone in the Appalachian Plateaus province. Aquifers consist mostly of sandstone in the coal field of the Interior Low Plateaus province and mostly of limestone in the remainder of that province in Kentucky. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

ALLUVIAL AQUIFER

The alluvial aquifer along the Ohio River is by far the most intensively used aquifer in Kentucky. Many towns and industries located along the river depend upon large surface supplies from the river and on ground-water supplies from shallow wells in the alluvium. Properly constructed wells near the river can induce infiltration of streamflow, which ensures dependable supplies (Gallaher and Price, 1965, p. 2). The quality of water in the alluvium generally is suitable for most uses but may need to be treated for excessive hardness and iron for some uses. Hardness commonly exceeds 300 milligrams per liter (mg/L) as calcium carbonate, and iron concentration commonly exceeds 1 mg/L. Contamination of the aquifer by wastes from industrial sites and from landfills and septic tank systems in urban areas poses the most serious water-quality-related problem. High ground-water levels are a potential problem in the Louisville area, where water levels are just a few feet below structures in some places.

TERTIARY AND CRETACEOUS AQUIFERS

The Tertiary and Cretaceous aquifers are dependable sources of potable ground water and could provide more water than is used at present (Hosman and others, 1968, p. D11; Boswell and others, 1965, p. C9). These aquifers crop out in the Coastal Plain province and thicken and dip to the southwest (fig. 1) (Davis and others, 1973, p. 31). Water in the aquifers is confined and stands at relatively shallow depths in wells. Wells capable of yielding more than 1,000 gallons per minute (gal/min) can be constructed in most of the Coastal Plain province. Water from the aquifers generally contains less than 250 mg/L of dissolved solids and is soft.

Table 2. Aquifer and well characteristics in Kentucky

[Mgal/d = millions of gallons per day; gal/min = gallons per minute; mg/L = milligrams per liter; ft = feet. Sources: Reports of the U.S. Geological Survey and Kentucky Geological Survey]

Aquifer name and description	Water withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Alluvial aquifer: Sand and gravel. Confined and unconfined.	115	50 – 125	140	25 – 500	5,000	Used as source or partial source for several municipal and industrial areas along Ohio River, including Owensboro, Hawesville, Brandenburg, Louisville, and Carrollton. Water generally hard to very hard and generally contains iron in excess of 1 mg/L. Aquifer is the coarse unconsolidated aquifer in Ohio, the glaciofluvial aquifer in Indiana, and terrace and alluvial sand aquifer in Tennessee.
Tertiary aquifers: Includes the Claiborne Group undivided and the Wilcox Formation. Mostly sand, silt, and clay. Confined except in outcrop area.	11.4	100 – 600	800	5 – 100	1,200	Supplies water for several towns including Hickman, Mayfield, Fulton, and Clinton and several rural water districts. Water generally meets national drinking-water regulations. Aquifer is Tertiary Sands aquifer in Tennessee and the Claiborne aquifer in Missouri.
Cretaceous aquifers: Includes the McNairy Formation. Mostly sand, silt, and clay. Confined except in outcrop area.	4.6	100 – 400	500	5 – 25	1,100	Supplies water for Murray, Benton, Reidland, and several rural water districts. Water generally meets national drinking-water regulations. Mica in sands may clog well screens in places. Aquifer is the Cretaceous sands aquifer in Tennessee and McNairy aquifer in Missouri.
Pennsylvanian sandstone aquifers: Sandstone, siltstone, and shale. Partly confined.	18.7	75 – 200	400	1 – 5	200	Used mainly for domestic and stock supplies. Some used for small municipal and industrial supplies, and some used in coal washing and water flooding for secondary recovery of oil. Water generally contains iron in excess of 0.3 mg/L and may contain chloride concentrations in excess of 250 mg/L at depths less than 100 ft. Aquifer is sandstone aquifer in Ohio and Upper and Lower Pennsylvanian aquifer in West Virginia.
Mississippian limestone aquifers: Limestone and shale. Partly confined.	17.9	100 – 400	500	2 – 10	500	Supplies water for Elizabethtown, Horse Cave, Park City, and several other small towns. Water generally hard; some deeper supplies contain hydrogen sulfide.
Ordovician limestone aquifers: Limestone and shale. Partly confined.	14.4	50 – 200	300	2 – 10	300	Supplies water mostly for domestic and stock use. Water generally hard. Some deeper supplies have chloride concentrations greater than 250 mg/L and may contain hydrogen sulfide.

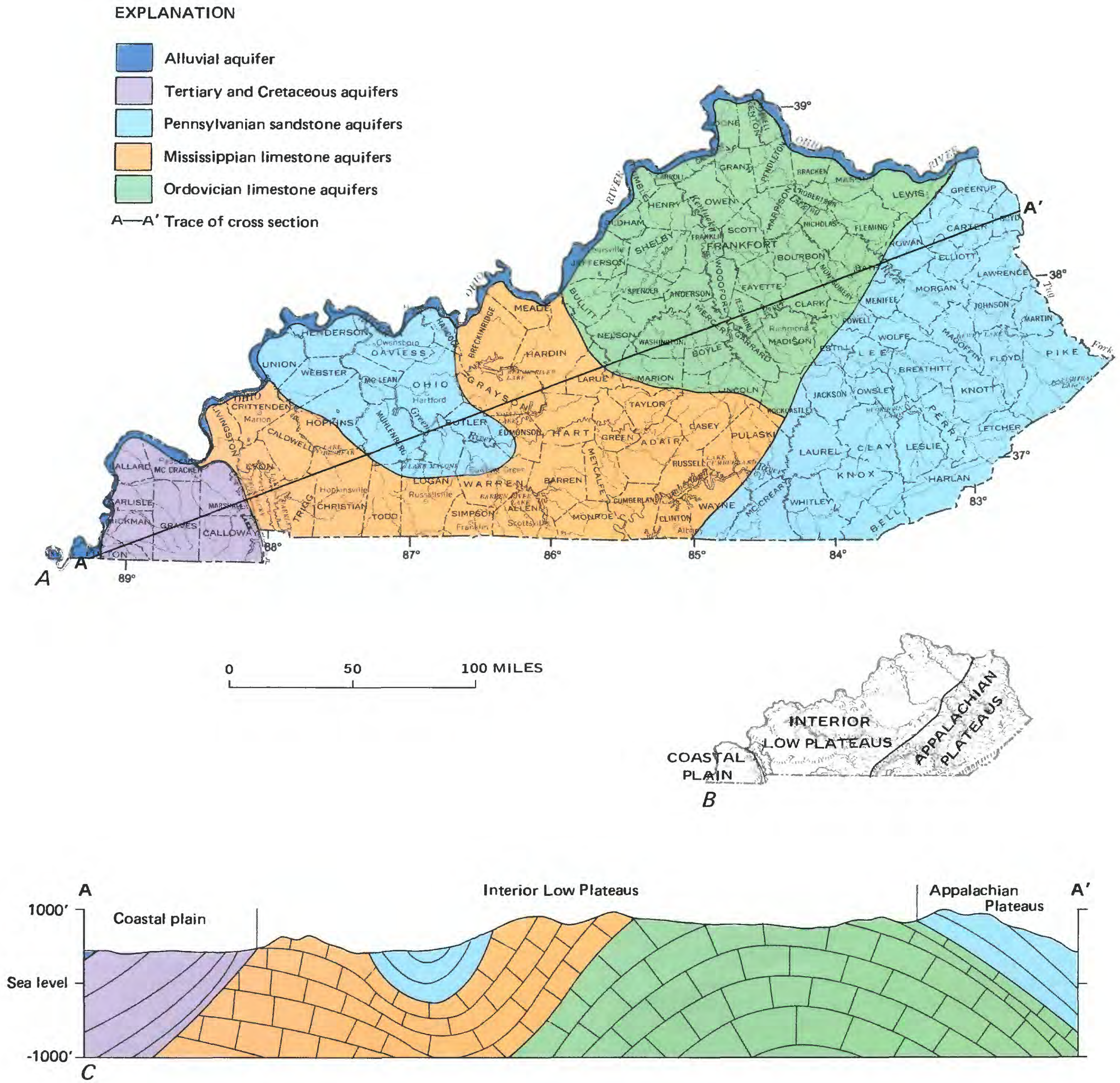


Figure 1. Principal aquifers in Kentucky. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Reports in Selected References. *B*, Fenneman, 1938; McFarlan, 1943; Raisz, 1954. *C*, Compiled by R. J. Faust from U.S. Geological Survey files.)

Pennsylvanian Sandstone Aquifers

The Pennsylvanian sandstone aquifers supply water mostly for domestic and stock use. In general, wells produce less than 5 gal/min, but wells in a few areas have produced about 200 gal/min (Maxwell and Devaul, 1962, p. 20). Water from Pennsylvanian sandstone aquifers generally contains iron in excess of 0.3 mg/L and may have chloride concentrations greater than 250 mg/L at depths of less than 100 feet in places (Price and others, 1962, p. 44). Some coal beds in the Pennsylvanian rocks also produce small quantities of water that may contain hydrogen sulfide. The production of coal, oil, and gas from the Pennsylvanian rocks affects the availability and quality of ground water. Mining disrupts local ground-water flow systems. Drainage from mines can enter the ground-water system and increase concentrations of selected constituents, particularly trace elements, in the water. Oil and gas production in the State can yield quantities of brine that may enter the ground-water system if not disposed of properly. Also, brine may migrate upward through abandoned and inadequately plugged wells to contaminate freshwater zones in the aquifers.

Mississippian and Ordovician Limestone Aquifers

The Mississippian and Ordovician limestone aquifers crop out over a large area of Kentucky (fig. 1). The aquifers supply water for several small towns and many domestic and stock users. Hardness as calcium carbonate and chloride concentration exceeds 250 mg/L in many supplies; hydrogen sulfide is present in some supplies (Brown and Lambert, 1963, p. 45; Palmquist and Hall, 1961, p. 27). Also, a significant potential for ground-water contamination exists where sinkholes and solution-formed openings facilitate the rapid infiltration of contaminants from land surface to the ground-water system. Sinkholes can form quickly in the limestone aquifers and damage manmade structures.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The distribution of ground-water withdrawals and trends of ground-water levels in Kentucky are summarized in figure 2. Most of the large pumping centers are in the alluvium along the Ohio River and in the Coastal Plain province.

Water levels have remained relatively stable in most of the State during the period for which records are available. One exception is the Louisville area (location 10, fig. 2) where intensive pumping and less-than-average rainfall caused a decline in water levels during the 1940's. Decreased pumping and greater-than-average precipitation caused a large water-level rise during the 1970's. In recent years, water levels have remained relatively constant except for seasonal fluctuations.

GROUND-WATER MANAGEMENT

A number of State agencies within the Department of Mines and Minerals and the Kentucky Cabinets of Human Resources and Natural Resources and Environmental Protection are responsible for comprehensive ground-water management. Specific State legislation and regulations that relate to ground-water protection or management are discussed below.

Water Quality Standards (401 Kentucky Administrative Regulation No. 5:031). Specific water-quality standards are established for aquatic life, domestic-water-supply use, recreational use, and outstanding resource waters (wild and scenic areas, nature preserves, etc.).

Water Resources Laws (Kentucky Revised Statutes, Chapter 151). Under provisions of this statute, a consumptive user of public water (except for agricultural uses, steam-generating plants, and domestic users) is required to obtain a permit from the Natural Resources and Environmental Protection Cabinet to withdraw 10,000 gallons per day or more.

Control of Water Pollution from Oil and Gas Facilities (401 Kentucky Administrative Regulation 5:090). Permits for the construction and operation of disposal wells for brine reinjection are obtained through the Division of Water. Liners are required for brine-holding pits, and brine injection is allowed only into geologically isolated formations having dissolved-solids concentrations greater than 10,000 parts per million (approximately 10,000 mg/L) of dissolved solids or into those formations that meet the requirements of exempted aquifers as established by the U.S. Environmental Protection Agency (40 CFR 146.4).

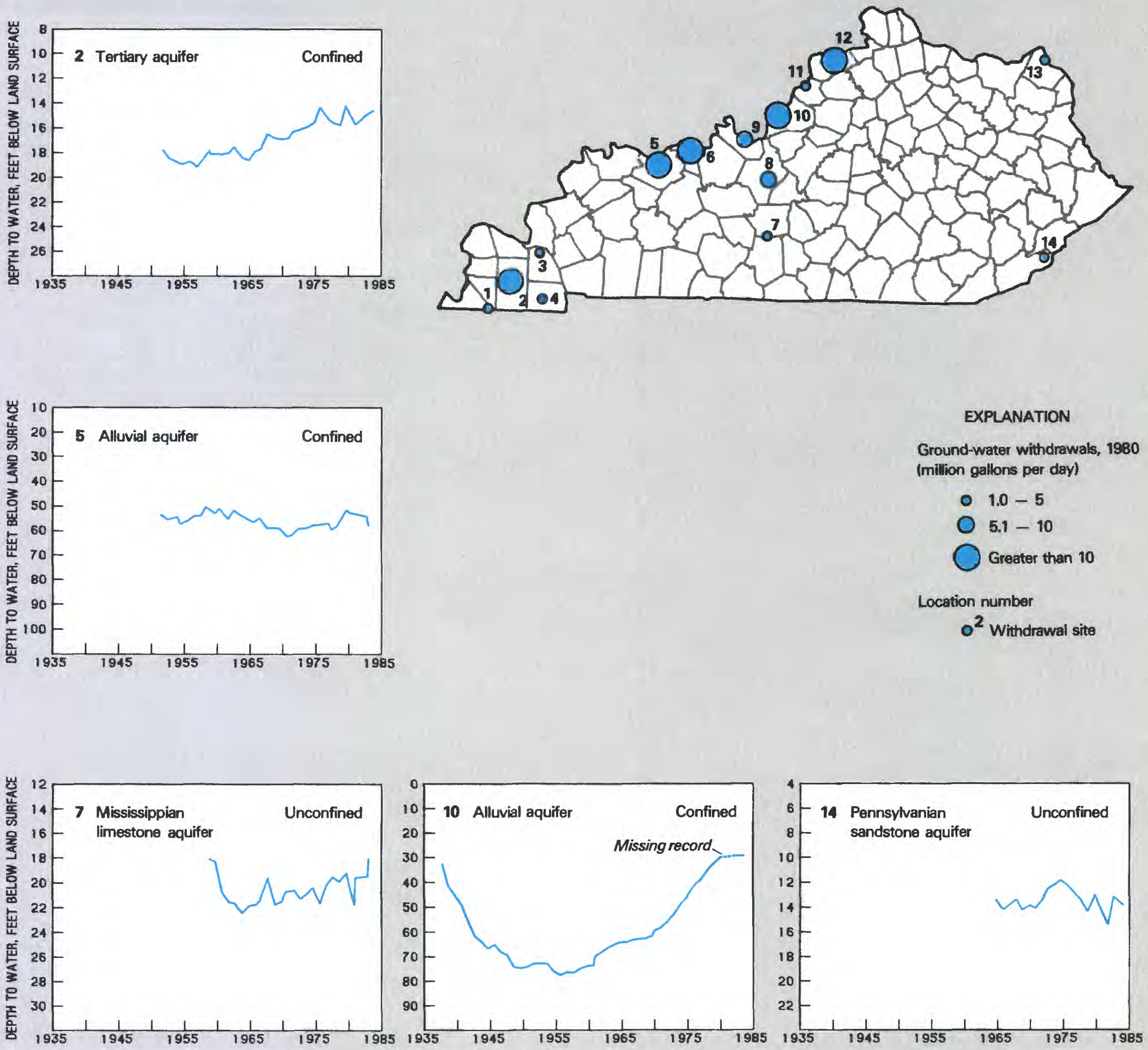
Permanent Program Regulations for Surface Coal Mining and Reclamation Operations and Coal Exploration Operations (405 Kentucky Administrative Regulation Chapters 8 through 24). The protection of ground-water quality and recharge capacity associated with surface and underground mining activities are addressed.

Waste Management Regulations (401 Kentucky Administrative Regulation Chapter 30). Solid- and hazardous-waste management regulations are administered by the Division of Waste Management. Performance standards for waste-disposal sites, including the protection of a ground-water contamination, are part of this responsibility.

Subsurface Sewage Disposal Regulations (815 Kentucky Administrative Regulation 20:141 and 20:160). These regulations specify such standards as the minimum size and capacity of private subsurface sewage-disposal systems and the minimum distance from the systems to drinking-water wells. Permits are issued from the Division of Consumer Health Protection, Cabinet for Human Resources.

Oil and Gas Regulations (805 Kentucky Administrative Regulation 1:020, 1:060, and 1:070). Plugging, casing, and operation of wells are accomplished in accordance with the regulations established by the Department of Mines and Minerals. Unreasonable damage to underground water supplies from waste oil and gas is prohibited.

In addition to the above State activities, the Kentucky Geological Survey is responsible for the maintenance of a statewide water-data network and the investigation of the State's water resources. These responsibilities are accomplished in cooperation with the U.S. Geological Survey. The research, data collection, and analysis provided by this cooperative program form an information base upon which ground-water-management decisions are made by appropriate State agencies. The U.S. Geological Survey also cooperates with other State and local agencies in studies of selected areas.



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Fulton	Tertiary	Public supply.
2	Meyfield	....do	Industrial, public supply.
3	Calvert City	Alluvial	Industrial.
4	Murray	Cretaceous	Public supply.
5	Owensboro	Alluvial	Industrial, public supply.
6	Hawesville	....do	Do.
7	Horse Cave	Mississippian limestone	Public supply.
8	Elizabethtown	....do	Do.
9	Brandenburg	Alluvial	Industrial, public supply.
10	Louisville	....do	Industrial.
11	Oldham County	....do	Public supply.
12	Carrollton	....do	Industrial, public supply.
13	Greenup	....do	Do.
14	Lynch	Pennsylvanian sandstone	Industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Kentucky. (Sources: Withdrawal data from Mull and Lee, 1984; water-level data from U.S. Geological Survey files.)

SELECTED REFERENCES

In addition to reports listed below, hydrologic and geologic information is available from the series of Bulletins, Water Resources Basic-Data Reports, and Reports of Investigations prepared cooperatively by the U.S Geological Survey and the Kentucky Geological Survey.

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Prepared by Robert J. Faust

For further information contact District Chief, U.S. Geological Survey, Federal Building, Room 572, 600 Federal Place, Louisville, KY 40202

LOUISIANA
Ground-Water Resources

Louisiana has abundant ground-water resources. Ground water is available in most of the State in quantity and quality suitable for one or more of the major-use categories. Ground water provides about one-half of the irrigation supplies (the largest category of water use) and 44 percent of the public-supply withdrawals (table 1). Ground water is the source for about 85 percent of all public-supply systems, for most industries (at least in part), and for virtually all rural users. In many areas of the State, aquifers can supply water for various uses, and wells of many public-supply systems yield water that can be distributed with little or no treatment.

GENERAL SETTING

Louisiana, situated in the Gulf Coastal Plain, is underlain by thick sequences of unconsolidated sedimentary deposits of sand and gravel that form productive aquifers and clay and silt that form confining beds. The prevailing dip of the deposits is southerly. The regional aquifers range in age from Pleistocene to Paleocene.

Water in the aquifers generally is confined, although water commonly is under water-table conditions in outcrop areas. Wells in some deep aquifers in south-central and southeastern Louisiana flow at the land surface. In general, under natural conditions, water in the aquifers moves in a southerly direction and toward major stream valleys. However, intensive pumping that creates depressions in the potentiometric (water-level) surface alters the natural flow system locally. Recharge is supplied by rainfall on outcrop areas, by seepage from streams, and by interaquifer leakage. Annual recharge rates range from about 1 to 12 inches (in.). Average annual rainfall in areas where aquifers are recharged ranges from 45 to 60 in. Discharge of water from shallow aquifers sustains the low flow of streams in Louisiana.

Freshwater is present to depths ranging from about 100 feet (ft) in the coastal areas to about 3,500 ft in parts of south-central Louisiana (Rollo, 1960). Saline water is present at some depth downdip in most aquifers, and, in southern Louisiana, aquifers that contain saline water may be located between aquifers that contain freshwater.

Ground-water temperatures range from about 65°F for shallow aquifers in the north to about 100°F for the deepest aquifers in south-central Louisiana. The temperatures tend to be constant at specific depths and increase at a rate of about 1°F for each 100 ft of depth.

PRINCIPAL AQUIFERS

The principal aquifers of Louisiana fall into five major aquifer groups. In order from youngest to oldest, the aquifer groups are alluvial, Pleistocene, Pliocene-Miocene, Cockfield and Sparta, and Wilcox-Carrizo. These aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Table 1. Ground-water facts for Louisiana

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Walter, 1982]

Population served by ground water, 1980	
Number (thousands)	2,889
Percentage of total population	69
From public water-supply systems:	
Number (thousands)	1,850
Percentage of total population	44
From rural self-supplied systems:	
Number (thousands)	1,039
Percentage of total population	25
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	12,000
Ground water only (Mgal/d)	1,800
Percentage of total	14
Percentage of total excluding withdrawals for thermoelectric power	27
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	270
Percentage of total ground water	15
Percentage of total public supply	44
Per capita (gal/d)	144
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	54
Percentage of total ground water	3
Percentage of total rural domestic	100
Per capita (gal/d)	52
Livestock:	
Ground water (Mgal/d)	13
Percentage of total ground water	1
Percentage of total livestock	70
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	460
Percentage of total ground water	26
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	5
Excluding withdrawals for thermoelectric power	12
Irrigation withdrawals:	
Ground water (Mgal/d)	990
Percentage of total ground water	55
Percentage of total irrigation	47

ALLUVIAL AQUIFERS

The alluvial aquifers underlie the flood plains of the Mississippi, Red, and Ouachita River valleys. The alluvial deposits typically consist of a confining layer of clay and silt that overlies sand and gravel. The aquifers generally thicken southward; the base of the aquifer is about 100 ft below land surface in the north to 250 to 450 ft below land surface in the south. The Mississippi River alluvial aquifer is the largest yielding unit; well yields are as much as about 7,000 gallons per minute (gal/min). The alluvial aquifers are not developed

Table 2. Aquifer and well characteristics in Louisiana

[Mgal/d = million gallons per day; ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and Louisiana Office of Public Works.]

Aquifer name and description	Water withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Alluvial aquifers: Fine to medium sand near the top, grading to coarse sand and gravel near the base. Generally confined.	271	100 - 250	400	500 - 2,500	7,000	Mississippi, Red, and Ouachita River valleys. Water generally hard to very hard and contains large concentrations of iron. Sulfate concentrations large locally in Red River valley. Local areas of very saline water in Red River and upper Mississippi River valleys. Contain only saline water in coastal areas. Major use is for irrigation and industry.
Pleistocene aquifers: Terrace aquifers: Fine sand near the top grading to coarse sand and cobble gravel near the base. Generally unconfined but may be confined locally.	–	50 - 150	200	40 - 400	1,000	Northern and central Louisiana. Saturated thickness variable. Water soft in some areas, hard in other areas. pH typically low. Surface disposal of wastes is potential for contamination. Major uses rural and domestic. Grouped with alluvial aquifers in Arkansas.
Chicot aquifer: Includes the Lake Charles "200-foot," "500-foot," and "700-foot" sands, and "upper" and "lower" sand units. Thick beds of sand and gravel divided by beds of silt and clay to the south. Confined except in and near the outcrop area.	995	50 - 800	1,000	500 - 2,500	4,000	Southwestern Louisiana. Iron concentration generally exceeds 1.0 mg/L and hardness ranges from 10 to 250 mg/L as calcium carbonate. Local salinity problems in coastal area, but some units contain freshwater to coastline. Primary aquifer for 13 southwestern parishes where it is intensively pumped for irrigation.
The "400-foot" and "600-foot" sands (at Baton Rouge) and upper Ponchatoula and Gonzales–New Orleans aquifers: Fine to coarse sand, some gravel. Generally confined.	126	100 - 800	1,000	500 - 1,000	2,500	Southeastern Louisiana. Water ranges from soft to hard; small to large iron concentration. Primary use is industrial. Extensive cones of depression in New Orleans and Baton Rouge areas due to industrial pumping. Equivalent to Citronelle aquifer in Mississippi. Withdrawals (126 Mgal/d) include those from the terrace aquifers.
Pliocene-Miocene aquifers: Evangeline, upper Jasper, lower Jasper, Catahoula aquifers: Fine to coarse sand, locally some gravel; interbedded with silt and clay. Generally confined.	299	200 - 2,200	2,800	200 - 1,200	3,000	Southwestern, western, and central Louisiana. Water generally soft with small to moderate amounts of iron. Locally color and fluoride may be excessive for public-supply use. Annual water-level declines in wells in some intensively pumped units are 1 to 2 ft.
The "1,200-foot" and deeper sands in Baton Rouge area and lower Ponchatoula and deeper aquifers in southeastern Louisiana (not shown in figure 1): Fine to coarse sand. Confined.	–	800 - 2,800	3,300	500 - 1,500	4,000	Southeastern Louisiana.Generally underlies Pleistocene aquifers. Water soft and of good quality for water-supply use; may have large iron concentrations locally. Extensively developed for public-supply and industrial use.
Cockfield and Sparta aquifers:Fine to medium sand interbedded with silt and clay; some indurated layers. Generally confined.	76	200 - 900	2,000	50 - 1,800	2,500	In western part of State, a few wells are as deep as 2,200 ft in Cockfield and 1,600 ft in Sparta. Water generally soft. Locally, water may have a large iron concentration. Sparta intensively pumped for industrial and public-supply use in northern Louisiana; extensive cone of depression extends into Arkan-. sas. Annual water-level declines of 1 to 3 ft in wells in Sparta.
Wilcox–Carrizo aquifer:Sand, very fine to medium; silty in many places. Thin interbeds of clay, silt, and lignite. Some indurated layers. Generally confined.	10	100 - 600	800	40 - 150	350	Water soft to moderately hard; locally, large iron concentrations. Used for local public supplies and domestic use. Equivalent to Carrizo-Wilcox aquifer in Texas.

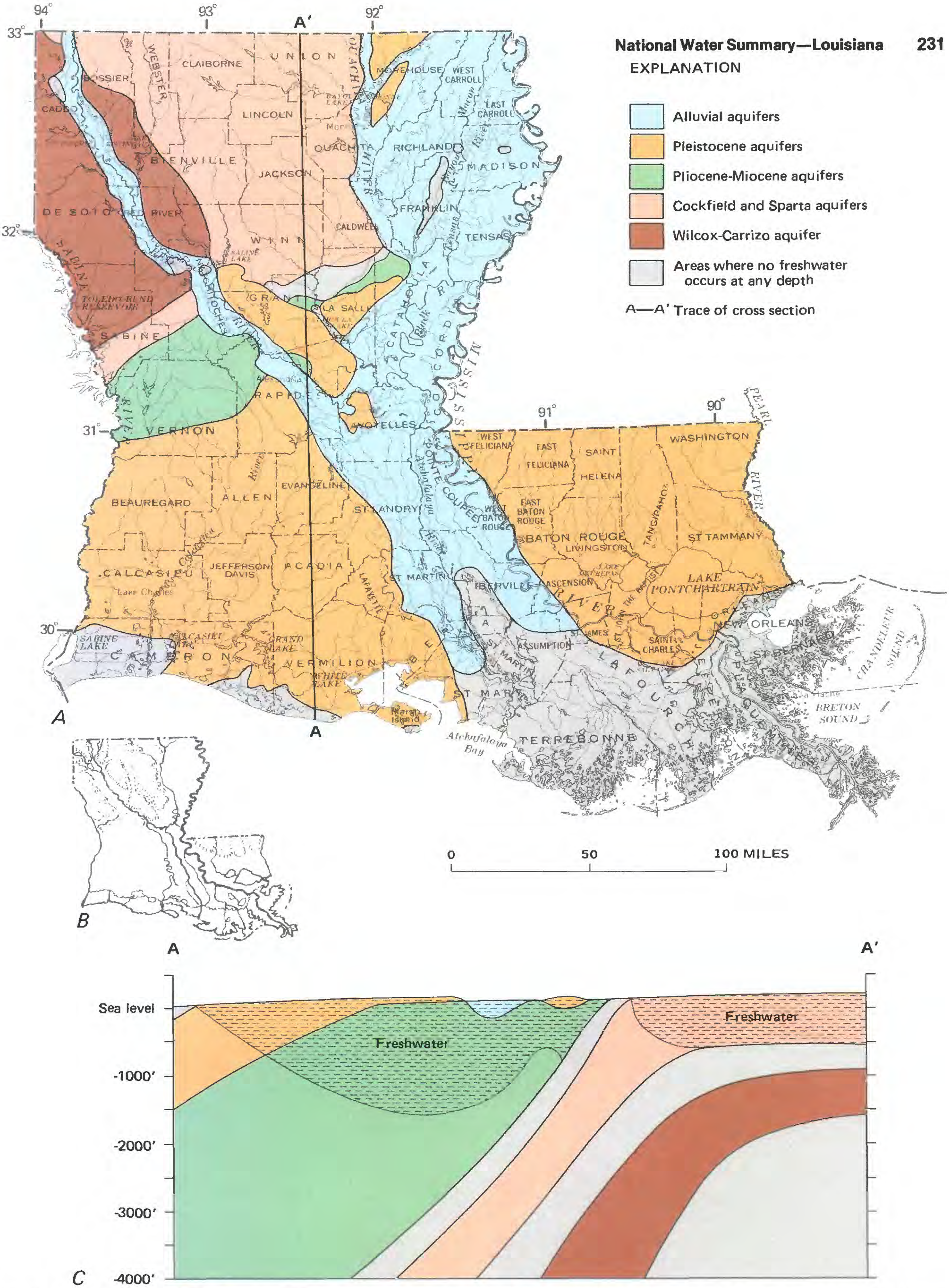


Figure 1. Principal aquifers in Louisiana. *A*, Geographic distribution. *B*, Physiographic diagram. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, G. T. Cardwell, H. C. McWreath III, and J. E. Rogers. *B*, Raisz, 1954. *C*, compiled by G. T. Cardwell from U. S. Geological Survey files.)

extensively, but the water is ideal for irrigation. The water is hard to very hard [200–450 milligrams per liter (mg/L) as calcium carbonate] and typically has high concentrations of iron (exceeding 1 mg/L). Slightly saline water in local areas in the Red and Mississippi River valleys may be the result of pollution by oil-field brines (Whitfield, 1975a, 1980).

PLEISTOCENE AQUIFERS

The Pleistocene aquifers are principal sources of freshwater in central, southwestern, and southeastern Louisiana. In central Louisiana, the terrace aquifers are important, though of limited potential. The aquifers range in depth from 50 to 200 ft. Saturated thickness ranges from 0 to 110 ft. Well yields range from 40 to 400 gal/min; potential yields are as much as 1,000 gal/min (Snider and Sanford, 1981). Typically, the water has a small concentration of dissolved solids (less than 150 mg/L), low pH (less than 6), and is soft (less than 60 mg/L as calcium carbonate).

The Pleistocene Chicot aquifer, which is the principal aquifer in southwestern Louisiana and is the most intensively pumped aquifer, provides about 56 percent of the total ground-water withdrawals in the State (Walter, 1982). Aquifer depths range from about 50 ft in northern outcrop areas to 800 to 1,000 ft in the coastal area. Typical depths of irrigation wells are 200 to 300 ft; public-supply wells at Lake Charles are about 700 ft deep. Irrigation wells yield as much as 4,000 gal/min from massive sands that may exceed several hundred feet in thickness. To the north, the water is hard (greater than 150 mg/L as calcium carbonate) but is suitable for irrigation; to the south, deeper sands yield soft (less than 60 mg/L as calcium carbonate) water of excellent quality for public-supply use.

In southeastern Louisiana, the Pleistocene aquifers range in depth from a few hundred feet to more than 1,000 ft and contain freshwater to depths of 700 to 800 ft in the southern part of the area. Principal individual aquifers are the "400-foot" and "600-foot" sands at Baton Rouge, the Gonzales–New Orleans aquifer (principal source in New Orleans), and the upper Ponchatoula aquifer. Individual sand units are commonly 50 to 150 ft thick and yield 500 to 1,000 gal/min of potable water.

Principal problems with the Pleistocene aquifers are (1) the limited production capacity of the terrace aquifers locally, (2) local saltwater problems in the Chicot aquifer, including encroachment in local coastal areas (Harder and others, 1967; Nyman, 1984), and (3) saltwater encroachment in the "600-foot" sand at Baton Rouge (Whiteman, 1979) and in the Gonzales–New Orleans aquifer (Rollo, 1966). Potential contamination from surface disposal of wastes is also a concern in some areas.

PLIOCENE-MIOCENE AQUIFERS

The Pliocene-Miocene aquifers form part of a large artesian basin in the western part of the Gulf Coastal Plain and supply potable water to many towns and cities. The Pliocene-Miocene aquifers include the Evangeline, Jasper, and Catahoula aquifers of central and southwestern Louisiana; the sands below the "600-foot" aquifer in the Baton Rouge area; and deeper sands in southeastern Louisiana. These aquifers have been described in detail in southwestern Louisiana by Whitfield (1975b) and in southeastern Louisiana by Nyman and Fayard (1978) and Buono (1983).

In the Evangeline aquifer in southwestern Louisiana, freshwater extends to a maximum depth of about 2,200 ft; in the underlying Jasper aquifer, freshwater extends to about 3,400 ft. The total sand thickness available for development ranges from about 100 to 1,000 ft. Yields of wells range from several hundred gallons per minute to as much as 3,000 gal/min. In southeastern Louisiana, individual sands tend to be thicker and average yields greater than in other areas. Sands typically are 50 to 250 ft thick and yields are as much as 4,000 gal/min (Cardwell and others, 1967). Depth to the base of the freshwater section in south-eastern Louisiana ranges from about 2,000 to 3,400 ft. The deepest freshwater well (3,354 ft) in the State taps a Miocene aquifer in southeastern Louisiana (Nyman and Fayard, 1978).

The principal problems pertaining to Pliocene-Miocene aquifers are local occurrences of large fluoride concentrations (greater than 2 mg/L), dark color (greater than 30 units), depletion of artesian head in intensively pumped areas (Torak and Whiteman, 1982), and local saltwater encroachment in the "1,500" foot and deeper sands of the Baton Rouge area (Whiteman, 1979).

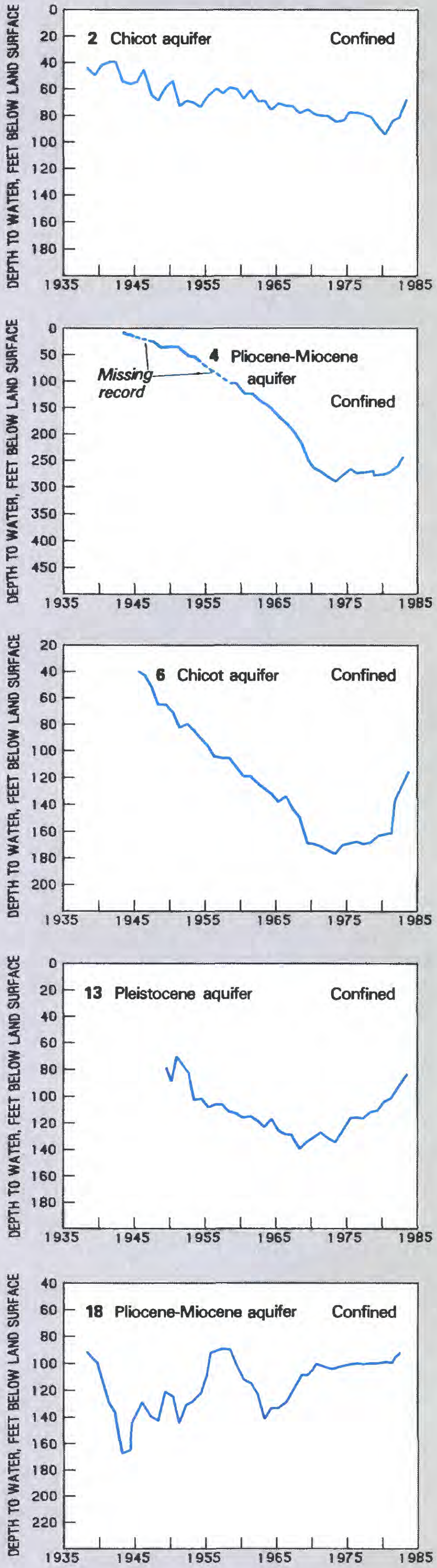
COCKFIELD AND SPARTA AQUIFERS

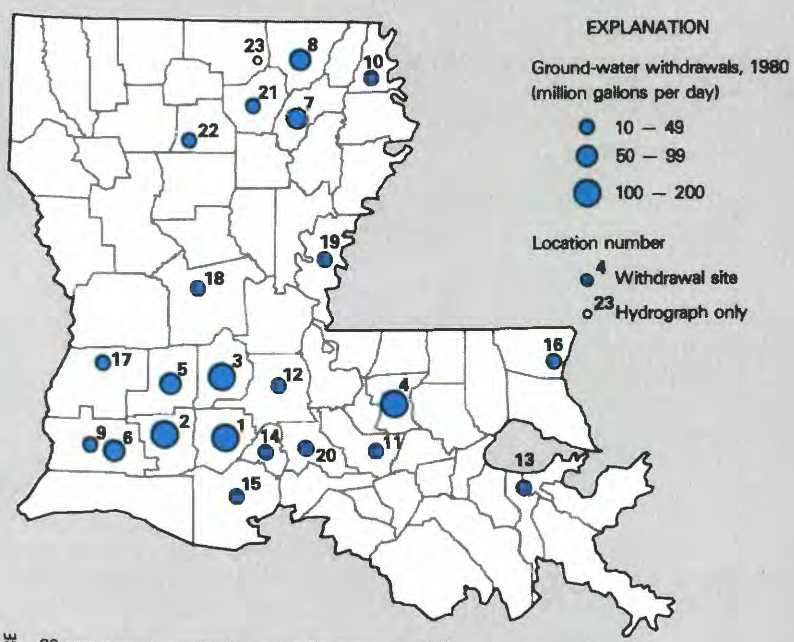
The Cockfield and Sparta aquifers are important to water users in northern Louisiana—the Cockfield principally in the northeast and the Sparta in the north-central part of the State. In much of the area where the Cockfield contains freshwater, it underlies the alluvial aquifer and generally yields water that is relatively soft compared to the hard water in the alluvium. Wells commonly range in depth from a few hundred feet to about 800 ft and yield from 50 to 500 gal/min. Water in the Cockfield typically has color greater than 30 units, a level that may be objectionable for public supply.

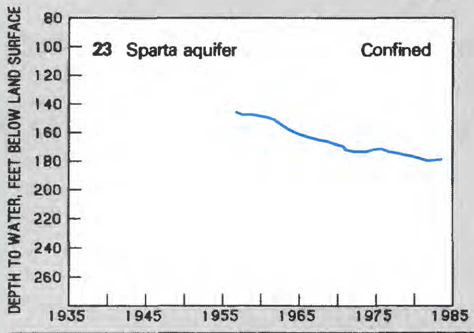
The areally extensive Sparta aquifer is the principal source of supply in north-central Louisiana and adjacent sections of Arkansas. Well depths range from 200 ft or less in the outcrop area in northwestern Louisiana to common maximum depths of about 900 ft, and well yields commonly range from 100 to 1,800 gal/min. Thickness of the aquifer is as much as 700 ft (Rogers and others, 1972). Freshwater in the Sparta aquifer is present to depths ranging from a few hundred feet to about 1,000 ft. The water generally is soft, and iron concentrations are variable but typically small (less than 0.3 mg/L) in the deeper sand units. The principal problem of the Sparta is declining water levels, with annual declines that range from 1 to 3 ft. Saltwater encroachment is a problem in the Monroe area.

WILCOX-CARRIZO AQUIFER

The Wilcox-Carrizo is the most important and areally extensive aquifer in northwestern Louisiana. However, the aquifer sands are typically thin and fine, which restricts well yields. Wells range in depth from about 100 to 600 ft, and typically wells yield from 40 to 150 gal/min and exceptional







WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Acadia Parish	Chicot	Irrigation, aquaculture.
2	Jefferson Davis Parish.	....do	Do.
3	Evangeline Parish	....do	Do.
4	Baton Rouge.	Pleistocene, Pliocene-Miocene.	Industrial, public supply.
5	Allen Parish	Chicot	Irrigation.
6	Lake Charles.	....do	Industrial, public supply.
7	Richland Parish	Alluvial.	Irrigation, aquaculture.
8	Morehouse Parish	....do	Irrigation.
9	Calcasieu Parish	Chicot	Irrigation, industrial.
10	East Carroll Parish	Alluvial.	Irrigation.
11	Iberville Parish.	....do	Industrial.
12	St. Landry Parish	Chicot	Irrigation.
13	New Orleans.	Pleistocene.	Industrial.
14	Lafayette Parish.	Chicot	Irrigation, public supply.
15	Vermilion Parish	....do	Irrigation.
16	Bogalusa	Pleistocene, Pliocene-Miocene.	Industrial, public supply.
17	De Ridder	Pliocene-Miocene	Industrial.
18	Alexandria.	Pleistocene, Pliocene-Miocene.	Public supply, industrial.
19	Concordia Parish	Alluvial.	Irrigation.
20	St. Martin Parish	Chicot	Irrigation, aquaculture.
21	West Monroe.	Sparta	Industrial, public supply.
22	Jonesboro-Hodge	....do	Industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Louisiana. (Sources: Withdrawal data from Walter, 1982; water-level data from U.S. Geological Survey files.)

wells as much as 350 gal/min. Deepest freshwater is approximately 800 ft. Water quality is somewhat variable but generally suitable for domestic and public-supply use.

GROUND-WATER WITHDRAWALS AND WATER LEVEL TRENDS

Although all major aquifer groups in Louisiana support some development, the Pleistocene aquifers are the most intensively pumped. In 1980, over 1.1 billion gallons per day was withdrawn from the Pleistocene aquifers; of this amount, 995 million gallons per day (Mgal/d) was pumped from the Chicot aquifer in southwestern Louisiana, mainly for irrigation (fig. 2). Water levels in wells in the Chicot have declined gradually (an annual average of about 1 ft) but, in recent years, the decline has ceased (locations 2 and 6, fig. 2). The hydrograph for location 6 reflects the effect of localized industrial pumping from the Chicot aquifer ("500-foot" sand) in the Lake Charles area. From 1973 to 1982, levels rose gradually because of decreases in pumping rates; in 1982, levels rose sharply when industrial ground-water withdrawals were reduced and augmented by surface water from the Sabine River.

In southeastern Louisiana, water levels in wells in the "400-foot" and "600-foot" sands at Baton Rouge declined as much as several hundred feet from 1920 to about 1970 (Morgan, 1961) but have risen 40 to 50 ft since then. Water levels also have risen in wells in the Gonzales-New Orleans aquifer (one of the Pleistocene aquifers in southeastern Louisiana) at New Orleans (location 13, fig. 2). Water levels in the terrace aquifers typically reflect changes in seasonal withdrawals and variations in precipitation (Rogers, 1981).

The shallow alluvial aquifers are connected hydraulically to major streams, and water levels generally reflect stream stages and effects of climatic cycles. In northeastern Louisiana, local shallow cones of depression may develop in intensively pumped areas remote from stream sources of recharge. About 270 Mgal/d was pumped from the alluvial aquifers in 1980, mostly from the Mississippi River alluvial aquifer.

The Pliocene-Miocene aquifer group is the second most intensively pumped (299 Mgal/d in 1980). Largest withdrawals are made at Baton Rouge, Alexandria (location 18, fig. 2), and De Ridder. Major development of the Pliocene-Miocene aquifers occurred later than for other aquifers, primarily because they are relatively deeper at population centers. Water levels in wells in the "2,000-foot" sand at Baton Rouge, which is pumped intensively for industrial and public-supply uses, declined sharply until about 1973, when reductions of industrial pumping caused water levels to rise (location 4, fig. 2). However, water levels are declining at annual rates of as much as 2 ft in most other areas where water is obtained from Pliocene-Miocene aquifers.

Water levels in wells in the Cockfield aquifer have not changed significantly, except for small declines in areas of relatively intensive development. However, levels in wells in the Sparta aquifer (fig. 2) show long-term declining trends dating back to about 1920. In 1980, 4 Mgal/d was pumped from the Cockfield and 72 Mgal/d from the Sparta aquifer (Walter, 1982).

Although the Wilcox-Carrizo aquifer is areally extensive, only about 10 Mgal/d was pumped from it in 1980. Because the pumping is dispersed, no apparent regional water-level trends have developed, although local declining water-level trends are evident near pumping wells.

GROUND-WATER MANAGEMENT

Five different State agencies have active roles in administering ground-water activities in Louisiana. The Department of Transportation and Development's Office of Public Works (OPW) licenses and regulates drillers of water wells, monitor wells, geotechnical boreholes, and heat pump wells, as well as those engaged in plugging abandoned wells and boreholes. The OPW registers all water wells drilled in Louisiana and maintains an active computer file of these wells. The OPW also administers the Louisiana Water Resources Information Center, which has the responsibility of indexing all available water-resources information for the State. The Department is the major State agency participating with the U.S. Geological Survey in a cooperative ground-water program of data collection, areal studies, and research.

The Department of Natural Resources has certain regulatory responsibilities relating to protection of ground water. The Department's Office of Conservation has jurisdiction over underground injection wells and also has regulatory functions relating to protection of ground water in areas of lignite mining and oil and gas development. The Louisiana Geological Survey maintains some ground-water functions, principally in support of the missions of the Department of Natural Resources and other State agencies.

The Louisiana Department of Health and Human Resources has responsibility for ensuring that drinking-water supplies are safe and of good quality and also enforces construction standards for public-supply wells. The newly formed Department of Environmental Quality has responsibilities for monitoring and protecting ground water related to regulation of solid and hazardous waste.

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Prepared by George T. Cardwell, Harry C. McWreath, III, and James E. Rogers

For further information contact District Chief, U.S. Geological Survey, P.O. Box 66492, Baton Rouge, LA 70896

MAINE
Ground-Water Resources

Ground water is a vital natural resource in Maine. Although ground water comprises less than 10 percent of the total freshwater withdrawals in the State, it is the source of water for 57 percent of the population; the rural population is almost entirely dependent on ground water. Industry and livestock supply are the other major users of ground water. Ground-water withdrawals, water-use information, and related statistics are given in table 1. The distribution of ground-water withdrawals is associated with the location of population centers. The greatest amount of pumping occurs in southwestern and coastal Maine with other ground-water withdrawals located near the large towns in central and northern Maine.

The quality of ground water is suitable for most uses. However, local contamination of aquifers has occurred from point sources, such as gasoline-storage tanks, salt-storage sites, industrial subsurface disposal systems, septic systems, sludge-disposal sites, and solid-waste landfills, and from nonpoint sources, such as highway deicing salts and agricultural practices. In some localities, increased concentrations of naturally occurring iron and manganese in ground water are severe enough to limit the use of the water unless it is treated. In water from some crystalline bedrock aquifers, large concentrations of naturally-occurring radioactive radon-222 have been observed, frequently exceeding 10,000 picocuries per liter (pCi/L).

GENERAL SETTING

Maine lies in the New England physiographic province of the Appalachian Highlands (Fenneman, 1938). Within the province are three divisions—the Seaboard Lowland, the New England Upland, and the White Mountain Section. The topography is diverse, ranging from coastal plains in southwestern Maine to mountainous regions in the northwestern part of the State. Many surficial features of the State were formed or modified during Pleistocene glaciation when outwash, ice-contact, and till deposits mantled the bedrock in a large part of the State.

Generally, precipitation is sufficient to replenish the water pumped from Maine's aquifers. Annual precipitation ranges from about 34 inches (in.) in the northeast to 55 in. in the northwest and north-central mountains and averages about 42 in. statewide (Knox and Nordenson, 1955). Water-level records show that water tables may have large annual fluctuations in response to climatic conditions, but the long-term depths to water remain relatively stable. A detailed study of the hydrology of the glaciofluvial aquifer in the little Androscoggin River valley indicated that about 45 percent of precipitation recharges stratified sand and gravel aquifers, whereas only 20 percent or less of precipitation recharges till (Morrissey, 1983).

PRINCIPAL AQUIFERS

Two principal types of aquifers underlie Maine—unconsolidated glacial deposits and bedrock composed of sedimentary, igneous, and metamorphic rocks. Bedrock in Maine is comprised of numerous rock types that have very complex structures. However, the bedrock can be grouped into two types based on hydrogeologic characteristics—carbonate and crystalline bedrock. The characteristics of the glaciofluvial and bedrock aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

Table 1. Ground-water facts for Maine

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Population data from U.S. Bureau of the Census, 1983, and Maine Ground Water Quantity Subcommittee, 1980; withdrawal data from Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	642
Percentage of total population	57
From public water-supply systems:	
Number (thousands)	135
Percentage of total population	12
From rural self-supplied systems:	
Number (thousands)	507
Percentage of total population	45
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	850
Ground water only (Mgal/d)	80
Percentage of total	9
Percentage of total excluding withdrawals for thermoelectric power	10
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	20
Percentage of total ground water	25
Percentage of total public supply	19
Per capita (gal/d)	148
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	26
Percentage of total ground water	32
Percentage of total rural domestic	98
Per capita (gal/d)	51
Livestock:	
Ground water (Mgal/d)	1.0
Percentage of total ground water	1
Percentage of total livestock	59
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	34
Percentage of total ground water	42
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	5
Excluding withdrawals for thermoelectric power	5
Irrigation withdrawals:	
Ground water (Mgal/d)	.2
Percentage of total ground water	.2
Percentage of total irrigation	3.3

GLACIOFLUVIAL AND TILL AQUIFERS

The glaciofluvial aquifer is composed of unconsolidated outwash and ice-contact deposits. The unconsolidated glaciofluvial deposits, which consist largely of sand and gravel, are the most favorable for development of large water-supply wells. A saturated glaciofluvial deposit contains about 35 percent water by volume. Outwash deposits were deposited by

Table 2. Aquifer and well characteristics in Maine

[Gal/min = gallons per minute; ft = feet; < = less than. Source: Reports of the U.S. Geological Survey and Maine Geological Survey.]

Aquifer name and description	Well characteristics: Depth (ft), Common range	Well characteristics: Yield (gal/min), Common range	Well characteristics: Yield (gal/min), May exceed	Remarks
Glaciofluvial aquifer:				
Outwash deposits: Stratified sand and gravel deposits in valley trains, outwash plains, or deltas. Percentage of gravel is greatest near ice-contact deposits and decreases seaward. Deposits contain some silt, clay, and cobbles. May overlie or interfinger with marine or glacial lake deposits. Generally unconfined.	35 – 120	10 – 100	2,000	Yield depends upon thickness and grain size of deposits; better yields where deposits are in hydraulic continuity with adjacent body of surface water for recharge. Water generally of good quality for most uses, but, in northern Maine, moderately hard. Large concentrations of iron and manganese commonly reported.
Ice-contact deposits: Deposits consist of well to poorly stratified deposits of sand, gravel, and cobbles, with some silt, clay, and boulders. Because the deposits were laid down under a variety of conditions, the variation in texture, sorting, and internal structure is great. Deposits overlie bedrock or till. May be overlain by younger unconsolidated units, principally marine deposits. Generally unconfined.	35 – 140	50 – 1,000	3,000	Generally, best source of large supplies of ground water. Yields depend upon thickness, sorting, and grain size of deposit. Better yields obtained where deposits are in hydraulic continuity with adjacent body of surface water for recharge. Associated landforms include kames, eskers, and crevasse fillings. Quality of water generally good for most uses. In some localities, large concentrations of iron and manganese severe enough to limit use with without treatment. Because of permeability and typically shallow water table, these deposits susceptible to contamination.
Till aquifer: Till is a heterogeneous mixture of clay, silt, gravel, cobbles, and boulders deposited directly from glacial ice. Forms a fairly continuous cover of varying thickness over bedrock in upland areas and occurs beneath younger deposits and above bedrock in some of the lowland areas. Generally unconfined.	10 – 30	<1	20	Source of water for numerous dug or drilled domestic wells. Generally low permeability. Yields water to wells very slowly. Wells likely to become dry in late summer when water tables are low. Quality of water generally good. Excessive iron concentrations may be a problem and, in northern part of State, water moderately hard to hard.
Carbonate bedrock aquifer: This unit consists of limestone, calcareous shale, and calcareous siltstone. May be confined locally.	20 – 800	10 – 30	600	Water contained primarily in secondary openings such as cleavage or bedding planes, joints, fractures, or solution openings. Carys Mills Formation, a bluish-gray limestone, is fairly widespread and constitutes principal calcareous aquifer. Water of good chemical quality for most uses but hard.
Crystalline bedrock aquifer: This unit consists of a variety of igneous and metamorphic rocks. Igneous rocks include granite, gabbro, diorite, granodiorite, and pegmatite and metamorphic rocks include schist, gneiss, quartzite, slate, and argillite. Locally confined at depth.	20 – 800	2 – 10	500	Crystalline bedrock dense and relatively impermeable and contains recoverable water in secondary openings such as joints, fractures, and bedding or cleavage planes. Chemical quality of water good for most uses. Concentrations of iron and manganese exceeding national drinking water regulations found in some wells. Large concentrations of radon 222 have been found in the water, primarily from wells finished in granite, pegmatite, and metamorphosed rocks.

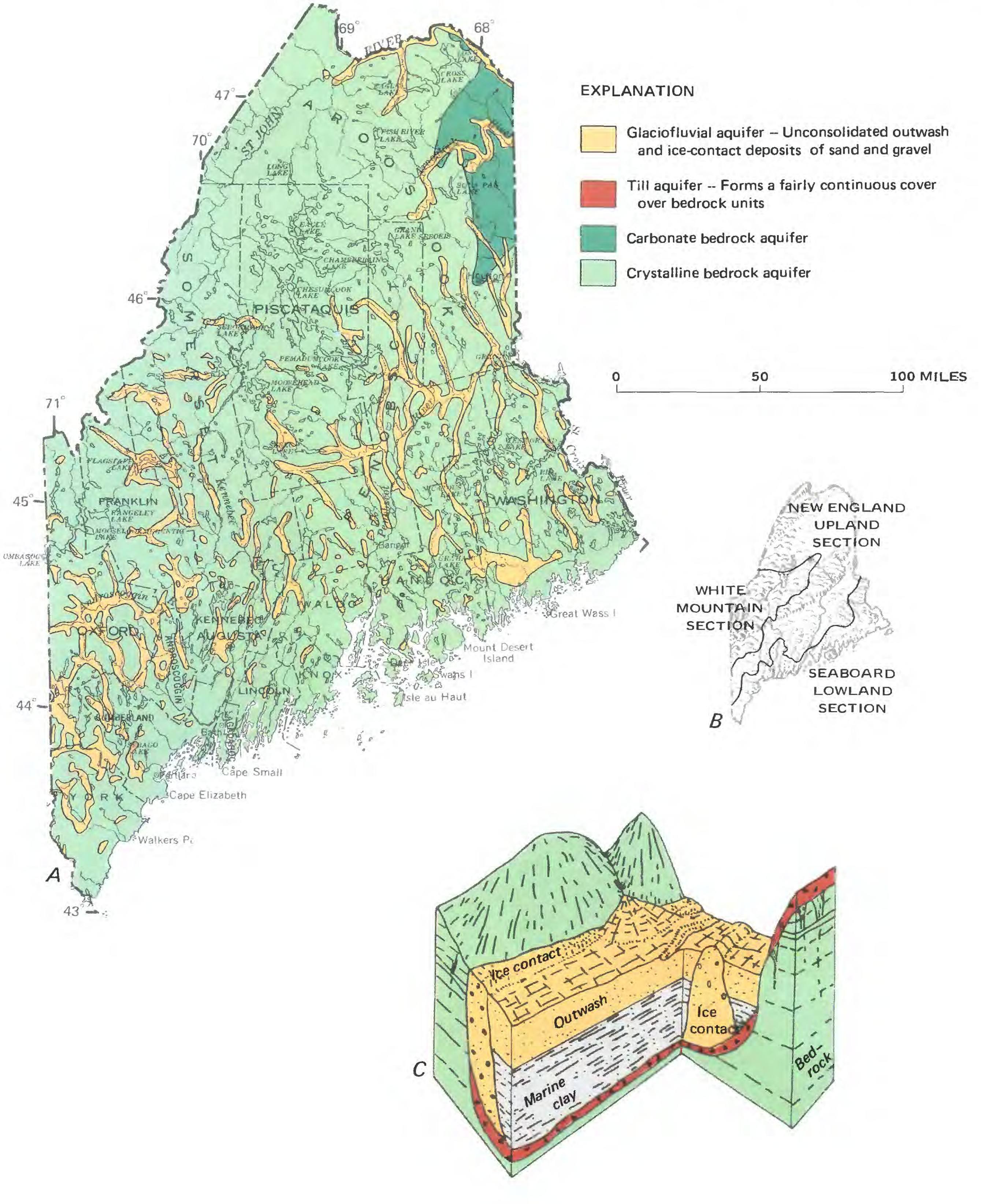


Figure 1. Principal aquifers in Maine. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Typical stratigraphic sequence. (See table 2 for more detailed descriptions of aquifers. Sources: *A*, Modified from Adamik, 1984. *B*, Fenneman, 1938; Raisz, 1954. *C*, Compiled by T. J. Maloney from U.S. Geological Survey files.)

meltwater streams near the margin of the glacier. Many of the outwash deposits are interlayered with relatively impermeable marine silt and clay deposits that may confine the water. Ice-contact deposits formed as sand and gravel settled from the meltwater that flowed under or through the glacier. Ice-contact deposits generally are thicker than outwash deposits. Outwash and ice-contact deposits fill most preglacial valleys, as shown by the elongated and discontinuous exposures of these aquifers in figure 1. These deposits are more common in coastal and central interior Maine but also are present in northeastern Maine along the valleys of major rivers. Most supply wells are located in deposits that have large saturated thicknesses and are recharged by surface water.

The quality of water in outwash and ice-contact deposits generally is suitable for most uses. In northern Maine, the water is moderately hard to hard. In scattered localities throughout the State, concentrations of iron and manganese are large enough to limit use. A study of the aquifers in southwestern Maine found an average iron concentration of 1.2 milligrams per liter (mg/L) and an average manganese concentration of 0.42 mg/L. These deposits are susceptible to contamination because they are very permeable, and pollutants can percolate readily to the water table from the land surface (Tolman and others, 1983).

Till is considered to be a major aquifer in Maine because of the large percentage of the population that relies upon it as a water source. Because yields are so small, the areal extent of till has not been illustrated in figure 1. The greatest expected yields from this aquifer [about 20 gallons per minute (gal/min); table 2] are only large enough for domestic, livestock, or commercial supply. Because they are shallow, many wells in till become dry during drought. Till is the most common surficial unit in the State. It overlies crystalline and carbonate bedrock nearly everywhere and commonly underlies ice-contact and outwash deposits. Till, which generally forms a thin discontinuous cover over bedrock in the upland areas, may be several hundred feet thick in the valleys and at the edges of valleys.

The quality of water from till is generally suitable for most uses, although locally high iron concentrations are a problem. In the northern part of the State, water from till is moderately hard to hard.

A typical sequence which can be found in the preglacial valleys of southern Maine is illustrated in figure 1. The block diagram shows the bedrock covered by a layer of till. Thick ice-contact sand-and-gravel deposits overlie the till along the valley walls and through the center of the valley. Marine silt and clay overlie the till and the lower part of the ice-contact deposits. Outwash sand-and-gravel deposits overlie the marine silt and clay and the upper part of the ice-contact deposits.

Carbonate Bedrock Aquifer

The carbonate bedrock aquifer in northeastern Maine consists of limestone, calcareous shale, and calcareous siltstone (fig. 1). Generally, the aquifer is confined. Water yield from the aquifer depends primarily on the number of secondary openings such as joints, fractures, bedding or cleavage planes, or solution openings. As indicated in table 2, the common yields from this aquifer range from 10 to 30 gal/min but may exceed 600 gal/min. Most wells completed in the aquifer were developed for domestic or farm use. Deep wells generally have the greatest yields. These large-yielding wells are used primarily for industrial or public supplies but also may be used for irrigation in some areas. The water quality in the carbonate bedrock aquifer is suitable for most uses, except that it is hard.

Crystalline Bedrock Aquifer

Crystalline bedrock underlies much of the State and is the most widespread aquifer. It consists of numerous igneous and metamorphic rock types. The hydraulic properties of these rock types are similar and are, therefore, considered to be part of a single aquifer. Water yield primarily depends on the number of secondary openings such as joints, fractures, and bedding or cleavage planes. Development of municipal or large industrial wells in crystalline bedrock generally is attempted only if no other source of ground- or surface-water supply is readily available because of the uncertainty of locating a highly fractured zone.

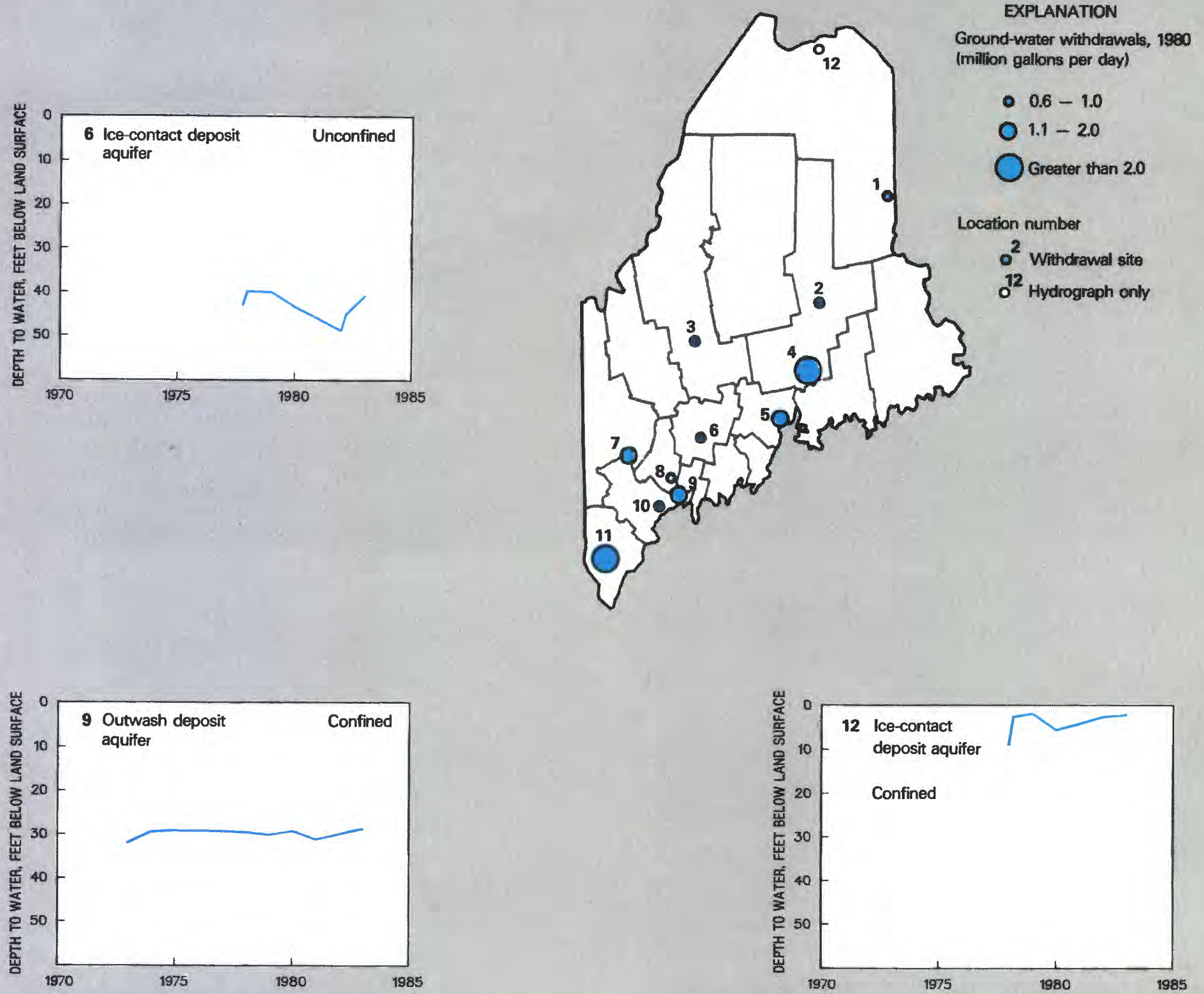
Expected yields for crystalline bedrock wells range from 2 to 10 gal/min but may exceed 500 gal/min (table 2). The quality of water from these aquifers generally is suitable for most uses. Some water supplies are treated to remove iron and manganese. Wells drilled in coastal areas have yielded brackish or salty water (Prescott, 1973; Tepper, 1980). Also, a study by the University of Maine at Orono (Hess and others, 1979) found levels of radioactive radon-222 gas in excess of 10,000 pCi/L in water from wells completed in granite, pegmatite, and high-grade metamorphic rocks.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Areas of major ground-water withdrawals for public-water supply are shown in figure 2. All these withdrawals are from ice-contact or outwash sand-and-gravel deposits. Data are not available for industrial ground-water use, except that self-supplied industrial withdrawals are estimated to account for more than 40 percent of the total ground-water withdrawals (table 1). Although most industrial wells are located in sand-and-gravel deposits, some large-yield wells (exceeding 400 gal/min) were developed in crystalline and carbonate bedrock (Prescott 1964, 1970).

Continuous water-level records that show the effects of pumping generally are not available in Maine. Where such water-level records are available, the data indicate that climate affects water-level changes to a greater degree than pumping stress. Long-term decline in the water levels of major aquifers has not been a problem in the State, because recharge from precipitation and surface water is sufficient to replenish water withdrawn. However, in southwestern coastal areas, water-supply shortages are beginning to occur as a result of the increasing demands of large summer tourist populations and a steadily increasing year-round population. Water-supply shortages are predicted for 57 percent of the towns in coastal Maine by the year 1990 (Caswell and Ludwig, 1978).

The hydrographs in figure 2 represent annual, lowest recorded water-levels observed in the major sand-and-gravel aquifers of Maine. Although the annual low water-levels fluctuate, the long-term water levels in all three wells have remained fairly stable. The well near the Brunswick-Topsham area (location 9, fig 2) has the longest continuous record. The water level for this well was about the same at the end of 1983 as it was 10 years earlier. During this 10-year period, the range of water level was only about 6 to 7 feet. The peaks in the hydrographs correlate well with the increased precipitation.



WITHDRAWAL SITES [Withdrawals are principally for public supply]		
No. on map	Geographic area	Aquifer
1	Houlton area.	Ice-contact deposit.
2	Lincoln area	Do.
3	Bingham area	Do.
4	Bangor area	Do.
5	Belfast area	Do.
6	Augusta area.	Do.
7	Paris-Norway area.	Outwash and ice-contact deposit.
8	Lisbon Falls area	Ice-contact deposit.
9	Brunswick-Topsham area.	Outwash deposit.
10	Yarmouth area	Ice-contact deposit.
11	Sanford area	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Maine. (Sources: Withdrawal and water-level data from the U.S. Geological Survey.)

GROUND-WATER MANAGEMENT

Several State agencies presently have statutory responsibilities for ground-water protection and management. The Department of Conservation, through the Maine Geological Survey and the Land Use Regulation Commission, is responsible for coordinating ground-water research, mapping ground-water availability, performing research into permit-related ground-water problems, and regulating activities that impact ground water in areas where population is sparse.

The Department of Environmental Protection, through its Bureaus of Water, Land, and Oil and Hazardous Materials, is reponsible for reviewing and licensing activities that impact ground water. This Department also is responsible for research into the effects of gasoline leaks and pesticides on ground water and for ground-water-quality assessments and emergency response and cleanup.

The Department of Human Services is involved with ground-water protection and management through its Drinking Water Program, Environmental Health Unit, and Public Health Laboratories. The Department is responsible for reviewing and approving new public water-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 Maine Land and Water Resources Council is examining the State's present statutes and regulations, agency programs and manpower, and agency activities that pertain to ground water in an effort to ensure protection of public health and continued availability of ground water.

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Prepared by Thomas J. Maloney and Derrill J. Cowing

For further information contact Chief, Maine Office, U.S. Geological Survey, 26 Ganneston Drive, Augusta, ME 04330

MARYLAND AND THE DISTRICT OF COLUMBIA
Ground-Water Resources

Ground water is an abundant natural resource in Maryland. Although it constitutes only 13 percent of total water used in the State, it is of substantial cultural and economic significance. The area east of Chesapeake Bay is dependent almost entirely on ground water for freshwater supplies. Maryland's aquifers provide water for nearly 1.3 million people (about 30 percent of the State's population) and for industry, irrigation, and other uses. In contrast, the District of Columbia depends mostly on surface-water supplies, although nearly 1 million gallons per day (Mgal/d) of ground water is used for industry. Ground water also is relied on for emergency backup for some hospitals, Government facilities, and embassies. Ground water was very important to the District of Columbia during its early years and was the sole source of water until the city began to use surface water in 1859 (Johnston, 1964, p. 42, 46). Ground-water withdrawals in Maryland and the District of Columbia in 1980 for various uses are given in table 1.

Table 1. Ground-water facts for Maryland and the District of Columbia

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Maryland–Herring, 1983; District of Columbia—Solley, Chase, and Mann, 1983]

	MD	D.C.
Population served by ground water, 1980		
Number (thousands)	1,279	0
Percentage of total population	30	0
From public water-supply systems:		
Number (thousands)	[1]540	0
Percentage of total population	13	0
From rural self-supplied systems:		
Number (thousands)	739	0
Percentage of total population	17	0
Freshwater withdrawals, 1980		
Surface water and ground water, total (Mgal/d)	1,400	340
Ground water only (Mgal/d)	175	0.8
Percentage of total	13	0.2
Percentage of total excluding withdrawals for thermoelectric power	17	0.4
Category of use		
Public-supply withdrawals:		
Ground water (Mgal/d)	65	0
Percentage of total ground water	37	0
Percentage of total public supply	9	0
Per capita (gal/d)	120	0
Rural-supply withdrawals:		
Domestic:		
Ground water (Mgal/d)	56	0
Percentage of total ground water	32	0
Percentage of total rural domestic	100	0
Per capita (gal/d)	75	0
Livestock:		
Ground water (Mgal/d)	7	0
Percentage of total ground water	4	0
Percentage of total livestock	54	0
Industrial self-supplied withdrawals:		
Ground water (Mgal/d)	34	0.8
Percentage of total ground water	19	100
Percentage of total industrial self-supplied:		
Including withdrawals for thermoelectric power	6	0.6
Excluding withdrawals for thermoelectric power	18	57
Irrigation withdrawals:		
Ground water (Mgal/d)	13	0
Percentage of total ground water	8	0
Percentage of total irrigation	54	0

[1] Estimated from data in Maryland Department of Natural Resources and Maryland Department of Health and Mental Hygiene, 1983b.

GENERAL SETTING

Average annual precipitation, based on the 30-year period of record (1951–80), ranges from about 37 to 47 inches (in.) in western Maryland and from about 42 to 47 in. in eastern Maryland. In the District of Columbia, average annual precipitation is about 43 in. Recharge rates vary, but, generally, about one-fourth to one-third of precipitation reaches the water table. A very small part of this ground water moves into the deeper aquifers; most discharges to nearby streams and provides about 50 to 70 percent of the flow of Maryland's streams.

Differing geologic features and landforms of the several physiographic provinces of Maryland and the District of Columbia cause significant differences in ground-water conditions from one part of the area to another. Physiographic provinces of Maryland are the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus (fig. 1). Physiographic provinces of the District of Columbia are the Coastal Plain and Piedmont. The Coastal Plain is underlain by gently dipping, unconsolidated strata. The Piedmont and Blue Ridge are underlain by crystalline rock and consolidated sedimentary units. Intensely folded and faulted consolidated sedimentary strata form the Valley and Ridge. These same strata are folded more gently in the Appalachian Plateaus.

PRINCIPAL AQUIFERS

Aquifers in Maryland and the District of Columbia generally are of two distinct types—unconsolidated aquifers of the Coastal Plain and consolidated sedimentary and crystalline aquifers of the other physiographic provinces (termed non-Coastal Plain aquifers). Principal aquifers and aquifer groups are described below and in table 2; their areal distribution is shown in figure 1. The aquifer groups include aquifers and interbedded confining beds; the confining beds are not delineated in figure 1.

COASTAL PLAIN AQUIFERS

The unconsolidated deposits underlying the Coastal Plain form a southeastwardly thickening sequence that consists of sand-and-gravel aquifers interlayered with silt and clay confining beds. These deposits are underlain by consolidated rock similar to that of the Piedmont, at depths ranging from zero at the Fall Line to about 8,000 feet at Ocean City. With the exception of the Columbia aquifer, the Coastal Plain aquifers generally are confined except where exposed or where overlain only by permeable surficial sediments.

The Columbia aquifer, which is the uppermost hydrogeologic unit of the Coastal Plain in most of Maryland east of Chesapeake Bay, is used as a principal water supply

Table 2. Aquifer and well characteristics in Maryland and the District of Columbia

[Gal/min = gallons per minute; ft = feet; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and Maryland Geological Survey.]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Coastal Plain Aquifers:				
Columbia aquifer: Sand, gravel, silt, clay, and slightly cemented gravelly sand. Generally unconfined.	20 – 150	50 – 500	1,500	A well in channel-fill gravel yielded 4,000 gal/min. Locally, water contains iron in excess of 0.3 mg/L. Nitrate contamination in some areas. Brackish water found in coastal areas.
Aquifers in Chesapeake Group: Multi-aquifer unit. Interbedded layers of sand, shells, gravel, silt, and clay. Generally confined.	90 – 500	10 – 400	1,000	Includes Pocomoke, Ocean City, Manokin, Frederica, Federalsburg, and Cheswold aquifers. Water contains iron in excess of 0.3 mg/L in some areas and generally is hard. Contains saltwater in some areas.
Piney Point aquifer: Sand, moderately glauconitic, and interbedded layers of shells, silt, and clay. Confined.	150 – 550	10 – 250	600	Water hard (exceeds 120 mg/L of calcium carbonate) in some areas; slightly saline in downdip areas.
Aquia aquifer: Sand, glauconitic; inter-bedded layers of silty clay and shells; cemented layers. Generally confined.	50 – 600	20 – 250	600	Iron concentrations exceed 0.3 mg/L in some areas. Locally, aquifer contains brackish water induced from Chesapeake Bay.
Magothy aquifer: Sand and fine gravel; interbedded thin layers of clay. Generally confined.	100 – 900	50 – 500	1,000	Iron concentration exceeds 0.3 mg/L, and pH less than 5.5 in some areas. Saltwater found in downdip areas.
Aquifers in Potomac Group: Multi-aquifer unit. Interbedded lenses of sand, gravel, silt, and clay. Generally confined.	30 – 1,250	100 – 1,000	2,000	Includes Patuxent and Patapsco aquifers and Potomac aquifer where undifferentiated. Large iron concentration (0.3 mg/L) and low pH present in some areas. Locally, contains brackish water induced from Chesapeake Bay and industrial pollutants. Saltwater found in downdip areas.
Non-Coastal Plain Aquifers:				
Aquifers in Newark Group: Sandstone, siltstone, shale, and conglomerate; some diabase dikes and sills. Unconfined to confined.	30 – 600	10 – 100	800	Water commonly hard; large iron and manganese concentrations in water from some wells; water from a few wells has a large sulfate concentration.
Appalachian sedimentary aquifers: Predominantly sandstone, shale, and siltstone; some limestone, dolomite and coal. Unconfined to confined.	30 – 400	2 – 50	200	Hard water and large iron and manganese concentrations in water are common problems. Brine present at varying depths below 500 ft. Locally, water has low pH and large sulfate and iron concentrations related to coal mining.
Carbonate aquifers: Limestone, dolomite, and marble; some shale and quartzose limestone. Unconfined to confined.	30 – 400	5 – 200	500	Water generally hard; large iron and manganese concentrations in water are local problems.
Piedmont and Blue Ridge crystalline aquifers: Schist, gneiss, phyllite, and metamorphosed igneous units; some quartzite. Unconfined to partly confined.	30 – 400	2 – 60	200	Low pH of water from many units may affect pipes and appliances. Some water contains large iron and manganese concentrations.

throughout that area. The approximate western limit of the aquifer is shown on the map in figure 1, and the relation of the aquifer to other Coastal Plain aquifers is indicated on the cross section. The aquifer generally is unconfined, but deeper zones locally are confined by clay layers. Thin surficial alluvium and terrace gravels are present elsewhere in Maryland, but these are not commonly used for water supply and, thus, are not shown in figure 1.

The aquifers in the Chesapeake Group are used mostly east of the Chesapeake Bay. These include the Cheswold, Federalsburg, and Frederica aquifers, which are used from Dorchester to Queen Annes Counties, and the Manokin, Ocean City, and Pocomoke aquifers, which are used in Somerset, Worcester, and Wicomico Counties. The Piney Point aquifer, which does not crop out, is tapped by wells in an area about 40 miles (mi) wide between Caroline and St. Marys Counties. The Aquia aquifer supplies water to an area about 50 mi wide between Kent and Queen Annes Counties in the northeast and Charles and St. Marys Counties in the southwest. The Magothy aquifer is used in a triangular area with corners in Cecil, Charles, and Dorchester Counties. Aquifers in the Potomac Group are used for water supply primarily north and west of Chesapeake Bay from Cecil to Charles Counties. From Baltimore County to Charles Coun-

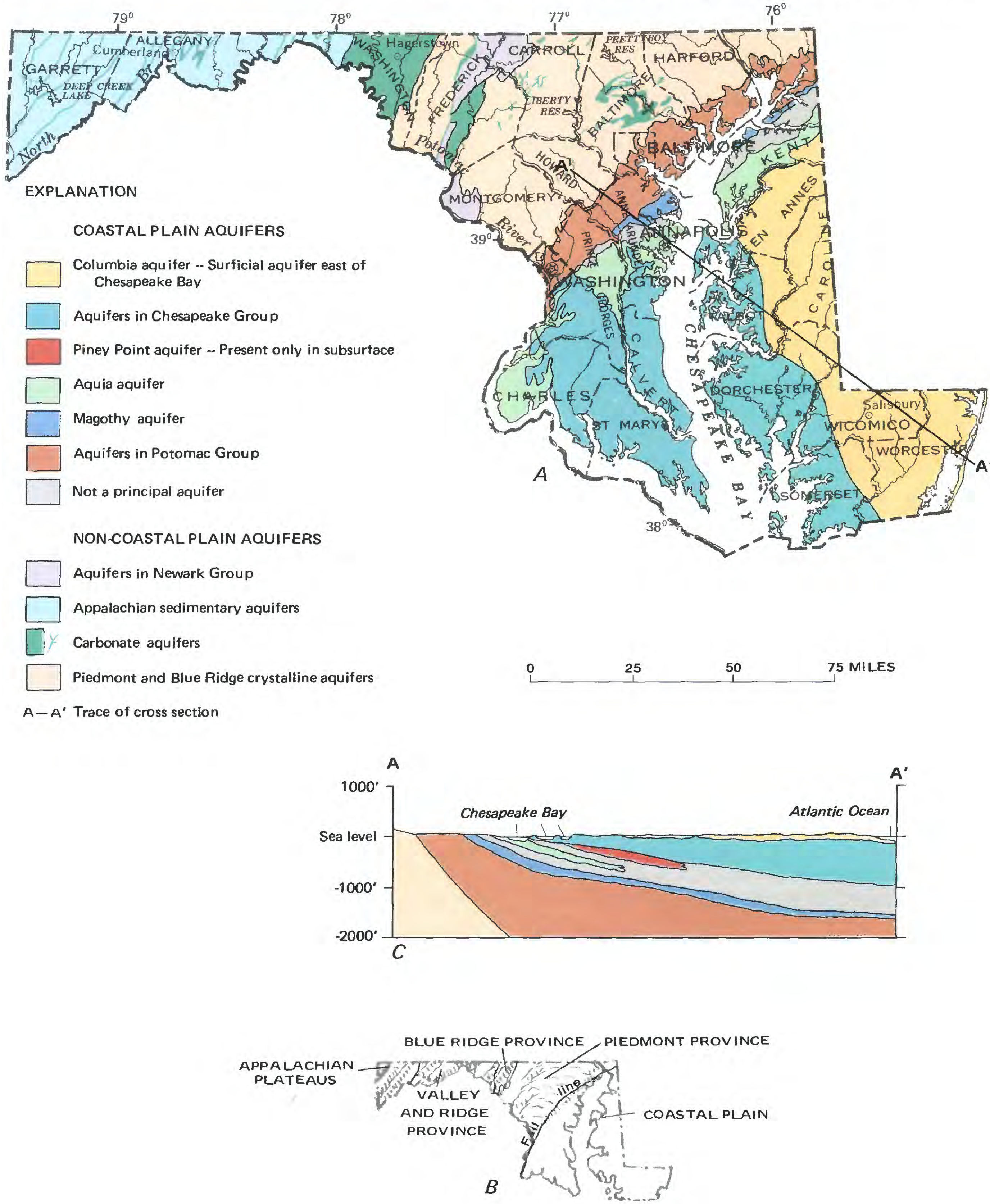

Figure 1. Principal aquifers in Maryland and the District of Columbia. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Otton and Richardson, 1958; Maryland Geological Survey, 1967; Cleaves and others, 1968; and Hansen, 1972. *B*, Raisz, 1954. *C*, compiled by L. J. McGreevy from U.S. Geological Survey files.)

ty, the group includes the Patuxent and Patapsco aquifers. In Cecil and Hartford Counties, the aquifers are not differentiated and are called the Potomac aquifer. The Patuxent and Patapsco aquifers are the only Coastal Plain aquifers used for water supply in the District of Columbia.

Well yields of Coastal Plain aquifers depend on thickness and intergranular permeability of the sand and gravel layers and on well construction. Where permeable layers are sufficiently thick, well fields may produce several million gallons per day. Most Coastal Plain aquifers contain saltwater in downdip areas. Natural water quality generally is suitable for most uses; locally, however, excessive concentration of iron [0.3 milligrams per liter (mg/L)] may exist and the water can be hard (120 mg/L as calcium carbonate). The water may also be acidic in some areas with pH values as low as 5. In a few locations, aquifers have been contaminated from surface sources. The presence of saltwater in the Coastal Plain aquifers is discussed by Meisler (1981), Cushing and others (1973), and Hansen (1972).

NON-COASTAL PLAIN AQUIFERS

Aquifers of the Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus consist of consolidated sedimentary and crystalline rock. Well yields depend on the presence of open fractures, although a few sandstones have some intergranular permeability. Well yields generally are small but may be as much as several hundred gallons per minute. Fracture openings in carbonate units (limestone, dolomite, and marble) commonly are enlarged by solution, and some wells that intercept enlarged openings have large yields. Aquifers in the Newark Group, the Appalachian sedimentary aquifers, and the carbonate aquifers generally are unconfined to partly confined in the upper hundred feet or so but may be confined at depth. The Piedmont and the Blue Ridge crystalline aquifers generally are unconfined to partly confined.

Natural water quality generally is suitable for most uses. The most common problems are iron and manganese concentrations, which sometimes exceed national drinking-water regulations (U.S. Environmental Protection Agency, 1982a,b); in some units, water hardness is in excess of 120 mg/L as calcium carbonate, and pH is less than 5. Brine underlies freshwater in the Appalachian sedimentary units but generally is at depths deeper than common drilling for ground-water wells. Locally, pollutants from surface sources have contaminated the ground water.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals and trends of ground-water levels near selected pumping centers are shown in figure 2. All centers that produce more than 1 Mgal/d are in the Coastal Plain, with the exception of a quarry north of Baltimore (location 1, fig. 2). The largest concentration of pumping is near Baltimore and Annapolis. Pumping centers that produce from 0.1 to 1 Mgal/d are distributed throughout the State.

Water levels generally decline in response to increases in pumping and recover as pumping is reduced. The hydrographs shown in figure 2 reflect the response of aquifers to pumping at selected withdrawal centers in the Maryland Coastal Plain. Increased pumping for private and public water supplies, powerplants, and military facilities has caused water levels to decline in the Aquia aquifer (location 10, fig. 2) and in the Magothy aquifer (location 8, fig. 2). Water levels in the Patuxent aquifer in the Glen Burnie area (location 4, fig. 2) have declined steadily since the mid-1950's in response to increasing withdrawals, principally for public supplies, from the Patuxent and Patapsco aquifers.

Water levels in the Piney Point aquifer near Cambridge (location 15, fig. 2) have recovered in response to reduced pumping. Withdrawals from the Piney Point aquifer were reduced partly because new wells were drilled to tap other aquifers and partly because water use declined. Water levels in the Patapsco aquifer in the Baltimore area (location 3, fig. 2) also show recovery. There, pumping induced movement of brackish water from the Chesapeake Bay to the Patapsco aquifer. This caused wells in the Patapsco aquifer to be abandoned in favor of the deeper Patuxent aquifer.

By contrast, little change in water level is noted in the hydrograph of a well in the Columbia aquifer near the major pumping center at Salisbury, Md. (location 16, fig. 2). The aquifer is unconfined, and the cone of depression caused by pumping diverts water from local streams; the diversion helps maintain ground-water levels, although streamflow may decline as a result.

GROUND-WATER MANAGEMENT

The District of Columbia relies mainly on surface water and has no specific legislation directed at ground-water management. In Maryland, however, ground-water management and planning legislation are extensive. Two State-level organizations implement most of the regulatory, planning, and research programs.

The Maryland Department of Health and Mental Hygiene, through its Office of Environmental Programs, is responsible primarily for regulatory and operational programs with regard to water-quality aspects of ground-water management. As part of its responsibilities, the Office of Environmental Programs issues well-construction permits (Code of Maryland Regulation 10.17.13, implemented in 1945), requires well-completion reports from licensed well drillers, and regulates the disposal of water to the ground-water system (Health-Environmental Article, 9-3222).

The Maryland Department of Natural Resources, through its agencies the Water Resources Administration and the Maryland Geological Survey, has a major role in ground-water-resource planning and management. The Water Resources Administration provides direction in the development, management, and conservation of the water of the State and regulates ground-water use through an appropriation-permit program (Natural Resources Article, 8-802, enacted in 1933). This program requires a permit to appropriate ground or surface water and requires water-use reports for withdrawals of 10,000 gallons per day or more. Domestic and farm users (including irrigation use) are exempt from these requirements. The Maryland Geological Survey is responsible for the maintenance of a statewide water-data network and the investigation of the State's water resources; these responsibilities are accomplished in cooperation with the U.S. Geological Survey. The research, data collection, and analyses provided by this cooperative program form an information base upon which ground-water management decisions are made by the Water Resources Administration.

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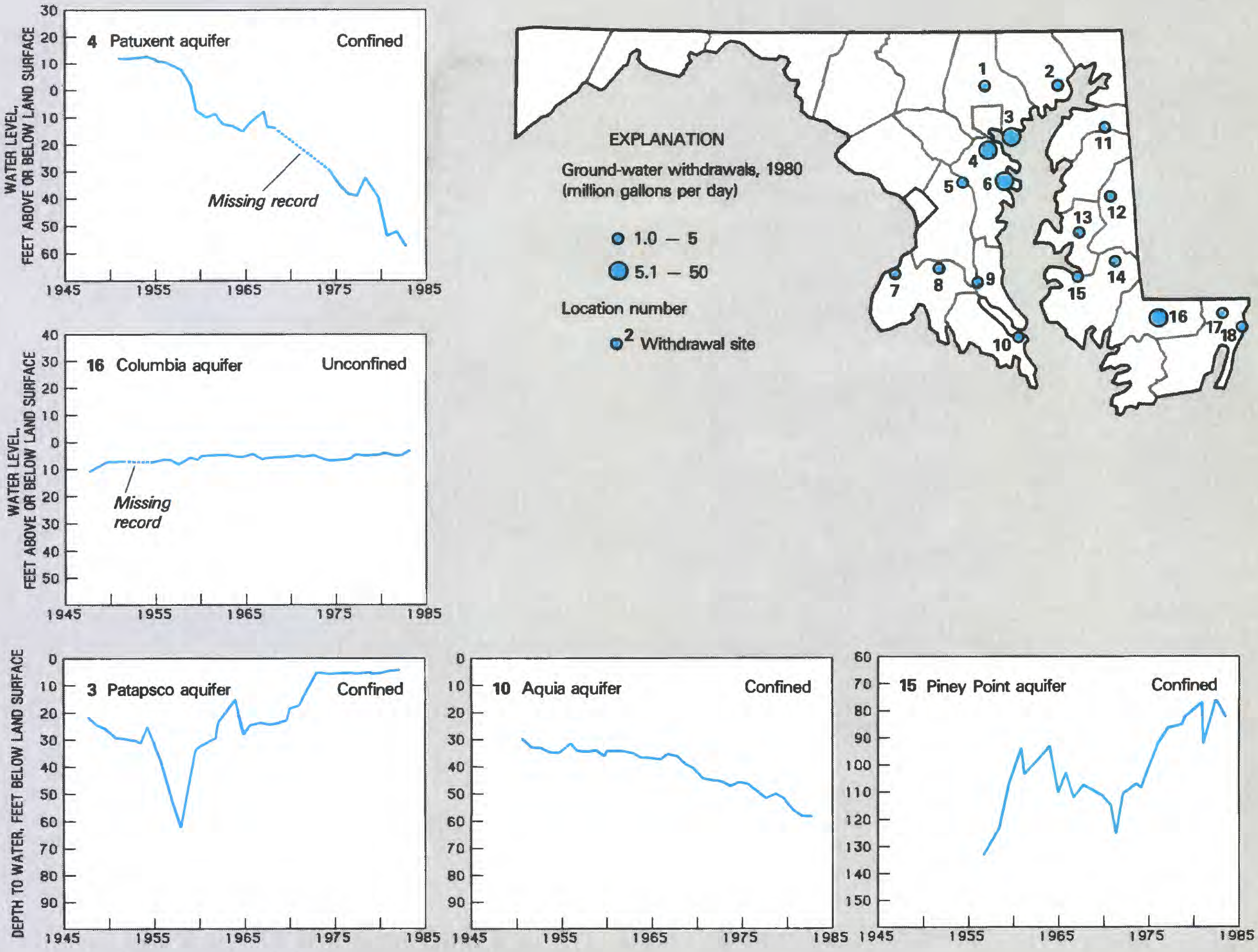

WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Texas area	Carbonate	Industrial.
2	Aberdeen area	Columbia, Potomac	Public supply.
3	Baltimore area	Patuxent, Alluvium, Patapsco	Industrial.
4	Glen Burnie area	Patapsco, Patuxent	Public supply, industrial.
5	Bowie area	....do	Industrial, public supply.
6	Annapolis area	Patapsco, Magothy	Public supply.
7	Indian Head area	Patapsco	Do.
8	Waldorf-La Plata area	Magothy, Patuxent, Patapsco	Do.
9	Chalk Point area	Magothy, Patapsco	Industrial.
10	Lexington Park area	Aquia, Piney Point	Public supply.
11	Chestertown area	Magothy	Do.
		Aquia	Public supply, industrial.
12	Ridgely area	Frederica	Do.
		Piney Point	Public supply.
		Manokin	Do.
		Federalsburg	Do.
13	Easton area	Magothy, Aquia	Do.
14	Hurlock area	Columbia	Industrial, public supply.
15	Cambridge area	Aquia, Piney Point	Public supply.
16	Salisbury area	Columbia	Public supply, industrial.
17	Showell area	....do	Industrial, public supply.
18	Ocean City area	Manokin	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Maryland and the District of Columbia. (Sources: Withdrawal data from Herring, 1983; Solley and others, 1983; water-level data from U.S. Geological Survey files.)

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Prepared by Laurence J. McGreevy and Judith C. Wheeler

For further information contact Chief, Maryland Office, Mid-Atlantic District, U.S. Geological Survey, 8600 La Salle Road, Towson, MD 21204

MASSACHUSETTS
Ground-Water Resources

One-third of the 5.7 million people in Massachusetts obtain their water supply from wells. Public-supply wells provide water to 1.5 million people, and private rural wells provide water to an additional 400,000 people (table 1). Although all the State's major urban areas use surface-water supplies, ground water is the primary source for 165 public supplies and a secondary source for an additional 33 public supplies. In 1980, an average 320 million gallons per day (Mgal/d) of fresh ground water was withdrawn for public, rural, industrial, and irrigation supplies. Of this, 59 percent was for public supply, 29 percent was for industrial self-supply, and 10 percent was for rural domestic supply (table 1).

Contamination and drought have affected the ground-water resource in the past. Degradation of ground-water quality by wastes and chemicals has caused water shortages. Between 1978 and 1981, 25 public-supply wells with a combined capacity of 23 Mgal/d were taken out of service because of ground-water contamination. Drought, caused by deficient precipitation, exacerbated these water-supply shortages in 1981, a year when 38 communities declared water emergencies. Also, road salt has contaminated local ground water, causing several public and private-supply wells to be taken out of service. In response to these and other ground-water problems, a ground-water-assessment program has been initiated by the Massachusetts Division of Water Resources and the U.S. Geological Survey. Ground-water-quality protection measures encouraged by State and Federal programs also are being implemented at the local government level.

Table 1. Ground-water facts for Massachusetts

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983, and Richard Thibedeau, Massachusetts Division of Water Resources, written commun., 1984]

Population served by ground water, 1980	
Number (thousands)	1,900
Percentage of total population	33
From public water-supply systems:	
Number (thousands)	1,500
Percentage of total population	26
From rural self-supplied systems:	
Number (thousands)	400
Percentage of total population	7
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	2,500
Ground water only (Mgal/d)	320
Percentage of total	13
Percentage of total excluding withdrawals for thermoelectric power	28
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	190
Percentage of total ground water	59
Percentage of total public supply	24
Per capita (gal/d)	127
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	32
Percentage of total ground water	10
Percentage of total rural domestic	100
Per capita (gal/d)	80
Livestock:	
Ground water (Mgal/d)	0.7
Percentage of total ground water	0.2
Percentage of total livestock	58
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	93
Percentage of total ground water	29
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	6
Excluding withdrawals for thermoelectric power	30
Irrigation withdrawals:	
Ground water (Mgal/d)	5
Percentage of total ground water	2
Percentage of total irrigation	28

GENERAL SETTING

Massachusetts is included in two physiographic provinces—the Coastal Plain and the New England Upland (Fenneman, 1938). The Coastal Plain province includes Cape Cod, Martha's Vineyard, and Nantucket (fig. 1); the province is characterized by plains and low hills underlain by a continuous blanket of unconsolidated sediments that cover bedrock to depths of 80 to 1,500 feet (ft). The upper 100 ft or more of these sandy sediments form the most productive aquifers in Massachusetts.

Except for the Connecticut Valley Lowland subdivision, the New England Upland province is underlain by crystalline metamorphic and igneous rocks that are covered by a discontinuous mantle of till and stratified drift. Topographic relief generally increases from the Seaboard Lowland in the east to the Berkshire Hills in the west. Stratified drift, which partly fills the valleys of the New England Upland, forms small, isolated, productive aquifers that are scattered throughout the province. The Connecticut Valley Lowland is underlain by a sequence of red sandstone, shale, conglomerate, and a basaltic lava flow, all dipping gently to the east where they are terminated by normal faults against the older crystalline rocks. Triassic and Jurassic rocks in this lowland are overlain by lacustrine sediments formed in postglacial Lake Hitchcock.

Ground-water recharge in Massachusetts is derived from precipitation which is rather uniformly distributed over the State at an average annual rate of about 44 inches (in.). Recharge rates are dependent on slope, soil permeability, and type of vegetation. Average annual recharge through soils developed on sand and gravel is estimated to be about 21 in. and through soils developed on glacial till, about 6 in. Most ground water is pumped from wells less than 300 ft deep. Unlike aquifers in most other parts of the country, aquifers in New England, in general, are relatively thin and many have limited areal extent, with the result that aquifers tend to have small storage capacity and are very susceptible to depletion during drought.

PRINCIPAL AQUIFERS

The principal aquifers in Massachusetts can be grouped according to general rock type into stratified glacial drift, sedimentary bedrock, carbonate rock, and crystalline bedrock. A brief description of each aquifer is given below and in

Table 2. Aquifer and well characteristics in Massachusetts

[gal/min = gallons per minute; ft = feet; in. = inch. Sources: Reports of the U.S. Geological Survey and Massachusetts]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Stratified-drift aquifer:[1] Sand and gravel with silt, glacial outwash, ice-contact, and delta deposits; some beach and dune deposits included. Moraines also contain till. Generally unconfined, locally confined.	60 - 120	200	100 - 1,000	2,000	Used extensively for public supply; also used for industry, fish hatcheries, agriculture, and rural supplies. Locally, large iron or manganese concentrations a problem. Some saline water intrusion in coastal areas. Low pH of water may corrode pipes and appliances.
Sedimentary bedrock aquifer: Red sandstone, shale, arkosic conglomerate, and basaltic lava flow. Generally, unconfined, confined at depth.	100 - 250	500	10 - 100	500	Used for rural supplies and some industry. Deep wells produce hard water.
Carbonate rock aquifer: Limestone, dolomite, and marble. Confined.	100 - 300	1,000	1 - 50	1,000	Used for rural supplies and some industry Water hard.
Crystalline bedrock aquifer: Metamorphic and igneous rock predominantly gneiss and schist. Confined.	100 - 400	1,000	1 - 20	300	Used for rural supplies. Locally, large iron concentrations a problem. Recently drilled wells generally deeper than older wells. Low pH of water may corrode pipes and appliances.

[1] Well depths and yields reported for stratified drift are for public-supply wells. Rural domestic wells yield 5-80 gal/min from 1¼- to 2½-inch-diameter well screens, 3 to 5 ft in length.

table 2, from youngest to oldest. The distribution of aquifers is shown in figure 1.

Stratified-Drift Aquifer

Stratified glacial drift provides water for virtually all public supplies that use ground water. The stratified-drift aquifer, which consists of layered sand and gravel with some silt, was deposited over bedrock by glacial meltwaters as the last Wisconsin continental glacier retreated from New England. In most of Massachusetts, these deposits form small but very permeable valley-fill aquifers (fig. 1).

Although these valley aquifers tend to have small volume and storage, they are very productive because of induced infiltration from traversing streams. However, as a result of infiltration induced by ground-water withdrawals, streamflows have been depleted and some small streams temporarily have ceased flowing. Public-supply wells in the stratified-drift aquifers generally are 24 in. in diameter, less than 100 ft deep, screened and gravel packed in the lower 20 percent of the aquifer, and yield several hundred gallons per minute. The water table commonly is less than 20 ft below land surface, but artesian conditions are present in a few locations.

In the southeastern corner of Massachusetts, the stratified-drift aquifer forms a continuous layer over bedrock rather than isolated valley deposits (fig. 1). Southern Plymouth County, Cape Cod, and the islands of Martha's Vineyard and Nantucket are mantled with 80 to several hundred feet of glacial moraine and outwash deposits of sand, gravel, and silt, with minor amounts of clay and some boulders (Guswa and LeBlanc, 1981; Delaney, 1980; Walker, 1980) (fig. 1). The upper 100 ft of the saturated parts of these deposits have been developed for public supplies. In areas not served by public supplies, water is obtained from 1¼- to 4-in.-diameter wells that are screened about 15 ft below the water table. The sediments underlying the northwestern part of Martha's Vineyard consist of Tertiary clay. In this part of Martha's Vineyard, sufficient quantities of ground water for domestic supply cannot be obtained at most locations. However, some widely scattered small sand lenses in the clay have been developed for rural domestic supplies.

Water quality of the stratified-drift aquifer generally is suitable for human consumption and most other uses (Frimpter and Gay, 1979). The water generally is acidic (pH 6.1), soft [20 milligrams per liter (mg/L) as calcium carbonate], and has small concentrations of dissolved solids (70 mg/L). Iron (as much as 8.8 mg/L) and manganese (as much as 0.9 mg/L) have been measured in ground water on Cape Cod. The greatest threat to water quality in these areally extensive water-table aquifers is from incompatible land uses. Sewage disposal through septic systems and municipal systems, landfills, dumps, road salt, and agricultural chemicals and pesticides are the most commonly recognized sources of ground-water-quality problems (Massachusetts Special Legislative Commission on Water Supply, 1981). In addition, two public-supply well fields and several private supplies have been affected by saltwater intrusion.

Sedimentary Bedrock Aquifer

The Triassic and Jurassic sedimentary bedrock aquifer in western Massachusetts consists principally of consolidated red sandstone, conglomerate and shale (fig. 1). Well yields depend on interception of open fractures, but some intergranular permeability, which is present in many of the sandstone units, sustains larger yields than would otherwise be expected. Well yields generally range from 10 to 100 gallons per minute (gal/min) but may exceed 500 gal/min (Walker and Caswell, 1977). Water generally is unconfined in the upper saturated 100 ft of the aquifer, but is confined at greater depths. Water from deep parts of the aquifer commonly is hard (greater than 300 mg/L) and may have large concentrations of sulfate (greater than 250 mg/L) and dissolved solids (greater than 600 mg/L) (see Wandle and Caswell, 1977).

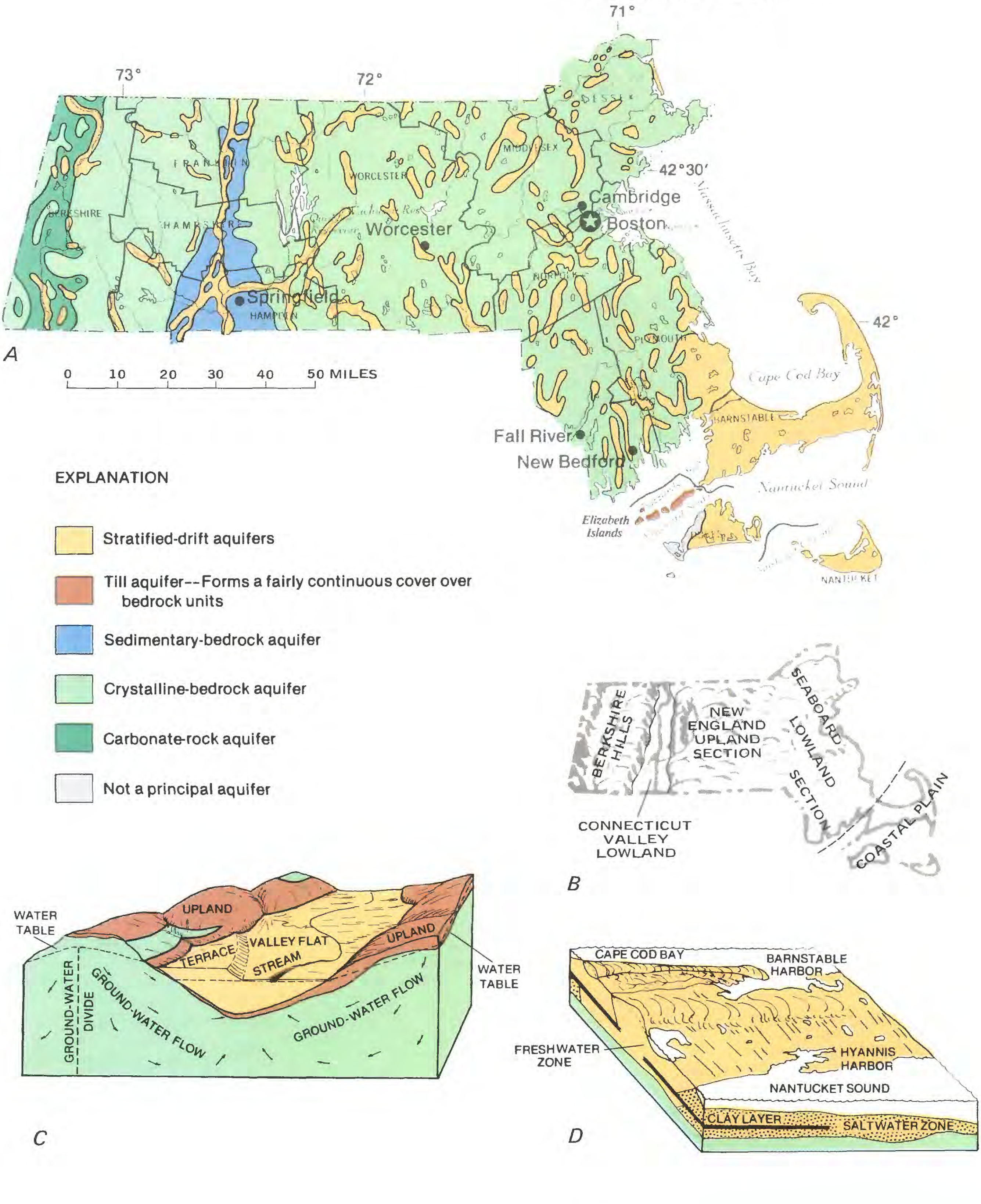


Figure 1. Principal aquifers in Massachusetts. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Valley-fill stratified-drift aquifer. *D*, Continuous blanket stratified-drift aquifer. (See table 2 for more detailed description of aquifers. Sources: *A*, Delaney and Maevsky, 1980; Norvitch and others, 1968; Walker and Caswell, 1977; Hansen and others, 1973. *B*, Fenneman, 1938; Raisz, 1954. *C*, Frimpter, 1981. *D*, Compiled by M. H. Frimpter from U.S. Geological Survey files.)

CARBONATE ROCK AQUIFER

The carbonate rock aquifer is present in Berkshire County and consists of limestone, dolomite, and marble formations interbedded with schist and quartzite (Norvitch and others, 1968) (fig. 1). Locally, fractures in these rocks have been enlarged by solution, which has considerably increased aquifer permeability. As a result, well yields that exceed 1,000 gal/min have been reported (Norvitch and Lamb, 1966). Wells completed in this aquifer provide industrial and rural domestic supplies but no public supplies. The aquifer commonly is confined. Water from the aquifer is hard (100–350 mg/L as calcium carbonate).

CRYSTALLINE BEDROCK AQUIFER

Rural areas rely mostly on the crystalline igneous and metamorphic bedrock aquifer for water supply. Ground water in sufficient quantities for individual home supplies can be obtained almost everywhere. Water is present in secondary openings (fractures, joints, and fault or shear zones) in these otherwise-impermeable rocks (Massachusetts Division of Water Resources, 1976). The crystalline bedrock aquifer is not used on Cape Cod, Martha's Vineyard, and Nantucket because it occurs at great depth, contains saline water, or is overlain by readily accessible water in stratified-drift aquifers.

Well yields of more than 300 gal/min have been obtained from the crystalline bedrock aquifer, but such yields are very uncommon. These large-yield wells are located in very fractured zones and near saturated stratified drift, which serves as a recharge source to the bedrock fractures. In a few areas, the yields of bedrock wells are small and may be insufficient for domestic supply. Wells in the bedrock are considered to be artesian because water in the wells almost always rises above the level at which it is found. Some wells in this aquifer yield water with objectionable quantities of iron (greater than 0.3 mg/L and as much as 20 mg/L). Ground water at some locations has been contaminated with road salt, petroleum products, solvents, pesticides, or sewage.

OTHER AQUIFERS

A thin layer of unconsolidated glacial till overlies bedrock throughout Massachusetts. Early rural homesteads obtained water from this till almost exclusively by means of large-diameter (36-in.) shallow (commonly less than 30 ft deep) dug wells or from springs. Till generally is not considered to be a source for water supplies today because wells in till have small yields and are susceptible to drought and pollution. Also, advanced well-drilling techniques have made other aquifers more accessible. However, on the sparsely populated Elizabeth Islands, till is the only aquifer available and it yields small quantities of water to large-diameter wells.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

In 1980, 23 pumping centers (towns or cities) produced more than 2 Mgal/d (fig. 2), 43 pumping centers produced 1 to 2 Mgal/d, and another 102 centers produced from 100,000 gallons per day to 1 Mgal/d (Richard Thibedeau, Massachusetts Division of Water Resources, written commun., 1984). Withdrawals are continuing to increase in response to increased demands, most notably on Cape Cod where the population increased by more than 50 percent during the 1970's.

Long-term water-level declines have not been observed in any aquifer (fig. 2). Although the quantity of water stored in the stratified-drift aquifers is small, these aquifers are almost invariably adjacent to streams from which infiltration may be induced to sustain withdrawal by wells. Even though water levels have not shown a declining trend in response to withdrawals, seasonal water-level changes may be pronounced. Generally, very little recharge from precipitation occurs during the 180-day summer growing season. Ground-water withdrawals during this period are largely from aquifer storage or induced infiltration from streams or both. As would be expected, water-level fluctuations in a well tapping an aquifer from which freshwater is pumped for public supply and a local fish hatchery (location 24, figure 2) are greater than in a nearby unstressed aquifer (location 25, fig. 2). On Cape Cod, long-term water level declines have not occurred near a pumping center (location 21, fig. 2) or near an area where pumping has not occurred (location 26, fig. 2).

GROUND-WATER MANAGEMENT

All State agencies with ground-water management and planning responsibilities are managed by the Massachusetts Executive Office of Environmental Affairs. These responsibilities are carried out by the Departments of Environmental Management and of Environmental Quality Engineering (Massachusetts Department of Environmental Quality Engineering, 1984).

The Massachusetts Water Resources Commission develops and coordinates water-resources planning and management functions of the departments of the Massachusetts Executive Office of Environmental Affairs. In recognition of the interdependency of surface and ground water, the Commission has recommended a policy of preventing undesirable streamflow depletion through allocation of ground-water withdrawals for public supply. The Commission also establishes criteria and priorities for all water-related cooperative programs with the Federal Government and with other agencies of the State.

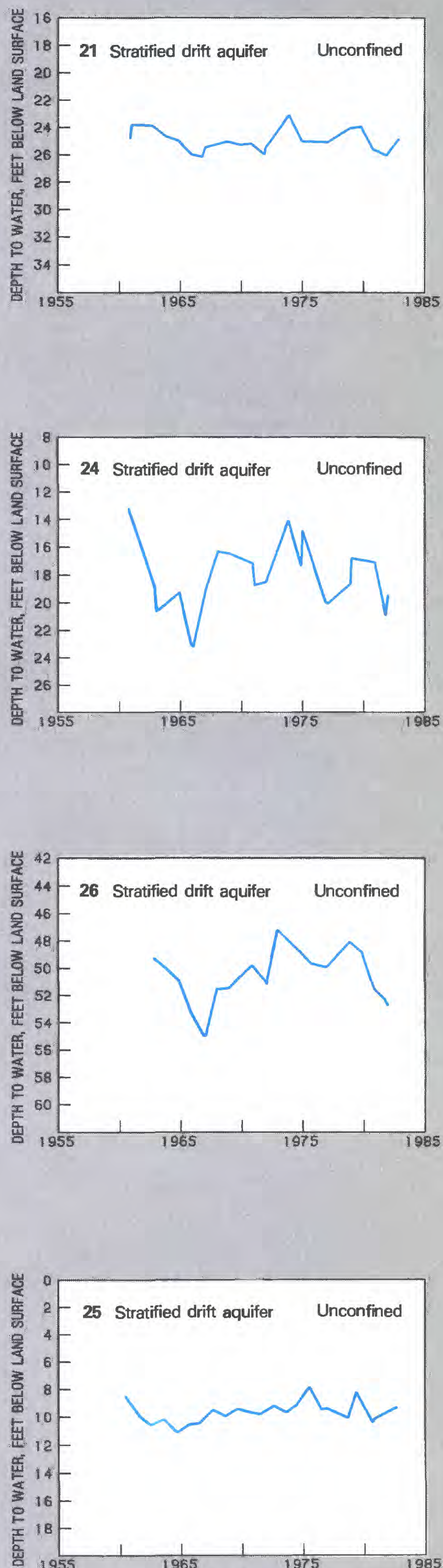
The Massachusetts Department of Environmental Management (MDEM) has two divisions responsible for water activities—the Division of Water Resources and the Bureau of Solid Waste Disposal. The Division of Water Resources collects and disseminates water-resources information and develops State water-resources plans (Water Resources Planning Regulations 313 CMR 2.00). This division administers water-resources data-collection and ground-water-assessment programs with the U.S. Geological Survey and with other Federal agencies. It also licenses well drillers and maintains records of well-completion reports.

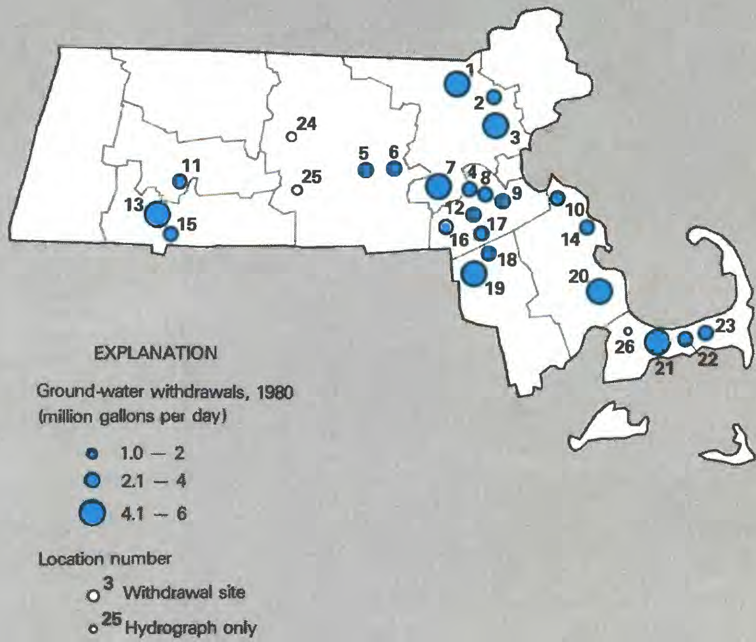
The Bureau of Solid Waste Disposal works to protect ground-water quality by planning for solid- and hazardous-waste disposal through regional facilities and by the dissemination of technical information.

The Massachusetts Department of Environmental Quality Engineering (MDEQE) has primary responsibility for ground-water quality through its Division of Water Supply, Division of Environmental Analysis, and Division of Hazardous Waste. The Division of Water Supply ensures drinking-water quality through its public-supply well-permit program. This division also collects and disseminates ground-water quality information and administers programs providing funds for water treatment and aquifer protection.

The Division of Environmental Analysis is the MDEQE's analytical laboratory. It regularly collects and analyzes samples of raw and treated public water supplies used for drinking-water purposes. It is also responsible for analyzing ground-water samples suspected of contamination.

The Division of Water Pollution Control of MDEQE is responsible for improving water quality and preventing ground-water pollution. It regulates discharges of polluting matter originating from point or major nonpoint sources into





WITHDRAWAL SITES [Aquifers are all stratified drift. Withdrawals are principally for public supply.]			
No. on map	Geographic area	No. on map	Geographic area
1	Chelmsford	13	Westfield
2	Wilmington	14	Marshfield
3	Woburn	15	Southwick
4	Wellesley	16	Franklin
5	Worcester	17	Foxborough
6	Shrewsbury	18	Mansfield
7	Natick	19	Attleboro
8	Needham	20	Plymouth
9	Dedham	21	Barnstable
10	Hingham	22	Yarmouth
11	Easthampton	23	Dennis
12	Walpole		

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Massachusetts. (Sources: Solley and others, 1983; Richard Thibedeau, Massachusetts Division of Water Resources, written commun., 1984.)

ground water by permit. It also administers MDEQE's water-resources inventory and water-quality research programs which it maintains in cooperation with universities and the U.S. Geological Survey (Isaac and others, 1983).

The Division of Hazardous Waste of MDEQE regulates activities with a large potential for ground-water contamination, responds to oil spills and other hazardous-waste accidents on an emergency basis, investigates illegal disposal activities, and supervises the cleanup of hazardous-waste sites. Its activities include the approval of ground-water monitoring programs, hydrogeologic studies, and evaluation of proposals for cleaning up contaminated ground-water.

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Prepared by Michael H. Frimpter

For further information contact District Chief, U.S. Geological Survey, 150 Causeway Street, Suite 1309, Boston, MA 02114

MICHIGAN
Ground-Water Resources

Ground water is the source of 17 percent of public-water supplies and nearly 100 percent of the domestic-water supplies in Michigan (Bedell, 1982). Ground water supplies 43 percent of the State's population; however, ground water accounts for only 4 percent of the total water used in the State because most supplies for large urban areas are from surface water, particularly the Great Lakes (Solley and others, 1983; Weist, 1978). Distant from the Great Lakes, water supplies generally are obtained from ground water. Ground-water withdrawal for irrigation is about 37 percent of the total water used for irrigation (Bedell and VanTil, 1979; Solley and others, 1983). Ground-water withdrawals in 1980 for various uses, and related statistics, are given in table 1.

Chemical characteristics of natural ground water in Michigan are determined primarily by the geologic environment through which the water flows. Natural ground water generally is suitable for human consumption and most other uses. Water from glacial deposits, at places, contains large concentrations of iron [2.5–5.0 milligrams per liter (mg/L)]; water from carbonate rocks is likely to be very hard (400–900 mg/L as calcium carbonate); and water from the Saginaw aquifer in the Saginaw Bay–Thumb area commonly is very mineralized (2,000–80,000 mg/L of dissolved solids). Throughout the State, salty water underlies freshwater at depths ranging from about 100 ft in the eastern part of the Lower Peninsula to about 900 ft in the northern part. Average dissolved-solids concentration of water from bedrock (535 mg/L) is about twice as great as the average concentration from glacial deposits (241 mg/L) (Cummings, 1980).

Michigan has identified more than 1,000 sites where ground water has been contaminated to some degree and an even greater number of sites where pollution is suspected (Michigan Department of Natural Resources, 1985). A wide range of contaminants is involved. At many sites, chlorinated hydrocarbons and hydrocarbons that are contained in fuel substances are the contaminants. Nitrates from surface sources have contaminated domestic ground-water supplies in concentrations of as much as 30 mg/L at some locations in the Lower Peninsula (Cummings and others, 1984).

Table 1. Ground-water facts for Michigan

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	3,978
Percentage of total population	43
From public water-supply systems:	
Number (thousands)	1,310
Percentage of total population	14
From rural self-supplied systems:	
Number (thousands)	2,668
Percentage of total population	29
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	15,000
Ground water only (Mgal/d)	530
Percentage of total	4
Percentage of total excluding withdrawals for thermoelectric power	18
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	220
Percentage of total ground water	41
Percentage of total public supply	17
Per capita (gal/d)	168
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	160
Percentage of total ground water	30
Percentage of total rural domestic	100
Per capita (gal/d)	60
Livestock:	
Ground water (Mgal/d)	17
Percentage of total ground water	3
Percentage of total livestock	77
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	62
Percentage of total ground water	12
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	1
Excluding withdrawals for thermoelectric power	3
Irrigation withdrawals:	
Ground water (Mgal/d)	77
Percentage of total ground water	14
Percentage of total irrigation	37

GENERAL SETTING

Michigan is divided into two principal physiographic provinces. The Lower Peninsula and the eastern part of the Upper Peninsula of Michigan are in the Central Lowland physiographic province. These areas are underlain by layered sedimentary bedrock of Paleozoic and Mesozoic age. The western part of the Upper Peninsula is a part of the Superior Upland physiographic province, which is underlain by igneous, metamorphic, and sedimentary rocks of Precambrian age. Glacial deposits cover most of the State.

Glacial deposits consist of sand, gravel, silt, clay, and boulders. Sand and gravel, such as in outwash and glaciofluvial deposits, are productive aquifers; mixtures of clay, silt, sand, gravel, and boulders, which form some till deposits, generally are poor aquifers. Lacustrine deposits that are predominantly sand are productive aquifers; those that are predominantly clay yield little or no water. In the northern part of the Lower Peninsula, glacial deposits in some areas are more than 800 feet (ft) thick; in most other areas in the State, the deposits are less than 200 ft thick.

In the Lower Peninsula and eastern Upper Peninsula, bedrock, which underlies glacial deposits and crops out at a few places, consists principally of Paleozoic shale, limestone, and sandstone. These rocks have been deformed into a structural feature known as the Michigan basin (Newcombe, 1933). Sandstone and limestone are productive aquifers and, where near enough to land surface to be recharged by precipi-

Table 2. Aquifer and well characteristics in Michigan

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U. S. Geological Survey and Michigan Department of Natural Resources, Geological Survey Division]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Glacial aquifers:					
Outwash and glaciofluvial deposits: Sand and gravel, contains silt and clay in places. Mostly unconfined.	25 - 200	400	1 - 1,000	2,000	Water generally hard; large iron concentrations common; deep wells may produce salty water in places.
Lacustrine sand: Sand, some gravel, and interbedded silt and clay. Mostly unconfined.	25 - 100	200	80 - 500	500	Used for domestic supplies in Saginaw Bay and Detroit areas; is salty in places at depth.
Till: Intermixed clay, silt, sand, gravel and boulders; sand and gravel lenses abundant in some areas. Confined and unconfined.	25 - 200	400	5 - 200	200	Primary source of domestic supply in western Upper Peninsula.
Bedrock aquifers:					
Saginaw Formation: Sandstone, siltstone, some shale, limestone, and coal. Mostly confined.	25 - 300	500	100 - 300	1,000	One of Michigan's most important bedrock aquifers; water generally hard; salty in places at depth.
Marshall Formation: Sandstone and siltstone. Mostly confined or semiconfined, unconfined at places.	25 - 200	400	100 - 500	1,500	Another of Michigan's important bedrock aquifers; salty in places and at depth.
Silurian-Devonian rocks: Limestone and dolomite; some shale and sandstone. Mostly confined.	25 - 150	200	10 - 300	500	Important aquifer in parts of eastern Upper Peninsula; water commonly hard.
Cambrian-Ordovician rocks: Sandstone, limestone, and dolomite. Mostly confined.	25 - 150	200	10 - 100	500	Important aquifer in eastern Upper Peninsula; water commonly very hard; salty in places and at depth.
Precambrian sandstone: Sandstone interbedded with siltstone. Mostly confined.	25 - 400	500	5 - 50	100	Important aquifer in western Upper Peninsula; salty in places.

tation, they produce freshwater. However, where deeply buried, these sedimentary rocks yield brackish or salty water. In some places, this brine is pumped for commercial use.

In the western Upper Peninsula, bedrock consists of Precambrian igneous, metamorphic, and sedimentary rocks. Igneous and metamorphic rocks generally are poor aquifers. Most ground-water production in this area is from glacial deposits and Precambrian sandstone. However, two public-water supplies are from old mine shafts in the igneous and metamorphic rocks.

Annual recharge to unconfined aquifers in Michigan ranges from 3 to 18 inches (in.) and is derived from precipitation which averages 31 in. annually. Some recharge moves to deep aquifers; however, most flows from shallow aquifers to nearby streams and accounts for about 55 percent of the State's streamflow.

PRINCIPAL AQUIFERS

The principal aquifers in Michigan consist primarily of glacial deposits and sedimentary bedrock. Characteristics of the aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

GLACIAL AQUIFERS

Lacustrine Sand Aquifers

Lacustrine sand is the major aquifer along Lake Huron northwest of Saginaw Bay and in parts of southeastern Michigan. This material was deposited when lake levels were higher in the Great Lakes basins. Some areas near Saginaw Bay and in southeastern Michigan are underlain by lacustrine clay, which yields little or no water. Dissolved-solids concentrations generally range from 100 to 500 mg/L.

Outwash and Glaciofluvial Aquifers

In the northern and western parts of the Lower Peninsula, outwash and glaciofluvial deposits generally are thick and coarse grained; in most of this area, ground-water supplies are abundant. In the western Upper Peninsula, however, outwash and glaciofluvial deposits tend to be thin and isolated; many wells in this area fail to yield sufficient supplies during periods of less-than-average precipitation. Dissolved-solids concentrations in all areas generally range from 100 to 500 mg/L.

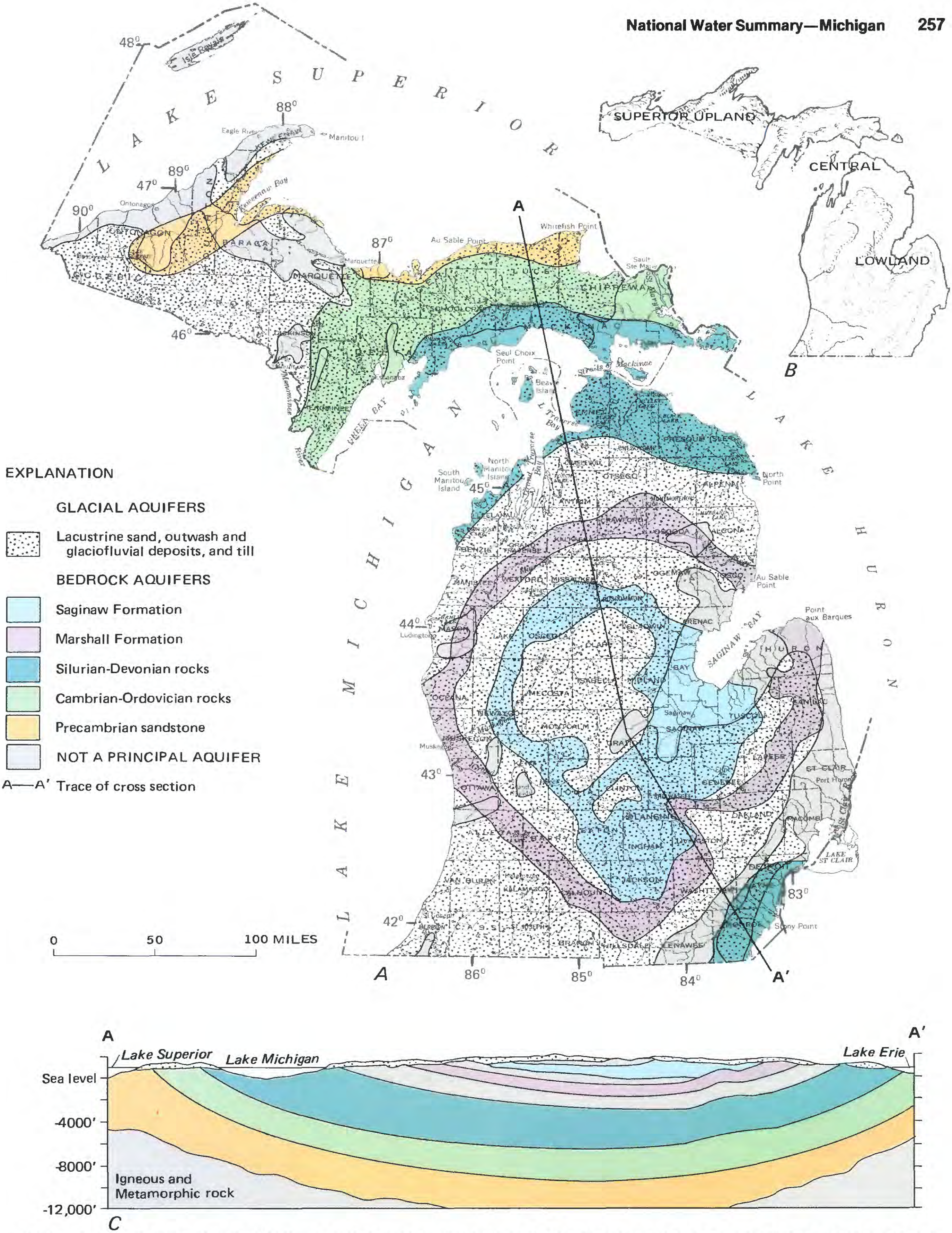


Figure 1. Principal aquifers in Michigan. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for more detailed description of aquifers. Sources: *A*, Farrand, 1982. *B*, Martin, 1936; Raisz, 1954. *C*, Compi led by N. G. Grannemann from U.S. Geological Survey files.)

Till Aquifers

In parts of the western Upper Peninsula, till generally contains lenses and beds of sand and gravel that provide sufficient water for domestic supplies. Elsewhere in the State, till consists of a poorly sorted mixture of rock materials of little permeability. Dissolved-solids concentrations generally range from 100 to 500 mg/L.

BEDROCK AQUIFERS

Saginaw Formation

The Saginaw Formation is an important aquifer in much of the central and eastern parts of the Lower Peninsula. The formation, which is of Pennsylvanian age, is primarily sandstone and siltstone in the Lansing area; it is siltstone and fined-grained sandstone interbedded with shale, limestone, coal, and gypsum in the Saginaw Bay area. Near Lansing, transmissivity of the formation ranges from 130 to 3,300 square feet per day (ft^2/d) depending on differences in degree of fracturing, number of bedding-plane fractures, thickness of the sandstone, and ratio of sand to shale. Sandstone at shallow depths is more permeable than deeply buried sandstone because fractures tend to decrease with depth (Vanlier and others, 1973). The formation is confined in most places. Recharge to the formation is primarily through the overlying glacial and lacustrine deposits. Water of the Saginaw Formation generally is hard; the average dissolved-solids concentration of the water is 1,600 mg/L (Cummings, 1980). Dissolved solids are less (300–800 mg/L) in areas where the aquifer is an important source for municipal supplies such as the Lansing area.

Marshall Formation

The Marshall Formation is one of the most productive bedrock aquifers in the State. The formation, which is of Mississippian age, is composed of siltstone and fine- to medium-grained sandstone. Transmissivity values for the Marshall Formation range from 2,700 to 67,000 ft^2/d (Vanlier, 1966), depending primarily on differences in thickness, size, and number of fractures. Although the Marshall Formation underlies much of the Lower Peninsula, it is used as an aquifer only in the southern part of the Lower Peninsula and in the Thumb area; elsewhere in the Lower Peninsula, water in the Marshall Formation is either too salty for use or other aquifers, closer to the land surface, are used. The formation is unconfined in some locations but generally is confined or semiconfined. Recharge to the formation is primarily through the overlying glacial and lacustrine deposits. Water of the Marshall Formation generally has a dissolved-solids concentration of less than 500 mg/L.

Silurian-Devonian Aquifers

Silurian-Devonian rocks, consisting principally of limestone and dolomite with some shale and sandstone, are aquifers in the northern and southeastern Lower Peninsula and in the southern part of the eastern Upper Peninsula (fig. 1). Transmissivities of these aquifers depend, to a large extent, on the number and interconnection of fractures and solution channels and on thickness. Silurian-Devonian aquifers generally are confined. Recharge to the formation is primarily through the overlying lacustrine deposits. Water of Silurian-Devonian rocks generally has a dissolved-solids concentration of less than 500 mg/L.

Cambrian-Ordovician Aquifers

Cambrian-Ordovician rocks are important aquifers in the east-central part of the Upper Peninsula. The rocks are principally fine- to coarse-grained sandstone in the lower part and limestone and dolomite in the upper part. Transmissivity values for these rocks depend primarily on lithology and thickness. Generally, the aquifers are confined. Recharge to the aquifers is primarily through the overlying glacial deposits. Dissolved-solids concentrations of water from Cambrian-Ordovician rocks range from about 150 to 2,000 mg/L.

Precambrian Sandstone Aquifers

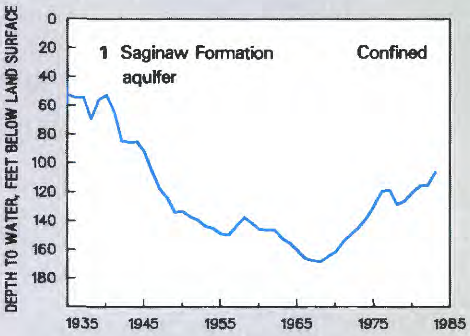
Precambrian sandstones are aquifers only in the northwestern Upper Peninsula where they are used by small communities and for domestic supplies. Because they are well-cemented and interbedded with siltstone and shale, Precambrian sandstones yield water primarily from fractures (Vanlier, 1963). Transmissivity values generally are small. At most places, the aquifer is confined. Recharge to the formation is primarily through the overlying glacial deposits. Dissolved-solids concentrations of water from Precambrian sandstones are generally less than 1,000 mg/L.

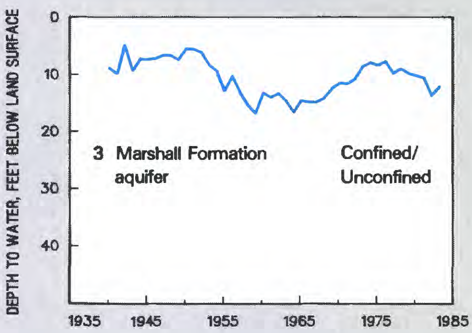
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

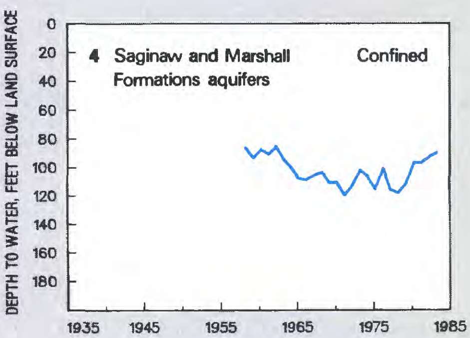
Location of major ground-water withdrawals and trends of ground-water levels near three locations are shown in figure 2. All major pumping centers are in the southern part of the Lower Peninsula; some tap bedrock aquifers, and others tap glacial deposits. Ground water is the source of water for 380 public-water supplies. Of these, 70 communities with a total population of 500,000 obtain water from the Marshall and Saginaw Formations.

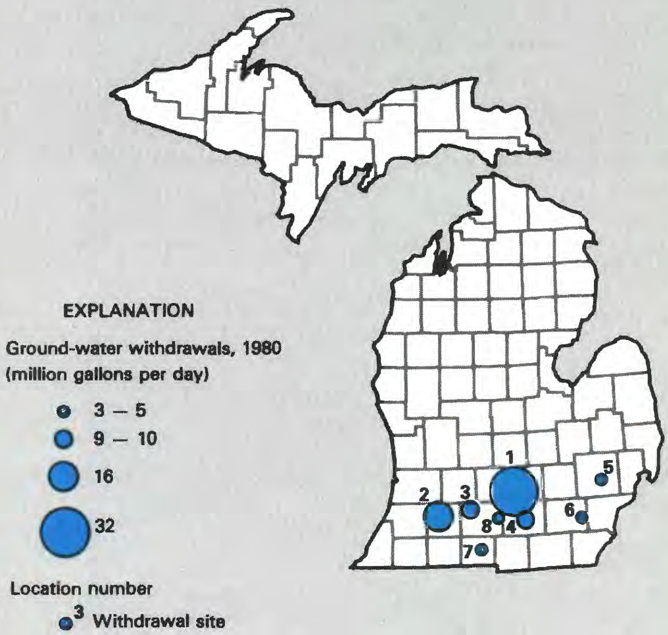
The Lansing metropolitan area withdraws the largest amount of ground water in the State. In 1983, the city of Lansing pumped 8.1 billion gallons (gal) from about 125 wells that tap the Saginaw Formation and unconsolidated glacial deposits. Four other water-supply systems in the area pumped 4.9 billion gal from about 50 wells. Intensive development of ground water in the area has produced a 100-square mile cone of depression. Near the center of the cone, water levels have declined as much as 160 ft.

Water levels generally decline in response to increases in pumping and recover as pumping is reduced. This effect, on a long-term basis, is shown by the hydrograph for Lansing (location 1). During the period of record shown in figure 2, the effects of discontinued pumpage from nearby production wells are shown by a rising water-level trend from 1969 to 1977 in the observation well.









WITHDRAWAL SITES [Withdrawals are principally for public supply]		
No. on map	Geographic area	Aquifer
1	Lansing, East Lansing, Michigan State University.	Saginaw Formation, glacial deposits.
2	Kalamazoo.	Glacial deposits.
3	Battle Creek	Marshall Formation.
4	Jackson.	Saginaw and Marshall Formations.
5	Waterford Township	Glacial deposits.
6	Ypsilanti, Ypsilanti Township.	Do.
7	Coldwater	Do.
8	Albion	Marshall Formation.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Michigan. (Sources: Withdrawal data from Bedell, 1982; water-level data from U.S. Geological Survey files.)

GROUND-WATER MANAGEMENT

Two State agencies, the Department of Public Health and the Department of Natural Resources, are involved in regulating and managing Michigan's ground-water resources.

The Department of Public Health, through the county health departments, issues permits for domestic and public-supply wells and requires well drillers to submit copies of drilling records to the county health departments. This department also monitors the quality of public-water supplies.

The Department of Natural Resources assists ground-water users by maintaining files of drilling records and by performing hydrogeologic and ground-water-quality studies. The Department also maps and describes geologic formations and monitors mineral wells and subsurface injection of brine.

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Prepared by N. G. Grannemann, F. R. Twenter, G. C. Huffman, and T. R. Cummings

For further information contact District Chief, U. S. Geological Survey, 6520 Mercantile Way, Suite 5, Lansing, MI 48910

MINNESOTA
Ground-Water Resources

Minnesota is a State renowned for its surface water. However, 94 percent of the public-supply water systems and 75 percent of all Minnesotans derive their domestic water supplies from ground water. In addition, about 88 percent of the water used for agricultural irrigation is supplied by ground water. Ground-water withdrawals for irrigation are competing for available supplies with nearby domestic wells, particularly in parts of western Minnesota where buried-drift aquifers are widely used. The quality of water in most aquifers statewide is suitable for most uses. However, ground water is unsuitable for some uses because of naturally occurring saline water along the western border of Minnesota and along the north shore of Lake Superior and because of nitrate contamination in the karst area of southeastern Minnesota. Ground-water withdrawals for various uses in 1980 and other related statistics are given in table 1.

Table 1. Ground-water facts for Minnesota

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	3,051
Percentage of total population	75
From public water-supply systems:	
Number (thousands)	1,910
Percentage of total population	47
From rural self-supplied systems:	
Number (thousands)	1,141
Percentage of total population	28
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	3,100
Ground water only (Mgal/d)	670
Percentage of total	22
Percentage of total excluding withdrawals for thermoelectric power	48
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	230
Percentage of total ground water	34
Percentage of total public supply	52
Per capita (gal/d)	120
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	120
Percentage of total ground water	18
Percentage of total rural domestic	100
Per capita (gal/d)	105
Livestock:	
Ground water (Mgal/d)	58
Percentage of total ground water	9
Percentage of total livestock	85
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	120
Percentage of total ground water	18
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	5
Excluding withdrawals for thermoelectric power	20
Irrigation withdrawals:	
Ground water (Mgal/d)	140
Percentage of total ground water	21
Percentage of total irrigation	88

GENERAL SETTING

Differing geologic features and land forms of Minnesota cause significant differences in ground-water conditions. Minnesota is situated on the southern margin of the Canadian Shield, which is a region of Precambrian crystalline and metamorphic rocks. In Paleozoic times, nearly 2,000 feet (ft) of clastic and carbonate sediment was deposited in a shallow depositional basin in southeastern Minnesota known as the Hollandale embayment. Minnesota's most productive aquifers consist of a sequence of sandstone, limestone, and dolomite beds in the Hollandale embayment (Delin and Woodward, 1984). During the Pleistocene Epoch, four continental glaciations advanced and retreated across Minnesota, blanketing the bedrock with drift as thick as 700 ft. Sand and gravel deposits in the drift constitute important aquifers, particularly in western Minnesota where the drift is thickest and where bedrock aquifers have small yields.

Precipitation, which ranges from about 19 inches (in.) in the northwestern corner of the State to about 32 in. in the southeastern corner, supplies water to four major drainage basins—Hudson Bay, St. Lawrence, Mississippi, and Missouri. As much as 30 percent of the precipitation infiltrates and becomes part of an extensive ground-water system.

PRINCIPAL AQUIFERS

The 14 principal aquifers (Adolphson and others, 1981) in Minnesota can be grouped according to general rock type into crystalline (igneous and metamorphic) rocks, volcanic rocks, sedimentary rocks (sandstone, sandstone and carbonate, and carbonate), and unconsolidated glacial drift and alluvium. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

UNCONSOLIDATED GLACIAL-DRIFT AQUIFERS

Surficial-Drift Aquifers

Surficial-drift aquifers are exposed at land surface and cover about one-third of the State. These aquifers consist of alluvial outwash, beach-ridge, valley-train, and ice-contact deposits (fig. 1). Extensive outwash deposits are a significant source of water for irrigation wells in central Minnesota. Generally, iron and manganese concentrations are greater than 1 milligram per liter (mg/L), and, locally, concentrations of nitrite plus nitrate as nitrogen exceed 30 mg/L.

Table 2. Aquifer and well characteristics in Minnesota

[Gal/min = gallons per minute; ft = feet; mg/L = milligrams per liter. Sources: Reports of the U. S. Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Unconsolidated glacial-drift aquifers:				
Surficial-drift aquifers: Sand and (or) gravel deposits located at or near land surface. Generally unconfined.	30 – 240	100 – 800	2,000	Generally good quality water. Large concentrations of iron and manganese in some areas. Nitrate contamination present in some areas.
Buried-drift aquifers: Sand and (or) gravel deposits located within thick drift. Generally confined.	80 – 380	100 – 600	1,500	Commonly hard water. Large iron, sulfate, and chloride concentrations in some areas, particularly where underlain by Cretaceous and Red River–Winnipeg aquifers.
Sedimentary bedrock aquifers:				
Cretaceous aquifer: Sandstone lenses near the base of a predominantly shale section. Generally confined.	280 – 620	10 – 250	1,000	Commonly hard water. Large sulfate, chloride, and dissolved-solids concentrations in many areas.
Upper Carbonate aquifer: Limestone, dolomite, and dolomitic limestone. Generally confined.	120 – 480	200 – 500	1,000	Includes Cedar Valley, Maquoketa, Dubuque, and Galena Formations. Locally, in karst area, water from a few wells contains large concentrations of nitrate and iron.
St. Peter aquifer: Fine- to medium-grained sandstone. Generally confined.	110 – 614	100 – 250	1,000	Generally good quality water. Large iron, sulfate, and manganese concentrations in some areas, particularly where overlain by Cretaceous aquifer.
Prairie du Chien–Jordan aquifer: Mainly dolomite and sandstone. Generally confined; unconfined near Minnesota and Mississippi Rivers.	170 – 910	500 – 1,000	2,700	Generally good quality water. Large iron and sulfate concentrations in some areas, particularly where overlain by Cretaceous aquifer. Locally, water has large concentrations of nitrate, iron, and manganese.
Red River–Winnipeg aquifer: Mainly sandstone and limestone with shale stringers. Generally confined.	260 – 480	100 – 250	500	Dissolved-solids concentrations range from 3,000 to 60,000 mg/L. Large iron, sodium, and chloride concentrations.
Ironton–Galesville aquifer: Mainly sandstone with interbedded shale and dolomitic sandstone. Generally confined.	170 – 640	40 – 400	1,500	Generally good quality water. Large concentrations of iron, sulfate, and hardness in some areas, particularly where overlain by Cretaceous aquifer.
Mount Simon–Hinckley aquifer: Sandstone siltstone, and shale. Generally confined.	90 – 1,130	400 – 700	2,000	Generally good quality water. Large iron, sulfate, boron, and chloride concentrations in some areas, particularly where overlain by Cretaceous aquifer.
Crystalline bedrock aquifers:				
North Shore Volcanics aquifer: A series of basaltic lava flows and interbedded sedimentary rocks. Generally confined.	20 – 930	5 – 25	100	Yields water from interflow sediments and from joints and fractures in basalt. Saltwater present in some areas north of Lake Superior.
Sioux Quartzite aquifer: Well-cemented quartzite. Commonly unconfined.	120 – 1,300	5 – 100	450	Commonly hard water. Large sulfate concentration, particularly where mixed with water from Cretaceous aquifer.
Proterozoic Metasedimentary aquifer: Thin-bedded gray to black argillite. Generally confined.	30 – 500	5 – 70	250	Small dissolved-solids concentration. Commonly used in conjunction with underlying Biwabik Iron Formation aquifer for public and industrial supplies.

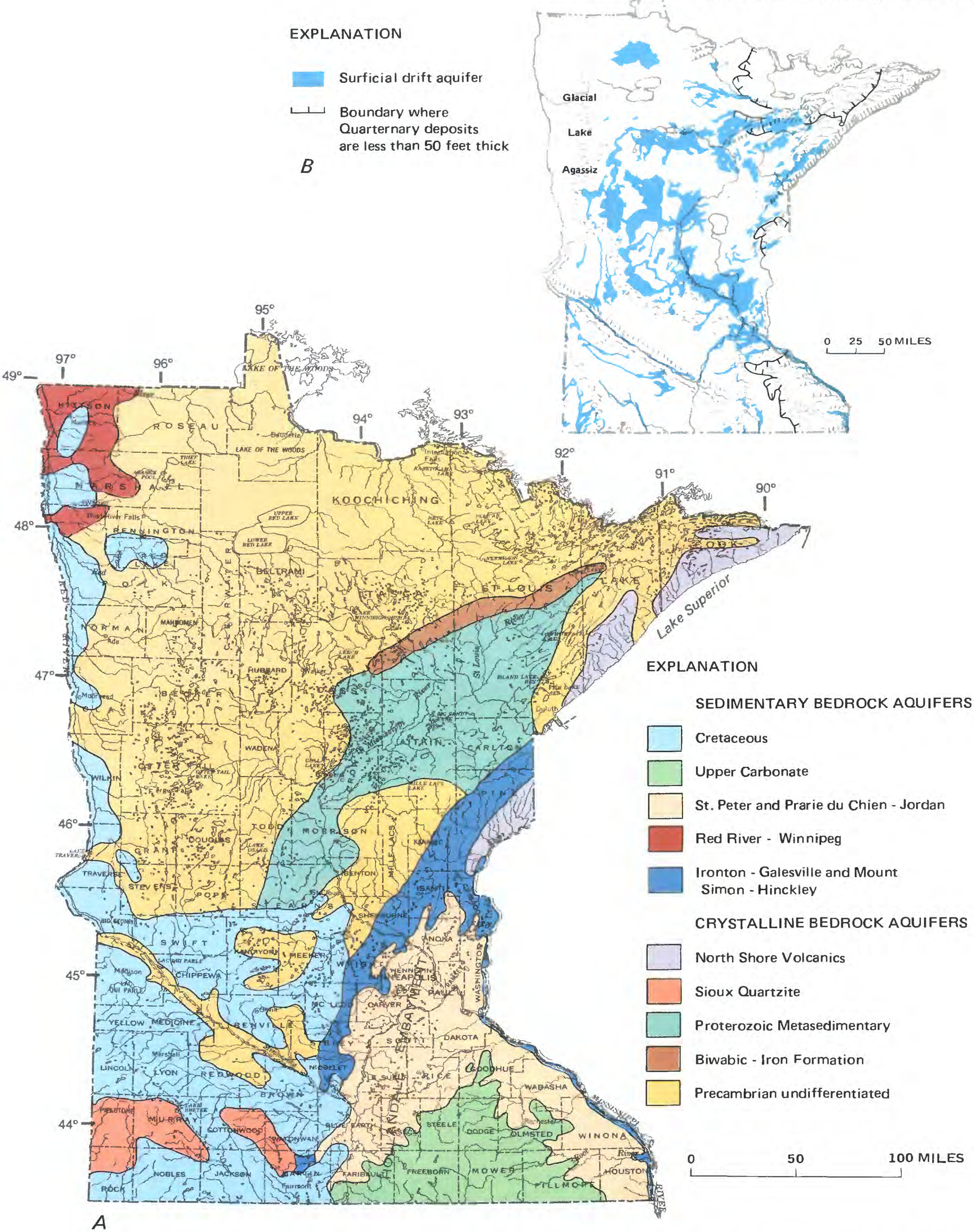


Figure 1. Principal aquifers in Minnesota. *A*, Geographic distribution of bedrock aquifers. *B*, Geographic distribution of surficial-drift aquifers and physiographic diagram. (See table 2 for more detailed description of the aquifers. Sources: *A*, Woodward, 1984. *B*, Compiled by D. G. Woodward from U.S. Geological Survey files; Raisz, 1954.)

Table 2. Aquifer and well characteristics in Minnesota—Continued

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Biwabik-Iron Formation aquifer: Ferruginous chert. Generally confined; unconfined locally.	170 - 600	250 - 750	1,000	Hard water and large iron concentration in some areas. Most productive source of ground water in Mesabi Iron Range.
Precambrian undifferentiated aquifer: granite, greenstone, and slate. Generally confined.	30 - 450	5 - 25	100	Commonly hard water. Large sulfate chloride concentrations found in areas.

Buried-Drift Aquifers

Buried-drift aquifers are present in nearly all areas of the State except in the northeast and southeast where the drift is thin or absent (fig. 1). Aquifers consist of discontinuous lenses of fine to coarse sand and gravel that are isolated from one another by till. Buried-drift aquifers are used extensively for supplying water to public-supply, irrigation, and farm wells in central and southwestern Minnesota. Locally, water in the aquifers can contain large concentrations of iron (4.6 mg/L), sulfate (1,200 mg/L), and chloride (1,000 mg/L).

Sedimentary Bedrock Aquifers

Cretaceous Aquifer

The Cretaceous aquifer underlies drift in southwestern and western Minnesota. Water from the aquifer is used primarily for rural domestic and stock supplies. It contains locally large concentrations of dissolved solids (3,540 mg/L), chloride (1,500 mg/L), and sulfate (1,700 mg/L), particularly in areas southwest of the Minnesota River (Woodward and Anderson, 1985).

Upper Carbonate Aquifer

The Upper Carbonate aquifer is present in the southern part of the Hollandale embayment and is the source of water for many public-supply, industrial, and rural domestic wells. Karst conditions exist in the eastern part of the aquifer, and ground water in this area commonly is contaminated from agricultural wastes and other nonpoint sources of pollution (Adolphson and others, 1981).

St. Peter Aquifer

The St. Peter aquifer is separated from the underlying Prairie du Chien–Jordan aquifer by the basal St. Peter confining bed in the Minneapolis–St. Paul area and directly overlies the Prairie du Chien–Jordan aquifer in the rest of the Hollandale embayment (Woodward, 1985b). Dissolved-solids concentrations range from 100 to 600 mg/L and hardness ranges from 200 to 400 mg/L as calcium carbonate (Ruhl and others, 1984b).

Prairie du Chien–Jordan Aquifer

The Prairie du Chien–Jordan aquifer is present in the central and southern parts of the Hollandale embayment. Water supplies from the aquifer have been slightly to moderately developed in the southeast and well developed in the Minneapolis–St. Paul metropolitan area where it provides about 80 percent of the annual ground-water supply (Horn, 1983). Locally, water from the aquifer has large concentrations of nitrate (29 mg/L), iron (1.4 mg/L), and manganese (420 mg/L) (Ruhl and others, 1985b).

Red River–Winnipeg Aquifer

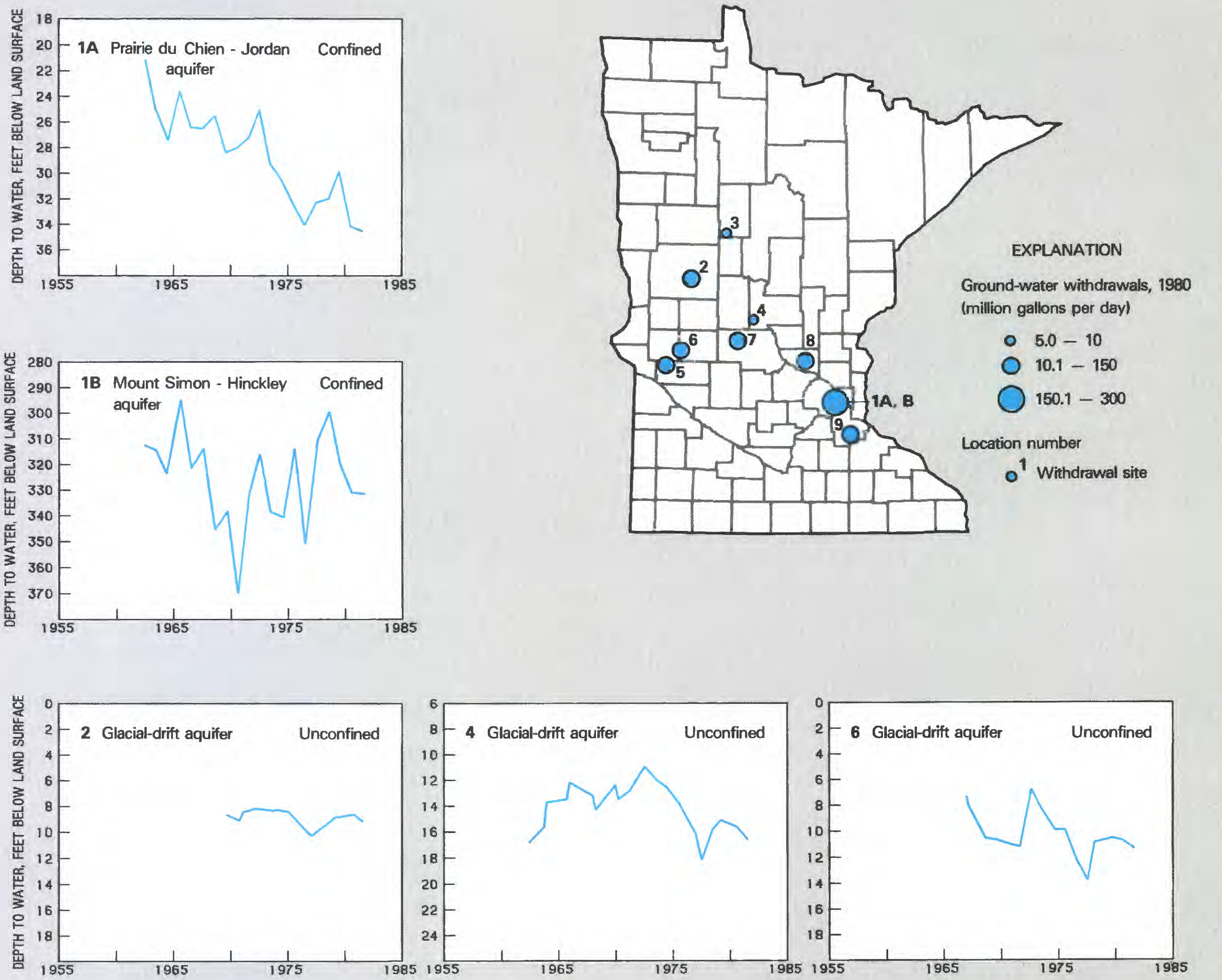
The Red River–Winnipeg aquifer underlies several hundred feet of till and lake sediments of Glacial Lake Agassiz in the northwest corner of the State. Water from the aquifer is very mineralized; dissolved-solids concentrations range from 3,000 to 60,000 mg/L. The water is a sodium chloride type (Ruhl and Adolphson, 1985).

Ironton-Galesville Aquifer

The Ironton–Galesville aquifer is present in most of the Hollandale embayment and is most commonly used in the northern and northwestern parts of the embayment. Dissolved-solids concentrations generally range from 200 to 650 mg/L (Ruhl and others, 1984).

Mount Simon–Hinckley Aquifer

The Mount Simon–Hinckley aquifer completely underlies the Hollandale embayment. About 10 percent of the ground water used in the Minneapolis–St. Paul metropolitan area comes from this aquifer. A long-term cone of depression has developed in the Minneapolis–St. Paul area as a result of extensive pumping over the past 80 years. The dominant water type is calcium-magnesium bicarbonate, but sodium-chloride-type water is present at depth in the southeastern part of the embayment (Wolf and others, 1984).



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1A, B	Minneapolis-St. Paul metropolitan area.	Prairie du Chien-Jordan, Ironton-Galesville, Mount Simon-Hinckley.	Public supply, industrial.
2	Otter Tail County. . .	Unconsolidated glacial-drift . .	Irrigation.
3	Hubbard and Wadena Counties.	. . . .do	Do.
4	Todd and Morrison Counties.	. . . .do	Do.
5	Swift and Stevens Counties.	. . . .do	Do.
6	Pope and Kandiyohi Counties.	. . . .do	Do.
7	Stearns County	. . . .do	Do.
8	Sherburne County . .	. . . .do	Do.
9	Dakota County	Prairie du Chien-Jordan, glacial-drift.	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Minnesota. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

CRYSTALLINE BEDROCK AQUIFER

North Shore Volcanics Aquifer

The North Shore Volcanics aquifer is the major bedrock aquifer along the north shore of Lake Superior. Water generally is obtained from the upper 300 to 400 ft where fractures and weathering are extensive. The aquifer is moderately developed for rural and public supply. Dissolved-solids concentrations range from 100 to 50,000 mg/L but commonly are about 1,300 mg/L.

Sioux Quartzite Aquifer

The Sioux Quartzite aquifer underlies most of southwest Minnesota; locally, it is an important aquifer, furnishing water to seven municipal and to numerous rural domestic and stock wells. Dissolved-solids concentrations generally are less than 900 mg/L, and total hardness is less than 400 mg/L as calcium carbonate.

Proterozoic Metasedimentary Aquifer

The Proterozoic Metasedimentary aquifer underlies drift in the north-central part of the State. The water is of the calcium-magnesium bicarbonate type and is used for numerous rural domestic and some public supplies.

Biwabik-Iron Formation Aquifer

The Biwabik-Iron Formation aquifer crops out in north-central Minnesota, and yields water to many public-supply and industrial wells along the Mesabi Iron Range. Altered zones associated with joints, fractures, and solution channels provide the secondary porosity and permeability. The water meets U.S. Environmental Protection Agency drinking-water regulations for most chemical constituents, although dissolved solids range from 157 to 390 mg/L, and the water locally contains large concentrations of iron (4.9 mg/L) and manganese (1.8 mg/L).

Precambrian Undifferentiated Aquifer

Precambrian igneous and metamorphic rocks underlie the entire State. These rocks yield limited supplies of water to rural domestic and livestock wells in the southwestern, central, and northeastern parts of Minnesota where fractures, faults, and weathered zones provide porosity and permeability. Calcium-magnesium bicarbonate type water is the most common in the aquifer, and dissolved-solids concentrations generally are less than 300 mg/L.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The largest ground-water withdrawals in the State, exclusive of the Minneapolis-St. Paul metropolitan area (location 1, fig. 2), are in major irrigated agriculture regions (fig. 2). Surficial- and buried-drift aquifers supply the irrigation water for all pumping centers except for Dakota County (location 9, fig. 2), which uses the Prairie du Chien–Jordan aquifer as its primary source for irrigation water. The largest concentration of pumping is in the seven-county Twin Cities metropolitan area.

The well hydrographs shown in figure 2 reflect the response of water levels to pumping at selected withdrawal centers. The effects of the mid-1970's drought are shown in the three hydrographs of drift wells (hydrographs 2, 4, 6), where water levels began to decline in 1972–1974 and remained below normal through 1977 as a result of increased pumping for irrigation. Little long-term change in water levels is noted in the well hydrographs in unconfined drift aquifers in irrigated areas.

Two aquifers, the Prairie du Chien–Jordan and Mount Simon–Hinckley, supply about 80 and 10 percent, respectively, of the ground water pumped in the Minneapolis–St. Paul metropolitan area. The Mississippi, Minnesota, and St. Croix Rivers are in hydraulic connection with and affect the pattern of flow in the Prairie du Chien–Jordan aquifer. Water generally flows toward these rivers from northeast, northwest, and south of Minneapolis and St. Paul. Consequently, intensive pumping has caused only localized cones of depression in the potentiometric surface of this aquifer (Schoenberg, 1984). From 1971 to 1980, average water levels in the Prairie du Chien–Jordan aquifer changed less than 5 ft in most of the area but rose or declined as much as 25 ft locally in response to pumpage and recharge. One hydrograph (location 1A, fig. 2) shows a general water-level decline in the Prairie du Chien–Jordan aquifer below western Minneapolis because of increased pumping for public supply. In contrast, the water level in the Mount Simon–Hinkley aquifer (location 1B, fig. 2), which has only a slight hydraulic connection with the rivers, is greatly affected by pumping. During 1971, the measurable cone of depression, centered in east-central Hennepin County, was about 25 miles in diameter. Decreased annual pumpage from the Mount Simon–Hinkley aquifer from 1971 to 1980 caused water levels in that aquifer to rise.

GROUND-WATER MANAGEMENT

Minnesota has extensive ground-water management and planning legislation. Three State-level organizations implement most of the regulatory and planning programs mandated by this legislation (Bruemmer and Clark, 1984):

The Minnesota Department of Natural Resources (MDNR), through its Division of Waters, has a major role in ground-water resource planning and management. The MDNR provides technical assistance on water-supply, conservation, and well-interference issues and manages an appropriation-permit program. This program requires that a permit be obtained to appropriate ground or surface water (with the exception of domestic use for 25 persons or less) and that annual pumpage be reported. The Division of Waters is responsible for maintenance of a statewide observation-well monitoring network, a water-use program, and investigation of the State's water resources. The research, data collection, and analyses provided by this program, which is operated in cooperation with the U.S. Geological Survey, constitute part of the data base used by the MDNR to make ground-water management decisions.

The Minnesota Department of Health (MDH) is concerned with the health-related and domestic-supply issues involving ground water. The MDH approves plans for public-supply wells, establishes and enforces well-construction standards, and licenses well drillers (Minnesota Statutes, Chapter 156A); requires well-completion reports for new wells; regulates, through permits, the reinjection of ground water and ground-water thermal-exchange devices (Minnesota Statutes, Chapter 156A.10); and administers the public water-supply regulations in concurrence with the Safe Drinking Act (Minnesota Statutes, Chapter 114.381 and 7 MCAR 1.145-1.150).

The Minnesota Pollution Control Agency (MPCA) administers programs dealing with ground-water-quality issues and pollution-control requirements (Minnesota Statutes, Chapters 115 and 116). The MPCA administers its programs through a system of rules:

- Preservation and protection of underground water in the State by preventing any new pollution and by abating existing pollution [6 MCAR § 4.8022 (WPC-22)].
- Regulation of sewage-sludge land spreading (6 MCAR § 4.6101-4.6136).
- Regulation of hazardous-waste facilities (6 MCAR § 4.9001-4.9010).
- Regulation of sanitary landfills (Minnesota Rule SW-6 and SW-12).
- Regulation of septic tanks and drainfields (6 MCAR § 4.8040).
- Regulation of storage of liquid products (WPC-4).
- Regulation of intrastate (6 MCAR § 4.8014) and interstate (6 MCAR § 4.8015) standards for water quality and purity.

The Environmental Response and Liability Act (Minnesota Statutes, Chapter 115B), passed in 1984, is referred to as the "Minnesota Superfund Act" and authorizes the MPCA to provide funds to clean up contamination sites and gain reimbursement later.

Permits are required for disposal practices and to operate facilities that could affect the quality of ground water. The MPCA maintains a network of 400 wells and springs to monitor ground-water quality throughout Minnesota.

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Prepared by Dennis G. Woodward

For further information contact District Chief, U.S. Geological Survey, Post Office Building, Room 702, St. Paul, MN 55101

MISSISSIPPI
Ground-Water Resources

Ground water constitutes 54 percent of all freshwater used in Mississippi, serving the water supply needs of 93 percent of the population. The largest use of fresh ground water—54 percent of the total withdrawal—is for irrigation and aquaculture. Most of Jackson's public-water supply is withdrawn from the Pearl River but about 50 percent of the water used in the surrounding metropolitan area is from ground-water sources. Columbus and Meridian are converting from surface-water sources to wells. The nearly exclusive dependence on ground water for public-water supply is the result of statewide availability of aquifers that contain water of quality suitable for most uses and that are capable of supplying large yields [more than 300 gallons per minute (gal/min)] to wells. Ground-water withdrawals for various uses in 1980 and other related statistics are given in table 1.

Table 1. Ground-water facts for Mississippi

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Callahan, 1983]

Population served by ground water, 1980	
Number (thousands)	2,339
Percentage of total population	93
From public water-supply systems:	
Number (thousands)	1,861
Percentage of total population	74
From rural self-supplied systems:	
Number (thousands)	478
Percentage of total population	19
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	2,900
Ground water only (Mgal/d)	1,500
Percentage of total	54
Percentage of total excluding withdrawals for thermoelectric power	82
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	230
Percentage of total ground water	15
Percentage of total public supply	18
Per capita (gal/d)	124
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	20
Percentage of total ground water	1
Percentage of total rural domestic	100
Per capita (gal/d)	42
Livestock:	
Ground water (Mgal/d)	8.0
Percentage of total ground water	0.5
Percentage of total livestock	77
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	[1]430
Percentage of total ground water	29
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	21
Excluding withdrawals for thermoelectric power	61
Irrigation withdrawals:	
Ground water (Mgal/d)	812
Percentage of total ground water	54
Percentage of total irrigation	35

[1] Includes 264 Mgal/d for aquaculture use and 2.3 Mgal/d for waterfowl.

GENERAL SETTING

With the exception of an area of a few square miles in Tishomingo County, Mississippi lies entirely in the East Gulf Coastal Plain and is underlain by deposits of clay, sand, gravel, chalk, marl, and limestone. The oldest exposed strata are consolidated Paleozoic rocks that crop out only in a few valleys in Tishomingo County (fig. 1). Cretaceous strata in northern Mississippi dip and thicken southwestward. In central and southern Mississippi, the dip of the younger Eocene strata gradually becomes southward.

Much of the water that reaches the water table moves downdip westward to southwestward into the confined aquifers (fig. 1). Ground water moves westward into the northeastern Mississippi subsurface from Alabama. In southern Mississippi, some ground water flows into the subsurface of Louisiana or discharges into the Gulf of Mexico.

Precipitation in Mississippi is about 54 inches (in.) annually. Average monthly precipitation ranges from about 2.4 in. in October to about 6.2 in. in March. The late winter and spring rains provide an excess of water that results in high streamflow and periodic flooding. Infiltration from the Mississippi River and other streams reaches a maximum in the late spring.

About 50 percent of Mississippi's precipitation evaporates or is consumed by vegetation, about 40 percent runs off as streamflow, and about 10 percent infiltrates to the water table. Additional recharge of the ground-water reservoir is derived from infiltration of surface waters.

Several hundred gallons per minute can be obtained from wells completed in at least one aquifer nearly anywhere in the State. Throughout northwestern Mississippi and at places in the southern part of the State, well yields of several thousand gallons per minute are not unusual. Water-quality problems commonly are related to iron in solution and to acidic water. More troublesome in some areas, however, is the prevalence of color in ground water caused by the presence of organic matter. Saltwater normally is present in the downdip parts of all aquifers; however, the base of freshwater extends to depths of more than 3,000 feet (ft) in some parts of the State (fig. 1). Saltwater intrusion has not been identified conclusively in coastal areas except locally where estuaries are connected hydraulically to shallow aquifers. Ground-water contamination from human activities is mostly restricted to oil-producing areas.

Table 2. Aquifer and well characteristics in Mississippi

[Gal/min = gallons per minute; mg/L = milligram per liter; ft = feet. Sources: Reports of the U.S. Geological Survey, Mississippi Bureau of Land and Water Resources, and Mississippi Research and Development Center]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Mississippi River alluvial aquifer: Sand, gravel, silt, and clay. Semiconfined.	50 – 140	200	500 – 3,000	5,000	Water hard, iron in solution generally exceeds 1.0 mg/L. Susceptible to pollution. Source of public water supply at Vicksburg (location 15, fig. 2).
Citronelle aquifers: Sand, gravel, silt, and clay. Generally unconfined.	50 – 200	250	50 – 300	500	Water soft, acidic, iron in solution generally exceeds 0.3 mg/L. Dissolved solids concentrations generally lower than 100 mg/L. Source for several public water supplies in southern part of State. Susceptible to pollution. Equivalent to Pliocene–Miocene aquifer in Alabama, Pleistocene aquifer in Louisiana.
Miocene aquifer system: Sand, clay, gravel, and silt. Generally confined.	50 – 1,500	2,400	50 – 1,500	5,000	Includes Graham Ferry, Pascagoula, and Hattiesburg Formations and Catahoula Sandstone. Water soft, sodium bicarbonate type; locally, iron exceeds 0.3 mg/L. Contaminated by oilfield brine locally. Principal source for public water supplies in southern one-third of State. Equivalent to Pliocene–Miocene aquifer in Alabama and Louisiana.
Oligocene aquifer system: Limestone, sand, silt, and clay. Generally confined.	150 – 1,000	1,200	10 – 150	400	Includes Vicksburg Group and Forest Hill Sand. Water soft, slightly alkaline. Source for a few public water supplies in south-central part of State. Part of Oligocene–Eocene aquifer in Alabama. Confining unit in Louisiana.
Eocene aquifer system:					
Cockfield aquifer: Sand, silt, clay, and lignite. Generally confined.	100 – 1,000	1,200	10 – 1,000	1,500	Water hard near outcrop, sodium bicarbonate type elsewhere. Locally, iron concentration exceeds 0.3 mg/L and color is more than 20 units. Largest withdrawal is for public water supply at Greenville (location 16, fig. 2). Part of Tertiary sand aquifer in Tennessee, Oligocene-Eocene aquifer in Alabama.
Sparta aquifer system: Sand, silt, clay, and lignite. Generally confined.	100 – 1,500	2,000	10 – 1,000	3,000	Water soft, sodium bicarbonate type. Locally iron concentration exceeds 0.3 mg/L and color is more than 20 units. Contaminated by oil-field brine locally. Source for many public water supplies in central and northwestern Mississippi. Part of Tertiary sand aquifer in Tennessee, Oligocene–Eocene aquifer in Alabama.
Winona–Tallahatta aquifer: Glauconitic sand and clay. Generally confined.	100 – 1,000	1,200	10 – 400	500	Water soft. Locally, iron concentration exceeds 3.0 mg/L, and color is more than 20 units. Source for public water supply for several small municipalities. Part of Tertiary aquifer in Tennessee. Oligocene-Eocene aquifer in Alabama. Confining unit in Louisiana.
Meridian–upper Wilcox aquifer: Sand, silt, clay, and lignite. Generally confined.	100 – 1,800	2,000	100 – 2,000	2,500	Water soft, acidic in the north. Locally iron concentration exceeds 0.3 mg/L, and color is more than 20 units. Source for many public water supplies in central and northwestern Mississippi. Largest withdrawal is at Greenwood (location 10, fig. 2). Part of Tertiary sand aquifer in Tennessee, Oligocene-Eocene aquifer in Alabama, and Wilcox-Carrizo aquifer in Louisiana.

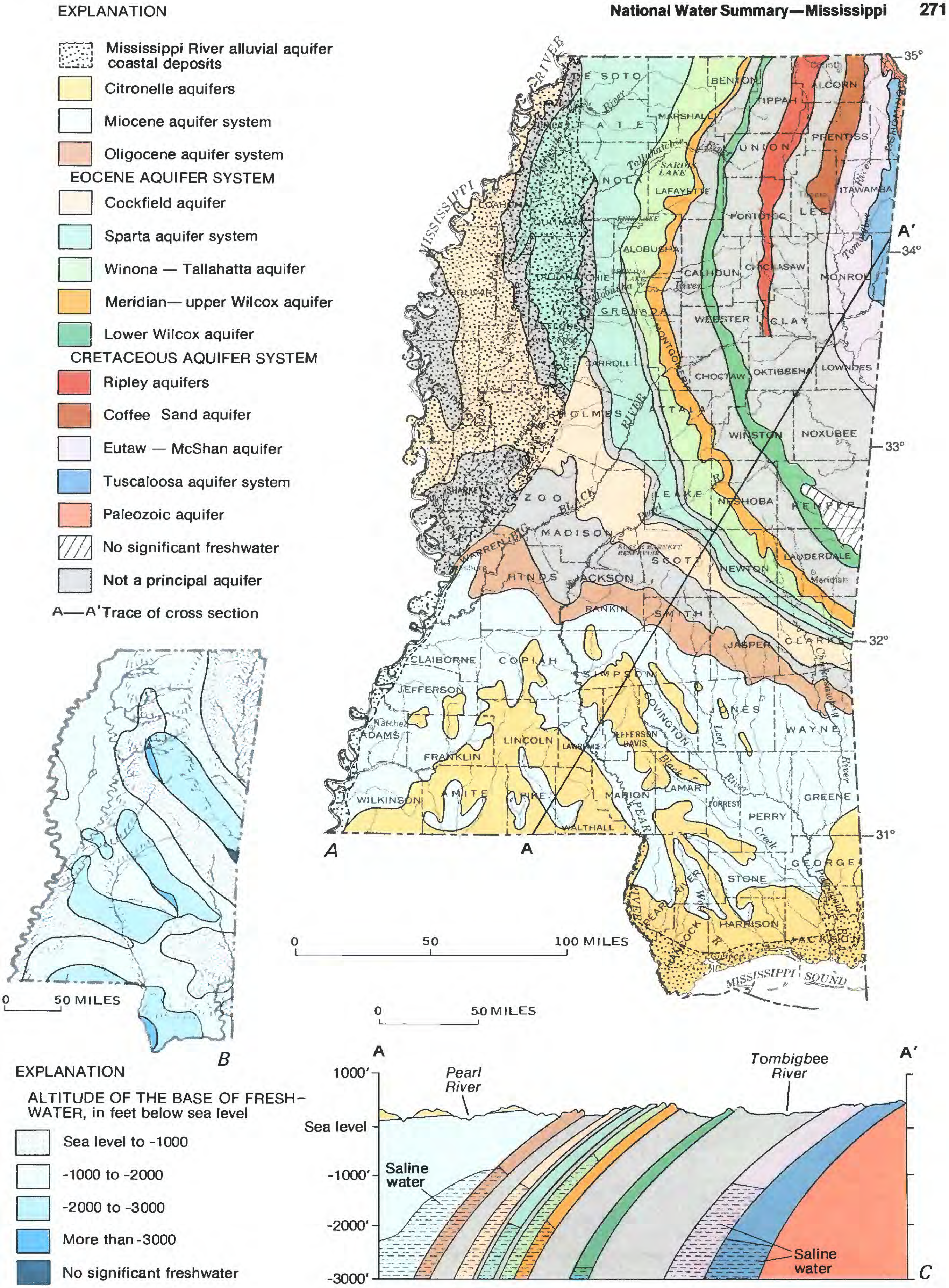


Figure 1. Principal aquifers of Mississippi. *A*, Geographic distribution. *B*, Altitude of the base of freshwater and physiographic diagram. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Modified from Bicker, 1969. *B*, Gandl, 1982; Raisz, 1954. *C*, Compiled by E. H. Boswell from U.S. Geological Survey files.)

Table 2. Aquifer and well characteristics in Mississippi—Continued

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Lower Wilcox aquifer: Sand, silt, clay, and lignite. Generally confined.	100 - 2,100	3,000	100 - 1,500	2,000	Water soft. Locally, iron concentration exceeds 0.3 mg/L. Contaminated by oil-field brine locally. Source for public water supplies throughout central and northwestern Mississippi. Largest withdrawal is at Meridian (location 22, fig. 2). Equivalent to Nanafalia-Clayton aquifer in Alabama and part of Tertiary sand in Tennessee.
Cretaceous aquifer system:					
Ripley aquifers: Sand, clay, sandstone, and limestone. Generally confined.	50 - 1,100	1,800	10 - 300	400	Water hard near outcrop, soft at depth. Source for several small public water supplies in extreme northern part of State. Part of Cretaceous aquifer in Tennessee.
Coffee Sand aquifer: Sand, clay and sandstone. Generally confined.	50 - 1,000	2,000	10 - 400	500	Water hard near outcrop, soft at depth. Source for several small public water supplies in extreme northern part of State. Part of Cretaceous aquifer in Tennessee.
Eutaw-McShan aquifer: Sand and clay. Generally confined.	100 - 1,500	1,800	10 - 500	600	Water hard near outcrop, soft at depth. Locally fluoride exceeds 1.0 mg/L. Source for numerous public water supplies in northern part of State. Largest withdrawals are at Tupelo and in Monroe County (locations 9 and 23, fig. 2). Equivalent to Eutaw aquifer in Alabama and part of Cretaceous aquifer in Tennessee.
Tuscaloosa aquifer system: Sand, gravel, silt, and clay. Generally confined.	100 - 2,000	2,400	50 - 1,500	2,000	Includes Gordo and Coker Formations, and locally, beds of Early Cretaceous age. Water soft to slightly hard, small dissolved-solids concentrations. Locally iron exceeds 0.3 mg/L. Source for numerous public water supplies in northwestern Mississippi. Largest withdrawals are in Columbus area and Monroe County (location 23, fig. 2). Equivalent to Tuscaloosa aquifer in Alabama.
Paleozoic aquifer: Limestone, chert, and clay. Generally confined.	100 - 600	1,000	100 - 900	1,000	In rocks of Mississippian age. Water generally hard. Locally, iron exceeds 0.3 mg/L. Used only in Alcorn and Tishomingo Counties (location 21, fig. 2). Part of Highland Rim carbonates in Tennessee and Paleozoic carbonates in Alabama.

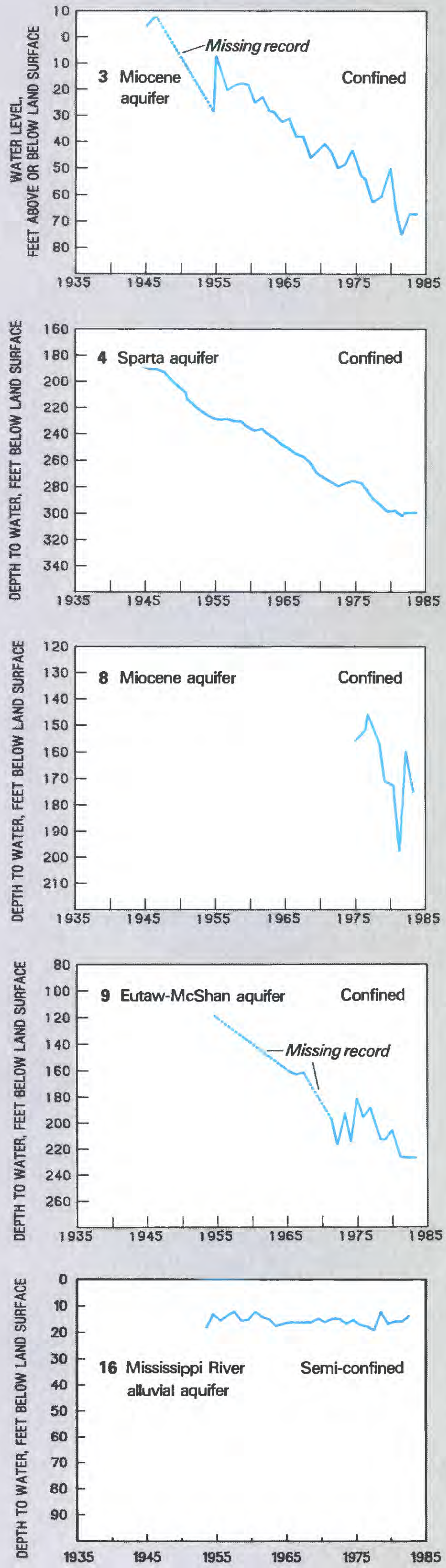
The southwestward dip of the strata and the overlap of freshwater in successively younger aquifers southward result in the availability of two or more separate aquifers for development in most places (fig. 1). Examples are use of both the Tuscaloosa aquifer system and the Eutaw-McShan aquifer at localities in the northeast; the Cockfield, Sparta, and Meridian-upper Wilcox aquifers in some mid-State localities; and the Meridian-upper Wilcox and lower Wilcox aquifers in many areas. Some geologic formations include two or more extensive water-bearing zones that function as a single system when considered on a regional basis (Sparta aquifer system). Other water-bearing formations are directly connected hydraulically and function as a single aquifer (Eutaw-McShan aquifer).

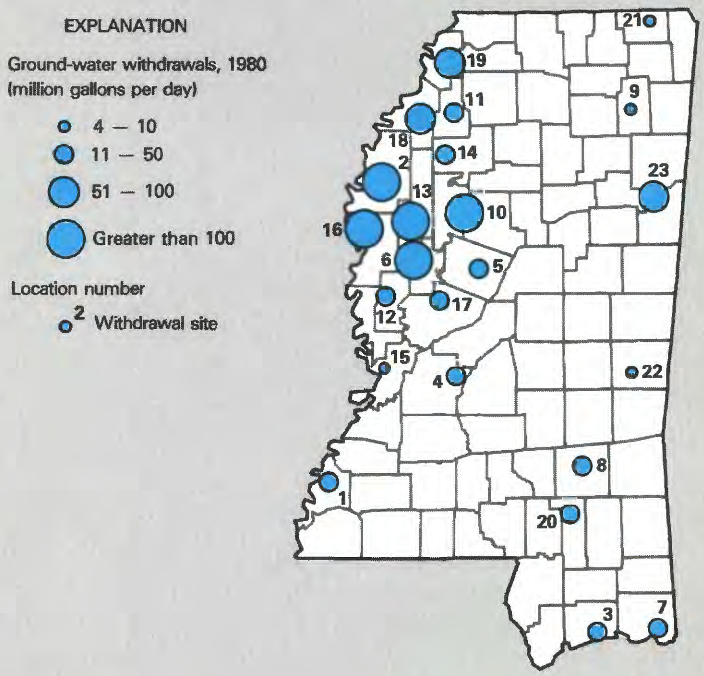
PRINCIPAL AQUIFERS

Except for the chert aquifer of Paleozoic age, which is the source of water for several public-water supplies in Alcorn and Tishomingo Counties, all principal aquifers in Mississippi consist of unconsolidated sand or sand and gravel strata that are irregular in thickness and physical character and exhibit extreme variation in their capability to store and transmit water (Wasson, 1980). The principal aquifers are discussed below and in table 2; their areal distribution is shown in figure 1.

Mississippi River Alluvial Aquifer

The extensive Mississippi River alluvial aquifer in the Delta area of northwestern Mississippi is an extremely prolific





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Natchez area.	MRAA[1], Miocene	Industrial, public supply.
2	Bolivar County	MRAA, Cockfield, Sparta-Wilcox.	Irrigation, public supply.
3	Harrison County . . .	Miocene	Public supply, industrial.
4	Jackson Metro area . .	Cockfield, Sparta	Do.
5	Holmes County	MRAA, Meridian-Upper Wilcox.	Do.
6	Humphreys County. .	MRAA, Sparta.	Irrigation, public supply.
7	Pascagoula-Moss Point.	Miocene	Industrial, public supply.
8	Laurel area.	. . . .do	Do.
9	Tupelo area	Tuscaloosa, Eutaw-McShan.	Public supply, industrial.
10	Greenwood area. . . .	MRAA, Meridian-Upper Wilcox.	Irrigation, public supply.
11	Quitman County . . .	MRAA, Meridian-Upper Wilcox.	Irrigation, industrial.
12	Sharkey County. . . .	MRAA	Irrigation.
13	Sunflower County . .	MRAA, Meridian-Upper Wilcox.	Irrigation, public supply.
14	Tallahatchie County.	. . . .do	Do.
15	Vicksburg area.	MRAA	Public supply, industrial.
16	Greenville area.	MRAA, Cockfield.	Irrigation, public supply.
17	Yazoo County.	MRAA, Sparta.	Do.
18	Clarksdale area	. . . .do	Do.
19	Tunica County	MRAA, Lower Wilcox . .	Do.
20	Hattiesburg area. . . .	Miocene	Public supply, industrial.
21	Corinth area	Paleozoic.	Irrigation.
22	Meridian area	Lower Wilcox	Public supply, industiral.
23	Northeastern Mississippi.	Tuscaloosa, Eutaw-McShan.	Industrial, public supply.

[1] Mississippi River alluvial aquifer

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Mississippi. (Sources: Withdrawal data from Callahan, 1983; water-level data from U.S. Geological Survey files.)

source of water that is used for irrigation, aquaculture (principally catfish farming), industrial cooling, and for one public supply (Vicksburg). The alluvium averages about 140 ft in thickness. Generally, the uppermost 20 to 30 ft is clay or other fine-grained material; underlying sand and gravel beds form the aquifer. Wells about 120 ft deep that produce 2,000 to 3,000 gal/min can be constructed nearly anywhere in the Delta.

The alluvial aquifer is recharged by the Mississippi River and smaller streams and, to a lesser extent, by direct infiltration of precipitation (Sumner and Wasson, 1984). Recharge also occurs on the east side of the delta where streams enter from the Bluff Hills and where water-bearing zones in the deeper aquifers are in contact with the alluvium.

Citronelle Aquifers

The Citronelle aquifers overlie older aquifers in southern Mississippi and are used for some public and industrial wells and extensively for small domestic and farm wells. The Citronelle originated as an extensive surficial fluvial deposit that has now been greatly dissected by streams. The relatively flat-lying, very permeable beds are a source of water for springs and seeps that sustain the low flow of streams and transmit recharge to underlying confined aquifer subcrops.

Miocene and Oligocene Aquifer Systems

The aquifers in southern Mississippi partly underlie the Citronelle aquifers and are separated from the underlying Eocene aquifers by several hundred feet of clay. In descending order, these aquifers are present in the Graham Ferry Formation, the Pascagoula Formation, the Hattiesburg Formation, the Catahoula Sandstone, the Vicksburg Group, and the Forest Hill Sand. All except the Vicksburg and the Forest Hill aquifers, which form the Oligocene aquifer system, are included in the Miocene aquifer system.

Some water wells in the Miocene aquifers are about 2,000 ft deep and the deepest well reaches 2,400 ft; however, geophysical logs made of oil tests in Hancock County show that freshwater extends to slightly more than 3,000 ft below sea level (fig. 1). Water wells about 1,000 ft deep on some of the barrier islands that form Mississippi Sound confirm that freshwater aquifers extend gulfward beyond the shoreline (Brown and others, 1944).

Eocene Aquifer System

The Eocene aquifers, exposed at the surface in north-central, northwestern, and central Mississippi, extend in the subsurface to the west, southwest, and south, and contain freshwater in about 50 percent of the State (Wasson, 1980). Included are the Cockfield, the Winona-Tallahatta, the Meridian-upper Wilcox, and the lower Wilcox aquifers and the Sparta aquifer system. All are regional in extent, and all except the Cockfield and lower Wilcox merge northward into a single aquifer south of Memphis, Tennesseee. The deepest water well in Mississippi (2,760 ft) taps the lower Wilcox aquifer in northern Wayne County. Geophysical logs made in oil test wells show that freshwater in this aquifer extends more than 3,000 ft below sea level in Smith County (fig. 1).

Cretaceous Aquifer System

The Cretaceous aquifers contain freshwater in about one-fourth of the State (Boswell, 1963). The outcrop area is in northeastern Mississippi. Cretaceous aquifers include the Ripley, the Coffee Sand, and the Eutaw-McShan aquifers, and the Tuscaloosa aquifer system. The Eutaw-McShan and Tuscaloosa aquifers extend into Alabama. The Ripley and the Coffee Sand aquifers, which are restricted to northern Mississippi generally north and west of Tupelo, extend into Tennessee and Arkansas. Freshwater extends to depths that exceed 3,000 ft below sea level in some areas more than 80 miles from the recharge areas (fig. 1), and some water wells exceed 2,000 ft in depth. The deepest wells that tap the Tuscaloosa aquifer system are located in the outcrop area of the Eocene aquifers (fig. 1).

Paleozoic Aquifer

The Paleozoic aquifer consists of the upper part of weathered, faulted limestone and chert; the aquifer is overlain by Cretaceous deposits in extreme northeastern Mississippi. Present development of the aquifer is restricted to Alcorn and Tishomingo Counties where well depths range from 100 to 600 ft (Wasson, 1980). Wells produce as much as 1,000 gal/min where large declines in water levels have not occurred. The water is moderately hard and, at some sites, contains more than 0.3 milligram per liter (mg/L) of iron.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Pumping centers that produce 4 million gallons per day (Mgal/d) or more of ground water are shown in figure 2. About three-fourths (1,143 Mgal/d in 1980) of the ground water used in Mississippi is pumped in the northwestern part of the State (fig. 2) from the Mississippi River alluvial aquifer for irrigation and aquaculture (Callahan, 1983). Water levels in the aquifer fluctuate seasonally, reaching high levels in the spring after recharge and declining to the lowest point in the fall following irrigation withdrawals and normal seasonal decline. The hydrograph for the alluvial aquifer near Greenville (location 16, fig. 2), indicates recovery of water levels in the aquifer after 1975; however, in some other areas (locations 2, 10, and 12), water levels lowered by the combination of drought conditions and unprecedented use of water for irrigation and aquaculture have not recovered in some areas (Sumner and Wasson, 1984).

Confined aquifers in Mississippi generally have shown a regional decline of about 2 ft annually during the last 30 years. The declines have attracted attention where pumping is concentrated in aquifers that are only a few hundred feet deep and pumping occurs near the top of the aquifer (locations 7, 9, and 21, fig. 2). The effects of water-level declines have elicited less concern in other areas where several hundred feet of available drawdown remains. The most pronounced water-level declines have been in the Paleozoic aquifer at Corinth (location 21), the Eutaw-McShan aquifer at Tupelo (location 9), the Sparta aquifer system at Jackson (location 4), and the Miocene aquifer system at Natchez, Pascagoula, Laurel, and Hattiesburg (locations 1, 7, 8, 20). Water-level recovery during the last several years at locations 7 and 8 is due to reductions in withdrawal and changes in pumping distribution.

GROUND-WATER MANAGEMENT

The 1956 omnibus water law passed by the Mississippi Legislature specifically excluded subsurface waters. It was not until 1976 that a ground-water bill, codified now as Sections 51-4-1 et. seq., Mississippi Code Annotated, 1972 (James I. Palmer, Jr., Governor's Office of Economic Development and Natural Resources, written commun., 1984) was enacted. The concept of "capacity use areas," wherein well spacing, well depths, and withdrawal rates are regulated, is the mechanism provided for dealing with areas having identifiable ground-water-supply problems. The major limitations of the 1976 Act are that it addresses only withdrawals in excess of 50,000 gallons per day (gal/d) and excludes agricultural and oil and gas uses. In 1983, the State legislature created the Mississippi Water Management Council to reexamine completely all State laws pertaining to surface and subsurface waters and to report recommended amendments to the 1985 session.

The Mississippi Department of Natural Resources administers and enforces, through its Bureau of Land and Water Resources, not only the 1956 surface-water and 1976 ground-water statutes but also the 1966 Water Well Drillers Licensing Act. Primacy in permitting waste injection in Mississippi (other than in connection with oil and gas production) has been assigned to the Department's Bureau of Pollution Control, which also has responsibility for permitting and monitoring hazardous-waste sites. On June 27, 1984, Mississippi became the second State to be given final authorization to operate its own hazardous-waste program. Primacy for permitting oil field waste injection has not been delegated by the U.S. Environmental Protection Agency (as of December 1984).

The Department's Bureau of Geology, basically a research organization, is authorized to investigate and report on water resources. The Mississippi State Board of Health ensures that public-water supplies meet chemical, bacteriological, and other standards.

Water-resources investigations in Mississippi are conducted cooperatively by the U.S. Geological Survey with the Mississippi Department of Natural Resources, 10 other State and local agencies and municipalities, and five Federal agencies.

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Prepared by Ernest H. Boswell

For further information contact District Chief, U.S. Geological Survey, 100 West Capitol Street, Jackson, MS 39269

MISSOURI
Ground-Water Resources

Ground water supplies the water needs of approximately 34 percent of Missouri's population. Although surface water supplies the 42 percent of the State's population that resides in the St. Louis and Kansas City areas, ground water is an important source for many other public supplies in the State. Ground water is the source of 74 percent of all rural domestic self-supplied water, 75 percent of all irrigation water, and 39 percent of all industrial self-supplied water (excluding water for thermoelectric power generation). Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

Table 1. Ground-water facts for Missouri

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Solley, Chase, and Mann, 1983; per capita withdrawals for rural-domestic supply from L. F. Emmett, U.S. Geological Survey, written commun., 1985]

Population served by ground water, 1980	
Number (thousands)	1,676
Percentage of total population	34
From public water-supply systems:	
Number (thousands)	1,520
Percentage of total population	31
From rural self-supplied systems:	
Number (thousands)	156
Percentage of total population	3
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	6,900
Ground water only (Mgal/d)	470
Percentage of total	7
Percentage of total excluding withdrawals for thermoelectric power	34
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	160
Percentage of total ground water	34
Percentage of total public supply	22
Per capita (gal/d)	105
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	68
Percentage of total ground water	14
Percentage of total rural domestic	74
Per capita (gal/d)	90
Livestock:	
Ground water (Mgal/d)	17
Percentage of total ground water	4
Percentage of total livestock	26
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	130
Percentage of total ground water	28
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2
Excluding withdrawals for thermoelectric power	39
Irrigation withdrawals:	
Ground water (Mgal/d)	98
Percentage of total ground water	21
Percentage of total irrigation	75

GENERAL SETTING

Physiographic features in Missouri reflect the geologic history and physical character of the underlying rock. The character of the underlying rock, in turn, has a marked effect on ground-water conditions.

Fenneman (1938) recognized three physiographic provinces in Missouri—the Coastal Plain, the Ozark Plateaus, and the Central Lowland. Each of the physiographic provinces is subdivided into one or more sections (fig. 1). In Missouri, the Coastal Plain province is represented by the Mississippi Alluvial Plain section, the Ozark Plateaus province by the Springfield-Salem Plateaus section, and the Central Lowland province by the Osage Plains and Dissected Till Plains sections.

The Mississippi Alluvial Plain (fig. 1) is underlain by a layer of alluvium that consists of Quaternary sand, gravel, silt, and clay as much as 150 feet (ft) thick. This alluvium underlies the entire Mississippi Alluvial Plain except for Crowleys Ridge, which is a line of low hills that extends from Scott County on the north, through Stoddard County and northern Dunklin County and on into northeastern Arkansas. In Missouri, rocks of Tertiary, Cretaceous, and Ordovician age crop out in Crowleys Ridge. The Tertiary and Cretaceous rocks are composed of sandstone and interbedded sand and clay that dip under the Quaternary rocks and thicken southward. Elsewhere in the Mississippi Alluvial Plain, rocks of Ordovician age underlie the Cretaceous to Quaternary rocks.

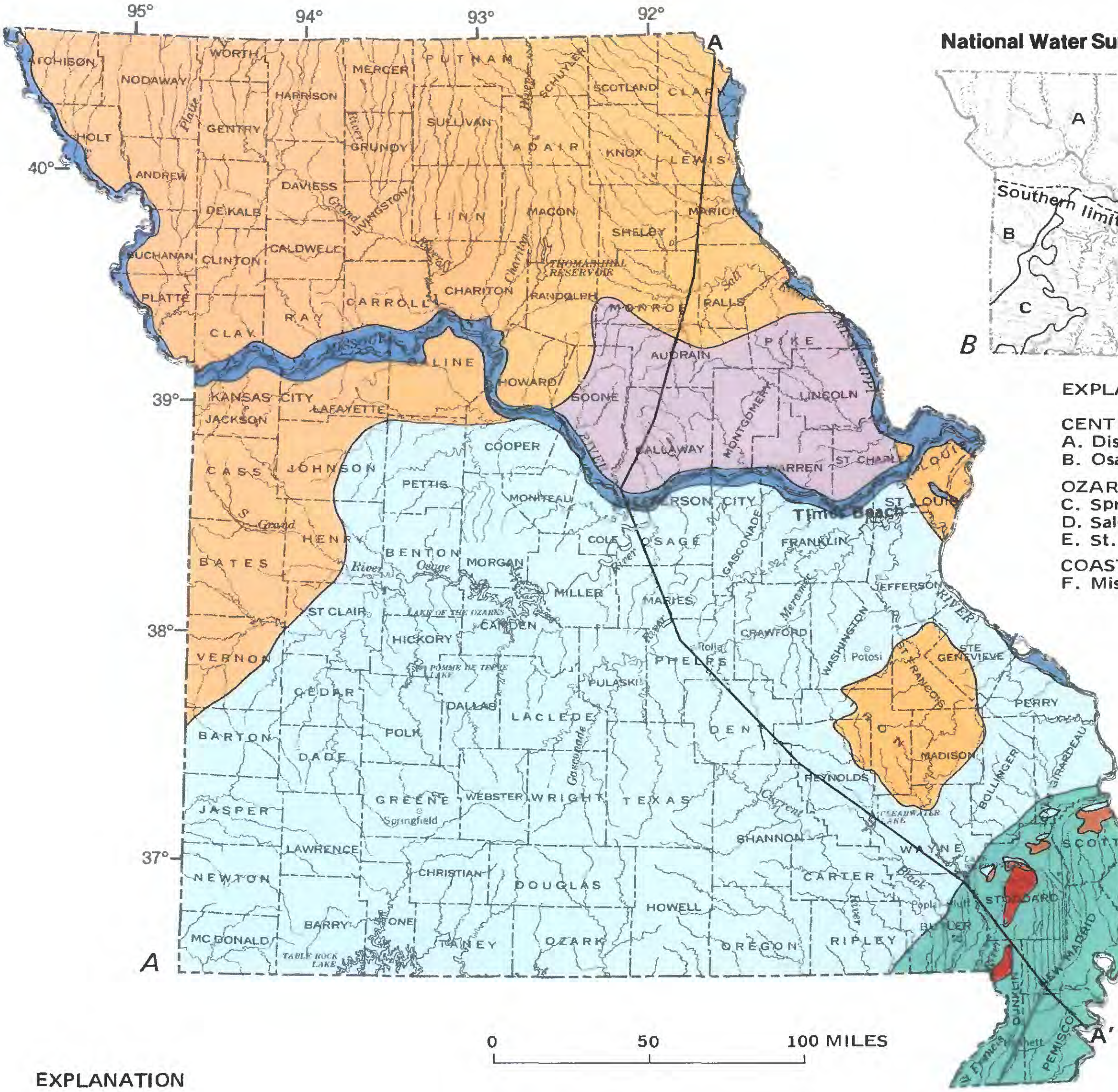
The Salem Plateau section (fig. 1) is that part of the Ozark Plateaus province that "is carved on Ordovician and older rocks, including isolated patches of younger sediments and excluding the St. Francois Mountains" (Fenneman, 1938, p. 647). The Ordovician and older rocks are primarily dolomite with minor interbeds of sandstone. Granite and rhyolite of Precambrian age crop out in the St. Francois Mountains. The other part of the Ozark Plateaus province, the Springfield Plateau section, is underlain by rocks of Mississippian age, which consist mainly of limestone, cherty limestone, and minor quantities of shale.

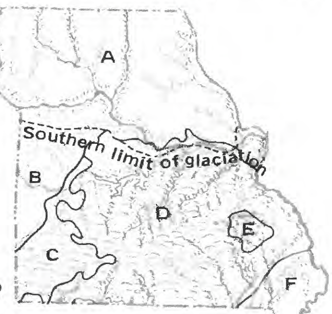
The Osage Plains section (fig. 1) of the Central Lowland province is underlain by rocks of Pennsylvanian age that consist of limestone, shale, sandstone, and conglomerate. These Pennsylvanian formations also contain coal, oil, and gas. The other section of the Central Lowland province in Missouri, the Dissected Till Plains (fig. 1), was once glaciated. In general, the southern limit of glaciation was the Missouri River. Drift deposited by the glaciers reaches a maximum recorded thickness of 400 ft. Rocks of Pennsylvanian and Mississippian age underlie the glacial drift and crop out where the drift has been removed by erosion.

Table 2. Aquifer and well characteristics in Missouri

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and Missouri State agencies.]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
			Principal aquifers		
Alluvial aquifers, major river valleys: Sand, gravel, silt, and clay. Unconfined to partly confined.	80 - 100	100	100 - 1,000	2,500	Water predominantly hard, calcium bicarbonate type. Concentrations of iron commonly exceed 5 mg/L and manganese, 0.75 mg/L. Water in the Missouri River alluvium ranges in dissolved-solids concentration from 250 to 1,500 mg/L.
Aquifers in the Mississippi Alluvial Plain:					
Alluvial aquifer: Sand, gravel, silt, and clay. Unconfined to partly confined.	80 - 150	150	1,000 - 2,000	4,000	Water hard to very hard calcium bicarbonate to calcium magnesium bicarbonate type. Concentrations of iron commonly exceed 5 mg/L. Dissolved-solids concentration of water generally is less than 500 mg/L.
Wilcox and Claiborne aquifers: Multiaquifer unit; interbedded layers of sand and clay. Confined, except where near land surface or where overlain by alluvium.	200 - 1,300	1,300	200 - 1,600	2,000	Present only in Mississippi Alluvial Plain. Water hard; iron concentrations commonly exceed 1.5 mg/L, but general quality suitable for most uses.
McNairy aquifer: Poorly consolidated, medium to coarse-grained sandstone; contains clay in places. Confined, except where near land surface or where overlain by alluvium.	100 - 2,000	2,000	100 - 500	1,000	Present only in Mississippi Alluvial Plain. Water soft and has a small iron concentration. Normally, water changes from calcium bicarbonate type in the recharge area to sodium bicarbonate type down flow path. Large concentrations of dissolved solids (may exceed 1,000 mg/L) and chloride (may exceed 400 mg/L) in water from deeper wells may make water unsuitable for some uses.
Ozark aquifer: Dolomite with minor sandstone. Confined except where near land surface.	200 - 1,700	1,700	15 - 700	1,000	Source of supply for public-supply, industrial, and domestic wells throughout Springfield and Salem Plateaus. Also used as source of irrigation water from deep wells in Barton and Vernon Counties. Hard, calcium magnesium bicarbonate type water. Equivalent to the Roubidoux aquifer in Oklahoma.
Kimmswick-Potosi aquifer: Dolomite with minor sandstone. Confined except where near land surface.	200 - 1,800	1,800	15 - 700	1,000	Primary source of ground water in seven-county area north of Missouri River. Hard, calcium magnesium bicarbonate type water.
			Other aquifers		
Glacial-drift aquifer: Sand, gravel, clay, silt, and boulders. Unconfined to confined.	100 - 250	250	5 - 200	500	Present only in Dissected Till Plains. Water a mixed calcium bicarbonate, sodium sulfate type. Water hard. Iron concentrations may exceed 20 mg/L; sulfate may exceed 1,400 mg/L. Dissolved-solids concentration ranges from 430 to 2,400 mg/L.
Sandstone and limestone aquifers in rocks of Pennsylvanian age: Shale, sandstone, limestone, siltstone, and coal. Unconfined near surface; partly confined to confined at depth.	100 - 400	400	1 - 15	25	Used in Osage Plains for domestic purposes when better quality water not available. Used to limited extent in north-central Missouri for domestic purposes. Locally, water may have dissolved-solids concentration in excess of 20,000 mg/L. Large dissolved-solids concentrations consist of sodium, chloride, and sulfate.





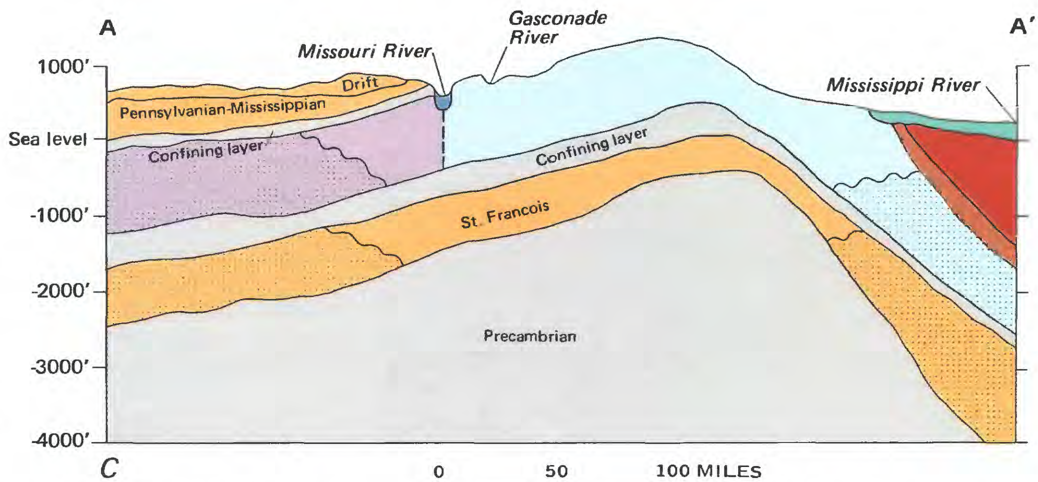


Figure 1. Principal aquifers of Missouri. *A*, Geographic distribution of most used aquifers. *B*, Physiographic diagram and sections. *C*, Generalized cross sections (A-A'). (See table 2 for more detailed description of the aquifers. Sources: *A*, *C*, Compiled by L. F. Emmett from U.S. Geological Survey files. *B*, Fenneman, 1938; Raisz, 1954.)

Table 2. Aquifer and well characteristics in Missouri—Continued

Aquifer name and description	Well characteristics: Depth (ft), Common range	Depth (ft), May exceed	Yield (gal/min), Common range	Yield (gal/min), May exceed	Remarks
Springfield Plateau aquifer: Limestone, chert, shale, and some dolomite in the southwest. Confined except where near land surface.	100 - 400	400	10 - 25	300	On Springfield Plateau, yields of domestic wells range from 5 to 20 gal/min. Near Joplin, some wells yield from 300 to 400 gal/min. Water hard, calcium bicarbonate type.
Limestone aquifer in rocks of Mississippian age: Limestone, chert, shale. Confined except where near land surface.	100 - 400	400	10 - 25	50	In Dissected Till Plains small supplies of potable but hard and moderately mineralized water available to wells less than 400 ft deep. Water hard, calcium bicarbonate type.
St. Francois aquifer: Sandstone and dolomite with some limestone and shale. Confined except where near land surface.	100 - 500	500	5 - 100	250	Principal area of use is in eastern Ozarks in vicinity of St. Francois Mountains. Includes Lamotte Sandstone and Bonneterre Formation. Used for domestic and public supply. Water hard, calcium magnesium bicarbonate type.

Two major rivers form boundaries or partial boundaries for the State. Missouri's eastern boundary is the Mississippi River. The Missouri River forms the northwest boundary and then at Kansas City cuts across the width of the State and enters the Mississippi River upstream from St. Louis. Both river valleys contain alluvial material as much as 120 ft thick.

Average annual precipitation ranges from about 32 inches (in.) in the northwest part of the State to about 48 in. in the southeast. As much as 10 to 15 percent of the average annual precipitation may infiltrate the ground, but as little as 1 percent may actually recharge the deep aquifers (Imes, 1985).

PRINCIPAL AQUIFERS

The principal aquifers in Missouri are the alluvial aquifers along the major river valleys, the aquifers present only in the Mississippi Alluvial Plain, the Ozark aquifer, and the Kimmswick-Potosi aquifer. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Alluvial Aquifers (Major River Valleys)

Large-scale withdrawals of water from the alluvial aquifers along river valleys have been limited to the Missouri, the Mississippi, and the lower Meramec River valleys. In the St. Joseph and Kansas City areas, water is pumped from the Missouri River alluvium for industrial purposes. Many cities also obtain water from the alluvium for public supplies; the cities of Independence, Marshall, and Columbia obtain water from the Missouri River alluvium, the city of St. Charles obtains water from the Mississippi River alluvium, and the cities of Valley Park and Kirkwood obtain water from the Meramec River alluvium. Water also is pumped from the alluvium for irrigation and for the flooding of waterfowl preserves.

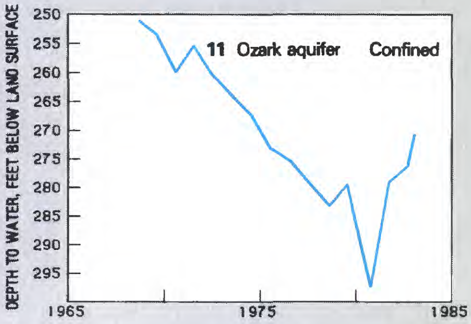
Water in the alluvium is unconfined to partly confined. In the Meramec River alluvium in St. Louis County and in the Mississippi River alluvium in St. Charles County, ground water in localized areas has larger-than-background sodium, chloride, iron, and manganese concentrations. The increased sodium and chloride concentrations may be the result of upward leakage of saline water from the underlying bedrock formations by natural processes or by means of abandoned deep wells (Miller and others, 1974, p. 37–41).

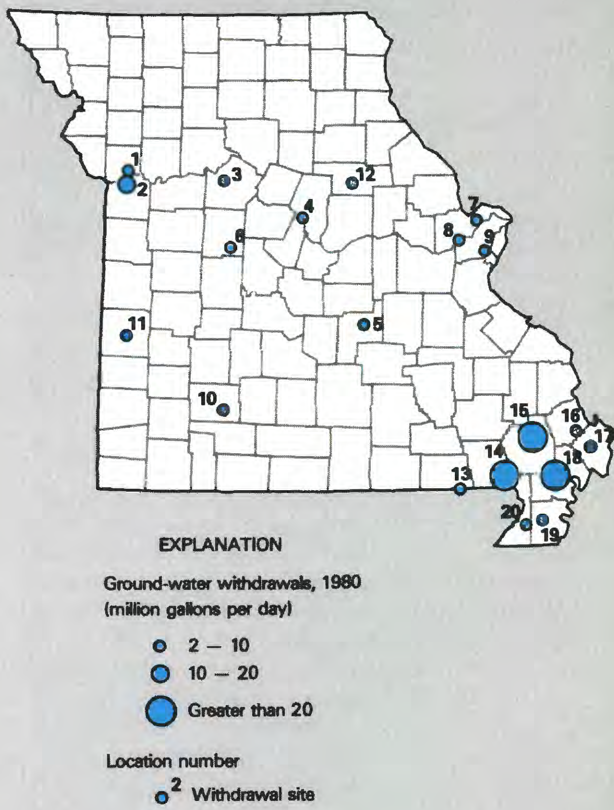
Aquifers in the Mississippi Alluvial Plain

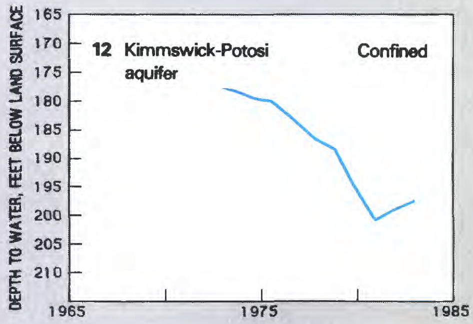
In the Mississippi Alluvial Plain area, the alluvial aquifer is present throughout with the exception of Crowleys Ridge and a few isolated hills near the Salem Plateau. Water in this aquifer is unconfined to partly confined (Luckey, 1985). By far the greatest use of water from the Mississippi River alluvial aquifer is for irrigation. About 90 percent of the ground water that is pumped for irrigation in the State is withdrawn from this alluvial aquifer. Other aquifers that are used in the Mississippi Alluvial Plain area are the Wilcox, the Claiborne, and the McNairy (table 2). The Wilcox and the Claiborne aquifers consist of sand of Tertiary age (Hosman and others, 1968), and the McNairy aquifer consists of sand of Cretaceous age (Boswell and others, 1965). These aquifers crop out along Crowleys Ridge and underlie the alluvium elsewhere in the Mississippi Alluvial Plain. Because the aquifers dip and thicken southward, well depths are shallowest in the north and deepest in the south. Municipalities and industries are the principal users of water from the Wilcox, the Claiborne, and the McNairy aquifers.

Ozark Aquifer

The Ozark aquifer, which consists of Cambrian and Ordovician age dolomite with minor quantities of sandstone,







WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Clay County.	Alluvial.	Public supply, industrial.
2	Independence	. . . .do	Public supply.
3	Marshall	. . . .do	Do.
4	Columbia.	Alluvial, Kimmswick-Potosi.	Do.
5	Rolla	Ozark.	Do.
6	Sedalia	. . . .do	Do.
7	St. Charles	Alluvial.	Do.
8	Weldon Spring area.	. . . .do	Do.
9	Kirkwood	. . . .do	Do.
10	Greene County area.	Ozark.	Industrial, public supply.
11	Barton and Vernon Counties.	. . . .do	Irrigation, public supply, industrial.
12	Audrain County area.	Kimmswick-Potosi . .	Do.
13	Ripley County.	Alluvial.	Irrigation.
14	Butler County.	. . . .do	Do.
15	Stoddard County . . .	. . . .do	Do.
16	Scott County	. . . .do	Do.
17	Mississippi County . .	. . . .do	Do.
18	New Madrid County.	. . . .do	Do.
19	Pemiscot County . . .	. . . .do	Do.
20	Dunklin County. . . .	. . . .do	Do.

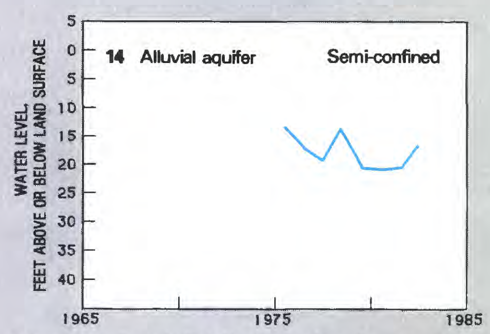


Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Missouri. (Sources: Withdrawal data from U.S. Geological Survey files; water-level data from Missouri Division of Geology and Land Survey files.)

is present at the surface throughout most of the Salem Plateau and underlies younger rocks on the Springfield Plateau and Osage Plains. Most of the large springs in Missouri discharge from openings in the dolomite where it crops out on the Salem Plateaus. Throughout the Springfield–Salem Plateaus and in the easternmost part of the Osage Plains, the Ozark aquifer is the primary source of ground water and it furnishes the majority of public supplies. In the Springfield area, water from the aquifer also is used for self-supplied industrial use. The Ozark aquifer also is a source of water to deep irrigation wells in Barton and Vernon Counties on the Osage Plain (Kleeschulte and others, 1984) and in Jasper and other counties on the Springfield–Salem Plateaus.

Kimmswick-Potosi Aquifer

Dolomite and minor quantities of sandstone of Cambrian and Ordovician age compose the Kimmswick-Potosi aquifer. This aquifer is the primary source of ground water north of the Missouri River in a seven-county area that is bounded on the east by St. Charles County, on the west by Boone County, and on the north by Audrain County (fig. 1). The Kimmswick–Potosi aquifer supplies water to most public-supply wells in the area and also supplies the deep irrigation wells in Audrain, Boone, and Montgomery Counties (Imes, 1985).

Many of the geologic formations that comprise the Ozark and the Kimmswick–Potosi aquifers are present throughout the western and northern parts of the State, but the water in them is too mineralized for use. The transition zone from fresh to mineralized ground water extends in an arcuate pattern from Barton County on the west to Pike County on the east (Fuller and others, 1967, p. 283). West and north of this line, water becomes progressively more mineralized, whereas water east and south of the line is fresh [less than 1,000 milligrams per liter (mg/L) of dissolved solids].

OTHER AQUIFERS

Minor aquifers of Missouri are the glacial-drift aquifer, the aquifers in rocks of Pennsylvanian and Mississippian age in northern and western Missouri, and the St. Francois aquifer that crops out near the St. Francois Mountains. The glacial-drift aquifer is present only in the Dissected Till Plains (fig. 1). The glacial drift ranges in thickness from 0 to 400 ft. In northeastern Missouri, the drift is thin and only locally productive. The north-central and northwestern parts of the State are underlain by thin till in the uplands and locally by relatively thick glacial outwash in buried valleys. Water in the buried valleys is confined. In the uplands, wells generally yield 15 gallons per minute (gal/min). In some of the buried valleys, wells may yield as much as 500 gal/min. The principal use of water from the glacial drift is for domestic and stock use.

Sandstone and limestone aquifers in rocks of Pennsylvanian age underlie the glacial drift in northern Missouri and are present at the surface in the Osage Plains. The aquifers have little permeability, and wells finished in the aquifers generally yield quantities of water suitable only for domestic and stock use.

Rocks of Mississippian age, principally limestone and cherty limestone, comprise the limestone aquifers present in the Dissected Till Plains and in the Springfield Plateau aquifer in southwestern Missouri. Many springs exist in the Springfield Plateau, but they are not as large or abundant as those in the Salem Plateau. Water from the limestone aquifers is used primarily for domestic and stock use. A few wells in the Joplin area provide water for industrial use. Some water is withdrawn for industrial use from abandoned lead-zinc mines in the Joplin area.

The St. Francois aquifer is comprised of the Lamotte Sandstone and Bonneterre Formation of Cambrian age. These formations crop out in and around the St. Francois Mountains, where the water generally is used for domestic supply. The water also is used for public supply where the overlying Ozark aquifer is thin or absent.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals and trends in ground-water levels at selected pumping locations are shown in figure 2. Only areas that withdraw 2 million gallons per day (Mgal/d) or more are shown.

Alluvial aquifers along the major river valleys, in addition to those shown in figure 2, constitute an important source of water for public supply and industrial use for many small towns. The alluvial aquifers also are the source of water for many irrigation wells and for wells used to flood waterfowl preserves. The principal alluvial aquifers are in hydraulic connection with and recharged by their streams.

One of the areas of major ground-water withdrawals in the State is the Mississippi Alluvial Plain, where large quantities of water are withdrawn from the alluvial aquifer to irrigate crops. In the alluvial aquifer, water levels are highest in the spring and then begin to decline in response to pumping. As a result, water levels generally are lowest in late summer or early fall and at the end of the growing season begin to recover. Because of the large rate of recharge to the aquifer, permanent lowering of water levels due to pumping has not occurred.

The Ozark aquifer is the primary source of ground water throughout the Springfield-Salem Plateaus and in a small area of the Osage Plains where the ground water is not too mineralized to use. Pumping from the Ozark aquifer has caused a large cone of depression in the Springfield area (location 10, fig. 2) (Emmett and others, 1978). The water-level response to pumping from the Ozark aquifer, where it is overlain by relatively impermeable to slightly permeable rocks that inhibit recharge, is shown in hydrograph 11 (fig. 2). A similar response for the Kimmswick–Potosi aquifer where it is overlain by relatively impermeable rocks is shown by hydrograph 12 (fig. 2). A continuous decline in water levels due to pumping has occurred at both of these locations, although recovery has occurred since 1981. A continued increase in pumping rate will lower water levels in these areas. Elsewhere in Missouri, ground-water conditions have not changed significantly, except in the vicinity of well fields.

GROUND-WATER MANAGEMENT

The Missouri Division of Geology and Land Survey (DGLS), the Missouri Division of Environmental Quality (DEQ), and the Missouri Division of Health (DOH) are the principal State organizations involved in ground-water activities. One of the duties of the DGLS is administration of the new Major Water Users Registration Act (Revised Statute 256), which requires that withdrawals of more than 100,000 gallons per day (gal/d) be reported annually to the DGLS. The DGLS also provides advice to the DEQ on casing depths for public-supply wells. The State Geologist, who also is the director of the DGLS, administers the rules and regulations of the State Oil and Gas Council (RS Mo. 259.010, 259.020, 259.030, 259.040). In so doing, the State Geologist maintains close watch over oil-and-gas drilling practices to ensure the protection of ground-water supplies. The DGLS, in cooperation with the U.S. Geological Survey, is responsible for maintaining a statewide data network and investigating the State's water resources. The DEQ supervises the design and construction of water-supply systems and, in cooperation with the DOH, monitors contaminants in water supplies.

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Prepared by Leo F. Emmett

For further information contact District Chief, U.S. Geological Survey, 1400 Independence Road, Mail Stop 200, Rolla, MO 65401.

MONTANA
Ground-Water Resources

Ground water is available in nearly every part of Montana but constitutes less than 2 percent of the total water withdrawals. However, 424,000 people, or about one-half of the State's 786,000 population, are supplied with water for domestic purposes from ground-water sources—230,000 people through public water-supply systems and 194,000 people through rural water-supply systems. The quantity of ground water withdrawn for public and rural-domestic supplies (68 million gallons per day) is about 0.5 percent of total statewide surface- and ground-water withdrawals (Montana Department of Natural Resources and Conservation, 1985). About one-half of the fresh ground-water withdrawals in the State is used for irrigation (Solley and others, 1983). Recent statistics related to withdrawals of ground water and its various uses are given in table 1.

Table 1. Ground-water facts for Montana

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Montana Department of Natural Resources and Conservation, 1985; irrigation data from Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	424
Percentage of total population	54
From public water-supply systems:	
Number (thousands)	230
Percentage of total population	29
From rural self-supplied systems:	
Number (thousands)	194
Percentage of total population	25
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	11,000
Ground water only (Mgal/d)	200
Percentage of total	2
Percentage of total excluding withdrawals for thermoelectric power	2
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	54
Percentage of total ground water	27
Percentage of total public supply	39
Per capita (gal/d)	235
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	14
Percentage of total ground water	7
Percentage of total rural domestic	94
Per capita (gal/d)	72
Livestock:	
Ground water (Mgal/d)	9
Percentage of total ground water	4
Percentage of total livestock	38
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	29
Percentage of total ground water	14
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	20
Excluding withdrawals for thermoelectric power	52
Irrigation withdrawals:	
Ground water (Mgal/d)	94
Percentage of total ground water	48
Percentage of total irrigation	1

GENERAL SETTING

Montana has two distinct hydrogeologic regimes. The first, which is in western and south-central Montana (Northern and Middle Rocky Mountains physiographic provinces, fig. 1), generally consists of a series of structurally complex mountain ranges separated by downfaulted intermontane valleys containing as much as 16,000 feet (ft) of Cenozoic basin-fill sediments. Annual precipitation ranges from 8 inches (in.) in the valleys to about 120 in. along the higher mountain crests. The second, which is in eastern and north-central Montana (Great Plains physiographic province, fig. 1), generally consists of moderately dissected plains underlain by Cenozoic and Mesozoic sedimentary rocks locally interrupted by small mountain ranges. Annual precipitation ranges from 12 to 30 in. on the plains.

Recharge to the ground-water system in Montana is derived mainly from precipitation. Recharge ranges from less than 1 in. per year in parts of the eastern plains to several inches in parts of the western mountains.

PRINCIPAL AQUIFERS

Aquifers in Montana consist of unconsolidated alluvial, glacial, and basin-fill deposits, and consolidated sedimentary rocks. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

CENOZOIC AQUIFERS

Alluvial, Glacial, and Basin-Fill Aquifers

Most ground water used in western and south-central Montana is derived from Cenozoic aquifers that consist of alluvial, glacial, and basin-fill deposits of unconsolidated to semiconsolidated gravel, sand, silt, and clay (fig. 1, table 2). In these areas, where the mountain snowpack provides an adequate supply of fresh surface water for most purposes, ground-water supplies generally are not well developed. However, an adequate water supply generally can be obtained at shallow depths in alluvium bordering major rivers.

Water in the alluvial aquifer is unconfined at most locations. Materials deposited by meltwater from mountain glaciers provide variable yields depending on the silt and clay content. Basin-fill deposits can yield an adequate water supply, usually within 200 ft of land surface, for stock and domestic purposes. Yields to wells completed in the alluvial and basin-fill deposits may be adequate for irrigation, public supply, or industrial purposes; such deposits supply water to the cities of Bozeman (Gallatin County), Missoula (Missoula County), Dillon (Beaverhead County), Kalispell (Flathead County), and Townsend (Broadwater County). Water in the glacial and basin-fill deposits usually is unconfined near the land surface and confined at deeper levels by layers of silt and clay.

In eastern and north-central Montana, ground water is the most reliable source of supply, except along the major rivers and streams where a fairly dependable supply of surface water can be obtained. Ground-water supplies in this region are available from Cenozoic alluvial and glacial deposits and from deeper aquifers (fig. 1, table 2).

Table 2. Aquifer and well characteristics in Montana

[Ft = feet; gal/min = gallons per minute; est. = estimated; mg/L = milligrams per liter. Sources: Davis and Rogers (1984); Levings (1982a, b, c, d); Noble and others (1982a, b); Feltis (1980c)]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Cenozoic aquifers:					
Western alluvial and basin-fill deposits: Unconsolidated sand, gravel, silt, and clay. Generally unconfined.	20 - 40	250	5 - 50 est.	1,500	Dissolved-solids concentration generally less than 300 mg/L near Helena and Missoula. Water quality in other areas probably similar.
Western glacial deposits: Unconsolidated sand, gravel, silt, and clay. Unconfined to confined.	50 - 300	900	5 - 50 est.	3,500	Dissolved-solids concentration generally less than 200 mg/L in northwestern Montana. Water quality in other areas probably similar.
Eastern alluvial deposits and terrace gravels: Unconsolidated sand, gravel, silt, and clay. Generally unconfined.	20 - 50	250	5 - 50 est.	1,000	Dissolved-solids concentration generally less than 2,000 mg/L.
Eastern glacial deposits: Unconsolidated sand, gravel, silt, and clay. Unconfined to confined.	20 - 60	200	5 - 10	1,000	Dissolved-solids concentration generally less than 2,200 mg/L.
Fort Union Formation: Moderately consolidated and interbedded shale, siltstone, sandstone, and coal. Unconfined to confined.	50 - 300	1,000	15 - 25	100	Dissolved-solids concentration generally less than 1,800 mg/L.
Mesozoic aquifers:					
Hell Creek Formation and Fox Hills Sandstone: Sandstone with some siltstone and shale. Confined except near outcrop areas.	150 - 500	1,000	5 - 20	200	Dissolved-solids concentration generally less than 1,200 mg/L. Includes Fox Hills-lower Hell Creek aquifer.
Judith River Formation: Sandstone with shale, siltstone, lignite, and coal. Confined except near outcrop areas.	200 - 600	1,000	5 - 15 est.	100	Dissolved-solids concentration generally less than 2,300 mg/L in central Montana. Water quality in other areas of Montana relatively unknown.
Eagle Sandstone: Interbedded sandstone and shale. Confined except near outcrop areas.	100 - 800	2,000	10 - 20 est.	200	Dissolved-solids concentration generally less than 2,300 mg/L in central Montana Water quality in other areas of Montana relatively unknown.
Kootenai Formation: Sandstone, siltstone, and shale. Confined except near outcrop areas.	100 - 900	3,000	10 - 30 est.	100	Dissolved-solids concentration generally less than 500 mg/L near outcrop areas in central Montana. Water quality in other areas of Montana relatively unknown.
Ellis Group: Sandstone, shale, limestone, and dolomite. Confined except near outcrop areas.	300 - 2,000	5,000	-	100	Dissolved-solids concentration generally less than 600 mg/L near outcrop areas. Water quality in other areas of Montana relatively unknown.
Paleozoic aquifer:					
Madison Group: Limestone, dolomite, anhydrite, and halite. Confined except near outcrop areas.	500 - 3,000	7,000	-	1,000	Dissolved-solids concentration generally less than 5,000 mg/L, but may exceed 300,000 mg/L in northeastern Montana.

Alluvial deposits are present mainly along the major river valleys. Water from these deposits is used for public and rural-domestic supplies near population centers along these river valleys. Locally, terrace gravel is developed for water, although supplies are affected by the generally limited saturated thickness and storage capabilities of the aquifer. One such deposit is exposed throughout large areas in Blaine, Valley, and Daniels Counties where it is a source of water for irrigation.

Pleistocene glacial debris deposited by a continental ice sheet forms a veneer over much of the plains of Montana north of 47°30′N. latitude and east of 112°W. longitude. The ice sheet also was responsible for altering river courses and subsequently burying ancient stream gravels with glacial drift. Recently discovered buried stream gravels in Roosevelt and Sheridan Counties are very productive aquifers, yielding sufficient quantities of water to wells for irrigation. The glacial deposits commonly yield adequate water supplies for stock and domestic needs. Water in the glacial deposits may be either confined or unconfined depending on their depth below the land surface and the silt and clay content of the overlying material.

Fort Union Aquifer

The Fort Union Formation consists primarily of moderately consolidated continental shale, siltstone, fine sand, sandstone, and coal. Well yields are sufficient for rural-domestic and livestock needs. Larger yields are sometimes

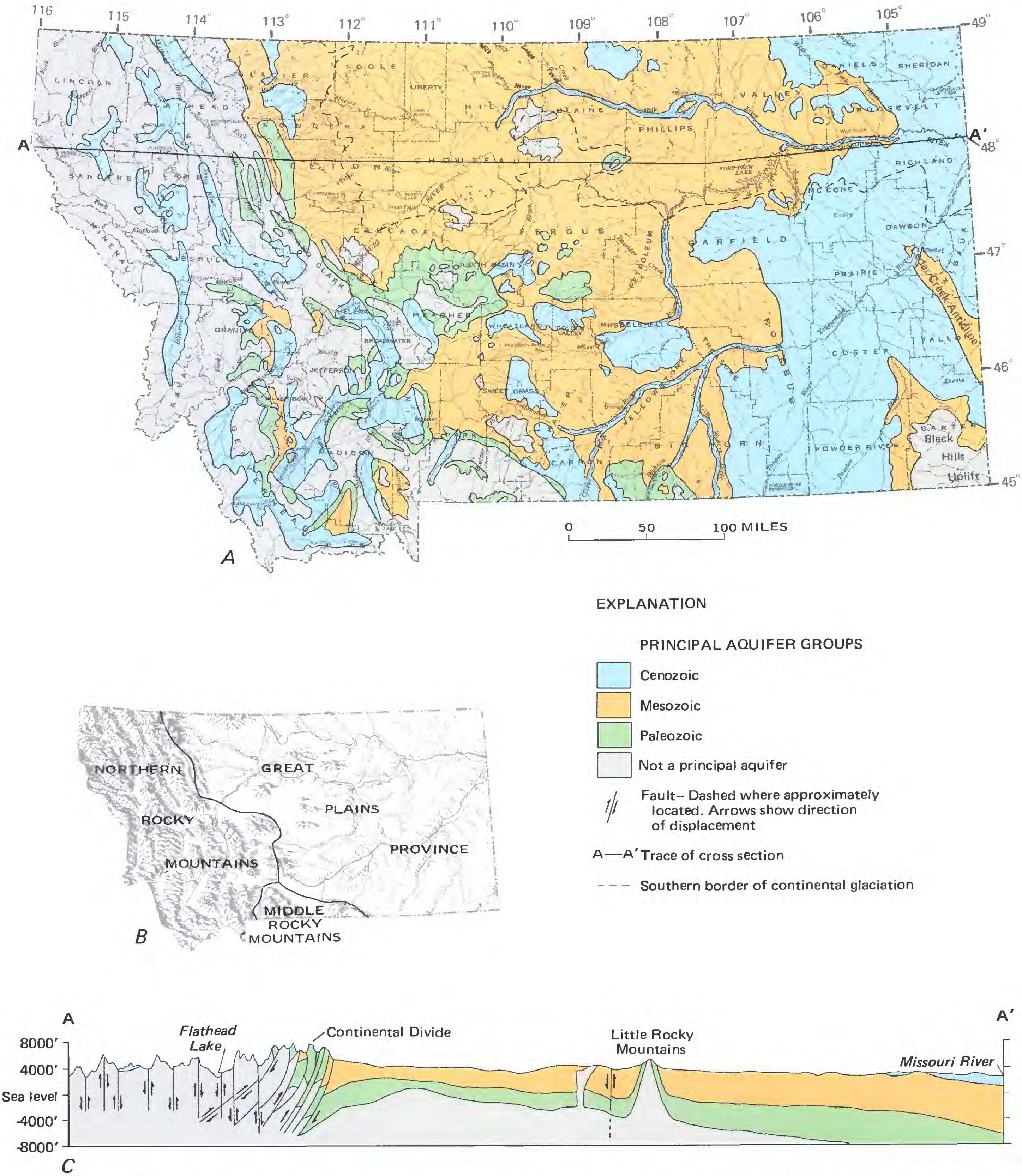


Figure 1. Principal aquifers in Montana. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for more detailed description of the aquifers. Sources: *A*, Ross and others, 1955. *B*, Fenneman, 1931; Raisz, 1954. *C*, American Association of Petroleum Geologists, 1972.)

available in clinker, which is rock that has been baked, fused, and fractured from the burning of underlying coal beds. Generally, shallow ground water flows from topographically high areas toward local surface drainages, and deeper ground water flows toward major surface drainages. Shallow ground water may be either confined or unconfined; deeper ground water generally is confined.

MESOZOIC AQUIFERS

Fox Hills-Lower Hell Creek Aquifer

The lower part of the Hell Creek Formation consists of lenticular sandstone with intertonguing siltstone and shale. Where present, the underlying Fox Hills Sandstone, which is of marine origin, is connected hydraulically to the Hell Creek. Together, these two units compose the Fox Hills-lower Hell Creek aquifer. This aquifer is used most extensively in Carter, Custer, Prairie, and Fallon Counties on the flanks of the Cedar Creek anticline and Black Hills uplift or along major streams and rivers where drilling depths are minimized (Levings, 1982c). Yields generally are adequate for stock and rural-domestic purposes and for public supply in some areas. Water in this aquifer is confined except near its outcrop.

Judith River, Eagle, Kootenai, and Ellis Aquifers

Beneath the Fox Hills Sandstone is a series of aquifers that consist mainly of sandstone separated by shale confining layers. The aquifers commonly yield adequate supplies for most stock and rural-domestic needs and, at places, may yield adequate water for public supplies. Most of the wells are drilled near the outcrop area of the aquifers or where a satisfactory shallower source of supply is not available. The Judith River Formation is developed most extensively in Phillips, Blaine, Hill, and Valley Counties (Levings, 1982a); the Eagle Sandstone in Hill, Liberty, Choteau, Glacier, and Fergus Counties (Levings, 1982d); and the Kootenai Formation and the Ellis Group in Cascade, Judith Basin, Fergus, and Petroleum Counties near the flanks of mountain ranges (Levings, 1982b, and Levings, 1983). Water in these aquifers is confined except along their outcrop areas.

PALEOZOIC AQUIFERS

Madison Aquifer

The Madison Group is the lowermost widespread aquifer in eastern and central Montana. It consists mainly of limestone with some dolomite, anhydrite, and halite. Rocks of the Madison Group crop out mostly in mountain ranges but dip steeply away from the mountains and lie deeply buried in most of the eastern part of the State. Precipitation is the primary source of recharge in outcrop areas. Several large perennial springs issue from rocks of the Madison Group in Cascade, Fergus, and Carbon Counties. The Madison Group has not been used extensively for water supplies because of the generally deep drilling needed, but its subsurface configuration and potentiometric surface are well known because of regionwide oil exploration drilling (Feltis, 1980a, b). In areas where permeability is enhanced by fracturing and solution, large yields are possible. Water in the Madison is confined except near outcrop areas. The water is fresh near outcrops but increases in salinity with depth and distance from the outcrop (Feltis, 1980c).

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals are listed and trends in ground-water levels near selected locations are shown in figure 2. Most of the withdrawals are from the near-surface unconsolidated Cenozoic aquifers.

Water levels in wells throughout the State have been monitored since the 1950's. Presently, water levels are measured at least annually in about 220 observation wells statewide. In the western part of the State, 64 observation wells tap Cenozoic aquifers. In the eastern part, 76 wells are completed in Cenozoic aquifers, 78 in Mesozoic aquifers, and 4 in Paleozoic aquifers. Data from the measurements are stored in computer files and are available to the public upon request. The data can be used to evaluate naturally fluctuating water levels as a result of climatic patterns and the effects of man's activities on the hydrologic system.

Water levels generally decline in response to increases in withdrawals or decreases in recharge and recover with increased recharge or as withdrawals are decreased. Hydrographs (locations 1, 2, 8, fig. 2) from Beaverhead, Missoula, and Blaine Counties show that the overall trend is no net change; declines in water levels are seasonal. These unconsolidated aquifers are all unconfined.

The hydrograph from Fallon County (location 6, fig.2) shows a long-term decline in water level from 1962 to 1973 for the Fox Hills-lower Hell Creek aquifer. The declines resulted from large water withdrawals for industrial, public supply, rural domestic, and stock uses. Decreases in withdrawals since the mid-1970's have resulted in a rise in water levels, although the present water level is still about 60 ft lower than the 1962 level at the location shown. The Fox Hills-lower Hell Creek aquifer is confined in this area.

GROUND-WATER MANAGEMENT

The 1973 Montana Water Use Act established a uniform central system for the acquisition, administration, and determination of all water rights. The Act also mandated the adjudication of all existing rights. To date, 10,500, or about 5 percent, of the State's existing water rights applications have been adjudicated, all in the Powder River Basin.

Appropriation of ground-water supplies for domestic, agricultural, or livestock purposes does not require a water-right permit if the maximum appropriation from the source well is less than 100 gallons per minute (gal/min). The only requirement is completion of a form within 60 days after completion of the well.

Appropriation of ground-water supplies requires a water-right permit if the maximum yield of the well is 100 gal/min or more or if the well is in a controlled ground-water area. Controlled ground-water areas can be established to protect water rights, an entire water resource, or public health in areas subject to pollution of water supplies.

Requirements to be met before issuance of a water-right permit are:

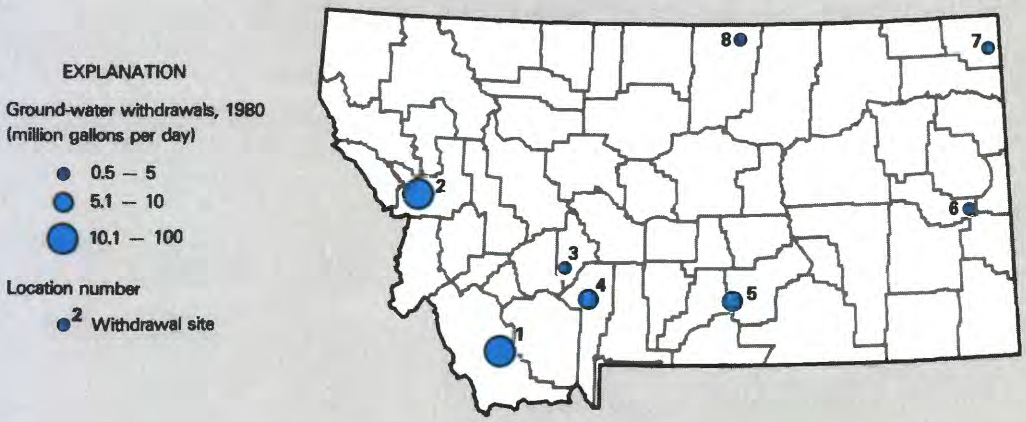
1. Unappropriated waters exist that the applicant can use in the quantity and at the time proposed in the application.

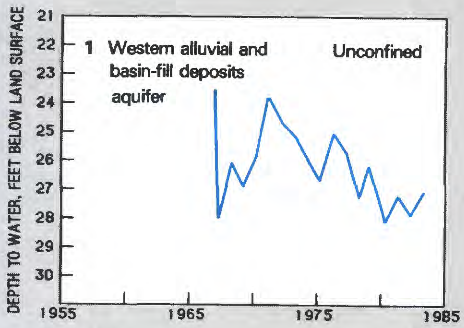
2. The rights of prior appropriators will not be adversely affected.

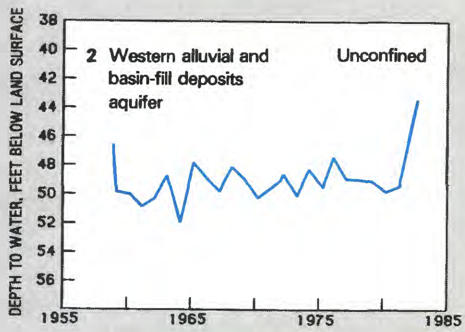
3. The proposed means of construction are adequate.

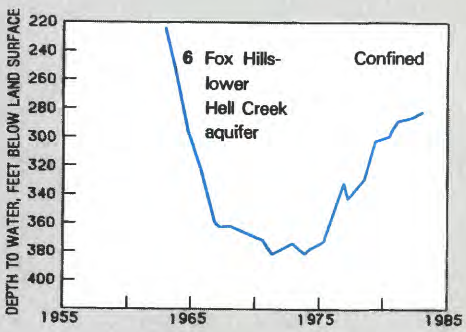
4. The proposed use is deemed a beneficial use.

5. The proposed use will not interfere unreasonably with other permitted, planned uses or developments or with water previously reserved for other uses.









WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Beaverhead County . .	Western alluvial and basin-fill deposits.	Irrigation.
2	Missoula County . . .	. . . .do	Industrial, public supply, irrigation.
3	Broadwater County . .	. . . .do	Irrigation.
4	Gallatin County	. . . .do	Do.
5	Yellowstone County.	Eastern alluvial deposits and terrace gravel.	Irrigation, public supply, rural domestic.
6	Fallon County.	Fox Hills-lower Hell Creek aquifer.	Public supply, industrial (in previous years).
7	Sheridan County . . .	Eastern glacial deposits.	Irrigation.
8	Blaine County	Eastern alluvial deposits and terrace gravel.	Do.

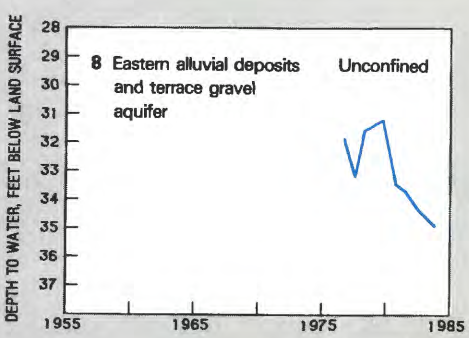


Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Montana. (Sources: Withdrawal data from Montana Department of Natural Resources and Conservation, 1985, and Solley and others, 1983; water-level data from U.S. Geological Survey files.)

6. The applicant proposing to use in excess of 10,000 acre-feet per year (15 cubic feet per second) must prove by clear and convincing evidence that the rights of prior appropriators will not be adversely affected.

Several State agencies implement most of the planning, regulatory, and research programs mandated by legislation in Montana. The Montana Department of Natural Resources and Conservation has the responsibility for administering water-resources and water-right programs and assists in the organization and operation of water-conservation districts. The Montana Department of Health and Environmental Sciences has the responsibility for regulating the quality of Montana's streams, lakes, and ground-water resources, including public-water supplies and wastewater management. The Montana Department of State Lands applies for and claims water for use on school-trust lands, maintains records of water rights attached to the State school-trust lands, and has indirect responsibility for water through various mining-reclamation acts. The Montana Universities Joint Water Resources Research Center, as the center of academic-oriented water research in Montana, conducts and coordinates specialized water studies, sometimes at the specific request of water-resource-management agencies.

The Montana Bureau of Mines and Geology is a nonregulatory agency responsible for conducting applied research projects on all aspects of the State's ground-water resources, maintaining a statewide ground-water information center and data base, and assisting governmental organizations and private citizens with water-related problems and requests. In addition, the Bureau has an active ground-water cooperative program with the U.S. Geological Survey to conduct local and regional hydrogeological investigations throughout the State. The research, data collection, and analyses provided through the program form an information base that helps regulating agencies make ground-water-management decisions and recommendations.

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Prepared by Julianne F. Levings, Robert E. Davis, and Charles Parrett

For further information contact District Chief, U.S. Geological Survey, Federal Building, Room 428, 301 South Park Avenue, Drawer 10076, Helena, MT 59626

NEBRASKA
Ground-Water Resources

Ground water supplied 59 percent of the total water used in Nebraska during 1980. About 82 percent of Nebraska's 1.57 million population (1980 census) is supplied with drinking water from aquifers. Approximately 6 percent of the total ground water used during 1980 was for domestic, stock, public, and industrial supplies. The other 94 percent was withdrawn from about 70,000 wells (Johnson and Pederson, 1984) to irrigate 6.2 million acres; this ranks Nebraska among the top three States in the Nation in use of ground water for irrigation. Development of the ground-water resource has caused declining water levels in some areas of the State. Ground-water withdrawals and other selected statistics are given in table 1.

Table 1. Ground-water facts for Nebraska

[Withdrawal data rounded to two significant figures and may not add to total because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Johnson and Pederson, 1984; Lawton, Veys, and Goodenkauf, 1983; Solley, Chase and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	1,291
Percentage of total population	82
From public water-supply systems:	
Number (thousands)	961
Percentage of total population	61
From rural self-supplied systems:	
Number (thousands)	330
Percentage of total population	21
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	12,000
Ground water only (Mgal/d)	7,100
Percentage of total	59
Percentage of total excluding withdrawals for thermoelectric power	73
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	230
Percentage of total ground water	3
Percentage of total public supply	77
Per capita (gal/d)	239
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	49
Percentage of total ground water	1
Percentage of total rural domestic	100
Per capita (gal/d)	148
Livestock:	
Ground water (Mgal/d)	93
Percentage of total ground water	1
Percentage of total livestock	80
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	66
Percentage of total ground water	1
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	3
Excluding withdrawals for thermoelectric power	85
Irrigation withdrawals:	
Ground water (Mgal/d)	6,700
Percentage of total ground water	94
Percentage of total irrigation	67

GENERAL SETTING

Nebraska is a predominantly agricultural State and has a semiarid to subhumid climate. The eastern one-fifth of the State lies in the Dissected Till Plains section of the Central Lowland physiographic province, and almost all of the rest of the State lies in the High Plains section of the Great Plains physiographic province. The boundary between the Central Lowland and the Great Plains Provinces is indistinct throughout much of Nebraska (Fenneman, 1931).

Most recharge to aquifers in Nebraska comes from infiltration of precipitation. Average annual precipitation ranges between 13 and 17 inches (in.) in western Nebraska and between 26 and 35 in. in the eastern part of the State (Bentall and Shaffer, 1979). In some localities, seepage from streams, lakes, irrigation canals, and applied irrigation water is a significant source of recharge. Estimates of recharge range from about 1 percent of average annual precipitation in areas of clayey soils to about 35 percent in areas of sandy soils.

PRINCIPAL AQUIFERS

Principal aquifers in Nebraska consist of unconsolidated deposits of gravel, sand, silt, and clay, and consolidated sandstone and carbonate rocks. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

AQUIFERS IN UNCONSOLIDATED DEPOSITS

Valley Alluvial Aquifers

Valley alluvial aquifers can be delineated only along major streams in eastern Nebraska (fig. 1) and are differentiable only in areas where another aquifer system—the High Plains aquifer system—is not present. The aquifers shown in figure 1 along the Missouri River and the Platte River, are each more than 30 feet (ft) thick and are connected hydraulically to the rivers. These aquifers generally are capable of large yields of water that is suitable for most uses. The aquifer along the Platte River in eastern Nebraska is the source of water supply for the city of Lincoln and also provides part of the water supply for Omaha. About 1 percent of the irrigation wells in Nebraska are completed in valley alluvial aquifers, and the only significant development for irrigation has occurred along the Missouri River where topography and soils are more suited for agricultural development.

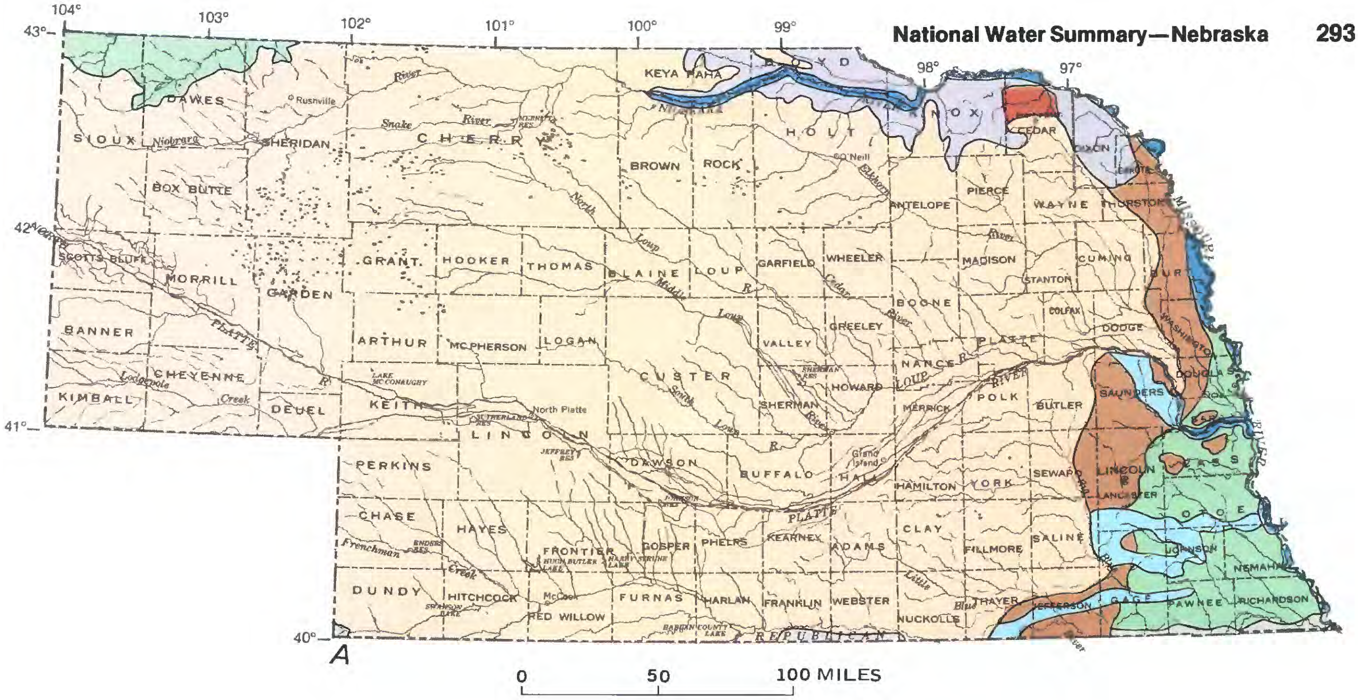
Paleovalley Alluvial Aquifers

Paleovalley alluvial aquifers are saturated alluvial deposits that fill older glacial or preglacial bedrock valleys. Only the larger of these aquifers are shown in figure 1 and, like the valley alluvial aquifers, are mappable only in eastern Nebraska where the High Plains aquifer system is not present. Most water pumped from these aquifers is for irrigation and about 2 percent of the irrigation wells in the State are completed in these aquifers. The paleovalley alluvial aquifers also supply a number of municipal systems and several rural water districts with water that is of suitable quality for most uses.

Table 2. Aquifer and well characteristics in Nebraska

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and Nebraska State agencies]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Aquifers in unconsolidated deposits:				
Valley alluvial aquifers: Unconsolidated sand, gravel, silt, and clay. Unconfined.	30 - 100	300 - 750	1,500	Differentiable only in areas where High Plains aquifer system not present. Locally, water contains excessive concentrations of iron.
Paleovalley alluvial aquifers: Unconsolidated sand, gravel, silt, and clay. Generally unconfined.	50 - 150	500 - 1,000	1,500	Differentiable only in areas where High Plains aquifer system not present.
High Plains aquifer system: Unconsolidated and poorly consolidated sand, gravel, silt, and clay. Unconfined to partially confined.	30 - 500	500 - 1,000	2,500	Aquifer system comprised of the Ogallala Formation and hydraulically connected sand, gravel, silt, and clay deposits. Nonpoint-nitrate contamination from agricultural sources in several areas where water table is less than 30 ft below land surface and soils are sandy.
Aquifers in consolidated sandstone and carbonate rocks:				
Niobrara aquifer: Chalk and silty marlstone. Unconfined.	75 - 200	300 - 750	1,000	Significant source of water only in areas where secondary porosity has developed. Locally overlain by saturated Quaternary sand and gravel deposits, which may be an adequate source of water or may be used in conjunction with Niobrara aquifer.
Dakota aquifer system: Fine to medium grained, poorly consolidated sandstone and interbedded clays. Where commonly used, generally unconfined or partially confined; confined throughout rest of State.	75 - 600	300 - 750	1,000	Locally overlain by saturated Quaternary sand and gravel deposits that may be an adequate source of water or may be used in conjunction with the Dakota aquifer. Water in areas where aquifer system is used is generally potable (less than 1,000 mg/L dissolved solids) except in west-central and northern Lancaster County where sodium chloride type water with over 40,000 mg/L dissolved solids occurs.
Undifferentiated aquifers in Cretaceous rocks: Chalk and sandstone. Unconfined to confined.	75 - 1,300	10 - 100	750	Locally overlain by saturated Quaternary sand and gravel deposits that may be an adequate source of water or may be used in conjunction with undifferentiated aquifers in Cretaceous rocks. Dissolved solids generally range between 1,000 and 1,500 mg/L.
Undifferentiated aquifers in Paleozoic rocks: Limestone, dolomite, and sandstone. Unconfined or partially confined in upper 200 ft; confined at depth.	30 - 2,200	10 - 200	500	Locally overlain by saturated Quaternary sand and gravel deposits that may be an adequate source of water or may be used in conjunction with undifferentiated aquifers in Paleozoic rocks. Water quality variable, dissolved solids generally less than 1,500 mg/L but may be as much as 6,000 mg/L.



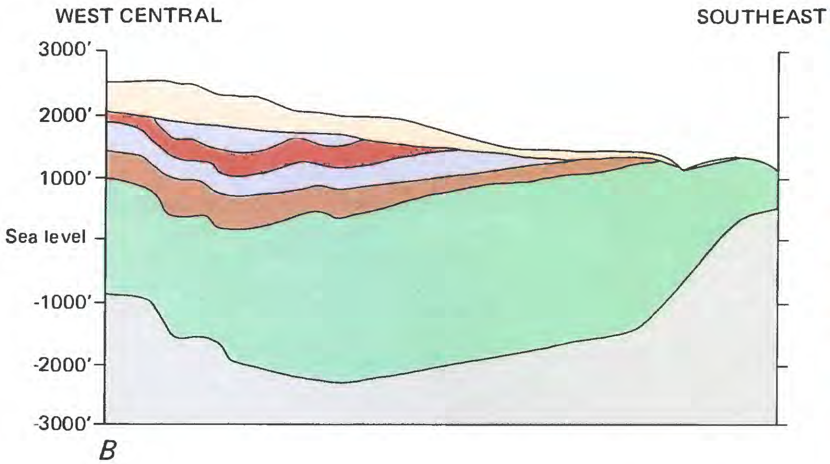
EXPLANATION

UNCONSOLIDATED ALLUVIAL AQUIFERS

- Valley alluvial aquifers
- Paleovalley alluvial aquifers

CONSOLIDATED SANDSTONE AND CARBONATE ROCK AQUIFERS

- High Plains aquifer system
- Niobrara aquifer
- Dakota aquifer system
- Undifferentiated aquifers in Cretaceous rocks
- Undifferentiated aquifers in Paleozoic rocks
- Not a principal aquifer



EXPLANATION

SATURATED THICKNESS OF HIGH PLAINS AQUIFER SYSTEM, in feet

- 0-200
- 200-400
- 400-600
- 600-800
- 800-1000
- Aquifer system does not occur

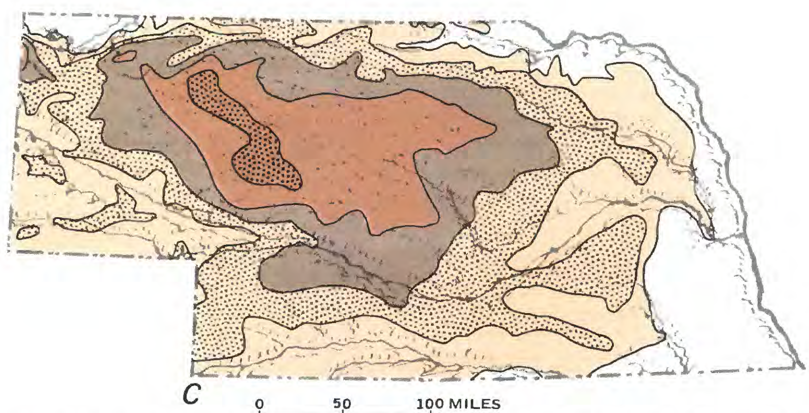


Figure 1. Principal aquifers in Nebraska. *A*, Geographic distribution. *B*, Saturated thickness of the High Plains aquifer and physiographic diagram. *C*, Generalized cross section. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Condra and Reed, 1936; Burchett, 1969; Reed, 1969; Ellis, 1984. *B*, Reed, 1954; Raisz, 1954. *C*, Pettijohn and Chen, 1983a.)

High Plains Aquifer System

Nebraska's largest and most productive aquifer, the High Plains aquifer system, was defined by Pettijohn and Chen (1983a) as including the Ogallala Formation and hydraulically connected sand, gravel, silt, and clay deposits of Tertiary and Quaternary age. The eastern margin of the aquifer system, which is difficult to delineate, was defined by the locations of streams that serve as hydrologic boundaries (Pettijohn and Chen, 1983a). Because many of the deposits included in the aquifer system are similar and are connected hydraulically with deposits in eastern Nebraska, some aquifer boundaries cannot be located precisely. The High Plains aquifer system has a greater average thickness and a greater areal extent in Nebraska than in other High Plains States (Weeks and Gutentag, 1981). It underlies about 85 percent of the State, and the saturated thickness exceeds 1,000 ft locally. Movement of water in the aquifer system generally is eastward, and natural discharge from the aquifer system is by evapotranspiration and by seepage into the streams that cross the area. Approximately 96 percent of the irrigation wells in Nebraska are completed in this aquifer system. Water from the aquifer system generally is of suitable quality for most uses; however, nonpoint-nitrate contamination from agricultural sources occurs in several areas of the State (Engberg, 1983).

AQUIFERS IN CONSOLIDATED SANDSTONE AND CARBONATE ROCKS

Niobrara Aquifer

The Niobrara aquifer is used in only a small area in northeastern Nebraska (Kent and others, 1981) but it probably underlies a large part of the High Plains aquifer system in central and eastern Nebraska. Available data indicate that the chalk and silty marlstone that comprise the Niobrara aquifer are relatively impermeable; but, in much of the area where it crops out or directly underlies the High Plains aquifer system, secondary porosity has developed due to fracturing and carbonate solution. Water from this aquifer is of suitable quality for most uses. Several public-supply wells and probably less than 100 irrigation wells are completed in the aquifer.

Dakota Aquifer System

The Dakota aquifer system (also known as the Great Plains aquifer) underlies almost all of Nebraska except the area of undifferentiated aquifers in Paleozoic rocks (fig. 1). The depth to water and the salinity of the water in the aquifer system increase toward the west and limit to eastern Nebraska the area where supplies of water for most uses can be obtained. In parts of western Nebraska, water in the aquifer system contains more than 100,000 milligrams per liter of dissolved solids; sodium and chloride are the main constituents (Ellis, 1984). Much of the area where the aquifer system is used is overlain by glacial drift. Well-completion data do not consistently indicate whether the source of water is glacial drift, the Dakota aquifer system, or both, making estimation of withdrawals difficult. Data from the Conservation and Survey Division, University of Nebraska-Lincoln, however, indicate that during 1980, about 7.5 million gallons per day (Mgal/d) was pumped from the Dakota aquifer system to provide water for 38 communities, and that there were about 400 irrigation wells completed in the Dakota aquifer system (D. R. Lawton, University of Nebraska-Lincoln, written commun., 1984).

Undifferentiated Aquifers in Cretaceous Rocks

In northern Nebraska, where undifferentiated aquifers in Cretaceous rocks are used, most wells are completed in the first bedrock formation that yields sufficient water for domestic and stock use. Consequently, wells may be completed in the Niobrara aquifer or the Dakota aquifer system.

Undifferentiated Aquifers in Paleozoic Rocks

Sedimentary rocks older than those of the Dakota aquifer system underlie most of Nebraska. However, they are used as sources of water only in the area shown in figure 1 as undifferentiated aquifers in Paleozoic rocks in southeastern Nebraska. The quality of water generally is suitable for most uses. These undifferentiated aquifers generally are zones of secondary porosity that have developed in the upper 200 ft of Pennsylvanian and Permian limestones, although thin, interbedded sandstone also may be connected hydraulically with these zones. Before about 1970, several deep wells completed in older Paleozoic rocks were used for industrial water supplies in Omaha, but most industrial supplies are now obtained from public-supply systems. Permeable zones in the glacial drift that overlies the Paleozoic rocks also are sources of water for domestic and stock use in eastern Nebraska.

OTHER AQUIFERS

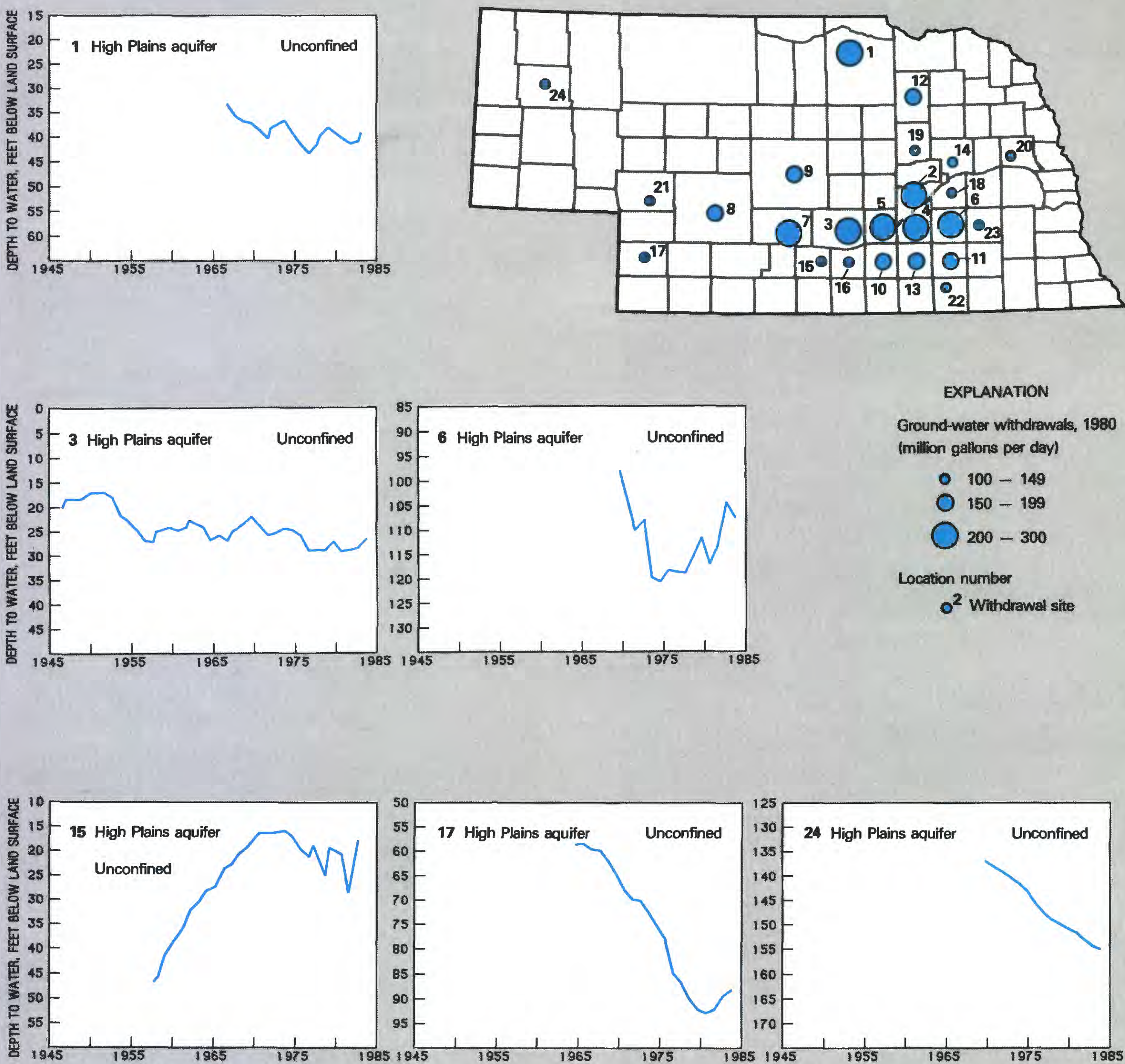
In extreme northwestern Nebraska, in an area of about 1,200 square miles (mi^2), reliable shallow aquifers are absent, and the potential of deep aquifers is unknown. For this report, the area has been mapped as undifferentiated aquifers in Paleozoic rocks (fig. 1); however, the Dakota aquifer system also may be a potential source of water in the area.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The largest ground-water withdrawals in Nebraska are from the High Plains aquifer system and occur where topography and soil conditions favor irrigated agriculture. These areas do not have distinct boundaries but are generalized and are based on the density of wells and the volume of withdrawals. County designated withdrawal areas where ground-water withdrawals exceed 100 Mgal/d are listed in order of production in figure 2. The largest withdrawal, 277 Mgal/d, is in Holt County in northern Nebraska (location 2, fig. 1). Six other pumping centers with production greater than 200 Mgal/d are located along the Platte River valley and in the adjacent Big Blue River basin (fig. 2).

Significant water-level declines in Nebraska generally are caused by the withdrawal of water for irrigation, and significant water-level rises result from recharge due to infiltration from surface-water irrigation systems. Continuous water-level rises or declines over many years reflect an imbalance in the recharge-discharge relation. Hydrographs in figure 2 are representative of water-level conditions in the State. Most significant water-level changes, compared to predevelopment conditions, have occurred in the scattered areas throughout the High Plains aquifer system. In that system, water levels have declined 10 ft or more throughout about 4,500 mi^2 and have risen 10 ft or more throughout about 2,000 mi^2. The maximum measured water-level decline is about 53 ft and the greatest rise is about 92 ft (Johnson and Pederson, 1984).

Some water-level changes are the result of seasonal fluctuations caused by withdrawal during the irrigation season followed by recovery, or partial recovery, during the nonirrigation season. The size and timing of these fluctuations also may be affected by the quantity of precipitation, the depth to water, and the infiltration rates of soils. Water-level fluctua-



WITHDRAWAL SITES

[All withdrawals are from High Plains aquifer, and are listed in order of production, from largest to smallest. Withdrawals are principally for irrigation.]

No. on map	Geographic area	No. on map	Geographic area	No. on map	Geographic area
1	Holt County.	9	Custer County.	17	Chase County.
2	Merrick County.	10	Adams County.	18	Polk County.
3	Buffalo County.	11	Fillmore County.	19	Boone County.
4	Hamilton County.	12	Antelope County.	20	Dodge County.
5	Hall County.	13	Clay County.	21	Keith County.
6	York County.	14	Platte County.	22	Thayer County.
7	Dawson County.	15	Phelps County.	23	Seward County.
8	Lincoln County.	16	Kearney County.	24	Box Butte County.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Nebraska. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

tions are accentuated where aquifers are partially confined. Little or no seasonal recovery is evident in Box Butte County (location 24, fig. 2); the data represent water-level trends in an area where annual precipitation is relatively small and the depth to water is relatively great, but marked seasonal fluctuation is shown in York County (location 6) which represents an area where annual precipitation is relatively large and the aquifer probably is partly confined.

A long-term water-level trend may show a temporary change or reversal. Such anomolies may last for only several years or may be a result of a permanent change that establishes a new trend. Such alternations may be caused by changes in amounts or patterns of precipitation or by changes in irrigation practices. Changes in the central Platte River valley (location 3, fig. 2), and Holt County (location 1, fig. 2) may reflect precipitation cycles. The downward trend in the upper Republican River basin (location 17, fig. 2) reversed during 1980, perhaps as a result of above-average precipitation and reductions in pumpage brought about by management restrictions. In south-central Nebraska, the long-term water-level rise, (location 15, fig. 2) has leveled off or reversed, perhaps due to increased withdrawals and to increased evapotranspiration losses and discharge to streams as water levels approach the land surface.

GROUND-WATER MANAGEMENT

Several State agencies are actively engaged in ground-water research, planning, regulation, and management. The Conservation and Survey Division of the University of Nebraska's Institute of Agriculture and Natural Resources has the responsibility for maintaining a natural resources data base, conducting research and investigations about most natural resources, reporting its findings, and assisting citizens in resource development and management.

The State Water Resources Research Institute in Nebraska is the Water Resources Center of the University of Nebraska-Lincoln. The Center administers and conducts water-resources research, disseminates information, and provides training. In 1984, the Center was merged with the Conservation and Survey Division.

The Nebraska Natural Resources Commission is the State's water planning and water-resources-development funding agency. The Commission manages the State's water-planning and review processes, including the analysis of State water-policy issues and studies of specific water problems. The Commission participates in ground-water modeling, recharge, and water-quality studies.

The Nebraska Department of Water Resources is responsible for regulatory programs relating to ground-water-quantity management, registration of all wells except those used solely for domestic purposes, and managing regulations relating to well spacing. Legislative Statute 75-577 provides that the Director of the Department preside over hearings initiated by Natural Resources Districts for creating Ground-Water Control Areas.

The Nebraska Department of Environmental Control is responsible for the protection and improvement of water quality in the State and administers the National Pollutant Discharge Elimination System permit program and water-quality standards. The Director is responsible for issuing exemptions to State underground water-protection standards.

The Nebraska Department of Health administers the National Safe Drinking Water Act and conducts a Public Water System Program to assure the safety of drinking water delivered to consumers.

Twenty-four Natural Resources Districts function as political subdivisions of the State; their boundaries approximate major drainage basins. The Districts coordinate land- and water-management programs with other governmental entities. Water-conservation activities include monitoring water levels and ground-water quality, cooperating in ground-water investigations, and managing Ground-Water Control Areas.

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Prepared by Michael J. Ellis, Richard A. Engberg, William M. Kastner, and Eugene K. Steele, Jr.

For further information contact District Chief, U.S. Geological Survey, 100 Centennial Mall North, Lincoln, NE 68508

NEVADA
Ground-Water Resources

Ground water is an important natural resource in Nevada. It provides about 20 percent of total water used in the State and, in a number of localities, provides the entire water supply. Moreover, surface-water supplies have been fully appropriated, so that further development must either rely on ground-water sources or the reallocation of surface-water supplies. More than 400,000 people—slightly more than 50 percent of the State's population—are supplied by ground water. More than 40 percent of the population (329,000 people) are supplied by public systems, and 9 percent (73,000 people) are supplied by rural systems. Irrigation is the largest use of ground water, accounting for about 74 percent of total ground-water withdrawals. Public and rural supplies account for about 15 percent of ground water used, and industrial self-supplied use is about 10 percent of total ground-water withdrawals. Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

GENERAL SETTING

Nevada is characterized by isolated, long, narrow, roughly parallel mountain ranges and broad intervening, relatively flat valleys and basins. The mountain ranges and valleys prompted Fenneman's (1931) "Basin and Range physiographic province" designation for most of Nevada, western Utah, and parts of adjacent States. Most mountain ranges in Nevada share common characteristics: they trend generally north-south; are approximately 40 to 80 miles (mi) long, with bases from 5 to 15 mi wide; and have crest altitudes of about 8,000 to more than 10,000 feet (ft) above sea level. Boundary Peak, located near the California border in Esmeralda County, is Nevada's highest point—13,140 ft above sea level. In contrast, about 60 percent of the State consists of extensive valleys, most of which are formed by structural depressions (basins) that have been partly filled by alluvial, colluvial, and lacustrine deposits, and some volcanic materials. The lowest point in the State (490 ft above sea level) is located on the Colorado River in Clark County. Within the State, 253 hydrographic areas have been identified for water-planning and management purposes (Rush, 1968, p. 1). In general, each area contains a basin-fill ground-water reservoir, mountain drainages that supply runoff and recharge, and topographically low areas where ground water is discharged by evapotranspiration.

On a statewide basis, Nevada is the most arid State in the Nation, with mean annual precipitation of about 9 inches (in.). Precipitation is strongly influenced by topography. Annual precipitation ranges from 3 in. in the more arid valleys to more than 40 in. on some of the higher mountains. The greater precipitation in the mountains results in localized moisture excesses that provide most of the State's surface runoff and recharge. An average of about 54 million acre-feet (acre-ft) of precipitation falls on Nevada each year in the form of rain and snow. Of this, most evaporates near where it falls; consequently, annual runoff from the mountains is only about 3.2 million acre-ft, and total annual recharge to ground-water reservoirs is only about 2.2 million acre-ft (Nevada Division of Water Planning, 1980, p. 6–8).

Internal drainage is a significant feature of the hydrology of much of Nevada. About 84 percent of the State is situated within the Great Basin, in which drainage is to low areas in enclosed basins rather than to the sea. Flow in the larger rivers generally decreases in the downstream reaches as water is lost as a result of evaporation, diversions, or infiltration. Some

Table 1. Ground-water facts for Nevada

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	402
Percentage of total population	50
From public water-supply systems:	
Number (thousands)	329
Percentage of total population	41
From rural self-supplied systems:	
Number (thousands)	73
Percentage of total population	9
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	3,600
Ground water only (Mgal/d)	710
Percentage of total	20
Percentage of total excluding withdrawals for thermoelectric power	20
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	93
Percentage of total ground water	13
Percentage of total public supply	40
Per capita (gal/d)	283
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	11
Percentage of total ground water	2
Percentage of total rural domestic	94
Per capita (gal/d)	151
Livestock:	
Ground water (Mgal/d)	3.7
Percentage of total ground water	1
Percentage of total livestock	31
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	71
Percentage of total ground water	10
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	30
Excluding withdrawals for thermoelectric power	45
Irrigation withdrawals:	
Ground water (Mgal/d)	530
Percentage of total ground water	74
Percentage of total irrigation	17

Table 2. Aquifer and well characteristics in Nevada

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey and Nevada Department of Conservation and Natural Resources]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Basin-fill aquifers: Sand, gravel, clay, and silt; mostly alluvial and lacustrine deposits. Sand and gravel deposits yield most water to wells. Confined and unconfined.	100 – 500	1,200	200 – 1,000	5,000	Upper 500 to 1,500 ft most permeable and generally contains fresh water. Provides almost all water pumped by major users in the State.
Volcanic rock aquifers: Welded tuff, bedded tuff, and lava flows in south-central Nevada; basalt flows in the Carson Desert. Also, some fractured andesite and associated rocks in western and northern Nevada. Confined and unconfined.	100 – 1,200	1,800	20 – 1,000	3,000	In southern Nevada, aquifers are commonly associated with calderas or other centers of volcanic activity. In other localized parts of western and northern Nevada, domestic and commercial supplies have been obtained from wells drilled into fractured volcanic rock.
Carbonate rock aquifers: Limestone and dolomite; few data on water-bearing zones. In southern Nevada, these zones appear to be related to extensive fracturing with little solution. In rest of State fractures may be enlarged by secondary solution. Generally confined.	600 – 2,000	5,000	50 – 1,000	3,400	Aggregate thickness of carbonate section between 10,000 and 30,000 ft throughout much of eastern and southern Nevada. Development to date limited to exploration drilling and testing. Aquifer not heavily pumped; however, it supplies water to numerous springs which are used for irrigation.

rivers flow into a terminal lake, such as Pyramid Lake in Washoe County or Walker Lake in Mineral County; in other rivers, most flow ceases before water can reach the lower end of the drainage system, and the system terminates in a large playa, such as the Carson Sink in Churchill County or the Black Rock Desert in Pershing and Humboldt Counties. In topographically closed basins, surface water generally drains to a playa in the low part of the basin.

PRINCIPAL AQUIFERS

Principal aquifers in Nevada consist of unconsolidated basin-fill deposits and carbonate bedrock. In some areas, the basin-fill deposits include interbeds of volcanic rock. These volcanic rocks are considered to be separate aquifer systems because their hydraulic characteristics differ from the basin fill and because, in south-central Nevada, they form extensive aquifers separate from the basin fill. The principal aquifers in Nevada are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

BASIN-FILL AQUIFERS

Basin-fill ground-water reservoirs are the major aquifers in Nevada. These reservoirs are composed of alluvial, colluvial, and lacustrine deposits and some volcanic rocks that partly fill the intermontane basins. Basin-fill deposits generally are 2,000 to 5,000 ft thick but, in some basins, exceed 10,000 ft in thickness. In most areas, sand and gravel deposits within the basin fill provide the only supply of ground water available for large-scale development. Generally, shallow deposits in the upper basin fill are more permeable than deposits at depth. To date, virtually all major ground-water development has been in areas of permeable basin fill.

The dissolved-solids content in ground water in basin-fill reservoirs ranges from less than 1,000 milligrams per liter (mg/L) to more than 35,000 mg/L. Throughout much of the State, ground water in these reservoirs is suitable or marginally suitable for most uses. Generally, in areas of natural recharge, such as mountainous watersheds and alluvial aprons at the margins of most valleys, ground water is fresh. Saline water occurs locally near some thermal springs and in areas where the aquifer includes materials that contain large amounts of soluble salts. In sink areas, such as the Carson Sink, the dissolved-solids concentration may exceed that of ocean water. The ground water beneath the playas of smaller closed basins may be brackish but ordinarily does not reach the concentrations found in the larger terminal sinks.

VOLCANIC ROCK AQUIFERS

Volcanic rocks are productive aquifers in parts of south-central and west-central Nevada. Volcanic rock aquifers have not been pumped heavily, but they are important because they are capable of transporting significant quantities of interbasin flow. The most heavily pumped volcanic rock aquifer in the State is a basalt aquifer in the Carson Desert of west-central Nevada. This aquifer is present about 500 ft below land surface and is overlain and underlain by basin-fill deposits. It

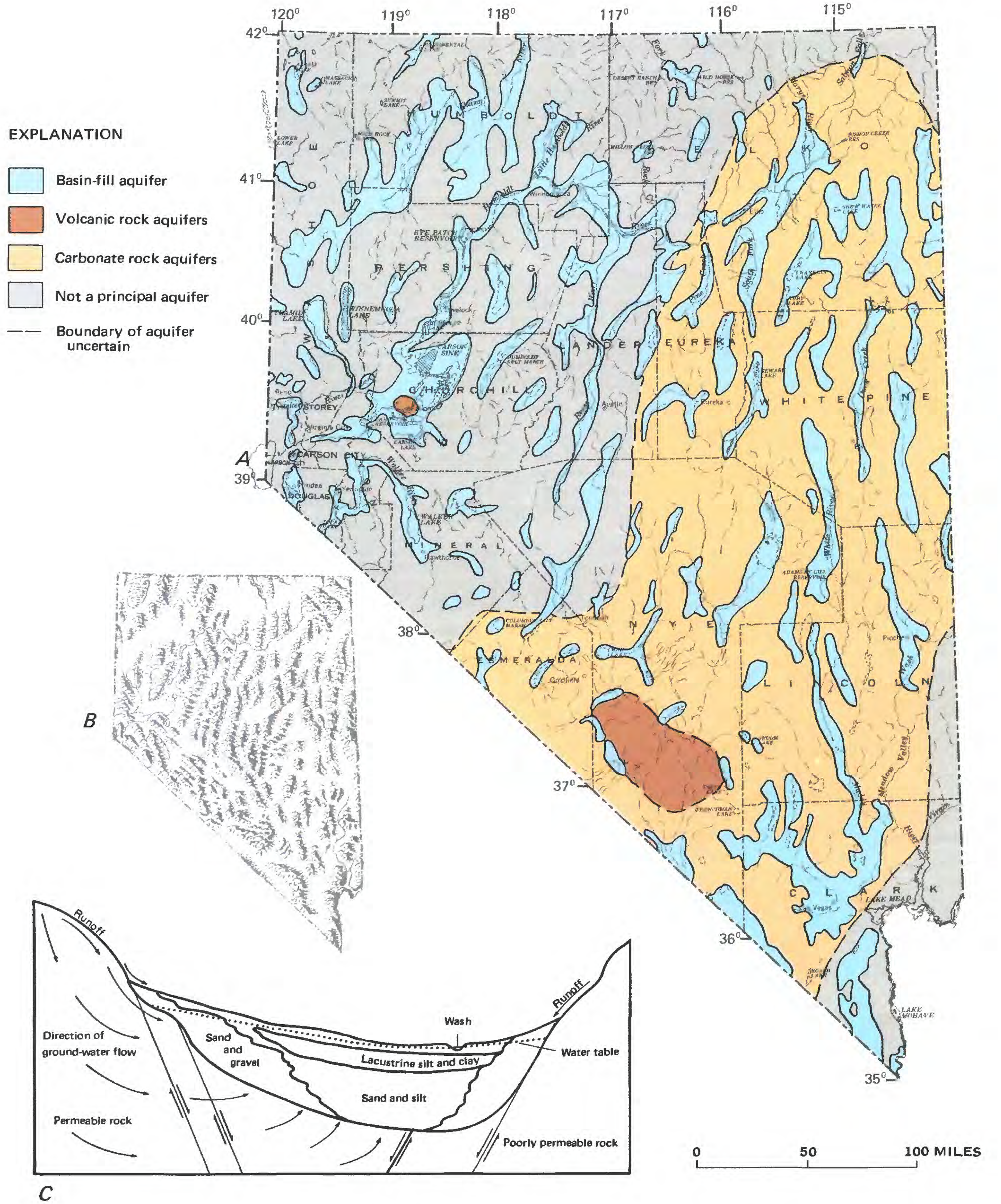


Figure 1. Principal aquifers in Nevada. *A*, Geographic distribution. *B*, Physiographic diagram. *C*, Generalized cross section showing typical distribution of sand and gravel deposits in a basin-fill aquifer. (See table 2 for a more detailed description of the aquifers. Sources: *A*, *C*, Compiled by Otto Moosburner from U.S. Geological Survey files. *B*, Raisz, 1954.)

is the only source of water supply for the city of Fallon and is pumped at a rate of about 1.5 million gallons per day (Mgal/d) (Glancy, 1981, p. 38). Aquifers of welded tuff, bedded tuff, and lava flows have been identified in parts of the Nevada Test Site. For example, in the mid-1960's, the welded-tuff aquifer was the sole aquifer used for water supply on Jackass Flats (Winograd and Thordarson, 1975, p. C31). Generally, wells in these aquifers yield adequate amounts of water for domestic and other low- to moderate-demand uses. In other localized areas throughout the State, volcanic rocks have yielded quantities of water adequate for rural-domestic supplies and stock water.

The chemical quality of water in volcanic rock aquifers generally is suitable for most uses. However, individual constituents may present a quality problem even though the dissolved-solids concentration may be low. In much of south-central Nevada, for example, the fluoride concentration in ground water exceeds national drinking-water regulations. The distribution of this high-fluoride ground water may be associated with volcanic tuff that is extensive in that area (Eakin and others, 1976, p. G12). Another example of a situation in which water quality may limit use of the resource is the basalt aquifer in the Carson Desert which has arsenic concentrations exceeding the national drinking-water regulations limits of 0.50 mg/L (Glancy, 1981, p. 32-33).

Carbonate Rock Aquifers

In eastern and southern Nevada, thick sequences of carbonate rock form a complex regional aquifer system or systems that are largely undeveloped and not yet fully understood. Secondary permeability in limestone and dolomite beds within this sequence has developed as a result of fracturing and enlargement of existing fractures by solution. The area underlain by carbonate rocks is characterized by relatively low volumes of runoff. Some basins, although topographically closed, are completely drained by subsurface flow; in other basins, the volume of spring discharge significantly exceeds that which would be reasonably expected to occur from local recharge. These features indicate regional flow in which recharge in a number of interconnected basins flows toward a regional sink or discharge area. Flow can be complex and may include substantial interaction with basin-fill reservoirs. Current studies indicate that flow paths may traverse as many as six basins and extend over 100 mi in length. Development to date has been limited, for the most part, to exploration drilling and testing in conjunction with Nevada Test Site operations or MX missile-siting investigations. Although very little water is pumped from the carbonate rock aquifers, they yield about 90 Mgal/d of spring discharge that is used primarily for irrigation (Smales and Harrill, 1971, p. 17). Several test wells have produced yields as large as 4.9 Mgal/d (Bunch and Harrill, 1984), and the carbonate rock aquifers may be capable of supporting significant development in some areas. One of the challenges involved in this development, however, will be to locate areas that will yield substantial amounts of water without seriously impacting the principal areas of spring discharge.

The chemical quality of ground water in carbonate rock aquifers generally is suitable for most uses. In eastern Nevada, reasonably good-quality water may occur at considerable depth as the result of deep circulation through the carbonate rock aquifers. Drill stem tests of carbonate rocks in oil test wells in western White Pine County indicate open fractures and fresh ground water at depths of as much as 9,400 ft below the top of the carbonate rock sequence (McJannett and Clark, 1960).

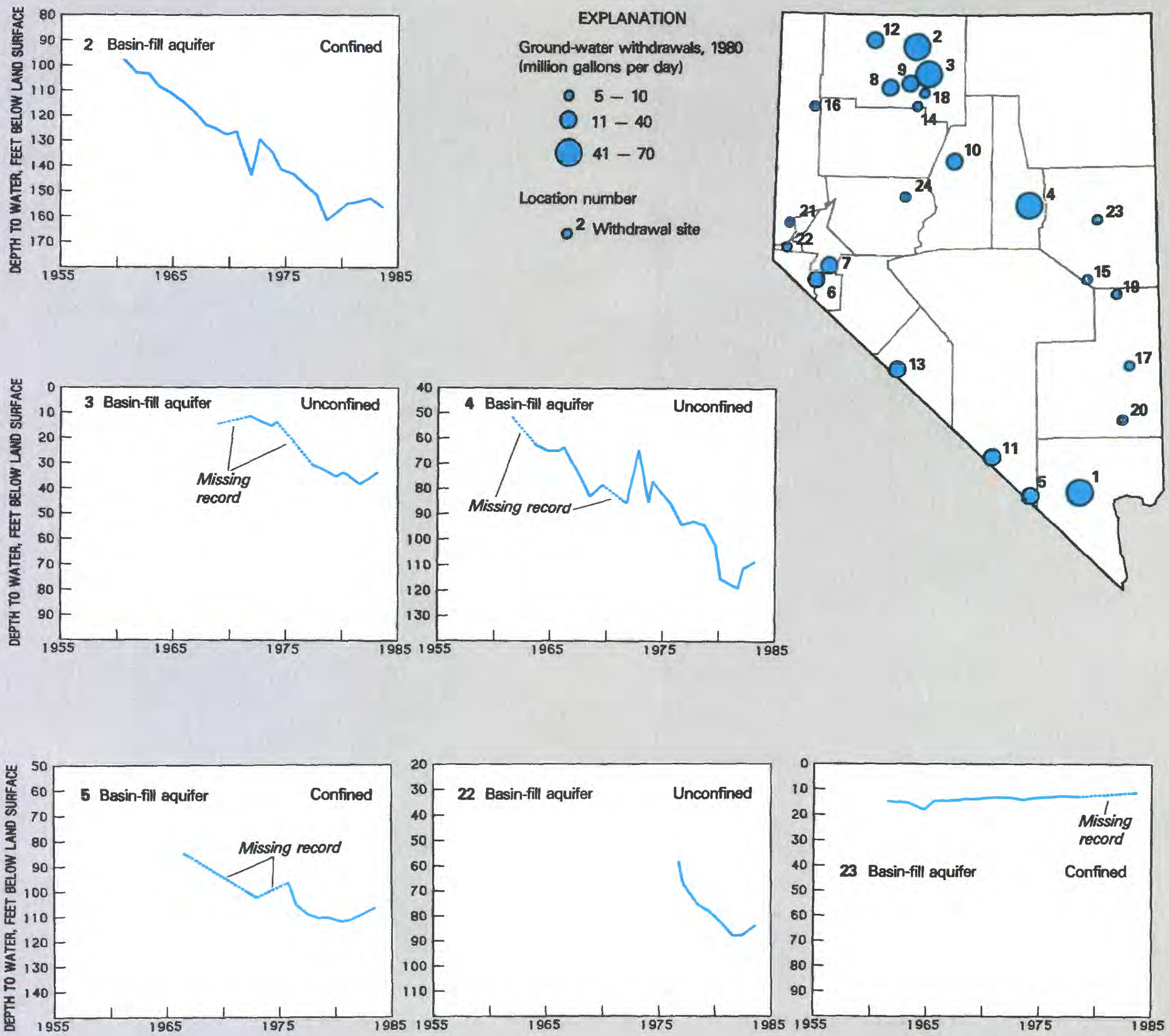
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

In Nevada, ground water is withdrawn at rates of slightly more than 700 Mgal/d. About 74 percent of this water is used for irrigation; the remainder is used mainly for public- and rural-water supplies or for self-supplied industrial purposes. Withdrawals are not distributed uniformly within the State but tend to be concentrated in a small number of basins. Figure 2 shows the areas of major withdrawals. Where pumping is concentrated in a specific area, water levels generally decline, as shown by the hydrographs of selected wells in Las Vegas, Paradise, Diamond, Pahrump, and Eagle Valleys, location 1, 3, 4, 5, and 22 (fig. 2), respectively. The winters of 1982-83 and 1983-84 were abnormally wet and resulted in a general increase in ground-water levels in wells from Paradise, Pahrump, and Eagle Valleys, locations 3, 5, and 22, respectively. The Steptoe Valley area (location 23, fig. 2) has not yet been stressed heavily by pumping; the hydrograph of a well in this area shows a gradual rise since the mid-1960's and an accelerated rise in the last several years.

Parts of Paradise Valley (location 3) have been pumped heavily and substantial water level declines have occurred. The rise of water levels in 1983 occurred because the lower reaches of the Little Humboldt River, which normally are dry, maintained significant flows for most of that period due to above average precipitation. Consequently, the hydrograph reflects recharge to the aquifer from the river. In other heavily pumped areas, recharge from rivers such as the Little Humboldt is not available, and consequently, water-level declines can continue during relatively wet periods.

GROUND-WATER MANAGEMENT

Ground-water use in Nevada is regulated by the Department of Conservation and Natural Resources through the State Engineer's Office. The concept of safe yield in individual basins is the basis of administration by the State Engineer. Basins that have experienced significant water-level declines due to ground-water withdrawal have been designated critical basins, thereby effectively limiting additional withdrawals. Currently, two critical basins are located near Reno and Carson City, one is near Eureka, and two are near Las Vegas. Protection of ground-water quality and prevention, control, and abatement of ground-water pollution is the responsibility of the Nevada Department of Environmental Protection.



WITHDRAWAL SITES [Withdrawals are from basin-fill aquifers]					
No. on map	Geographic area	Principal uses	No. on map	Geographic area	Principal uses
1	Las Vegas Valley	Public supply, industrial.	13	Fish Lake Valley	Irrigation.
2	Orovada Subarea	Irrigation.	14	Grass Valley	Do.
3	Paradise Valley	Do.	15	White River Valley	Do.
4	Diamond Valley.	Do.	16	Hualapai Flat Valley . . .	Do.
5	Pahrump Valley.	Do.	17	Panaca Valley	Do.
6	Smith Valley.	Do.	18	Winnemucca Segment . .	Do.
7	Mason Valley	Do.	19	Lake Valley	Do.
8	Desert Valley	Do.	20	Lower Meadow Valley . .	Do.
9	Silver State Valley	Do.	21	Truckee Meadows.	Public supply, industrial.
10	Middle-Lower Reese Valley. .	Do.	22	Eagle Valley	Do.
11	Amargosa Desert Valley . . .	Do.	23	Steptoe Valley.	Irrigation.
12	Pine Forest Valley	Do.	24	Dixie Valley	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Nevada. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

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Prepared by Otto Moosburner and James R. Harrill

For further information contact Chief, Nevada Office, U.S. Geological Survey, Federal Building, 705 North Plaza Street, Carson City, NV 89701

NEW HAMPSHIRE
Ground-Water Resources

Ground water is an important natural resource in New Hampshire. Although ground water supplied only 17 percent of freshwater withdrawn for all uses in 1980, it supplied public and private water systems with about 52 million gallons per day (Mgal/d) that served about 550,000 people, or 60 percent of the population (Solley and others, 1983). Of the 27 municipalities with a population of greater than 7,000, 9 are served by systems that use ground water, 11 by water systems that use surface water, and 7 by systems that use combined sources (New Hampshire Water Supply and Pollution Control Commission, 1982). Ground-water withdrawals for various uses in 1980 and related statistics are given in table 1.

Quality of ground water in New Hampshire generally is suitable for human consumption and most other uses; 80 percent of ground-water withdrawals in 1980 supplied drinking-water systems. Locally, the chemical quality of ground water may reflect land-use practices. Degradation of water quality, for example, may occur in unsewered residential and village areas and near underground storage tanks, industrial sites, waste-disposal sites, agricultural land, and highways.

Table 1. Ground-water facts for New Hamphire

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	550
Percentage of total population	60
From public water-supply systems:	
Number (thousands)	392
Percentage of total population	43
From rural self-supplied systems:	
Number (thousands)	158
Percentage of total population	17
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	380
Ground water only (Mgal/d)	65
Percentage of total	17
Percentage of total excluding withdrawals for thermoelectric power	21
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	43
Percentage of total ground water	66
Percentage of total public supply	48
Per capita (gal/d)	110
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	9.1
Percentage of total ground water	14
Percentage of total rural domestic	98
Per capita (gal/d)	55
Livestock:	
Ground water (Mgal/d)	0.2
Percentage of total ground water	0.3
Percentage of total livestock	25
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	13
Percentage of total ground water	20
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	5
Excluding withdrawals for thermoelectric power	6
Irrigation withdrawals:	
Ground water (Mgal/d)	0
Percentage of total ground water	0
Percentage of total irrigation	0

GENERAL SETTING

New Hampshire lies in the glaciated Appalachian ground-water region and in the Seaboard Lowland, New England Upland, and White Mountain sections of the New England physiographic province (fig. 1). The bedrock consists of metasedimentary rock in about two-thirds of the State and intrusive rock in about one-third of the State (Billings, 1956).

Recharge to the ground-water system is derived from precipitation. Average annual rainfall is about 43 inches (in.), ranging from about 40 in. in the lowlands to as much as 70 in. in the White Mountains. The greatest runoff occurs in the mountains (Knox and Nordenson, 1955). Recharge rates have not been determined adequately, but probably range from 14 to 20 in. annually.

PRINCIPAL AQUIFERS

The two principal types of aquifers in New Hampshire are unconsolidated glacial deposits, primarily stratified drift and crystalline bedrock. The characteristics of these aquifers are described below and in table 2; their areal distribution is shown in figure 1.

STRATIFIED-DRIFT AQUIFERS

Ground-water exploration and development for public supply in New Hampshire has been most successful in thick, saturated, stratified-drift deposits of unconsolidated sand or sand and gravel. These deposits are present primarily in the valley lowlands throughout the State and also in some inter-stream areas in the southeastern lowlands (fig. 1). Many of these deposits are isolated from one another and form independent ground-water systems (Cotton, 1975b, 1976b, 1977b).

The term "stratified-drift aquifer" encompasses several types of glacial aquifers. Stratified-drift deposits formed by meltwater streams adjacent to or beneath glaciers are termed "ice-contact deposits." Those deposits formed by meltwater streams beyond ice margins are termed "outwash deposits." In some areas ice-contact deposits may yield larger amounts of water to wells than outwash because they may have greater saturated thickness and tend to be coarser grained (Bradley, 1964). Detailed geohydrologic investigations may distinguish between ice-contact and outwash deposits, but, for the purposes of this report, these are not mapped separately in figure 1. Both of these glaciofluvial sequences may include deltaic deposits that formed where meltwater streams entered standing water bodies. Deltas commonly are good aquifers. Some

Table 2. Aquifer and well characteristics in New Hampshire

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Principal aquifers:					
Stratified-drift aquifers: Unconsolidated glaciofluvial sand or sand and gravel. Generally unconfined.	40 - 80	90	100 - 500	600	Includes deltaic deposits of ice-contact and outwash sequences. Quality generally suitable for human consumption.
Crystalline bedrock aquifer: Igneous and metamorphic rocks that contain recoverable water only in open fractures (secondary porosity). Generally confined.	100 - 600	800	1 - 10	100	Zones where bedrock extensively fractured may yield larger quantities of water. Quality generally suitable for human consumption.
Other aquifers: Till deposits of unconsolidated, nonstratified, heterogeneous mixture of clay to boulder-sized material, deposited either at the base of moving glacial ice or as a residue left by melting ice. Unconfined.	10 - 20	30	1 - 3	5	Poor aquifer but in places yields enough water to large-diameter dug wells to supply single-family domestic needs. Quality generally suitable for human consumption. Till not mapped on fig. 1A, but commonly overlies bedrock.

sand and gravel aquifers in valley lowlands are overlain by fine-grained glacial lake-bottom (lacustrine) deposits. These fine-grained deposits are included in the stratified-drift deposits in figure 1.

Ground water in stratified-drift deposits generally is of a quality suitable for human consumption and most other uses. Most of the water is clear and colorless and contains virtually no suspended matter and few bacteria; dissolved-solids concentrations seldom exceed 300 milligrams per liter (mg/L). Water in the stratified-drift aquifers generally is soft (less than 60 mg/L hardness as calcium carbonate). Water-quality problems include elevated concentrations of iron (7.3 mg/L) and manganese (7.05 mg/L), which restrict usefulness of the water in some areas.

Crystalline Bedrock Aquifer

The crystalline bedrock aquifer is a complex of igneous and metamorphic rocks that contain water available to wells only in open fractures. The size, number, distribution, and degree of interconnection of fractures are highly variable; in general, however, fractures are few and, when present, generally decrease in size and number with depth. Thus, the overall storage capacity of bedrock is small and tends to decrease with depth. Wells that penetrate bedrock commonly yield dependable supplies of water suitable for single-family domestic needs, and, for this purpose, bedrock is a principal aquifer. Domestic wells generally are less than 600 feet deep and yield less than 10 gallons per minute. Zones where bedrock is extensively fractured, however, may yield larger quantities of water. Many small water systems that serve residential developments use bedrock wells, and application of exploration technology has enabled several municipal water-supply systems to use the bedrock aquifer. Presently, six municipalities, including Hampton and Salem, use bedrock wells that have capacities of 500,000 gallons per day or more.

Water in the crystalline bedrock aquifer is soft to moderately hard (20 to 80 mg/L hardness as calcium carbonate). Arsenic in concentrations of greater than 0.05 mg/L has been reported in bedrock wells in parts of southern and central New Hampshire. Data from radiological analyses of water from the bedrock aquifer suggest that naturally occurring radon gas in water may present problems in some areas.

OTHER AQUIFERS

Some wells in New Hampshire are completed in till. Till is generally an unsorted mixture of clay- to boulder-sized rock material deposited directly by glacial ice. It is discontinuous on the bedrock surface and generally is less than a few tens of feet thick. Because it has low permeability, till generally is an unproductive aquifer. However, the quality of water in till is suitable for most purposes and in places, it yields enough water to supply single-family needs from large-diameter dug wells, although this yield may not be dependable during droughts. Many old domestic wells are in till and some new wells are finished in till. However, it is a significant aquifer only for domestic needs. Till is listed in table 2 but is not mapped in figure 1 because it would obscure most of the crystalline bedrock aquifer.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Areas of major municipal withdrawals of ground water are shown in figure 2. Wells or well fields that normally produce more than 0.1 Mgal/d are concentrated in the more populous southern one-half of the State. Average total daily pumpage from these areas is more than 24 Mgal/d. In addition, it is estimated that more than 18 Mgal/d is pumped from about 650 other public-supply and private stockholder wells that are classified as public-supply wells, as defined by

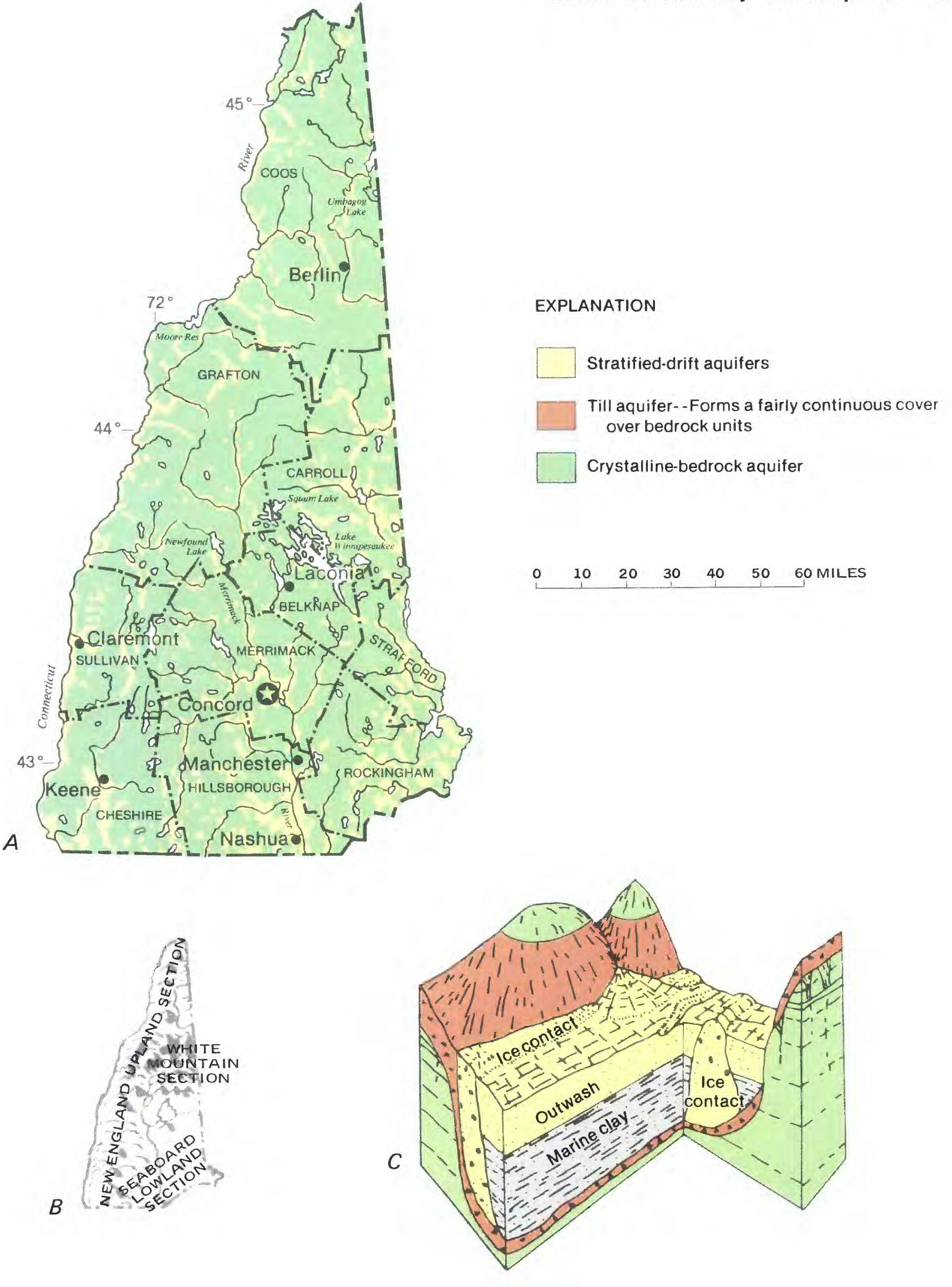


Figure 1. Principal aquifers in New Hampshire. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Block diagram showing typical stratigraphic sequence of aquifer materials. (See table 2 for a more detailed description of the aquifers. Source: *A*, *C*, Compiled by R. E. Hammond and J. E. Cotton from U.S. Geological Survey files. *B*, Feneman, 1938; Raisz, 1954.)

the Safe Drinking Water Act (Public Law 93-235). Industrial withdrawals have not been inventoried systematically, but estimated withdrawals are 13 Mgal/d.

Water levels near production wells decline in response to pumping and recover to differing degrees during nonpumping periods. However, progressive long-term water-level declines within the aquifers have not been documented. Annual water-level fluctuations (fig. 2) reflect climatic conditions.

GROUND-WATER MANAGEMENT

The three agencies that are most involved with ground-water activities are the Water Supply and Pollution Control Commission, the Division of Public Health Services (Department of Health and Welfare), and the Water Resources Board. Memorandums of Agreement among these agencies help clarify roles and responsibilities with respect to ground-water concerns. Responsibility generally is divided so that the Water Supply and Pollution Control Commission and the Division of Public Health Services share responsibility for protecting ground and surface water from contamination and for assuring that the quality of water delivered for public consumption is tested periodically and meets minimum safety standards. The Water Resources Board is responsible for determining water availability through resource investigations, including programs with the U.S. Geological Survey, and water consumption through registration of and reporting by water users. The Council on Resources and Development, formed with members from the State agencies and chaired by the Director of State Planning, adjudicates disagreements among member agencies.

State legislation relating to ground-water management appears in several sections of the Revised Statutes Annotated (RSA). RSA 4 authorizes the New Hampshire Office of State Planning to undertake statewide water-resource planning. The New Hampshire Water Supply and Pollution Control Commission administers surface- and ground-water quality protection programs as set forth in RSA's 131, 148, and 149. Under RSA 149:8,III.(a), the commission has established a permit program for "the discharge or disposal of wastes which may significantly and adversely affect the groundwaters of the state".

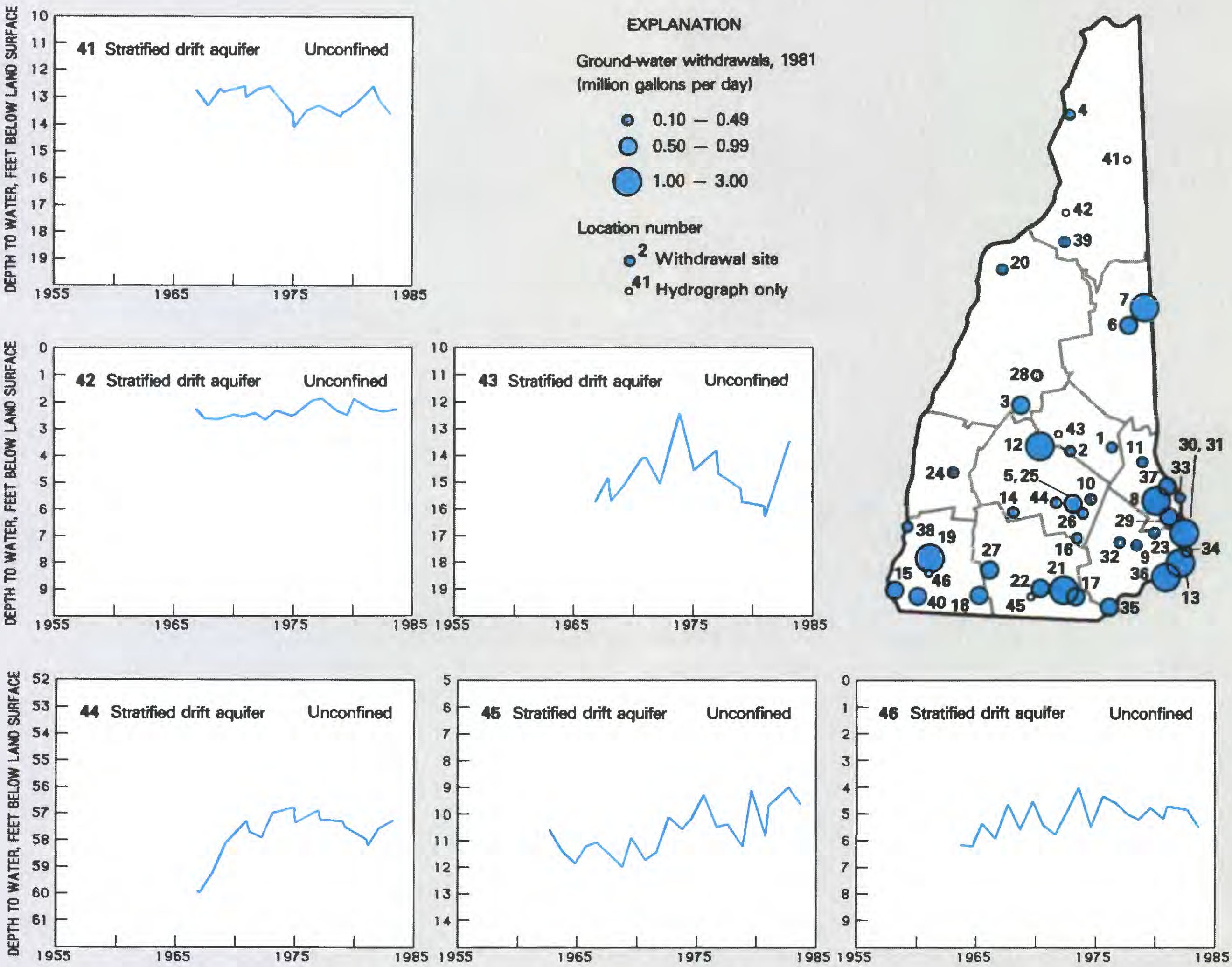
The Office of Waste Management within the New Hampshire Division of Public Health Services administers the solid and hazardous waste management programs under RSA's 147-A, 147-B, and 149-M, and ground-water protection and monitoring are important components of these programs. Management and disposal of radioactive waste is authorized by RSA 125, 56-77K.

The New Hampshire Water Resources Board is authorized and directed to investigate ground-water resources of the State, in cooperation with the U.S. Geological Survey, by Chapter 376 of the Laws of 1955. RSA 489-B established the Water Well Board to license water-well contractors and pump installers and to obtain data on all new well construction through a reporting procedure. RSA 155-E (Chapter 481 of the 1979 Session Laws) provides for regulation of commercial excavations of earth by local governments through a permit system. The statute prohibits the granting of permits under certain conditions, including any excavation that would significantly damage sand and gravel aquifers.

Chapter 402 of the 1983 Session Laws amended RSA 481.1 to declare "the groundwaters of the state are an integral part of the overall water resources and that such groundwater resources must be conserved, protected, allocated and otherwise managed to insure the uses most favorable to the public good." Under Chapter 402, the Water Resources Board is authorized to ascertain water use through registration of and reporting by water users. Chapter 402 directed the Water Resources Board to develop and recommend to the General Court policies and a water-resources-management plan to determine priority water uses and an allocation plan to conserve, distribute, and otherwise manage the water resources of the State. That plan was distributed to the New Hampshire Senate and House of Representatives in July 1984.

Several other State agencies are involved with water resources in general and ground-water resources in particular. The use of land is a significant factor that affects ground-water quantity and quality. Thus, the New Hampshire Office of State Planning and the Regional Planning Commissions, which provide land-use planning assistance to municipalities, provide technical aid in developing local ground-water management and protection programs.

The New Hampshire Department of Agriculture regulates use of fertilizers and, in conjunction with the Pesticide Control Board, regulates the use of pesticides and herbicides. The Department of Resources and Economic Development ensures compliance with laws governing forest practices and mining. The State Geologist within this Department provides geologic assistance, including mapping, to resource investigators. The Public Utilities Commission grants public utilities rights to supply water to specified service areas after consideration of the source and adequacy of the supply.



WITHDRAWAL SITES [Withdrawals are principally for public supply]					
No. on map	Geographic area	Aquifer	No. on map	Geographic area	Aquifer
1	Alton	Stratified drift.	22	Milford	Stratified drift.
2	Belmont	Do.	23	Newmarket	Do.
3	Bristol	Do.	24	Newport	Do.
4	Colebrook	Do.	25	Pembroke	Do.
5	Concord	Do.	26	Pembroke	Do.
6	Conway	Do.	27	Peterborough	Do.
7	Conway, North	Do.	28	Plymouth	Do.
8	Dover	Do.	29	Portsmouth	Do.
9	Epping	Do.	30	Portsmouth	Do.
10	Epsom	Do.	31	Peace Air Force Base	Do.
11	Farmington	Do.	32	Raymond	Do.
12	Franklin	Do.	33	Rollinsford	Stratified drift, Crystalline bedrock.
13	Hampton	Stratified drift, Crystalline bedrock.	34	Rye	Stratified drift.
14	Henniker	Stratified drift.	35	Salem	Stratified drift, Crystalline bedrock.
15	Hinsdale	Do.			
16	Hooksett	Do.			
17	Hudson & Litchfield	Do.	36	Seabrook	Do.
18	Jaffrey	Do.	37	Somersworth	Stratified drift.
19	Keene	Do.	38	Walpole	Do.
20	Lisbon	Do.	39	Whitefield	Crystalline bedrock.
21	Merrimack	Do.	40	Winchester	Stratified drift.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in New Hampshire. (Sources: Withdrawal data from New Hampshire Water-Supply and Pollution Control Commission, 1982; water-level data from U.S. Geological Survey files.)

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Prepared by John E. Cotton and Robert E. Hammond

For further information contact Chief, New Hampshire Office, U.S. Geological Survey, 525 Clinton Street, RFD 2, Bow, NH 03301

NEW JERSEY
Ground-Water Resources

Ground water is used extensively throughout New Jersey for public, industrial, domestic, and agricultural supply. Nearly 3.5 million people (45 percent of New Jersey's population) depend on ground water. In 1980, about 730 million gallons per day (Mgal/d) of freshwater was pumped from aquifers in the State (Solley and others, 1983). However, areal and seasonal variations in ground-water withdrawals can be significant. Ground-water withdrawals for various uses in 1980 and other statistics are given in table 1.

Table 1. Ground-water facts for New Jersey

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	3,420
Percentage of total population	45
From public water-supply systems:	
Number (thousands)	2,570
Percentage of total population	35
From rural self-supplied systems:	
Number (thousands)	850
Percentage of total population	10
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	2,900
Ground water only (Mgal/d)	730
Percentage of total	25
Percentage of total excluding withdrawals for thermoelectric power	37
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	450
Percentage of total ground water	62
Percentage of total public supply	40
Per capita (gal/d)	175
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	75
Percentage of total ground water	10
Percentage of total rural domestic	100
Per capita (gal/d)	88
Livestock:	
Ground water (Mgal/d)	2
Percentage of total ground water	0.3
Percentage of total livestock	67
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	160
Percentage of total ground water	22
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	10
Excluding withdrawals for thermoelectric power	20
Irrigation withdrawals:	
Ground water (Mgal/d)	40
Percentage of total ground water	6
Percentage of total irrigation	73

GENERAL SETTING

The Coastal Plain is the largest physiographic province in New Jersey. It lies southeast of the Fall Line, where it intersects the Piedmont province in a series of falls along river courses. The geology of the Coastal Plain is characterized by unconsolidated sand, gravel, silt, and clay thickening seaward from a featheredge at the Fall Line to more than 6,500 feet (ft) thick in southern Cape May County (Gill and Farlekas, 1976). The highly permeable beds of coarse material form aquifers that differ in areal extent and thickness. Slightly permeable interbeds of silt and clay form confining beds, which restrict the vertical flow of water.

North of the Fall Line, areal boundaries of aquifers roughly correspond to the physiographic divisions of the State. Aquifers in the Newark Group underlie the Piedmont province, upland crystalline rocks underlie the Highlands province, and Paleozoic sedimentary rocks form the Valley and Ridge province (fig. 1).

New Jersey receives an average of 44 inches (in.) of precipitation annually, of which approximately 15 to 39 in. recharge the ground-water reservoir.

PRINCIPAL AQUIFERS

The principal aquifers of New Jersey are classified into two groups—Coastal Plain aquifers south of the Fall Line and non-Coastal Plain aquifers north of the Fall Line. The aquifers are described below and in table 2 from youngest to oldest; their areal distribution is shown in figure 1.

COASTAL PLAIN AQUIFERS

The five principal Coastal Plain aquifers are the Kirkwood-Cohansey aquifer system, the Atlantic City 800-foot sand, the Wenonah-Mount Laurel aquifer, the Englishtown aquifer, and the Potomac-Raritan-Magothy aquifer system. All but the Kirkwood-Cohansey are confined except where they crop out or are overlain by permeable surficial deposits. The aquifers are recharged directly by precipitation in outcrop areas, by vertical leakage through confining beds, and by seepage from surface-water bodies.

More than 75 percent of the freshwater supply in the New Jersey Coastal Plain is from ground water. In the Coastal Plain, high-capacity production wells used for public supply commonly yield 500 to 1,000 gallons per minute (gal/min), and many exceed 1,000 gal/min. Water quality is satisfactory except for local excessive iron concentrations [as much as 460 milligrams per liter (mg/L)] in several aquifers, including the Potomac-Rariton-Magothy, and for local contamination from saltwater intrusion and waste disposal. In the unconfined Kirkwood-Cohansey aquifer system water is brackish or salty in some coastal areas. In confined aquifers, salinity generally increases with depth in the southern and southeastern parts of the Coastal Plain.

Table 2. Aquifer and well characteristics in New Jersey

[Mgal/d = millions of gallons per day; gal/min = gallons per minute; ft = feet. Source: Reports of the U.S. Geological Survey]

Aquifer name and description	Aquifer withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Coastal Plain aquifers:					
Kirkwood–Cohansey aquifer system: Sand, quartz, fine to coarse grained, pebbly; local clay beds. Unconfined.	70	20 – 350	500 – 1,000	1,500	Ground water occurs generally under water-table conditions. Aquifer system extends from southern Monmouth County to Delaware Bay and from 12 mi southeast of the Delaware River to the Atlantic Ocean. Aquifer thickness can exceed 350 ft. Brackish and salty water may occur in coastal areas.
Atlantic City 800-foot sand: Sand, quartz, medium to coarse grained, gravel, fragmented shell material. Confined.	20	450 – 950	600 – 800	1,000	Principal confined artesian aquifer supplying water along the barrier beaches in Cape May, Atlantic, and Ocean Counties. Aquifer thickness generally ranges between 100 and 150 ft. Water quality suitable for most uses.
Wenonah–Mount Laurel aquifer: Sand, quartz, slightly glauconitic, very fine to coarse grained, layers of shells. Confined.	5	50 – 600	50 – 250	500	Important confined aquifer in the northeast and southwest part of the Coastal Plain. Aquifer thickness generally range between 60 and 120 ft. Water quality suitable for most purposes.
Englishtown aquifer: Sand, quartz, fine to medium grained, local clay beds. Confined.	12	50 – 1,000	300 – 500	1,000	Important source of water for Ocean and Monmouth Counties. Confined aquifer thickness generally ranges between 60 and 140 ft. Excellent water quality.
Potomac–Raritan–Magothy aquifer system: Alternating layers of sand, gravel, silt, and clay. Confined.	243	50 – 1,800	500 – 1,000	2,000	Highly productive and most used confined aquifer in the Coastal Plain. Aquifer system extends throughout Coastal Plain and attains maximum thickness of 4,100 ft. Includes two aquifers in northern Coastal Plain: Farrington and Old Bridge aquifers. Salty water increases with depth and in downdip direction. Excellent water quality but large iron concentrations in some areas.
Non-Coastal Plain aquifers:					
Glacial valley-fill aquifers: Sand, gravel, interbedded silt and clay. Generally unconfined except where overlain by lake silt and clay or till.	--	10 – 300	100 – 1,000	2,000	North of terminal moraine occur principally as channel fill in preglacial stream valleys; south of moraine, as outwash plains and valley trains. Important aquifers in Bergen, Essex and Morris Counties. Water quality suitable for most uses.
Aquifers in the Newark Group: Shale and sandstone: Shale, sandstone, some conglomerate. Unconfined to partially confined in upper 200 ft; confined at greater depth.	--	30 – 1,500	10 – 500	1,500	Most productive aquifers in Essex, Passaic and Union Counties. Water generally hard; may have large concentrations of iron and sulfate. Saltwater has intruded areas of large ground-water withdrawal near bays and estuaries.

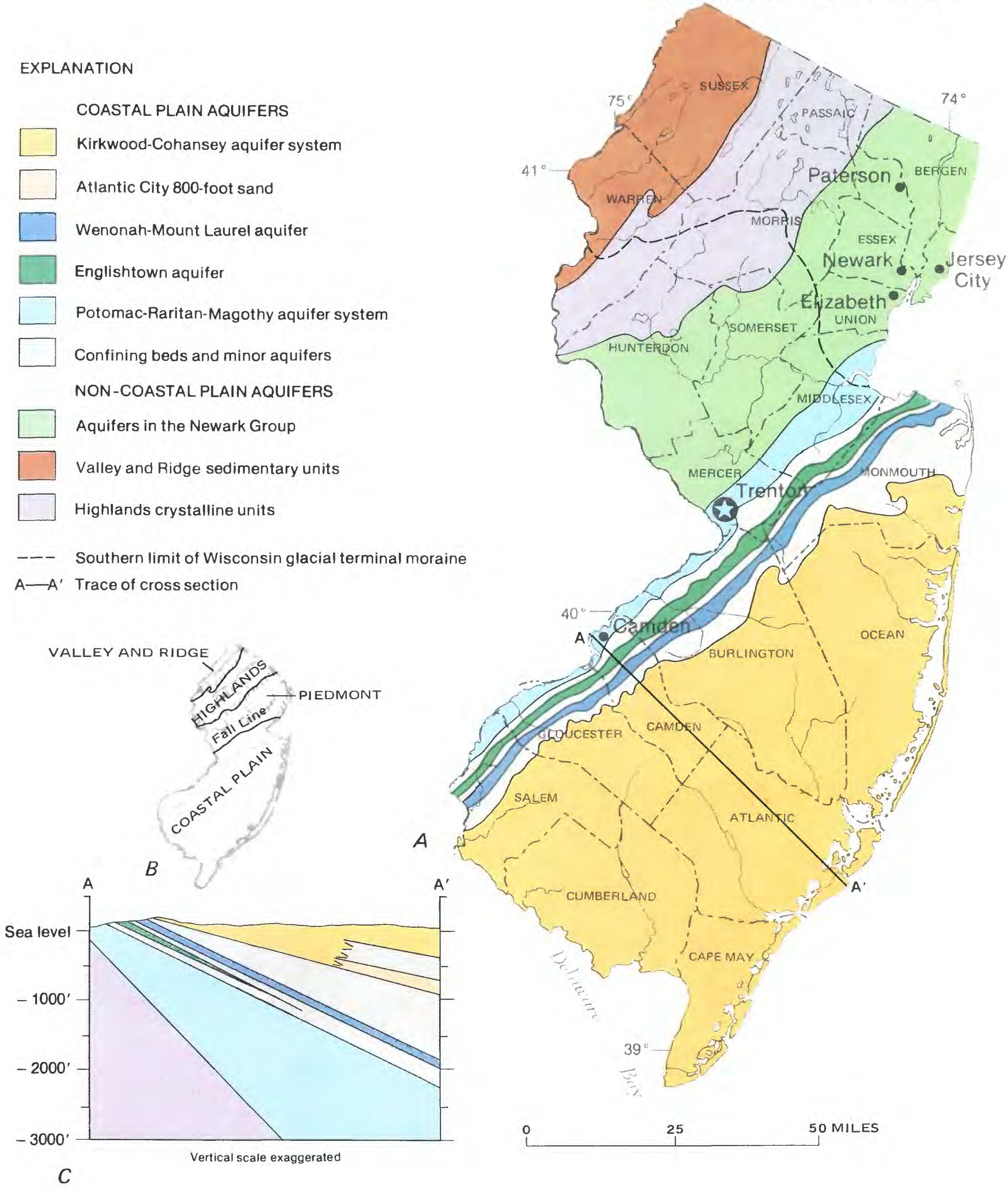


Figure 1. Principal aquifers in New Jersey. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A') of the Coastal Plain. (See table 2 for more detailed description of the aquifers. Sources: *A*, *C*, Compiled by O. S. Zapecza from U.S. Geological Survey files. *B*, Owens and Sohl, 1969; Raisz, 1954.)

Table 2. Aquifer and well characteristics in New Jersey—Continued

Aquifer name and description	Aquifer withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Valley and Ridge sedimentary units: Predominantly limestone and shale; some dolomite, calcareous sandstone and siltstone, sandstone, conglomerate and slate. Confined and unconfined.	--	150 - 400	5 - 500	1,500	Highest yields from cavernous limestones and in weathered and fractured zone within 300 ft of land surface. Locally excessive iron, hardness, and low pH.
Highlands crystalline units: Gneiss, marble, quartzite, pegmatite; some schist, amphibolite and granite. Includes thin belts of conglomerate, sandstone, not significant as aquifers. Confined and unconfined.	--	35 - 800	5 - 50	400	Most water obtained from weathered and fractured zone in upper 300 ft; high yields in or near major fault zones. Excellent source of water for domestic use in some areas.

NON-COASTAL PLAIN AQUIFERS

North of the Fall Line, the principal aquifers consist of glacial valley-fill deposits; fractured shales, limestones, sandstones, conglomerate; and crystalline rocks. These aquifers include the glacial valley-fill aquifers, the Newark Group aquifers, the carbonate aquifers within the valley and ridge sedimentary units, and the igneous and metamorphic crystalline rocks of the Highlands crystalline units.

Stratified drift and till underlie valleys north of the Wisconsin terminal moraine (fig. 1). The stratified drift, poorly sorted sand and gravel with interbedded silt, silty sand, and clay, forms the glacial valley-fill aquifers. The aquifers generally are not more than 30 to 40 ft thick. However, the aquifers may comprise channels up to 300 ft thick in pre-Pleistocene stream valleys. These glacial valley-fill aquifers are narrow beltlike deposits that are too small in areal extent to be shown in figure 1. The stratified drift can yield water to wells and can retain substantial amounts of water from precipitation, which increases yields in the underlying bedrock aquifers. In some areas, till, which consists of a veneer of unsorted clay, silt, sand, and gravel 10 to 30 ft thick, acts as a confining unit (Barksdale and others, 1943).

Glacial valley-fill aquifers are the most productive source of ground water in some northeastern counties in New Jersey (Vecchioli and Miller, 1973). These aquifers may yield as much as 2,000 gal/min to public supply and industrial wells. Their potential for supplying water has been largely overlooked in northwestern counties; however, the New Jersey Geological Survey and U.S. Geological Survey have begun programs to define this resource.

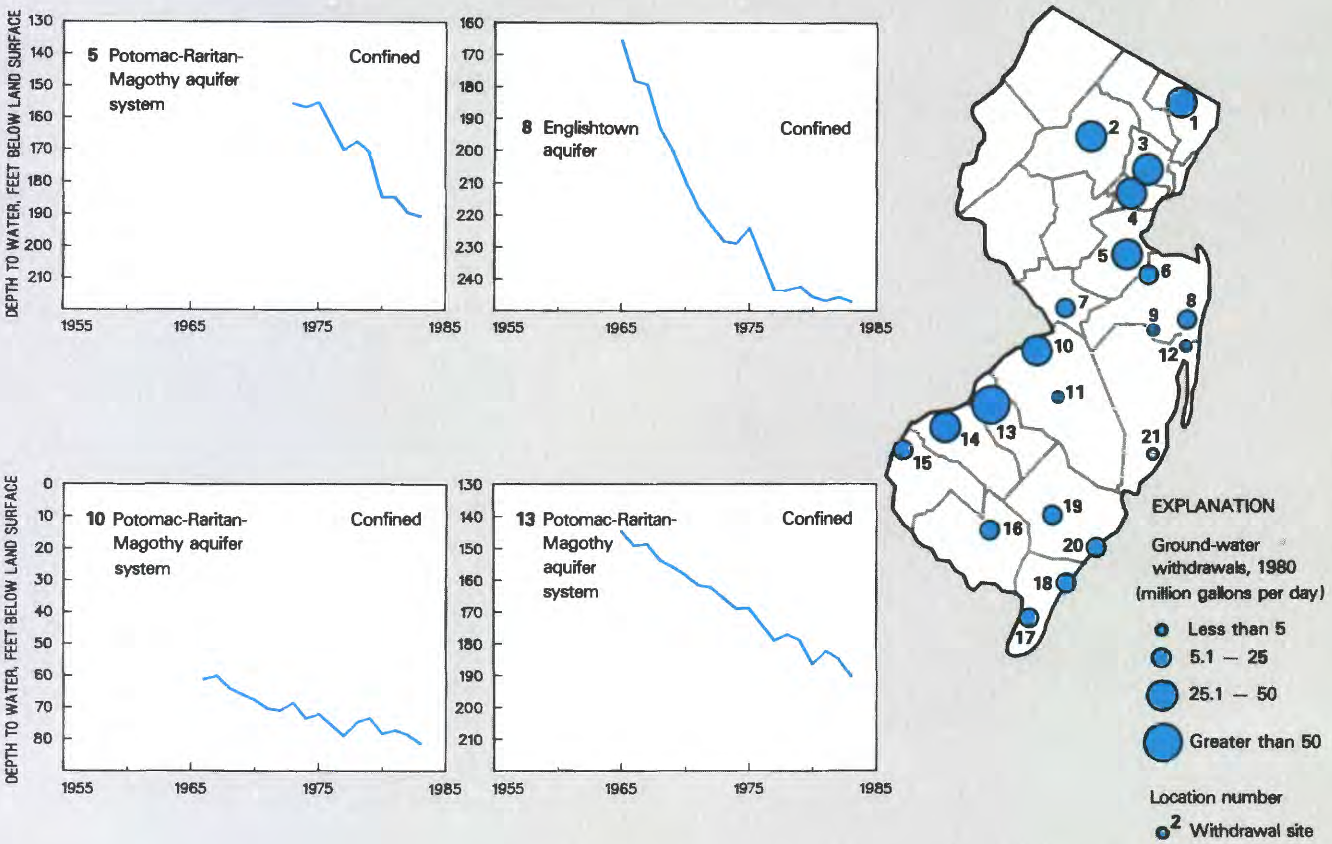
Aquifers in the Newark Group, present in the Piedmont physiographic province (fig. 1), consist of shale and sandstone. Water generally is present in weathered joint and fracture systems in the upper 200 or 300 ft (Barksdale and others, 1958). Below a depth of 500 ft, fractures are fewer and smaller, and water availability is reduced, depending on rock type. In coarse-grained sandstones, ground water also is present in intergranular pore spaces. In several counties, the shale and sandstone of the Newark Group are the most productive aquifers and yield as much as 1,500 gal/min (Carswell and Rooney, 1976; Nemickas, 1976).

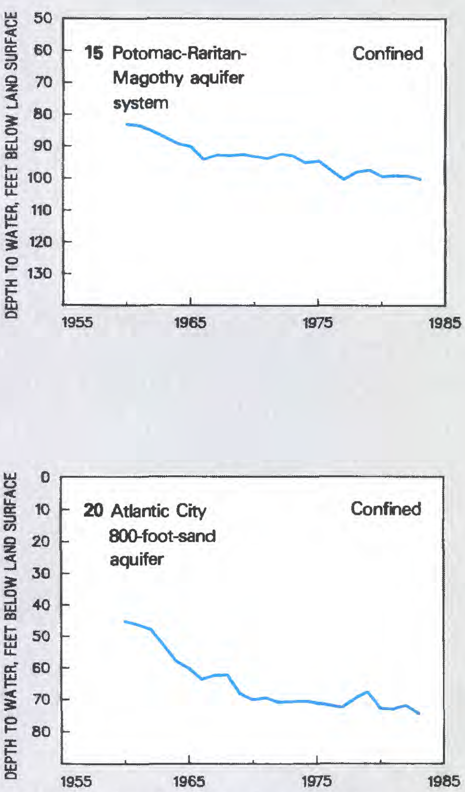
In the Valley and Ridge sedimentary units, the most productive aquifers are carbonate rocks that commonly yield large supplies of water, especially where overlain by stratified glacial deposits. Cavities and solution channels in the rock provide storage and avenues for water movement. In the crystalline highlands, water is available in weathered and fractured zones, usually within 300 ft of the land surface. With the exception of carbonates, yields from other consolidated sedimentary rocks (poorly fractured sandstones and shales) and from crystalline rocks are limited by the degree of weathering and fracturing and do not exceed more than a few hundred gallons per minute.

Non-Coastal Plain aquifers generally yield water of satisfactory quality but are susceptible to local contamination because of their proximity to the land surface. The water in valley and ridge sedimentary units and in aquifers of the Newark Group generally is hard (concentrations exceeding 120 mg/L hardness as calcium carbonate) and may have locally excessive concentrations of iron (11 mg/L) and sulfate (1,800 mg/L) (Nemickas, 1976). Near tidal areas, pumping has caused saltwater intrusion in some aquifers.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Since the 1900's, ground-water withdrawals have increased in New Jersey and have resulted in regional declines in water levels in several aquifers. Many water-supply problems associated with the increase in ground-water withdrawals have been documented. These problems include declining ground-water levels in confined aquifers which induce movement of brackish or saline water from surface-water bodies or adjacent aquifers. The location of 21 major pumping centers throughout the State is shown in figure 2. Hydrographs at six selected pumping centers illustrate the response of water-levels to withdrawals at one point within these centers.





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Bergen County	Glacial valley-fill, Newark Group.	Public supply.
2	Morris County.	. . . .do	Do.
3	Essex County	. . . .do	Do.
4	Union County.	. . . .do	Do.
5	Middlesex County. . . .	Potomac-Raritan-Magothy system.	Public supply, industrial.
6	Monmouth County . . .	. . . .do	Public supply.
7	Mercer County	. . . .do	Public supply, industrial.
8	Monmouth County . . .	Englishtown	Public supply.
9	Monmouth County . . .	Wenonah-Mount Laurel.	Do.
10	Burlington County . . .	Potomac-Raritan-Magothy system.	Public supply, industrial.
11	Burlington County . . .	Wenonah-Mount Laurel. .	Do.
12	Ocean County.	Englishtown	Public supply.
13	Camden County.	Potomac-Raritan-Magothy system.	Public supply, industrial.
14	Gloucester County . . .	. . . .do	Do.
15	Salem County	. . . .do	Industrial, public supply.
16	Cumberland County . .	Kirkwood-Cohansey . . .	Irrigation, public supply.
17	Cape May County. . . .	. . . .do	Public supply, irrigation.
18	Cape May County. . . .	Atlantic City 800-foot-sand.	Public supply.
19	Atlantic County.	Kirkwood-Cohansey . . .	Irrigation, public supply.
20	Atlantic County.	Atlantic City 800-foot-sand.	Public supply.
21	Ocean County.	. . . .do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in New Jersey. (Sources: Withdrawal and water-level data from U. S. Geological Survey files.)

In the Coastal Plain, the Potomac-Raritan-Magothy aquifer system is the most heavily pumped aquifer. Most of the pumping is concentrated near the Delaware River from Salem to Mercer Counties and near Raritan Bay in Middlesex and Monmouth Counties (locations 5 and 6, fig. 2). Withdrawals from the Potomac-Raritan-Magothy aquifer system have more than doubled from 120 Mgal/d in 1956 to about 245 Mgal/d in 1980 (Vowinkel, 1984). Four major pumping centers that use this aquifer and representative hydrographs are shown at locations 5, 10, 13, and 15, figure 2.

More than 75 Mgal/d is pumped from the Potomac-Raritan-Magothy aquifer system in Camden County. Water levels in the New Brooklyn 2 observation well (location 13, fig. 2) have declined about 45 ft from 1965 to 1983—a head loss of about 2.5 ft each year. These lowered water levels have induced recharge of water from the Delaware River to the aquifer and induced leakage from the overlying Englishtown and Wenonah-Mount Laurel aquifers. Further north in Burlington County, water levels in the Potomac-Raritan-Magothy aquifer have declined about 20 ft from 1965 through 1983 (location 10, fig. 2). Water levels in the Point Airy observation well in Salem County (location 15, fig. 2) have declined about 20 ft from 1960 through 1983. Ground-water withdrawals in Salem County from the Potomac-Raritan-Magothy aquifer system in 1980 were about 6 Mgal/d.

In the northern part of the Coastal Plain two aquifers have been defined within the Potomac-Raritan-Magothy aquifer system—the Farrington aquifer and the Old Bridge aquifer. The hydrograph of water levels near location 5 (fig. 2) illustrates a 35-ft decline in the Potomac-Raritan-Magothy aquifer system from 1973 through 1983. Induced recharge of brackish water into the aquifer from Raritan Bay and adjacent tidal areas has been documented for more than 40 years (Barksdale and others, 1943). Large ground-water withdrawals near location 6 (fig. 2) have caused a decline in water levels and a reversal in the direction of ground-water flow in the Old Bridge aquifer.

The greatest water-level declines in the State have occurred in the Englishtown aquifer. Water levels in the Allaire State Park observation well in Monmouth County have declined almost 90 ft from 1965 through 1983 (location 8, fig. 2). In 1980, about 12 Mgal/d was pumped from this aquifer. Water-level fluctuations in the Atlantic City 800-foot sand are represented by a well hydrograph at location 20 (fig. 2). This aquifer is pumped heavily along the Atlantic Coast in Cape May, Atlantic, and Ocean Counties. In 1980, withdrawals from the Atlantic City 800-foot sand ranged from 38 Mgal/d in August to 13 Mgal/d in November (Vowinkel, 1984).

In non-Coastal Plain areas, approximately 150 Mgal/d is pumped from ground-water reservoirs for public supply. Withdrawals from ground water by public-supply purveyors are significant in Bergen (30 Mgal/d), Morris (30 Mgal/d), Essex (40 Mgal/d), and Union (30 Mgal/d) Counties (locations 1-4, respectively, fig. 2). Ground-water withdrawals by public-supply purveyors in each of the remaining counties located north of the Fall Line generally are less than 8.5 Mgal/d.

Ground-water levels have declined locally in the glacial valley-fill aquifers especially in Morris and Essex Counties (Meisler, 1976) and in the Newark Group aquifers in Union County.

GROUND-WATER MANAGEMENT

The New Jersey Department of Environmental Protection, Division of Water Resources (NJDEP/DWR), is the primary agency responsible for managing and regulating water resources in the State. State control of surface-water use began in 1910. In 1947, the State was authorized to delineate areas where the control of diversions of subsurface and percolating waters was necessary to protect their natural replenishment (New Jersey Law 1947, c. 375). This statute required users withdrawing more than 100,000 gallons per day (gal/d) in delineated areas to obtain a permit and report withdrawal information to the State. Another measure adopted in 1947 licensed well drillers and required a State permit prior to drilling a well. Since January 1981, all users of 100,000 gal/d or more of surface water, ground water, or both are required to obtain a permit and report monthly withdrawal rates to the NJDEP/DWR.

Since 1974, the New Jersey legislature has rewritten all laws pertaining to water supply and water quality. The New Jersey Water Supply Management Act (1981), the Water Supply Bond Act (1981), and the New Jersey Water Supply Authority Act (1981) are elements of the State program to protect and manage ground-water resources. Every 5 years, NJDEP/DWR revises and updates the State Water Supply Plan. Procedures to handle emergency conditions caused by droughts are included in the Management Act.

The Water Supply Bond Act provides a Water Supply Fund of $350 million for planning, designing, acquiring, and constructing water-supply facilities. A referendum in 1983 also allows the bond funds to be used for ground-water studies that do not involve construction.

In addition to NJDEP/DWR, other State governmental agencies have an interest in water supply. The New Jersey Water Supply Authority was established in 1981 by the New Jersey Water Supply Authority Act; the Authority controls specific State water supplies and may issue bonds to finance water-supply projects. The North Jersey District Water Supply Commission was established in 1916 to provide water to northern counties in New Jersey; it is one of the largest purveyors of potable water in the State. The Delaware River Basin Commission, established in 1961, has as members the Federal Government and the States of Delaware, New Jersey, New York, and Pennsylvania. In New Jersey, the Commission has regulatory responsibility over the area draining into the Delaware River and its tributaries; this area covers approximately 40 percent of the State. The agency has broad powers over the planning, development, and control of water and related natural resources of the Delaware River basin.

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Prepared by B. Pierre Sargent, George M. Farlekas, and Otto S. Zapecza

For further information contact District Chief, U.S. Geological Survey, 402 East State Street, Trenton, NJ 08608

NEW MEXICO
Ground-Water Resources

Ground-water resources supply almost one-half of the water used in New Mexico. Approximately 47 percent of the water used in the State is from wells, and about 89 percent of New Mexico's 1.36 million people derive their water from ground-water-supply systems. Almost all of the State's rural water supplies are derived from ground water. Even though the largest cities in the State use ground water for public supply, the largest use of ground water is for the irrigation of 861,000 acres of farm land within the State. Of the 1.8 billion gallons per day (bgd) of ground water pumped annually, 1.6 bgd is used to irrigate crops (Solley and others, 1983). Locally, ground water is an abundant natural resource. However, it is not evenly distributed throughout the State; many areas have little ground water, and some areas that once had seemingly adequate ground-water supplies are now experiencing water-level declines because of large withdrawals. Ground-water withdrawals for various uses and other related statistics are given in table 1.

Table 1. Ground-water facts for New Mexico

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	1,207
Percentage of total population	89
From public water-supply systems:	
Number (thousands)	798
Percentage of total population	59
From rural self-supplied systems:	
Number (thousands)	409
Percentage of total population	30
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	3,900
Ground water only (Mgal/d)	1,800
Percentage of total	47
Percentage of total excluding withdrawals for thermoelectric power	47
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	190
Percentage of total ground water	10
Percentage of total public supply	90
Per capita (gal/d)	238
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	32
Percentage of total ground water	2
Percentage of total rural domestic	97
Per capita (gal/d)	78
Livestock:	
Ground water (Mgal/d)	9.6
Percentage of total ground water	0.5
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	18
Percentage of total ground water	1
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	25
Excluding withdrawals for thermoelectric power	98
Irrigation withdrawals:	
Ground water (Mgal/d)	1,600
Percentage of total ground water	86
Percentage of total irrigation	44

GENERAL SETTING

New Mexico is located in several physiographic provinces—the Basin and Range, the Colorado Plateaus, the Great Plains, and the Southern Rocky Mountains (fig. 1). Consequently, the geology and physiography of New Mexico are very diverse, ranging from large mountainous areas of igneous and sedimentary rock to wide expanses of relatively flat-lying unconsolidated deposits and consolidated sedimentary rock. The diversity of geology and land forms causes significant differences in the availability and quality of water in the State.

Recharge to the ground-water system in New Mexico is derived from infiltration of precipitation, surface water, and irrigation return flow. Normally, precipitation ranges from 6 to 35 inches per year; the greatest quantities occur at highest altitudes in the mountains. Most streamflow and recharge to the ground-water system in the State comes from snowmelt during the spring and from thunderstorms during the summer.

PRINCIPAL AQUIFERS

The principal aquifers in the State have been grouped into four types—valley-fill aquifers, basin-fill aquifers, sandstone aquifers, and limestone aquifers (fig. 1). The valley-fill aquifers are mostly unconsolidated alluvium and terrace deposits that are adjacent to the major rivers in the State. The basin-fill aquifers are mostly unconsolidated fluvial and eolian deposits that are present in most of the major structural basins of the Basin and Range province and the High Plains deposits that are located in the Great Plains province. (Fig. 1 shows the relation between the valley-fill and basin-fill aquifers near Albuquerque.) The sandstone aquifers are composed of a series of sandstones in the San Juan Basin, which is situated in the Colorado Plateaus province. The limestone aquifers are in the southeast, central, and west-central part of the State and are composed of limestone, dolomite, gypsum, and anhydrite. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

VALLEY-FILL AQUIFERS

The valley-fill aquifers consist mostly of alluvial and terrace deposits that border the major rivers in the State. Those of major importance are located along the Rio Grande, which flows from north to south through the center of the State, the Rio Chama in the north, the San Juan River in the northwest, and the Pecos River in the southeast. These

Table 2. Aquifer and well characteristics in New Mexico

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Valley-fill aquifers: Sand, gravel, silt, and clay; mostly alluvial and terrace deposits. Mostly unconfined.	50 - 200	500	100 - 500	3,000	Principal aquifers are alluvial and low terrace deposits of Quaternary and Tertiary age, associated with Rio Grande, Rio Chama and Pecos, and San Juan Rivers. Water quality suitable for most uses.
Basin-fill aquifers: Sand, gravel, silt, and clay; mostly fluvial, lacustrine, and eolian deposits. Unconfined and confined.	100 - 500	3,000	100 - 500	3,000	Principal aquifers are Santa Fe Group of Quaternary and Tertiary age in Rio Grande valley, bolson deposits in the central and southwestern part of State, and High Plains aquifer of Tertiary age, which consists of Ogallala Formation and associated alluvial and eolian deposits in the eastern part of the State. Locally, water may not be suitable for municipal or domestic use because of excessive salinity.
Sandstone aquifers: Mostly very fine and medium-grained sandstone of marine and continental origin. Usually confined except in outcrop areas.	200 - 2,000	6,000	50 - 100	1,200	Principal aquifers are Ojo Alamo Sandstone, Nacimiento and San Jose Formations of Tertiary age (Tertiary sandstone aquifers locally significant in the San Juan Basin area but are not shown on fig. 1), Dakota Sandstone, Gallup Sandstone, Dalton Sandstone Member of the Crevasse Canyon Formation, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone of Cretaceous age; and the Entrada Sandstone, Westwater Canyon Member of Morrison Formation of Jurassic age. Water quality near outcrop areas ordinarily suitable for most uses.
Limestone aquifers: Mostly limestone, dolomite, gypsum, anhydrite. Usually confined.	500 - 1,000	1,500	400 - 800	3,000	Principal limestone aquifer is the San Andres Limestone of Permian age in Pecos River valley, Rio San Jose valley, and locally in part of Guadalupe County. Locally, water may not be suitable for municipal and domestic use because chlorides may exceed 500 mg/L.

aquifers generally are less than 200 feet (ft) thick. The valley fill along the Rio Grande and Pecos River provides large quantities of water to wells (Bjorklund and Maxwell, 1961; Welder, 1983). Wells drilled in these areas commonly penetrate deeper aquifers to increase yields. The water generally is fresh [less than 1,000 milligrams per liter (mg/L) dissolved solids]; however, in places, slightly saline water may be present in the aquifers. Water is discharged from the aquifers by wells, spring flow, evapotranspiration, and seepage to the rivers.

BASIN-FILL AQUIFERS

The basin-fill aquifers are comprised mostly of materials that have been eroded from the mountainous areas and transported by either streams or wind into structural or topographic basins. Two very distinct basin-fill areas occur in New Mexico. One is the deep troughs and intermontane valleys of the Basin and Range province (filled with material commonly called bolson deposits), and the other is in the Great Plains province where a broad expanse of alluvial fans and other stream and wind-blown deposits commonly are referred to as the High Plains aquifer. The thickness of basin-fill deposits in the Rio Grande valley may be as much as 20,000 ft, but the water contains more than 1,000 mg/L dissolved solids generally below a depth of 3,000 ft. This aquifer is the source of water for Albuquerque, the most populous city in the State, and also provides a partial supply to Santa Fe, the capital. In most areas, the deposits range in thickness from only a few hundred feet to 2,000 ft. The High Plains aquifer, located along the eastern border of the State, has a maximum thickness of about 400 ft and an average thickness of about 200 ft. Water from this aquifer generally contains less than 1,000 mg/L dissolved solids. Discharge from the basin-fill aquifers occurs mostly as a result of pumpage for irrigation and municipal supplies, of infiltration to the valley-fill aquifers, and of underflow to Texas.

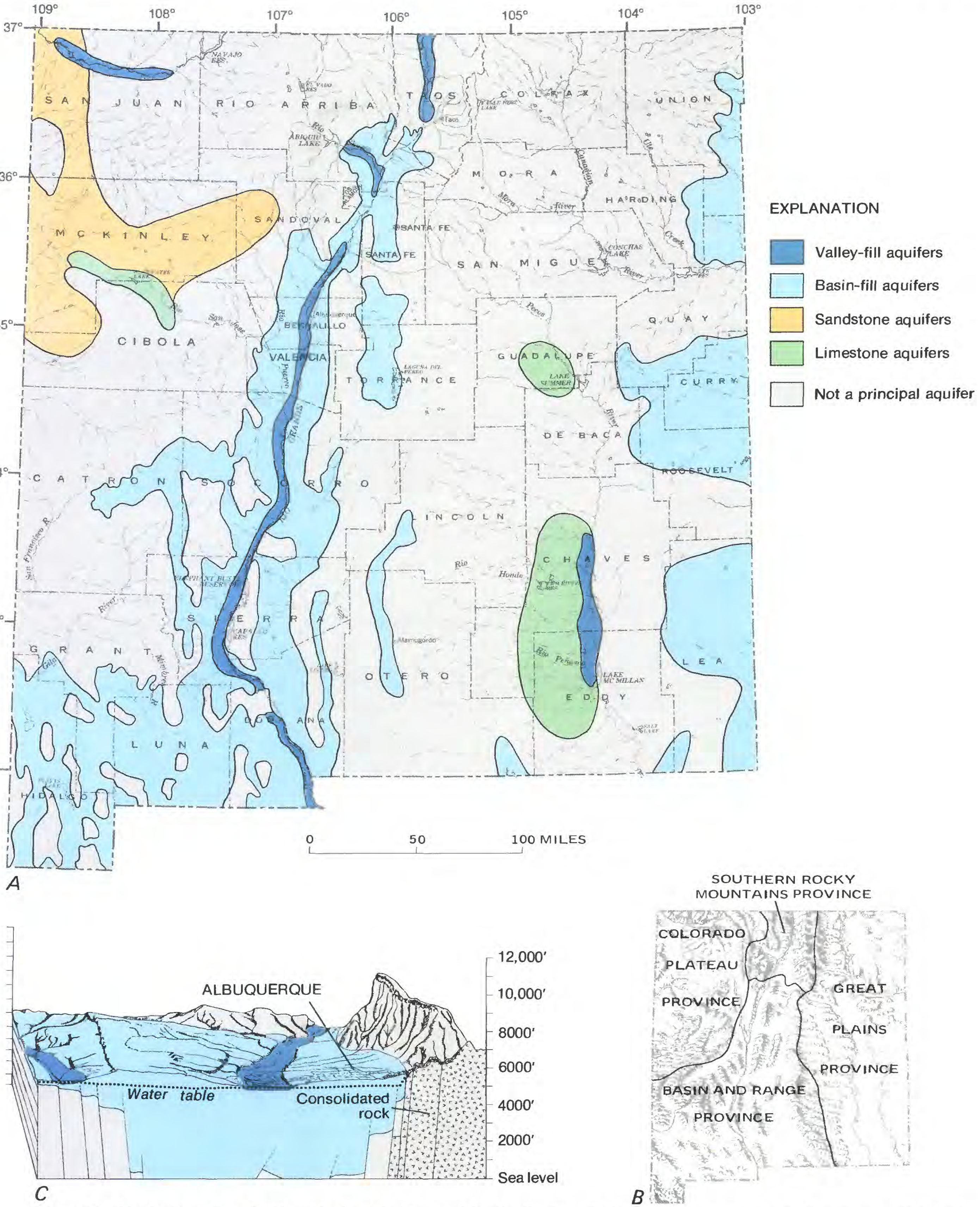


Figure 1. Principal aquifers in New Mexico. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Block diagram showing a valley-fill and a basin-fill aquifer and their relation to consolidated rocks of the mountains that bound the basin near Albuquerque. (See table 2 for a more detailed description of aquifers. Sources: *A*, New Mexico State Engineer Office, 1967. *B*, Fenneman, 1930; Raisz, 1954. *C*, Bjorklund and Maxwell, 1961.)

Sandstone Aquifers

The sandstone aquifers are located in the San Juan Basin part of the Colorado Plateau province. These aquifers are a series of hydraulically interconnected sandstones. Some of the sandstones in this sequence are marine in origin and others are continental. The series of sandstones are exposed around the perimeter of the basin and are recharged by precipitation and ephemeral streams. The quality of the water in the sandstone generally is fresh near outcrop areas and for some distance down the flow path but may deteriorate with depth as it flows toward discharge areas in the northwestern part of the basin (Lyford, 1979). The total thickness of sedimentary rocks in the basin probably is more than 15,000 ft (Stone and others, 1983). Some of the ground water in the aquifers discharges to the San Juan River, some evaporates, and some discharges to the Rio Grande. Much of the water in the lower sandstones may move upward through partially impermeable confining layers to other aquifers or to the land surface in the central part of the basin where it evaporates or is used by plants. Water is also withdrawn for industrial, public, agricultural, and rural supplies.

Limestone Aquifers

The limestone aquifers are a major source of water in the southeastern and central parts of the State near the Pecos River (Welder, 1983) and in the western part of the State near the Rio San Jose. The aquifers are productive in these areas because of the secondary solution and fracture permeability that has developed in the rock. Primary recharge to these aquifers is from infiltration of precipitation, from surface water from tributaries of the Pecos River, and from the Rio San Jose. Discharge from the aquifers is mainly from wells and springs. Although these aquifers are quite extensive at depth in the southern and western parts of the State, the water generally is too saline for most uses outside the area shown in figure 1.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The counties with the largest ground-water withdrawals are shown in figure 2. These nine counties account for 79 percent of the total ground water withdrawn in the State. By far the greatest use of water in these counties is irrigation, except in Bernalillo County (location 1, fig. 2) where urban use exceeds agricultural use. In five of the nine counties, irrigation use accounts for 93 to 98 percent of the total ground-water withdrawals. The largest water-level declines have occurred in areas where large quantities of water for irrigation are withdrawn from closely spaced wells. Withdrawals of water for urban use are likely to continue to increase slowly.

Water-level declines in the valley-fill aquifers generally have been small along the Rio Grande and San Juan River systems due to increased seepage of ground water from adjacent aquifers and recharge of irrigation water and streamflow, which tend to moderate the water-level changes. The hydrograph from a well in Bernalillo County (location 1, fig. 2), completed in the basin- and valley-fill aquifer, is representative of this phenomena. Location 1 is near the source of public-water supply for the city of Albuquerque. In the valley-fill aquifer along the Pecos River valley, water-level declines of 120 ft have been reported in areas that are intensively pumped for irrigation.

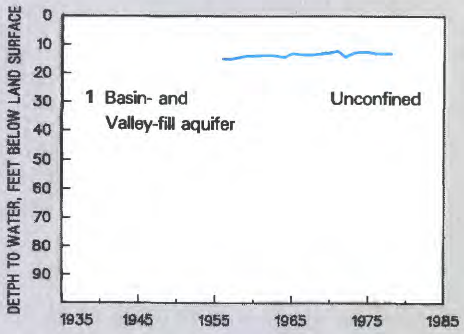
Water-level declines in the basin-fill aquifers generally have been greater than those in the valley-fill aquifers. In many areas where irrigation wells are closely spaced and pumped regularly, declines of 20 to 60 ft have occurred (location 9, fig. 2), and, in places, declines as great as 120 ft have been reported during the past 25 to 30 years. The average well density in this area is two wells per square mile. Water levels in the High Plains aquifer have been declining at a rate of about 2 ft per year in irrigated areas. The hydrograph shown in Lea County (location 5, fig. 2) represents a well completed in the High Plains aquifer, where the density of irrigation wells ranges from three to five per square mile.

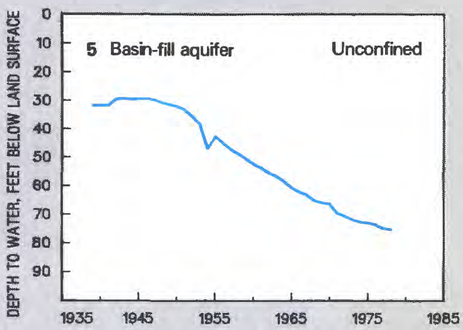
The water levels in wells completed in the sandstone aquifers in the San Juan Basin of northwestern New Mexico have declined 50 to 300 ft during the past 30 years, even though the density of large-capacity wells in this area is sparse. Ground water has been pumped mostly for industrial purposes, public supplies, and mine dewatering. During the past few years, a decrease in mining activities has decreased the need to pump ground water in the area and allowed some recovery in water levels, although water levels continue to decline in remote areas.

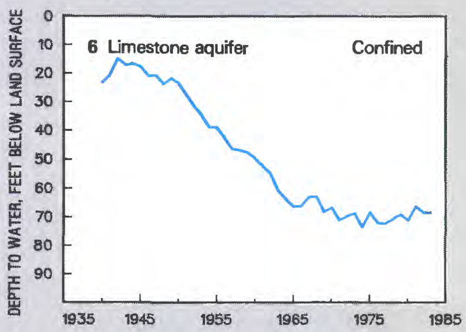
The water-level change in the limestone aquifer is represented by a hydrograph of a well in Chaves County (location 6, fig. 2) where the density of irrigation wells is about six per square mile. Water levels have declined as much as 230 ft in the southern part of this aquifer since 1905. Declines of 75 to 100 ft are common in areas with extensive withdrawals of ground water for irrigation. The change in slope of the hydrograph in 1966 may be due to increased annual precipitation in the basin and to a small reduction in ground-water withdrawals. In Cibola County, the water levels have declined as much as 40 ft since the late 1940's. In Guadalupe County, the aquifer is not pumped intensively and water levels have shown little change.

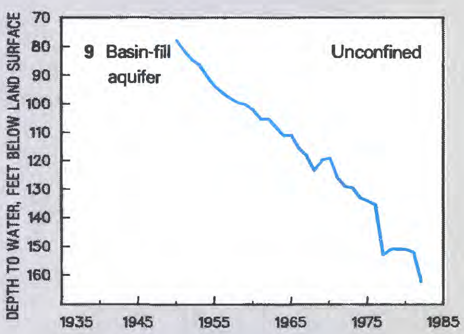
GROUND-WATER MANAGEMENT

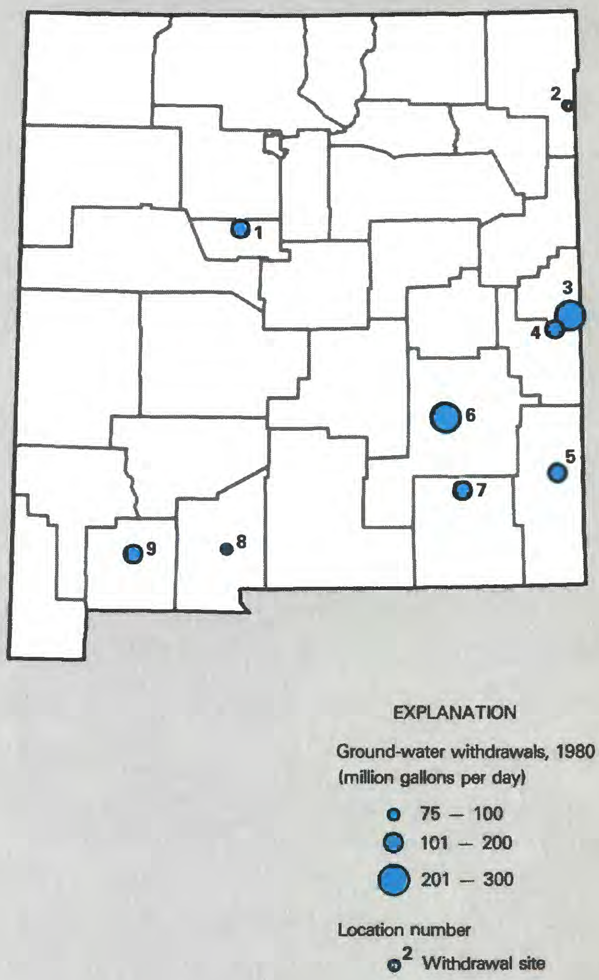
The first laws regarding water use in New Mexico were established by the New Mexico Territorial Legislature in 1851. In 1931, the State Legislature imposed a permit system for the appropriation of ground water, which, with slight modifications, is still in effect (Harris, 1984). Ground-water use in New Mexico is regulated by the New Mexico State Engineer. Areas have been designated in which appropriation of additional ground water is allowed only by permit; at present, 31 such areas, designated "Declared Underground-Water Basins," represent about 69 percent of the total area of the State. The basic authority for water-quality protection is vested in the Water Quality Control Commission, of which the State Engineer is a member. Primary responsibility for enforcing Commission regulations that protect the quality of ground water in the State has been delegated by the Commission to the New Mexico Environmental Improvement Division. The New Mexico State Engineer and the U.S. Geological Survey collect ground-water data and conduct cooperative investigations of ground-water resources throughout the State.











WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Bernalillo County. .	Basin- and Valley-fill . .	Public supply.
2	Union County. . . .	Basin-fill	Irrigation.
3	Curry County	. . . .do	Do.
4	Roosevelt County. .	. . . .do	Do.
5	Lea County	. . . .do	Irrigation, industrial.
6	Chaves County . . .	Limestone	Irrigation.
7	Eddy County	. . . .do	Do.
8	Dona Ana County. .	Basin-fill	Irrigation, public supply.
9	Luna County	. . . .do	Irrigation.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in New Mexico. (Sources: Withdrawal data from New Mexico State Engineer; water-level data from U.S. Geological Survey files.)

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Prepared by Donald Hart, Jr.

For further information contact District Chief, U.S. Geological Survey, 505 Marquette, N. W., Albuquerque, NM 87102

NEW YORK
Ground-Water Resources

More than 6 million of New York's 17.5 million residents rely on ground water for drinking supplies. Of those who depend on ground water, more than one-half live on Long Island where ground-water withdrawals for all uses total 486 million gallons per day (Mgal/d). A total of 487 Mgal/d is withdrawn in Upstate counties. Ground-water withdrawals for various uses and related statistics are given in table 1.

For ease of discussion, New York's ground-water resources are separated into two regions—Long Island and Upstate. In this summary, Upstate New York is considered to include all counties north of the Counties of Bronx, New York (Manhattan), and Richmond (Staten Island).

GENERAL SETTING

Upstate New York is located in several physiographic provinces (fig. 1)—the Adirondack, the New England, the St. Lawrence Valley, the Appalachian Plateaus, the Valley and Ridge, the Piedmont, and the Central Lowland. Crystalline rocks dominate the Adirondack and New England provinces. Carbonate rocks are present in outcrop fringes (escarpments) along the northern and eastern edges of the Appalachian Plateaus province, in isolated areas of the St. Lawrence Valley province and in eastern New York. Shale, the most extensive bedrock unit, is present in the Appalachian Plateaus, western Central Lowland, and Valley and Ridge provinces. Sandstone is present in the Piedmont, St. Lawrence Valley, and eastern Central Lowland provinces.

Bedrock in Upstate New York is covered with glacial deposits of till and stratified drift of variable thickness. The till mantles the uplands and small tributary valleys and usually is found beneath stratified drift in the larger valleys. Stratified drift (partly reworked by modern streams) forms the floors of large valleys and flat plains or terraces where bedrock relief is low. The stratified drift includes lacustrine and beach deposits of clay, silt, and sand and meltwater deposits of sand and gravel. The sand and gravel deposits form the principal aquifer systems of Upstate New York (fig. 1).

Recharge to Upstate New York's ground-water systems is derived from precipitation. Average annual precipitation ranges from 32 inches (in.) in the Central Lowland and St. Lawrence Valley provinces to more than 50 in. in the Adirondack and Catskill (eastern Appalachian Plateaus province) regions. In most of Upstate New York the amount of recharge ranges from 1 to 50 percent of the precipitation; however, in the areas of the stratified-drift valley-fill aquifer, the recharge can be considerably greater because of the runoff from surrounding hills (Heath, 1964).

Long Island lies in the Coastal Plain province (fig. 1) and is underlain by drift, principally stratified sand and gravel. Recharge to the Long Island ground-water system is derived solely from precipitation. Average precipitation is 43 in. per year (Cohen and others, 1968). Although recharge rates may differ according to land use, about 50 percent of the precipitation reaches the water table. Some of this ground water flows to the deeper aquifers.

Table 1. Ground-water facts for New York

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: New York State Department of Environmental Conservation, 1982; New York State Department of Health, 1981; Solley, Chase and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	6,133
Percentage of total population	35
From public water-supply systems:	
Number (thousands)	3,919
Percentage of total population	22
From rural self-supplied systems:	
Number (thousands)	2,214
Percentage of total population	13
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	7,900
Ground water only (Mgal/d)	970
Percentage of total	12
Percentage of total excluding withdrawals for thermoelectric power	28
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	500
Percentage of total ground water	51
Percentage of total public supply	23
Per capita (gal/d)	127
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	170
Percentage of total ground water	18
Percentage of total rural domestic	89
Per capita (gal/d)	75
Livestock:	
Ground water (Mgal/d)	37
Percentage of total ground water	4
Percentage of total livestock	65
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	250
Percentage of total ground water	25
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	4
Excluding withdrawals for thermoelectric power	11
Irrigation withdrawals:	
Ground water (Mgal/d)	21
Percentage of total ground water	2
Percentage of total irrigation	46

PRINCIPAL AQUIFERS

UPSTATE

Principal aquifers in Upstate New York consist of unconsolidated glacial stratified-drift and valley-fill deposits and consolidated clastic and carbonate sedimentary rocks, some of which have been metamorphosed. The principal aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics in New York

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Upstate				
Stratified-drift–Lacustrine and ice-contact deposit aquifers: Sand and gravel. Unconfined.	10 - 300	10 - 50	100	In most areas, deposits consist entirely of sand. Excessive iron concentrations.
Valley-fill deposit aquifers: Sand and gravel. Generally confined.	3 - 200	100 - 1,000	3,000	Glacial outwash and alluvium interbedded with clay and silt in many valleys are most productive water-bearing material in New York. Locally excessive iron or manganese concentrations.
Carbonate-rock aquifers: Limestone, dolomite, and marble. Unconfined in most areas.	10 - 300	50 - 150	200	Carbonate rocks are most productive bedrock unit in State. Water from this unit usually hard and contains hydrogen sulfide gas in some areas. From Niagara Falls to vicinity of Syracuse and in St. Lawrence valley, deep wells yield slightly salty water and, in places, water with a sulfate concentration that may exceed 300 mg/L.
Sandstone aquifers: Includes both sandstone and conglomerate. Confined in most areas.	3 - 500	50 - 100	100	Sandstone is the second most productive bedrock unit in New York. Water commonly slightly hard and has excessive iron concentration locally.
Long Island				
Upper glacial aquifer (includes Jameco and Port Washington aquifers): Outwash deposits (mostly between and south of terminal moraines but also interlayered with till) consist of quartzose sand, fine to very coarse, and gravel, pebble to boulder sized. Unconfined.	50 - 500	50 - 1,000	1,500	Main source of drinking water in central and eastern Suffolk County. Contains high concentration of nitrates and organic compounds in western Long Island. Saline water problems in extreme eastern end of Long Island.
Magothy aquifer: Sand, fine to medium, clayey in part; interbedded with lenses and layers of coarse sand and sandy and solid clay. Gravel is common in basal 50 to 200 ft.	150 - 1,100	50 - 1,200	2,000	Supplies most of the ground water for public-supplied drinking water in Queens, Nassau, and western Suffolk Counties. Saline water in North and South Forks and near Jamaica Bay.
Lloyd aquifer: Sand, fine to coarse, and gravel, commonly with clayey matrix; some lenses and layers of solid and silty clay; locally contains thin lignite layers and iron concretions.	150 - 1,100	50 - 1,000	1,200	Main source of drinking water for northwest shore of Long Island barrier islands to south. Saline water in North and South Forks and extreme west end of barrier islands.

Stratified-Drift Aquifers

Stratified-drift deposits of thick sand and gravel (valley fill) underlie flood plains and terraces along the larger streams and occupy preglacial or glacial valleys that lack perennial streams. The distinguishing feature of the valley-fill aquifers is their linearity and close proximity to contiguous streams (fig. 1). Many valley-fill aquifers are overlain, and thus confined locally, by fine-grained sediments. Induced infiltration from streams commonly occurs where pumped wells are close to the streams (Waller and Finch, 1982). Elsewhere, particularly in the northern one-half of New York, glacial lake and beach sands on uplands also contain significant aquifers.

The stratified drift forms unconfined, shallow aquifers that are susceptible to contamination from surface sources. Quality of water in the stratified drift generally is excellent and suitable for human consumption and most other uses; however, water in some areas contains excessive iron [as high as 0.33 milligrams per liter (mg/L)] and manganese (as high as 0.14 mg/L) concentrations that require treatment in some areas. In some aquifers, water is saline at relatively shallow depth between Buffalo and Syracuse as a result of ground-water dissolution of gypsum and halite beds. Toxic waste contamination has been reported in some valley-fill deposits, and 36 public water-supply wells have been closed as of January 1984 because of organic contamination (L. J. He-

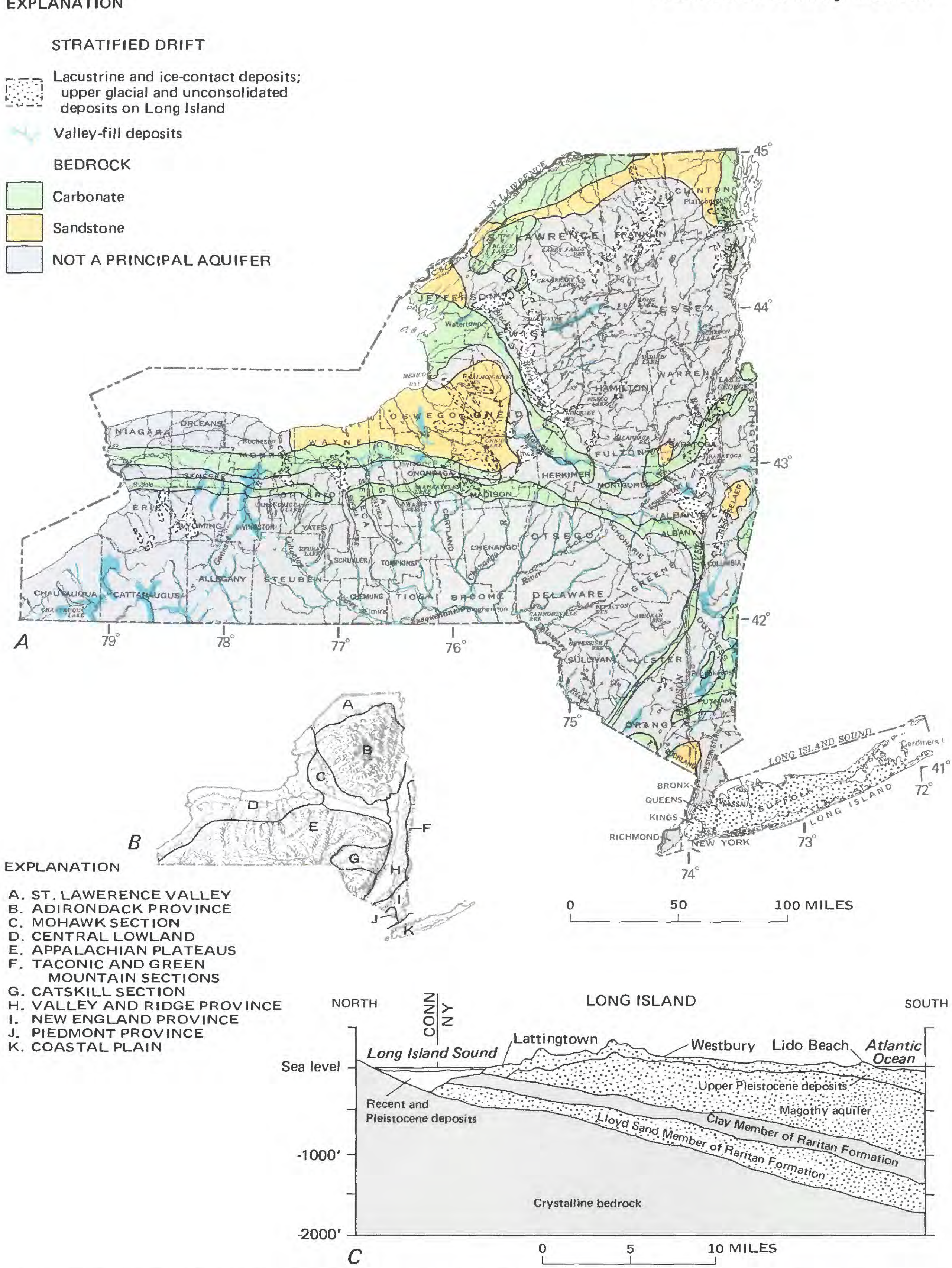


Figure 1. Principal aquifers in New York. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized north-south geologic section, Long Island). (See table 2 for more detailed description of the aquifers. Sources: *A*, Heath, 1964; Kantrowitz and Snavely, 1982. *B*, Fenneman, 1938; Raisz, 1954. *C*, Cohen and others, 1968.)

tling, New York State Department of Health, written commun., 1984).

Carbonate and Sandstone Bedrock Aquifers

Bedrock forms significant aquifers only in the sandstones of the Piedmont and St. Lawrence Valley provinces and in the carbonates, as shown in figure 1. Quality of water generally is suitable for most uses, but a median hardness exceeding 700 mg/L as calcium carbonate is a problem in the carbonate aquifers. Saline water is present at shallow depth in the western one-half of the State.

Long Island

The principal aquifers of Long Island consist of unconsolidated clastic sediment; they are the upper glacial aquifer of Pleistocene age and the Magothy and Lloyd aquifers of Cretaceous age. These aquifers are continuous throughout Long Island (fig. 1) except along the north shore and northern Kings County, where the formations making up the Magothy and Lloyd have been eroded by glaciation. The aquifers are described below and in table 2; only the upper glacial aquifer is shown in figure 1.

Upper Glacial Aquifer

The upper glacial aquifer consists of the saturated upper part of the highly permeable Pleistocene and Holocene deposits. Saltwater encroachment is a current problem on the islands and peninsulas of eastern Suffolk County and is a potential problem along all of Long Island's shores. Septic systems and agricultural and lawn fertilizers locally have resulted in elevated chloride (300 mg/L) and nitrate-nitrogen (22 mg/L) concentrations (Katz and others, 1977), and pesticides, industrial wastes, and landfill leachate (Kimmel and Braids, 1980) have contributed to pollution of the aquifer.

Magothy Aquifer

The Magothy aquifer consists of the Cretaceous Magothy Formation and the Matawan Group, undifferentiated. The Magothy aquifer and overlying upper glacial aquifer are connected hydraulically except in the south, where they are separated by a confining unit. Saltwater encroachment in this aquifer is a problem in southern coastal areas of Nassau and Queens Counties and at the eastern end of Long Island. Contamination by organic chemicals is a current and potential problem in many parts of the island.

Lloyd Aquifer

The Lloyd aquifer consists of the Lloyd Sand Member of the Raritan Formation. The aquifer is separated from the overlying Magothy aquifer by a thick, fine-grained, confining unit in the Raritan Formation (fig. 1). Saltwater encroachment either already occurs or is a potential problem in the eastern one-half of Suffolk County and in parts of the barrier islands of Nassau County.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals and trends in ground-water levels in New York State are indicated in figure 2; the withdrawals are compiled by county and include only those pumping centers that withdraw more than 10 Mgal/d. Pumping centers are plotted at the major pumping-center site or, where major pumping centers are not present, at the center of the county.

Upstate

Of the counties that withdraw more than 10 Mgal/d in Upstate New York (New York State Department of Health, 1981), all but two (Orange and Dutchess) draw most of their water from valley-fill aquifers. Orange and Dutchess Counties withdraw more water from bedrock than from valley fill and also have the smallest public supply use of the nine major ground-water users of the Upstate New York counties.

Water levels in the Upstate aquifers respond to withdrawals at nearby pumping centers, but because the withdrawals are relatively low and induced recharge from streams is relatively large, water-level declines are minimal. Two of the hydrographs for Upstate New York (locations 5 and 9, fig. 2) indicate that long-term water-level declines have not occurred. The hydrograph for location 12 reflects a decline in water levels until 1968 when recovery began.

Long Island

Since the late 1930's, withdrawals for public-supply and industrial uses have increased steadily. Withdrawals for farm use and irrigation are minimal. In general, pumping centers are distributed evenly throughout the four Long Island counties except for major pumping centers that have been developed in each of the three major aquifers in Queens County.

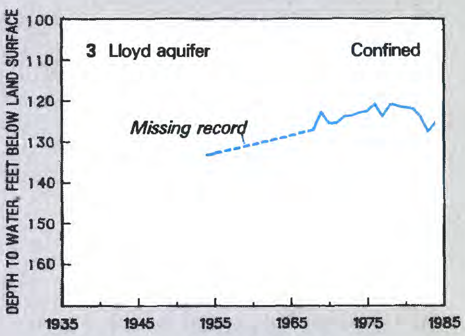
The Long Island hydrographs in figure 2 (location 3) reflect the response of three aquifers to withdrawals in Queens County. The water-level recovery in the Lloyd and Magothy aquifers has resulted from a reduction in pumpage and from the recharge of aquifers with cooling water, decisions implemented to counteract saltwater encroachment. Water-level changes in the two eastern counties of Long Island, Nassau and Suffolk, generally reflect changes in amounts of precipitation rather than changes in pumping.

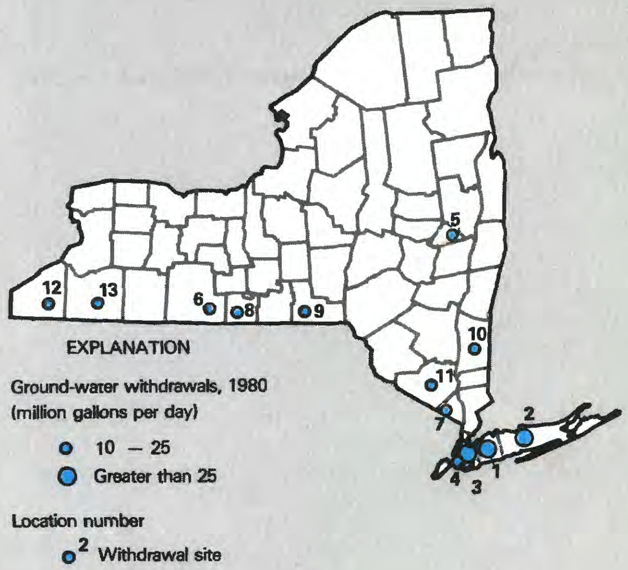
GROUND-WATER MANAGEMENT

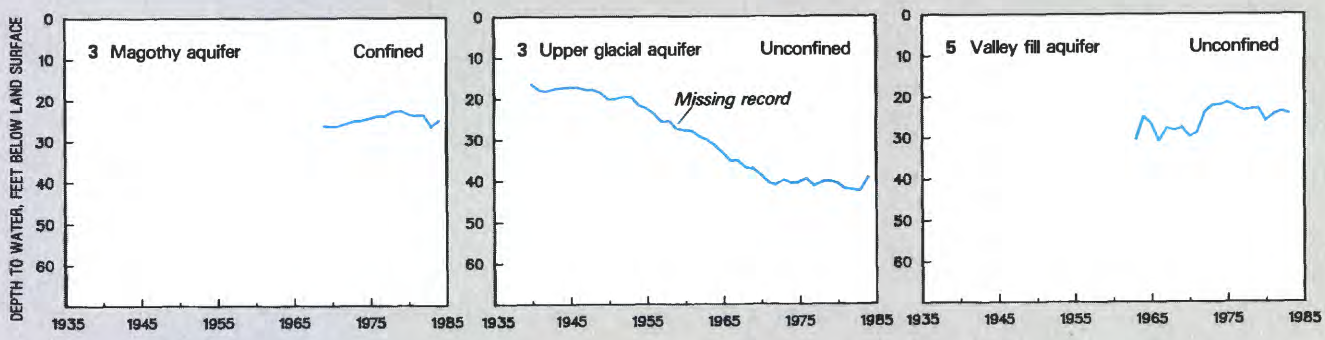
The two State agencies with responsibilities most directly related to ground-water management are the New York State Department of Health (DOH) and the New York State Department of Environmental Conservation (DEC).

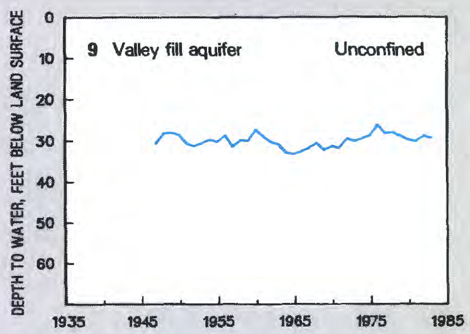
Under the Public Health Law and Part 5 of the State Sanitary Code, DOH ensures that public water-supply systems are operated properly and maintained to ensure a safe and adequate supply. The program involves regulation, periodic monitoring of water quality, inspection of systems, emergency response to problems of supply or quality, laboratory services, and establishment of drinking-water standards.

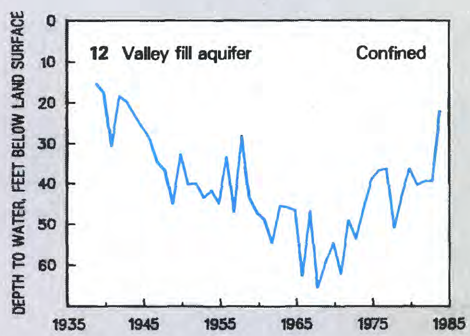
DEC is responsible for administering the State's environmental-quality and natural-resource programs, including those relating to the control of water pollution and management of water resources. Major elements of the DEC's water program that are integral to ground-water management include water-resources planning, ambient water-quality standards and classification of ground water, and water-discharge permits and programs that provide for the development, operation, and maintenance of municipal wastewater facilities. The DEC established a system of ground-water classifications and standards in 1967; the most recent revision was in 1978. Also, the New York State Pollutant Discharge Elimination System Program, which regulates point-source municipal, industrial, and commercial wastewater discharges, including those to the subsurface, is administered by the DEC. The State Public Water Supply Permit Program, administered by DEC, requires that new ground-water withdrawals for public supply be approved by both DEC and DOH. On Long Island, where groundwater quantity is a major issue, the DEC administers a well-permit program that has regulatory control of all major withdrawals.











WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
		Long Island	
1	Nassau	Upper glacial, Magothy, Lloyd.	Public supply.
2	Suffolk	. . . .do	Do.
3	Queens	. . . .do	Do.
4	Kings	Upper glacial.	Industrial.
		Upstate	
5	Schenectady . .	Valley fill	Public supply.
6	Steuben	. . . .do	Do.
7	Rockland. . . .	Valley fill, sandstone	Do.
8	Broome.	Valley fill	Do.
9	Chemung. . . .	. . . .do	Do.
10	Dutchess	Carbonate, valley fill	Rural domestic.
11	Orange	Shale, valley fill	Do.
12	Chautauqua . .	Valley fill	Public supply.
13	Cattaraugus . .	. . . .do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of greatest depth to water in selected wells in New York. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

The Long Island aquifer system has been designated as a "sole-source" aquifer by the U.S. Environmental Protection Agency. In addition to the DEC and DOH, several local agencies on Long Island implement major parts of the overall program to manage and protect the ground water. Local agencies with major regulatory responsibilities include the Nassau, Suffolk, and New York City Departments of Health. Other local agencies with important ground-water-related activities include the Long Island Regional Planning Board, the Suffolk County Water Authority, the Nassau County Department of Public Works, and the New York City Department of Environmental Protection.

Under Section 208 of the Clean Water Act, the DEC recently has prepared Ground-water Management Programs for both Long Island and Upstate New York. All of the previously mentioned local agencies were major participants in developing the program on Long Island.

In addition to the above agencies, two interstate river-basin commissions— the Delaware River Basin and the Susquehanna River Basin Commission—share limited ground-water management responsibility with the State.

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Prepared by Roger M. Waller, Edward J. Koszalka and Deborah S. Snavely

For further information contact District Chief, U.S. Geological Survey, P.O. Box 1669, Albany, NY 12201

NORTH CAROLINA
Ground-Water Resources

Ground water is a vital natural resource in North Carolina. Ground water supplies more than 3.2 million people,or about 55 percent of the State's total population. Its economic significance is substantial, particularly in the Coastal Plain province (fig. 1), where high-yielding aquifers supply most municipalities, industries, rural areas, and livestock. In the Piedmont and Blue Ridge provinces, ground water serves slightly more than one-half of the 4 million residents (Mann, 1978). Besides withdrawals for public supply, the largest ground-water withdrawals in the State are for mining and quarrying operations and process water for a number of textile and chemical industries. Withdrawals for irrigation represent a small, but increasing, percentage of total ground-water use, particularly in the Coastal Plain. Ground-water withdrawals for various uses and other related statistics are given in table 1.

GENERAL SETTING

North Carolina is located in three physiographic provinces—the Coastal Plain, Piedmont, and Blue Ridge (fig. 1). The Coastal Plain aquifers generally are unconsolidated and consist of beds of sand, gravel, and limestone separated by clay or clayey layers and lenses. These strata dip and thicken southeastward and together comprise a wedge lying on crystalline bedrock (fig. 1). The Piedmont and Blue Ridge provinces are, for the most part, underlain by massive crystalline and metamorphic rocks that are covered nearly everywhere by a clayey or sandy regolith consisting of weathered parent rock material and alluvium.

Recharge to the ground-water system in North Carolina is derived from precipitation that ranges from about 44 to 54 inches (in.) in the Piedmont and Coastal Plain provinces and from about 40 to 80 in. in the Blue Ridge province (Eder and others, 1983). The amount of precipitation that recharges the ground-water system averages about 20 percent of annual precipitation (Winner and Simmons, 1977; Daniel and Sharpless, 1983). Most ground-water recharge moves through shallow aquifers and discharges to streams; only a small part (less than 1 in. in the Coastal Plain) recharges deeper aquifers.

PRINCIPAL AQUIFERS

The principal aquifers in North Carolina are the surficial, the Yorktown, the Castle Hayne, and the Cretaceous located in the Coastal Plain and the crystalline rock aquifer located in the Piedmont and Blue Ridge provinces. These aquifers are described below and in table 2; their areal distribution is shown in figure 1.

SURFICIAL AQUIFER

The surficial aquifer is a near-surface deposit of either marine-terrace sand and clay, or sand dunes. It is a principal aquifer in three areas where it is commonly more than 50 feet (ft) thick—the Sand Hills in the southwestern Coastal Plain, the narrow coastal strip of barrier islands called the Outer Banks, and the eastern one-half of the mainland north of Pamlico Sound (fig. 1). In the Sand Hills, where the aquifer may be more than 250 ft thick, it serves as a source for public supplies and irrigation for numerous golf courses (North Carolina Department of Natural Resources and Community Development, 1979). Water from this aquifer in the Sand Hills area has dissolved-solids concentrations less than 25 milligrams per liter (mg/L) and hardness less than 10 mg/L as calcium carbonate; the pH commonly is below 6, making it corrosive. Sands that form the Outer Banks are the only source of freshwater along much of the northeastern coast. The freshwater in these sands often has a dissolved-solids concentration of 500 mg/L and hardness of about 200 mg/L as calcium carbonate. On the mainland north of Pamlico Sound, the surficial aquifer ranges from 50 to 200 ft thick and may yield as much as 1 million gallons per day (Mgal/d) to single wells or small well fields. Here, water from the aquifer usually has dissolved-solids concentrations of less than 200 mg/L and hardness of less than 100 mg/L as calcium carbonate; the pH, however, may be as low as 5, which renders the

Table 1. Ground-water facts for North Carolina

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	3,234
Percentage of total population	55
From public water-supply systems:	
Number (thousands)	474
Percentage of total population	8
From rural self-supplied systems:	
Number (thousands)	2,760
Percentage of total population	47
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	8,100
Ground water only (Mgal/d)	770
Percentage of total	10
Percentage of total excluding withdrawals for thermoelectric power	20
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	70
Percentage of total ground water	9
Percentage of total public supply	12
Per capita (gal/d)	148
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	140
Percentage of total ground water	18
Percentage of total rural domestic	100
Per capita (gal/d)	51
Livestock:	
Ground water (Mgal/d)	33
Percentage of total ground water	4
Percentage of total livestock	85
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	490
Percentage of total ground water	64
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	6
Excluding withdrawals for thermoelectric power	17
Irrigation withdrawals:	
Ground water (Mgal/d)	39
Percentage of total ground water	5
Percentage of total irrigation	30

Table 2. Aquifer and well characteristics in North Carolina

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U. S. Geological Survey and the North Carolina Department of Natural Resources and Community Development]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Surficial aquifer: Sand, silt, clay, and gravel. Generally unconfined or partially confined.	40 - 65	175	25 - 200	500	Important aquifer in Sand Hills, northeast North Carolina, and Outer Banks. Water only slightly mineralized, except at depth in coastal areas where it is salty. Iron problems common. Equivalent to Columbia aquifer in Virginia.
Yorktown aquifer: Sands and clay. Partially confined or confined.	50 - 150	190	15 - 90	500	Includes Yorktown Formation and minor sands in Pungo River Formation. Important aquifer in northern Coastal Plain. Water is salty in coastal areas. Iron problems common. Equivalent to Yorktown–Eastover aquifer in Virginia.
Castle Hayne aquifer: Limestone, sandy limestone, and sand. Generally confined.	70 - 200	400	200 - 500	2,000	Includes Belgrade and River Bend Formations, Castle Hayne Limestone and Beaufort Formation. Castle Hayne Limestone is major aquifer in eastern Coastal Plain. Iron and hydrogen sulfide are problems near aquifer's western limit. Water is salty at depth near coast.
Cretaceous aquifer: Sand, clayey sand, and clay. Confined.	100 - 600	800	200 - 400	1,400	Includes Peedee, Black Creek, and Cape Fear Formations. Most widely used aquifer in Coastal Plain. Water has low mineral content. Iron problems common. Water is salty at depth in eastern Coastal Plain. Equivalent to Potomac aquifer in Virginia and Black Creek and Middendorf aquifers in South Carolina.
Crystalline rock aquifer: Crystalline igneous, metasedimentary and metavolcanic rock. Semiconfined to confined.	75 - 200	300	5 - 35	200	Large well yields dependent on interception of fractures; sustained yields dependent on thickness of saturated regolith overlying fractured-rock aquifer. Dissolved solids average about 170 mg/L. Water slightly acidic and may be corrosive. Locally high in iron and silica.

water corrosive. The aquifer generally is unconfined to partially confined throughout most of the Coastal Plain, but where it is more than 50 ft thick, water usually is confined in the deeper parts due to differences in lithology.

Yorktown Aquifer

The Yorktown aquifer is present at shallow depths in the northern Coastal Plain. A few high-producing wells tap the Yorktown. Elizabeth City in Pasquotank County draws 1.3 Mgal/d from a well field that taps the aquifer. Water in the Yorktown aquifer generally has dissolved-solids concentrations of less than 500 mg/L and hardness of less than 300 mg/L as calcium carbonate.

Castle Hayne Aquifer

The Castle Hayne aquifer is the most productive aquifer in North Carolina. Wells that yield more than 1,000 gallons per minute (gal/min) can be readily developed in this aquifer and yields may exceed 2,000 gal/min. The Castle Hayne is the major source of freshwater in the southeastern coastal area where nearly all other aquifers contain some saltwater. Water from the Castle Hayne aquifer usually has a hardness ranging from 80 to 300 mg/L as calcium carbonate (Wilder and others, 1978) and requires treatment for some uses. It commonly contains concentrations of silica higher than 50 mg/L. The aquifer generally is confined, except near its western limit where it is unconfined or partially confined.

Cretaceous Aquifer

The Cretaceous aquifer is the principal aquifer in much of the central and southern Coastal Plain. The aquifer has only moderate hydraulic conductivity but is very thick. For this reason, a number of well fields in the Cretaceous aquifer are able to produce more than 1 Mgal/d. Water from the Cretaceous aquifer typically is soft with hardness commonly less than 20 mg/L as calcium carbonate. The water occasionally contains concentrations of fluoride higher than 1.5 mg/L, the maximum limit for public supplies in this area. The aquifer is confined throughout its areal extent.

Crystalline Rock Aquifer

The crystalline rock aquifers of the Piedmont and Blue Ridge provinces consist generally of fractured crystalline igneous and metamorphic rock that has low porosity and, therefore, little storage capacity. Well yields are sustained by water stored in the saturated regolith that overlies the frac-

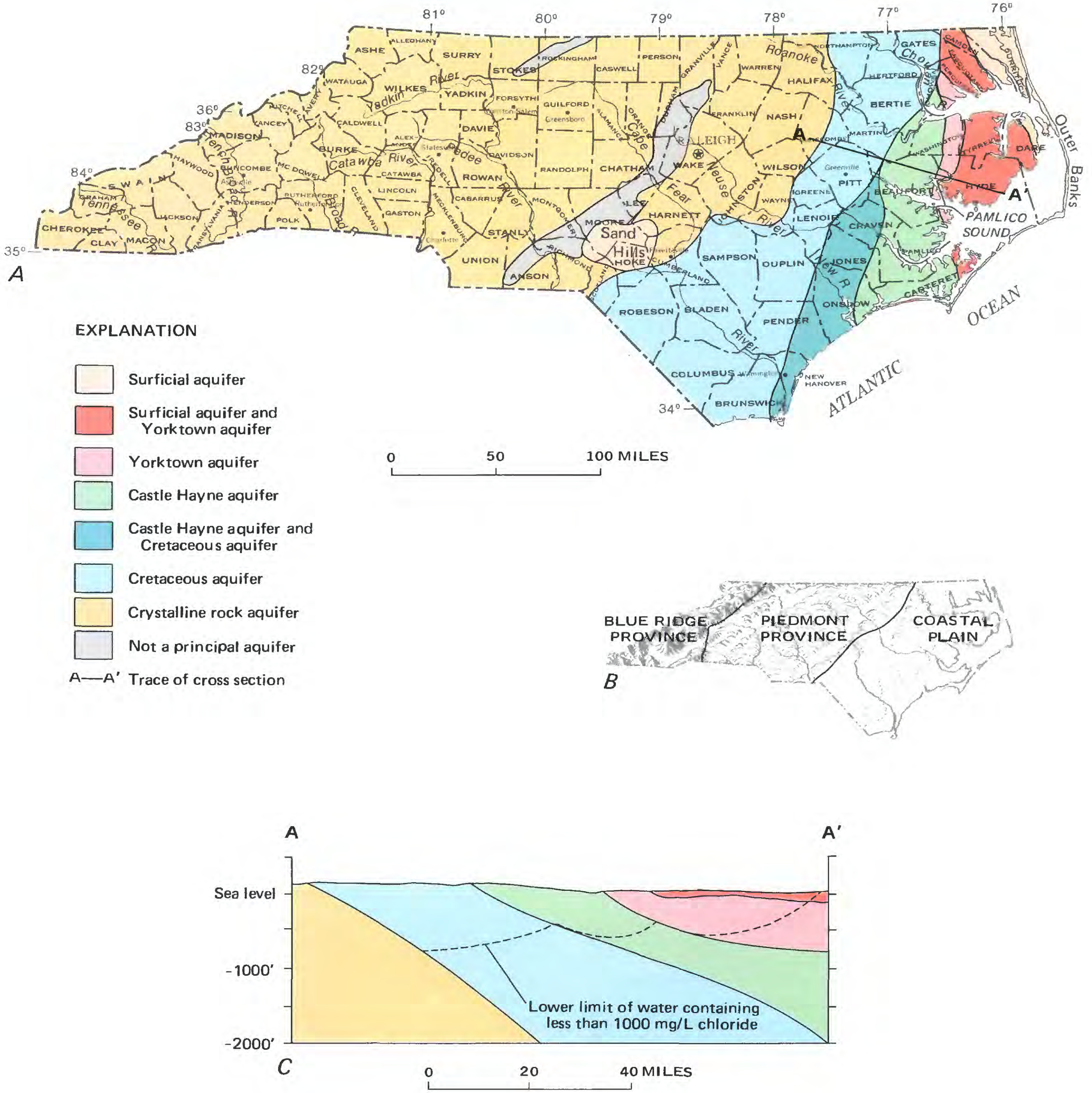


Figure 1. Principal aquifers of North Carolina. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'), Coastal Plain. (See table 2 for more detailed description of aquifers. Sources: *A*, *C*, compiled by R. W. Coble from U.S. Geological Survey and North Carolina Department of Natural Resources and Community Development files. *B*, Fenneman, 1938; Raisz, 1954.)

tured bedrock. Success in constructing high-yield wells in this terrane depends on interception of water-bearing fracture systems that are overlain by saturated regolith. The chance of intercepting interconnected fractures is greatest in valleys and draws and least on ridges and hilltops. The average yield of wells in the crystalline rock is low—about 10 to 25 gal/min; however, yields of 200 gal/min or more are common. Water from the crystalline rock has a dissolved-solids concentration that is commonly about 170 mg/L and rarely exceeds 250 mg/L. Hardness generally is less than 100 mg/L as calcium carbonate. Because of the low buffering capacity of the water, corrosion can be a problem where the dissolved-solids concentration is less than 100 mg/L, even though pH values range from 6.3 to 6.7.

OTHER AQUIFERS

Triassic basins within the crystalline rock terrane of the Piedmont are areas from which the principal aquifers are absent (fig. 1); these basins consist of downfaulted blocks of crystalline rock. The basins are filled with clay, silt, fine-grained sandstone, and conglomerate, into which, in some places, basalt dikes have intruded. In this terrane, chances of constructing wells that yield more than a few gallons per minute are slight.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals and water levels for selected observation wells near pumping centers are shown in figure 2. Generally, water levels decline in response to increases in pumping and recover when pumping is reduced. The hydrographs in figure 2 are representative of response of water levels to pumping in the Coastal Plain.

Water-level declines are not widespread in the surficial aquifer. Pumping 1 Mgal/d from a battery of shallow wells near Elizabeth City (near location 1, fig. 2) resulted in no measurable decline in water level in an observation well only 0.5 mile (mi) from the well field.

Only minor withdrawals are made from the Yorktown aquifer, which is readily recharged; thus, major areal water-level declines have not occurred in this aquifer. In the Belhaven area, withdrawals of 1.2 Mgal/d have resulted in less than 10 ft of decline in 16 years as shown by the hydrograph (location 5, fig. 2).

The largest ground-water withdrawals in North Carolina are from the Castle Hayne aquifer to dewater one mine and three quarries. About 65 Mgal/d are withdrawn from the confined Castle Hayne aquifer to reduce the artesian pressure, thereby facilitating dewatering of the overlying phosphate ore beds. Water levels in the Castle Hayne have declined 5 ft or more over an area of 1,300 square miles in response to this pumping (North Carolina Groundwater Section, 1974). The hydrograph for the Castle Hayne observation well, which is adjacent to the mining area (location 6, fig. 2), shows the rapid decline in water level when pumping began in 1965; stabilization of the water level was achieved in 1966 when the amount of induced leakage into the aquifer and a reduction in the amount of natural discharge from the aquifer compensated for the amounts of withdrawal. Changes in water level since the late 1960's are the result of fluctuating pumping rates and movement of the center of pumping as different parts of the ore body are mined. Other withdrawals from the Castle Hayne aquifer range from 11 to 18 Mgal/d at three quarries (locations 8, 11, 16, fig. 2). Because the Castle Hayne generally is unconfined in the area of the quarries, the geographic extent of the cones of depression is limited.

Widespread withdrawals from the Cretaceous aquifer have resulted in continuing declines in water levels in this aquifer throughout much of the Coastal Plain. The Cretaceous aquifer observation well (location 7, fig. 2) reveals that, after a well field was established near the observation well in 1968, water levels have declined more than 80 ft. Periods of water-level recovery and apparent stability are the result of short periods of decreased withdrawal rates. Water levels in the Cretaceous aquifer in the northern Coastal Plain have declined over an area of several thousand square miles in North Carolina because of withdrawals of 35 Mgal/d or more near Franklin, Va., 10 mi north of the State line. Declines near the line (location 26, fig. 2) have been as much as 45 ft since 1966 and are estimated to be as much as 100 ft since the early 1940's when extensive withdrawals began.

Water-level declines because of withdrawals from the crystalline rock aquifer are not widespread. Water pumped from the aquifer is supplied from the saturated portion of the overlying regolith. Recent research shows that withdrawals from the crystalline rock aquifer are reflected in local cones of depression in the overlying regolith (Daniel and Sharpless, 1983).

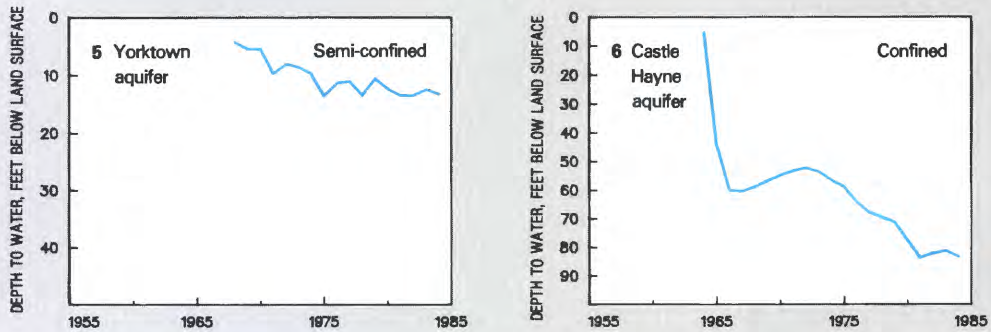
GROUND-WATER MANAGEMENT

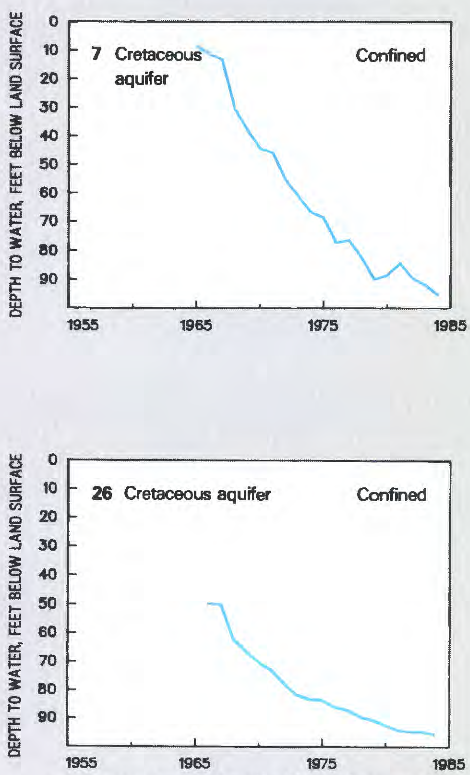
The North Carolina Department of Natural Resources and Community Development (NRCD) implements most of the regulatory and planning procedures related to ground-water resources in the State. The Division of Environmental Management (DEM) within NRCD, has the major responsibility for ground-water management and regulatory programs. The Environmental Management Commission has authority over the permitting process and has made the Groundwater Section of DEM directly responsible for issuing permits for well construction and ground-water withdrawals. The Commission may designate an area as a Capacity-Use Area whenever the renewal and replenishment of the ground-water supplies are believed to be threatened. To date, the Commission has established only one such area in east-central North Carolina. However, additional areas are being considered for Capacity-Use Area designation.

A permit must be obtained from the Groundwater Section of DEM for (l) the construction of public-supply, industrial, and irrigation wells, (2) wells with a designed capacity of 100,000 gallons per day (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 Well Construction Act of 1967, Article 7-87-88). Injection wells for waste-disposal purposes currently are prohibited by State statute. All well drillers must register annually with NRCD and are required to report all well completion and abandonments.

In addition to a water-use permit in Capacity-Use Areas for users withdrawing more than 100,000 gal/d, NRCD also may require these users to adhere to established maximum withdrawal rates; the agency also can establish the minimum water levels resulting from pumping in certain areas.

The NRCD Division of Water Resources (DWR) collects data on the use of ground water statewide through its water-use data program. The DWR includes ground water in special regional or river basin water-resources studies with primary emphasis on the availability of ground water to meet water-supply needs for municipal and industrial use and for agricultural irrigation. The DWR also provides technical assistance to local goverment water utilities in considering ground water as a source of supply for public-water systems. Technical information on ground water is also available through the





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Elizabeth City area . . .	Yorktown	Public supply.
2	Hobgood area	Cretaceous	Industrial.
3	Robersonville-Williamston area.	. . . .do.	Public supply.
4	Greenville-Farmville area.	. . . .do	Do.
5	Belhaven area	Yorktown	Public supply, industrial.
6	Aurora area	Castle Hayne. . . .	Mining.
7	Kinston-Graingers-Cove City area.	Cretaceous.	Public supply, industrial.
8	New Bern area.	Castle Hayne. . . .	Quarrying.
9	Seymour Johnson AFB.	Cretaceous.	Other.
10	Havelock-Cherry Point area.	Castle Hayne. . . .	Public supply and other.
11	Belgrade area	. . . .do	Quarrying.
12	Camp Lejeune.	. . . .do	Other.
13	Jacksonville area	Cretaceous.	Public supply.
14	Rose Hill-Wallace area.	. . . .do	Public supply, industrial.
15	Clinton area	. . . .do	Public supply.
16	Castle Hayne area	Castle Hayne. . . .	Quarrying.
17	Wilmington area.	. . . .do	Industrial.
18	New Hanover-Brunswick beaches.	. . . .do	Public supply.
19	Raeford area.	Cretaceous.	Do.
20	Sand Hills area.	Surficial	Public supply, irrigation.
21	Laurinburg area	Cretaceous.	Public supply.
22	Lumberton area.	. . . .do	Industrial.
23	Elizabethtown area . . .	. . . .do	Public supply, industrial.
24	Whiteville area.	. . . .do	Do.
25	Marion area	Crystalline rock . .	Industrial.

Figure 2. Areal distribution of ground-water withdrawals and graphs of annual greatest depth to water in selected wells in North Carolina. (Sources: Withdrawal and water- level data from U.S Geological Survey and North Carolina Department of Natural Resources and Community Development files.)

seven regional offices of the DEM.

The Department of Human resources (DHR), through its Division of Health Services, has responsibility for monitoring solid and hazardous waste disposal sites to prevent contamination of ground-water supplies. The DHR oversees the human-health aspects of public water-supply systems, including review of plans and specifications for water treatment and distribution facilities, approval of sources of raw water, establishment of drinking-water standards, and requirements for monitoring the quality of drinking water delivered by public systems.

Individual and cooperative ground-water research, data collection, and project investigations are conducted individually and cooperatively among the NRCD, the DHR, and the U.S. Geological Survey.

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Prepared by Ronald W. Coble, Gerald L. Giese, and Jo L. Eimers

For further information contact District Chief, U.S. Geological Survey, 300 Fayetteville Street Mall, Raleigh, NC 27602

NORTH DAKOTA
Ground-Water Resources

Ground water is one of North Dakota's most valuable resources. Sixty-two percent of the 653,000 people living in the State rely on ground water for domestic supply. It is the only source of water for thousands of farm families and their livestock. Almost all smaller cities and villages depend solely on ground water as a source of supply. Increasingly, ground water is being used to irrigate crops and grasslands during protracted dry spells common to North Dakota. During recent years, the number of rural water-distribution systems in which thousands of farms and rural residences are connected by underground pipeline to a single water source (usually a grouping of wells that pump ground water) has been increasing rapidly. Ground-water withdrawals during 1982 for various uses are given in table 1.

GENERAL SETTING

North Dakota is divided into the Great Plains physiographic province in the west and the Central Lowland physiographic province in the east (fig. 1). The eastern part of the Great Plains and the Central Lowland provinces are covered with unconsolidated glaciofluvial and glaciolacustrine deposits and glacial tills of Quaternary age. These deposits are more productive and generally yield less mineralized water than that of the underlying sedimentary rocks. In contrast, the aquifers in the sedimentary rocks tend to be more areally continuous and widespread than the unconsolidated rocks. Ground water occurs in sedimentary rock aquifers of Precambrian and Paleozoic age; in the Dakota (Great Plains), Pierre, Hell Creek–Fox Hills aquifers of Cretaceous age; and in the Fort Union aquifers of Tertiary age.

All the sedimentary rocks of Paleozoic, Cretaceous, and Tertiary age in North Dakota were deposited in the extensive Williston structural basin. The central and deepest part of this basin is in McKenzie County in the westernmost part of the State, where the total thickness of the sediments exceeds 15,000 feet (ft). These sediments gradually thin in an eastward direction and are missing in the southeastern part of the State where Precambrian rocks directly underlie the glacial-drift deposits.

Precambrian granitic rocks underlie all of North Dakota and generally are not considered to be an aquifer. However, in the eastern part of the State, small local supplies of water can be obtained from the fractures. Water also is obtained from the Paleozoic aquifer in the eastern part of the State where Paleozoic rocks directly underlie the glacial drift.

Precipitation in North Dakota varies from 13 inches (in.) in the west to more than 20 in. in the east. Much of this precipitation does not recharge ground water because potential evaporation ranges from more than 40 in. in the southwest to 31 in. in the northeast (U.S. Department of Commerce, 1982). In west-central North Dakota, 6 to 29 percent of the precipitation recharges the water table; of that amount, 10 to 50 percent occurs during snowmelt (Rehm and others, 1982). Recharge estimates are not available for other areas of the State.

Table 1. Ground-water facts for North Dakota

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Patch and Haffield, 1982; J. C. Patch, North Dakota State Water Commission, written commun., 1984]

Population served by ground water, 1982	
Number (thousands)	406
Percentage of total population	62
From public water-supply systems:	
Number (thousands)	258
Percentage of total population	39
From rural self-supplied systems:	
Number (thousands)	148
Percentage of total population	23
Freshwater withdrawals, 1982	
Surface water and ground water, total (Mgal/d)	1,000
Ground water only (Mgal/d)	110
Percentage of total	11
Percentage of total excluding withdrawals for thermoelectric power	11
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	31
Percentage of total ground water	29
Percentage of total public supply	54
Per capita (gal/d)	120
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	17
Percentage of total ground water	16
Percentage of total rural domestic	100
Per capita (gal/d)	115
Livestock:	
Ground water (Mgal/d)	7
Percentage of total ground water	7
Percentage of total livestock	40
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	2
Percentage of total ground water	2
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	0.3
Excluding withdrawals for thermoelectric power	25
Irrigation withdrawals:	
Ground water (Mgal/d)	50
Percentage of total ground water	46
Percentage of total irrigation	37

PRINCIPAL AQUIFERS

Principal aquifers in North Dakota consist of two types—unconsolidated (glaciofluvial and glaciolacustrine) deposits and sedimentary bedrock. The aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

UNCONSOLIDATED AQUIFERS

Unconsolidated deposits contain the most productive aquifers in North Dakota. The aquifers consist of highly

Table 2. Aquifer and well characteristics in North Dakota

[Gal/min = gallons per minute; ft = feet; mg/L = milligrams per liter; Sources: geologic and hydrologic reports of the U.S. Geological Survey and the North Dakota State Water Commission]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Unconsolidated aquifers:				
Englevale: Sand, gravel, silt, and silty clay. Confined and unconfined.	0 – 80	1 – 1,000	1,500	Water hard to very hard. Large concentrations of iron (mean concentration of 1.9 mg/L) and manganese (mean concentration of 0.4 mg/L). Suitable for irrigation.
Oakes: Sand, gravel, silt, and silty clay. Confined and unconfined.	0 – 100	1 – 500	700	Water moderately hard to very hard. Locally large concentrations of iron (0.1–10 mg/L). Suitable for irrigation.
Page: Sand and gravel. Confined and unconfined.	10 – 180	1 – 300	500	Water very hard. Locally large concentrations of iron (0.01–0.4 mg/L). Suitable for irrigation.
Spiritwood: Sand and gravel interbedded with silt and clay. Confined and unconfined.	0 – 300	1 – 1,000	1,500	Water mostly hard. Locally large concentrations of iron (0.4–9.1 mg/L). Suitable for irrigation.
Sundre: Sand and gravel. Confined and unconfined.	50 – 300	1 – 500	1,000	Water mostly hard. Generally large concentrations of iron (generally greater than 2 mg/L). Suitable for public supply or irrigation.
West Fargo: Sand, gravel boulders, and clay lenses. Confined.	100 – 250	10 – 1,000	1,300	Water hard to very hard. Suitable for public supply and selected industry.
Consolidated aquifers:				
Fort Union aquifer system: Sandstone, siltstone, claystone, and lignite.	0 – 900	1 – 100	150	Water generally soft. Sodium sulfate bicarbonate water. Locally large concentrations of sulfate (50–9,600 mg/L) and iron (0.01–42 mg/L). Generally not suitable for irrigation.
Hell Creek–Fox Hills aquifer system: Sandstone, siltstone, claystone, and shale.	0 – 2,000	1 – 150	300	Water soft. Sodium bicarbonate sulfate water. Generally not suitable for irrigation.
Great Plains aquifer system: Sandstone, siltstone, and shale.	500 – 5,500	10 – 60	1,000	Water salinity (mean dissolved-solids concentration 7,300 mg/L) limits use to oil recovery in western part of State and stock watering in eastern part of State.
Madison Group aquifer: Limestone, some sandstone and shale.	200 – 6,000	–	–	Highly saline (mean dissolved-solids concentration 19,000 mg/L). Undeveloped in State.

permeable glaciofluvial sand and gravel deposits and glaciolacustrine deposits. Some of these deposits are tens of square miles in area and are as much as 100 ft thick. Commonly, aquifers are linear in shape with tributary branches and have some resemblance to surface-drainage systems (fig. 1). Several of the most productive of the unconsolidated aquifers—the Englevale, Oakes, Page, Spiritwood, Sundre, and West Fargo—are described in table 2.

Test drilling and other geohydrologic data indicate that well yields range from 1 to as much as 500 gallons per minute (gal/min). In some parts of the aquifers, usually where they are thickest, yields of more than 500 gal/min can be obtained. In many areas in which areally extensive, thick unconsolidated deposits are lacking, water can be obtained from thin isolated beds of sand and gravel, but amounts are generally 10 gal/min or less. Nevertheless, these small aquifers are present in sufficient numbers to yield adequate amounts of water for domestic needs of most farmsteads.

Sedimentary Bedrock Aquifers

Fort Union Aquifer System

The uppermost bedrock aquifer system includes sandstone and lignite beds that are present mainly in the Fort Union Formation in the western one-half of the State. In general, these aquifers are variable in horizontal extent and thickness. Consequently, the aquifers in the Fort Union Formation are less reliable sources for development than are the deeper aquifers. Water in the Fort Union Formation, although commonly somewhat mineralized (table 2), is used by farms, ranches, and small communities for most purposes except for irrigation.

Hell Creek–Fox Hills Aquifer System

The Hell Creek–Fox Hills aquifer system, underlying the Fort Union, is within an extensive sandstone that underlies all

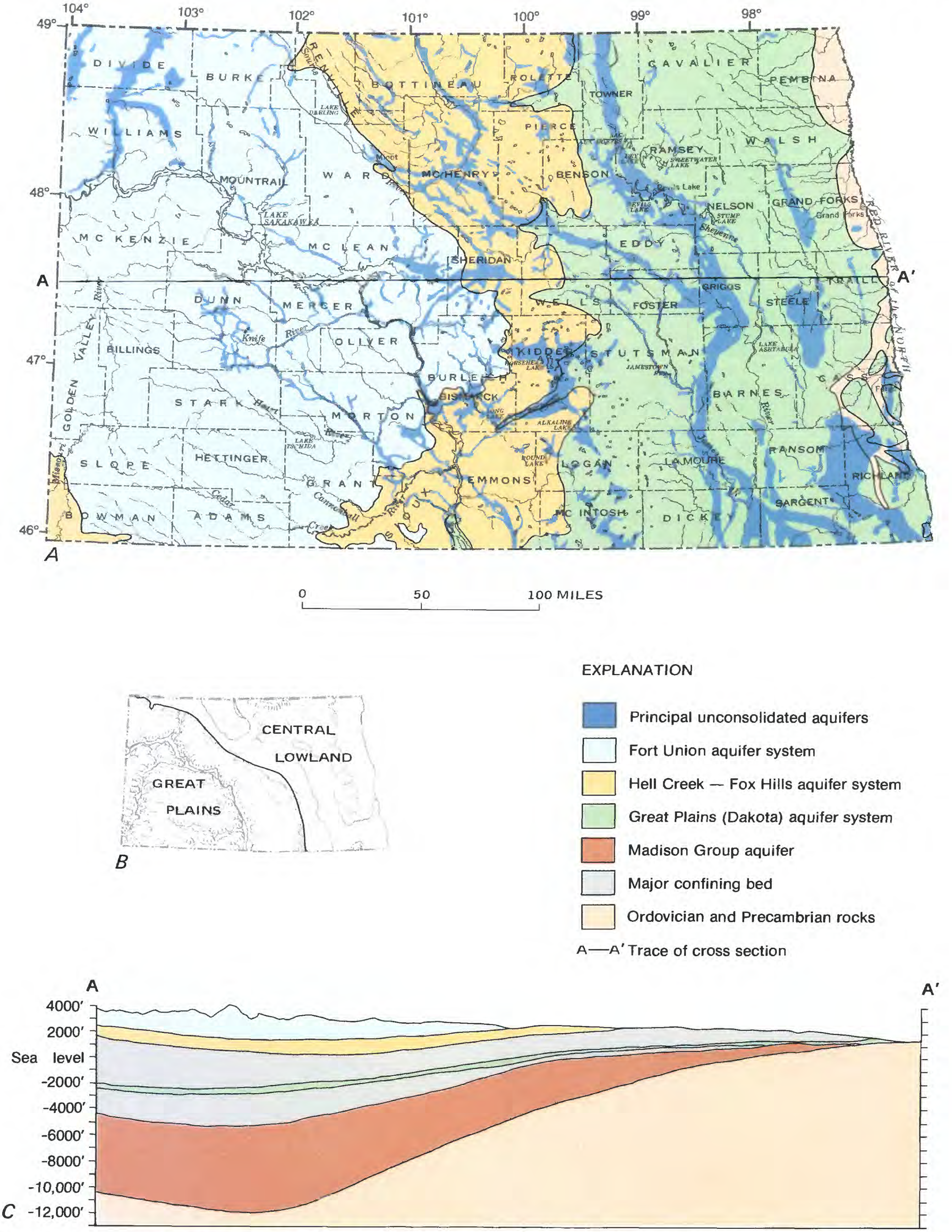


Figure 1. Principal aquifers in North Dakota. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A′) showing bedrock aquifers. (See table 2 for a more detailed description of the aquifers. Sources: *A*, North Dakota State Water Commission, 1982. *B*, Fenneman, 1946; Raisz, 1954. *C*, Paulson, 1983.)

but the eastern one-third of the State. The sandstone beds are mainly within the Fox Hills Sandstone, but they also form part of the lower part of the overlying Hell Creek Formation. Less-continuous sandstones and siltstones constitute the remaining aquifers in the system. In most places, water in the Hell Creek-Fox Hills aquifer system is under artesian pressure, but the pressure is not sufficient to produce flowing wells except in low-lying areas such as major river valleys. This aquifer system is a relatively dependable source of water because of its wide extent and uniform character. It supplies water to many farms and ranches and to several small cities in central and western North Dakota.

Great Plains Aquifer System

The Great Plains aquifer system, which underlies most of the State, consists of several sandstone layers that usually are referred to as the Dakota Sandstone aquifer, or simply the Dakota aquifer. Most of the wells completed in the Great Plains aquifer system are in the southeastern part of the State.

The water of the Great Plains aquifer system generally is unsuitable for many uses because of salinity. However, in many areas, it is the only readily available source. Water from the aquifer is valued particularly for watering livestock during the winter because of the relatively warm temperature of the water. In western North Dakota, the aquifer is used both as a source and a sink in connection with oil-field operations; water is pumped from the aquifer for use in repressurizing depleted oil reservoirs, and waste brine from the reservoirs is reinjected into the aquifer.

Madison Group Aquifer

The Great Plains aquifer system is separated from the underlying Madison Group aquifer by thick deposits of shale and other fine-grained rocks of Jurassic and Triassic age, which yield virtually no water to wells. The Madison Group aquifer underlies the entire State except for a small area near the North Dakota–Minnesota boundary. The aquifer, which consists mostly of limestone, but also includes some sandstone and shale, contains the oldest (Paleozoic) sedimentary rocks in North Dakota. The top of this aquifer is only a few hundred feet below land surface near the eastern edge of the State, from there it dips westward to depths of about 6,000 ft. Very little is known about the water-yielding properties of the rocks in this aquifer. In most parts of North Dakota, aquifer depths preclude well drilling. In addition, data from oil wells completed in this aquifer indicate that the water is saline and not usable for most purposes.

Other Aquifers

Between the Hell Creek–Fox Hills aquifer system and the Great Plains (Dakota) aquifer system there is a layer of undifferentiated rocks that consist mainly of shale and other fine-grained materials. In most of the State, these rocks yield virtually no water to wells. However, in the eastern one-third of the State, where the Hell Creek–Fox Hills aquifer system is missing, these rocks may be suitable for the development of small supplies because the upper part of the shale is fractured locally.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

During 1982, an average of about 107 million gallons per day (Mgal/d) of ground water was withdrawn from aquifers in North Dakota (Patch and Haffield, 1982). This is about the same as was withdrawn in 1975, but is a decrease of about 12 percent from a high in 1980 (Solley and others, 1983). Because most of these withdrawals are for supplementary irrigation, they vary with amount and timing of precipitation.

The quantities withdrawn for each purpose in 1982 are shown in table 1. The largest withdrawals are for irrigation, followed by public supply and rural domestic. Irrigation alone accounts for nearly 50 percent of the ground-water withdrawals in North Dakota.

Irrigation of crops with ground water has increased steadily in North Dakota since about 1960 when probably fewer than six irrigation wells existed in the State. During 1982, nearly 1,500 wells pumped a total of 50 Mgal/d during the irrigation season (Patch and Haffield, 1982). Almost 100,000 acres were irrigated with ground water in North Dakota during 1982.

As an aid in determining the hydrologic budget, a statewide network of observation wells was established in the 1930's and has been maintained by the U.S. Geological Survey and the North Dakota State Water Commission. Hydrographs for selected wells in the State, one of the products of this network, are illustrated in figure 2.

The hydrograph for location 4 (fig. 2), is the record of an observation well developed in the Spiritwood aquifer. The Spiritwood is a major unconsolidated rock aquifer system that extends northward across the State. The system is comprised of glaciofluvial and glaciolacustrine materials. Confined conditions predominate, although unconfined conditions occur locally. The aquifer crops out in some areas and is more than 300 ft below land surface in others.

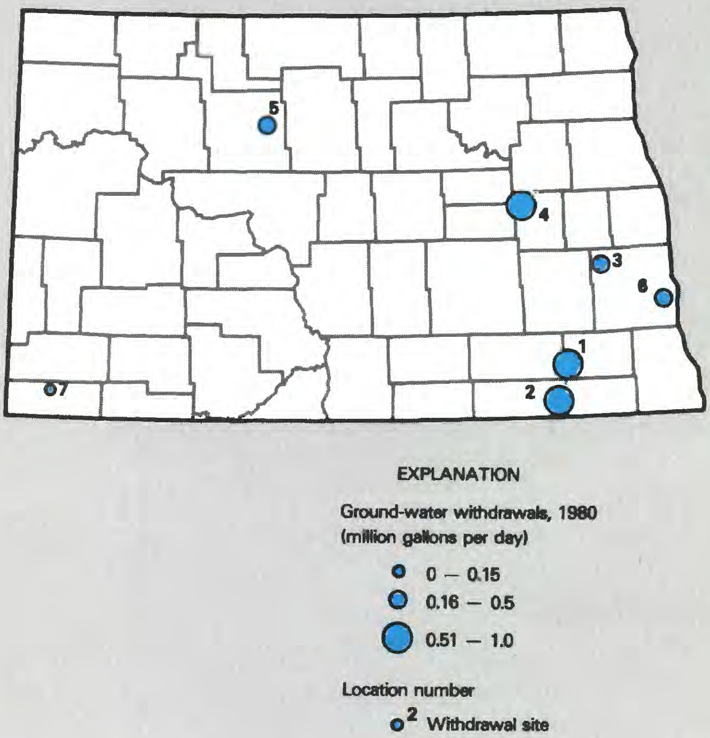
The record of an observation well near several water-supply wells for the city of Minot is shown on the hydrograph for location 5 (fig. 2). The water level in the well has declined moderately since pumping started in the late 1970's. The aquifer is confined at this point, is in a buried river channel, and is about 170 ft below land surface. Little water was pumped from the aquifer in the early 1970's.

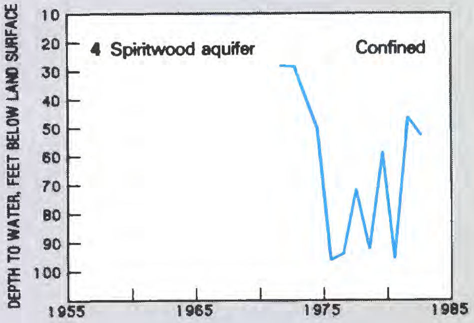
The hydrograph for location 6 (fig. 2), which is from a well completed in a buried glaciofluvial aquifer (West Fargo aquifer) developed for public and industrial supplies, shows a decline representative of trends in the aquifer. Depth to the top of the aquifer at this well site is about 120 ft. Pumping from the aquifer began in the latter part of the 19th century. In some areas, water levels in wells, which were near or above land surface at the city of West Fargo in 1896, declined to as much as 122 ft below land surface in 1981.

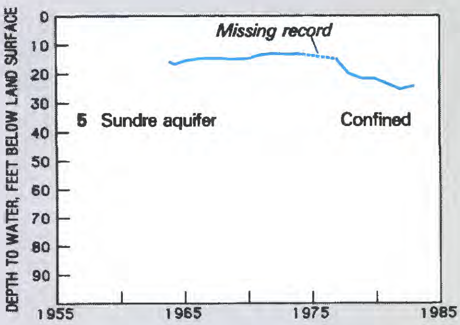
The record of an observation well developed in the Hell Creek–Fox Hills aquifer system is shown on the hydrograph for location 7 (fig. 2). The decline in water levels is indicative of the cone of depression that has developed around the city of Bowman as a result of pumping for the municipality. The top of the aquifer is about 950 ft below land surface at the observation well.

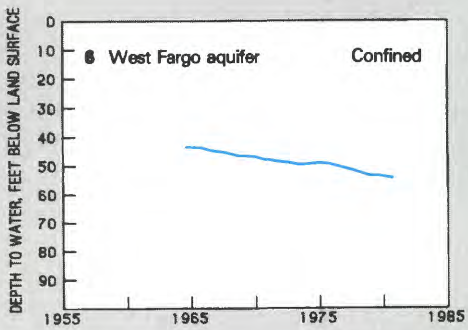
GROUND-WATER MANAGEMENT

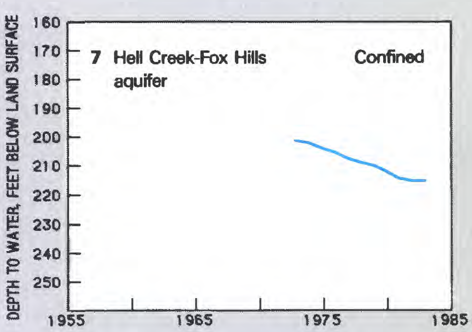
North Dakota's water laws are based on the doctrine of prior appropriation (North Dakota State Water Commission, 1977). The doctrine of prior appropriation does not recognize water ownership or the right to use the water as being inherent with ownership of the land. Rather, the right to use the water is based on the concept of first in time, first in right and has the added qualification that the use be beneficial. The State Constitution, section 210, states, "All flowing streams and natural water courses shall forever remain the property of the











WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Englevale area	Englevale.	Irrigation.
2	Oakes area	Oakes.	Do.
3	Page area.	Page.	Do.
4	East-central North Dakota.	Spiritwood.	Do.
5	Minot area	Sundre	Public supply.
6	West Fargo area	West Fargo.	Public supply, industrial.
7	Southwestern North Dakota.	Hell Craek-Fox Hills.	Public supply, rural.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in North Dakota. (Sources: Withdrawal data from Patch and Haffield, 1982; water-level data from U.S. Geological Survey files.)

State for mining, irrigating, and manufacturing purposes." More specifically, in regard to ground water, chapter 61-01-01, item 2, of the North Dakota Century Code states, "Waters under the surface of the earth whether such waters flow in defined subterranean channels or are diffused percolating underground waters * * * belong to the public and are subject to appropriation for beneficial use and the right to the use of these waters for such use, shall be acquired pursuant to the provisions of chapter 61-04." That chapter deals with the appropriation of water and describes the procedures for acquiring water-use permits.

At the present time, water-use permits are required only for public supply and for irrigation and industrial purposes. Permits are not required for domestic, livestock, or fish and wildlife purposes unless the annual appropriation exceeds 12.5 acre-feet. Necessary permits are issued by the State Engineer.

North Dakota has a continuing program designed to insure the safe and orderly development of the State's ground-water resources. During the past 25 years, ground-water resources have been identified and described on a county-by-county basis as part of a cooperative program involving each county of the State, the North Dakota State Water Commission, the North Dakota Geological Survey, and the U.S. Geological Survey. In some counties with large areas of federally owned lands, other Federal agencies such as the U.S. Forest Service and U.S. Bureau of Land Management also have been involved. Digital models of some of the larger and more intensively developed aquifers in the State have been developed by the North Dakota State Water Commission and the U.S. Geological Survey.

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Prepared by Orlo A. Crosby

For further information contact District Chief, U.S. Geological Survey, 821 East Interstate Avenue, Bismarck, ND 58501

OHIO
Ground-Water Resources

Ground water serves the needs of 42 percent of Ohio's population. An estimated 740 million gallons per day (Mgal/d) of ground water is withdrawn for domestic, industrial, and agricultural purposes (Eberle and McClure, 1984). Many people in Ohio depend on ground water as the only practical source of supply. Water-quality characteristics differ according to aquifer type. Although water-quality problems related to human activities exist in Ohio, they tend to be localized. Water levels in areas of large withdrawal are stable and even have risen in some places in response to lessened industrial demand. In some suburban areas, declining water levels are resulting from continued population growth. Ground water withdrawals for various uses in 1980 and related statistics are given in table 1.

GENERAL SETTING

Ohio includes parts of three physiographic provinces (Fenneman, 1938)—the Central Lowland province to the west, the Appalachian Plateaus province to the east, and the Interior Low Plateaus province in a small part of southern Ohio (fig. 1).

Virtually all recharge to Ohio's aquifers is from precipitation. A water budget based on a long-term annual precipitation average of 39 inches (in.) shows that about 6 in. eventually reaches the ground-water system (Norris, 1969, p. 26). Of this 6 in., about 4 in. is returned to the atmosphere through evapotranspiration, and 2 in. contributes to ground-water flow, which ultimately discharges to springs, lakes, and streams. Annually, the 740 Mgal/d of water pumped from Ohio aquifers (table 1) is equivalent to about 0.4 in. of rainfall. Recharge ranges widely throughout the State because of differences in physiography and the lithologic character of the soil and underlying bedrock.

Much of the Central Lowland of Ohio is underlain by carbonate rock of Devonian and Silurian age. In southwestern Ohio, preglacial erosion of the Cincinnati Arch has exposed Ordovician shale and limestone (Norris and Fidler, 1973). The Appalachian Plateaus region is underlain by an eastward-thickening succession of shale, sandstone, and coal-bearing strata that range from Mississippian to Permian in age. Bedrock, which is nearly flat lying in western Ohio, dips toward the southeast in eastern Ohio (fig. 1).

Several glacial advances, which covered nearly all of the carbonate rock area of Ohio and part of the Appalachian Plateaus (fig. 1), profoundly altered the preglacial drainage system (Stout and others, 1943). Within the glaciated part of the Appalachian Plateaus, the preglacial upland surface was similar to the more rugged, thoroughly dissected terrain typical of the present unglaciated part of southeastern Ohio. The western one-half of Ohio was once a region of weathered carbonate rock which had a well-developed drainage system that was disrupted completely after glaciation began. Glacial deposits that range from coarse-grained outwash to fine-grained lacustrine sediments fill and bury many preglacial valleys. Till overlies much of the glaciated region. Considerable ground-water resource development has focused on the coarse unconsolidated deposits (Bernhagen, 1947).

Table 1. Ground-water facts for Ohio

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Eberle and McClure, 1984; and Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	4,529
Percentage of total population	42
From public water-supply systems:	
Number (thousands)	2,719
Percentage of total population	25
From rural self-supplied systems:	
Number (thousands)	1,810
Percentage of total population	17
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	13,000
Ground water only (Mgal/d)	740
Percentage of total	6
Percentage of total excluding withdrawals for thermoelectric power	32
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	390
Percentage of total ground water	52
Percentage of total public supply	27
Per capita (gal/d)	143
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	91
Percentage of total ground water	12
Percentage of total rural domestic	90
Per capita (gal/d)	50
Livestock:	
Ground water (Mgal/d)	24
Percentage of total ground water	3
Percentage of total livestock	60
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	240
Percentage of total ground water	32
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2.0
Excluding withdrawals for thermoelectric power	15.7
Irrigation withdrawals:	
Ground water (Mgal/d)	1.9
Percentage of total ground water	0.3
Percentage of total irrigation	36

PRINCIPAL AQUIFERS

Two principal types of aquifers underlie Ohio—unconsolidated (glaciofluvial and alluvial) deposits and sedimentary bedrock. The characteristics of the aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

UNCONSOLIDATED AQUIFERS

The unconsolidated aquifers are composed of either coarse- or fine-grained sediments (fig. 1). Both types are composed mainly of materials of glacial origin. The coarse-grained unconsolidated aquifers generally consist of highly permeable sand and gravel; much of the sand and gravel is

Table 2. Aquifer and well characteristics in Ohio

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey and Ohio Department of Natural Resources]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Unconsolidated aquifers:					
Coarse-grained aquifers: Sand and gravel, generally coarse, with admixtures of clay and silt. Generally unconfined.	25 – 200	300	100 – 500	2,000	Watercourse deposits comprising State's most productive aquifers. Glacial outwash and alluvium also found in terrace and kame deposits in upland areas, in buried valleys, and within till layers having favorable recharge characteristics. Large iron content common.
Fine-grained aquifers: Sand, generally fine, with clay, silt, and gravel. May be locally confined by clay or till.	25 – 200	300	25 – 50	100	Valley fill of abandoned stream valleys; thick to thin lenses within till layers. Permeability often reduced by high clay and silt content. Deposits in many places lack hydraulic connection with recharging streams. Large iron content common.
Sedimentary bedrock aquifers:					
Shaly sandstone and carbonate aquifers: Fine- to medium-grained sandstone interbedded with shale, coal, clay, siltstone, and thin limestone. Confined and unconfined.	25 – 100	300	1 – 5	25	Strata of Mississippian, Pennsylvanian, and Permian age. Permeable, saturated rocks lack continuity. Recharge limited in upland areas; vertical permeability low. Water in some places soft. Iron and chloride content may be large locally. Despite meager yields, section important source of domestic supply for much of southeastern Ohio.
Sandstone aquifers: Massive to thin-bedded units of fine-grained to conglomeratic sandstone, mostly quartz cemented by calcite, silica, iron, and clay. Confined and unconfined.	25 – 300	400	5 – 25	250	Mississippian rocks of regional extent, such as Berea and Black Hand Sandstones and less extensive Pennsylvanian rocks in Pottsville and Allegheny Formations. Pennsylvanian rocks generally are open textured and, where situated favorably with respect to recharge, are important sources of domestic and small public supplies. Water quality generally good, but saline downdip and generally below 300 ft.
Shale aquifers: Shale and sandy shale. Generally confined.	0 – 50	100	0 – 3	5	Devonian and Mississippian age. Mostly overlain by glacial sediments of low permeability. Hydrogen sulfide common in the shale.
Carbonate aquifers: Limestone and dolomite, mostly massive. Some shale and gypsiferous interbedding. Generally confined.	25 – 300	400	5 – 300	500	Silurian and Devonian age. Certain areas have very good yields to wells from fractures and preglacial weathered rocks. Water generally very hard and may be highly mineralized with calcium and magnesium sulfates. Hydrogen sulfide prevalent in gypsiferous units. Water saline below 500 ft. An important source of water over a large area despite quality problems.
Shaly carbonate aquifers: Thinly interbedded gray shales and limestones. Generally confined.	0 – 50	100	0 – 5	10	Ordovician age. Repetitious sequence of shale and limestone. Yields are meager, especially in upland areas.

alluvium derived from glaciofluvial outwash present along the courses of some modern streams; thus, these aquifers sometimes are referred to as "watercourse" aquifers. The productivity of well fields developed in such aquifers may be enhanced by induced infiltration from streams. Large ground-water withdrawals in several counties (fig. 2) are from major aquifers of this type. Coarse-grained unconsolidated aquifers in the northwestern corner of the State (fig. 1) underlie glacial till, are locally under artesian pressure, and are highly productive. Extensive kame-terrace deposits of water-bearing gravel and sand are important groundwater sources in northeastern Ohio.

The fine-grained unconsolidated aquifers are similar to the coarse-grained unconsolidated aquifers in form and origin but are less permeable because of higher percentages of mixed fine sand, silt, and clay. Generally, productivity is lower in the fine-grained aquifers than in the coarse grained (table 2). Included in the fine-grained unconsolidated aquifers are tills

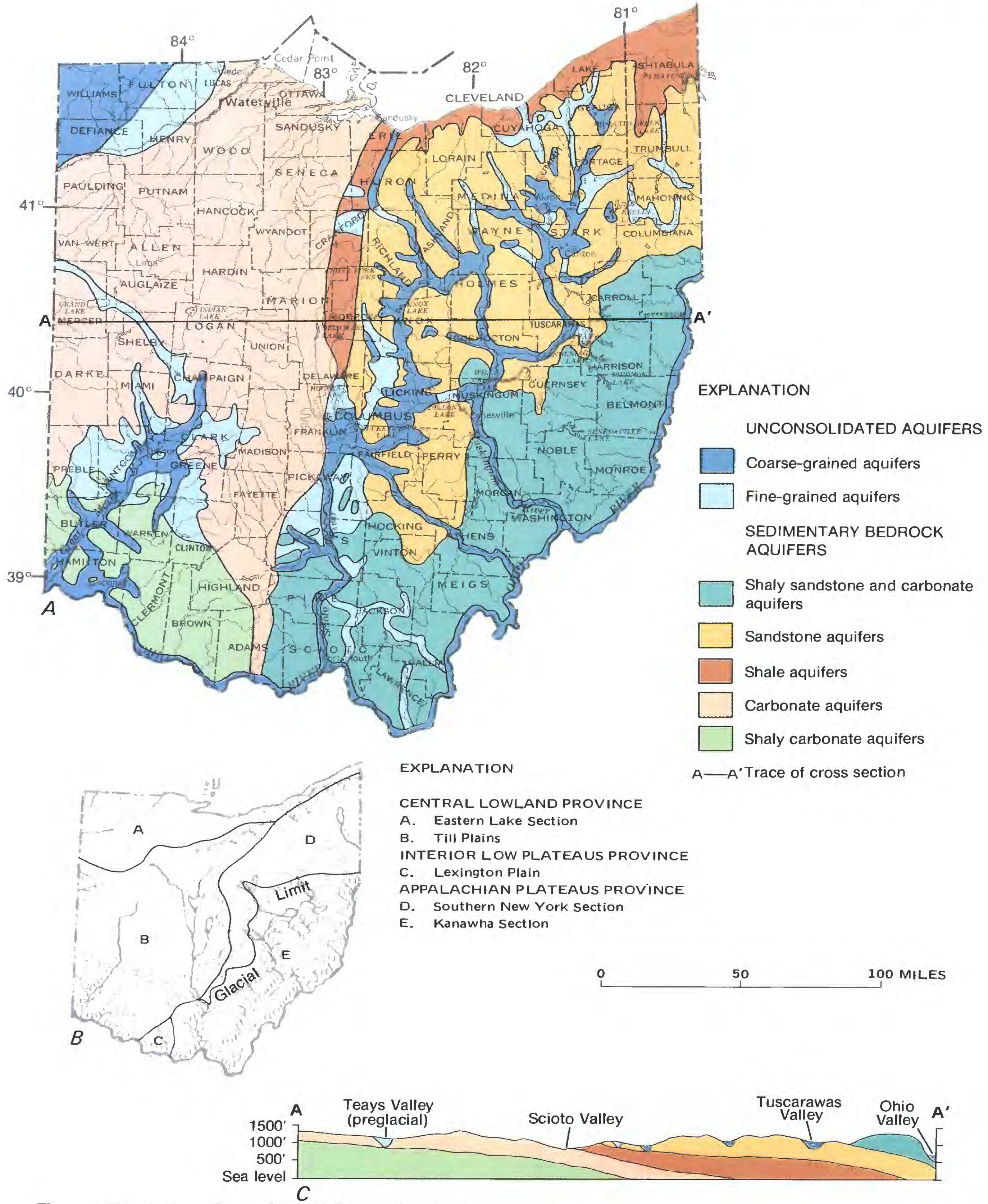


Figure 1. Principal aquifers in Ohio. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Files of the Ohio Department of Natural Resources, Division of Water. *B*, Fenneman, 1938; Raisz, 1954. *C*, Files of the Ohio Department of Natural Resources, Division of Geological Survey.)

that contain thin or localized stratified lenses of sand and gravel. Some buried valleys in Ohio, such as the preglacial Teays valley (fig. 1), are filled in places with fine-grained materials. Several preglacial valleys filled with fine-grained alluvium extend beyond the limit of glaciation (fig. 1).

The principal water-quality problem in the unconsolidated aquifers of Ohio is excessive concentrations of iron, which may exceed 2 milligrams per liter (mg/L) locally and make frequent reconditioning of screens in large wells necessary. Local problems include the threat of contamination from chemical spills, landfill leachates, excessive amounts of salt, or hydrogen sulfide, in places where excessive pumping may induce flow of low-quality water from the bedrock.

Sedimentary Bedrock Aquifers

The principal source of water supply for much of the unglaciated upland area of southeastern Ohio (fig. 1) is from shaly sandstone or thin limestone aquifers. These strata, which range from Mississippian to Permian in age, are dominated by low-yielding shales and shaly sandstones that include numerous coal-bearing strata. In some places, small water supplies are available in fractured coal beds. Vertical permeability is greatly restricted, and yields in upland areas (in perched systems above drainage) are very meager (Ohio Department of Natural Resources, 1978, p. 168–172). Water-bearing zones in the regions typically are shallow (less than 100 ft). Large-diameter, gravel-packed wells commonly are constructed in this low-yield material so that reservoir space is available to collect water, which flows at rates generally of less than 1 gallon per minute. Locally, the aquifers may be affected by concentrations of 500 to 1,000 mg/L of chloride. In some coal-producing areas, acid ground water (pH of less than 7.0) may occur.

Several sandstone aquifers in northeastern Ohio are of regional extent and are important ground-water sources for individual and small public supplies. These include the Berea and Black Hand Sandstones of Mississippian age and several sandstone members of the Pottsville and Allegheny Formations of Pennsylvanian age. Stratigraphic equivalents of these sandstones in south-central Ohio are less permeable than in the north and are not good sources of water in that area. Water quality is similar to that of the shaly sandstone and thin limestone aquifers.

The Lake Erie coastline of northeastern Ohio is underlain by shale of Devonian and Mississippian age (fig. 1) that yields only small amounts of water to wells. Moreover, the overlying glacial cover, for the most part, yields little beyond the barest of domestic needs. Objectionable levels of hydrogen sulfide in excess of 1.0 mg/L are common.

Silurian-age limestone and dolomite and Devonian limestone comprise the carbonate aquifer system (fig. 1) of much of western Ohio. Glacial cover is uneven and consists of valley fill and terminal moraine in some places; it can provide a good source of ground water. In other areas where the bedrock is nearly exposed or overlain by lacustrine silts, the glacial cover is not a source of water. Along the flanks of the Cincinnati Arch in the south, the carbonate section thins to basal Silurian remnants under a thin cover of older glacial drift. Well yields are correspondingly lower in the area. The northeastern part of western Ohio contains an area of high-yielding wells that tap a preferentially weathered zone, which developed when carbonate section was periodically exposed as land mass during the Paleozoic Era (Norris, 1971).

Within much of the carbonate aquifer region, water pumped for potable use is highly mineralized. The dissolved-solids content, which typically exceeds 1,000 mg/L, usually consists of sulfates and bicarbonates of calcium, magnesium, and sodium (Sedam and Stein, 1970). In places, hydrogen sulfide concentration may be considerably in excess of 1.0 mg/L.

The southwestern corner of Ohio near Cincinnati is underlain by shale and a thin limestone aquifer of Ordovician age. Away from the watercourse (coarse unconsolidated) aquifers that traverse the area, the rocks that form the uplands have very low hydraulic conductivity, and only very small ground-water yields can be expected. Glacial cover of the uplands is mostly thin, weathered, older till and generally is a poor source of water.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The 19 principal areas of ground-water withdrawal shown in figure 2 are based on 1980 data (Eberle and McClure, 1984). Fourteen additional counties, not shown on the figure, withdraw between 5 to 10 Mgal/d. Only two Ohio counties pumped less than 1 Mgal/d in 1980. In all but one of the withdrawal areas identified in figure 2, the coarse unconsolidated aquifers are the chief source of ground water.

The hydrograph for location 4 (fig. 2) shows a period of recovery following large ground-water withdrawals in the 1950's and 1960's. This reflects changing industrial demands for ground water. Water levels in Dayton, for example, have risen sharply in recent years in response to a slackening of industrial pumping, according to data collected by the Ohio Department of Natural Resources.

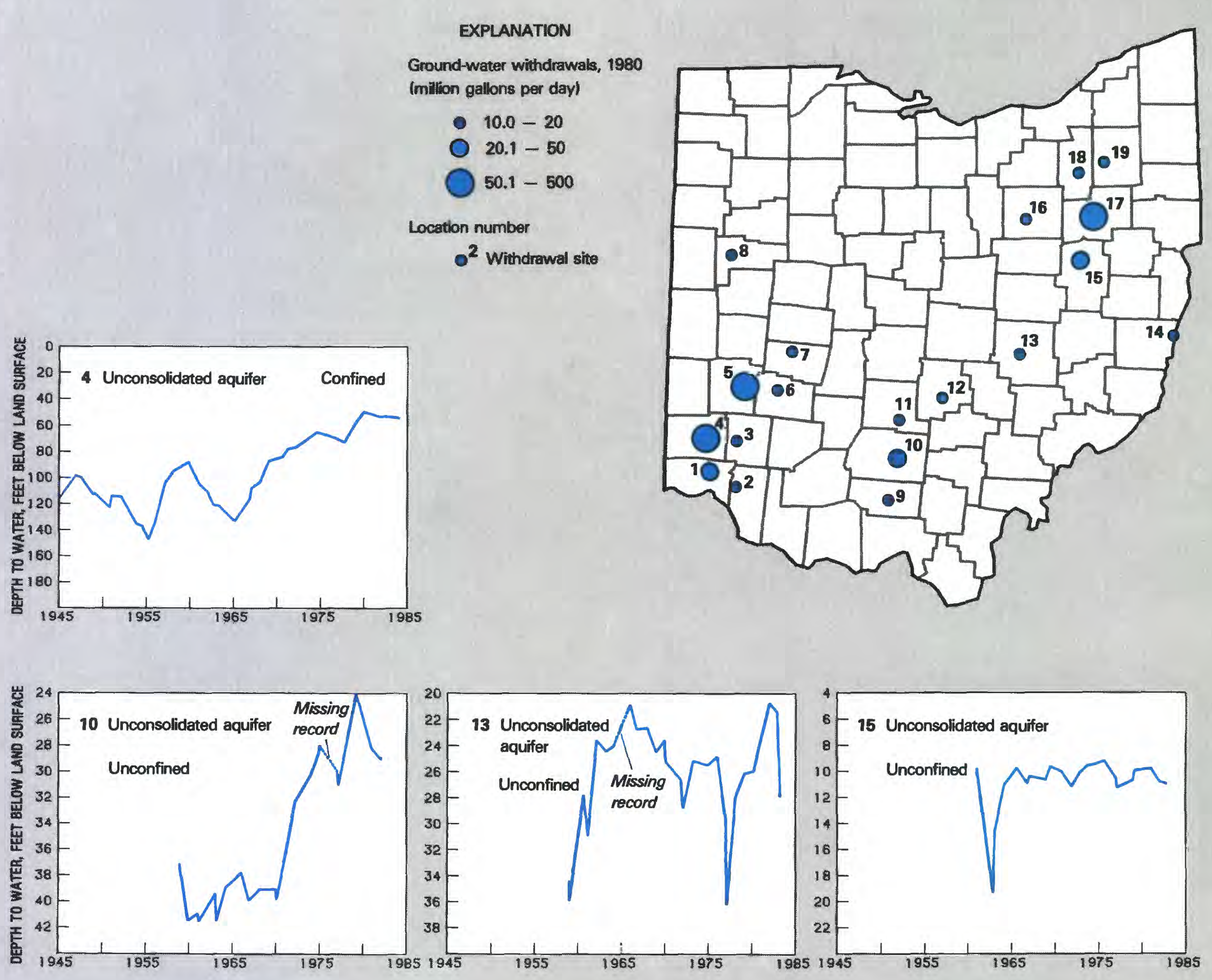
The hydrographs in figure 2 indicate that water-level declines in the State's most productive aquifers are not long term and suggest that, except for seasonal variations, declining water levels are not a statewide problem. However, declining water levels are a problem in certain areas, such as the southeastern suburbs of Cleveland, where suburban population growth is placing new demands on the available supply.

GROUND-WATER MANAGEMENT

The Ohio Department of Health regulates the drilling of private water wells used for drinking water through rules set forth in 1981. The Department requires permits to be issued by the county boards of health in each of the State's 88 counties.

Since 1949, the Ohio Department of Natural Resources, Division of Water, has required that a copy of the drilling record for any newly constructed or modified water well be filed with the Division. The water-well record repository assists the Division in its mission of providing assistance to ground-water users. The Division also offers recommendations for optimum development of ground-water resources for public supply. A statewide ground-water-level monitoring program is conducted cooperatively by the U.S. Geological Survey and the Division.

The Ohio Environmental Protection Agency is responsible for regulations to protect public-water supplies. It issues permits to control waste-water discharge from public and industrial sources and to regulate landfills and other hazardous waste disposal operations that could affect ground-water resources. To accomplish this work, the Agency performs geologic evaluations related to proposed and existing land-disposal facilities, investigates water-well contamination complaints, provides hydrogeologic information to the general public and to the technical community, and maintains a semiannual water-quality monitoring program of selected wells in principal aquifers (Stein, 1974).



WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Cincinnati area	Unconsolidated	Industrial, public supply.
2	Clermont County	....do	Public supply.
3	Labanon-Franklin area	....do	Do.
4	Hamilton-Middletown area.	....do	Industrial, public supply.
5	Dayton area	....do	Public supply, industrial.
6	Xenia area	....do	Do.
7	Springfield area	....do	Public supply.
8	Auglaize County	Carbonate, unconsolidated.	Industrial, public supply.
9	Piketon area	Unconsolidated	Industrial.
10	Chillicothe area	....do	Industrial, public supply.
11	Circleville area.	Unconsolidated, carbonate.	Do.
12	Lancaster area	Unconsolidated, sandstone.	Public supply, industrial.
13	Zanesville area.	....do	Do.
14	Ballaire-Martins Ferry area.	Unconsolidated	Public supply.
15	Tuscarawas County.	Unconsolidated, sandstone.	Industrial, public supply.
16	Wooster area.	....do	Public supply, industrial.
17	Canton area	....do	Do.
18	Akron area.	....do	Do.
19	Portage County	....do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Ohio. (Sources: Withdrawal data from Eberle and McClure, 1984; water-level data from U.S. Geological Survey files.)

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Prepared by Alan C. Sedam, Frank W. Giessner, and Michael Eberle

For further information contact District Chief, U.S. Geological Survey, 975 West Third Avenue, Columbus, OH 43212

OKLAHOMA
Ground-Water Resources

Ground water constitutes about 56 percent of the fresh water used in Oklahoma and is one of the State's most important natural resources. In the western one-half of Oklahoma, ground water is the most important source of water for domestic and irrigation supply. About 1.2 million people within the State (41 percent of the total population) are served by ground water. Extensive irrigation in the western part of the State, including the Panhandle, accounts for about 76 percent of the fresh ground-water withdrawals.

GENERAL SETTING

Recharge to aquifers in the State is predominantly from precipitation, which ranges from about 16 inches per year (in./yr) in the western Panhandle to about 54 in./yr in southeastern Oklahoma. Most of the precipitation is returned to the atmosphere by evapotranspiration, which ranges from 16 inches (in.) in the west to more than 36 in. in the east. Consequently, recharge from precipitation ranges from less than 0.25 in./yr in the Panhandle to about 10 in./yr in the east (Pettyjohn and others, 1983). The alluvial aquifers also receive some recharge from streamflow.

Oklahoma contains the Great Plains, Central Lowlands, Ozark Plateaus, Ouachita, and Coastal Plain physiographic provinces (fig. 1). The Great Plains are underlain predominantly by the Ogallala Formation of Tertiary age. The Central Lowlands are underlain by redbeds of Permian age and marine shales with interbedded sandstone, limestone, and coal of Pennsylvanian age. The Ozark Plateaus and Ouachita provinces are underlain predominantly by marine limestone, shale, and sandstone of Cambrian through Mississippian age. The Coastal Plain province is underlain by the Antlers Formation of Cretaceous age, which consists of nonmarine sandstone and clay and marine limestone and clay.

PRINCIPAL AQUIFERS

Principal aquifers in Oklahoma are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

ALLUVIAL AQUIFERS

The alluvial aquifers consist of alluvium and terrace deposits of Quaternary and Tertiary age along the major rivers—the Arkansas (including the Salt Fork Arkansas), the Cimarron, the North Canadian, the Canadian, the Washita, and the North Fork Red Rivers. These deposits generally extend from 1 mile (mi) to as much as 15 mi from the rivers, and their thickness ranges from a few feet to about 300 feet (ft). Yields range from about 100 gallons per minute (gal/min) to more than 1,200 gal/min where saturated thicknesses are large. The alluvium and terrace deposits are generally unconfined and consist of sand, silt, clay, and gravel. In some areas, overlying dune sand forms a part of the aquifer.

Table 1. Ground-water facts for Oklahoma

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	1,240
Percentage of total population	41
From public water-supply systems:	
Number (thousands)	662
Percentage of total population	22
From rural self-supplied systems:	
Number (thousands)	578
Percentage of total population	19
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	1,700
Ground water only (Mgal/d)	960
Percentage of total	56
Percentage of total excluding withdrawals for thermoelectric power	61
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	86
Percentage of total ground water	9
Percentage of total public supply	28
Per capita (gal/d)	130
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	29
Percentage of total ground water	3
Percentage of total rural domestic	83
Per capita (gal/d)	50
Livestock:	
Ground water (Mgal/d)	8.2
Percentage of total ground water	1
Percentage of total livestock	12
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	103
Percentage of total ground water	11
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	23
Excluding withdrawals for thermoelectric power	35
Irrigation withdrawals:	
Ground water (Mgal/d)	730
Percentage of total ground water	76
Percentage of total irrigation	84

UNCONSOLIDATED AND SEMICONSOLIDATED AQUIFERS

High Plains Aquifer

The single largest source of ground water in the State is the High Plains aquifer, which consists of the Ogallala Formation of Tertiary age and associated alluvium and terrace deposits of Quaternary age. Saturated thickness of this aquifer ranges from a few feet to more than 500 ft. This aquifer consists mostly of fine sand and silt with lesser quantities of clay, gravel, and minor beds of limestone and caliche (Hart and others, 1975). Yields range from 100 to 1,000 gal/min; exceptional wells may exceed 1,500 gal/min. Most of the

Table 2. Aquifer and well characteristics in Oklahoma.

[Mgal/d = millions of gallons per day; ft = feet; acre-ft = acre-feet; mg/L = milligrams per liter; gal/min = gallons per minute; Sources: Reports of the U. S. Geological Survey.]

Aquifer name and description	Aquifer withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Alluvial aquifers:					
Arkansas River and Salt Fork Arkansas River alluvium and terrace deposits: Clay and silt in upper part grading downward into fine to coarse sand with local lenses of fine gravel. Maximum thickness 60 ft alluvium, 150 ft terrace. Saturated thickness 25 to 70 ft. Generally unconfined.	30	50 – 100	200 – 500 (alluvium): 100 – 200 (terrace):	800 400	Calcium magnesium bicarbonate type water, very hard with dissolved-solids concentrations less than 500 mg/L. Intensively pumped wells near river may induce inflow of river water with chloride concentrations of 350 to 830 mg/L.
Cimarron River alluvium and terrace deposits: Silt and clay in upper part grading downward into sandy clay, sand, and fine gravel; maximum thickness about 80 ft. Terrace deposits nearly everywhere overlain by dune sand as much as 100 ft thick. Generally unconfined.	23	50 – 150	100 – 200 (alluvium): 100 – 500 (terrace):	400 800	Water generally calcium magnesium bicarbonate type, very hard; dissolved-solids concentrations generally are less than 500 mg/L. Intensively pumped wells near river may induce inflow. During greater-than-normal precipitation dune sand and terrace deposits become saturated causing local water-logging of the lands.
North Canadian River alluvium and terrace deposits: Fine to coarse sand with minor clay and silt and local lenses of basal gravel overlain by dune sand. Thickness of alluvium averages about 30 ft; terrace maximum thickness about 300 ft. Generally unconfined.	51		300 – 600 (alluvium): 100 – 300 (terrace):	1,200 500	Water generally calcium bicarbonate type, hard to very hard; dissolved-solids concentrations less than 1,000 mg/L.
Canadian River alluvium and terrace deposits: Clay and silt in upper part grading downward into fine to coarse sand with thin lenses of basal gravel. Maximum thickness 60 ft; saturated thickness 20 to 40 ft. Generally unconfined.	8		100 – 400 (alluvium): 50 – 100 (terrace):	600 200	Water generally calcium magnesium bicarbonate type; hard to very hard; dissolved-solids concentrations generally less than 1,000 mg/L.
Washita River alluvium and terrace deposits: Silt and clay grading downward into fine to medium sand, average thickness 64 ft, maximum thickness 120 ft for alluvium. Terrace deposits silt and fine sand with maximum thickness of 50 ft. Generally unconfined.	7	50 – 100	100 – 300 (alluvium): 20 – 100 (terrace):	600 -	Water generally calcium magnesium bicarbonate type; dissolved-solids concentrations less than 1,000 mg/L.
North Fork Red River alluvium and terrace deposits (Beckham and Tillman terraces): Alluvium is silt and clay grading downward into fine to coarse sand; maximum thickness about 70 ft. Terraces about 50 percent fine to coarse sand, 50 percent silt and clay. Beckham average thickness about 70 ft; Tillman about 40 ft. Generally unconfined.	28	50 – 150	100 – 200 (alluvium): 200 – 500 (Beckham terrace): 200 – 500 (Tillman terrace):	500 900 1,100	Generally calcium magnesium bicarbonate or calcium sulfate type water, hard to very hard; dissolved-solids concentrations 1,000 to 2,000 mg/L. In Tillman terrace, water levels have declined 1 to 20 ft. Beckham terrace water levels have declined as much as 10 ft; approximately 10 percent of water in storage has been depleted.
Unconsolidated and semiconsolidated aquifers:					
High Plains aquifer: Ogallala Formation of Tertiary age and associated alluvium and terrace deposits of Quaternary age; sand, siltstone, clay, gravel, thin limestones, and caliche. Generally unconfined.	373	100 – 500	100 – 1,000	2,000	Chief source of water supplies in the High Plains of Oklahoma. Water generally hard but suitable for most uses. Water levels have declined as much as 100 ft in some areas.
Bedrock aquifers:					
Antlers aquifer: Sandstone of Cretaceous age. Friable sandstone, silt, clay, and shale; average thickness about 450 ft. Unconfined where exposed but confined toward south where overlain by less permeable rocks.	5	50 – 200 (unconfined) 200 – 800 (confined)	50 – 100 (land surface) 100 – 500 (at depth)	1,700 -	Sodium or calcium bicarbonate type water where aquifer exposed; dissolved-solids concentrations generally less than 1,000 mg/L but may be as much as 3,000 mg/L. Volume of water in storage with dissolved solids less than 1,000 mg/L estimated at 32 million acre-feet. Comparable to Trinity aquifer in Texas.

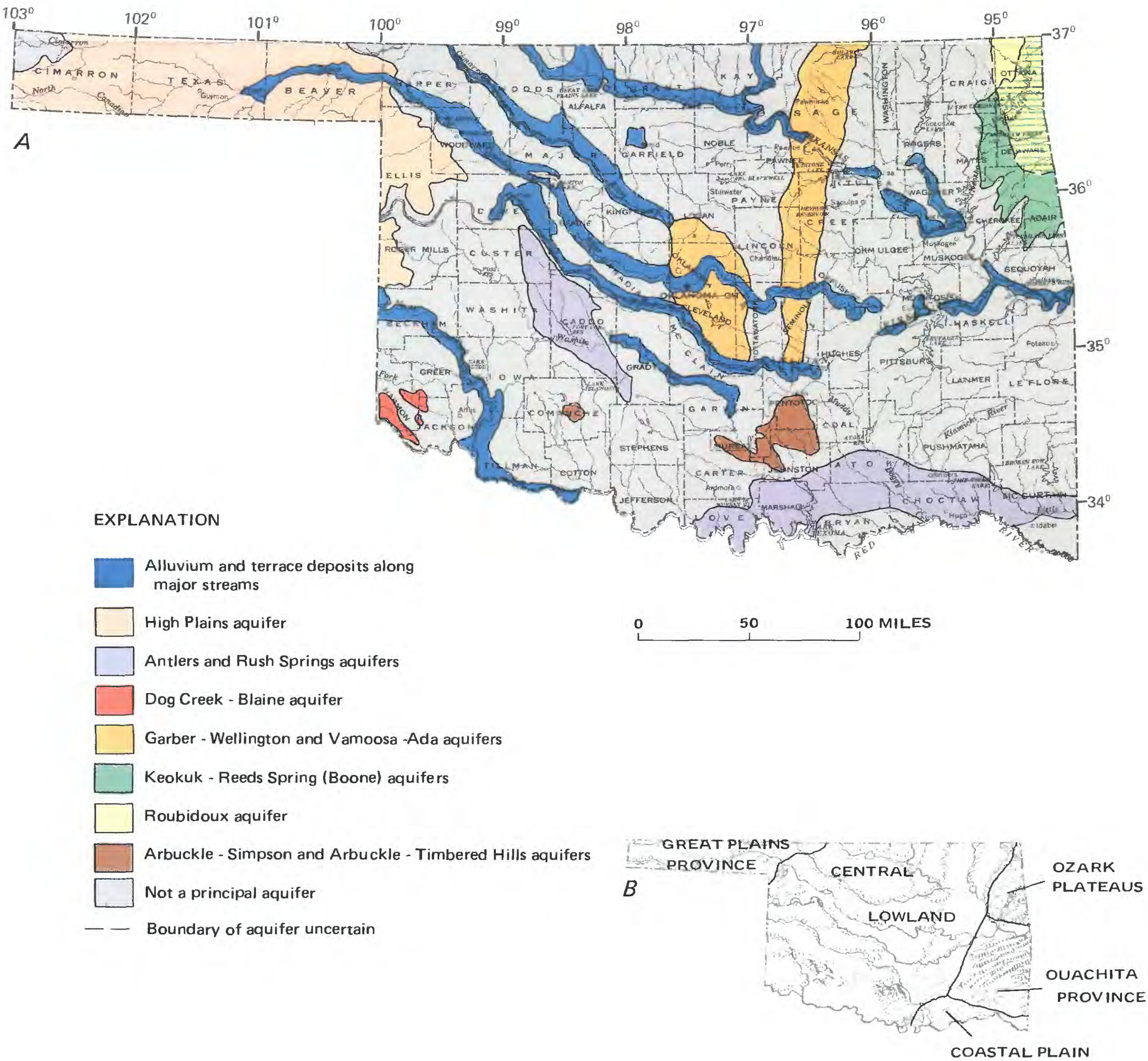
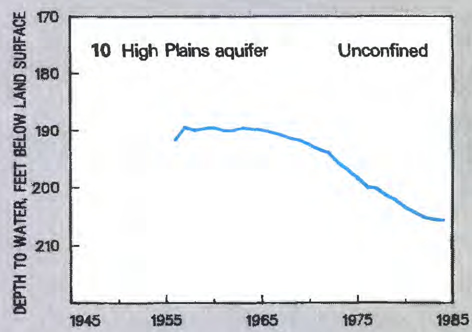
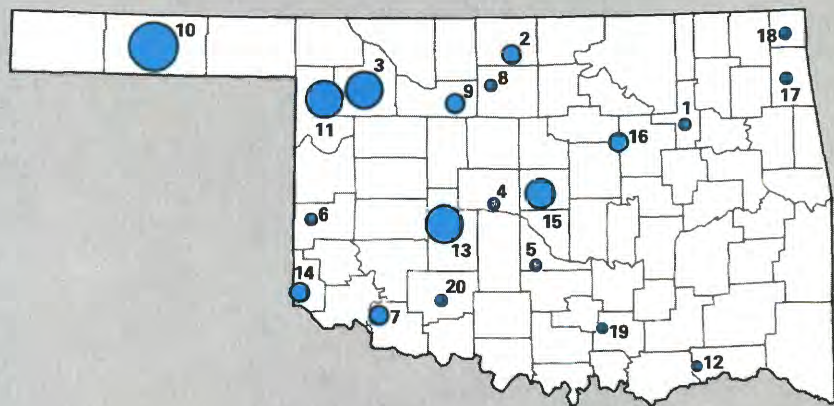


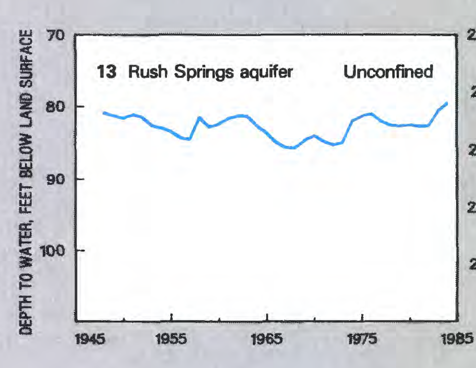
Figure 1. Principal aquifers in Oklahoma. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Marcher, 1972. *B*, Fenneman, 1946; Raisz, 1954.)

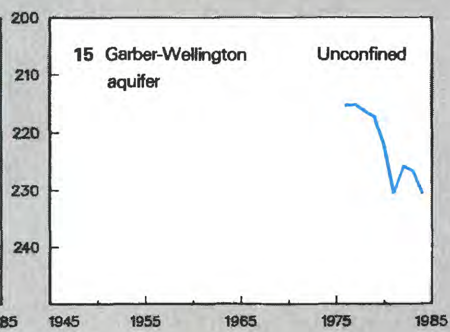
Table 2. Aquifer and well characteristics in Oklahoma—Continued

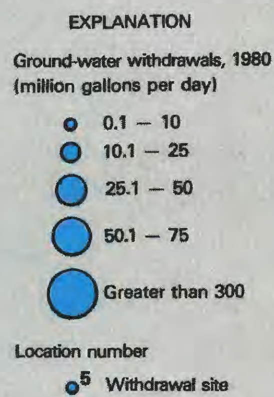
Aquifer name and description	Aquifer withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Rush Springs aquifer: Fine-grained sandstone with some shale, dolomite, and gypsum; 200 to 300 ft thick. Unconfined to partly confined in deeper parts of aquifer.	54	200 - 400	200 - 600	1,000	Calcium bicarbonate type water; dissolved-solids concentrations generally less than 500 mg/L. In heavily pumped areas, water levels have declined as much as 50 ft.
Dog Creek-Blaine aquifer: Interbedded gypsum, dolomite, and siltstone, 300 to 400 ft thick. Water occurs in solution openings in gypsum; generally unconfined.	25	100 - 200	100 - 500	2,500	Generally calcium sulfate chloride type water; total dissolved solids 2,000 to 6,000 mg/L. Unsuitable for drinking, but intensively used for irrigation. Water levels may decline as much as 50 ft, but aquifer is recharged by surface runoff into sinkholes and solution openings.
Garber-Wellington aquifer: Fine-grained sandstone with shale and siltstone; maximum thickness about 900 ft; saturated thickness 150 to 650 ft. Generally unconfined to partly confined where aquifer is near the surface or confined where overlain by less permeable rocks.	41	100 - 200 (unconfined) 200 - 900 (confined)	100 - 300	500	Generally calcium magnesium bicarbonate type water; dissolved-solids concentration generally less than 500 mg/L. Becomes more saline with depth and in western part of area. Underlain by salt water that may move upward in areas of heavy pumpage. Locally, the potentiometric surface has been lowered 100 to 200 ft. Contaminated by oil field brines and wastes in some areas where aquifer is near surface.
Vamoosa-Ada aquifer: Fine- to very fine-grained sandstone, siltstone, shale, and conglomerate. Thickness of water-yielding sandstone 100 to 550 ft. Unconfined where near land surface; confined in west where overlain by less permeable rocks. Equivalent to the Douglas aquifer in Kansas.	10	100 - 500	100 - 300	500	Generally sodium bicarbonate or sodium calcium bicarbonate type water; dissolved-solids concentration less than 500 mg/L, but increase to 1,000 mg/l with depth near potable-water-salt-water interface. Estimated 60 million acre-ft of potable water in storage. Most withdrawals for public and industrial use.
Keokuk-Reeds Spring (Boone) aquifer: Weathered residual chert and clay in upper part; very cherty limestone in lower part; maximum thickness 500 ft. Unconfined to confined.	3	50 - 300	1 - 10	80	Calcium bicarbonate type water, hard to very hard; dissolved-solids concentrations generally less than 500 mg/L. Because of lithology, readily susceptible to contamination from surface sources. Springs can yield 600 to 3,500 gal/min.
Roubidoux aquifer: Fractured dolomite containing two or three sandy zones; confined. Equivalent to Ozark aquifer in Kansas and Missouri.	5	800 - 1,200	150	600	Water moderately hard but suitable for most uses. Principal water supply for municipalities and industries in Ottawa County.
Arbuckle-Simpson aquifer: Limestone, dolomite, and sandstone 5,000 to 9,000 ft thick. Water occurs in solution openings and fractures; confined to unconfined.	6	100 - 2,500	100 - 500	2,000	Calcium magnesium bicarbonate type water, very hard; dissolved-solids concentration generally less than 500 mg/L. Volume of water in storage estimated to be 9 million acre-ft. Springs can yield as much as 18,000 gal/min.
Arbuckle-Timbered Hills aquifer: Limestone, dolomite, sandy dolomite, mudstone, and conglomerate; generally confined.	2	100 - 2,800	90 - 600	600	Water generally soft, but fluoride concentrations exceed 1.6 mg/L nearly everywhere and may be as much as 35 mg/L. Springs can yield as much as 200 gal/min.





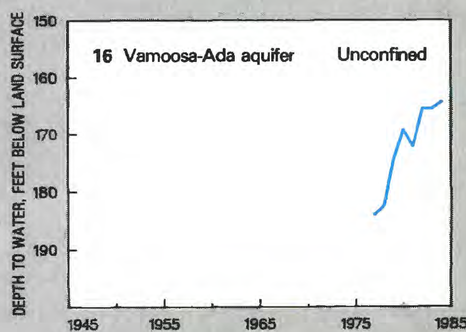






WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Tulsa	Arkansas River alluvial deposits.	Public supply.
2	Salt Fork Arkansas . . . . River.	Salt Fork Arkansas River alluvial deposits.	Public supply, irrigation.
3	N. Canadian River.	N. Canadian River alluvial deposits.	Irrigation.
4	Canadian-Cleveland County.	Canadian River alluvial deposits.	Do.
5	Washita River	Washita River alluvial deposits.	Irrigation, public supply.
6	N. Fork Red River	N. Fork Red River alluvial deposits.	Irrigation.
7	Tillman Terrace	Red River alluvial terrace deposits.	Do.
8	Enid Area	Terrace deposits. .	Public supply.
9	Cimarron Terrace	Cimarron alluvial, terrace deposits.	Irrigation.
10	High Plains.	High Plains (Ogallala).	Do.
11	High Plains.	. . . .do	Do.
12	Southeast Oklahoma . . .	Antlers	Irrigation, public supply.
13	Rush Springs area	Rush Springs. . . .	Irrigation.
14	Harmon-Jackson-Greer Counties.	Dog Creek-Blaine.	Do.
15	Oklahoma City area. . . .	Garber-Wellington.	Public supply.
16	East-Central Oklahoma. .	Vamoosa-Ada . . .	Do.
17	Northeast Oklahoma . . .	Keokuk-Reeds Spring.	Do.
18	Northeast Oklahoma . . .	Roubidoux.	Do.
19	Arbuckle Mtn area	Arbuckle-Simpson	Irrigation, public supply.
20	Lawton area	Arbuckle-Timbered Hills.	Miscellaneous.



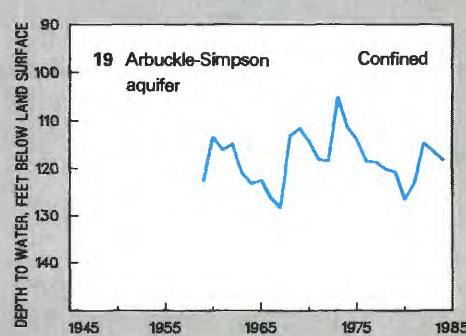


Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Oklahoma. (Sources: Withdrawal data from Pettyjohn and others, 1983; water-level data from U.S. Geological Survey files.)

water from the High Plains aquifer is used for irrigation, but it also is the principal source of domestic and industrial supply in the High Plains of Oklahoma. The water is suitable for most uses.

Bedrock Aquifers

Antlers Aquifer

The Antlers aquifer in southeastern Oklahoma contains large quantities of water. Due to the greater precipitation and the resulting availability of surface water in the southeastern part of the State, this aquifer is not used to its full potential (Marcher and Bergman, 1983). In the unconfined part of the aquifer, where the sandstone is at the land surface, yields range from 50 to 100 gal/min. In the confined part, the aquifer yields from 100 to 500 gal/min. The water generally is suitable for all uses but may be saline at depth.

Rush Springs Aquifer

The Rush Springs aquifer, a fine-grained sandstone in the west-central section of the State, is used extensively for irrigation (Carr and Bergman, 1976). Yields generally range from 200 to 600 gal/min, and some wells may yield as much as 1,000 gal/min. Water generally is suitable for all uses. In areas of intensive irrigation pumpage, water levels have declined as much as 50 ft.

Dog Creek-Blaine Aquifer

The Dog Creek-Blaine aquifer in extreme southwestern Oklahoma contains water in solution openings in gypsum. The water is used extensively for irrigation (Havens, 1977), but it contains excessive quantities of calcium sulfate (gypsum) in solution that renders it unsuitable for drinking [dissolved solids range from 2,000 to 6,000 milligrams per liter (mg/L)]. During the pumping season, drawdowns may be as much as 50 ft, but the aquifer is recharged rapidly by surface runoff that flows into sinkholes and solution openings. Wells commonly yield from 100 to 500 gal/min, but yields of 2,500 gal/min are not unusual.

Garber-Wellington Aquifer

In central Oklahoma, the Garber-Wellington aquifer is the principal water supply for several of the Oklahoma City suburbs. The aquifer generally consists of fine-grained sandstone, shale, and siltstone with a maximum thickness of 900 ft. Several water-yielding zones, which become confined with depth, are present in the aquifer (Bingham and Moore, 1975). Water quality generally is suitable for all uses. Wells commonly yield from 100 to 300 gal/min. Local areas of intensive pumpage have caused drawdowns of 100 to 200 feet. Excessive pumpage may cause upwelling of brine which is present at depth.

Vamoosa-Ada Aquifer

The Vamoosa-Ada aquifer extends in a band from north to south in east-central Oklahoma (Bingham and Bergman, 1980; Bingham and Moore, 1975). Aggregate thickness of water-yielding sandstone ranges from 100 to 550 ft. Where it is near the land surface, the aquifer is unconfined, but down-dip (to the west) the aquifer is confined. Most withdrawals from this relatively undeveloped aquifer are for public supply and industrial use. The water quality generally is suitable for all uses in the upper part of the aquifer but becomes increasingly saline near the interface between the potable and saline water in the deeper confined part of the aquifer. Excessive pumpage may cause upwelling of this saline water. Oil-field brines and wastes resulting from past operations have caused some local contamination.

Keokuk-Reeds Spring (Boone) Aquifer

In northeastern Oklahoma, the Keokuk-Reeds Spring (Boone) aquifer is a dependable source of water where it is near the land surface (Marcher and Bingham, 1971). It generally yields less than 10 gal/min to wells but yields as much as 3,500 gal/min from springs. The Keokuk-Reeds Spring aquifer consists of residual chert and cherty limestone. The small yields from wells preclude any large-scale development of the aquifer for other than domestic purposes. The water generally is suitable for most uses but is hard to very hard. Because of interconnecting sinkholes and cavern development, the Boone has the potential to be readily contaminated by surface sources.

Roubidoux Aquifer

Underlying part of the Keokuk-Reeds Spring aquifer is the Roubidoux aquifer, which consists of fractured dolomite that contains several sandy zones (Marcher and Bingham, 1971). The Roubidoux is not exposed at the surface in Oklahoma. The water is moderately hard and is the principal public and industrial water supply in Ottawa County in extreme northeastern Oklahoma. Wells commonly yield 150 gal/min, but may yield as much as 600 gal/min. The Roubidoux aquifer in Oklahoma is equivalent to the Ozark aquifer of Missouri and Kansas.

Arbuckle-Simpson Aquifer

In the Arbuckle Mountain area in south-central Oklahoma, limestone, dolomite, and sandstone units from 5,000 to 9,000 ft thick form the Arbuckle-Simpson aquifer (Hart, 1974). The aquifer is largely undeveloped and contains an estimated 9 million acre-feet of water in storage. Wells in the aquifer yield from 100 to 500 gal/min with some wells yielding as much as 2,500 gal/min; springs may yield from 50 to 18,000 gal/min. Water from the Arbuckle-Simpson aquifer commonly is very hard due to its residence in limestone.

Arbuckle-Timbered Hills Aquifer

The Arbuckle-Timbered Hills aquifer in southwestern Oklahoma underlies the Lawton area (Havens, 1977). The aquifer yields 90 to 600 gal/min of soft water to wells; springs may flow as much as 200 gal/min. Fluoride concentrations in the water exceed 1.6 mg/L nearly everywhere and may be as much as 35 mg/L, which effectively prevents any widespread use of the water for public supply.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Ground water is the principal source of water for irrigation in Oklahoma. The Tulsa, Oklahoma City, and Lawton metropolitan areas depend on surface water for their major water supplies, whereas most smaller communities and individual users depend on ground water for domestic water supplies.

Major centers of ground-water withdrawal and water-level trends in selected wells are shown in figure 2. The largest ground-water withdrawal area in the State is in the High Plains aquifer in the western part of the State (locations 10 and 11, fig. 2). Other major withdrawal centers are located in the Rush Springs aquifer (location 13, fig. 2) and in the alluvium and terrace deposits along the North Canadian River (location 3, fig. 2). The Garber-Wellington aquifer near Oklahoma City (location 15) provides numerous individual domestic supplies and is used for public supply by several suburban communities in the Oklahoma City area.

Representative hydrographs for aquifers throughout the State are shown in figure 2. The observation well for the High Plains (Ogallala) aquifer is located near the principal withdrawal area for the High Plains in Texas County (location 10, fig. 2). The hydrograph shows the steady decline of water levels in this well in response to prolonged irrigation pumpage. The observation well completed in the Rush Springs aquifer (location 13, fig. 2) is somewhat removed from any main pumping centers. The hydrograph shows some water-level rises caused by increased recharge from above-normal precipitation. The hydrograph for the Garber-Wellington aquifer in the Oklahoma City area (location 15, fig. 2) shows a decline in water levels, probably in response to pumpage for public-supply and individual domestic use. The well in the Vamoosa–Ada aquifer (location 16, fig 2) is an abandoned public-supply well; the water-level rise shown by the hydrograph is probably caused by reduced pumpage in the area. Water levels in the confined Arbuckle–Simpson aquifer (location 19, fig. 2) vary considerably, generally in response to annual variations in recharge. There is no large-scale pumpage from this aquifer.

GROUND-WATER MANAGEMENT

Oklahoma's statutory system to regulate ground-water use underwent major revision in 1972, and the current system of regulation consists of the 1972 statutory framework with some minor amendments since that date. The major features of the current Ground Water Law, codified as 82 O.S. Supp. 1981,§§1020.1-1020.22, combine aspects of individual personal property ownership in ground water and a regulatory aspect of ground-water reasonable use and regulation.

The Oklahoma Water Resources Board has primary responsibility for regulatory and operational programs with regard for managing ground water. As part of its responsibilities, the Board manages a ground-water appropriation and permit program. Only domestic use is exempt from permit requirements. The Board also administers a water-well drillers' license and enforcement program and conducts hydrologic surveys of each fresh ground-water basin or subbasin to determine the maximum annual yield.

State organizations involved in ground-water activities in support of the management process include the Environmental and Ground Water Institute at the University of Oklahoma, Oklahoma Geological Survey, Oklahoma Water Resources Board, and Water Research Center at Oklahoma State University. The U.S. Geological Survey participates in cooperative programs with the Oklahoma Geological Survey and the Oklahoma Water Resources Board in which ground-water research, investigations, and data collection are accomplished.

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Prepared by John S. Havens and Melvin V. Marcher, U.S. Geological Survey; "Ground-Water Management" section written by James W. Schuelein, Oklahoma Water Resources Board

For further information contact District Chief, U.S. Geological Survey, 215 Dean A. McGee Avenue, Room 621, Oklahoma City, OK 73102

OREGON
Ground-Water Resources

Ground water is an important natural resource in Oregon. An estimated 1.6 million persons (about 60 percent of Oregon's population) depend on ground water for all or part of their daily water needs (Solley and others, 1983). A total of 1.1 billion gallons per day of ground water were withdrawn in 1980; of this amount, 75 percent was for irrigation use, 12 percent for rural-domestic and livestock use, 7 percent for industrial use, and 6 percent for public-supply use. Ground-water use is expected to increase in the future because the State's population is growing and because the summertime flow of many streams is inadequate to meet the present and future demand. Ground-water withdrawals for various uses in 1980 and related statistics are given in table 1.

Ground-water-related problems in Oregon include water-level declines due to excessive pumping, contamination, and, in some areas, limited availability. No major widespread contamination of ground water has been detected in Oregon; however, there are many instances of local degradation and contamination from septic tanks, waste lagoons, and accidental spills. Naturally occurring brackish water limits the use of some Oregon ground water, particularly in the western part of the State.

GENERAL SETTING

Oregon is divided into 10 physiographic divisions (fig. 1, Dicken, 1965)—of which four are in western Oregon (the Willamette Valley, the Coast Range, the Western Cascades, and the Klamath Mountains) and six are in eastern Oregon (the High Cascades, the Blue Mountains, the Deschutes-Umatilla Plateau, the High Lava Plain, the Basin and Range, and the Owyhee Upland). In western Oregon, one of the more important divisions is the Willamette Valley. The valley is a structural basin and lowland where about 65 percent of Oregon's population live. It is underlain by sediment that forms productive aquifers. The other physiographic divisions in western Oregon—the Coast Range, the Western Cascades, and the Klamath Mountains—are steep, rugged, and extensively forested. The Coast Range is underlain by gently folded marine sedimentary rocks and basalt, the Western Cascades by altered volcanic rocks, and the Klamath Mountains by metamorphic and intrusive igneous rocks. Most aquifers in each of these three divisions yield small quantities of water.

In eastern Oregon, five of the physiographic divisions generally have productive aquifers in most areas. The sixth area, the Blue Mountain division, is topographically and geologically diverse and includes mountain ranges and intervening basins and valleys, all underlain by a variety of rock types, including metamorphic, intrusive, igneous, sedimentary, and altered volcanic rocks. In most of the area, aquifers yield little water to wells although there are some productive aquifers. However, these productive aquifers frequently are unsuitable for development because the terrain is too steep and rugged. The remaining physiographic divisions of eastern Oregon are mentioned, where pertinent, within the discussions of principal aquifers that follow.

The Cascade Range (fig. 1) is a high volcanic mountain range that separates Oregon into a relatively humid western part and an arid eastern part. Annual precipitation in Oregon varies with altitude and ranges from about 25 to 180 inches (in.) in western Oregon and from about 10 to 80 in. in eastern Oregon. Differences in precipitation between these two areas greatly affect the occurrence, development, and use of ground water in each part of the State; for example, annual ground-water recharge is less than 1 in. in much of eastern Oregon but is as much as several inches in some parts of western Oregon.

Table 1. Ground-water facts for Oregon

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1984	
Number (thousands)	[1]1,599
Percentage of total population	61
From public water-supply systems:	
Number (thousands)	344
Percentage of total population	13
From rural self-supplied systems:	
Number (thousands)	1,255
Percentage of total population	48
Freshwater withdrawals, 1984	
Surface water and ground water, total (Mgal/d)	6,800
Ground water only (Mgal/d)	1,100
Percentage of total	17
Percentage of total excluding withdrawals for thermoelectric power	17
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	66
Percentage of total ground water	6
Percentage of total public supply	29
Per capita (gal/d)	192
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	130
Percentage of total ground water	11
Percentage of total rural domestic	87
Per capita (gal/d)	104
Livestock:	
Ground water (Mgal/d)	7.1
Percentage of total ground water	1
Percentage of total livestock	27
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	80
Percentage of total ground water	7
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	15
Excluding withdrawals for thermoelectric power	16
Irrigation withdrawals:	
Ground water (Mgal/d)	850
Percentage of total ground water	75
Percentage of total irrigation	14

[1] Calculated from information in Solley and others, 1983.

PRINCIPAL AQUIFERS

Principal aquifers in Oregon consist of unconsolidated to consolidated sediments and several types of volcanic and pyroclastic rocks. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics in Oregon

[Ft = feet; gal/min = gallons per minute. Sources: Numerous geologic and hydrologic reports listed in Selected References.]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Basin-fill and alluvial aquifers: Sand, gravel, silt and clay, interbedded. Sandstone, siltstone, and conglomerate. Includes lacustrine, alluvial-fan and some tuff deposits, and dune and beach sands. Unconfined and confined.	50 - 300	100 - 500	2,000	Maximum thickness about 2,000 ft near La Grande. Thickness greater than 1,000 ft in Portland area, and generally less than 300 ft elsewhere. In southeastern Oregon, aquifers form and outline floors of structural basins, which also are discharge areas for adjacent flow systems. Water quality generally good. Saline water may be present, however, near coast and near playas in southeastern Oregon. May be very sensitive to contamination in areas where water table shallow.
Volcanic and sedimentary aquifers: Basalt, andesite, some rhyolite, tuff and agglomerate, tuffaceous sediments, sand and gravel, silt, and clay, interbedded. Unconfined and confined.	100 - 600	50 - 300	3,000	Erupted from or derived through erosion of numerous exposed and concealed volcanic vents distributed throughout outcrop area. Outcrop area mainly rough, undeveloped upland terrain. Well data sparse. Depth to water table may exceed several hundred feet in many places in uplands. Water generally of good quality for most uses.
Columbia River Basalt aquifer: Basalt, accordantly layered with some tuffaceous sedimentary interbeds. Mostly confined.	100 - 600	200 - 500	2,000	Most water from interflow zones between lava flows. Thickness in Oregon may exceed 5,000 ft. Outcrop areas in Blue Mountains are in rough, sparsely populated uplands and, in general, are unlikely sites for development of large-capacity wells. Water generally good quality for most uses.

Basin-Fill and Alluvial Aquifers

Basin-fill and alluvial aquifers are present in all parts of the State (fig. 1), but not all the aquifers can be developed to yield large quantities of water. These aquifers include unconsolidated to consolidated basin-fill sediments, alluvium, and coastal dune and beach deposits. Numerous thin, narrow alluvial aquifers are present along principal streams but are not shown in figure 1. In northern and western Oregon, the aquifers include all sediments that overlie the Columbia River Basalt Group; in southeastern Oregon, they include only the younger basin-fill sediments. Maximum thickness of the basin-fill is 2,000 feet (ft) near La Grande, Oregon, 1,000 ft in the Portland area (fig. 1), and elsewhere less than 300 ft thick.

The most extensive and productive basin-fill and alluvial aquifer underlies the Willamette Valley. The most productive parts of this aquifer are sand and gravel beds that underlie the flood plains of the Willamette River and its major tributaries (Helm and Leonard, 1977). Along the Columbia River near Portland, the Portland Water Bureau is developing a well field that will tap two confined aquifers in the Troutdale Formation (one of which consists of cemented sand and gravel and the other of sandstone) and a third, shallower, semiconfined sand and gravel aquifer of glaciofluvial origin. Production wells in this third aquifer are less than 200 ft deep and each is capable of yielding more than 10,000 gallons per minute (gal/min), which is an extraordinarily good yield.

The well field near Portland is being developed as an emergency public-water supply to provide backup to the present surface-water source in the Bull Run watershed. When completed, the pumping capacity of the well field will exceed 100 million gallons per day (Mgal/d) (R. F. Willis, Portland Waste Bureau, written commun., 1977).

Quality of water in basin-fill and alluvial aquifers generally is suitable for most uses; concentrations of dissolved solids range from 24 to 3,940 milligrams per liter (mg/L). The median concentrations are 165 mg/L in western Oregon (McFarland, 1983) and 212 mg/L in eastern Oregon (Gonthier, 1984).

Volcanic and Sedimentary Aquifers

Volcanic and sedimentary aquifers underlie three physiographic divisions in eastern Oregon and the High Cascades section of the Cascade Range (fig. 1). The aquifers are complex and consist of an assemblage of differing proportions of volcanic and sedimentary rocks. The volcanic rocks are chiefly basalts and andesites that were erupted from numerous exposed and concealed vents and fissures scattered throughout the outcrop areas in eastern Oregon. These rocks generally are faulted and are flat lying to gently dipping. In many areas, volcanic rocks are interlayered with ash, cinders, and tuffaceous sediment derived, in part, by erosion and redeposition of the volcanic rocks. Clastic sediments commonly are more abundant than volcanic rocks in structural basins. The total thickness of the volcanic and sedimentary rocks may exceed several thousand feet locally. Wells that supply water for irrigation and other large uses generally yield 50 to 300 gal/min and generally range in depth from 100 to 600 ft.

Much of the area underlain by the volcanic and sedimentary aquifers is mountainous and has a short growing season. For this reason, the aquifers generally are developed only in

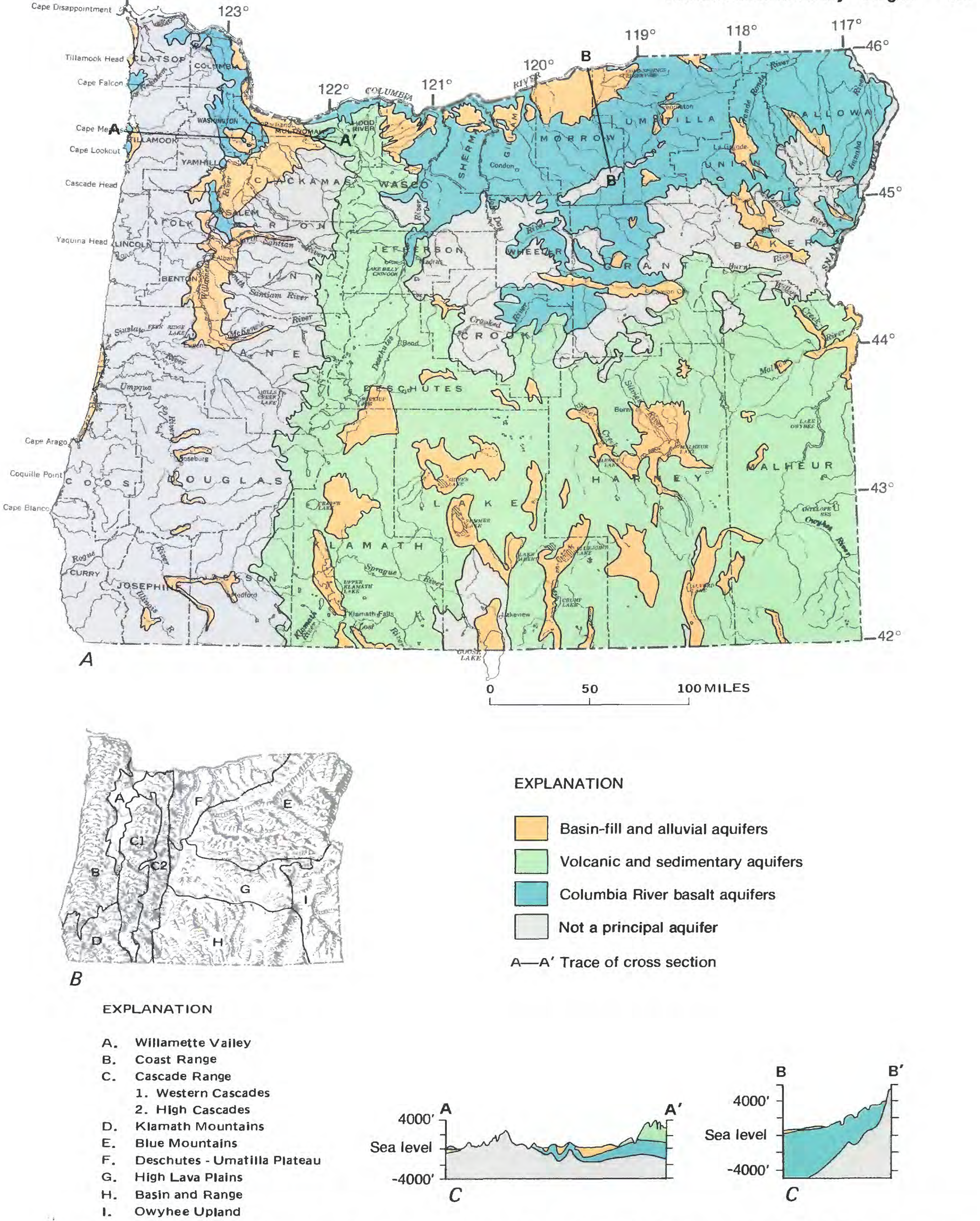


Figure 1. Principal aquifers in Oregon. *A*, Geographic Distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross sections (A-A', B-B'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Wells and Peck, 1961; Walker, 1977. *B*, Dicken, 1965; Raisz, 1954. *C*, McFarland, 1982; Gonthier, 1984.)

the basins, and very little is known about the hydrology of the aquifers outside the basins.

Surface drainage is poorly developed on the volcanic and sedimentary rocks of the High Lava Plains region and in parts of the High Cascades, and drainage is internal in the Basin and Range and in parts of the Owyhee Upland regions. Therefore, precipitation readily infiltrates into the ground in most of the outcrop areas. In the High Cascades, ground-water recharge from snowmelt can be as much as tens of inches. Recharge of ground water in the High Cascades discharges chiefly to the tributaries of the Klamath or Deschutes Rivers on the east side of the Cascades or to western Oregon streams. Elsewhere, the amount of recharge to this aquifer generally is small because the amount of precipitation is small.

The quality of water in the volcanic and sedimentary aquifers generally is suitable for most uses; dissolved-solids concentration ranges from 32 to 2,840 mg/L, and the median concentration is 71 mg/L (Gonthier, 1984).

COLUMBIA RIVER BASALT AQUIFER

The aquifers in the Columbia River Basalt Group underlie a 50,000 square mile (mi^2) area in Oregon, Washington, and Idaho. The group consists of numerous Miocene basalt lava flows, with a few tuffaceous sedimentary interbeds, that comprise five separate formations. Together, these rocks probably exceed a thickness of 5,000 ft locally beneath the Deschutes-Umatilla Plateau where the rocks dip gently northward and are overlain in places by sediments (fig. 1). The most important formations in the group in Oregon, from youngest to oldest, are the Saddle Mountains, Wanapum, and Grande Ronde Basalts. The Grande Ronde is the thickest and most extensive. Wells drilled for irrigation, public-supply, or industrial use in the basalt generally yield 200 to 500 gal/min and are 100 to 600 ft deep.

The Columbia River Basalt aquifer is present in northwestern Oregon in the northern part of the Willamette Valley but is much thinner and not a major source of water in those areas. Water in the Columbia River Basalt aquifer generally is suitable for most uses. Dissolved-solids concentrations in eastern Oregon range from 50 to 695 mg/L; the median concentration is 238 mg/L (Gonthier, 1984). In western Oregon, the dissolved-solids concentrations range from 50 to 18,500 mg/L; the median concentration is 178 mg/L (McFarland, 1983).

GROUND-WATER WITHDRAWALS

Most of Oregon's major ground-water withdrawal areas and hydrographs from five selected observation wells in these areas are shown in figure 2. Many withdrawal centers that consist of only a few large-capacity wells may not be shown because reliable, current estimates of the quantities of water pumped are not available. At least two of the larger withdrawal centers shown in figure 2 are springs (locations 10, 15); the withdrawal shown for each spring site is that part of the total springflow that actually was used.

Recent studies in the Umatilla-Morrow County area (Ann Davies-Smith, U.S. Geological Survey, written commun., 1984) indicate that the total annual withdrawals from the Columbia River Basalt aquifer in that area ranged from 70 to 77 Mgal/d from 1979 through 1982 and that an estimated additional 25 Mgal/d was withdrawn from the shallow basin-fill and alluvial aquifer that overlies the basalt (D. D. Harris, U.S. Geological Survey, written commun., 1984). Locations 3 and 4 (fig. 2) are near the centers of the most intensively developed areas in both aquifers; the remainder of the pumpage is distributed outside these locations. Declines of 20 ft or more have occurred in the Columbia River Basalt aquifer (location 3, fig. 2) beneath a 530-mi^2 area and declines of 200 ft or more have occurred beneath a 20-mi^2 area (Ann Davies-Smith, U.S. Geological Survey, written commun., 1984).

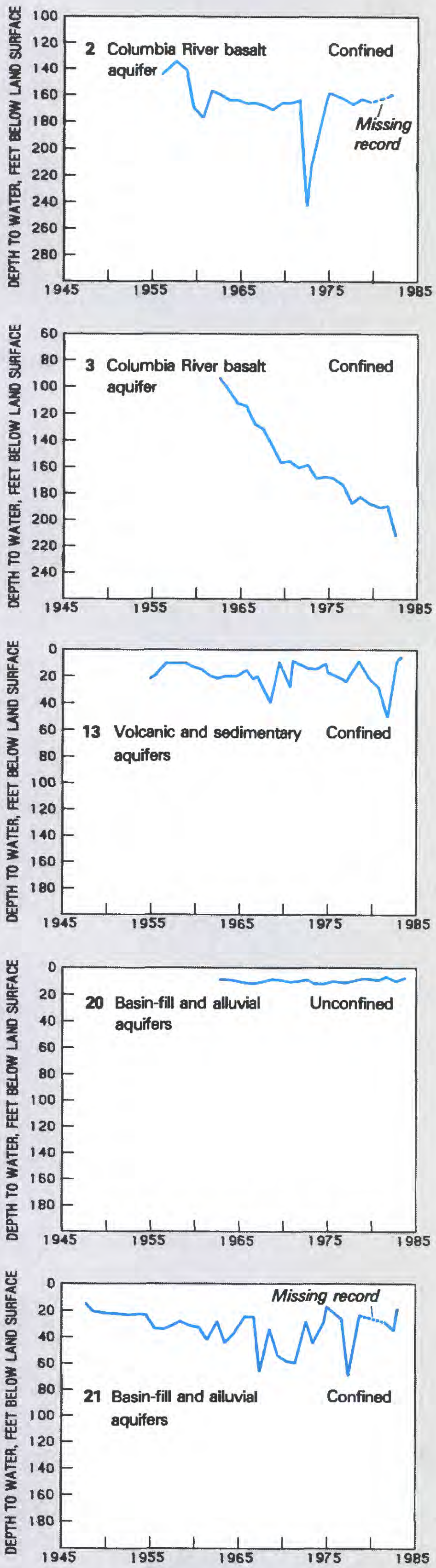
As of 1982, four areas in Oregon had been declared critical ground-water areas by the Oregon Water Resources Department (Oregon Water Resources Department, 1983)—Cow Valley (location 8, fig. 2), The Dalles (near location 2, fig. 2), Cooper Mountain–Bull Mountain (near location 22, fig. 2), and the Ordnance area (near location 3). Water-level declines in the first three critical areas have stabilized. In 1966, for example, the State declared a 20-mi^2 area of The Dalles a critical ground-water area because of declining water levels and took action to reduce withdrawals from the confined Columbia River Basalt aquifer in that area. The hydrograph (location 2, fig. 2) shows the effects of the reduction in withdrawals, though water levels were stable after 1966 except during the drought of 1972–73.

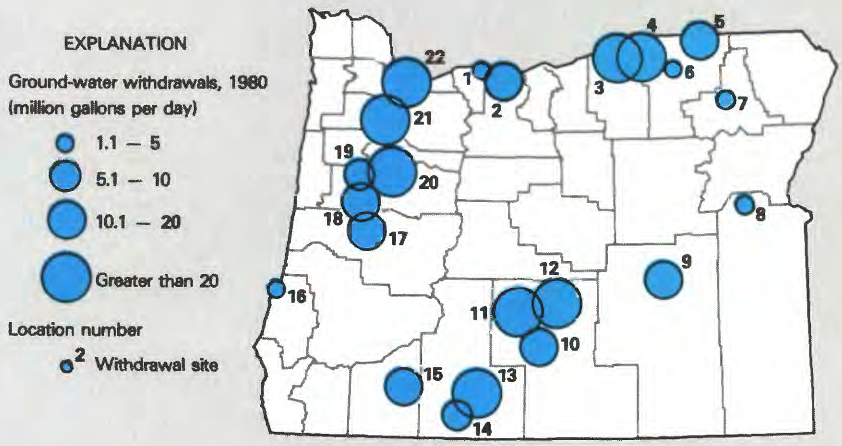
Another area with declining water levels is the Fort Rock Valley- Christmas Lake Valley areas (locations 11, 12, fig. 2). A combined total of about 80 Mgal/d was pumped in 1980 from the basin-fill and alluvial aquifers and from the underlying volcanic and sedimentary aquifers beneath this area (D. W. Miller, Oregon Water Resources Department, written commun., 1984). This quantity is distributed rather uniformly in each valley. The two aquifers are connected hydraulically, and they respond to pumping stresses as a single aquifer system. The large withdrawal rate probably is greater than the average annual recharge to the aquifer system, and water-level declines are being noted. A temporary moratorium is in effect that delays the issuance of new water-rights permits until a preliminary study of the situation by the Oregon Water Resources Department (OWRD) is completed.

Reliable, current estimates of ground-water withdrawals in the Willamette Valley are not available, but estimates made in the late 1960's and early 1970's indicated that withdrawals were substantial and probably in excess of 120 Mgal/d; the rate probably is much greater today. This pumpage is both widely distributed and localized; some of the areas of more localized pumpage are shown in figure 2 (Helm and Leonard, 1977). The well hydrographs from two of the more intensively pumped areas within the valley (locations 20, 21, fig. 2) indicate that recharge and discharge are in balance in the valley. The well hydrograph for the Klamath Basin (location 13, fig. 2) also indicates this is true for part of that area.

GROUND-WATER MANAGEMENT

Oregon law gives the Director of the Oregon Water Resources Department (OWRD) the authority to issue permits to appropriate the State's ground and surface waters for beneficial uses and also gives the Department responsibility of ensuring that water supplies are adequate for human consumption. The Director has the authority to take action to limit adverse impacts, such as well interference with existing water rights and ground-water pollution, where joint voluntary action among users is inadequate. The Director also regulates licensing of water-well drillers and establishes water-well construction criteria. The OWRD is the principal cooperator with the U.S. Geological Survey in investigation of the State's ground-water resources. These activities include data collection, data analyses, and interpretive studies that together form an information base for ground-water resource planning and management. The Department of Environmental Quality (DEQ) is responsible for establishing and enforcing rules designed to prevent contamination of Oregon ground-water resources.





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Hood River (Springs)	Volcanic and sedimentary.	Public supply.
2	Northern Wasco County . .	Columbia River basalt, Basin-fill and alluvial.	Irrigation.
3	Eastern Morrow County . .	. . . .do	Do.
4	Western Umatilla County.	. . . .do	Do.
5	Milton-Freewater area . . .	Basin-fill and alluvial, Columbia River basalt.	Do.
6	Pendleton	Columbia River basalt, Basin-fill and alluvial.	Public supply.
7	Grande Ronde Valley. . . .	. . . .do	Irrigation.
8	Cow Valley	Volcanic and sedimentary.	Do.
9	Harney Valley	Volcanic and sedimentary, basin-fill and alluvial.	Do.
10	Ana River Springs.	Basin-fill and alluvial.	Do.
11	Fort Rock Valley	Basin-fill and alluvial, volcanic and sedimentary.	Do.
12	Christmas Lake Valley . . .	. . . .do	Do.
13	Klamath Basin.	Volcanic and sedimentary.	Do.
14	Klamath Falls	Basin-fill and alluvial.	Public supply.
15	Big Butte Springs (Medford).	Volcanic and sedimentary.	Do.
16	Coos Bay-North Bend . . .	Basin-fill and alluvial.	Do.
17	Eugene-Springfield area . .	. . . .do	Irrigation, public supply.
18	Harrisburg-Halsey area . . .	. . . .do	Irrigation.
19	Corvallis-Albany area. . . .	. . . .do	Do.
20	North Santiam area.	. . . .do	Do.
21	French Prairie-Molalla area.	. . . .do	Do.
22	Portland area	. . . .do	Irrigation, public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Oregon. (Sources: Withdrawal data from several sources cited in selected references; water-level data from U.S. Geological Survey files.)

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Prepared by Joseph B. Gonthier

For further information contact District Chief, U.S. Geological Survey, 847 NE 19th Avenue, Suite 300, Portland, OR 97232

PENNSYLVANIA
Ground-Water Resources

More than one-third of the people of Pennsylvania depend on ground water for freshwater supply. Ground-water use is greatest in the population centers of southeastern and southwestern Pennsylvania. However, the percentage of the population that depends on ground water is usually greater in rural areas. As an example, Warren County, a sparsely populated area, obtains about 97 percent of its water needs from ground water (Becher, 1971). Ground water is the sole source of supply to more than one-half of the private water-supply companies in Pennsylvania and almost two-thirds of the average streamflow in the State is derived from ground-water discharge.

GENERAL SETTING

Pennsylvania's diverse and complex geology manifests itself in four distinct physiographic provinces (fig. 1)—the Coastal Plain, the Piedmont, the Valley and Ridge, and the Appalachian Plateau. The Coastal Plain consists of unconsolidated layers of sand, gravel, and clay that dip gently to the southeast and underlie relatively flat lowlands. The Piedmont is made up of diverse rock types, many of which have been severely deformed and altered; rolling lowlands characterize the northwest and southeast, and the middle of the province consists of a belt of broad highlands and ridges. The Valley and Ridge province consists of rock layers that have been deformed into a series of folds in which resistant sandstone produces long, narrow ridges separated by long valleys underlain by limestone and shale. Glacial deposits mantle the northeastern part of the province. The physiography of the Appalachian Plateaus is dominated by gently warped or tilted layers of sandstone and shale; the province is a ruggedly hilly area, mountainous in part, and contains intricately dissected plateaus and broad ridges.

Glacial deposits thinly mantle the northwestern and northeastern parts of the State. Many preglacial valleys are completely filled with the deposits, which form important ground-water reservoirs.

Precipitation in Pennsylvania ranges from 39 to 50 inches (in.) annually, and averages 44 in. About 55 to 60 percent of the precipitation falls during the warm one-half of the year, most occurring during intense rain storms. Precipitation during the cool one-half of the year falls mostly as snow or slow, steady rain.

PRINCIPAL AQUIFERS

Four principal types of aquifers exist in Pennsylvania—unconsolidated sand-and-gravel aquifers that consist of Coastal Plain sediments and glaciofluvial and alluvial deposits, sandstone and shale aquifers that consist of interbedded sandstone and shale, carbonate aquifers, and crystalline bedrock aquifers that consist of igneous and metamorphic rocks. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Table 1. Ground-water facts for Pennsylvania

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = millions gallon per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	5,204
Percentage of total population	44
From public water-supply systems:	
Number (thousands)	2,180
Percentage of total population	18
From rural self-supplied systems:	
Number (thousands)	3,024
Percentage of total population	26
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	16,000
Ground water only (Mgal/d)	1,000
Percentage of total	6
Percentage of total excluding withdrawals for thermoelectric power	6
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	240
Percentage of total ground water	23
Percentage of total public supply	16
Per capita (gal/d)	110
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	150
Percentage of total ground water	15
Percentage of total rural domestic	100
Per capita (gal/d)	50
Livestock:	
Ground water (Mgal/d)	54
Percentage of total ground water	5
Percentage of total livestock	88
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	560
Percentage of total ground water	55
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	4
Excluding withdrawals for thermoelectric power	15
Irrigation withdrawals:	
Ground water (Mgal/d)	22
Percentage of total ground water	2
Percentage of total irrigation	14

UNCONSOLIDATED SAND AND GRAVEL AQUIFERS

Unconsolidated aquifers are composed of sand and gravel that overlies bedrock. These aquifers range in thickness from only a few feet to more than 200 feet (ft) and are present in the northwestern, northeastern, and extreme southeastern parts of the State (fig. 1) and in some of the major stream valleys. The aquifers in stream valleys are made up of glacial valley-fill deposits and recent alluvial deposits.

Large amounts of water are stored in and can move freely through these aquifers. Yields to wells range from 100 to 2,300 gallons per minute (gal/min), depending on thickness of water-yielding zone, size and uniformity of the sand and

Table 2. Aquifer and well characteristics in Pennsylvania

[Mgal/d = millions of gallons per day; ft = feet; mg/L = milligrams per liter; gal/min = gallons per minute; Source: Becher, 1971.]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Unconsolidated sand and gravel aquifers: Sand, gravel, and clay. Unconfined to confined.	20 - 200	250	100 - 1,000	2,300	Present as valley-fill aquifers in northwestern and northeastern parts of State and as Coastal Plain aquifer in the southeast.
Sandstone and shale aquifers: Fractured sandstone and shale. Unconfined to confined.	80 - 200	400	5 - 60	600	Commonly yields soft water with less than 200 mg/L dissolved solids.
Carbonate aquifers: Limestone and dolomite. Unconfined to confined.	100 - 250	500	5 - 500	2,250	Commonly yields very hard water with more than 250 mg/L dissolved solids.
Crystalline bedrock aquifers: Fractured igneous and metamorphic rocks. Unconfined to confined.	75 - 150	-	5 - 25	220	Commonly yields small to moderate amounts of soft water containing less than 200 mg/L dissolved solids. Locally developed in conjunction with overlying unconsolidated sand-and-gravel aquifers.

gravel, and construction of the well. Water quality is variable and dependent on mineral content and quality of stream water, which provides recharge to the aquifers.

Sandstone and Shale Aquifers

The dominant lithology in the sandstone and shale aquifers vary with location and depth throughout the State. In one area and at a particular depth, the shale layer may be the primary source of water because it is considerably thicker than the sandstone layer. However, in very short lateral or vertical distances, wells in the sandstone may yield more water than those in the shale.

The sandstone aquifer contains moderate amounts of water that flows easily through a network of narrow openings formed by intersecting fractures, partings between rock layers, and pore spaces within the rock. Wells yield 5 to 60 gal/min of soft water [less than 60 milligrams per liter (mg/L) hardness as calcium carbonate], containing less than 200 mg/L of dissolved solids.

The shale aquifers contain moderate to large amounts of water in the partings of the shale. The water flows with difficulty between rock layers throughout networks of fine cracks and openings, and, generally, the shale yields less water to wells (5 to 25 gal/min) than the sandstone. Water is hard (121 to 180 mg/L as calcium carbonate), and dissolved-solids concentrations ranging from 200 to 250 mg/L are common.

Carbonate Aquifers

In some areas of the Commonwealth, the carbonate aquifers may be composed entirely of either limestone or dolomite, but, in most cases, both lithologies are present. In some locations of south-central Pennsylvania, the aquifers are extremely tight and only slightly fractured; in these places, the aquifers yield very little water to wells. In most locations, however, the yields are significant, and maximum yields are exceeded only by those from the unconsolidated valley-fill aquifers.

Volumes of water stored in limestone and dolomite are highly variable, depending on the site and interconnection of solution channels, fractures, and partings between rock layers where these features exist. Yields to wells of 5 to 500 gal/min of very hard (greater than 180 mg/L hardness as calcium carbonate), mineralized (greater than 250 mg/L dissolved solids) water are common.

Crystalline Bedrock Aquifers

Most of the crystalline bedrock aquifers in Pennsylvania are located in the southeastern part of the Commonwealth. Small to moderate amounts of water are stored in the rocks and move with difficulty through networks of fine fractures. Yields to wells of 5 to 25 gal/min of soft (less than 60 mg/L as calcium carbonate), fresh (less than 200 mg/L dissolved solids) water are common. However, water from some of the aquifers in gneiss and granite is moderately hard (exceeding 60 mg/L as calcium carbonate) and the iron content may exceed 0.3 mg/L.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Hydrographs showing ground-water-level fluctuations over time at selected sites in Pennsylvania are shown in figure 2. The ground-water observation-well network in Pennsylvania, operated on a cooperative basis by the U.S. Geological Survey and the Pennsylvania Bureau of Topographic and Geologic Survey, consists of 62 wells located in 62 of the State's 67 counties. Most wells are in rural areas, and, therefore, water levels recorded in these wells reflect the responses of aquifers to seasonal changes rather than to human activities. One exception is an observation well in Philadelphia County (location 14, fig. 2). For years, the U.S. Navy at Philadelphia obtained its water supply from the ground-water system. However, organic contamination of the ground water forced the Navy to shift to an alternative source of supply. The results of this cessation of pumping has been a recovery of water levels of almost 25 ft since about 1955, when pumping ceased.

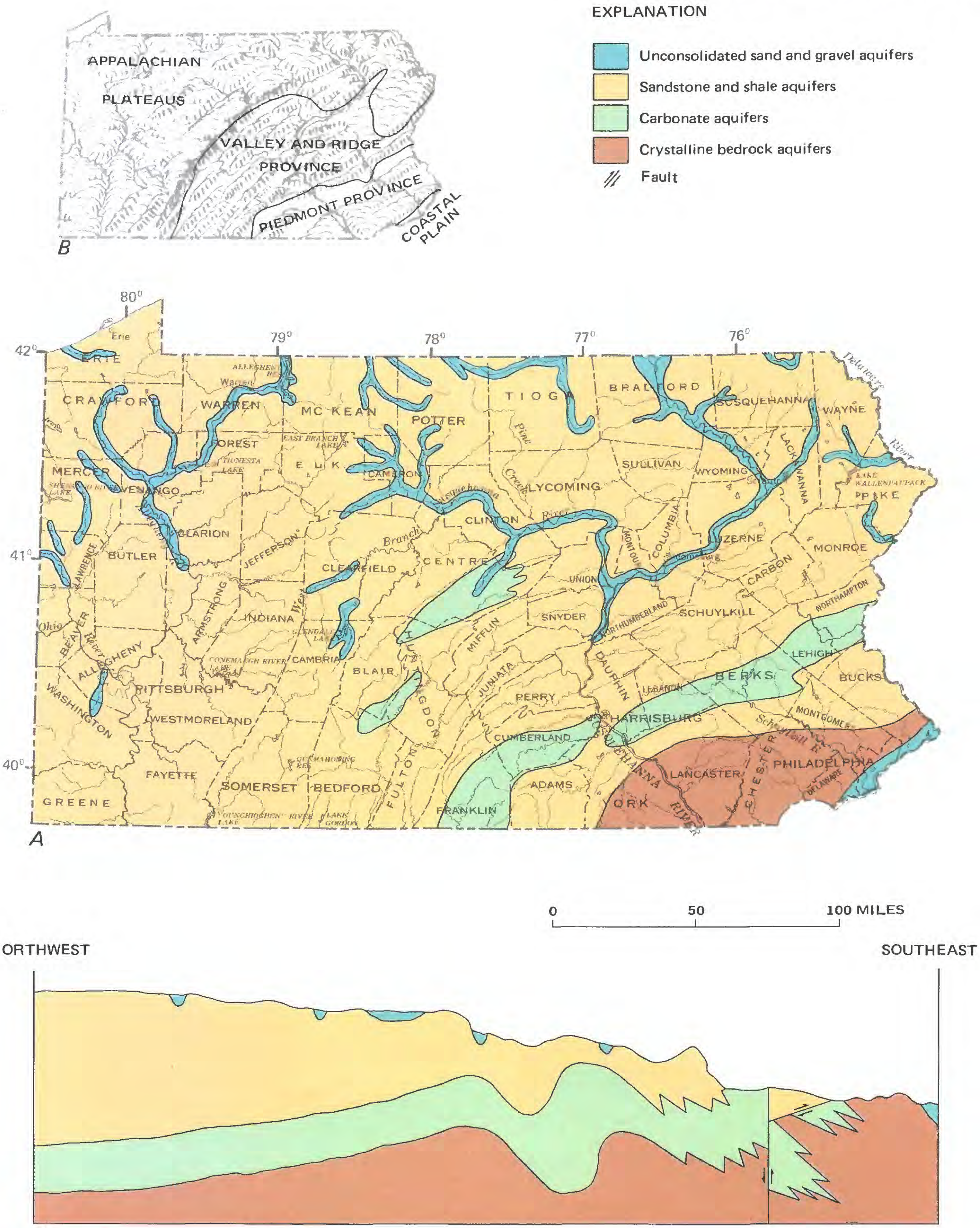


Figure 1. Principal aquifers of Pennsylvania. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section. (See table 2 for a more detailed description of the aquifers. Sources: *A*, *C*, compiled by J. H. McCoy from U.S. Geological Survey files. *B*, Raisz, 1954.)

The withdrawals in figure 2 represent total pumpage for the indicated county. Location 2, for example, is located near Pittsburgh, but the withdrawal rate of more than 60 Mgal/d is from an area of more than 400 square miles (mi^2) of Allegheny County.

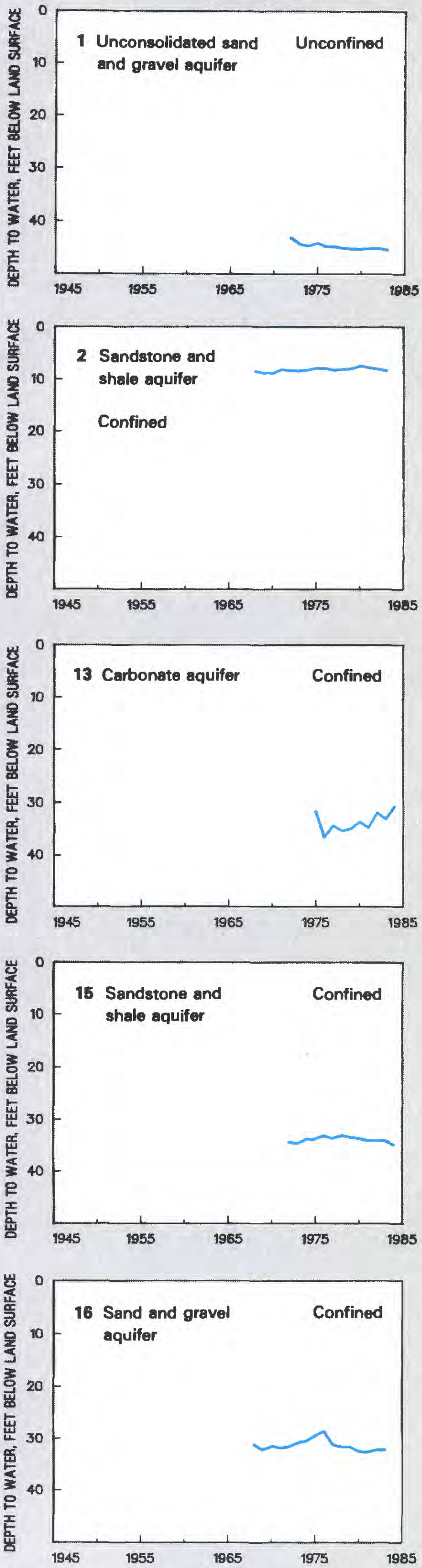
GROUND-WATER MANAGEMENT

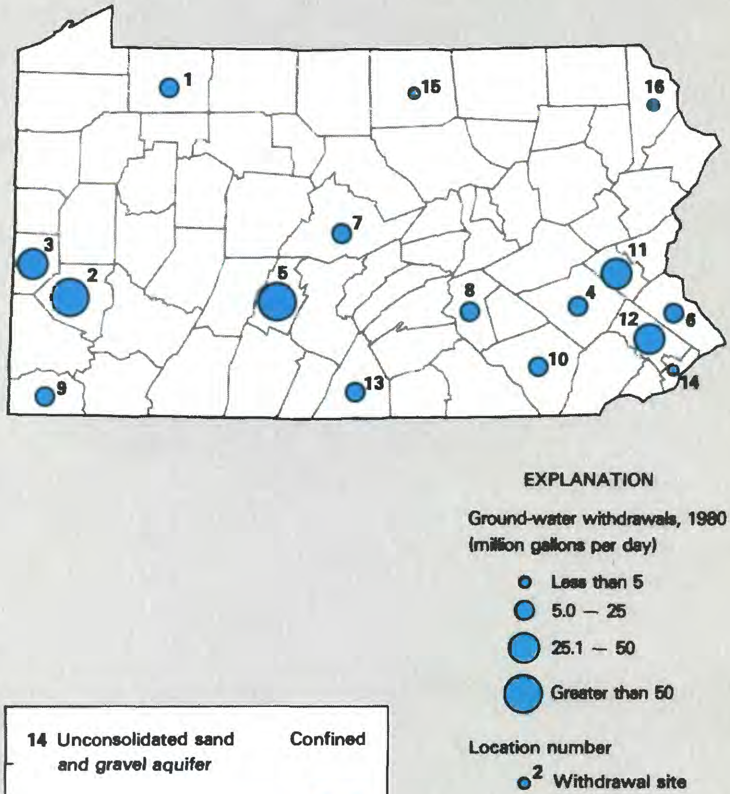
The Pennsylvania Department of Environmental Resources (PADER) is the State agency responsible for developing water-management policies and practices. A comprehensive "State Water Plan," developed by the PADER, forms the basis for water-resource management in the State. Several offices and bureaus within the Department conduct hydrologic studies of ground-water resources independently and in cooperation with the U.S. Geological Survey.

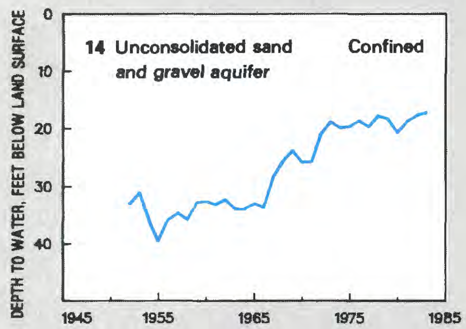
Existing State statutes and regulatory programs do not comprehensively address the allocation of ground water among competing users or provide for long-term management of ground-water resources. At present, Pennsylvania's statutes provide that each adjoining landowner has an equal and correlative right to make reasonable use of the ground water below his land. Two statutes focus on ground-water aspects of water-resource management: the Water Well Drillers License Act and the Clean Streams Law. The Water Well Drillers License Act is essentially a driller-registration program that is administered by the Pennsylvania Bureau of Topographic and Geologic Survey. The Clean Streams Law is primarily a regulatory act to control and prevent pollution of State waters. Springs and underground waters are included specifically within the law, which prohibits discharges of sewage or industrial waste unless authorized by permit and done in accordance with regulations adopted by the PADER.

The Delaware and Susquehanna River Basin Commissions (DRBC and SRBC, respectively), established by interstate compact to provide comprehensive planning and regulation of water resources, play an increasingly important role in managing the ground waters of the eastern two-thirds of Pennsylvania. Pursuant to their project-review authority, the DRBC and SRBC require approval of proposed ground-water activities that may have a "substantial effect" on basin waters to assure consistency with commission-adopted comprehensive plans and with "the proper conservation, development, management, or control of the water resources of the basin" (R. T. Weston, PADER, written commun., 1984). Both commissions generally limit their review to projects involving ground-water withdrawals in excess of 100,000 gallons per day (gal/d). In addition to "project review" powers, both commissions are authorized to regulate withdrawals within designated areas or under emergency shortage conditions. The DRBC has exercised this authority in part, through the designation of a ground-water protected area in southeastern Pennsylvania and the invocation of emergency powers during droughts of the 1960's and 1980 and 1981.

A ground-water protected area program, instituted by DRBC and the Commonwealth, is intended to improve management of ground water in a 1,500-mi^2 section of predominantly Triassic lowland formations in southeastern Pennsylvania. The protected area comprises all or portions of Montgomery, Bucks, Chester, Berks, and Lehigh Counties. Within the designated area, ground-water withdrawals are carefully regulated to accomplish the most effective, long-term utilization of the resource. Under the DRBC regulations, any new withdrawal or increase in withdrawal from an existing well of 10,000 gal/d or more requires a DRBC permit. Owners of existing or proposed wells, from which withdrawals of more than 10,000 gal/d are expected, must consult with the DRBC at least 1 month before exploratory drilling and submit a hydrologic report as part of the DRBC permit-application process.







WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Warren County	Unconsolidated sand and gravel, sandstone and shale.	Public supply, rural domestic.
2	Allegheny County. . .	. . . .do	Public supply, industrial.
3	Beaver County.	. . . .do	Industrial.
4	Berks County	Carbonate	Public supply.
5	Blair County.	Carbonate, sandstone and shale.	Public supply, industrial.
6	Bucks County	Sandstone and shale. .	Do.
7	Centre County.	Carbonate	Public supply.
8	Dauphin County . . .	Carbonate, sandstone and shale.	Do.
9	Greene County	Sandstone and shale. .	Mining.
10	Lancaster County . . .	Carbonate, crystalline bedrock.	Public supply, industrial.
11	Lehigh County	Carbonate	Public supply.
12	Montgomery County.	Sandstone and shale. .	Do.
13	Franklin County . . .	Carbonate	Public supply, rural-domestic.
14	Philadelphia County.	Unconsolidated sand and gravel.	Industrial.
15	Tioga County	Sandstone and shale, send and gravel.	Public supply, rural-domestic.
16	Wayne County.	. . . .do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Pennsylvania. (Sources: Withdrawal data from the Pennsylvania Department of Environmental Resources; water-level data from the U.S. Geological Survey files.)

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Prepared by H. J. McCoy

For further information contact District Chief, U.S. Geological Survey, P.O. Box 1107, Harrisburg, PA 17108

PUERTO RICO
Ground-Water Resources

Ground water, which is an important resource in Puerto Rico, constitutes about 22 percent of the total water used on the main island. On the south coast, 50 percent of the water used is withdrawn from aquifers. Along the north coast, wells supply about 20 percent of the domestic, commercial, and industrial water demands. During the last 10 years, development of ground-water sources for public-water supply has increased at an annual rate of about 5 million gallons per day (Mgal/d). In the near future, the amount of ground water used for public supply may surpass the amount used for irrigation. Ground-water resources supply most of the water requirements for the pharmaceutical and the electronics industries, the two largest industrial employers. Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

GENERAL SETTING

The geology of Puerto Rico is characterized by a complex central core consisting mostly of volcanic and intrusive rocks that are flanked on the north and south by clastic sediments and limestone. The volcanic rocks are predominately ashy shale, agglomerate, and tuff, most of which are thoroughly indurated. Clastic sediments, which are composed predominately of poorly sorted mixtures of gravel, sand, and finer materials, predominate along the south coast where a series of coallesced alluvial fans has formed a coastal plain that averages 3 miles (mi) in width and extends eastward a total of 38 mi from Ponce. The limestone has been eroded in most parts of the south coast. At the north coast, the limestone has been subjected to extensive dissolution, which has produced a mature karst topography.

Recharge to the aquifers in Puerto Rico, including the offshore islands, is derived mainly from precipitation. Average annual rainfall is 75 inches (in.) on the main island but its location within the northeast trade winds and its mountainous interior influence the areal distribution. Near the coast on the north shore, annual average precipitation is 60 in.; it increases to 100 in. at the divide and decreases to an average of 35 in. along most of the south shore. The offshore islands receive an average annual rainfall of from 40 to 45 in. About 55 percent of the average annual rainfall is lost to evapotranspiration on the main island, and as much as 95 percent, on the offshore islands. Depending on local geology and physiography, recharge to the aquifers ranges from as much as 20 in. in the north-coast limestone belt to 5 in. or less in the alluvium-filled areas of the south coast and on the island of Vieques.

PRINCIPAL AQUIFERS

The principal aquifers in Puerto Rico are the North Coast limestone aquifer, the South Coastal Plain aquifer, the alluvial valley aquifers, and the Esperanza and Resolución Valley aquifer (on the island of Vieques). These aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Water quality of Puerto Rico's principal aquifers generally is suitable for most uses. Ground water is of a calcium-bicarbonate type in most areas, and contains dissolved-solids concentrations ranging from 200 to 500 milligrams per liter (mg/L). However, the Esperanza and Resolución Valley aquifer in Vieques contains a sodium bicarbonate water with a dissolved-solids concentration as high as 700 mg/L. Excessive iron (0.14 mg/L) and manganese (1.4 mg/L) concentrations are common in wells on the east coast of the main island (Gómez-Gómez and Guzmán-Ríos, 1982). Saltwater upconing and intrusion are potential threats throughout the coastal areas but do not represent a general water-quality problem at present. The main water-quality problem appears to be contamination by organic compounds. In 1983, wells in three public-supply well fields that were found to be contaminated with volatile organics were closed (Guzmán-Ríos and Quiñones-Marquéz, 1984); two of the well fields tapped the North Coast limestone aquifer and the other tapped the South Coastal Plain aquifer.

Table 1. Ground-water facts for Puerto Rico

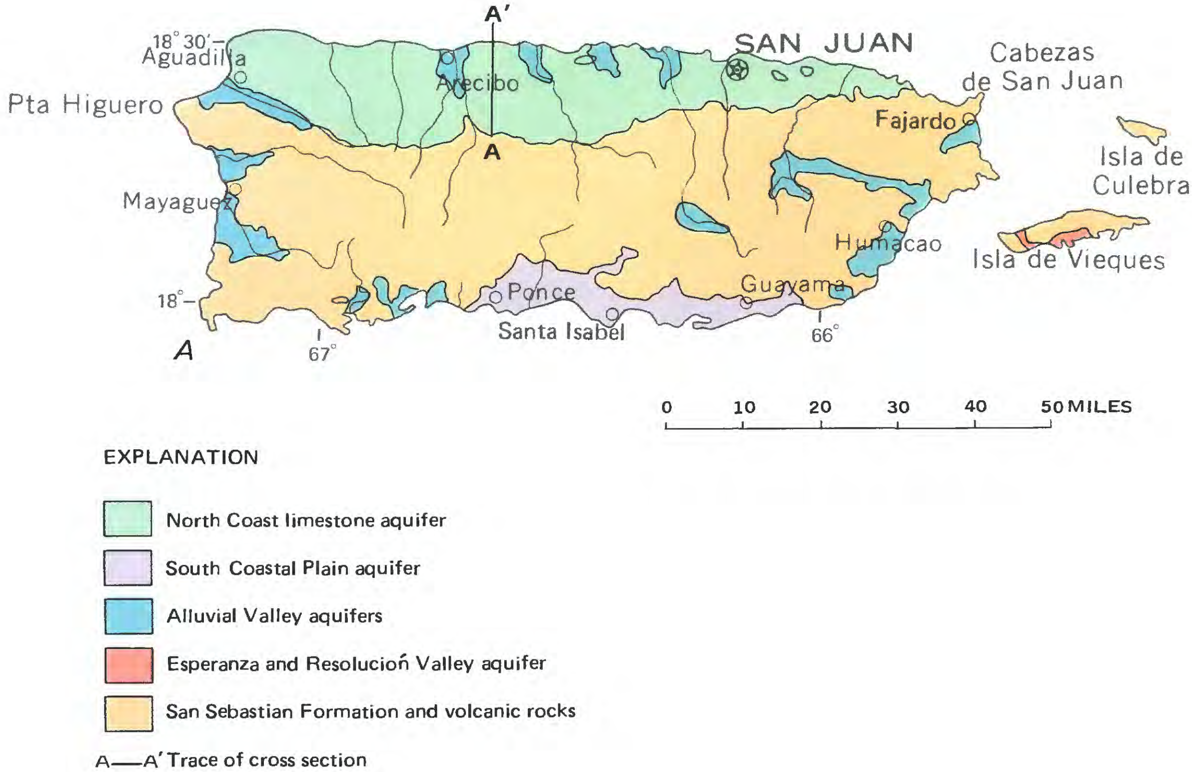
[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	853
Percentage of total population	26
From public water-supply systems:	
Number (thousands)	640
Percentage of total population	20
From rural self-supplied systems:	
Number (thousands)	213
Percentage of total population	6
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	1,100
Ground water only (Mgal/d)	246
Percentage of total	22
Percentage of total excluding withdrawals for thermoelectric power	35
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	75
Percentage of total ground water	30
Percentage of total public supply	22
Per capita (gal/d)	117
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	18
Percentage of total ground water	6
Percentage of total rural domestic	42
Per capita (gal/d)	85
Livestock:	
Ground water (Mgal/d)	3.0
Percentage of total ground water	1
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	57
Percentage of total ground water	23
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	3
Excluding withdrawals for thermoelectric power	21
Irrigation withdrawals:	
Ground water (Mgal/d)	100
Percentage of total ground water	40
Percentage of total irrigation	34

Table 2. Aquifer and well characteristics in Puerto Rico

[Mgal/d = million gallons per day; ft = feet; gal/min = gallons per minute. Sources: Gómez-Gómez and Heisel, 1980; Gómez-Gómez, Dacosta, and Orona, 1983; Ward and Truxes, 1964]

Aquifer name and description	Aquifer withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Well characteristics: Depth (ft) May exceed	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
North Coast limestone aquifer:						
Aymamón part: Middle and upper parts very pure chalky limestone, high secondary porosity. Basal part less pure limestone. Unconfined.	25	150 - 250	300	250 - 500	800	Ground water exists as a freshwater lens over saltwater. Upconing of saltwater a major problem. Important source of public-water supply for Barceloneta, Manatí, Vega Baja, Vega Alta, and Dorado.
Aguada part: Hard thick-bedded to massive calcarenite, locally rubbly. Contains alternating beds of clayey limestone. Unconfined.	25	100 - 200	250	100 - 250	500	Same conditions as with Aymamon part of aquifer. Important source of public-water supply for above municipalities plus Arecibo and Toa Baja.
Cibao part: Interbedded sequence of marl, chalk, limestone, sand and clay. Clastics materials predominate towards east and west, limestone in the middle part. Unconfined at outcrops; confined at depth.	10	100 - 300	2,000	50 - 100	200	Artesian zone mainly tapped by industry at Barceloneta and Manatí. Near coast wells penetrate 1,000 to 2,000 ft. Yields as much as 1,000 gal/min.
Lares part: Thin-bedded limestone at base, changing upward to a thick-bedded and massive, dense limestone. Thins east and west from central area, eventually pinching out at margins of limestone belt. Unconfined at outcrops; confined at depth.	6	300 - 400	400	0 - 50	50	At the outcrop area very poor yields; wells must penetrate in excess of 300 ft to reach water table. Near coast few wells tap this aquifer exclusively.
South Coastal Plain aquifer: Coarse sand and gravel as lenses at central areas of coalescing fans; finer material prevails near shore and interfluvial areas. Unconfined; locally semiconfined near coast.	120	100 - 150	200	300 - 500	1,000	Approximately 90 percent of withdrawals for irrigation. important public water-supply source for Ponce, Juana Díaz Santa Isabel, Coamo, and Salinas.
Alluvial valley aquifers: Alluvium of north, east, and west valleys is high in fine sand, silt, and clay, with most gravel at inland areas; at south coast alluvium is higher in coarse grained material; at interior valleys alluvium is mainly clay and rock fragments. Unconfined; interior valleys semiconfined.	40	100 - 150	200	50 - 150	800	Saltwater upconing and seawater intrusion widespread at coastal valleys on north, east, and south. Iron and manganese concentrations high at east valleys. Important public water-supply source for municipalities of Arecibo, Manatí, Yabucoa, Maunabo, Guayanilla, Yauco, Guánica, Cabo Rojo, Hormigueros, and San Germán.
Esperanza and Resolución Valley aquifer: Fine-grained alluvium derived from dioritic rocks, at Resolución underlain by weathered and fractured rock. Mostly semiconfined.	0	50 - 80	100	30 - 50	100	Only major freshwater resource in the island. Aquifers have long-term potential yield of 0.5 Mgal/d. Until 1978 provided 0.4 Mgal/d for public water supply. Slight saltwater intrusion reported at some wells but not severe on stand-by use.



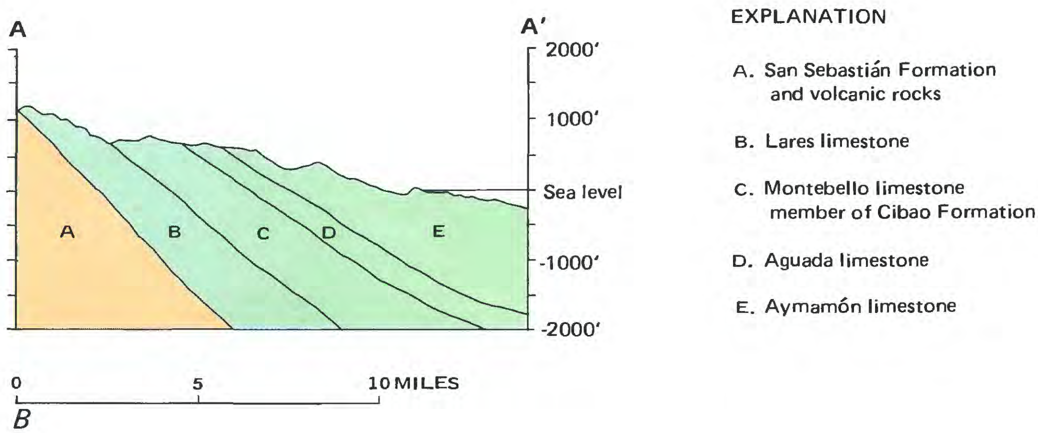


Figure 1. Principal aquifers in Puerto Rico. *A*, Geographic distribution. *B*, Generalized cross section (A-A') showing principal hydrologic units of the North Coast limestone aquifer. (See table 2 for a more detailed description of the aquifers. Sources: *A*, *B*, Compiled by F. Gómez-Gómez from U.S. Geological Survey files.)

North Coast Limestone Aquifer

The North Coast limestone aquifer is the principal source of water for municipalities and industries between Arecibo and the metropolitan area of San Juan. Ground water is under water-table conditions in the shallow parts of the Lares, Aguada, and Aymamón Limestones and the Cibao Formation, and under artesian conditions in deeper sections of the Cibao Formation and Lares Limestone (fig. 1). The water-table aquifer within the Aguada and Aymamón Limestones is principally a lens of freshwater that overlies saltwater; in general, the aquifer is 200 feet (ft) thick inland and thins toward the shore.

Yields to wells that tap the North Coast limestone aquifer depend mainly on the extent of secondary porosity that has developed mainly by dissolution of the carbonate rock. In general, the most productive parts of the water-table aquifer are the Aymamón and Aguada Limestones. Yields from wells drilled into the Cibao Formation and Lares Limestone are typically one order of magnitude lower except within the confined parts of the aquifer.

South Coastal Plain Aquifer

The South Coastal Plain aquifer provides one-half of the water used on the south coast of Puerto Rico. Of this, 100 million gallons per day (Mgal/d) are withdrawn for irrigation. The aquifer generally is unconfined except locally near the coast where semiconfined conditions exist. The aquifer consists of coalescing alluvial fans from 300 ft thick at Ponce to as much as 2,000 ft thick near Santa Isabel. Eastward of Santa Isabel, the thickness of the alluvium averages 150 ft. Near the coast throughout most of the western one-half of the South Coastal Plain aquifer, freshwater in the aquifer is underlain by saltwater at depths of more than 250 ft.

Alluvial Valley Aquifers

The alluvial valley aquifers are locally important sources for public supply. In most areas, the ground water is unconfined, but semiconfined conditions are present locally. Valleys are incised into limestone bedrock on both the north and the south coasts. Alluvium is as much as 300 ft thick at the north coast valleys and as much as 200 ft thick in the south coast valleys. The valleys that are incised in volcanic rock generally contain alluvium consisting predominately of fine-grained material. On the west coast, alluvium is as much as 450 ft thick; on the east coast, it is as much as 400 ft thick (Gómez-Gómez and Heisel, 1980). In the east-central interior valleys of Cayey and Caguas-Juncos, alluvial deposits generally are less than 100 ft thick and consist predominately of clay and rock fragments.

Esperanza and Resolución Valley Aquifer

The Esperanza and Resolución Valley aquifer was, until recently, the only freshwater source for the 8,000 inhabitants of the island of Vieques. Since 1978, the island is served by a public-supply pipeline from Puerto Rico. The aquifer consists of alluvial deposits as much as 70 ft thick. Ground water is mostly under semiconfined conditions.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The principal areas of ground-water withdrawals and trends in ground-water levels at selected areas in Puerto Rico are shown in figure 2.

The largest areas of withdrawal from the North Coast limestone aquifer (mostly from the Aymamón and Aguada Limestones) are located within the municipalities west of metropolitan San Juan and east of Arecibo. These withdrawals are principally for public-water supply (85 percent) and industrial-self supplied use (15 percent). Water in the North Coast Limestone aquifer is unconfined at this point and water levels do not show any major trend (location 5, fig. 2). However, within the confined aquifer (Cibao Formation), water levels in wells have dropped about 140 ft in 9 years. Withdrawals from the confined aquifer are estimated to be about 5 Mgal/d, mainly concentrated at Barceloneta (location 2, fig. 2).

The rise and fall of water levels in the South Coastal Plain aquifer are more significant than those in the North Coast limestone aquifer. Water levels in the South Coastal Plain aquifer near the city of Santa Isabel decline because of intensive irrigation and pumpage. However, they recover rapidly in response to ground-water recharge from heavy rainfall (location 12, fig. 2).

Water levels in wells in the alluvial valley aquifers (location 14, fig. 2) generally decline during low streamflow periods and recover during the highflow season (September-November). Increased withdrawals from these wells probably would lower the water table and induce inland movement of the seawater-freshwater interface (Bennett, 1976; Robison and Anders, 1973). Locally excessive pumpage of wells may induce upconing of saltwater; this occurred at the Río Grande de Manatí alluvial valley (north-central Puerto Rico), even though water levels did not decline significantly (Gómez-Gómez, 1984).

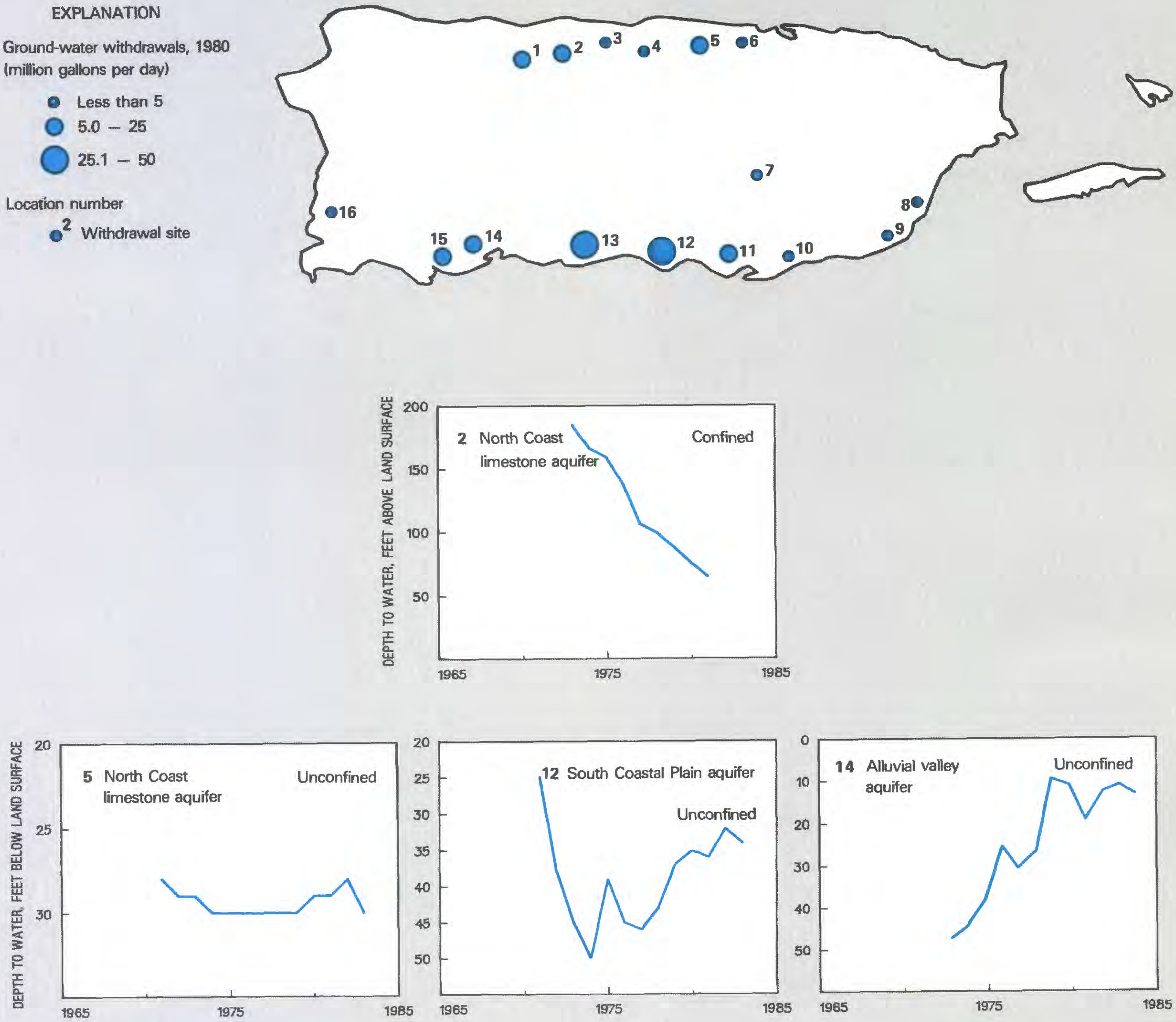
Ground-water withdrawals from the Esperanza and Resolución Valley aquifer on Vieques reached a peak of about 0.5 Mgal/d in 1978. Most of the wells in the valley were affected by saltwater intrusion and (or) upconing. At present, no significant withdrawals are occurring due to the existence of the fresh-water pipeline from Puerto Rico. A recent investigation indicates that water quality in the aquifer is improving (Sigfredo Torres-Gonzáles, U.S. Geological Survey, written commun., May 1984).

GROUND-WATER MANAGEMENT

The Government of the Commonwealth of Puerto Rico has enacted extensive ground-water legislation. The Puerto Rico Department of Natural Resources (DNR) has been entrusted with the implementation of most of the elements of the water law of 1976 that pertain to ground water. A system of permits for wells is in effect, and major regulations regarding the management and conservation of the ground-water resources are now in effect.

The Environmental Quality Board of Puerto Rico (EQB) manages most of the programs dealing with water quality, including a comprehensive underground injection program. The Puerto Rico Aqueduct and Sewer Authority (PRASA), an independent agency of the Government, operates the islandwide public water-supply system, which serves approximately 93 percent of Puerto Rico's population, as well as most light industry and commercial establishments. The PRASA recently has completed a comprehensive plan to develop additional supplies, including extensive withdrawals from the northern and southern coast aquifers.

The DNR, the EQB, the PRASA, and the Puerto Rico Department of Agriculture are the principal cooperators in the water-resources investigation program with the Caribbean District of the U.S. Geological Survey. As part of the cooperative program, a comprehensive 5-year appraisal of the ground-water resources of the north coast was begun in fiscal year 1984. An islandwide well inventory also was begun in 1984 to develop a computerized data bank for the use of the



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Arecibo	Alluvial valley	Public supply.
2	Barceloneta	North Coast limestone	Industrial, public supply.
3	Manati	Alluvial valley	Public supply, industrial.
4	Manati-Vega Baja	North Coast limestone	Do.
5	Vega Alta-Dorado	....do	Public supply, industrial, irrigaation.
6	Ton Baja	....do	Public supply.
7	Cayey	Alluvial valley	Do.
8	Yabcoa	....do	Public supply, industrial.
9	Maunabo	....do	Public supply.
10	Guayama	South Coastal Plain	Public supply, industrial.
11	Salinas	....do	Irrigation, public supply.
12	Santa Isabal	....do	Do.
13	Ponce	....do	Do.
14	Yauco	Alluvial valley	Irrigation, industrial, public supply.
15	Guanica	....do	Irrigation, public supply.
16	Cabo Rojo	....do	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water i n selected wells in Puerto Rico. (Sources: Withdrawal data from Gómez-Gómez and others, 1983; U.S. Army Corps of Engineers, 1980; water-level data from U.S. Geological Survey files.)

DNR and the EQB. A network of 57 wells is being sampled annually for major dissolved inorganic constituents and organic contaminants under the cooperative program. Ground-water flow models have been developed and calibrated in four basins for use by the DNR and the PRASA to achieve optimal aquifer development.

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Prepared by Ferdinand Quiñones-Marquéz, Fernando Gómez-Gómez, and Allen Zack

For further information contact District Chief, U.S. Geological Survey, G.P.O. Box 4424, San Juan, PR 00936

RHODE ISLAND
Ground-Water Resources

Ground water is a locally abundant and widely used resource in Rhode Island. In 1980, ground water supplied 22 percent of the freshwater used for all purposes and supplied drinking water to 24 percent of the State's 947,000 people (table 1). Most ground-water withdrawals were for public supply (51 percent) and for self-supplied industry (35 percent). Only 1.3 percent of ground-water withdrawals was used for irrigation. Withdrawal of ground water for public supplies nearly doubled from 1960 to 1980 [from 10 to 19 million gallons per day (Mgal/d)], whereas ground-water withdrawal for self-supplied industry decreased slightly (from 15 to 13 Mgal/d) (MacKichan and Kammerer, 1961; Solley and others, 1983). Reserves are adequate to meet a substantial part of the State's future public-supply and industrial water needs. Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

The quality of ground water in Rhode Island generally is suitable for human consumption and most other uses, except locally where it has been contaminated by land use activities. The water is soft, slightly acidic, and generally contains dissolved solids in concentrations of less than 150 milligrams per liter (mg/L).

Because of high aquifer permeability and the depth to the water table, which in most cases is small, ground water in Rhode Island is extremely susceptible to contamination. Local contamination of ground water has resulted from leaking gasoline tanks; leaching of hazardous chemicals from landfills, of salt from uncovered storage piles, and of fertilizers, pesticides, and herbicides applied to agricultural land and lawns; and other land use practices. Accidental spills of organic solvents have resulted in contamination of eight public-supply wells and more than 100 domestic wells.

Table 1. Ground-water facts for Rhode Island

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	224
Percentage of total population	24
From public water-supply systems:	
Number (thousands)	142
Percentage of total population	15
From rural self-supplied systems:	
Number (thousands)	82
Percentage of total population	9
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	170
Ground water only (Mgal/d)	37
Percentage of total	22
Percentage of total excluding withdrawals for thermoelectric power	21
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	19
Percentage of total ground water	51
Percentage of total public supply	15
Per capita (gal/d)	134
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	4.9
Percentage of total ground water	13
Percentage of total rural domestic	100
Per capita (gal/d)	60
Livestock:	
Ground water (Mgal/d)	0.1
Percentage of total ground water	0.3
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	13
Percentage of total ground water	35
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	36
Excluding withdrawals for thermoelectric power	36
Irrigation withdrawals:	
Ground water (Mgal/d)	0.5
Percentage of total ground water	1
Percentage of total irrigation	9

GENERAL SETTING

Rhode Island is in the New England Upland and Seaboard Lowland sections of the New England physiographic province and in the Glaciated Appalachian ground-water region (Fenneman, 1938) (fig. 1). The physiography of Rhode Island affects the distribution of precipitation and, thus, the amount of water available to recharge aquifers.

Precipitation is the ultimate source of all ground water in Rhode Island. Average annual precipitation ranges from 42 inches (in.) near Narragansett Bay to 48 in. in the west-central part of the State (Kent and Providence Counties). Studies of ground-water recharge from precipitation have not been made in Rhode Island, but using data from New York and Connecticut (Pluhowski and Kantrowitz, 1964; Mazzaferro and others, 1979), it is estimated that approximately 8 to 9 in. of precipitation recharges ground water in areas of till, and 21 to 25 in. recharges ground water in areas of stratified drift. Significant recharge also is induced from streams and other bodies of surface water when intensive pumping occurs from wells located near them.

Ground water typically occurs under unconfined conditions throughout the State. Locally, however, ground water is confined beneath thick, areally extensive layers of silt and clay in stratified drift. Stratified-drift, till, and bedrock aquifers are interconnected hydraulically, which enables ground water to flow from one unit to the other. The aquifers also are connected hydraulically to streams.

PRINCIPAL AQUIFER

Aquifers in Rhode Island are of two types—unconsolidated glacial deposits and metasedimentary and crystalline bedrock. The glacial deposits, which consist of stratified drift and till (unstratified drift), mantle and largely conceal the bedrock that underlies the State. Stratified drift, which is the principal aquifer, underlies about one-third of the State, mainly as valley fill. The water-bearing characteristics of the stratified-drift aquifer is discussed below and in table 2; its areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics in Rhode Island

[Gal/min = gallons per minute; ft = feet. Sources: Reports of the U.S. Geological Survey and Rhode Island Water Resources Board]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Depth (ft) May exceed	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Principal aquifer:					
Stratified drift aquifer: Moderately to well sorted lenses of gravel, sand, and silt deposited by glacial meltwater streams. In places, interbedded with clay, silt, and silty sand deposited in glacial lakes. Unconfined, locally confined.	75 - 125	150	100 - 700	1,500	Moderately to very permeable. Induced recharge from streams a major source of water to most wells. Water from some wells show increases in manganese concentration after being put into production. Wells near tidal rivers, Narragansett Bay, and ocean may induce infiltration of saltwater.
Other aquifers:					
Till aquifer: Unsorted boulders, gravel, sand, silt, and clay. Unconfined.	10 - 25	30	1 - 5	10	Minor aquifer; little permeability Serves chiefly as storage reservoir supplying recharge to underlying bedrock and down-gradient bodies of stratified drift. Water quality generally good to excellent, but domestic wells contaminated readily by nearby septic systems. Many wells become dry during droughts.
Bedrock aquifer: Indurated to metamorphosed sedimentary rocks in the vicinity of Narragansett Bay; igneous and metamorphic rocks, chiefly granite and granite gneiss elsewhere. Unconfined.	100 - 300	500	1 - 20	50	Minor aquifer; principal source of water to wells in areas not served by public water supply. Water quality generally excellent, but locally contains excessive concentrations of iron.

STRATIFIED DRIFT AQUIFERS

Stratified drift is the only aquifer type in Rhode Island capable of sustaining yields adequate for large public, industrial, and irrigation supplies. In most parts of the State, stratified drift consists of interbedded, lenticular deposits of gravel, sand, and silt that were laid down by glacial meltwater streams. In a few areas, thick layers of clay, silt, and fine to very fine sand deposited in glacial lakes are interbedded with, or underlie, deposits of coarse sand and gravel. In the northern part of the State, stratified drift partly fills the centers of the valleys. In the lowland areas bordering Narragansett Bay and in much of the central and southern parts of the State, stratified drift fills, and, in some locations, completely conceals, preglacial channels in the bedrock. These sediments are commonly 75 to 100 feet (ft) thick near the axes of buried channels and, in some localities, are as much as 300 ft thick. In most places the water table is within 20 ft of land surface and fluctuates 3 to 5 ft during the year.

Yields of wells in stratified drift are extremely variable, ranging from a few gallons per minute to about 1,500 gallons per minute (gal/min). Yields of 100 to 700 gal/min generally are obtainable from wells at some locations in all major stratified-drift aquifers. Where stratified drift is thick and very permeable, it forms major ground-water reservoirs that have the potential for providing large quantities of water for public-supply and industrial use (Lang, 1961).

Induced recharge from streams is a major source of water to most intensively pumped wells in stratified-drift aquifers in Rhode Island. Such wells usually are located within a few hundred feet of a stream. Some of them, such as public-supply wells adjacent to the Blackstone River in Providence County, may derive virtually all their water from induced recharge.

The chemical quality of ground water derived largely from induced infiltration of streamflow is determined, in large part, by the quality of the streamflow. Water in most reaches of freshwater streams contains less than 150 mg/L of dissolved solids. Aquifers adjacent to tidal rivers, Narragansett Bay, and Block Island Sound are subject to contamination by induced infiltration of saline water. Contamination of stratified drift by induced infiltration of saline water has occurred near tidal streams in Providence County (Bierschenk, 1959) and in Bristol County (Bierschenk, 1954).

Concentrations of manganese have increased from less than 0.05 mg/L, which is the national drinking-water regulation (U.S. Environmental Protection Agency, 1982a), to more than 1.0 mg/L in water from some intensively pumped wells in stratified drift. The manganese is derived from organic-rich sediments that line the bottoms of some streams and manganese minerals that coat aquifer materials. Manganese is dissolved from these materials when the infiltrating water is made corrosive by loss of its dissolved oxygen. Biochemical reactions deplete dissolved oxygen as the water moves through organic-rich streambed sediments (Johnston and Dickerman, 1974; Silvey and Johnston, 1977).

OTHER AQUIFERS

Other aquifers in Rhode Island of importance, but not considered principal aquifers, are the till and bedrock aquifers. Each is discussed below and in table 2.

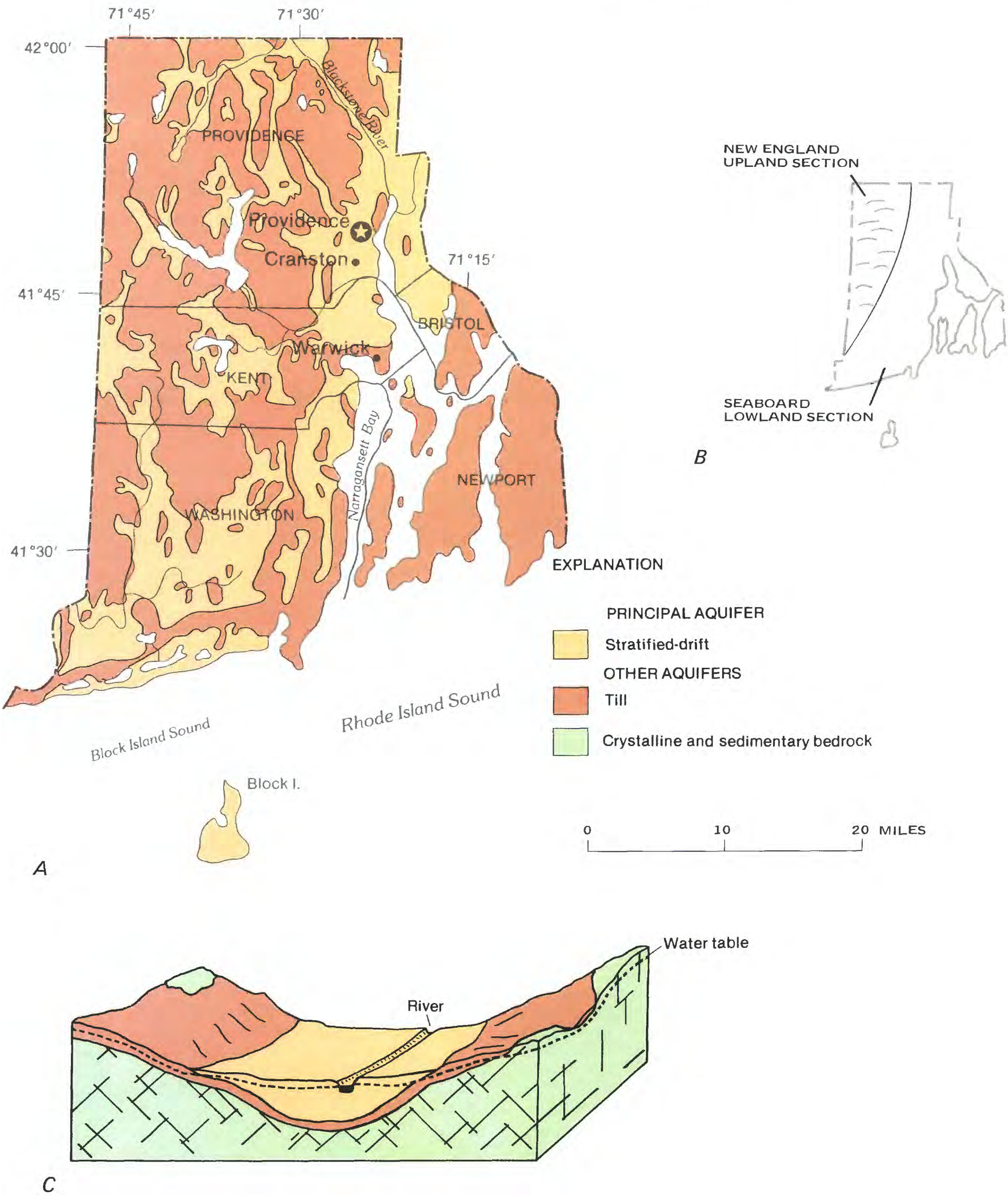


Figure 1. Principal aquifers in Rhode Island. *A*, Geographic distribution. *B*, Physiographic divisions. *C*, Block diagram showing vertical distribution of principal aquifers. (See table 2 for more detailed description of the aquifers. Sources: *A*, Lang, 1961. *B*, Fenneman, 1938. *C*, Compiled by H. E. Johnston from U.S. Geological Survey files.)

Till Aquifer

The till aquifer functions primarily as a storage reservoir that supplies water by natural gravity drainage to underlying bedrock and to downgradient stratified-drift aquifers. The till consists of an unsorted mixture of boulders, gravel, sand, silt, and clay. Permeability is small, and yields of large-diameter dug wells in this aquifer are commonly less than 2 gal/min. Thickness of the till averages about 20 ft and its saturated thickness averages between 5 and 10 ft. In winter and spring, when the water table is high, water levels in till commonly are within 5 to 10 ft of land surface, even in hilly areas. Because seasonal fluctuations of the water table commonly are 8 to 10 ft, till may become unsaturated locally during dry periods of summer and fall; for this reason, till is an unreliable source of water in many areas. Most of the shallow dug wells that once supplied homes and farms in areas underlain by till have been replaced by wells drilled into the underlying bedrock.

Bedrock Aquifers

The bedrock aquifer consists of well-indurated to metamorphosed sedimentary rocks near Narragansett Bay; elsewhere, bedrock consists of crystalline rocks, mainly granite and granite gneiss (Quinn, 1971). The water in bedrock is stored and transmitted through networks of narrow, widely spaced fractures that generally decrease in size and number with depth. Most of the fracture openings are present at depths of less than 300 ft in crystalline rocks and less than 500 ft in metamorphosed sedimentary rocks (Cushman and others, 1953). Yields of wells in bedrock generally do not exceed 50 gal/min, and most yield 10 gal/min or less; about 3 percent yield less than 1 gal/min (Allen, 1953). More than 90 percent of the wells drilled in bedrock yield supplies adequate for domestic use. Large concentrations of iron are present in water from some bedrock wells. Concentrations of iron of as much as 25 mg/L have been reported (Allen, 1953, p. 45), but values greater than 1.0 mg/L are uncommon.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Ground-water withdrawals from pumping centers in the stratified-drift aquifer in Rhode Island range from about 0.5 to 3.7 Mgal/d (fig. 2). Most large withdrawals are from pumping centers located within a few hundred feet of a stream. Withdrawals near these pumping centers generally are rapidly replenished by recharge induced from the streams. Therefore, nearby ground-water levels remain relatively stable. The hydrograph for the South Kingstown area (location 9, fig. 2) is representative of long-term water-level fluctuations at that location. Much of the recharge at that site is induced recharge from streams.

A gradual decrease in industrial pumpage of ground water in the Providence area of Providence County has resulted in a gradual rise in water levels in much of the area. Water levels near location 5 (fig. 2) illustrate this rising trend, which began about 1972; in 1978, the well flowed at the surface.

GROUND-WATER MANAGEMENT

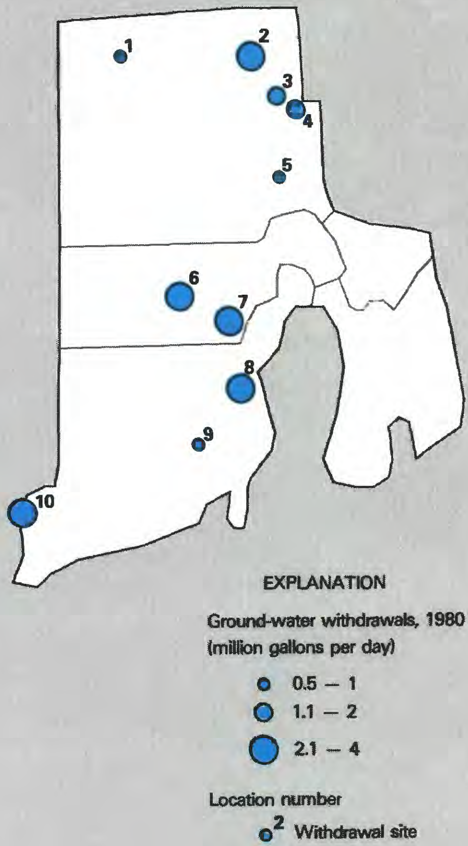
Ground-water management and planning in Rhode Island are the responsibilities of several State agencies. The Rhode Island Statewide Planning Program prepares and updates policies relating to development, management, and protection of ground-water resources but has no explicit legal authority to do so. The Rhode Island Department of Health is required by statute (Rhode Island General Laws, 46–13–1. et seq.) to ensure the quality of water delivered by public-supply systems, which includes all supplies having at least 15 service connections that regularly serve 25 or more people for 60 days or more during the year. More than 400 such systems, most supplied by ground water, are in service. The Health Department is also authorized (Rhode Island General Laws, 46–14–1, et seq.) to order abatement of pollution that poses a threat to a public supply.

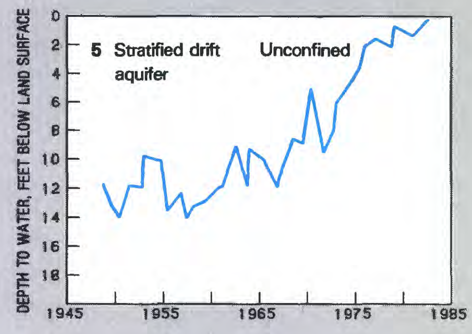
Principal legal authority for developmental planning, management, and protection of the quality of Rhode Island's ground-water resources is vested in the Rhode Island Water Resources Board (WRB) and the Rhode Island Department of Environmental Management (DEM).

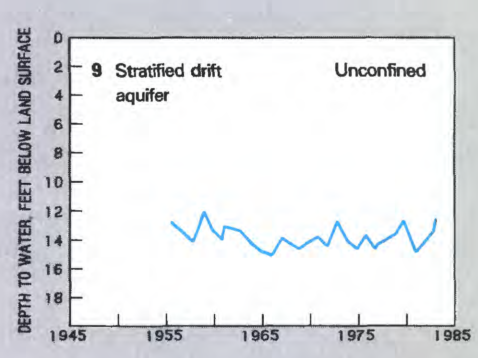
The WRB is charged under Rhode Island General Laws (46–15–1, et seq.) with formulating a long-range plan and implementing programs for developing of the State's major water resources, including ground water, needed for public supply. Under this statute, plans by public-supply systems for acquiring additional ground-water supplies from new sources must be approved by the WRB. Ground-water withdrawals for other than public-supply use are not regulated. The statute also authorizes registration of well drillers by the WRB, which requires drillers to submit well-completion reports. Less specific provisions of Chapter 46–15 empower the WRB to function as a steward of all the State's water resources and to develop policies controlling allocation, interbasin transfers, and conservation of water resources.

Under Rhode Island General Laws (46–12–1, et seq.), the DEM is the State's designated water-pollution-control agency. The DEM has the responsibility for regulating waste discharges to surface and ground water. Under this statute, the DEM is authorized to classify ground and surface water and to establish rules and regulations for the protection of both. A classification system and rules and regulations for protection of surface-water resources are in place. A comprehensive strategy for protecting ground-water quality is presently (1984) being developed by the DEM.

Investigations of water resources and collection of geohydrologic data by the U.S. Geological Survey are done in cooperation with the DEM and WRB. These investigations and the accumulated geohydrologic data provide most of the information available on ground-water resources in Rhode Island.







WITHDRAWAL SITES

[Aquifers are all stratified drift]

No. on map	Geographic area	Principal uses
1	Burrillville	Public supply.
2	Cumberland-Lincoln	Do.
3	Lincoln.	Do.
4	Pawtucket	Do.
5	Providence.	Industrial.
6	West Greenwich.	Public supply.
7	East Greenwich	Do.
8	North Kingstown	Do.
9	South Kingstown	Do.
10	Westerly	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Rhode Island. (Sources: Withdrawal data and water-level data from U.S. Geological Survey files.)

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Prepared by Herbert E. Johnston

For further information contact Chief, Rhode Island Office, U.S. Geological Survey, John O. Pastore Federal Building and U.S. Post Office, Providence, RI 02903

SOUTH CAROLINA
Ground-Water Resources

Fresh ground water is available in most of South Carolina. Although it provides only about 4 percent of total water used in the State, it serves 42 percent of the population, or about 1.33 million people. Most large withdrawals of ground water are obtained from Coastal Plain aquifers in the southeastern two-thirds of the State. Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

GENERAL SETTING

South Carolina is located in three physiographic provinces (fig. 1)—the Coastal Plain province, which occupies approximately the southeastern 63 percent of the State; the Piedmont province, which occupies roughly 35 percent of the State; and the Blue Ridge province, which occupies about 2 percent of the State (Fenneman, 1938). Coastal Plain deposits consist of consolidated and unconsolidated sediments of continental and marine origin that thicken from a few feet at the Fall Line to more than 4,000 feet (ft) at the southern tip of the State. The Piedmont and Blue Ridge provinces are underlain by metamorphosed sedimentary, volcanic, and igneous rocks. Most of the area is mantled by a layer of chemically weathered bedrock called saprolite, which ranges in thickness from a few feet to about 100 ft, but generally is less than 50 ft thick.

Recharge to the ground-water system in South Carolina is from precipitation. Statewide average annual precipitation is slightly more than 48 inches (in.) (Snyder and others, 1983) and ranges from an average of 46 in. in part of the central area of the State to 80 in. in the Blue Ridge province. Ground-water recharge ranges from less than 1 in. in parts of the Piedmont–Blue Ridge to about 15 in. in parts of the Coastal Plain.

PRINCIPAL AQUIFERS

Principal aquifers in South Carolina consist of unconsolidated to partly consolidated sediments of the Coastal Plain province and igneous and metamorphic rocks of the Blue Ridge and Piedmont provinces. The aquifer names commonly used in South Carolina are, for the most part, synonymous with the names of geologic formations that contain the principal water-bearing materials. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

COASTAL PLAIN AQUIFERS

The formations of the Coastal Plain consist of unconsolidated or partly consolidated sediments, including sand, gravel, clay, limestone, marl, coquina, and shale. Many of the formations of the Coastal Plain are excellent aquifers that are able to store and transmit large quantities of water.

Shallow Aquifer

A shallow aquifer occurs throughout the Coastal Plain but is not mapped in figure 1. In general, the aquifer consists of deposits that range in age from Cretaceous to Holocene, is less than 100 ft thick, and contains water under unconfined conditions, although semiconfined conditions may be present locally. The aquifer is used mostly for domestic and other small supplies, but, in some areas, such as North Myrtle Beach where very permeable beds of coquina are present, yields can exceed 500 gallons per minute (gal/min). Water quality is extremely variable, as are yields, but the aquifer is a valuable resource in many areas, particularly for rural domestic use. Recharge is from local rainfall; therefore, water levels tend to fluctuate seasonally.

Table 1. Ground-water facts for South Carolina

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Lonon and others, 1983]

Population served by ground water, 1980	
Number (thousands)	1,330
Percentage of total population	42
From public water-supply systems:	
Number (thousands)	530
Percentage of total population	17
From rural self-supplied systems:	
Number (thousands)	800
Percentage of total population	25
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	5,800
Ground water only (Mgal/d)	210
Percentage of total	4
Percentage of total excluding withdrawals for thermoelectric power	21
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	82
Percentage of total ground water	40
Percentage of total public supply	22
Per capita (gal/d)	155
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	57
Percentage of total ground water	28
Percentage of total rural domestic	100
Per capita (gal/d)	71
Livestock:	
Ground water (Mgal/d)	6
Percentage of total ground water	3
Percentage of total livestock	55
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	46
Percentage of total ground water	22
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	1
Excluding withdrawals for thermoelectric power	5
Irrigation withdrawals:	
Ground water (Mgal/d)	15
Percentage of total ground water	7
Percentage of total irrigation	27

Table 2. Aquifer and well characteristics in South Carolina

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and several State agencies]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Coastal Plain aquifers:				
Shallow aquifer: Sand, gravel, and coquina. Unconfined. (Not shown in fig. 1).	20 - 100	5 - 10	500	Tapped mostly for domestic use. Variable water quality with local problems. Concentrations of iron greater than 1 mg/L, and pH less than 5.5 in many areas.
Floridan aquifer system: Fossiliferous limestone. Confined.	80 - 250	100 - 300	2,000	Principal aquifer in southern South Carolina. Saltwater encroachment a potential problem. Water predominantly calcium bicarbonate type except in coastal areas where it is salty.
Tertiary sand aquifer: Fine to course quartzose sand. Confined to unconfined.	100 - 300	50 - 200	700	Interfingers with limestone in southern Barnwell County. Concentrations of dissolved solids less than 50 mg/L near recharge areas; water predominantly a sodium bicarbonate type downdip except near the coast where it is salty.
Black Creek aquifer: Thinly laminated sand and clay lenses. Confined.	200 - 700	50 - 400	900	Principal source of ground water in Horry and Georgetown Counties (Myrtle Beach area). Water predominantly calcium carbonate type with concentrations of iron greater than 3 mg/L near recharge areas, a sodium bicarbonate type downdip, and salty in northeast Horry County and along southern coast. Equivalent to Cretaceous aquifer in North Carolina.
Middendorf aquifer: White and gray sand and gravel. Confined.	200 - 2,000	200 - 700	2,000	Most intensively used in the upper Coastal Plain. Concentrations of dissolved solids are less than 50 mg/L; concentrations of iron greater than 1 mg/L in the upper Coastal Plain. Water predominantly sodium bicarbonate type downdip, and salty in northeast Horry County. Equivalent to Cretaceous aquifer in North Carolina.
Piedmont and Blue Ridge aquifers: Fractured igneous and metamorphic rocks and saprolite. Confined to unconfined.	50 - 300	10 - 30	300	Small yields and areal variability limit large-scale use. Water quality variable in dissolved solids and major constituents.

Floridan Aquifer System

The Floridan aquifer system in South Carolina includes parts of some Miocene formations, but the principal water-bearing units are the Santee and Ocala Limestones of Eocene age. These formations consist of creamy-white to yellow fossiliferous limestone. Typically, the upper part of each unit, particularly the Ocala Limestone, contains extensive loosely cemented shell deposits. These limestones are the facies equivalents of the Eocene sands of the Tertiary sand aquifer. The Floridan aquifer system extends over a wide triangle in the southern part of South Carolina (fig. 1). It is capable of yielding as much as 2,000 gal/min of water suitable for public supply, but common yields range from 100 to 300 gal/min.

Tertiary Sand Aquifer

The Tertiary sand aquifer includes permeable parts of the Congaree, the Warley Hill, the McBean, and the Barnwell Formations, listed in ascending order. The water-bearing sands have limited extent and are present mostly in the upper part of the Coastal Plain between the Savannah and Congaree Rivers. Well yields range from 50 to 200 gal/min but may exceed 700 gal/min.

Black Creek Aquifer

The Black Creek aquifer, of Cretaceous age, ranges in thickness from a few feet in updip areas to about 400 ft in coastal areas. The Black Creek aquifer is the most important source of ground water in Horry and Georgetown Counties. Wells in the two-county area yield 50 to 400 gal/min but may exceed 900 gal/min. The quality of the water in the Black Creek aquifer in Horry and Georgetown Counties generally is acceptable for drinking water except for fluoride concentrations of as much as 7 milligrams per liter (mg/L), chloride concentrations that exceed the 250 mg/L national drinking-water regulation (U.S. Environmental Protection Agency, 1982a, b) in some areas, and dissolved-solids concentrations of as much as 1,800 mg/L in some areas. The large fluoride concentrations in the water are believed to be caused by shark teeth in the Black Creek Formation (Zack, 1980). Saltwater is present in parts of the Black Creek aquifer but is not precisely

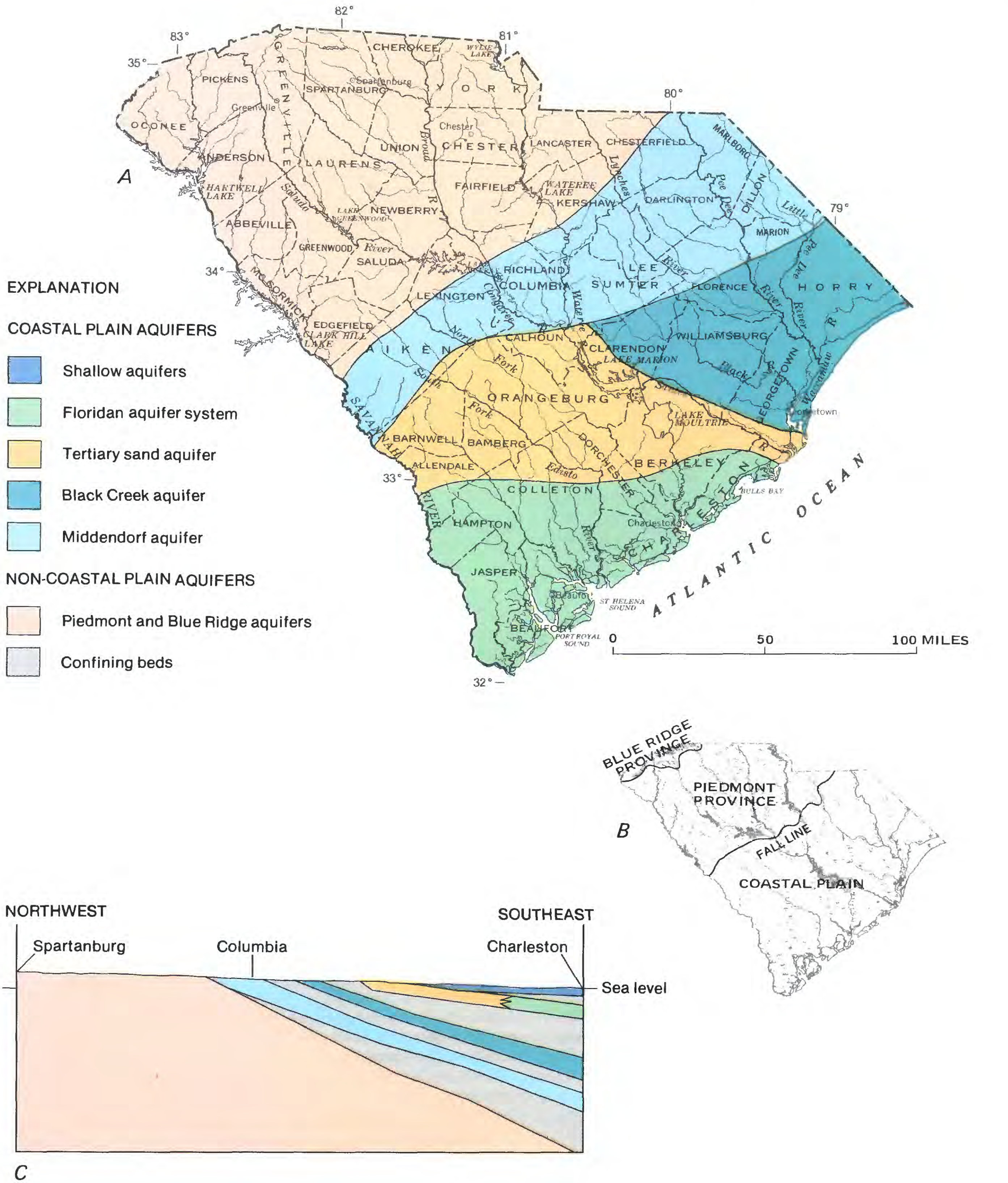


Figure 1. Principal aquifers in South Carolina. *A*, Delineations indicating the most widely used aquifers. *B*, Physiographic diagram and divisions. *C*, Generalized cross section. (See table 2 for a more detailed description of the aquifers. Sources: *A*, *C*, Compiled by W. R. Aucott from U.S. Geological Survey files. *B*, Fenneman, 1938; Raisz, 1954.)

located at this time. In general, the water becomes more mineralized toward the south and southwest and along the coast near the North Carolina–South Carolina boundary.

Middendorf Aquifer

The Middendorf aquifer is the most areally extensive aquifer in the Coastal Plain. The aquifer consists of one or more white and gray sand and gravel beds separated in some areas by clay beds. This aquifer yields large quantities of water, which meets national drinking-water regulations, to numerous wells in the upper and middle regions of the Coastal Plain (fig. 1). In Sumter and Florence Counties, where it is most widely used, the aquifer is about 200 ft thick; yields to individual wells generally range from 200 to 700 gal/min but may exceed 2,000 gal/min.

PIEDMONT AND BLUE RIDGE AQUIFERS

The massive crystalline igneous and metamorphic rocks in the Piedmont and Blue Ridge provinces have little permeability, and individual aquifers are not areally extensive. The largest yields are from wells constructed in fracture zones in the rocks. Many large-diameter dug wells have been constructed in the saprolite overlying the unweathered bedrock. Water levels usually rise in winter and spring when rainfall is greatest and decline during summer and early fall when evapotranspiration is greatest. The water generally is suitable for most domestic uses.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Most major ground-water withdrawal areas are in the Coastal Plain where aquifers are most productive (fig. 2). Water levels generally decline in response to increases in pumping and recover as pumping is reduced. The hydrographs in figure 2 represent conditions in the Coastal Plain of South Carolina near the major withdrawal areas.

Ground-water withdrawal has caused water-level declines of about 120 ft in the Black Creek aquifer in the Myrtle Beach area (location 12, fig. 2). The annual rate of decline in the Myrtle Beach area had increased to about 5 ft by 1977 (Spigner and others, 1977, p. 16) and had further increased to 9.5 ft by 1984 at the center of the cone of depression (CH2MHill, Inc., 1984, p. 3-1). The decline at Conway (location 5, fig. 2), 15 miles from the Myrtle Beach center of pumping, was about 60 ft from 1950 to 1982.

Most wells in the Florence area (location 7, fig. 2) are screened in the Middendorf aquifer. Water levels at the center of pumpage in that area have declined about 150 ft since 1940 when major pumping began (W. R. Aucott and G. K. Speiran, U.S. Geological Survey, written commun., 1984). [The hydrograph for location 7 (fig. 2) shows water-level changes on the perimeter of the cone of depression and, therefore, declines are less.] Although withdrawal in the Sumter area (locations 16 and 17, fig. 2) is greater than that for either Myrtle Beach or Florence, drawdown near the center of pumping is only about 25 ft, probably because the aquifer at Sumter has greater transmissivity than the aquifers at the other two locations and is closer to recharge areas. Pumping at the Savannah River Plant (location 15, fig. 2) has lowered water levels in the Black Creek and Middendorf aquifers in that area about 15 ft at the center of the cone of depression but has not significantly affected water levels because of the large transmissivity of the aquifer.

Public supply and industrial withdrawals from the Floridan aquifer system have lowered water levels at least 160 ft in the Savannah, Ga., area. The cone of depression resulting from these withdrawals extends into southern South Carolina, and water levels in the Floridan aquifer system on Hilton Head Island (location 10, fig. 2) are now below sea level, which has created the possibility of saltwater intrusion from outcrop areas at or north of Port Royal Sound. In addition, pumping may cause upward migration of saltwater from the deep part of the aquifer system. Pumping on Hilton Head Island probably has contributed to water-level declines and also has increased the danger of saltwater contamination.

Ground-water withdrawals for irrigation are seasonal, usually are spaced widely, and are located mostly in the upper part of the Coastal Plain where aquifer yields are large. Because of these conditions and the small withdrawals, water levels in the Coastal Plain have shown only a seasonal response to pumping, and no deep permanent cones of depression have developed.

GROUND-WATER MANAGEMENT

The South Carolina Department of Health and Environmental Control (DHEC) and the South Carolina Water Resources Commission (WRC) are responsible for protecting the quality of ground-water resources of the State. The DHEC programs include

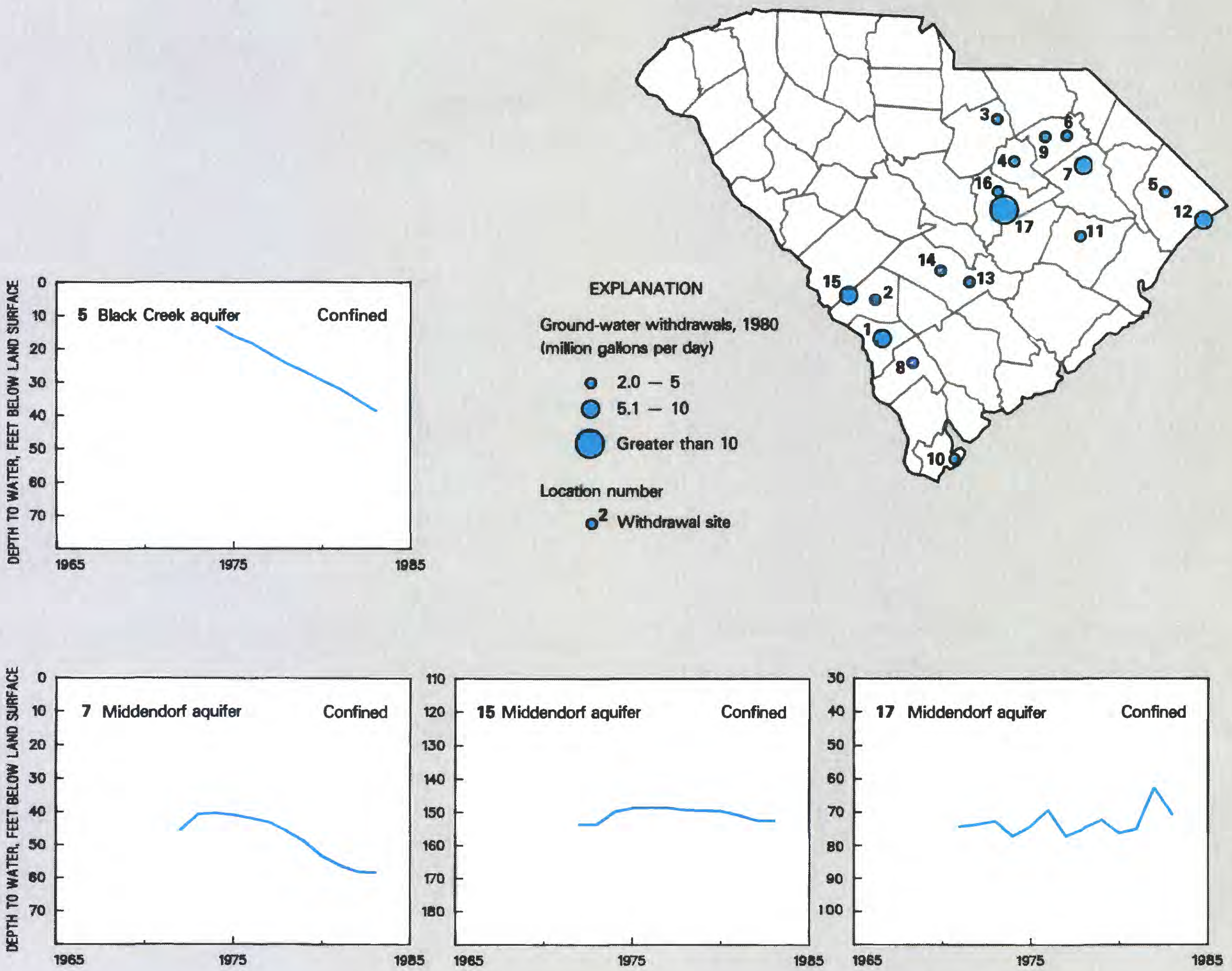
1. Review and permitting of all public supply wells for proper design and construction.

2. Regulation of the water-well drilling industry to ensure compliance with minimum well-construction standards.

3. Regulation of all sites of potential ground-water contamination, such as pits, ponds, lagoons, feedlots, and injection wells, in compliance with proper monitoring and clean-up activities.

The WRC water-management program is authorized by the Ground Water Use Act of 1969. This program is designed to protect aquifers in designated areas (Capacity Use Areas) by regulating the design, construction, spacing, and abandonment of wells to protect the aquifers from saltwater intrusion and over-pumping. All ground-water users that withdraw more than 100,000 gallons per day (gal/d) must obtain a permit from the Commission and must report monthly water use on a quarterly basis. Under the Act, the Commission is authorized to regulate ground-water withdrawals within the Capacity Use Areas. The program is designed primarily to minimize the effect of intensive localized pumping.

Ground-water data and technical assistance are provided to ground-water users by the U.S. Geological Survey in cooperation with the DHEC, the WRC, and other State agencies. The DHEC primarily is responsible for protecting aquifers from the introduction of foreign materials, and the USGS and the WRC are responsible for describing the geologic framework and evaluating aquifer yields, water quality, and problems.



WITHDRAWAL SITES			
No. on map	Geographic area	Aquifer	Principal uses
1	Allendale County	Black Creek, Tertiary sand	Irrigation.
2	Barnwell	Tertiary sand	Public supply, industrial.
3	Bethune	Middendorf	Industrial.
4	Bishopville	....do	Public supply, industrial.
5	Conway	Black Creek, Middendorf	Do.
6	Darlington	Middendorf, Black Creek	Do.
7	Florence	....do	Public supply.
8	Hampton	Floridan	Industrial.
9	Hartsville	Middendorf	Public supply.
10	Hilton Head	Floridan	Do.
11	Kingstree	Black Creek, Middendorf	Do.
12	Myrtle Beach-North Myrtle Beach	....do	Do.
13	Orangeburg County	Tertiary sand, Middendorf	Irrigation.
14	Orangeburg	Middendorf	Industrial.
15	Savannah River Plant	Middendorf, Black Creek	Do.
16	Sumter County	Middendorf	Irrigation.
17	Sumter-Shaw AFB	Middendorf, Black Creek	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in South Carolina. (Sources: Withdrawal data from U.S. Geological Survey files and Lonon and others, 1983; water-level data from U.S. Geological Survey files.)

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Prepared by William F. Lichtler and Walter R. Aucott

For further information contact District Chief, U.S. Geological Survey, 1835 Assembly Street, Suite 658, Columbia, SC 29201

SOUTH DAKOTA
Ground-Water Resources

Ground water constitutes a large and reliable source of water for domestic, stock, public-supply, irrigation, and industrial use in South Dakota. Most of the State is underlain by one or more aquifers that yield small to very large supplies of water of differing quality. Seventy-seven percent of the population of 695,000 is served by ground water. Ground-water withdrawals in 1980 and related statistics are given in table 1.

West of the Missouri River, 76 percent of the water used is from surface sources; irrigation accounts for 73 percent of this use. In contrast, municipalities and industry in this area depend on ground water for more than 50 percent of their supplies. Ground water supplies about 95 percent of the rural domestic demand for fresh water.

East of the Missouri River, ground water is by far the largest source of freshwater and accounts for about 70 percent of all water used. Of the total ground water withdrawn, irrigation uses 60 percent, and municipalities and industry together use 6 percent. Ground water also provides more than 90 percent of the rural-domestic supply. The presence of relatively shallow ground-water sources, greater annual rainfall than in the west, and a lack of convenient on-stream storage sites have contributed to this pattern of water use in eastern South Dakota.

GENERAL SETTING

The Missouri River divides the State into two distinct physiographic and geologic areas (fig. 1). West of the river, bedrock generally is at or near the surface, and the area is characterized by deep valleys and canyons, buttes, and broad flat uplands typical of the Great Plains physiographic province (Fenneman, 1931). East of the river, the area is characterized by low, rolling hills and potholes typical of the glaciated parts of the Central Lowland physiographic province. These distinct differences in the geology and topography east and west of the Missouri River result in major differences in ground-water conditions, development, and use in the two areas.

The average annual precipitation in South Dakota is about 18 inches (in.); it ranges from about 13 in. in the northwestern corner of the State to about 25 in. in the southeastern corner. However, precipitation can vary greatly from year to year. The annual precipitation has ranged from 7.5 to 50 in. Periods of successive dry years or years that are wetter than normal are frequent (U.S. Geological Survey and U.S. Bureau of Reclamation, 1975).

Recharge to the shallow aquifer in the glaciated and unglaciated areas is largely through infiltration of precipitation that falls on the immediate area. The mechanism of recharge to the deeper bedrock aquifers is not yet fully understood. However, some recharge doubtlessly occurs in the Black Hills because streams cross the exposed surfaces of the aquifers (U.S. Geological Survey and U.S. Bureau of Reclamation, 1964).

PRINCIPAL AQUIFERS

The principal aquifers in South Dakota can be grouped into glacial drift and alluvial and consolidated sedimentary bedrock aquifers. The aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

Table 1. Ground-water facts for South Dakota

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	533
Percentage of total population	77
From public water-supply systems:	
Number (thousands)	321
Percentage of total population	46
From rural self-supplied systems:	
Number (thousands)	212
Percentage of total population	31
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	690
Ground water only (Mgal/d)	330
Percentage of total	48
Percentage of total excluding withdrawals for thermoelectric power	48
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	52
Percentage of total ground water	16
Percentage of total public supply	68
Per capita (gal/d)	162
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	21
Percentage of total ground water	6
Percentage of total rural domestic	94
Per capita (gal/d)	99
Livestock:	
Ground water (Mgal/d)	81
Percentage of total ground water	25
Percentage of total livestock	88
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	26
Percentage of total ground water	8
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	54
Excluding withdrawals for thermoelectric power	55
Irrigation withdrawals:	
Ground water (Mgal/d)	150
Percentage of total ground water	45
Percentage of total irrigation	33

GLACIAL-DRIFT AND ALLUVIAL AQUIFERS

One of the two principal ground-water systems in the State is the glacial drift that constitutes the surface deposits over most of the area east of the Missouri River. Most of these glacial deposits are till (Flint, 1955), a relatively impermeable and heterogeneous mixture of boulders, gravel, and rock fragments of all sizes incased in fine-grained material, such as silt and clay. The aquifers in the drift primarily are unconsolidated sand and gravel outwash deposited by meltwaters from glaciers. Although they may occur as sheets or ribbons of permeable, water-yielding material lying on or beneath the till, they are more commonly complex systems of sand and gravel layers within the body of till. The drift is as

Table 2. Aquifer and well characteristics in South Dakota

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and the South Dakota Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Glacial-drift and alluvial aquifers: Outwash and alluvium; unconsolidated sand, gravel, and silt. May be confined or unconfined.	20 - 400	3 - 50	2,000	Glacial drift underlies most of State east of Missouri River. Alluvium found along major streams. Water fresh to moderately saline; commonly suitable for irrigation. Big Sioux aquifer in southeastern South Dakota yields adequate supplies for Sioux Falls, State's largest city.
Sedimentary bedrock aquifers:				
High Plains aquifer: Sand, fine to medium; unconsolidated to poorly consolidated sandstone, silt, gravel, and clay. Unconfined.	10 - 570	5 - 100	1,500	Most common source of water on Pine Ridge and Rosebud Indian Reservations. Supplies towns of Martin and Pine Ridge. Some irrigation development. Water quality generally suitable for most uses. Consists of lower Ogallala Formation and Arikaree Formation Miocene age.
Fort Union–Hell Creek–Fox Hills aquifers: Sandstone, very fine to fine-grained, poorly consolidated; soft clay; lignite beds. Unconfined.	100 - 1,000	2 - 40	500	Most common source of water in northwestern South Dakota. Fox Hills aquifer supplies towns of Bison, Lemmon, and Timber Lake. Water commonly fresh.
Niobrara–Codell aquifer: Shale, chalky, and fine-grained quartz sandstone. Confined or unconfined.	150 - 300	2 - 30	300	Used extensively for livestock and domestic purposes in central South Dakota and southern James River basin. Water generally soft and moderately saline.
Dakota-Newcastle aquifer: Sandstone, interbedded with shale and siltstone. Confined.	300 - 4,000	2 - 50	1,500	Major source of water for domestic and stock use. Supplies water to many small public-supply systems. Water commonly moderately saline to very saline.
Inyan Kara aquifer: Sandstone, interbedded with shale and siltstone. Confined.	200 - 4,900	5 - 40	1,000	Considered to be an underdeveloped source of water for domestic and stock use. Water quality ranges from fresh in west to moderately saline in east to very saline in north.
Sundance aquifer: Shale interbedded with fine-grained sandstone, limestone, and sandy shale. Confined.	100 - 5,400	5 - 100	1,000	Important source of water for livestock in central part of State. Water commonly saline except near surface exposures in the west.
Minnelusa aquifer: Five major sandstone units separated by limestone, dolomite, shale, and anhydrite beds. Confined.	100 - 6,800	5 - 100	4,000	Major ground-water reservoir. Source for stock and domestic wells in central and western South Dakota. Water of suitable quality for irrigation (slightly saline or fresh) obtained from several wells near outcrops in the Black Hills. Most wells completed in Minnelusa flow.
Madison aquifer: Limestone, and dolomite containing beds of shale, anhydrite, and halite. Confined.	100 - 9,000	10 - 100	2,000	May be most important bedrock aquifer system in South Dakota. Comprises one or more aquifers that can yield large quantities of fresh to saline water under significant artesian pressure. Several producing wells are more than 4,000 ft deep. Supplies such western South Dakota towns as Philip, Midland, Eagle Butte, and Dupree.
Red River aquifer: Dolomite and dolomitic limestone. Confined.	1,100 - 9,700	5 - 100	1,000	Although not being used as a principal source of water in South Dakota, considered a major artesian aquifer. Dissolved-solids concentrations may exceed 60,000 mg/L. Maximum water temperatures of about 250 degrees Farenheit reported.
Deadwood aquifer: Sandstone, soft, thin-bedded, slabby dolomite and limestone; limestone-pebble conglomerate; and beds of glauconitic shale. Confined.	40 - 10,200	3 - 50	500	Except in the Black Hills area, aquifer not used, and potential for development, although probably significant, is not known. Salinity may range from moderately saline to very saline.

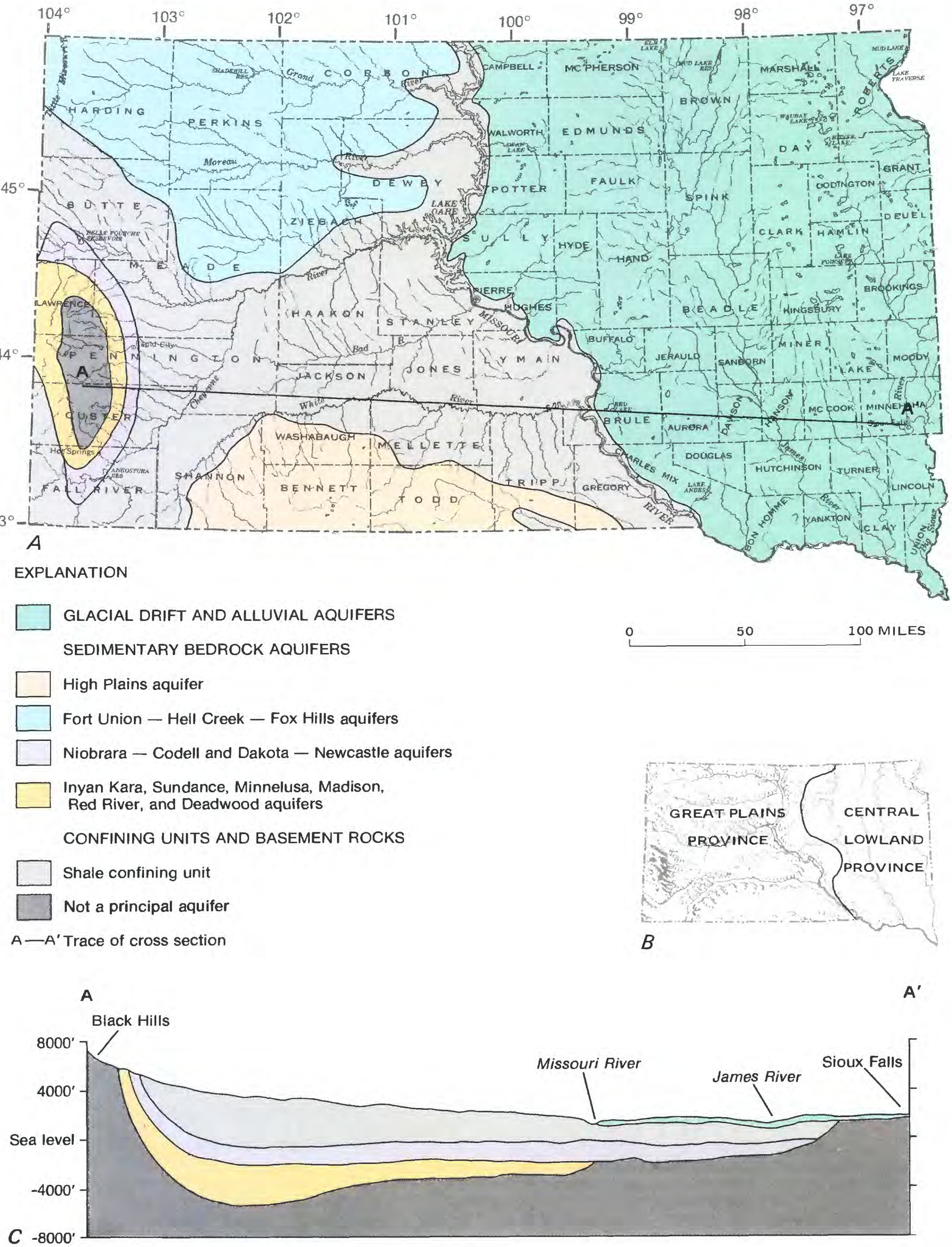


Figure 1. Principal aquifers in South Dakota. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Modified from U.S. Geological Survey and U.S. Bureau of Reclamation, 1975. *B*, Fenneman, 1931; Raisz, 1954. *C*, Compiled by E. F. LeRoux from U.S. Geological Survey files.)

much as 800 feet (ft) thick in the northeast part of the State but probably averages about 150 ft. The maximum thickness of permeable aquifer material within the drift is 225 ft. Recharge to the aquifers generally is from local precipitation or infiltration from streams.

Some aquifers in glacial drift, such as the Tulare, the Big Sioux, and the Warren, have been mapped in detail as part of cooperative water-resources studies by the U.S. Geological Survey and the South Dakota Geological Survey (Howells and Stephens, 1969); however, because of their complexity and individually limited areal extent, they are not shown in figure 1 of this report.

SEDIMENTARY BEDROCK AQUIFERS

The second principal aquifer system, which includes all aquifers in the State with the exception of the glacial-drift and alluvial aquifers, is the only source of ground water west of the Missouri River, except for a few small areas of alluvium along major streams. Although commonly very mineralized and found at relatively great depth away from the Black Hills, water from these aquifers is used extensively for rural-domestic and stock supply. Several of the bedrock aquifers extend into eastern South Dakota beneath the glacial drift (fig. 1).

High Plains Aquifer

The High Plains aquifer is composed of the lower Ogallala Formation and the Arikaree Formation of Miocene age. The aquifer generally is unconfined and is recharged by local precipitation and snowmelt.

Fort Union-Hell Creek-Fox Hills Aquifers

In the northwestern part of the State, thin beds of lignite in the Fort Union and Hell Creek aquifers provide water. The Fox Hills sandstone yields supplies ample for small towns. The area underlain by these aquifers is sparsely populated, and the aquifers provide adequate quantities of water to farms, ranches, and several small communities.

Niobrara-Codell Aquifer

The Niobrara-Codell aquifer, which underlies much of the State, is at land surface around the Black Hills in western South Dakota and locally in southeastern South Dakota. Although usually not as important as some of the other aquifers in the State, it is important in the central part of South Dakota for domestic and stock use.

Dakota-Newcastle Aquifer

The Dakota-Newcastle aquifer underlies more than 66,000 square miles in South Dakota (fig. 1) and has an average thickness of about 150 ft (Schoon, 1971). It generally is thickest east of the Missouri River where it is as much as 460 ft thick. In the north-central to northwestern part of the State, however, the aquifer is not present or is a silty and sandy shale or siltstone less than 50 ft thick. The Dakota-Newcastle aquifer is a major source of water in South Dakota. Thousands of farm, ranch, and domestic wells and dozens of public-supply wells tap the aquifer. Development is greatest in the James River basin. The water is under artesian pressure and flows from wells in the Missouri River and in the James River valleys, although the water must be pumped in much of the State. Flow rates of as much as 1,500 gallons per minute (gal/min) have been measured by the U.S. Geological Survey, but most yields of flowing wells are less than 15 gal/min.

Inyan Kara, Sundance, Minnelusa, Madison, Red River, and Deadwood Aquifers

The older bedrock aquifers—Inyan Kara, Sundance, Minnelusa, Madison, Red River, and Deadwood—underlie much of the western one-half of the State. They are exposed at the surface around the Black Hills uplift in western South Dakota, plunge deeply beneath the surface toward the east, and terminate against quartzite basement rock near the center of the State (fig. 1).

The Madison and the Red River aquifers are extensive areally in the western part of the State. The Madison aquifer can yield large quantities of water and supplies a number of small towns west of the Missouri River. Although the Red River aquifer exists in a major oil-producing formation in the State, it has not been developed as an aquifer; however, based on information from oil test wells, it is considered to be a potentially important source of water.

The other deep, confined bedrock aquifers primarily are sandstone, commonly interbedded with shale, siltstone, or limestone. Except for the Deadwood aquifer, they are all important sources of water for domestic and stock supply in the central and western parts of the State. Although moderately saline to very saline (table 2) away from the Black Hills, the water is used in many areas because it is the only water economically available. Before the advent of rural water systems, hauling water many miles for domestic use in these areas was a common practice, which continues to this day in some areas.

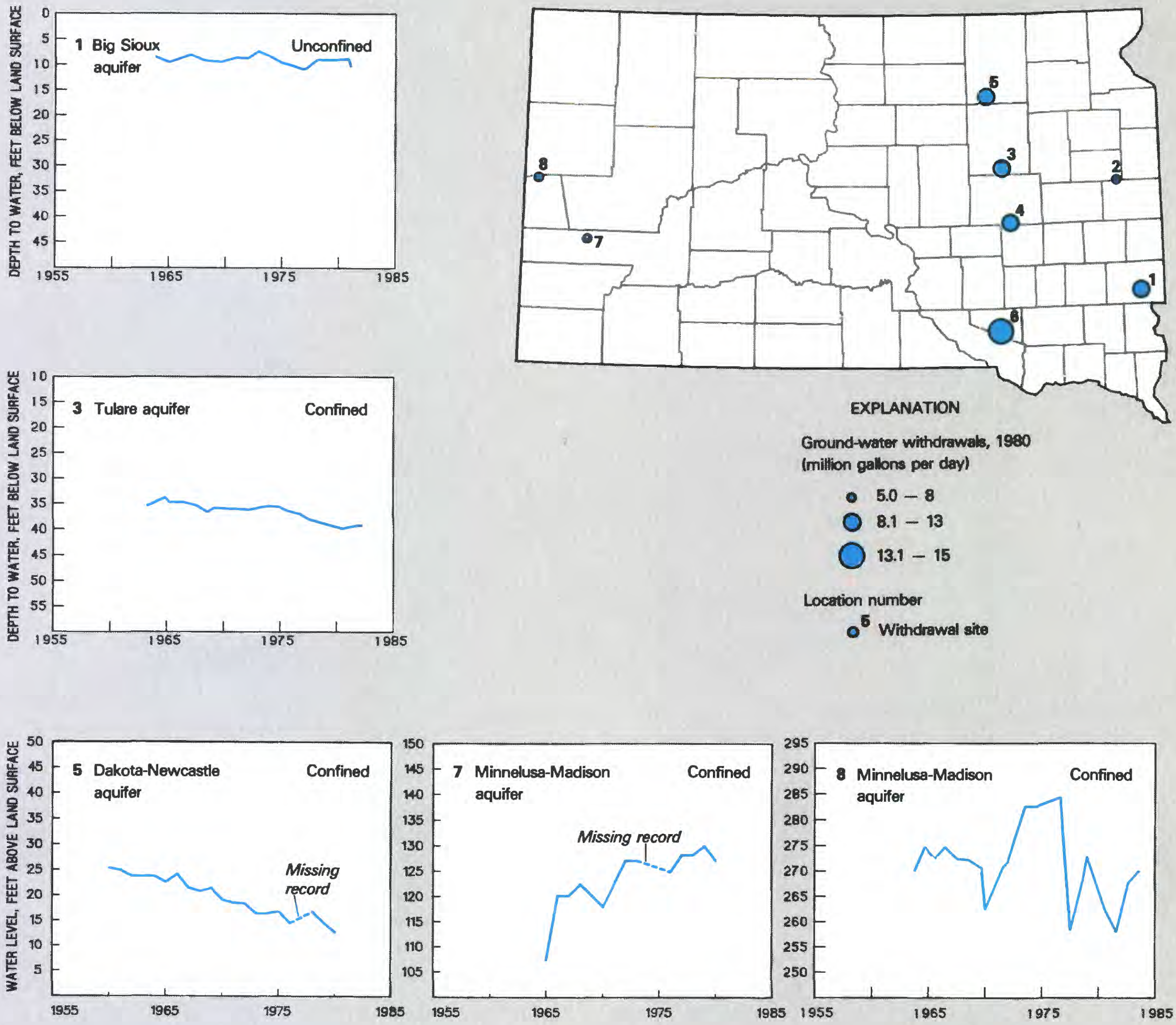
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

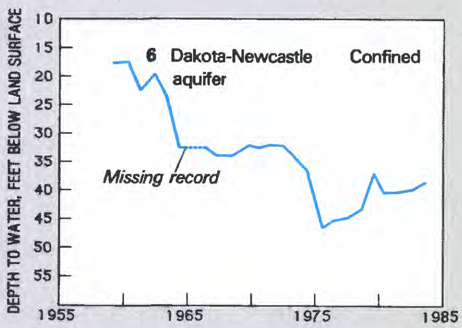
The distribution of major ground-water withdrawals and trends of ground-water levels near selected withdrawal centers are shown in figure 2. The withdrawal centers generally are broad areas covering parts of several counties. The largest groupings of pumping wells are at Sioux Falls (location 1, fig. 2), in several counties in the Brookings area (location 2, fig. 2), and in the James River valley (locations 3 and 4, fig. 2).

Flowing wells discharge about 170 million gallons per day from bedrock aquifers in South Dakota. Many flowing wells are clustered along major river valleys (locations 5, 6, fig. 2) in the eastern part of the State and also along the periphery of the Black Hills of western South Dakota (locations 7, 8, fig. 2).

Water levels generally decline in response to an increase in withdrawals and recover as withdrawals are decreased. Except for local areas of intensive pumping, the long-term trends in the unconfined aquifers do not show any decline. The hydrographs in figure 2 are representative of one unconfined and five confined aquifers. The water level in a well completed in the unconfined Big Sioux aquifer in the glacial drift (location 1, fig. 2) declined several feet between 1974 and 1976 because of decreased recharge from precipitation and increased withdrawal for public supply at Sioux Falls.

In a well completed in the confined Tulare aquifer in the glacial drift, a water-level decline of several feet was measured from 1974 to 1980 (location 3, fig. 2). This decline was caused by decreased recharge and increased withdrawal for irrigation. Water-level declines of only a few feet in this aquifer have little or no effect on the yield of nearby wells. In contrast, water levels in wells that penetrate the confined Dakota-Newcastle aquifer have declined more than 400 ft locally since the 1880's because of discharge of flowing wells. Water levels in this aquifer have continued to decline in many areas. Between 1960 and 1980, the water level declined 13 ft in one well in the Aberdeen area (location 5, fig. 2) and 30 ft between





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
		Glacial drift	
1	Sioux Falls.	Big Sioux.	Public supply.
2	Brookings area.	. . . .do	Public supply, irrigation.
3	Huron-Redfield area . .	Tulare	Irrigation.
4	Huron-Mitchell area. . .	Warren	Do.
		Bedrock	
5	Aberdeen area	Dakota-Newcastle. .	Rural domestic and livestock.
6	Yankton-Brule area . . .	. . . .do	Do.
7	Southern Black Hills . .	Minnelusa-Madison.	Public supply, rural domestic.
8	Northern Black Hills . .	. . . .do	Irrigation, public supply, industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in South Dakota. (Sources: Withdrawal data from Solley and others, 1983; water-level data from U.S. Geological Survey files.)

1960 and 1975 in another well in the Yankton–Brule area (location 6, fig. 2). The levels decline as new flowing wells are completed in the aquifer for rural-domestic and livestock water supplies.

In some wells completed in the confined Minnelusa and Madison aquifers in the Black Hills area, water levels have declined nearly 200 ft because of increased numbers of flowing wells used for irrigation, public supply, and industrial supplies (fish hatcheries). Since 1960, however, water levels generally have stabilized and have even risen 20 to 30 ft at location 7 (fig. 2). This is caused by a decrease in the flow of older wells and an increase in recharge from streams during years of greater-than-average runoff.

GROUND-WATER MANAGEMENT

Management of the State's ground-water resources is accomplished through a water record and permit system and a State Water Plan administered by the South Dakota Department of Water and Natural Resources (SDDWNR). In the SDDWNR, the Office of Water Policy provides the technical policy analysis needed to implement the State Water Plan, and the Division of Geological Survey is charged with studying and mapping the ground-water resources of the State. The Division of Water Development, also within the SDDWNR, has the responsibility to coordinate development and management of South Dakota's water resources for maximum public benefit; the Division of Water Quality reviews ground-water-quality data to determine if contamination is occurring or if additional legal authority is required to protect the quality of ground water; and the Division of Water Rights is charged with licensing and other functions concerned with regulation and management of the waters of the State. Although State law does not allow withdrawals from an aquifer to exceed the average annual recharge, it does not regulate the effects of pumping on flowing wells.

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Prepared by E. F. LeRoux and Louis J. Hamilton

For further information contact District Chief, U.S. Geological Survey, Federal Building, Room 317, 200 4th Street, S.W., Huron, SD 57350

TENNESSEE
Ground-Water Resources

More than one-half of the population of Tennessee relies on ground water for drinking-water supplies. Twenty-one percent of the water withdrawal in the State (exclusive of thermoelectric use) is ground water. Ground water provides more than 250 million gallons per day (Mgal/d) for public and rural-domestic supplies, 190 Mgal/d to self-supplied industries, and more than 13 Mgal/d for irrigation and livestock uses. In West Tennessee, nearly all public supplies, industries, and rural residents use ground water; Memphis, the largest city in Tennessee, is completely supplied by ground water. Ground-water withdrawals for various uses in 1980 and related statistics are listed in table 1.

GENERAL SETTING

Differing geologic features and land forms in Tennessee (fig. 1) cause significant differences in ground-water conditions. The Coastal Plain province of West Tennessee is underlain by unconsolidated sand, gravel, and clay that dip to the west and contain water in intergranular openings. The Highland Rim and Central Basin in Middle Tennessee and the Western Valley are underlain by nearly horizontal lying carbonate rocks that contain water in solution-enlarged openings. The Cumberland Plateau is underlain by sandstone, conglomerate, and shale. The Sequatchie Valley and the Valley and Ridge province of East Tennessee are underlain by intensely faulted and folded limestone, dolomite, sandstone, and shale. Water exists in fractures, faults, and bedding-plane openings. The mountains of the Blue Ridge province are underlain by massive crystalline and metasedimentary rocks which contain water in fractures.

Ground water in Tennessee is recharged by precipitation. Average annual precipitation is about 50 inches (in.) across the State; more than 60 in. falls on the mountains at the eastern edge of the State, and less than 40 in. falls on the leeward side of these mountains (U.S. Geological Survey, 1970). Only about one-fifth of the precipitation actually enters the ground-water system; the remainder runs off to streams or reenters the atmosphere by evapotranspiration (Zurawski, 1978).

PRINCIPAL AQUIFERS

Tennessee has nine principal aquifers—the alluvial, the Tertiary sand, the Cretaceous sand, the Pennsylvanian sandstone, the Mississippian carbonate, the Ordovician carbonate, the Knox, the Cambrian-Ordovician carbonate, and the crystalline rock. These aquifers are described below and in table 2; their areal distribution is shown in figure 1.

ALLUVIAL AQUIFER

The alluvial aquifer underlies the flood plain of the Mississippi River and its tributaries and the southern end of the Western Valley of the Tennessee River. The aquifer, which consists of sand and gravel with interbeds of clay, is used primarily for rural-domestic supplies and for some irrigation. This aquifer is capable of yielding more than 1,500 gallons per minute (gal/min) to wells in the Mississippi River area. At the southern end of the Western Valley, this aquifer supplies 1.4 Mgal/d for public supply in Hardin County. In some areas, iron concentrations exceed 1.0 milligrams per liter (mg/L).

Table 1. Ground-water facts for Tennessee

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Graham, 1982; Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	2,320
Percentage of total population	51
From public water-supply systems:	
Number (thousands)	1,450
Percentage of total population	32
From rural self-supplied systems:	
Number (thousands)	870
Percentage of total population	19
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	10,000
Ground water only (Mgal/d)	460
Percentage of total	5
Percentage of total excluding withdrawals for thermoelectric power	21
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	210
Percentage of total ground water	46
Percentage of total public supply	40
Per capita (gal/d)	150
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	43
Percentage of total ground water	9
Percentage of total rural domestic	100
Per capita (gal/d)	49
Livestock:	
Ground water (Mgal/d)	7.0
Percentage of total ground water	2
Percentage of total livestock	17
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	190
Percentage of total ground water	42
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2
Excluding withdrawals for thermoelectric power	11
Irrigation withdrawals:	
Ground water (Mgal/d)	6.4
Percentage of total ground water	1
Percentage of total irrigation	51

TERTIARY SAND AQUIFER

The Tertiary sand aquifer is the most productive aquifer in Tennessee. It underlies the western part of the Coastal Plain and includes the Memphis Sand of the Claiborne Group and the Fort Pillow Sand of the Wilcox Group. The Tertiary sand aquifer consists of a sequence of interbedded sand and clay that ranges in thickness from 100 feet (ft) in the outcrop area where ground water is unconfined to about 2,000 ft near the Mississippi River where the ground water is confined. This aquifer supplies water to most industries and municipalities in West Tennessee. Major withdrawal centers include Memphis, Millington, Germantown, Jackson, Union City, Crockett County, and Dyersburg (fig. 2). Well yields from the Tertiary sand aquifer commonly range from 200 to 1,000 gal/min and can exceed 2,000 gal/min. Iron concentrations in some areas exceed 1.0 mg/L.

Table 2. Aquifer and well characteristics in Tennessee

[Ft = feet; gal/min = gallons per minute; Sources: Reports of the U.S. Geological Survey and Tennessee State agencies]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Alluvial aquifer: Sand, gravel, and clay. Unconfined.	10 – 75	100	20 – 50	1,500	Large iron concentrations in some areas. Local contamination at some landfills.
Tertiary sand aquifer: A multiaquifer unit of interbedded sand, clay, silt, and some gravel and lignite. Confined, unconfined in the outcrop area.	100 – 1,300	1,500	200 – 1,000	2,000	Includes Memphis Sand of Claiborne Group and Fort Pillow Sand of Wilcox Group. Problems with large iron concentration in some places.
Cretaceous sand aquifer: A multiaquifer unit of interbedded sand, clay, marl, and gravel. Confined, unconfined in the outcrop area.	100 – 1,500	2,500	50 – 500	1,000	Includes McNairy and Coffee Sands, and Tuscaloosa Formation. Water used primarily in the outcrop area.
Pennsylvanian sandstone aquifer: A multiaquifer unit, primarily sandstone and conglomerate, interbedded with shale and some coal. Unconfined near land surface, confined at depth.	100 – 200	250	5 – 50	200	Permeability is from fractures, faults and bedding-plane openings. Principal water-bearing units are Rockcastle Sandstone and Sewanee Conglomerate. Large iron concentrations are a problem.
Mississippian carbonate aquifer: A multiaquifer unit of limestone, dolomite, and some shale. Unconfined or partly confined near land surface; may be confined at depth.	50 – 200	250	5 – 50	400	Water occurs in solution openings and bedding-plane openings. Principal water-bearing units are Ste. Genevieve (Monteagle), St. Louis and Warsaw Limestones and Fort Payne Formation. Susceptible to pollution. Water generally hard; large iron, sulfide, or sulfate concentrations problems in some areas.
Ordovician carbonate aquifer: A multiaquifer unit of limestone, dolomite, and shale. Partly confined to unconfined near land surface; confined at depth.	50 – 150	200	5 – 20	300	Principal water-bearing units are Bigby, Carters, Ridley, and Murfreesboro Limestones. Water generally hard; some large sulfide or sulfate concentrations in places. Units susceptible to contamination.
Knox aquifer: Primarily dolomite With some limestone. Confined.	700 – 1,200	1,400	1 – 10	20	A deep aquifer; occurs under most of Middle and west Tennessee. Away from Central Basin, water generally has large concentrations of dissolved solids.
Cambrian-Ordovician carbonate aquifer: Extremely faulted multiaquifer unit of limestone, dolomite, sandstone, and shale; structurally complex. Unconfined; confined at depth.	100 – 300	400	5 – 200	2,000	Principal water-bearing units are carbonate rocks in Chickamauga Limestone, Knox Group, and Honaker Dolomite. Water is generally hard. Brine below 3,000 ft.
Crystalline rock aquifer: A multi-aquifer unit of dolomite, granite gneiss, phyllite, and metasedimentary rocks overlain by thick regolith; alluvium and colluvium in some valleys. Generally unconfined.	50 – 150	200	5 – 50	1,000	Large yields occur primarily in valleys with dolomite or deep colluvium and alluvium. Shady Dolomite is a principal aquifer. Low pH and large iron concentrations may be problems in some areas.

Cretaceous Sand Aquifer

The formations of the Cretaceous sand aquifer are the McNairy and the Coffee Sands, and the Tuscaloosa Formation. The formations crop out in the eastern part of the Coastal Plain and underlie the Tertiary sand aquifer to the west. The Cretaceous sand aquifer is used primarily in and near the outcrop area where it supplies water for municipal, industrial, and rural use. Water in the aquifer is unconfined in the outcrop area and confined in the subsurface farther west. The Cretaceous sand aquifer is underlain by the Ordovician carbonate aquifer and Knox aquifer.

Pennsylvanian Sandstone Aquifer

The Pennsylvanian sandstone aquifer in the eastern part of Tennessee includes sandstone and conglomerate. The water-bearing openings in these rocks consist of fractures, faults, and bedding-plane openings. Well yields generally are 5 to 50 gal/min, although some wells produce more than 200

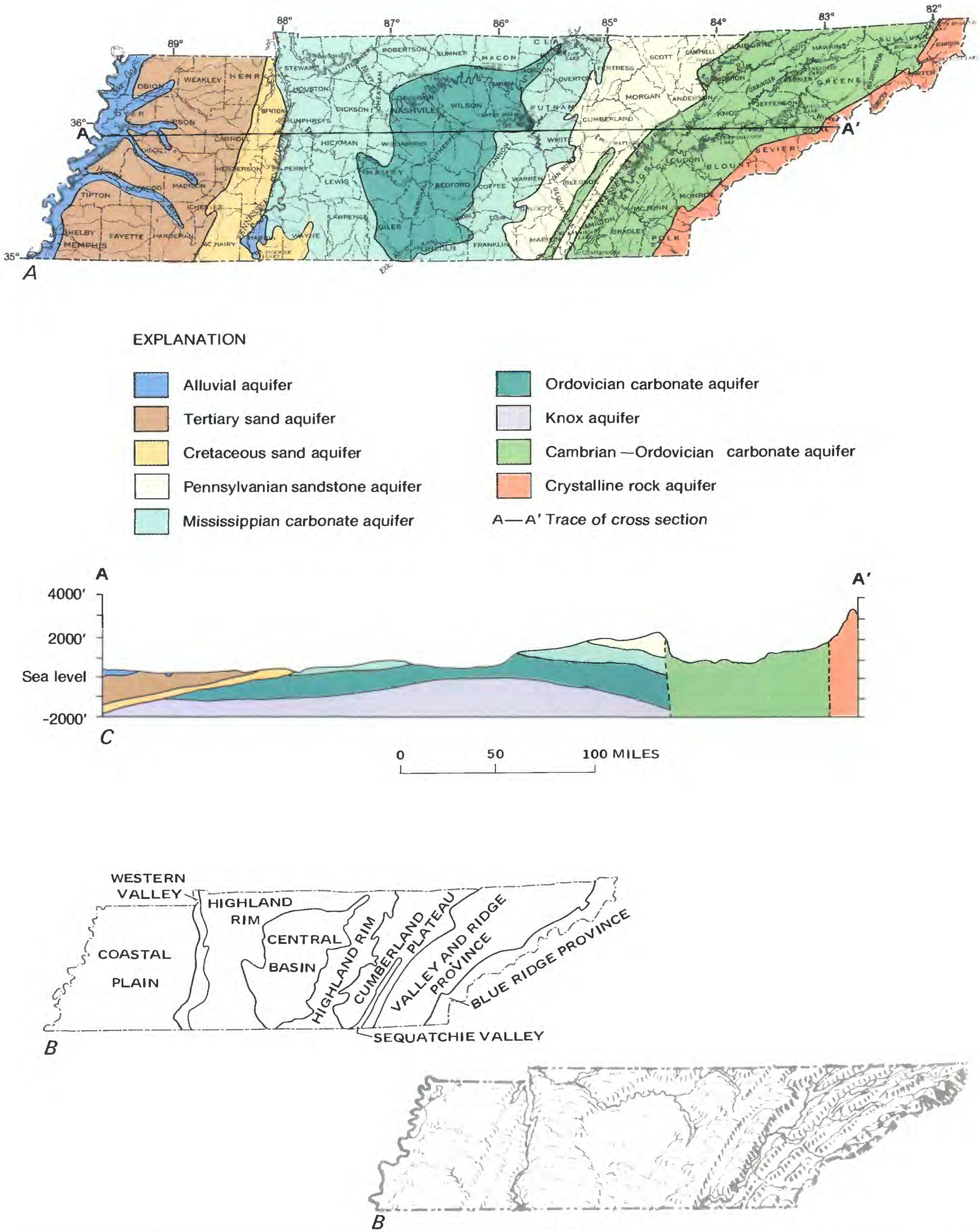


Figure 1. Principal aquifers in Tennessee. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Miller, 1974; *B*, Fenneman, 1946; Raisz, 1954; Miller, 1974; *C*, Compiled by M. W. Bradley from U.S. Geological Survey files.)

gal/min. Sandstone and conglomerate, particularly the Rockcastle Sandstone and Sewanee Conglomerate, supply most of the water used for rural-domestic supplies. Iron concentrations of greater than 1.0 mg/L and pH of less than 6.0 are problems in some areas.

MISSISSIPPIAN AND ORDOVICIAN CARBONATE AQUIFERS

The formations that comprise the Mississippian carbonate aquifer in the Highland Rim and the Ordovician carbonate aquifer in the Central Basin are primarily limestone and dolomite, with small amounts of shale. Water in these carbonate aquifers occurs in solution-enlarged openings and is confined to partly confined near land surface; water may be confined at depth. These aquifers are important sources of drinking water for rural users and some public supplies.

The Mississippian carbonate and Ordovician carbonate aquifers are connected to land surface by caves and sinkholes in many areas and are susceptible to contamination. In general, the water hardness exceeds 200 mg/L as calcium carbonate. In the Highland Rim, iron and sulfate concentrations in water from the Mississippian carbonate aquifer may exceed 0.30 and 500 mg/L, respectively. The odor of sulfide is detectable in water from some wells.

The principal water-bearing formations of the Mississippian carbonate aquifer are the Ste. Genevieve (Monteagle), the St. Louis, and the Warsaw Limestones and the Fort Payne Formation. The regolith that overlies the Mississippian carbonate aquifer commonly is 30 to 100 ft thick, stores ground water, and releases it to openings in the underlying bedrock. In some areas of the southeastern Highland Rim, the Mississippian carbonate aquifer contains gravel zones in the regolith that yield as much as 400 gal/min to wells.

The principal water-bearing formations of the Ordovician carbonate aquifer are the Bigby, the Carters, the Ridley, and the Murfreesboro Limestones. The regolith that overlies this aquifer commonly is less than 10 ft thick. Some well yields exceed 300 gal/min.

KNOX AQUIFER

The Knox aquifer underlies Middle Tennessee and parts of West Tennessee. Water in the aquifer flows through interconnected solution openings and along bedding planes in the upper two formations of the Knox Group at depths of 800 to 1,500 ft. Although the aquifer is not a principal aquifer in terms of significant numbers of users or in providing large amounts to single users, it does provide water for rural-domestic use where ground water cannot be obtained at shallower depths. Sulfate concentrations that exceed 500 mg/L and sulfide gas are problems in some areas. Dissolved-solids concentrations in water from the Knox aquifer may exceed 10,000 mg/L in areas outside the Central Basin.

CAMBRIAN-ORDOVICIAN CARBONATE AQUIFER

The Cambrian-Ordovician carbonate aquifer provides water for some cities and industries and practically all rural-domestic use in the Valley and Ridge province of East Tennessee. The aquifer consists of extensively faulted limestone, dolomite, sandstone, and shale. The principal water-bearing units are carbonate rocks of the Chickamauga Limestone, the Knox Group, and the Honaker Dolomite of the Conasauga Group. Major pumping centers in this aquifer are Chattanooga, Elizabethton, and Jefferson City (fig. 2). Some wells that penetrate large, extensive, and interconnected solution openings yield as much as 2,000 gal/min. The hardness of the water in the Cambrian-Ordovician carbonate aquifer generally exceeds 200 mg/L as calcium carbonate. Brines may be present below a depth of 3,000 feet.

CRYSTALLINE ROCK AQUIFER

The crystalline rock aquifer of the Blue Ridge province supplies water for industrial, some municipal, and most rural purposes. The water-bearing units consist of dolomite such as the Shady Dolomite; fractured igneous, metamorphic, and metasedimentary rocks; and, in some areas, regolith. Wells and springs in dolomite yield more than 1,000 gal/min (Maclay, 1962). Wells in the igneous and metamorphic rocks yield 5 to 50 gal/min from fractures. Some wells in regolith, which is present in some valleys, yield more than 100 gal/min. Iron concentrations that exceed 1.0 mg/L and pH of less than 6.0 are problems in several areas in the Blue Ridge province.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

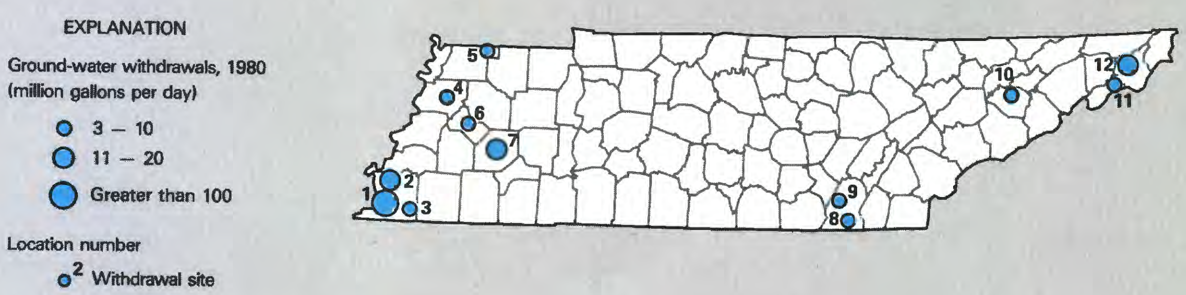
Of the 34 pumping centers in Tennessee that produce more than 1 Mgal/d, 20 of these are in West Tennessee. Statewide, there are 12 pumping centers that withdraw more than 3 Mgal/d each (fig. 2). The largest ground-water withdrawals are in Memphis and surrounding Shelby County (locations 1-3, fig. 2) where more than 190 Mgal/d is withdrawn for public and industrial use. In East Tennessee, areas of large ground-water withdrawals are Elizabethton (location 12, fig. 2), Jefferson City (location 10, fig. 2), and the Chattanooga area (locations 8, 9, fig. 2).

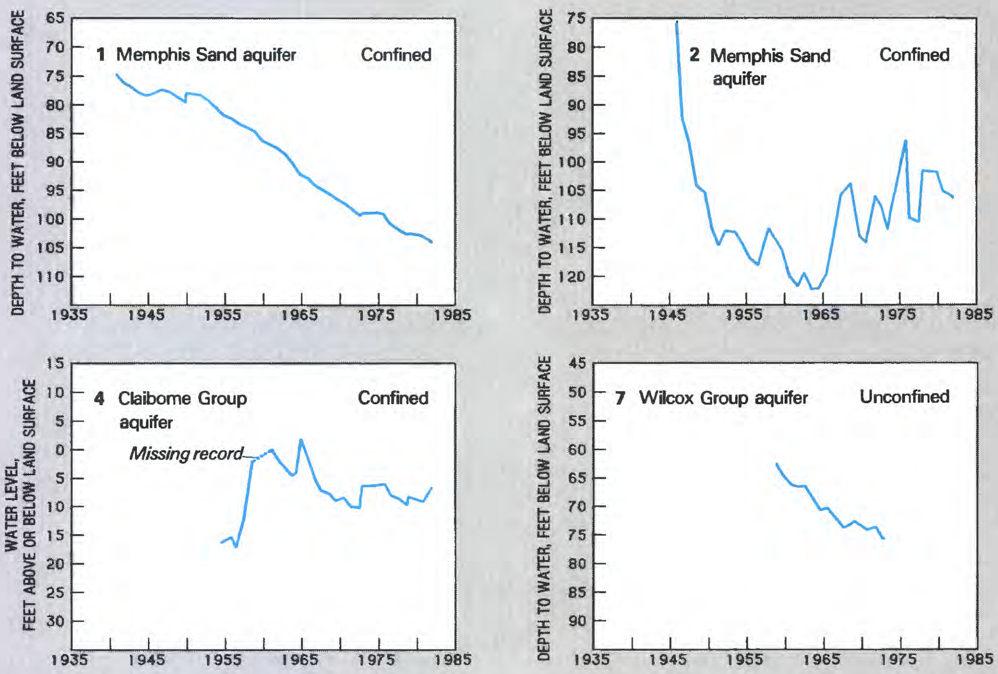
Hydrographs from wells near Memphis (locations 1, 2, fig. 2) show fluctuations in water levels that result from changes in pumpage. Water levels in the Memphis Sand (Claiborne Group) of the Tertiary sand aquifer have declined in response to yearly increases in pumpage since about 1950 (location 1, fig. 2); however, water levels remain above the top of the aquifer and represent a decline in artesian head rather than a dewatering of the aquifer. The Fort Pillow Sand (Wilcox Group) of the Tertiary sand aquifer, underlying the Memphis Sand, was pumped intensively between 1945 and about 1962. During this period, the water level in this part of the Tertiary sand aquifer declined about 45 ft (location 2, fig. 2). Since 1962, pumpage has decreased, and water levels have recovered about 20 ft. Pumpage at Jackson, primarily from the Wilcox Group, has increased steadily to more than 13 Mgal/d, and water levels have declined since the 1950's (location 7, fig. 2). In the rest of West Tennessee, long-term water levels show only seasonal fluctuations, as typified by the hydrograph for a well in Dyersburg (location 4, fig. 2).

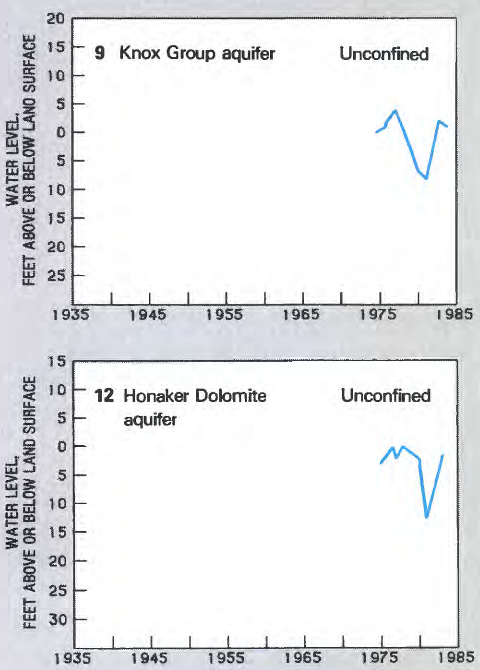
Ground-water levels in Middle and East Tennessee have not been affected significantly by pumping. The well in the Chattanooga area (location 9, fig. 2) is near a well field that is withdrawing about 0.5 Mgal/d. Water levels fluctuate almost daily in response to changes in pumping but do not show long-term declines. Water levels were lowest during the dry years from 1979 through 1981 but have recovered during subsequent years of normal rainfall. The hydrograph for the well near Elizabethton (location 12, fig. 2) also shows the effect of the drought, but no long-term declines.

GROUND-WATER MANAGEMENT

The Tennessee Department of Health and Environment, Office of Water Management, is responsible for ground-water management. The Groundwater Protection Division issues licenses to qualified well-drilling contractors, requires conformance with well-construction regulations, and receives reports of well completions as mandated by the Water Well Drillers







WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principel uses
1	Memphis	Memphis Sand. . . .	Public supply, industrial.
2	Millington	. . . .do	Do.
3	Germantown.	. . . .do	Do.
4	Dyersburg	Claiborne Group . .	Do.
5	Union City.	. . . .do	Do.
6	Crockett County . .	. . . .do	Do.
7	Jackson.	Wilcox Group	Do.
8	East Chattanooga . .	Knox, Chicamauga Limestone.	Public supply.
9	Hixon.	Knox Group.	Do.
10	Jefferson City	. . . .do	Public supply, mining.
11	Johnson City	Shady Dolomite. . .	Public supply.
12	Elizabethton.	Honaker Dolomite. .	Public supply, industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Tennessee. (Sources: Withdrawal data from files of the Tennessee Division of Water Management; water-level data from U.S. Geological Survey files.)

Act (Tennessee Code Annotated 69-11-101, et seq.). The Water Supply Division requires community suppliers to submit designs for new facilities for State review and approval, requires compliance with design and construction guidelines, requires water treatment, and requires the treatment-plant operator to be trained and licensed (Tennessee Code Annotated 68-13-701, et seq.). The Office of Water Management requires that the State be notified when a user withdraws more than 50,000 gal/d (Tennessee Code Annotated 69-8-105, et seq.). In addition, the Office of Water Management supports investigations related to human health and ground-water protection.

The Tennessee Division of Geology is responsible for enforcement of the regulations of the Tennessee Oil and Gas Board. These regulations are intended to protect the quality of fresh ground water in areas of oil and gas development.

Tennessee intends to seek primacy in the implementation of the Underground Injection Control Program within the State (Tennessee Water Quality Control Board, 1983). If this program does become the responsibility of the State, the Groundwater Protection Division will be responsible for enforcement.

The U.S. Geological Survey collects hydrologic data and performs research in ground-water occurrence, movement, and water quality in cooperation with local and State agencies and in support of other Federal agencies (Department of Energy, Corps of Engineers, and Tennessee Valley Authority).

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Prepared by Michael W. Bradley and Este F. Hollyday

For further information contact District Chief, U.S. Geological Survey, A-413 Federal Building, Nashville, TN 37203

TEXAS
Ground-Water Resources

Ground-water resources are vitally important in satisfying the demands for freshwater in Texas. Many cities, industries, and irrigators, as well as most rural inhabitants, depend on this resource because of its accessibility, potability, and small cost.

During 1980, aquifers supplied 61 percent of the total freshwater used in Texas. During that year, 9.7 billion gallons per day (bgd) of fresh ground water was withdrawn for irrigation, public supply, industrial use, and rural domestic and livestock supply. Almost 7 million people, or about one-half of the State's total population, are served by ground water from public- and rural-supply systems. Among the various categories for ground-water uses, irrigation accounts for more than 80 percent of the fresh ground-water withdrawals. Public-supply use accounts for only 10 percent of the fresh ground-water withdrawals. Industrial, rural-domestic, and livestock uses comprise less than 10 percent of withdrawals. Ground-water withdrawals during 1980 for various uses and other related statistics are given in table 1.

Table 1. Ground-water facts for Texas

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Texas Department of Water Resources, 1984b, unpublished data[1]]

Population served by ground water, 1980	
Number (thousands)	6,921
Percentage of total population	47
From public water-supply systems:	
Number (thousands)	4,439
Percentage of total population	31
From rural self-supplied systems:	
Number (thousands)	[1]2,482
Percentage of total population	16
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	16,000
Ground water only (Mgal/d)	9,700
Percentage of total	61
Percentage of total excluding withdrawals for thermoelectric power	62
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	840
Percentage of total ground water	9
Percentage of total public supply	46
Per capita (gal/d)	190
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	300
Percentage of total ground water	3
Percentage of total rural domestic	84
Per capita (gal/d)	123
Livestock:	
Ground water (Mgal/d)	110
Percentage of total ground water	1
Percentage of total livestock	49
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	430
Percentage of total ground water	4
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	23
Excluding withdrawals for thermoelectric power	24
Irrigation withdrawals:	
Ground water (Mgal/d)	8,000
Percentage of total ground water	83
Percentage of total irrigation	70

[1] Includes public water-supply systems for communities with populations of less than 1,000.

GENERAL SETTING

Ground-water resources in Texas occur within all four physiographic provinces in the State—Basin and Range, Great Plains, Central Lowland, and Coastal Plain (fig. 1). These principal landforms also are associated with differences in the occurrence of ground water. The Basin and Range province in the far western part of the State contains ground-water supplies from permeable alluvium that fills deep troughs in bedrock. Significant ground-water resources underlie the Great Plains, a broad southeasterly sloping highland in northwest and west-central Texas. There, ground water usually is unconfined and is contained in stream-deposited sediments of the High Plains and in marine limestone of the Edwards Plateau. The Central Lowland of north-central Texas is underlain by westward-dipping limestone and sandstone that form a terrain of moderate-to-low relief. Ground-water supplies in this region generally are less abundant than elsewhere in the State. The Coastal Plain, which occupies much of the southern and eastern parts of Texas, slopes gently southeastward toward the Gulf of Mexico. There, wedge-shaped layers of unconsolidated gravel, sand, silt, and clay thicken seaward and contain large volumes of mostly confined water.

Ground water in Texas is derived from precipitation, which varies greatly in amount across the State. Average annual precipitation ranges from about 8 inches (in.) in far west Texas to about 56 in. in the extreme southeastern part of the State. Although precipitation greatly affects the rate of recharge to the aquifers, the slope of the land, the type of rocks exposed, and the evaporation and transpiration in the area also affect the recharge. In general, annual recharge rates range across the State from fraction of an inch in far west Texas and on the High Plains to several inches in east Texas. Recharge rates are equivalent to a significant part of the annual precipitation in some limestone areas where large openings in the rocks permit very rapid infiltration of water.

Ground water is available throughout the State although in different quantities. Eighty percent of the State is underlain by seven principal aquifers and 16 recognized minor aquifers. The remaining 20 percent of the State, where principal or minor aquifers are not present, contain small but undependable supplies.

PRINCIPAL AQUIFERS

Seven aquifers in Texas collectively supply most of the ground water used in the State. These principal aquifers have regional significance and have the ability to supply large quantities of water in about two-thirds of the State. The principal aquifers are, from northwest to southeast, the High Plains (Ogallala), alluvium and bolson deposits, Edwards-Trinity (Plateau), Edwards (Balcones fault zone), Trinity,

Table 2. Aquifer and well characteristics in Texas

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey and Texas Department of Water Resources]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Depth (ft) May exceed	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Alluvium and bolson deposits aquifer: Sand, gravel, silt, and clay. Unconfined in most places.	100 - 1,000	1,500	500 - 900	2,500	Important source of irrigation and public supply water in west Texas, north central Texas, and along Brazos River. Substantial water-level decline in some areas.
Gulf Coast aquifer system: Multi-aquifer unit composed of interbedded and interlensing sand, silt, clay, and gravel. Confined in most places.	200 - 1,500	3,000	300 - 1,500	4,500	Underlies most of the State's Coastal Plain from lower Rio Grande Valley northeastward into Louisiana. Water fresh, but dissolved-solids concentrations increase downdip. In Houston district, intensive pumpage has caused large water-level declines and land-surface subsidence. Includes Chicot, Evangeline, and Jasper aquifers.
High Plains (Ogallala) aquifer: Sand, gravel, silt, clay, and caliche. Unconfined.	200 - 600	900	100 - 1,000	2,000	Major aquifer on High Plains of Texas. Water fresh and characteristically very hard. Large-scale pumpage rapidly consuming available supplies.
Carrizo-Wilcox aquifer: Sand, sandstone, clay, silt, gravel, and lignite that are mostly interconnected hydrologically. Unconfined in the upper 50 to 100 ft in places; confined at depth.	200 - 1,000	5,500	300 - 800	3,000	One of most extensive aquifers in Texas. Water used for irrigation in Winter Garden area and for public supply and industrial purposes statewide. Aquifer contains most of the State's lignite reserves. Water quality gradually deteriorates downdip. Equivalent to the Wilcox-Carrizo aquifer in Louisiana.
Edwards (Balcones fault zone) aquifer: Limestone, dolomite, and marl; extensively faulted, fractured, and cavernous. Confined and unconfined.	100 - 1,000	2,500	400 - 1,200	16,000	Supplies municipal and industrial water numerous cities and towns, including total municipal supply for San Antonio. Capacities of wells operated by San Antonio are among largest in the world. Discharges water through many of largest springs in Texas.
Edwards-Trinity (Plateau) aquifer: Sandstone, sand, and clay in lower part and limestone, dolomite, and marl in upper part. Confined and unconfined.	150 - 300	800	50 - 200	3,000	Important source of water for irrigation and for small cities and some industries in west-central Texas. Springflow constitutes a large part of base flow of several scenic streams which, in turn, provides important recharge to Edwards (Balcones fault zone) aquifer.
Trinity aquifer: Sandstone and sand interbedded with conglomerate, caliche, and shale in lower part; sand interbedded with shale and clay in upper part. Confined in most places.	150 - 400	3,000	100 - 300	1,000	Intensively developed for municipal and industrial purposes in Dallas-Fort Worth area; large water-level declines there. Available as water supply in large area of central and north Texas. Water fresh in most of aquifer, but quality deteriorates downdip.

Carrizo-Wilcox, and Gulf Coast system. These aquifers are described below and in table 2, from youngest to oldest; their areal distribution, where they yield water containing less than 3,000 milligrams per liter (mg/L) of dissolved solids, is shown in figure 1.

Alluvium and Bolson Deposits Aquifer

The alluvium and bolson deposits are present in many isolated areas and are important sources of water for irrigation and public supply in the western one-half of the State and for irrigation along the Brazos River in the eastern part of the State. In far western Texas, the bolson deposits are several thousand feet thick in places, and some contain freshwater to depths of more than 1,000 feet (ft.). The city of El Paso obtains 85 to 90 percent of its water needs from the alluvium and bolson deposits. Large-scale pumping for irrigation is occurring from many of the bolson deposits, and the pumping is causing continuing water-level declines. The water quality ranges from fresh to slightly saline. However, intensive pumping in some areas has induced local migration of saline water into the freshwater areas (Gates and others, 1980).

Gulf Coast Aquifer System

The Gulf Coast aquifer system underlies an area from the coastline inland 100 miles and extends from Mexico to Louisiana. It is a multiaquifer system that consists of interbedded and interfingering beds of sand, silt, clay, and gravel and includes the Chicot, the Evangeline, and the Jasper

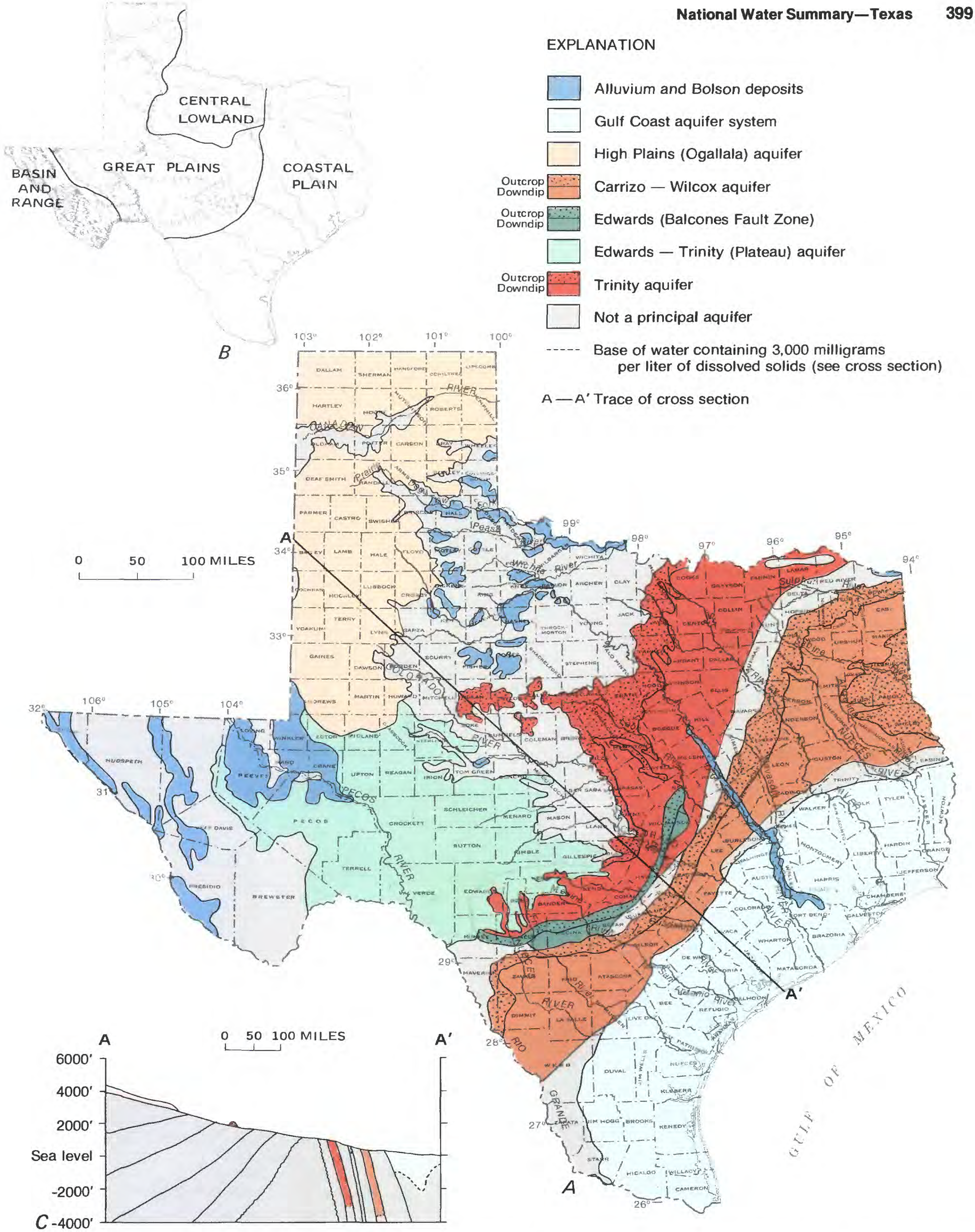


Figure 1. Principal aquifers in Texas. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Modified from Texas Department of Water Resources, 1984b. *B*, Fenneman, 1946; Raisz, 1954. *C*, Compiled by E. T. Baker, Jr., from U.S. Geological Survey files.)

aquifers. Intensive pumping for public supply and industrial use in the Houston metropolitan area has lowered water levels and decreased artesian pressure, which have caused land subsidence of almost 10 ft in some places (Gabrysch, 1982). Elsewhere in the coastal region, extensive pumping of ground water, mainly for rice irrigation, has resulted in land subsidence of generally less than 0.5 ft, although some areas have subsided more than 1.5 ft (Baker and Follett, 1973; Ratzlaff, 1982). Saltwater encroachment may occur in coastal areas because of large freshwater withdrawals. The typical range of dissolved solids in water from this aquifer system is from 300 to 1,000 mg/L.

High Plains Aquifer

The High Plains (Ogallala) aquifer occurs at or near the surface of most of the High Plains, and is one of the most intensively developed aquifers in the Nation. It consists of unconsolidated sand, gravel, silt, and clay and contains caliche deposits. In Texas, it supplies water to about 75,000 irrigation wells (Texas Department of Water Resources, 1981). Large-scale pumpage is consuming rapidly the available ground-water supplies (Baker and Wall, 1976; Muller and Price, 1979), and, unless effective conservation measures are implemented, the irrigated acreage will be decreased by slightly more than one-half of the present acreage by the year 2030 (Texas Department of Water Resources, 1984a). The water is fresh and, in many places, contains less than 500 mg/L of dissolved solids.

Carrizo-Wilcox Aquifer

The Carrizo-Wilcox aquifer is one of the most extensive in Texas and supplies water for all categories of wells from Mexico northeastward into Arkansas and Louisiana. The aquifer consists of hydrologically interconnected sand, sandstone, clay, silt, and gravel of the Wilcox Group and overlying Carrizo Sand, both of Eocene age. Most of the State's lignite also is in the Wilcox Group. The water is mostly confined, and large-capacity flowing wells are common in many areas. The typical range in dissolved-solids concentration in water is from 200 to 1,500 mg/L. Water suitable for most uses is present at depths of as much as 5,500 ft.

Edwards (Balcones Fault Zone) Aquifer

The Edwards (Balcones fault zone) aquifer is a very productive aquifer. It consists of limestone, dolomite, and marl and is present in a narrow zone in the central and south-central parts of the State, where the cities of San Antonio and Austin are located. The aquifer provides water to numerous cities, including the total public supply for San Antonio. The capacities of wells operated by San Antonio are among the largest in the world; some wells yield more than 16,000 gallons per minute. Industrial and irrigation water also is pumped from the aquifer. Some of the largest springs in the State result from the discharge of water from the aquifer. The dissolved-solids concentration in ground water typically ranges from 300 to 1,200 mg/L. Saline water that contains hydrogen sulfide gas is present in the aquifer downdip of the freshwater; this water may become a water-quality concern because of the potential for updip intrusion into the fresher water during a long-term drought.

Edwards-Trinity (Plateau) Aquifer

The Edwards-Trinity (Plateau) aquifer supplies water mostly for irrigation but also for many small cities and some industries and for rural domestic and livestock use in a large part of west-central Texas. The aquifer consists of sandstone and sand overlain by limestone. Springflow from the aquifer sustains much of the base flow of many streams that cross the outcrop. This flow recharges the Edwards (Balcones fault zone) aquifer in losing reaches downstream. The typical range of dissolved solids in water is 400 to 1,000 mg/L (Baker and Wall, 1976).

Trinity Aquifer

The aquifer in the Trinity Group extends through a large area of north and central Texas. It consists of sandstone and sand beds interbedded with conglomerate, caliche, shale, and clay. This aquifer has been intensively developed for public supply and industrial use in the Dallas-Fort Worth area, where a large decrease in artesian head and increased pumping costs have occurred. In many other areas, the aquifer supplies water for irrigation and for rural domestic and livestock use. The typical range in dissolved-solids concentration is 500 to 1,500 mg/L.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

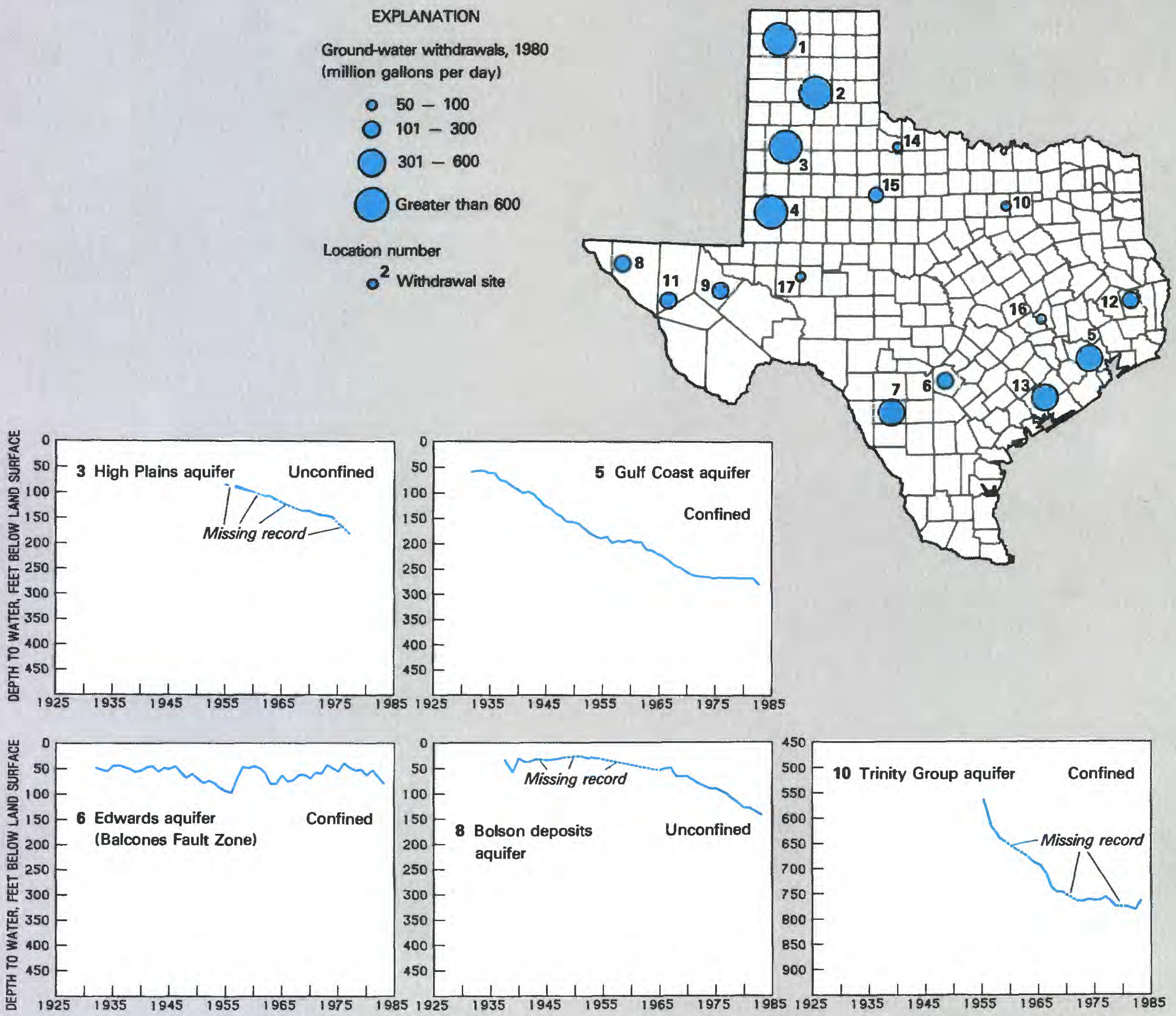
The areas of large ground-water withdrawals and the trends of ground-water levels in representative wells are shown in figure 2. The effect of pumpage on water levels is shown by hydrographs of wells that represent many of the major aquifers.

About two-thirds, or about 6,500 million gallons per day (Mgal/d), of the total volume of fresh ground water withdrawn during 1980 was from the High Plains (Ogallala) aquifer (locations 1-4, fig. 2). Almost all this water was used for irrigation. This pumpage has caused a steady decline in water levels in wells as is shown by the hydrograph of a well completed in the High Plains (Ogallala) aquifer at location 3. Water levels in this well have declined more than 130 ft since 1936; this represents a decrease in the quantity of water in storage.

Large withdrawals are made from the Gulf Coast aquifer system for public supply, irrigation, and industrial uses (locations 5, 12, 13, fig. 2). Location 13 represents mostly pumpage for irrigation of rice in a multicounty area where almost 600 Mgal/d was withdrawn. The most intensive pumping is in the Houston and adjacent areas (location 5, fig. 2) where almost 500 Mgal/d was withdrawn mostly for public supply. This pumpage has caused water levels in a representative well in the city of Houston to decline from about 50 ft below land surface in 1931 to about 250 ft below land surface in 1983. The water-level decline in the Houston area, unlike the decline on the High Plains, represents decreasing artesian pressure and not dewatering of the aquifer.

In south Texas, a large volume of fresh ground water is withdrawn in the Winter Garden area (location 7, fig. 2). During 1980, from 300 to 400 Mgal/d was pumped, mostly for irrigation, and about two-thirds of this volume was from the Carrizo-Wilcox aquifer.

Location 6 (fig. 2) is centered on Bexar County where the city of San Antonio (the third largest city in the State) and its environs pumped almost 250 Mgal/d during 1980. The water was withdrawn from the Edwards (Balcones fault zone) aquifer, and four-fifths of it was for public supply. The hydrograph that represents the aquifer in the San Antonio area (location 6) indicates no significant trend during the last 50 years. Although the maximum fluctuation (based on end-of-year measurements) was almost 60 ft from 1932 to 1983, the lowest water level occurred in 1956 at the end of a long-term drought, and the highest water level occurred in 1976 after abundant rainfall. In spite of ever-increasing



WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	High Plains (Canadian basin).	High Plains (Ogallala).	Irrigation.
2	High Plains (Red basin).	....do	Do.
3	High Plains (Brazos basin).	....do	Do.
4	High Plains Colorado basin).	....do	Do.
5	Houston region ...	Gulf Coast	Public supply.
6	San Antonio	Edwards (Balcones Fault Zone).	Do.
7	Winter Garden....	Carrizo-Wilcox. ..	Irrigation.
8	El Paso-Dell City ..	Alluvium, Bolson deposits.	Irrigation, public supply.
9	Pecos and Reeves Counties.	Alluvium......	Irrigation.
10	Dallas-Fort Worth.	Trinity Group ..	Public supply.
11	Van Horn ..	Bolson deposits.	Irrigation.
12	Lower Neches basin.	Gulf Coast, Carrizo-Wilcox.	Industrial, public supply.
13	Middle Gulf Coast.	Gulf Coast	Irrigation.
14	North-central Red basin.	Alluvium.....	Do.
15	North-central Brazos basin.	....do	Do.
16	East-central Brazos basin.	Carrizo-Wilcox, alluvium.	Public supply, Irrigation.
17	West-central Colorado basin.	Edwards-Trinity (Plateau).	Irrigation.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Texas. (Sources: Withdrawal data from Texas Department of Water Resources, 1984b; water-level data from U.S. Geological Survey files.)

pumpage, water levels in wells continue to fluctuate, predominantly from variations in recharge from rainfall.

Large volumes of ground water are withdrawn in west Texas mostly from the alluvium and bolson deposits. From 100 to 300 Mgal/d was pumped during 1980 from each of three areas in far western Texas, and in west-central Texas three other areas had withdrawals of from 50 to 300 Mgal/d, mostly for irrigation. About 75 percent of the pumpage at locations 9 and 11 (fig. 2) was for irrigation, whereas about 60 percent of the pumpage at location 8 (fig. 2) was for irrigation and almost 40 percent was for public supply by the city of El Paso. The hydrograph of an El Paso well completed in a bolson deposit (location 8) shows a pronounced downward trend during the nearly 50 years of record. In this well, the water level has declined about 125 ft.

In the Dallas–Fort Worth area of north Texas (location 10, fig. 2), 50 to 100 Mgal/d was withdrawn from the Trinity aquifer, mostly for public supply, and water levels in wells have been declining steeply. The hydrograph of a well completed in the Trinity Group (location 10) shows a decline of more than 200 ft in the water level over an approximately 30-year period. The water level in this well is now between 700 and 800 ft below land surface. The decline in water levels represents a decrease in artesian pressure and not a dewatering of the aquifer.

GROUND-WATER MANAGEMENT

Ground water in Texas, unlike surface water, is the property of the landowner, and its use is subject to very few limitations, in accordance with the "English" or common-law doctrine of riparian rights. Owners of land overlying defined ground-water reservoirs or aquifers may adopt voluntary well regulation through mutual association in "underground water conservation districts." Section 52.001, Texas Water Code, provides the framework for these districts, and to date, 12 have been created, but only 9 are currently active (Texas Department of Water Resources, 1984b). The act creating the underground water districts was amended by the 63rd Legislature in 1973 (House Bill 935), primarily to allow for the control of land subsidence caused by withdrawal of ground water.

Three State agencies are actively engaged in various phases of the State's water-resources programs. These are the Texas Department of Water Resources, the Railroad Commission of Texas, and the Texas Department of Health. The Texas Department of Water Resources is the State agency that has been given primary responsibility for implementing the provision of the State's Constitution and laws relating to the conservation, protection, and development of both surface- and ground-water resources. Ground-water data are collected and analyzed independently and in cooperation with the U.S. Geological Survey or other Federal and State agencies. The Railroad Commission of Texas has the responsibility for protecting ground water from possible pollution that may result from the exploration, development, and production of petroleum, natural gas, and geothermal resources, as well as from surface mining of lignite, coal, and uranium. The Texas Department of Water Resources assists the Railroad Commission in their responsibilities by making recommendations for the protection of usable-quality ground water in connection with the exploration for and production of oil, gas, and other minerals, as well as the disposal of oil-field brine by injection into subsurface formations. The Texas Department of Health regulates the disposal of muncipal and mixed municipal-industrial solid wastes, establishes drinking-water standards for public-water supplies, and has primacy in administering the provisions of the Federal Safe Drinking Water Act.

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Prepared by Ernest T. Baker, Jr.

For further information contact District Chief, U.S. Geological Survey, Federal Building, Room 649, 300 East 8th Street, Austin, TX 78701

TRUST TERRITORY OF THE PACIFIC ISLANDS, SAIPAN, GUAM, AND AMERICAN SAMOA
Ground-Water Resources

Ground water is of vital importance to the people of the Trust Territory of the Pacific, Saipan, Guam, and American Samoa. Practically all the ground water produced is used for public supply. On the island of Saipan, nearly 5.5 million gallons per day (Mgal/d) is produced to provide water for about 15,000 people and a growing tourist industry. About 80 percent of the 110,000 residents on Guam rely on water pumped from the Mariana Limestone in the northern part of the island. Average water production from surface and ground-water sources amounts to nearly 33 Mgal/d, of which 26 Mgal/d is from ground-water sources. On Moen, about 0.8 Mgal/d from ground-water sources supplements surface water supply to meet the needs of about 7,000 people. On Tutuila, American Samoa, which has a population of about 28,000 people, average pumpage from ground-water sources for public and industrial supply is about 4.3 Mgal/d.

GENERAL SETTING

Rainfall is the principal source of recharge to the ground-water reservoirs of the Pacific Islands. In limestone areas, such as Saipan and northern Guam, surface water supplies are limited and ground water is the primary recoverable water resource. The geographic location of the islands are shown in fig. 1.

Saipan has an area of 48 square miles (mi^2) and is the second largest of the Mariana Islands. It has a tropical climate with an average annual rainfall of 81 inches (in.), ranging from 70 in. in the southwestern lowlands to 91 in. in the central ridge. L mestone and sediments comprise more than two-thirds of the island, and the remainder consists of volcanic rocks, various unconsolidated surficial deposits, marshes, and lakes. As much as 35 percent of rainfall may recharge the limestone aquifers.

Guam is a tropical island with an area of 212 mi^2. It is the largest and southernmost of the Mariana Islands. Guam has an average annual rainfall of about 85 in., ranging from about 80 inches on the coastal lowlands to about 100 in. in the mountainous areas in southern Guam. As much as 35 percent of rainfall may recharge the limestone aquifers. The principal rock in northern Guam is the Barrigada Limestone, which is underlain by volcanic rock of the Alutom Formation and overlain by a veneer of the Mariana Limestone. The mountainous terrain in central and southern Guam consists mostly of volcanic rock of the Alutom and Umatac Formations.

Moen is one of the 19 volcanic islands of the State of Truk, within the Trust Territory of the Pacific Islands; it has a land area of 7.2 mi^2. The climate is warm and humid and rainfall averages 144 in. a year. An estimated 30 percent of the rainfall may recharge the volcanic aquifer on Moen.

Tutuila is the largest island in American Samoa and has an area of 53 mi^2. Mean annual precipitation in Tutuila varies according to location and elevation. At low elevations, mean annual rainfall ranges from 125 to 200 in. and, at the crest of mountain ranges, rainfall averages more than 250 in. An estimated 30 percent of the rainfall may recharge the volcanic rock aquifer on Tutuila.

PRINCIPAL AQUIFERS

Ground water in Saipan, Guam, Moen, and Tutuila is present as perched water and basal water (freshwater that rests on denser saltwater). A third type of ground water on Saipan and Guam is parabasal water, which is in continuity with basal water but rests on the impervious volcanic basement rather than on saltwater (Mink, 1976, p. 22)

The aquifers of Saipan, Guam, Moen, and Tutuila are described below by island and also in table 1; except for Moen, their areal distribution is shown in figure 1.

ISLAND OF SAIPAN

The two most prominent aquifers in Saipan are the Mariana and Tagpochau Limestones. Ground water occurs as unconfined basal water in the Mariana Limestone and as basal, parabasal, and perched water in the Tagpochau Limestone. The largest concentration of wells is located in the central and southern part of Saipan; the wells in the central area tap the highly permeable Tagpochau Limestone. Water quality of springs at higher elevations (in the Tagpochau Limestone) is suitable for most uses, although concentrations of bicarbonate are fairly high, and dissolved iron concentrations range from 0.3 to 0.5 mg/L; dissolved iron can affect taste, color, and turbidity (Van der Brug, 1984). Heavy pumping of the basal freshwater on Saipan has induced inland movement of saline ground water, and chloride concentrations of more than 1,000 mg/L are found in water from many wells.

ISLAND OF GUAM

The two most extensive limestone aquifers in Guam are the Barrigada and Mariana Limestones that rest unconformably on a mass of low-permeability volcanic rocks of the Alutom Formation. The Mariana Limestone is a complex of reef and lagoonal limestone that underlies most of northern Guam. The Barrigada Limestone, which underlies the Mariana,

Table 1. Aquifer and well characteristics in the Trust Territory of the Pacific, Saipan, Guam, and American Samoa

[Ft = feet; gal/min = gallons per minute; mi = mile. Sources: Reports of the U.S. Geological Survey and other reports of State and local agencies of the Trust Territory of the Pacific, Saipan, Guam, and American Samoa]

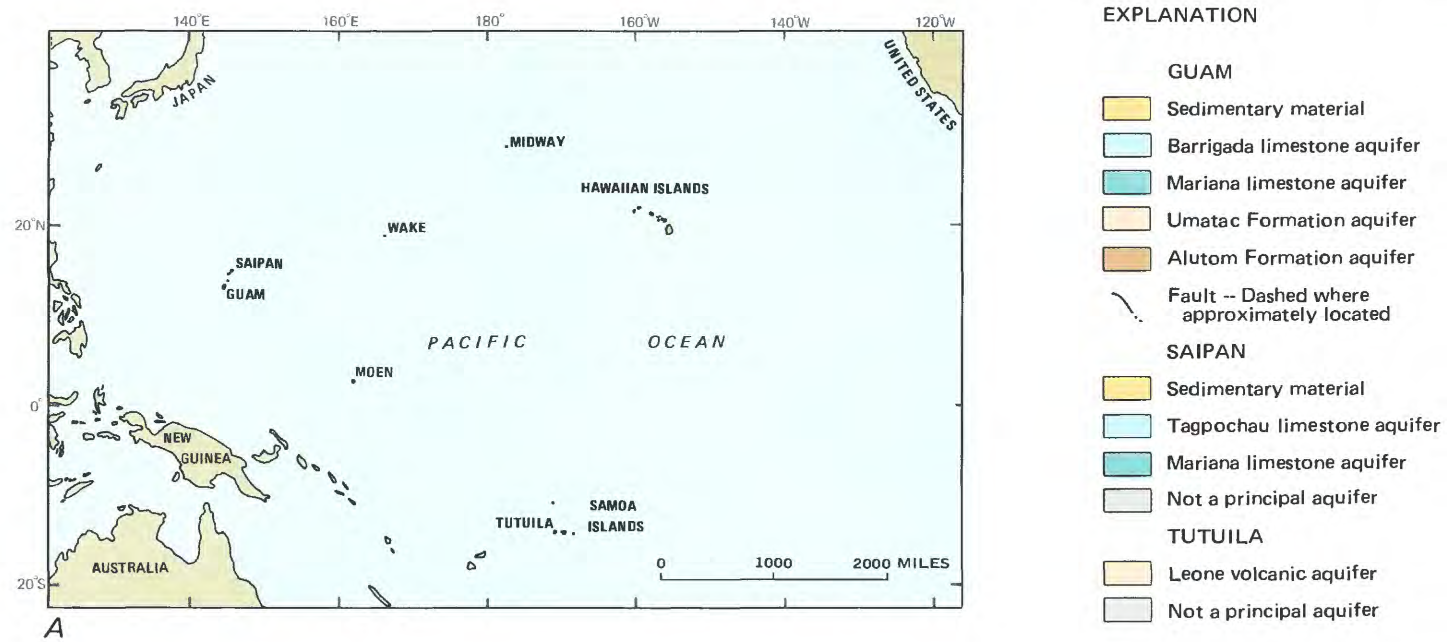
Aquifer name and description	Well characteristics: Depth (ft) Common range	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Saipan: Mariana Limestone: Includes clastic and reef limestone, sand and gravel between elevations of 100 to 500 ft. Unconfined.	40 - 260	40 - 80	150	Very permeable. Most productive source of ground water.
Tagpochau Limestone: Includes tuffaceous, transitional carbonate facies and undifferentiated limestone. Unconfined.	100 - 500	25 - 200	300	Very permeable. Most predominant limestone formation and underlies nearly one-half of Saipan.
Guam: Mariana Limestone: A complex of reef and lagoonal limestone. Underlies most of the north half of Guam. Maximum thickness is greater than 500 ft. Unconfined.	200 - 500	100 - 300	400	Generally large permeability. Sea-water intrusion poses problems along coastal areas. Designated a "sole-source" aquifer.
Barrigada Limestone: Pure detrital limestone and massive. Width of outcrop averages about 1 mi. Thickness probably greater than 540 ft. Unconfined.	200 - 500	100 - 300	500	Very permeable. Wherever rock extends below sea level, it contains fresh basal ground water about 7 feet above sea level. Supplies numerous wells.
Moen: Truk volcanics: Basalt, andesite and trachyte lava flows. Alluvium in valley bottoms and calcareous sand and limestone along coastal shores. Unconfined.	40 - 100	15 - 50	70	Little permeability in volcanic rock. Surficial sediments permeability low but generally larger than volcanic rock.
Tutuila, American Samoa: Leone volcanics: Basaltic lava flows. Sedimentary materials underlie the volcanic rocks, alluvial deposits underlying valley floors, and beach deposits along coastal shores. Unconfined.	90 - 250	100 - 300	400	Permeability moderate to large. Beach deposits highly permeable. Yield water to wells at rates of 50 to 330 gal/min.

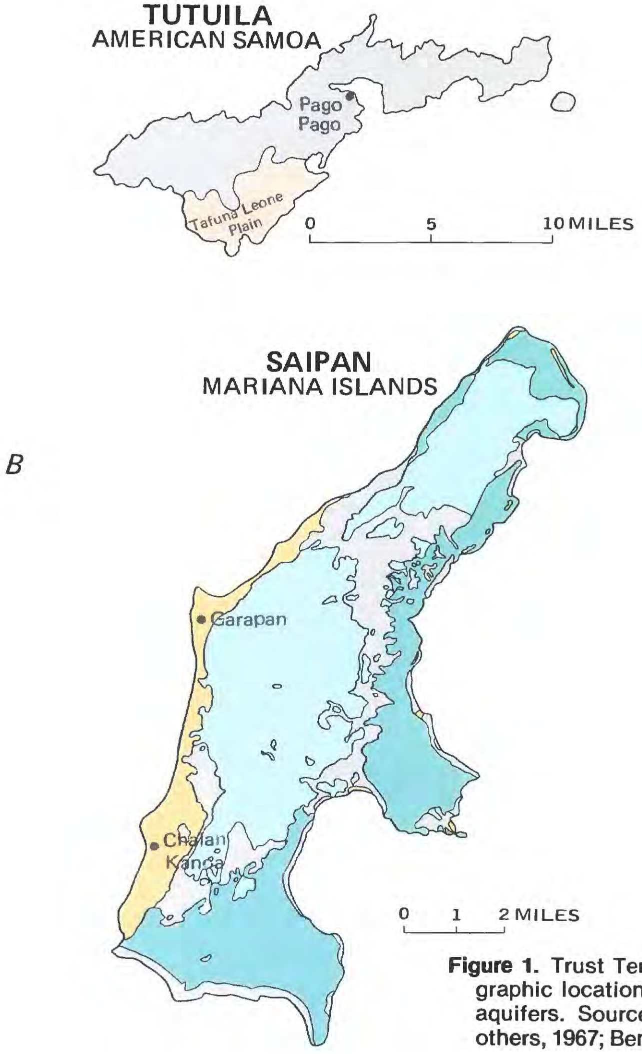
consists of pure detrital limestone, fine grained, with a thickness that probably exceeds 500 feet (Ward and others, 1965). The Barrigada Limestone yields water readily to wells. It is the major source of water supply for Guam, and has been designated as a "sole-source" aquifer. About 70 percent of the public supply of Guam comes from ground water pumped from about 100 production wells. The sustainable yield of the aquifer is estimated to be 60 Mgal/d (Barrett and others, 1982). The basalt lava flows of the Alutom Formation in central Guam and the Umatac Formation in southern Guam have low permeability, and no appreciable amounts of water have been obtained from wells drilled in them.

The hardness of ground water in northern Guam averages about 200 milligrams per liter (mg/L) as calcium carbonate. Guam's ground water also contains 2 to 2.5 mg/L nitrate as nitrogen. Cesspool leachate is suspected to be a major cause of nitrate contamination, which, although elevated, does not exceed the national drinking-water regulation of 10 mg/L (U.S. Environmental Protection Agency, 1982a,b). The dissolved-solids concentration of water in limestone ranges from 200 to 900 mg/L. As the demand for freshwater continues to rise, overpumping may cause contamination of the aquifers by reducing hydraulic head at the pumping center, thereby inducing seawater intrusion.

Island of Moen

On Moen, ground water currently is being developed in the Capital area (fig. 2) to supplement surface-water supplies. The aquifers are located in basaltic flows interspersed with dikes and interbedded with pyroclastic flows and conglomerates of the Truk volcanic series (Stark and others, 1958). In general, the ground-water quality on Moen is suitable for most uses and is predominantly a magnesium bicarbonate type (Van der Brug, 1983).





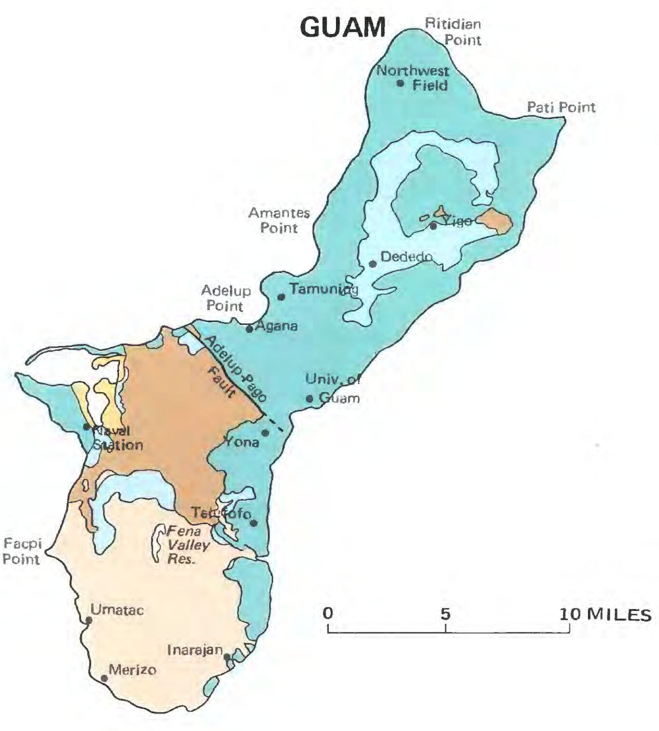


Figure 1. Trust Territory of the Pacific Islands, Saipan, Guam, and American Samoa. *A*, Geographic location. *B*, Principal aquifers. (See table 1 for a more detailed description of the aquifers. Sources: *A*, U.S. Geological Survey, 1970. *B*, Cloud and others, 1956; Tracey and others, 1967; Bentley, 1975.)

Island of Tutuila

On Tutuila, American Samoa, the principal source of ground water is aquifers beneath the Tafuna-Leone plain. The aquifers are located in thin bedded basaltic flows and in underlying beach and lagoonal deposits of the Leone volcanic series. The basal aquifers are unconfined and generally yield about 200 gallons per minute to wells. The amount of estimated freshwater stored in the aquifer is 50,000 acre-feet (acre-ft), and the annual recharge to the aquifer is roughly estimated to be 30,000 acre-ft (Bentley, 1975). About 20 Mgal/d flows through the aquifer at an average rate of 5 feet per day from the inland recharge area to the sea (Paul Eyre, U.S. Geological Survey, written commun., June, 1984).

The chemical quality of fresh ground water in Tutuila generally is suitable for most uses. The constant threat of contamination of wells by sea water in dry periods is caused by upconing of the underlying sea water. The chloride concentration of water from wells in the Tafluna-Leone plain have ranged from 7 to 1,200 mg/L from 1975 to 1983. The recommended limit for chloride in drinking water is 250 mg/L (U.S. Environmental Protection Agency, 1982b).

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Major areas of ground-water withdrawals in each island is shown in figure 2. Trends in ground-water levels for Guam and Tutuila also are shown in figure 2. Water-level trends are not shown for Saipan and Moen because of a lack of long-term records, although short-term water-level records from Saipan indicate that ground-water levels may be declining in some areas of that island.

The hydrographs for locations 3 and 4 (fig. 2) are representative of water levels in the Barrigada Limestone and Mariana Limestone aquifers on Guam. Increased pumping for private- and public-water supplies and military facilities, and the prolonged drought in 1982 and 1983 have contributed to slight declines in water levels since 1974 in the aquifers; however, long-term declines have not occurred. The similarity in the hydrographs is indicative of the good hydrologic connection which exists between the limestones. Water levels in Guam are very responsive to tidal fluctuations, a fact not visible in the hydrograph plot of annual minimum water levels shown here.

On Tutuila, American Samoa, water levels have risen slightly since 1975, as shown in the hydrograph for location 6 (fig. 2), which is in the Leone volcanics aquifer. The increase can be attributed to increases in recharge which have kept pace with or exceeded increases in ground-water withdrawals.

GROUND-WATER MANAGEMENT

The governments of Saipan, Truk, and American Samoa have not enacted specific legislation and regulation for ground-water management. The Trust Territory Environmental Protection Board monitors the quality of water resources on Saipan and the Trust Territory islands.

Management of Guam's water resources is vested in the Guam Environmental Protection Agency (GEPA), created by the 1973 Guam Environmental Protection Agency Act (Title LXI, Chapter I). The GEPA is responsible for planning activities and development of regulations to insure the conservation of Guam's water resources. The U.S. Geological Survey, in cooperation with the GEPA, collects, stores, and retrieves hydrologic data and provides technical assistance.

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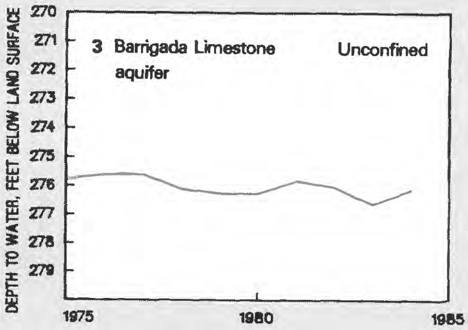
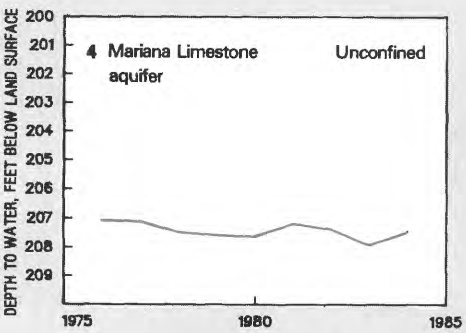
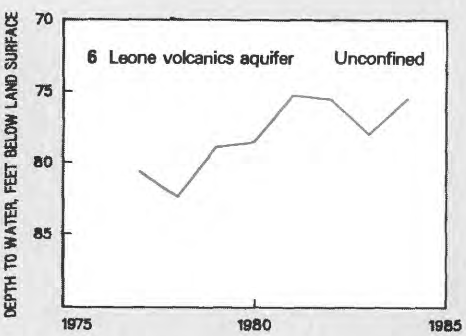
Prepared by Santos Valenciano

For further information contact District Chief, U.S. Geological Survey, P. O. Box 50166, Honolulu, HI 96850







WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
	Saipan:		
1	Maui IV area. . . .	Tagpochau Limestone . .	Public supply.
2	Kobler, Isley Fields.	Mariana Limestone	Do.
	Guam:		
3	Northern Guam . .	Barrigada Limestone . . .	Do.
4	Chalan, Pago, Mangilao areas.	Mariana Limestone	Do.
	Moen:		
5	Capital area	Truk volcanics.	Do.
	Tutuila:		
6	Tufana area	Leone volcanics	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Trust Territory of the Pacific, Saipan, Guam, and American Samoa. (Sources: Withdrawal and water-level data from U.S. Geological Survey files.)

U.S. VIRGIN ISLANDS
Ground-Water Resources

Freshwater is a scarce commodity in the Virgin Islands. To meet the demand, all available sources are tapped, including traditional rooftop-rainfall catchments and desalinization of seawater. Although freshwater supplies have been augmented through the years by large-scale desalination, the demand has never been met. Ground water is an important resource on all three islands, providing about 18 percent of the freshwater supply for the Territory's population of 100,000. Excluding production of desalinated seawater by the Government, ground water represents 50 percent of the available freshwater supply. The other 50 percent is provided by rooftop-rainfall catchments. The aquifers in the three islands can be classified as poor in terms of yield and water quality. Throughout most areas, yields are less than 15 gallons per minute (gal/min) and dissolved-solids concentrations are more than 1,000 milligrams per liter (mg/L). Locally, however, water quality is not a major constraint in development of supplies. At sites where yields to wells are acceptable but water does not meet national drinking-water regulations (U.S. Environmental Protection Agency, 1982a, b), withdrawals are made for other household uses or for use in reverse-osmosis water-treatment units. Ground-water withdrawals in 1982 for various uses and related statistics are given in table 1.

Table 1. Ground-water facts for U.S. Virgin Islands

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: CH2M Hill Southeast, Inc., 1983; Solley, Chase, and Mann, 1983; Torres-Sierra and Dacosta, 1984]

Population served by ground water, 1982	
Number (thousands)	40
Percentage of total population	42
From public water-supply systems:	
Number (thousands)	32
Percentage of total population	34
From rural self-supplied systems:	
Number (thousands)	8
Percentage of total population	8
Freshwater withdrawals, 1982	
Surface water and ground water, total (Mgal/d)	6.0
Ground water only (Mgal/d)	1.1
Percentage of total	18
Percentage of total excluding withdrawals for thermoelectric power	18
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	0.5
Percentage of total ground water	45
Percentage of total public supply	12
Per capita (gal/d)	16
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	0.6
Percentage of total ground water	55
Percentage of total rural domestic	100
Per capita (gal/d)	75
Livestock:	
Ground water (Mgal/d)	0
Percentage of total ground water	0
Percentage of total livestock	0
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	0
Percentage of total ground water	0
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	0
Excluding withdrawals for thermoelectric power	0
Irrigation withdrawals:	
Ground water (Mgal/d)	0
Percentage of total ground water	0
Percentage of total irrigation	0

GENERAL SETTING

The U.S. Virgin Islands consists of the three major islands of St. Thomas [32 square miles (mi^2)], St. John (19 mi^2), and St. Croix (82 mi^2), and several small cays; total land area is approximately 133 mi^2. St. Thomas and St. John are characterized by steep topography, with maximum elevations greater than 1,200 feet (ft) above sea level. In contrast, St. Croix is characterized by low rolling hills that dominate two-thirds of the island and reach a maximum elevation of 1,088 ft at the Northside Range. Average annual precipitation is 45 inches (in.) at St. Thomas and St. John, and 40 in. at St. Croix. However, the local relief and the northeast Trade Winds cause the rainfall distribution to differ by as much as 15 in. among the islands. Overall, about 5 percent of the annual rainfall recharges the aquifers, 94 percent is lost to evapotranspiration, and 1 percent runs off to the sea (Jordan and Cosner, 1973). Depending on the local geology, recharge to the aquifers ranges from 0.5 to 5 in. annually. The islands consist mostly of volcanic and intrusive rocks.

PRINCIPAL AQUIFERS

The principal aquifers in the U.S. Virgin Islands are the Kingshill aquifer of central St. Croix and the coastal embayment aquifer and the volcanic rock aquifer on all three islands (fig. 1). The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Ground-water quality in the U.S. Virgin Islands is affected mainly by precipitation which contains large concentrations of salts derived from sea-spray-laden air (Jordan and Cosner, 1973). The salt concentration in ground water is further increased by the high rate of evapotranspiration. "Freshwater," or water not affected by saltwater intrusion, contains from 500 to 2,000 mg/L of dissolved solids. Water from the volcanic rock aquifer generally has the smallest dissolved-solids concentration but usually contains concentrations of nitrate exceeding 10 mg/L as nitrogen. Other major water-quality problems that affect aquifers are contamination by sewage effluents discharged to streams and septic tanks,

Table 2. Aquifer and well characteristics in the U.S. Virgin Islands

[Ft = feet; Mgal/d = millions of gallons per day; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Cosner, 1972; Jordan and Cosner, 1973; Jordan, 1975; Stevens, Gómez-Gómez, and Alicea, 1981); CH2M Hill, Southeast, Inc., 1983]

Aquifer name and description	Aquifer withdrawals in 1980 (Mgal/d)	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Kingshill aquifer: A complex of reef and lagoonal limestone, marl, calcareous sandstone, and sand and gravel. Alluvium blankets most of aquifer along the coast and within drainage basins. Unconfined.	0.8	100 - 150	200	25 - 40	50	Dissolved solids vary considerably with depth; generally 1,500 to 3,000 mg/L but exceed 20,000 mg/L in some wells.
Coastal embayment aquifer: Weathered rock, overlain by alluvium and beach deposits. Generally semiconfined; unconfined conditions may exist within surficial deposits.	0.1	50 - 100	150	15 - 25	40	Water generally contains more than 2,000 mg/L of dissolved solids; used to supply reverse-osmosis units and desalination plants.
Volcanic rock aquifer: Weathered or fractured rocks. Semiconfined and confined.	0.3	100 - 150	300	5 - 10	15	Wells commonly yield water with nitrate concentrations in excess of national drinking-water regulations.

saltwater infiltration from leaky seawater mains, and saltwater intrusion induced by excessive withdrawals. The water in the three principal aquifers is a sodium bicarbonate or sodium chloride type.

Kingshill Aquifer

Regionally, the Kingshill is the most productive in the U.S. Virgin Islands. It underlies about 25 mi^2 of central St. Croix. Throughout most areas, the Kingshill aquifer consists of alternating layers of reef and lagoonal limestone interbedded with marl, calcareous limestone, and sand and gravel. Alluvium blankets most of the aquifer along the coast and within drainage basins. The aquifer is unconfined and contains a lens of relatively freshwater that overlies saline water (Robison, 1972). Few wells tap the aquifer's maximum saturated thickness, which may be 200 ft near the coast (fig. 1). Inland, the aquifer thins out at its contact with the volcanic rocks of the Northside and Eastend Ranges.

Coastal Embayment Aquifer

The coastal embayment aquifer is present on each island. The aquifer consists of relatively thick deposits of unconsolidated sediments overlying weathered and fractured volcanic rocks. Locally, a shallow water table is present where sediments are coarse grained. At other sites, fine-grained sediments predominate, and the water-producing zone is under semiconfined conditions. Depending on local hydrogeologic setting, the source of freshwater to wells within the coastal embayment aquifers may be derived predominately from induced seepage from the volcanic rock aquifers and induced recharge from the overlying sediments. In general, the coastal embayment aquifer provides sufficient yield to wells, but water is mostly saline.

Volcanic Rock Aquifer

The volcanic rock aquifer is present on each of the islands. The aquifer consists of lava flows, fluvial tuffs, and breccias. Water in this aquifer is under confined to semiconfined conditions in fractures or in the weathered-rock mantle. This aquifer is tapped almost exclusively by domestic self-supplied users except on the island of St. John. The aquifer was mostly untapped until after the 1960's. At St. John, the volcanic rock aquifer augments the public-water supply consisting of desalinated water barged from St. Thomas. Other well fields have been developed within the Virgin Islands National Park on St. John to supply the needs of visitors.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Well yields in the U.S. Virgin Islands differ by location and season. Local differences in an aquifer are controlled principally by the hydrogeologic setting and well construction; seasonal differences are more significant because of the limited extent of the aquifers and the dependence on rainfall for recharge. Withdrawals at a major public water-supply well field near Fredericksted, St. Croix (within a coastal embayment aquifer), in late 1967 had to be decreased from 100,000 to 30,000 gallons per day (gal/d) because of saltwater intrusion (Jordan, 1975). Similarly, water levels at a well field in the Kingshill aquifer declined so greatly during 1967 that well yields were reduced to 10,000 gal/d from the long-term potential yield of 100,000 gal/d. In this particular instance, the annual rainfall had been decreasing during three consecutive years, from 50 in. in 1965 to 30 in. in 1967. Within the volcanic rock aquifers some wells have become dry.

The principal areas of ground-water withdrawals within each of the three major U.S. Virgin Islands are shown in

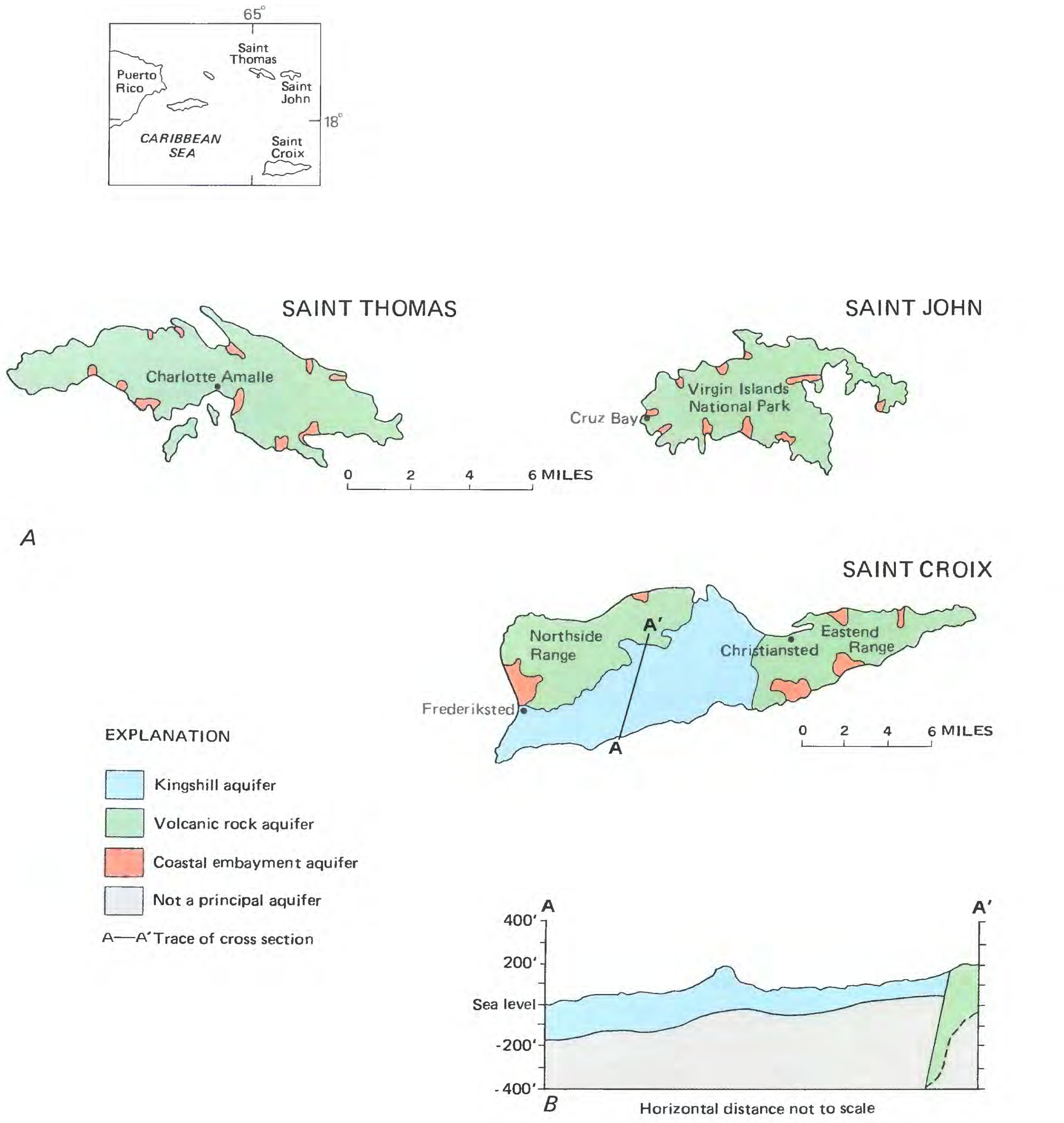


Figure 1. Principal aquifers in the U.S. Virgin Islands (inset map shows actual relative location of islands). *A*, Geographic distribution. *B*, Generalized cross section (A-A') showing thickness of the Kingshill aquifer, central St. Croix. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Cederstrom, 1950; Jordan, 1975. *B*, Donnelly, 1960.)

figure 2. The greatest amount of pumpage is from the Kingshill aquifer in central St. Croix. Within this area, public water-supply wells are estimated to yield 0.5 Mgal/d or approximately 27 percent of public-supply withdrawals on the island. A lesser amount (about 0.2 Mgal/d) is estimated to be withdrawn by private wells for commercial water sales and domestic use. Withdrawals from the volcanic rock aquifer at the three islands are estimated to be 0.3 Mgal/d. Most of these withdrawals are for domestic use by commercial (hotel and condominium facilities) and institutional (public housing projects) establishments on St. Thomas. Withdrawals from the coastal embayment aquifer is estimated to be 0.2 Mgal/d. This withdrawal rate, equally distributed between St. Thomas and St. Croix, is mostly for domestic use by commercial and institutional establishments.

Long-term water-level records representative of the various aquifers in the U.S. Virgin Islands are sparse. However, water levels are known to fluctuate seasonally in response to rainfall and pumpage. The only water-level records that cover a period of several years are those in the volcanic rock aquifer on St. Thomas and St. John, and the Kingshill aquifer on St. Croix; these records were obtained by the U.S. Geological Survey during the 1960's (Jordan, 1975; Jordan and Cosner, 1973). Estimated water-level declines average 10 ft regionally (location 9, fig. 2) and more than 30 ft locally in the Kingshill aquifer, based on sparse records covering 1919 through 1967 (Jordan, 1975). This decline probably was caused by increased evapotranspiration resulting from reversion of abandoned farm and pastureland to brush and trees. A network of water-level observation wells was established in recent years by the U.S. Geological Survey in cooperation with the Government of the U.S. Virgin Islands. Water-level records at selected sites (locations 1, 7, and 9) are shown in figure 2.

GROUND-WATER MANAGEMENT

The Virgin Islands Department of Conservation and Cultural Affairs (DCCA) is charged with the administration and enforcement of all laws relating to water resources and water pollution under Title 3, Chapter 22 of the Virgin Islands Code. This government agency also has control over well-construction permits and water appropriation. The Virgin Islands Department of Public Works is responsible for the distribution of desalinated water produced by the Water and Power Authority. Under Section 153 of Title 12, appropriation permits are not required if pumpage is less than 500 gal/d. In 1984, the U.S. Geological Survey, in cooperation with the Water Resources Research Center of the College of the Virgin Islands, completed a demonstration project intended to show the feasibility of increasing ground-water withdrawals from small basins in the islands. Long-term monitoring of ground-water levels at 25 wells is being done by the U.S. Geological Survey in cooperation with the Department of Public Works of the Virgin Islands. A water-use inventory for St. Thomas was completed in 1984 (Torres-Sierra and Dacosta, 1984). The research, data collection, and analyses collected by the cooperative water resources program provide a basis to assist the Government of the U.S. Virgin Islands in the management of the ground-water resources.

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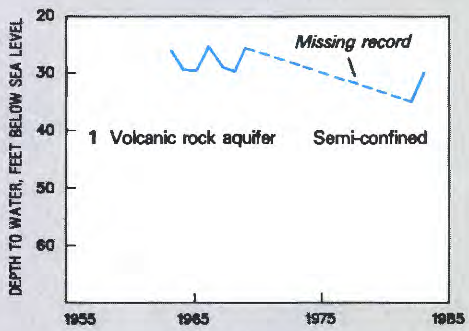
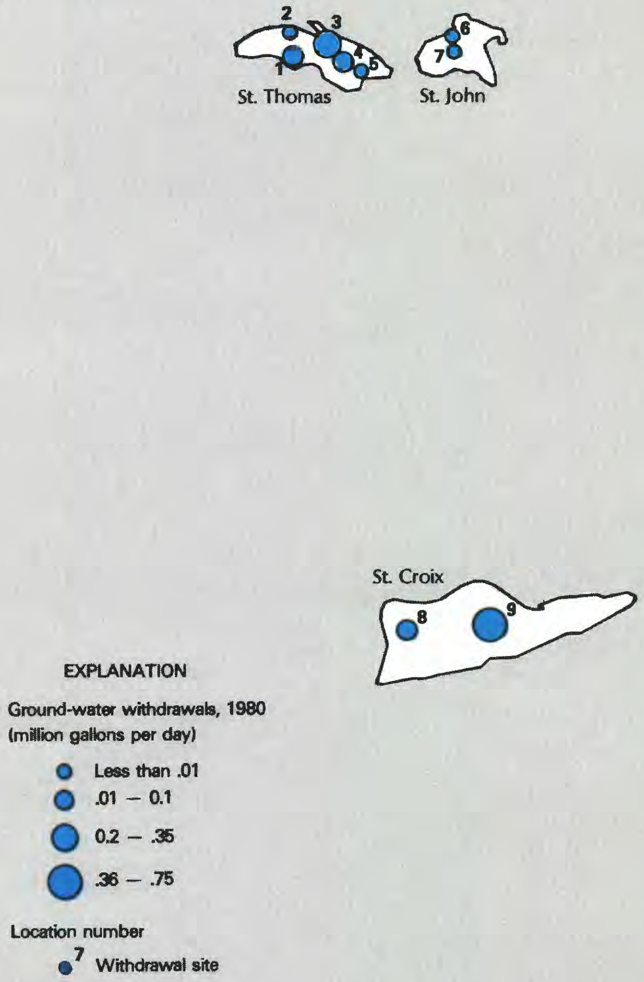
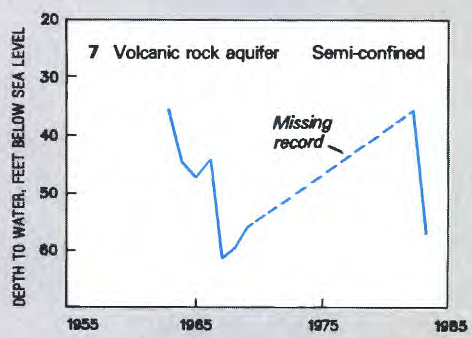
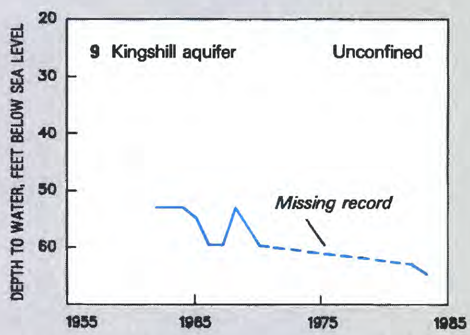
Prepared by Fernando Gómez-Gómez, Ferdinand Quiñones-Marquez, and Allan L. Zack

For further information contact District Chief, U.S. Geological Survey, GPO Box 4424, San Juan, Puerto Rico 00936









WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principel uses
1	South Side.	Volcanic rock	Domestic.
2	Little North Side . .	Coastal embayment. .	Commercial.
3	Great North Side . .	Coastal embayment, volcanic rock.	Do.
4	New.	Volcanic rock	Domestic, commercial.
5	Frenchmans Bay . .	Coastal embayment. .	Domestic.
6	Maho Bay	Volcanic rock	Commercial.
7	Cruz Bay.	. . . .do	Public supply.
8	Westend	Coastal embayment. .	Do.
9	Prince.	Kingshill	Public supply, domestic.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in the U.S. Virgin Islands. (Sources: Withdrawal data from reports of U.S. Virgin Island government agencies; water-level data from U.S. Geological Survey files.)

UTAH
Ground-Water Resources

Ground water is an important natural resource in Utah, but it is secondary to surface water as a water source in the State. During 1980, wells and springs used for public supply provided about 18 percent of the total water used (table 1). If the quantity of water from springs used for irrigation, domestic, stock, and industrial use were known and included, the total ground-water use probably would be at least 20 percent of the total water use. Ground water is the major source for public supply—about 63 percent of Utah's population depends on ground water for freshwater.

In some of the basins of western and southwestern Utah, most of the irrigation water comes from ground water. Basinwide, progressive water-level declines are occurring only in the Beryl–Enterprise area in the southwestern corner of the State.

GENERAL SETTING

The eastern one-half of Utah is located in the Middle Rocky Mountains and Colorado Plateaus physiographic provinces and the western one-half of the State is in the Basin and Range province. The Middle Rocky Mountains and Colorado Plateaus provinces are areas of mountain ranges, high plateaus, and broad basins, which locally have been incised deeply by the Colorado River and its tributaries. Consolidated rock, mostly flat lying in the Colorado Plateaus province, is at or near land surface throughout much of the area. The Colorado Plateaus province contains most of Utah's energy resources. The Basin and Range province, which contains most of Utah's population and agriculture, consists of desert basins that alternate with generally north-trending mountain ranges. The basins are underlain by thick deposits of unconsolidated fill.

Precipitation ranges from about 5 inches (in.) on the Great Salt Lake Desert to more than 40 in. on the mountains. In several basins in western Utah, recharge is less than 2 percent of the precipitation. However, in some basins along the west side of the Wasatch Range, recharge exceeds 20 percent of precipitation.

PRINCIPAL AQUIFERS

Utah contains four principal types of aquifers—unconsolidated valley-fill and basin-fill deposits, sandstone, and carbonate rocks. Of the four principal types of aquifers, none forms a single, widespread, hydraulically connected system. The aquifers are described below and in table 2; their areal distribution is shown in figure 1.

UNCONSOLIDATED VALLEY-FILL AQUIFERS

Most unconsolidated valley-fill aquifers, which consist mostly of alluvium, are present in stream valleys (some of which are also structural depressions or basins) in the Middle Rocky Mountains and Colorado Plateaus provinces (fig. 1). Only the major valley-fill aquifers are shown in figure 1.

Table 1. Ground-water facts for Utah

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Indicated in footnotes]

Population served by ground water, 1981[1]	
Number (thousands)	960
Percentage of total population	63
From public water-supply systems:	
Number (thousands)	870
Percentage of total population	57
From rural self-supplied systems:	
Number (thousands)	90
Percentage of total population	6
Freshwater withdrawals, 1980[2]	
Surface water and ground water, total (Mgal/d)	4,300
Ground water only (Mgal/d)	770
Percentage of total	18
Percentage of total excluding withdrawals for thermoelectric power	18
Category of use, 1983[3]	
Public-supply withdrawals:	
Ground water (Mgal/d)	240
Percentage of total ground water	35
Percentage of total public supply	66
Per capita (gal/d)	256
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	31
Percentage of total ground water	5
Percentage of total rural domestic	90
Per capita (gal/d)	344
Livestock:	
Ground water (Mgal/d)	37
Percentage of total ground water	5
Percentage of total livestock	80
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	72
Percentage of total ground water	11
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	14
Excluding withdrawals for thermoelectric power	16
Irrigation withdrawals:	
Ground water (Mgal/d)	300
Percentage of total ground water	44
Percentage of total irrigation	10

[1] Population was estimated using 1981 data from Hooper and Schwarting (1982) and modified using data from U.S. Bureau of the Census (1980) and with an estimate of rural population dependent on ground water using 1981 data from Holmes and others (1982, table 2). Public supplies include water from springs.

[2] 1980 withdrawals based on data from Solley, Chase, and Mann (1983) and modified using more recent data from Hooper and Schwarting (1982) and Herbert and others (1981).

[3] 1983 withdrawals from wells estimated from Avery and others (1984) and includes about 5 percent additional withdrawals for areas and public supplies not included in that survey. Public-supply withdrawals include water from springs. Withdrawals from springs are based on 1981 data from Hooper and Schwarting (1982).

Table 2. Aquifer and well characteristics in Utah

[Mgal/d = millions of gallons per day; ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey and Utah Department of Natural Resources]

Aquifer name and description	Water withdrawals in 1983 (Mgal/d)	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Unconsolidated valley-fill aquifers: Sand, silt, gravel, and clay; mostly alluvial. Unconfined and confined.	[1]56	50 – 200	600	10 – 750	2,000	Thickness commonly 50 to 200 ft but can be as much as 800 ft where valleys are structural depressions. Most water fresh but locally slightly to moderately saline. Provides water supplies for city of Ogden from Ogden Valley east of Ogden; and for irrigation in Uinta Basin in Duchesne and Uintah Counties; along Sevier River and its tributaries in Sanpete, Sevier, Piute, and Garfield Counties; along Fremont River near Loa; along Virgin River near St. George; and in Spanish Valley at Moab.
Unconsolidated basin-fill aquifers: Sand, coarse gravel, clay, and silt; mostly alluvial and lacustrine. Confined and unconfined.	[1]500	100 – 500	1,000	200 – 1,000	6,000	Thickness as much as several thousand feet; in most basins probably only 500 to 1,500 ft is permeable and contains freshwater. In areas of major withdrawals, water mostly fresh, but slightly saline to briny water present; provides water supplies for most major cities and all irrigation areas in Basin and Range province in Utah.
Sandstone aquifers: Very fine to medium-grained sandstone and includes some siltstone to coarse sandstone; fracturing increases permeability. Confined and unconfined.	[1]4	100 – 1,000 depending on depth to aquifer	2,000	50 – 500	3,000	Includes Entrada, Navajo, and Wingate Sandstones of Triassic and Jurassic age and their equivalents; thickness can be more than 2,000 ft locally. Water ranges from fresh near recharge areas to briny where aquifers deeply buried. Provides water supplies for cities of St. George, Moab, and Kanab and for irrigation near St. George and Kanab.
Carbonate-rock aquifer: Limestone and dolomite, probably includes solution-enlarged fractures. Confined and unconfined.	[2]3	–	–	–	–	Largely unknown and unused; discharges about 40 Mgal/d of slightly to moderately saline water from two large spring areas in west-central Utah. Only two known large-yield (2,000–3,000 gal/min) wells completed in this aquifer in 1984.

[1] Estimated from data in Avery and others (1984). [2] 1979 data from files of the U.S. Geological Survey.

Recharge to the valley-fill aquifers is mostly by seepage from streams, underflow from bordering consolidated rock, direct infiltration of precipitation, and seepage from canals and irrigated fields. Most natural discharge is by seepage to streams and by evapotranspiration. Discharge also occurs from wells and drains; wells flow under artesian pressure in the lower parts of some valleys. Most water in valley fill is fresh, but slightly saline to briny water is present, mostly in areas of natural discharge. Further development of the valley-fill aquifers may decrease streamflow.

Unconsolidated Basin-Fill Aquifers

Unconsolidated basin fill in the Basin and Range province (fig. 1) constitutes the most extensively used aquifers in the State. These aquifers, which contain the largest volume of fresh and slightly saline water in Utah, are equivalent to basin-fill aquifers in Nevada and Idaho. They are lithologically similar to the valley-fill aquifers but commonly are thicker and more areally extensive.

Recharge to the basin-fill aquifers is mostly by underflow from consolidated rock of the bordering mountains and by seepage from streams, canals, and irrigation water, with some by direct infiltration of precipitation. Natural discharge of ground water occurs mostly in low parts of basins by evapotranspiration, by seepage to streams, and by springs. Discharge also occurs by use of wells and drains; many wells in the middle to lower parts of basins flow under artesian pressure. Ground water in areas of major withdrawals from basin fill is mostly fresh. Slightly saline to briny water, however, is present, mostly in areas of natural ground-water discharge. Further development of basin-fill aquifers to supply the State's rapidly increasing population has the potential for causing declining water levels, decreasing artesian pressures, decreased streamflow, changes in water quality, and possible land subsidence.

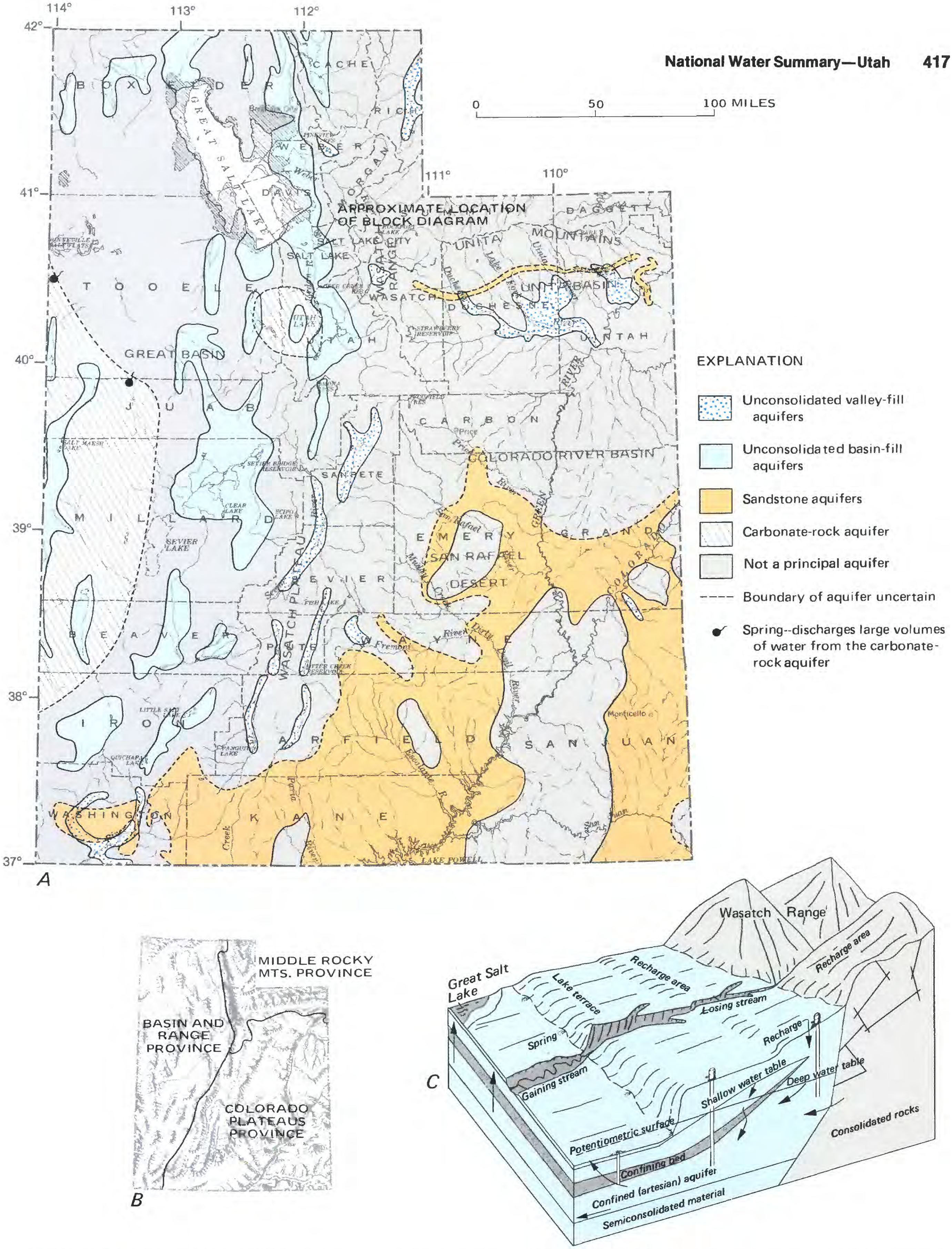


Figure 1. Principal aquifers in Utah. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Block diagram showing typical characteristics of a basin-fill aquifer of the Basin and Range province. (See table 2 for more detailed descriptions of the aquifers. Sources: *A*, Compiled by J. S. Gates and G. W. Freethey from U.S. Geological Survey files. *B*, Fenneman, 1946; Raisz, 1954. *C*, Hely, Mower, and Harr, 1971, fig. 3.)

SANDSTONE AQUIFERS

Sandstone underlies a broad area of southern and southeastern Utah, mostly in the Colorado Plateaus province (fig. 1). These aquifers are equivalent to sandstone aquifers in adjacent areas of Colorado, New Mexico, and Arizona. These sandstones, primarily the Entrada, the Navajo, and the Wingate Sandstones of Triassic and Jurassic age, are the most widespread and probably contain the most water of usable quality that is present in the consolidated-rock units in that area. However, other less-extensive consolidated-rock units also are locally important as aquifers.

Recharge to the sandstones, which occurs mostly in upland areas where the aquifers are near the land surface, is by direct infiltration of precipitation and seepage from streams. Most natural discharge of ground water is seepage to the Colorado River and its tributaries. Water in the sandstones ranges from fresh in most recharge areas to briny where aquifers are deeply buried and ground-water movement is slow.

The sandstone aquifers are not developed extensively by wells at present. In some areas, the aquifers contain large quantities of water in storage but do not yield large quantities of water to wells. Use of water from the sandstone aquifers for energy development in eastern and southern Utah may reduce streamflow in the Colorado River system.

CARBONATE-ROCK AQUIFER

The carbonate-rock aquifer is not well known, but is found along the western edge of Utah; another similar system, almost as unknown, is present in central Utah (fig. 1). This aquifer is equivalent to the carbonate-rock aquifer in adjacent parts of Nevada. Little is known about recharge areas and mechanisms; however, part of the recharge to the western system is in Nevada. The only known discharge is from two large areas of springs in the western system (fig. 1) producing slightly to moderately saline water and from two wells in the central system. Further development of the carbonate-rock aquifer is hindered by the difficulty of locating permeable zones, the large depth to the aquifer locally, and water that may be unsuitable for some uses.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

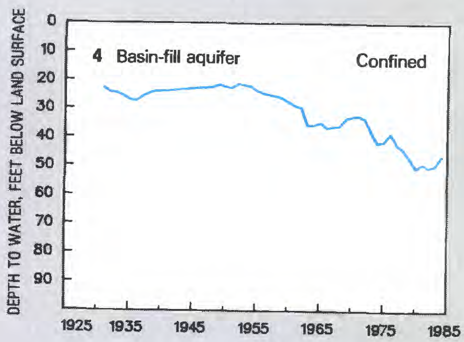
Withdrawals of ground water in 13 basins are shown in figure 2. Pumpage from these basins accounts for more than 85 percent of the ground-water withdrawals from wells in Utah. In several of these basins, surface-water supplies are small, and ground water is the chief supply for all uses. These include the Curlew Valley, the Tooele Valley, and the Beryl-Enterprise area. In all but 2 of the 13 basins, irrigation is the principal use of ground water and, in some basins, accounts for more than 95 percent of the total annual withdrawals (Avery and others, 1984, table 2).

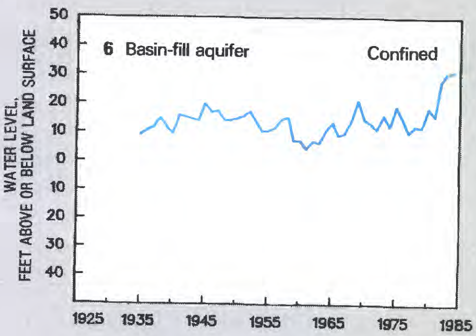
In the basins that include major cities—the Cache Valley, the East Shore area, the Salt Lake Valley, and the Utah and Goshen Valleys—combined withdrawals of ground water for public supply, industrial, domestic, and livestock use are larger than irrigation withdrawals.

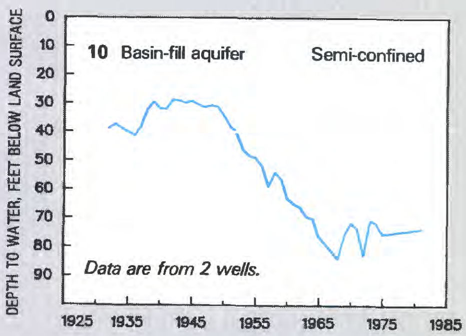
Use of ground water from springs for irrigation began soon after the State was settled in 1847. However, large-volume withdrawals of water from wells for irrigation, especially in central and southwestern Utah, did not begin until the late 1940's; withdrawals increased rapidly until the 1970's. Since the early 1970's, withdrawals for irrigation have fluctuated in response to changes in precipitation and the availability of surface water. Much of the land readily irrigible by well water has been put into production, and the State has imposed limits on withdrawals from several of the basins in southwestern Utah. As an example, withdrawals from wells in Pahvant Valley (location 9, fig. 2) increased from 16 million gallons per day (Mgal/d) during 1946 to 104 Mgal/d during 1977, but then decreased to 37 Mgal/d during 1983 because of greater-than-average precipitation and consequent increase in surface-water supplies (Avery and others, 1984, fig. 27).

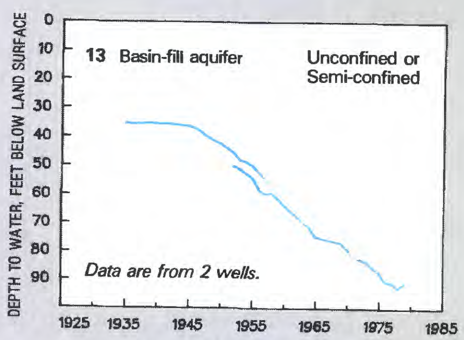
Water levels declined in several areas between the late 1940's and early 1950's (generally the high point for water levels since measurements began in the early 1930's) and 1984. Local areas of decline exist in the densely populated basins in northern Utah, such as the East Shore area where declines of more than 50 feet (ft) occurred from 1953 to 1984 west of Ogden (location 3, fig. 2), and the Salt Lake Valley where more than 25 ft of decline occurred from 1953 to 1984 southeast of Salt Lake City (location 4, fig. 2). These declines are due mainly to pumping for public supply and industrial use; areas with declines of more than 25 ft are of limited areal extent in any basin. Declines in basins in north-central Utah, which generally receive more recharge than basins to the west and southwest, generally were small from about 1950 to 1984. Also, water levels have risen locally; the hydrograph for location 6 (fig. 2) shows that the 1984 measurement was the highest yearly low water level in a well in Utah Valley since measurements began in 1935.

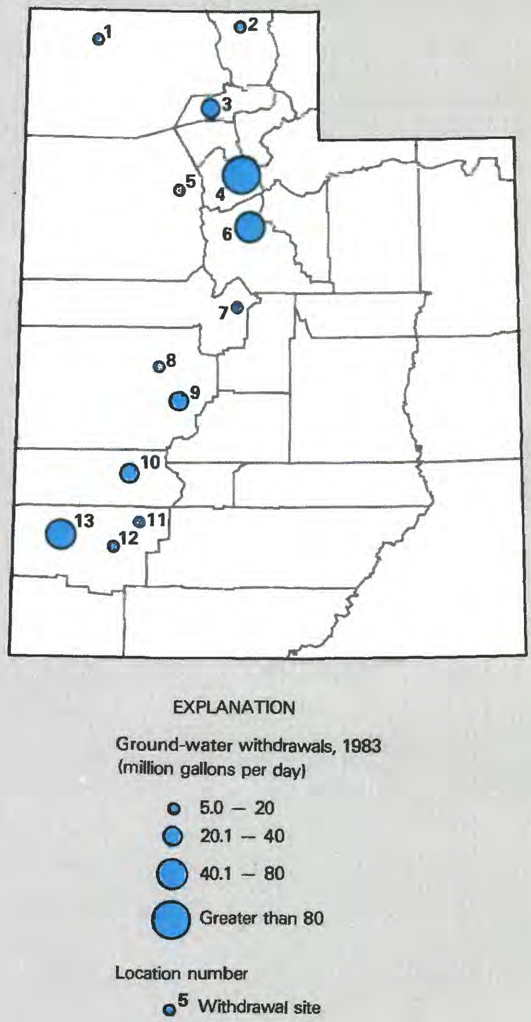
In west-central and southwestern Utah, water levels declined from 8 to about 50 ft and declines were relatively widespread from about 1950 to between 1964 and 1968 (location 10, fig. 2). Declines were caused largely by pumping for irrigation; however, part of the declines probably resulted from less-than-normal precipitation from about 1948 to about 1966. Ground-water declines in these basins during the middle 1960's appeared to be permanent and to mark the early stages of ground-water mining. Some land subsidence from withdrawal of ground water occurred in the Milford area (Mower and Cordova, 1974, p. 7–8, 37). Since the middle 1960's, overall precipitation has been greater than average, especially between 1980 and 1983. Water levels in large parts of west-central and southwestern Utah rose from 1963 to 1984 in response to increased recharge and decreased pumping that occurred because more surface water was available for use. Water levels in a large part of Cedar City Valley (location 12, fig. 2) for example, rose more than 17 ft (Appel and others, 1983, fig. 42; Avery and others, 1984, fig. 55). The water level in one well rose 36.7 ft. Between the spring of 1983 and the spring of 1984, water-level rises locally were significant. In Pahvant Valley, for example, the water-level rise in one well was 32.5 ft in a single year (location 9, fig. 2). The greater-than-average precipitation since the middle 1960's thus has stabilized water levels (location 10, fig. 2, from 1969 to 1981), and even resulted in widespread rises. At present, the basins in











WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Curlew Valley	Basin fill	Irrigation.
2	Cache Valley.	. . . .do	Irrigation, industrial, public supply, rurel domestic and livestock.
3	East Shore area	. . . .do	Public supply, irrigation, industrial, rural domestic and livestock.
4	Salt Lake Valley.	. . . .do	Public supply, industrial, rural domestic and livestock, irrigation.
5	Tooele Valley	. . . .do	Irrigation, public supply.
6	Utah and Goshen Valleys.	. . . .do	Irrigation, rural domestic and livestock, public supply, industrial.
7	Juab Valley	. . . .do	Irrigation, public supply.
8	Sevier Desert.	. . . .do	Irrigation, industrial, public supply.
9	Pahvant Valley	. . . .do	Irrigation.
10	Milford area	. . . .do	Do.
11	Parowan Valley	. . . .do	Do.
12	Cedar City Valley	. . . .do	Irrigation, public supply.
13	Beryl-Enterprise area . .	. . . .do	Irrigation, industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Utah. (Sources: Withdrawal data from Avery and others, 1984.)

west-central and southwestern Utah are not considered to be areas of ground-water mining.

Ground water is being mined in the Beryl–Enterprise area in western Iron County. Water levels in part of the Beryl–Enterprise area declined steadily between the mid-1940's (when pumping for irrigation increased substantially) and 1979 (location 13, fig. 2). The maximum decline is about 60 ft, and fluctuations in precipitation have had little or no effect on water levels.

GROUND-WATER MANAGEMENT

Ground-water use in Utah is regulated by the Utah Department of Natural Resources, Division of Water Rights, which has designated several basins and areas where appropriation of additional ground water is not allowed. Withdrawals for irrigation from four southwestern basins have been limited by court decrees, and discharge from irrigation wells in these basins is metered to verify compliance. In other areas, appropriations of ground water are not allowed because of the potential effect on surface water, and, in some areas, only appropriations of ground water for domestic use are allowed. The appropriation of ground water is restricted in more than one-half of the State.

Protection of ground-water quality and prevention, control, and abatement of ground-water pollution are the responsibility of the Utah Department of Health, Division of Environmental Health.

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Prepared by Joseph S. Gates

For further information contact District Chief, U.S. Geological Survey, 1745 West 1700 South, Salt Lake City, UT 84104

VERMONT
Ground-Water Resources

Water systems that use ground water serve 54 percent of the 511,000 people in Vermont. Public systems serve 113,000 people, and private and rural systems serve 162,000 people. Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

Quality of ground water in Vermont aquifers generally is suitable for most purposes. Locally, the chemical quality of ground water reflects land-use practices. Degradation of water quality may occur in unsewered residential villages and ski areas and near underground storage tanks, industrial sites, waste-disposal sites, agricultural land, and highways.

GENERAL SETTING

Vermont is in the Glaciated Appalachian ground-water region and in the Valley and Ridge, St. Lawrence Valley, and New England physiographic provinces (Fenneman, 1938). The major lowlands in western Vermont are underlain predominantly by carbonate rocks; the remainder of the State is underlain, for the most part, by crystalline rocks (fig. 1).

Recharge to the ground-water system is derived from precipitation. Average annual rainfall is about 41 inches (in.), ranging from about 32 in. in the Champlain Valley to 60 in. in the Green Mountains. The greatest annual runoff (30 in. or more) occurs in the southern Green Mountains (Knox and Nordenson, 1955). Recharge rates have not been determined but probably range from 12 to 20 in.

PRINCIPAL AQUIFERS

Unconsolidated deposits and bedrock are the two principal types of aquifers in Vermont. Unconsolidated aquifers consist of stratified drift; bedrock aquifers consist of two types—carbonate and crystalline rocks. The characteristics of unconsolidated and bedrock aquifers are described below and in table 2; their areal distribution is shown in figure 1.

STRATIFIED-DRIFT AQUIFERS

Unconsolidated glacial-drift deposits were formed during continental glaciation. Stratified-drift deposited by glacial meltwater streams formed deposits that have the greatest potential to yield water where saturated thickness is large and recharge occurs. Stratified-drift deposits are present primarily in the valley lowlands throughout the State and also in some interstream areas along the western edge of the Green Mountains (fig. 1). Many of these deposits are isolated from one another and form independent ground-water systems.

Stratified-drift deposits formed by meltwater streams beyond ice margins are termed "outwash deposits." Those deposits formed by meltwater streams adjacent to or beneath glaciers are termed ice-contact deposits. In some areas, ice-contact deposits may yield larger amounts of water to wells than outwash because they may have greater saturated thickness and are coarser grained. Although detailed investigations may distinguish between outwash and ice-contact deposits, they are not distinguished in figure 1. Both of these glaciofluvial sequences may include deltaic deposits, formed where meltwater streams entered temporary glacial ponds and lakes. These deltas commonly are good aquifers. Fine-grained lake deposits, which are common in the Connecticut Valley and the Champlain Lowlands, are nonproductive aquifers; however, because sand or sand-and-gravel aquifers may be present beneath these fine-grained lake sediments, they are included in the stratified-drift aquifers in figure 1. Water in glacial deposits generally is of good quality and is suitable for most uses. Locally, concentrations of iron [more than 0.1 milligrams per liter (mg/L)], manganese (more than 0.05 mg/L),

Table 1. Ground-water facts for Vermont

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	275
Percentage of total population	54
From public water-supply systems:	
Number (thousands)	113
Percentage of total population	22
From rural self-supplied systems:	
Number (thousands)	162
Percentage of total population	32
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	340
Ground water only (Mgal/d)	45
Percentage of total	13
Percentage of total excluding withdrawals for thermoelectric power	50
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	17
Percentage of total ground water	38
Percentage of total public supply	35
Per capita (gal/d)	150
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	17
Percentage of total ground water	38
Percentage of total rural domestic	85
Per capita (gal/d)	105
Livestock:	
Ground water (Mgal/d)	5.7
Percentage of total ground water	12
Percentage of total livestock	62
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	5.2
Percentage of total ground water	11
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2.0
Excluding withdrawals for thermoelectric power	35
Irrigation withdrawals:	
Ground water (Mgal/d)	0.3
Percentage of total ground water	1
Percentage of total irrigation	19

Table 2. Aquifer and well characteristics in Vermont

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Principal Aquifers:					
Stratified-drift aquifer: Unconsolidated glaciofluvial sand or sand and gravel. Unconfined.	40 - 70	80	30 - 400	600	Includes deltaic deposits of ice-contact and outwash sequences. Quality generally suitable for human consumption.
Crystalline bedrock aquifer: Crystalline rock units consist of metasedimentary, metavolcanic, and igneous rocks that contain recoverable water only in open fractures (secondary porosity). Generally confined.	100 - 600	800	1 - 10	100	Zones where bedrock is fractured extensively may yield larger quantities of water. Quality generally suitable for human consumption.
Carbonate bedrock aquifer: Carbonates have been subjected to solution weathering along fractures with associated increase in hydraulic conductivity. Generally confined.	100 - 300	500	5 - 20	300	Units metamorphosed to varying degree primarily in the Champlain lowland and Vermont Valley. Quality generally suitable for human consumption.
Other aquifers:					
Till Aquifers: Unconsolidated, nonstratified, heterogeneous mixture of clay to boulder-sized material, deposited either at the base of moving glacial ice or as a residue left by melting ice. Unconfined.	10 - 20	30	1 - 3	5	Till a poor aquifer but, in places yields enough water to large-diameter dug wells to supply single family domestic needs. Quality generally suitable for human consumption. Till not mapped in figure 1 but commonly overlies bedrock.

and chloride (more than 250 mg/L) approach or exceed national secondary drinking-water regulations (U.S. Environmental Protection Agency, 1982b). The water generally is soft.

Crystalline Bedrock Aquifer

The crystalline bedrock aquifer has little or no primary porosity. The occurrence and movement of water in these rocks depend on the presence and degree of interconnection of fractures, which provide secondary storage and avenues of ground-water flow. The number of fractures generally decreases with depth. Thus, the storage capacity of bedrock is small and generally decreases with depth. Wells that penetrate crystalline bedrock commonly yield dependable supplies of water suitable for single family domestic needs, and, for this purpose, bedrock is a principal aquifer. Domestic wells generally are less than 600 feet (ft) deep and yield less than 10 gallons per minute (gal/min).

Zones where crystalline bedrock is extensively fractured may yield larger quantities of water than the bedrock as a whole. Many small public supplies and a few municipal wells obtain water from crystalline bedrock. Fracture-trace analysis has helped in siting a few of the most productive wells.

Ground water generally is of good quality, although in some areas concentrations of iron, manganese, sodium, and chloride and hardness exceed national drinking-water regulations (U.S. Environmental Protection Agency, 1982a). In the upper Winooski River basin, for example, the maximum concentrations, in milligrams per liter, were iron (0.66), manganese (1.60) and chloride (150) (Hodges and others, 1977). Water in the crystalline-bedrock aquifer is soft or moderately hard.

Carbonate Bedrock Aquifer

The carbonate bedrock aquifer, which is present primarily in the Champlain Lowlands and the Vermont Valley in the western part of the State (fig. 1; Doll and others, 1961), formed when carbonate rocks, such as limestone and dolomite, were metamorphosed to marble. The carbonate bedrock aquifer may yield more water than the crystalline bedrock aquifer where water-bearing fractures have been enlarged by solution of carbonate minerals. Such weathering has increased the storage capacity and hydraulic conductivity in parts of the aquifer. The municipal well in Arlington (location 16, fig. 2) taps these rocks. Two production wells at the Pittsford National Fish Hatchery (west-central Vermont) have recently been completed in the Forestdale Marble; one was pumped at 900 gal/min and the other at 300 gal/min. Quality of water is suitable for most purposes; hardness is commonly moderately hard to hard.

Other Aquifers

Some wells in Vermont are completed in till, which is an unsorted mixture of clay to boulder-sized rock debris deposited directly by glacial ice. Till discontinuously mantles the bedrock surface and generally is less than a few tens of feet thick; the thickness can vary considerably over short distances. Dug wells in till commonly are used for domestic

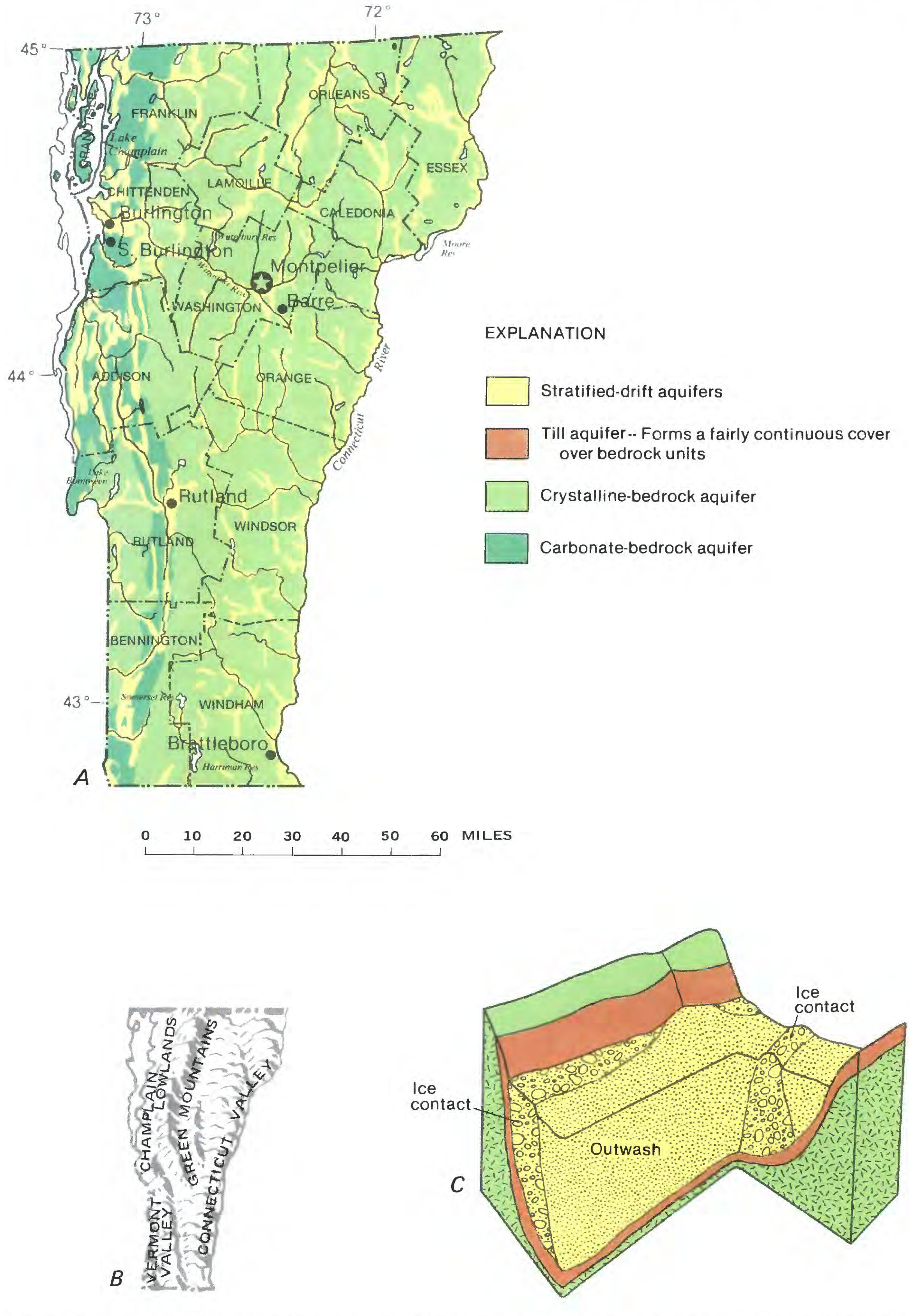


Figure 1. Principal aquifers in Vermont. *A*, Geographic distribution. *B*, Physiographic diagram. *C*, Typical stratigraphic sequences of aquifer materials. (See table 2 for a more detailed description of the aquifers. Sources: *A, C*, Compiled by R. E. Hammond and J. E. Cotton from U.S. Geological Survey files. *B*, Raisz, 1954.)

purposes. These wells have a large diameter (typically 3 ft) that provides storage capacity within the well bore; this storage capacity compensates for the typically low hydraulic conductivity of the aquifer material. Many old domestic wells are in till, and some new wells are still dug in till each year. Till is important only for domestic needs and is not mapped in figure 1.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Municipal centers where more than 0.05 million gallons per day (Mgal/d) of ground water is withdrawn are shown in figure 2. Pumpage from these areas totals about 11 Mgal/d. An estimated 6 Mgal/d is pumped from about 420 other public-supply wells and from privately owned wells that are classified as public-supply wells.

Annual water-level fluctuations respond to seasonal differences in the rate of ground-water recharge, natural discharge, and rates of pumping. Hydrographs in figure 2 reflect natural dynamic equilibrium of the ground-water regimes. No progressive long-term water-level declines have been observed in the aquifers.

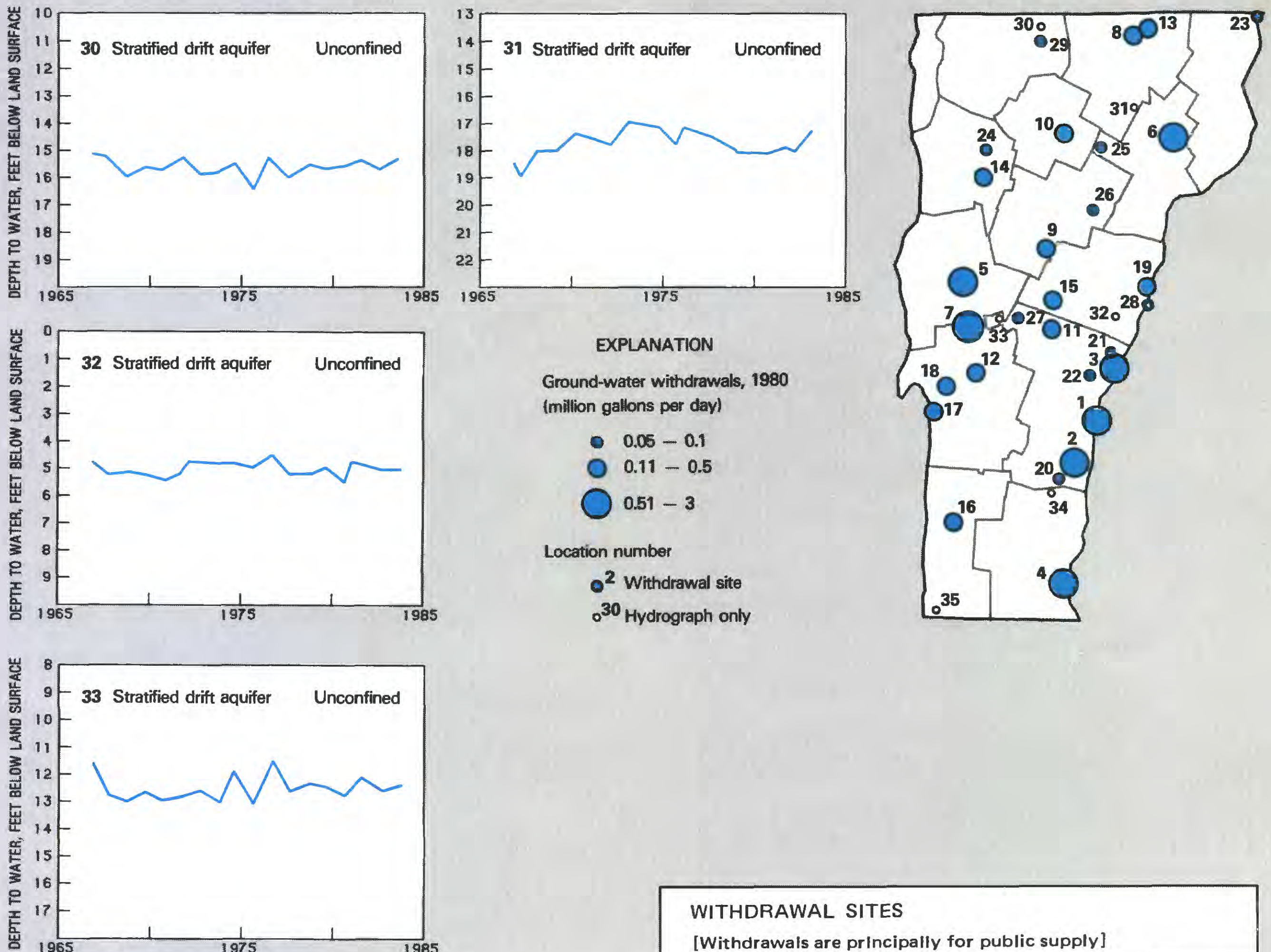
GROUND-WATER MANAGEMENT

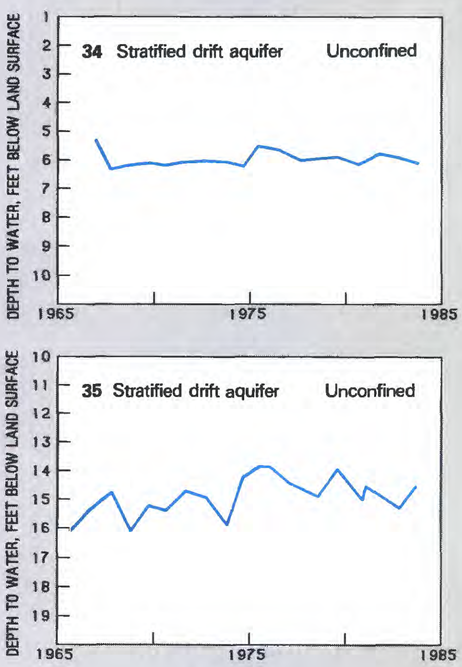
The management of ground water in Vermont is divided primarily among three State agencies—the Department of Agriculture, the Department of Health (a Division of the Agency of Human Services), and the Department of Water Resources and Environmental Engineering (DWREE), which is a unit of the Agency of Environmental Conservation. The Department of Agriculture regulates the use and storage of pesticides; the Department of Health protects drinking-water supplies; and the DWREE protects, regulates and, where necessary, controls the ground-water resources.

The three Departments are represented on a Ground Water Coordinating Committee, which serves as a clearing house for the exchange of information relating to ground water. The Committee recommends policies to the member agencies that have the statutory authority.

Within the DWREE, water-management programs are divided among the following units: Water Supply, Technical Review, Pollution Control, Construction, Solid Waste, Hazardous Waste, Permits and Compliance, Monitoring and Surveillance, and Ground Water Management. Some of these program areas relate primarily to surface water or to air-pollution concerns, but they also address ground-water management as it relates to their functional responsibilities.

The Ground Water Management Unit addresses the broadest range of ground-water issues. The following program areas are within the purview of this Unit: Water Well Driller Licensing and Well Reporting, Ground-Water Level Monitoring (in cooperation with the U.S.Geological Survey), Aquifer Protection Area Mapping, Underground Injection Control (except permitting functions which are done by Permits and Compliance), Data Management, Special Studies, Technical Assistance, Application Review for the Land Use and Development and Injection Well Permits, Public Information and Education, and Administration. The State Geologist, the University of Vermont, and the Agency of Transportation also have roles in the management of ground water.





WITHDRAWAL SITES

[Withdrawals are principally for public supply]

No. on map	Geographic area	Aquifer
1	Windsor	Stratified drift.
2	Springfield	Do.
3	Hartford	Do.
4	Brattleboro	Do.
5	Middlebury	Do.
6	Lyndonville	Do.
7	Brandon	Do.
8	Newport	Do.
9	Northfield	Do.
10	Morrisville	Do.
11	Bethel	Do.
12	Proctor	Do.
13	Derby Center	Do.
14	Richmond	Do.
15	Randolph	Do.
16	Arlington	Carbonate rock.
17	Poultney	Stratified drift.
18	Castleton	Do.
19	Bradford	Do.
20	Chester	Do.
21	Norwich	Do.
22	Quechee	Do.
23	Canaan	Do.
24	Jericho	Do.
25	Hardwick	Do.
26	Plainfield	Do.
27	Rochester	Do.
28	Fairlee	Do.
29	Enosburg Falls	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Vermont. (Sources: Withdrawal data from the Vermont Department of Water Resources and Environmental Engineering; water-level data from U.S. Geological Survey files.)

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Prepared by John E. Cotton and Robert E. Hammond

For further information contact Chief, New Hampshire Office, U.S. Geological Survey, RFD 2, 525 Clinton Street, Bow, NH 03301

VIRGINIA
Ground-Water Resources

Ground water is an invaluable natural resource in Virginia and contributes significantly to meeting the current freshwater needs of the State. Ground water is an important source of public and industrial water supply for parts of Virginia, such as the Eastern Shore Peninsula and many rural areas. However, most of the major metropolitan areas of the State rely mainly on surface water. An abundant supply of ground water is present throughout most of Virginia. Ground water constitutes 30 percent of the total freshwater withdrawals (excluding thermoelectric) and provides freshwater, by means of public and rural water-supply systems, for about 41 percent (Kull, 1983) of Virginia's approximately 5.3 million residents (U.S. Bureau of Census, 1983). Ground-water withdrawals in 1980 and related statistics are given in table 1.

GENERAL SETTING

Virginia lies within five physiographic provinces, each of which is characterized by distinctive geologic features and landforms that cause significant differences in ground-water conditions. These five physiographic provinces (fig. 1), from east to west, are the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus. The Coastal Plain is underlain by a wedge of gently eastward-dipping, unconsolidated sediments. The Piedmont and Blue Ridge are underlain predominantly by crystalline rock, and the Valley and Ridge and Appalachian Plateaus are underlain by thick sequences of consolidated sedimentary rock (Virginia Division of Mineral Resources, 1964).

Precipitation is the primary source of recharge to the ground-water system within Virginia. Average annual precipitation ranges from about 36 to 50 inches (in.). The largest amount of precipitation falls along the extreme southwestern and southeastern parts of the State; the least amount falls along parts of the western boundary of the State. Annual recharge to the ground-water system from precipitation ranges from about 8 in. in each of the four western physiographic provinces to about 10 in. in the Coastal Plain. Ground water discharges to the local streams and sustains streamflow during periods of little or no precipitation. Natural ground-water inflow and outflow occur along Virginia's boundaries with adjacent States and the Atlantic Ocean. Some induced inflow occurs in the Coastal Plain along Virginia's southern boundary as a result of ground-water withdrawals in Virginia.

Table 1. Ground-water facts for Virginia

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Kull, 1983; Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	2,189
Percentage of total population	41
From public water-supply systems:	
Number (thousands)	707
Percentage of total population	13
From rural self-supplied systems:	
Number (thousands)	1,482
Percentage of total population	28
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	5,600
Ground water only (Mgal/d)	370
Percentage of total	7
Percentage of total excluding withdrawals for thermoelectric power	30
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	100
Percentage of total ground water	28
Percentage of total public supply	17
Per capita (gal/d)	149
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	150
Percentage of total ground water	40
Percentage of total rural domestic	100
Per capita (gal/d)	100
Livestock:	
Ground water (Mgal/d)	3
Percentage of total ground water	1
Percentage of total livestock	10
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	110
Percentage of total ground water	29
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	2
Excluding withdrawals for thermoelectric power	24
Irrigation withdrawals:	
Ground water (Mgal/d)	8
Percentage of total ground water	2
Percentage of total irrigation	29

PRINCIPAL AQUIFERS

Three principal types of aquifers underlie Virginia—unconsolidated sediments, sedimentary bedrock, and crystalline bedrock. For this discussion, these aquifers have been grouped into unconsolidated Coastal Plain aquifers and sedimentary and crystalline bedrock aquifers, and are described accordingly from youngest to oldest in the following text and table 2; their areal distribution is shown in figure 1.

UNCONSOLIDATED COASTAL PLAIN AQUIFERS

The Coastal Plain province consists of a layered sequence of sand and gravel aquifers separated by silt and clay confining beds. These sediments, which overlie bedrock, thicken and dip eastward from their western limit (the Fall Line). Their thickness ranges from zero at the Fall Line to about 6,000 feet (ft) in the northern part of the Eastern Shore Peninsula (fig. 1). This aquifer system is divided into an unconfined aquifer, which is known as the Columbia aquifer, and underlying confined aquifers, which provide the largest water yields. The major ground-water supply in the Coastal Plain is from several confined aquifers identified as the Chickahominy-Piney Point, the Aquia, the Brightseat, and the Potomac. However, in the eastern part of Virginia Coastal Plain, the fresh ground water is from the unconfined Columbia aquifer and another confined aquifer known as the Yorktown-Eastover aquifer.

In the western and central parts of the Coastal Plain, water from the confined aquifers generally is suitable for human consumption as well as for most other uses; eastward,

Table 2. Aquifer and well characteristics in Virginia

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and the Virginia State Water Control Board]

Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Unconsolidated Coastal Plain aquifers					
Columbia aquifer: Sand and gravel, commonly clayey; interbedded with silt and clay. Generally unconfined, semiconfined locally.	30 – 50	100	5 – 250	350	Most productive in eastern areas; aquifer very thin to missing in western areas. Large concentrations of iron (more than 0.3 mg/L) and nitrate (more than 10.0 mg/L as nitrogen) in some areas. Salty water in coastal regions.
Yorktown–Eastover aquifer: Sand, commonly shelly; interbedded with silt, clay, shell beds, and gravel. Mostly confined, unconfined in outcrop area.	30 – 200	300	5 – 500	1,000	Multi-aquifer unit. Largest yields in eastern areas; aquifer very thin to missing in western areas. Salty water in lower part of aquifers in eastern areas.
Chickahominy–Piney Point aquifer: Sand, moderately glauconitic, shelly; interbedded with silt, clay, and thin indurated shell beds. Mostly confined, unconfined in outcrop area.	100 – 300	400	10 – 350	700	Important aquifer in central parts of Coastal Plain; yields moderate to abundant supplies to domestic, small industrial, and municipal wells. Water soft calcium-sodium bicarbonate type; suitable for most uses.
Aquia aquifer: Sand, glauconitic, shelly; interbedded with thin, indurated shell beds, and silty clay intervals. Mostly confined, unconfined in in outcrop area.	100 – 400	500	20 – 200	600	Important aquifer in northern two-thirds of Coastal Plain; yields moderate supplies to domestic, small industrial, and municipal wells. Water soft sodium bicarbonate type, with iron locally exceeding 0.3 mg/L.
Brightseat aquifer: Sand, interbedded with silt and clay. Confined.	350 – 800	900	50 – 350	700	Multi-aquifer unit. Restricted to subsurface in north-central part of Coastal Plain. Important source for seafood processing industries in north-central area. Water is a soft sodium bicarbonate type and contains less than 200 mg/L dissolved solids.
Potomac aquifer: Sand and gravel, commonly clayey; interlensing with silt and clay. Mostly confined, unconfined in outcrop area.	200 – 1,200	1,300	100 – 1,500	2,500	Multi-aquifer unit. Principal source for ground water in Coastal Plain. Large concentrations of iron (more than 0.3 mg/L), sodium (more than 100 mg/L), and fluoride (more than 1.4 mg/L) in some areas. Water in eastern areas contains more than 250 mg/L chloride.
Sedimentary and crystalline bedrock aquifers					
Piedmont:					
Mesozoic basin aquifer: Shale, sandstone, siltstone and limestone-quartz conglomerate intruded by diabase; some thin coal beds. Generally unconfined.	50 – 300	400	10 – 100	1,000	Water generally hard; large dissolved-solids concentrations (more than 500 mg/L).
Crystalline aquifer: Schist, gneiss, slate, phyllite, greenstone, quartzite, and metamorphosed granite. Generally unconfined.	35 – 200	300	2 – 15	200	Water generally suitable for most uses; hardness varies with rock type. Water from granites and light-colored metamorphic rocks is soft. Water from dark-colored igneous and metamorphic rocks moderately hard. Saprolite, which may exceed 100 ft in thickness, provides considerable storage to fractured zone.
Blue Ridge:					
Crystalline aquifer: Granite and gneiss. Generally unconfined.	50 – 400	500	1 – 15	40	Water generally suitable for most uses; hardness varies with rock type (similar to fractured rocks of Piedmont). Yield generally increases with saprolite thickness.

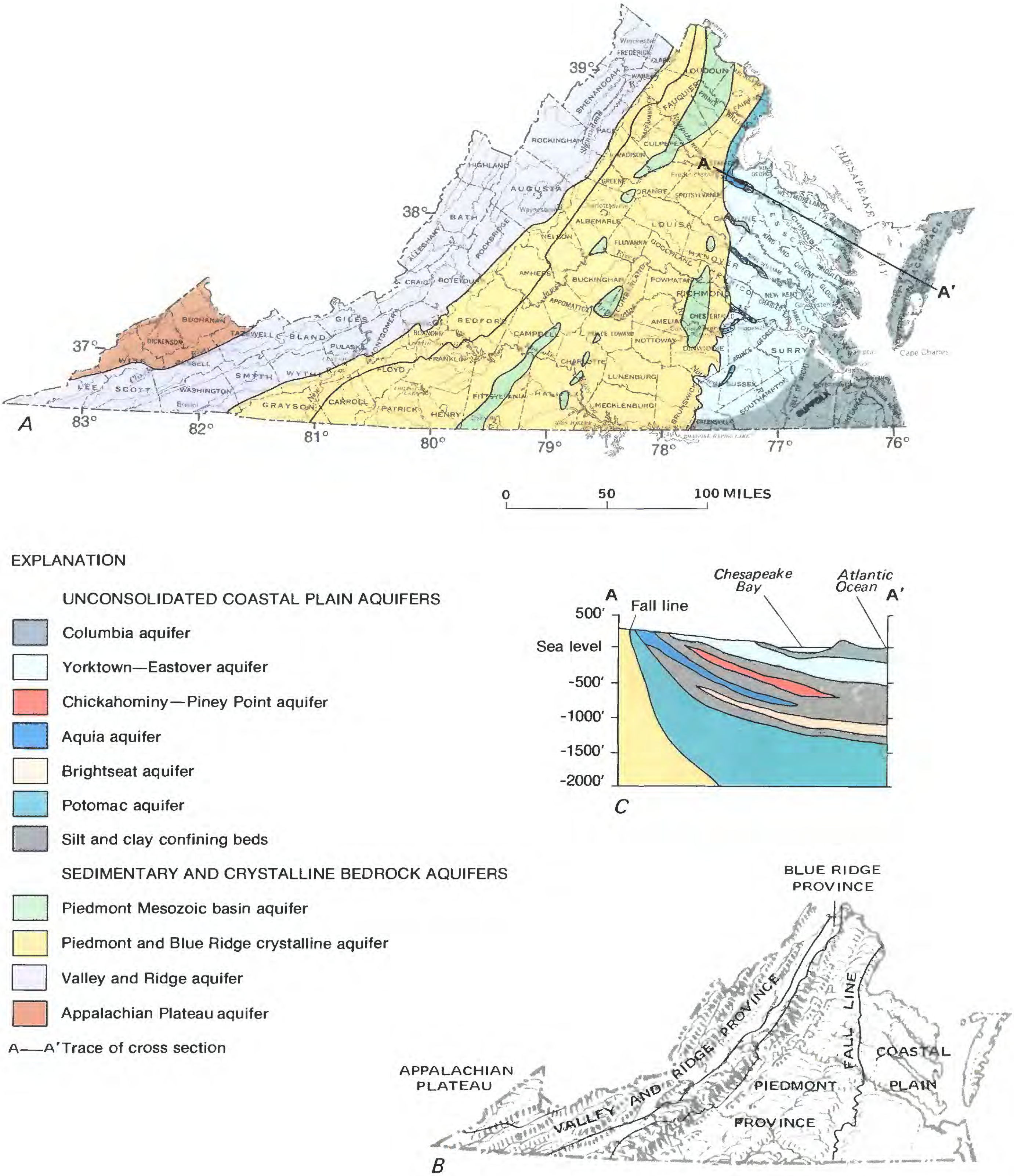


Figure 1. Principal aquifers in Virginia. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section (A-A'). (See table 2 for more detailed description of the aquifers. Sources: *A*, *C*, Compiled by A. A. Meng from U.S. Geological Survey and the Virginia State Water Control Board files. *B*, Fenneman, 1938; Raisz, 1954).

Table 2. Aquifer and well characteristics in Virginia—Continued

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Valley and Ridge:					
Consolidated sedimentary aquifer: Limestone and dolomite (primary rock types), shale, sandstone, and siltstone. Generally unconfined.	50 - 300	400	50 - 500	3,000	Water commonly hard to very hard. When present, thick overlying alluvium provides large storage to underlying solution cavities and fractures. Potential for biological and chemical contamination exists where fractures and solution cavities exposed at land surface.
Appalachian Plateaus:					
Consolidated sedimentary aquifer: Sandstone, shale, siltstone, and coal. Generally unconfined.	50 - 200	300	1 - 50	200	Water moderately hard. Locally contains iron in excess of 0.3 mg/L and manganese in excess of 0.05 mg/L. Iron concentrations in excess of 0.3 mg/L and sulfate concentrations in excess of 150 mg/L can result from coal mining.

the aquifers become increasingly saline with depth. Also in the western part of the Coastal Plain, natural radioactivity of as much as 45 picocuries per liter (pCi/L), which exceeds State drinking water standards of 15 pCi/L, has been reported for some public-supply wells. In the eastern part of the Coastal Plain, water from the unconfined Columbia aquifers also is suitable for most uses; however, the aquifer is extremely susceptible to contaminants by bacteria, fertilizer, and pesticides because it frequently occurs close to the land surface. Also, locally the water contains large concentrations of naturally occurring chemical constituents such as iron [more than 0.3 milligrams per liter (mg/L)] and manganese (more than 0.05 mg/L).

Sedimentary and Crystalline Bedrock Aquifers

Water-bearing rocks west of the Coastal Plain generally are unconfined, extremely fractured, consist of several rock types (depending on the physiographic province), and generally are overlain by saprolite that is more than 100 ft thick in places. Generally, the saprolite cover, which is thickest in the lowlands and thinnest on the uplands, provides ample storage for water recharging the underlying fractured-rock systems.

In the Piedmont province, the principal aquifers are the Mesozoic basin aquifer, composed of diabase, sandstone, and shale, and the crystalline bedrock aquifer, which consists mainly of fractured schist, gneiss, and slate. In the Blue Ridge province, the principal aquifers consist of fractured granite and gneiss. In the Valley and Ridge and the Appalachian Plateaus provinces, the principal aquifers are consolidated sedimentary rocks that are predominantly limestone and dolomite with some shale, sandstone, and siltstone in the former and sandstone, siltstone, shale, and coal in the latter.

Fractured rock and the overlying saprolite are important sources of domestic water supply in rural parts of the State west of the Fall Line in each of the four provinces. Yields of wells that penetrate these materials generally depend on the thickness of the saprolite, the number and size of intercepted fractures in the bedrock, and the topographic setting (Trainer and Watkins, 1975).

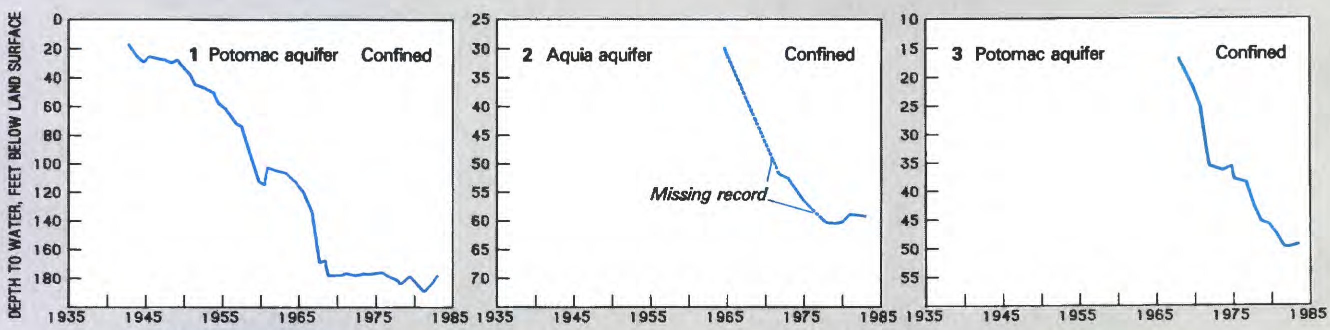
Solution cavities and fractures in the limestones and dolomite (carbonate) rocks of the Valley and Ridge provide the greatest yields of all the fractured-rock aquifers [50-500 gallons per minute (gal/min)] and rival the most productive unconsolidated aquifers in the Coastal Plain (table 2). The carbonate rocks also have the greatest potential for large-scale withdrawal of ground water west of the Fall Line. Yields from wells that penetrate the other aquifers west of the Fall Line commonly range from 10 to 100 gal/min in the Mesozoic basins of the Piedmont, 2 to 15 gal/min in the crystalline bedrock aquifers of the Piedmont, and 1 to 50 gal/min in the Appalachian Plateaus (table 2).

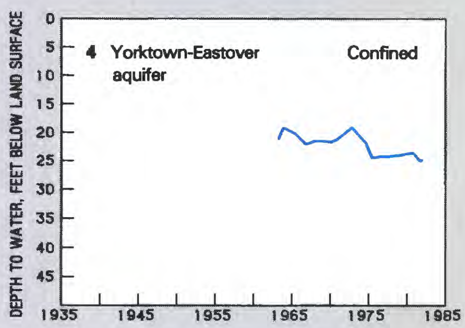
Water from the sedimentary and crystalline bedrock aquifers generally meets State drinking-water standards. Hardness, particularly in the carbonate aquifers, is a common problem. The carbonate aquifers also have a greater potential for contamination because many are recharged directly by water from streams by way of sinkholes. Other water-quality problems include large concentrations of iron (more than 0.3 mg/L), manganese (more than 0.05 mg/L) and sulfate (more than 150 mg/L); low pH (less than 6.0); and local bacterial and chemical contamination. Water from some public-supply wells in the Piedmont crystalline bedrock aquifer also contains natural radioactivity in excess of State drinking-water standards of 15 pCi/L.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Water levels generally decline in response to increased pumping and recover as pumping is reduced. The hydrographs in figure 2 represent water-level fluctuations in the Coastal Plain aquifers of Virginia. These hydrographs show the trends in ground-water levels in response to pumping at four withdrawal centers, locations of which are shown in figure 2. The two largest centers each produce more than 30 million gallons per day (Mgal/d). The largest is located in the Coastal Plain near Franklin (location 1, fig. 2) and the other is in the Rockingham-Augusta-Rockbridge County area (location 5, fig. 2) of the Valley and Ridge area.

The withdrawal of ground water for industry and public-water supply in southeastern Virginia began about 40 years ago, increased steadily through 1967, then remained relatively constant to the present (1984). The continued withdrawal of ground water has caused a steady decline of water levels and the expansion of cones of depression around major withdrawal centers. The pumpage has caused water levels to decline in the Potomac aquifer (location 3, fig. 2). Water levels in the Aquia and Potomac aquifers in the West Point area (location 2, fig. 2) have been declining steadily since the mid-1960's in response to increased pumpage rates, principally for light





WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Franklin area	Potomac	Industrial, public supply.
2	West Point area	Potomac, Aquia, Chickahominy-Piney Point.	Do.
3	Tidewater area.	Potomac	Do.
4	Eastern shore area.	Yorktown-Eastover	Do.
5	Rockingham-Augusta-Rockbridge County area.	Consolidated sedimentary.	Industrial.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Virginia. (Sources: Withdrawal data from T. K. Kull, written commun., 1984, and Virginia State Water Control Board, 1979; water-level data from U.S. Geological Survey files.)

industry and public supplies from the Aquia and Chickahominy-Piney Point aquifers. By contrast, little change in water level has been observed in a well in the Yorktown-Eastover aquifer on the Eastern Shore Peninsula (location 4, fig. 2), where water has moved downward from the overlying unconfined aquifer in response to variable pumpage from the underlying Yorktown-Eastover aquifer.

GROUND-WATER MANAGEMENT

Ground water in Virginia is managed by the State Water Control Board as authorized by the Groundwater Act of 1973. The Act places with the Board the responsibility for designating "Groundwater Management Areas" to control the rate of ground-water withdrawal when excessive declines are observed in ground-water levels or artesian pressures, there is substantial interference between wells, the available ground-water supply is being or is about to be withdrawn, or actual or anticipated pollution of ground-water supplies occurs.

Two areas have been designated as "Groundwater Management Areas"—the Eastern Shore Peninsula and southeastern Virginia (counties and cities east of the Fall Line and south of the James River). Within these areas, withdrawals of more than 50,000 gallons per day (gal/d) must be permitted and reported. Public, domestic, and agriculture users are exempt; therefore, only industrial and commercial users must comply. Elsewhere in the State, users who withdraw more than 10,000 gal/d are required to report annual withdrawals to the Board. This is authorized by Reglation II, enacted in 1982.

The Virginia State Department of Health cooperates with the Virginia State Water Control Board and is authorized to regulate the use and quality of ground water to protect the public health. The Health Department regulates public-supply systems, domestic-supply systems with onsite septic systems, and solid-waste-disposal facilities.

The State of Virginia has an Interstate Cooperative Agreement with Maryland and North Carolina to exchange information about wells and pumpage near their mutual boundaries. In 1982, the Governors of Virginia and North Carolina reconstituted the North Carolina–Virginia Water Resources Management Committee to renew dialogue between the two States over their mutual problems regarding water supply and water quality. Following these discussions, the State of Virginia has authorized funds for a ground-water investigation of southeastern Virginia to be conducted in cooperation with the U.S. Geological Survey.

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Prepared by Andrew A. Meng, III, John F. Harsh, and Thomas K. Kull

For further information contact Hydrologist-in-Charge, Virginia Office, U.S. Geological Survey, 200 West Grace Street, Room 304, Richmond, VA 23220

WASHINGTON
Ground-Water Resources

Ground water is used extensively throughout Washington for domestic, commercial, industrial, and agricultural purposes, and constitutes a resource of considerable economic value. At present, 71 percent of the State's population is served by water-supply systems that rely on ground water (table 1); in many areas of the State, such as some of the islands in Puget Sound, ground water is the only source of supply (Cline and others, 1982; Whiteman and others, 1983).

Use of ground water has been relatively small in comparison with the total amount available (Foxworthy, 1979). Of the 8,200 million gallons per day (Mgal/d) of freshwater withdrawn in Washington in 1980, only 9 percent was from ground-water sources; most of the remainder was surface-water withdrawals for irrigation, primarily in eastern Washington. Ground-water withdrawals for various uses in 1980 and related statistics are given in table 1.

Because almost all surface water in Washington is allocated at present, additional water-related development, by necessity, will rely on ground water. Consequently, the demands and competition for ground water are expected to increase in the future.

The quality of ground water in Washington, with a few exceptions, is very good and suitable for most uses (Van Denburgh and Santos, 1965). In intensively developed coastal areas, seawater intrusion has restricted the utility of the ground water, especially for drinking. A recent study by Dion and Sumioka (1984), however, indicates that the seawater intrusion is localized and that the problem probably did not worsen between 1968 and 1978.

Table 1. Ground-water facts for Washington

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	2,932
Percentage of total population	71
From public water-supply systems:	
Number (thousands)	2,100
Percentage of total population	51
From rural self-supplied systems:	
Number (thousands)	832
Percentage of total population	20
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	8,200
Ground water only (Mgal/d)	750
Percentage of total	9
Percentage of total excluding withdrawals for thermoelectric power	9
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	300
Percentage of total ground water	40
Percentage of total public supply	37
Per capita (gal/d)	143
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	40
Percentage of total ground water	5
Percentage of total rural domestic	78
Per capita (gal/d)	48
Livestock:	
Ground water (Mgal/d)	4.1
Percentage of total ground water	0.5
Percentage of total livestock	67
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	150
Percentage of total ground water	20
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	15
Excluding withdrawals for thermoelectric power	15
Irrigation withdrawals:	
Ground water (Mgal/d)	260
Percentage of total ground water	34
Percentage of total irrigation	4

GENERAL SETTING

Washington is a State with diverse physiography. The north-trending Cascade Range (fig. 1) forms a barrier that divides the State into two areas of entirely different physiography and climate. West of the Cascades are the Puget Trough, which is underlain by glacial drift and contains a large marine embayment (Puget Sound) dotted with islands, and the Olympic Mountains, which separate the Puget Trough from the Pacific Ocean (Fenneman, 1931). East of the Cascade Range are the Northern Rocky Mountains, in the northeastern part of the State, and the Columbia Plateau, a broad expanse of generally flat terrane underlain by a series of layered volcanic flows.

The Cascades divide Washington into semiarid eastern and humid western parts. Annual precipitation ranges from 8 inches (in.) in the drier parts of eastern Washington to about 200 in. in the rain forests of the Olympic Mountains. Consequently, the bulk of the runoff generated within Washington occurs in the western part of the State, largely during the winter. The Columbia, the Spokane, and the Snake Rivers, however, flow into eastern Washington and supply even more streamflow than is generated within the State.

The contrast in precipitation between eastern and western Washington is reflected in the rates of ground-water recharge in those areas. Annual recharge in eastern Washington may be 1 in. or less, whereas in western Washington the rate may be as much as several inches. These relative recharge rates largely determine the patterns of ground-water occurrence, availability, and use across the State.

PRINCIPAL AQUIFERS

The principal aquifers of Washington consist predominantly of unconsolidated sedimentary rocks (glacial-drift and terrace and valley-fill aquifers) and volcanic rocks (Columbia River Basalt aquifer). These aquifers are described below and in table 2; their areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics in Washington

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey and Washington Department of Ecology]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Principal Aquifers:					
Glacial drift aquifer: Sand and gravel units of glacial outwash and the more permeable units found locally in glacial till. Unconfined.	50 - 250	400	1 - 1,000	10,000	Used extensively in the Puget Sound region and Spokane Valley for domestic, public-supply, and industrial purposes. Varies greatly in water-yielding capability. Iron concentration of water in Puget Trough commonly exceeds 0.3 mg/L.
Terrace and valley-fill aquifer: Sand and gravel with some silt and clay. Unconfined.	50 - 300	400	10 - 1,000	4,500	Used extensively near Vancouver for industrial supplies. Water quality generally suitable for most purposes.
Columbia River Basalt aquifer: Alternating layers of dense but locally fractured basalt, and interbeds of unconsolidated sand and gravel. Confined to unconfined.	50 - 750	900	150 - 3,000	6,000	Used extensively in the Columbia Plateau region for irrigation purposes. Sodium concentration of water locally large enough to restrict use for irrigation.
Other Aquifers:					
Alluvial aquifer: Unconsolidated silt, sand, gravel, and cobbles, deposited along streams, deltas, and coastal beaches. Unconfined.	20 - 50	100	5 - 50	200	Used predominantly for domestic supplies. Water quality generally suitable for most purposes. Occurrence not depicted in figure 1.
Crystalline rock aquifer: Dense, consolidated sedimentary, metamorphic, and igneous rocks which have local secondary permeability because of fractures and faults. Confined to unconfined.	20 - 200	300	1 - 10	50	Neither a dependable nor productive source of water. Well yields relatively small and very erratic. Occurrence not depicted in figure 1.

GLACIAL-DRIFT AQUIFER

The glacial-drift aquifer is composed chiefly of glacial outwash and the more permeable units within glacial till. In the Puget Sound region and the Spokane Valley, this aquifer provides most of the water used for domestic, public-supply, and industrial purposes; the aquifer has been accorded Federal "sole-source" status in the Spokane Valley, under Section 1424 (e) of the Safe Drinking Water Act of 1974 (Public Law 93-523).

In the Columbia Plateau region, the aquifer is used primarily for single-family domestic purposes inasmuch as greater yields generally can be obtained from the underlying basalt (Molenaar and others, 1980). Because of various modes of deposition, the glacial-drift aquifer differs greatly in composition and water-yielding capability. Wells that tap thick layers of extremely permeable sand or gravel yield as much as 10,000 gallons per minute (gal/min); wells that tap layers of less-permeable silt or till may yield only enough water for single-family domestic supplies.

Dissolved-solids concentrations in the glacial drift generally are less than 150 milligrams per liter (mg/L). Nitrate concentrations are less than 1.0 mg/L as nitrogen in most wells, but concentrations exceeding that level have been found in parts of Pierce, Skagit, and Whatcom Counties and probably are caused by agriculture or septic tanks.

A common, but natural, water-quality problem in the glacial drift aquifer of the Puget Trough is the occurrence of iron in concentrations greater than 0.3 mg/L, which is the national drinking-water regulation (U.S. Environmental Protection Agency, 1982b) for domestic water supplies.

TERRACE AND VALLEY-FILL AQUIFER

The terrace and valley-fill aquifer consists chiefly of sand and gravel and is found on the west side of the Olympic Peninsula, near Vancouver, and in the Kittitas and the Yakima Valleys. Yields from this aquifer range from a few gallons per minute, suitable for single-family domestic purposes, to about 4,500 gal/min near Vancouver, where the water is used primarily for industrial purposes.

COLUMBIA RIVER BASALT AQUIFER

The aquifer in the Columbia River Basalt Group is composed of numerous lava flows and interbeds of unconsolidated sand and gravel and extends into Idaho and Oregon. The maximum thickness of the aquifer is near Pasco, Washington, in the Columbia Plateau and probably exceeds 6,000 feet (ft). The most important formations in the aquifer, from youngest to oldest, are the Saddle Mountains Basalt, the Wanapum Basalt, and the Grande Ronde Basalt of the Columbia River Basalt Group. Water in this aquifer is present mostly in fractures, rubble zones, and sand and gravel interbeds between lava flows. Because of the great vertical and horizontal heterogeneity of this thick, extensive aquifer, well yields are extremely variable. The most productive wells generally tap several water-bearing zones; yields of 3,000 gal/min are common, and some in excess of 6,000 gal/min have been reported. These relatively large yields encourage the use of the ground water for the irrigation of crops on the Columbia Plateau. Dissolved-solids concentrations in the Columbia River Basalt aquifer generally range from 250 to 500 mg/L, and iron concentrations commonly are less than

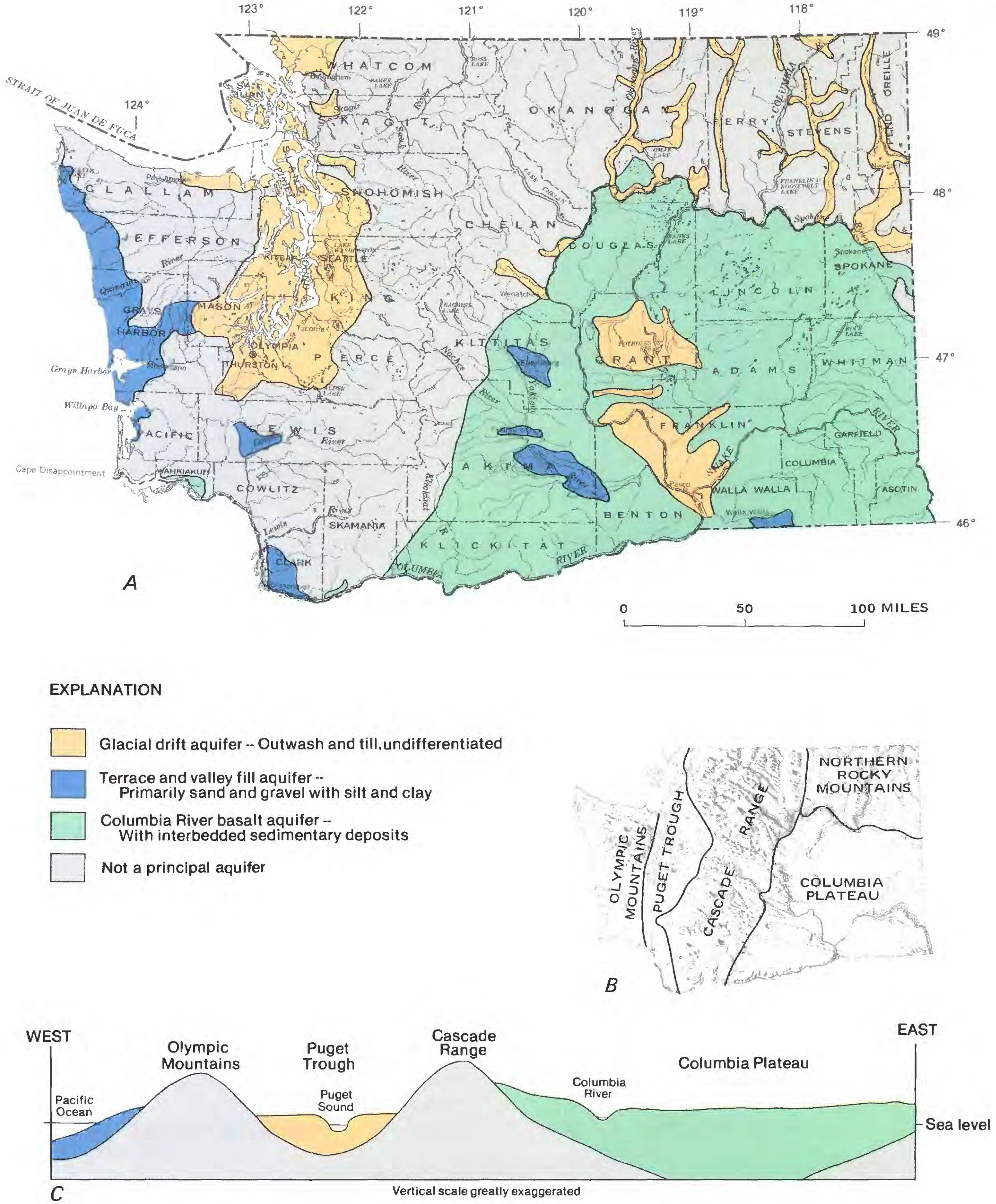


Figure 1. Principal aquifers in Washington. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross section. (See table 2 for a more detailed description of the aquifers. Sources: *A*, Huntting and others, 1961. *B*, Fenneman, 1931; Raisz, 1954. *C*, Molenaar and others, 1980.)

0.01 mg/L. Nitrate concentrations generally are less than 1.0 mg/L, but concentrations exceeding this amount have been found in large areas of Adams, Franklin, Grant, and Lincoln Counties. In addition, concentrations exceeding 5.0 mg/L have been reported near the cities of Yakima and Walla Walla.

Irrigators in the south-central and eastern parts of the Columbia Plateau have reported recently that water from the Columbia River Basalt aquifer locally contains excessive concentrations of sodium relative to other metallic ions. Use of this water for irrigation has led to decreased soil permeabilities and a consequent reduction in crop yields. Preliminary studies by the U.S. Geological Survey have indicated that the largest sodium concentrations are associated with the oldest, and generally deepest, basalt flows and that the problem is a natural one.

In a large part of its extent, the Columbia River Basalt aquifer is mantled by differing thicknesses of glacial drift, fine-grained loess, and younger basalt. These mantling units are saturated only locally because, in most areas, they drain into permeable basalt.

OTHER AQUIFERS

Other aquifers in Washington are of less significance than those described above and are not shown in figure 1 but are described in table 2. They consist of alluvium and of dense crystalline rocks. The alluvial aquifer consists of the silt, sand, gravel, and cobbles deposited along streams, deltas, and coastal beaches. Reported yields from this aquifer commonly are small (5–50 gal/min) but are adequate for domestic purposes, its predominant use. In some areas, large-diameter wells in the alluvial aquifers yield 50 to 200 gal/min for public-supply and industrial purposes.

The igneous, sedimentary, and metamorphic rocks that underlie the Olympic, the Cascade, and the Northern Rocky Mountains (see fig. 1) compose the crystalline rock aquifer. Some of these rocks are geologically older than the aquifers discussed previously (Huntting and others, 1961). Although this aquifer has local secondary permeability because of fractures and faults and supplies water to wells, the aquifer as a whole is neither a productive nor a dependable source of water.

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The locations of major areas and types of ground-water withdrawals in Washington (Dion and Lum, 1977; Solley and others, 1983) are shown in figure 2, along with water-level hydrographs for selected wells in those areas. Most of the ground water withdrawn in western Washington is for public supply in King and Pierce Counties and for industry in Clark County. Most of the ground water withdrawn in eastern Washington is for irrigation in Adams, Franklin, Lincoln, and Grant Counties, for public supply in Spokane County, and for industry in Yakima County.

Ground-water levels in parts of the Columbia Plateau have declined as a result of the extensive use of ground water for agricultural and other purposes to the point that the declines currently affect wells drilled for other, competing purposes. One area of significant water-level decline is the Odessa-Lind area of Adams County (Cline, 1984), where approximately 800 large-capacity wells withdraw water from the Columbia River Basalt aquifer for irrigation. Water levels have been declining in parts of that area by as much as 10 ft annually for 20 years. An example of the seasonal and long-term declines experienced in the Odessa–Lind area is provided by the hydrograph of the Adams County well (location 6, fig. 2).

A second area of significant water-level declines is the Pullman, Washington–Moscow, Idaho, area. There, ground-water development has been so great that the resulting cone of depression has reportedly reached the boundaries of the ground-water basin.

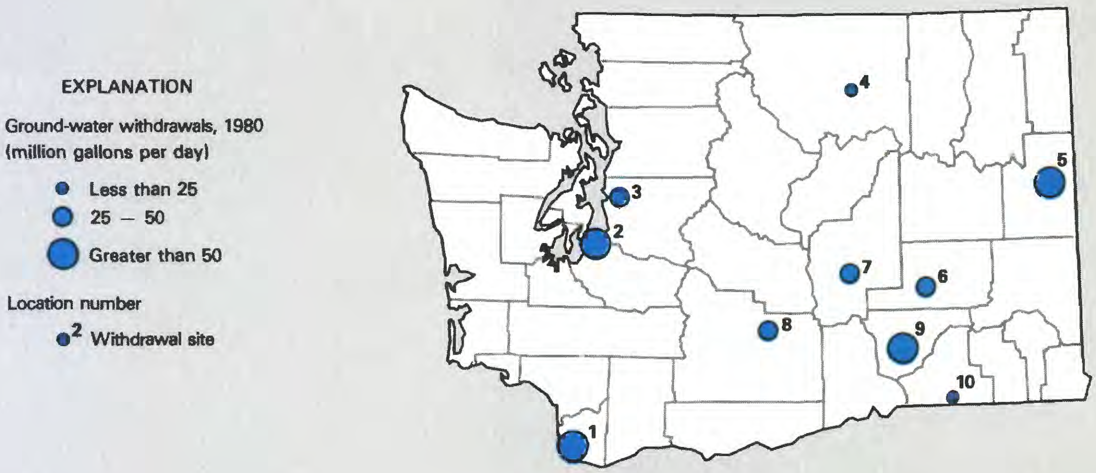
The hydrographs at locations 2 and 5 (fig. 2) of Pierce and Spokane Counties, respectively, show no significant trend as a result of large ground-water withdrawals from the glacial-drift aquifer. They illustrate that, at current withdrawal rates, recharge of the glacial-drift aquifer is adequate to maintain water levels.

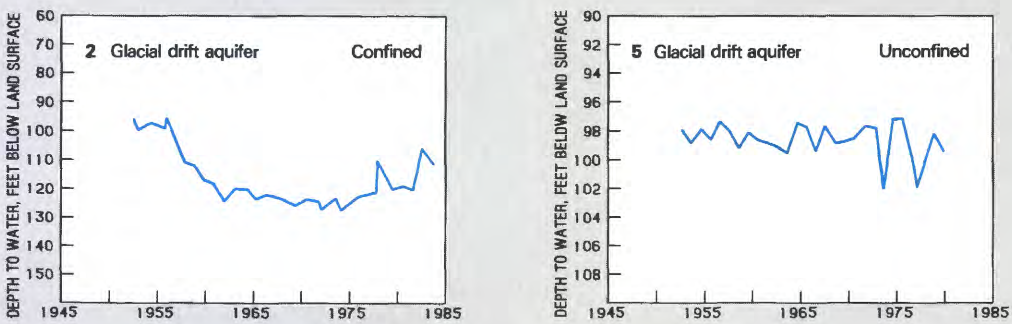
A problem of excessive ground water exists in parts of the Columbia Plateau where levels have risen as much as 300 ft and have created drainage problems in areas such as the Quincy Basin and Yakima River basin. These basins have been irrigated with water diverted from the Columbia and the Yakima Rivers. Excess irrigation water applied to the fields which has percolated to the water table and leakage from canals are the causes of the water level rise.

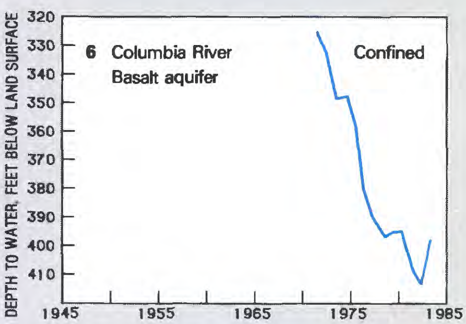
GROUND-WATER MANAGEMENT

Ground water in Washington is regulated chiefly by the Washington Department of Ecology (WDOE) and the Washington Department of Social and Health Services (DSHS). The WDOE is responsible for administering all ground waters of the State and issues water rights based on chapter 90.44 of the Revised Code of Washington (RCW). Potential users of ground water who wish to withdraw more than 5,000 gallons per day (gal/d) must make application to the WDOE, which then determines if the proposed use is in the public interest. Prime considerations include the effects of the proposed withdrawal on surface-water bodies and on ground-water levels. If the proposed withdrawal threatens to lower ground-water levels more than 10 ft annually, the application usually is denied. The WDOE recently has denied many applications in the Odessa–Lind area, where ground-water levels have declined significantly because of intensive irrigation pumpage. The WDOE also regulates all well drillers and well-drilling activity in Washington and conducts technical investigations unilaterally and in cooperation with the U.S. Geological Survey.

The protection of ground-water quality is the concern of the WDOE and the DSHS. Under chapter 90.48 of the RCW, the WDOE has been designated the State water-pollution control agency and is responsible for administering the Underground Injection Control provisions of the Federal Safe Drinking Water Act of 1974 (Public Law 93–523) and any ground-water provisions of the Federal Clean Water Act. The DSHS is charged with administering the drinking-water protection aspects of the Federal Safe Drinking Water Act and, under chapter 43.20 of the RCW, regulates public water systems.







WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Clark County	Terrace and valley fill.	Industrial.
2	Pierce County	Glacial drift	Public supply.
3	King County.	. . . .do	Do.
4	Okanogan County. . .	. . . .do	Irrigation, industrial.
5	Spokane County . . .	. . . .do	Public supply, irrigation.
6	Adams County	Columbia River Basalt.	Irrigation.
7	Grant County	. . . .do	Do.
8	Yakima County	Terrace and valley fill.	Industrial, public supply.
9	Franklin County . . .	Columbia River Basalt.	Irrigation, public supply.
10	Walla Walla County . .	. . . .do	Do.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Washington. (Sources: Withdrawal data from Dion and Lum, 1977; Solley, Chase, and Mann, 1983. Water-level data from U.S. Geological Survey files.)

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Prepared by Norman P. Dion

For further information contact District Chief, U.S. Geological Survey, 1201 Pacific Avenue, Suite 600, Tacoma, WA 98402

WEST VIRGINIA
Ground-Water Resources

Ground water is an important resource that is used throughout West Virginia for public, domestic, and industrial supply. Ground-water withdrawals in 1980 accounted for only 4 percent of the total freshwater used in the State; however, it was the source of supply for about 53 percent of the total population in the State and about 90 percent of the rural population.

In the unconsolidated alluvial deposits along the Ohio and Kanawha Rivers and the limestone areas in the eastern part of the State, ground water is plentiful and the potential for further development is good. In most of the western two-thirds of the State, however, ground water is less plentiful and, generally, only small quantities of water are obtainable.

In the southern part of the State, numerous abandoned underground coal mines contain large supplies of potable ground water. In 1980, approximately 70 public-supply systems pumped more than 7 million gallons of water per day (Mgal/d) from these abandoned coal mines to supply about 82,000 people and commercial users (Lessing and Hobba, 1981). Underground mines in McDowell, Wyoming, and Raleigh Counties produced from 10 to 27 Mgal/d in 1980, principally for industrial and public supply (Stevens and Lessing, 1982). Ground-water withdrawals in 1980 for various uses, and related statistics, are given in table 1.

Table 1. Ground-water facts for West Virginia

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)	1,039
Percentage of total population	53
From public water-supply systems:	
Number (thousands)	411
Percentage of total population	21
From rural self-supplied systems:	
Number (thousands)	628
Percentage of total population	32
Freshwater Withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	5,600
Ground water only (Mgal/d)	220
Percentage of total	4
Percentage of total excluding withdrawals for thermoelectric power	22
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	49
Percentage of total ground water	22
Percentage of total public supply	27
Per capita (gal/d)	119
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	18
Percentage of total ground water	8
Percentage of total rural domestic	95
Per capita (gal/d)	29
Livestock:	
Ground water (Mgal/d)	1
Percentage of total ground water	0.5
Percentage of total livestock	13
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	150
Percentage of total ground water	68
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	3
Excluding withdrawals for thermoelectric power	18
Irrigation withdrawals:	
Ground water (Mgal/d)	0.1
Percentage of total ground water	0
Percentage of total irrigation	8

GENERAL SETTING

West Virginia is divided into three physiographic provinces, each with distinctive principal rock types and ground-water characteristics (fig. 1). The western and central parts of the State are in the Appalachian Plateaus physiographic province. The nearly flat-lying, consolidated sedimentary rocks that underlie this area have been eroded by streams and rivers to form steep hills and deeply incised valleys. The Allegheny Mountains section of the Appalachian Plateaus province is underlain by gently to moderately folded strata. The eastern part of the State is in the Valley and Ridge physiographic province. The consolidated sedimentary rocks underlying this area are faulted extensively and folded sharply; the folded strata form a series of northeast-trending valleys and ridges. The Blue Ridge province includes only a very small area along the easternmost part of the State.

Precipitation is the primary source of recharge to the ground-water systems in West Virginia. Average annual precipitation ranges from about 30 inches (in.) in the western part of the Eastern Panhandle to 40 in. in the western and southern parts of the State and to about 60 in. in the higher mountainous areas in the east-central part (Allegheny Mountains) of the State. Annual recharge to the ground-water system from precipitation ranges from 2 to 6 in. in areas underlain mostly by shale to about 6 to 12 in. in areas underlain mostly by sandstone and limestone (Hobba, 1985). A major percentage of the amount that recharges the ground-water system discharges to nearby streams; very little moves into deeper aquifers.

PRINCIPAL AQUIFERS

Two principal types of aquifers underlie West Virginia—unconsolidated alluvial deposits and sedimentary bedrock aquifers. The major aquifers of West Virginia have been categorized informally by geologic age. The formal rock stratigraphic units within the principal aquifers are those used by the West Virginia Geological and Economic Survey. The characteristics of the principal aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

Table 2. Aquifer and well characteristics for West Virginia

[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey, the West Virginia Geological and Economic Survey, and the West Virginia Department of Natural Resources, Division of Water Resources]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Well characteristics: Depth (ft) May exceed	Well characteristics: Yield (gal/min) Common range	Well characteristics: Yield (gal/min) May exceed	Remarks
Alluvial aquifers					
Sand and gravel, interbedded with silt and clay. Generally unconfined to semiconfined locally.	25 - 100	140	50 - 1,500	3,000	Used as source for public and industrial supplies along the Ohio and Kanawha Rivers. Water generally suitable for most uses but hard to very hard and has large iron sulfate, manganese, organic compounds, and chloride concentrations in some areas.
Sedimentary bedrock aquifers					
Upper Pennsylvanian aquifers: Dunkard Group (Permian or Pennsylvanian age), Monongahela Group, Conemaugh Group: Nearly horizontal, predominantly shale with sandstone, siltstone, coal, and limestone. Generally unconfined in hilltop and hillside areas to partly confined and confined in valleys.	50 - 300	400	1 - 30	200	Used mainly for domestic and farm supplies. Reports of insufficient yields more common from hilltop and hillside wells than from valley wells. Water suitable for most uses, but moderately hard to very hard, alkaline, and has large iron concentration locally.
Lower Pennsylvanian aquifers: Allegheny Formation (Middle Pennsylvanian age), Pottsville Group: Nearly horizontal, predominantly sandstone with shale, siltstone, coal, and some limestone. Generally unconfined in hilltop and hillside areas to partly confined and confined in valleys.	50 - 300	400	1 - 100	300	Used mainly for domestic and farm supplies but has moderate-to-good potential for small industrial and public supplies. Water good for most uses, but generally hard to very hard and has large iron and manganese concentrations locally.
Mississippian aquifers: Mauch Chunk Group, Greenbrier Group, Maccrady Formation, Pocono Group: Moderately folded, predominantly sandstone and limestone with shale. Unconfined at shallow depth and confined at greater depth.	50 - 200	300	1 - 100	200	Yields are adequate for domestic, farm, and small commercial supplies. Predominantly limestone Greenbrier Group a source of large-yielding springs that supply small to large industrial supplies. Yields of springs range from 50 to 2,000 gal/min and average about 180 gal/min. Water suitable for most uses but generally moderately hard to very hard and has large iron concentrations locally. Greenbrier Group aquifer very susceptible to pollution from surface sources.
Devonian aquifers:					
Hampshire Formation, Chemung Group, Millboro Shale, Onesquethaw Group: Nearly horizontal to moderately folded, predominantly shale and siltstone with sandstone and some limestone. Generally unconfined at shallow depth to confined at greater depth.	50 - 300	500	1 - 25	50	Yields adequate for domestic, farm, and small industrial supplies where units crop out in valley areas. Water suitable for most uses; generally soft to moderately hard, and alkaline.
Oriskany Sandstone, Helderberg Group: Very folded, predominantly limestone and sandstone with some shale. Generally unconfined at shallow depth to confined at greater depth.	50 - 300	500	2 - 200	1,000	Yields adequate for domestic, farm, and moderately large industrial and public supplies. Units are source of large springs that yield 50 to 15,000 gal/min. Water is generally suitable for most uses but is hard to very hard. Helderberg unit very susceptible to pollution from surface sources.

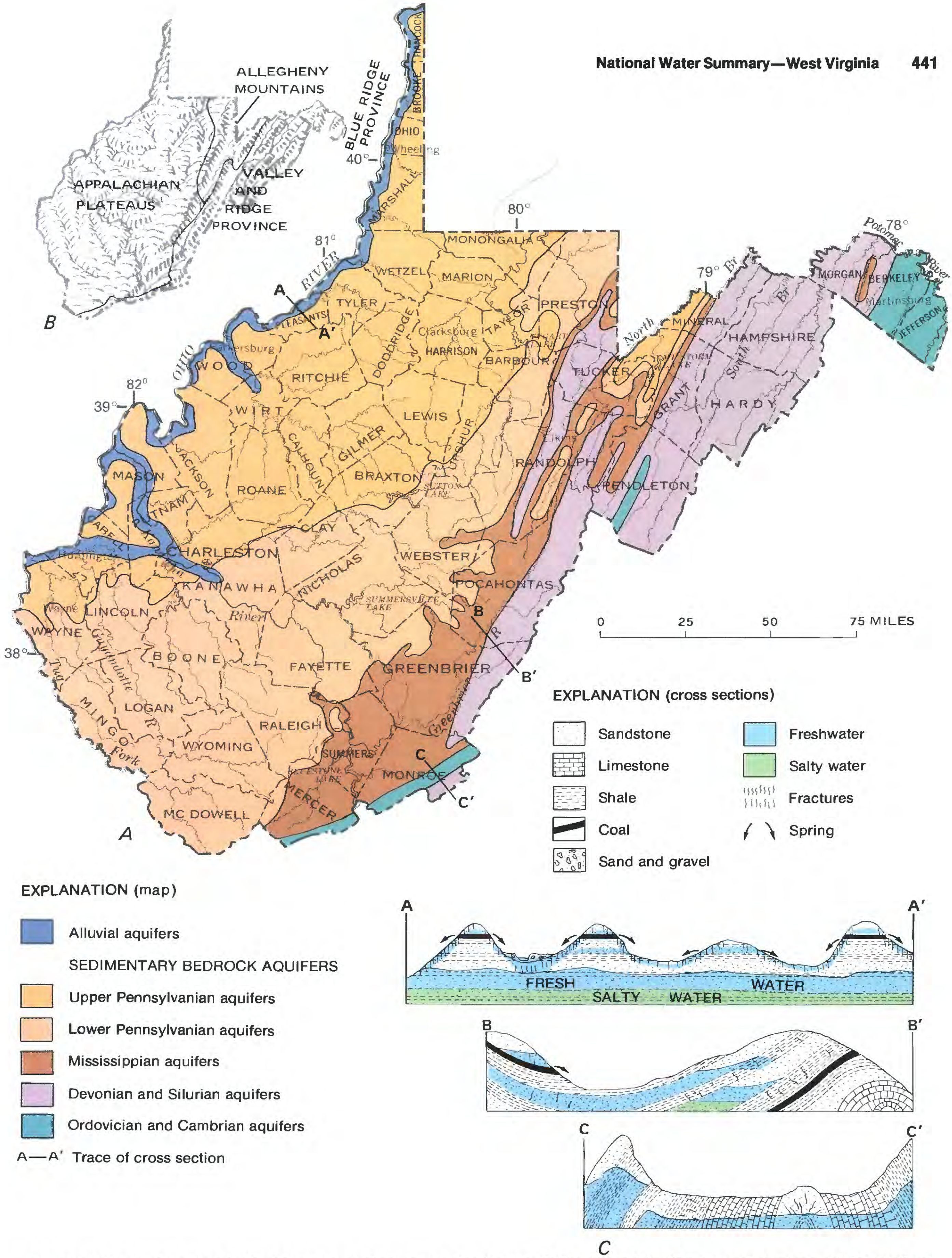


Figure 1. Principal aquifers in West Virginia. *A*, Geographic distribution. *B*, Physiographic diagram and divisions. *C*, Generalized cross sections (A-A', B-B', C-C') showing lithology and the occurrences of water. (See table 2 for a more detailed description of the aquifers. Sources: *A*, *C*, Modified from Landers, 1976. *B*, Fenneman, 1938; Raisz, 1954.)

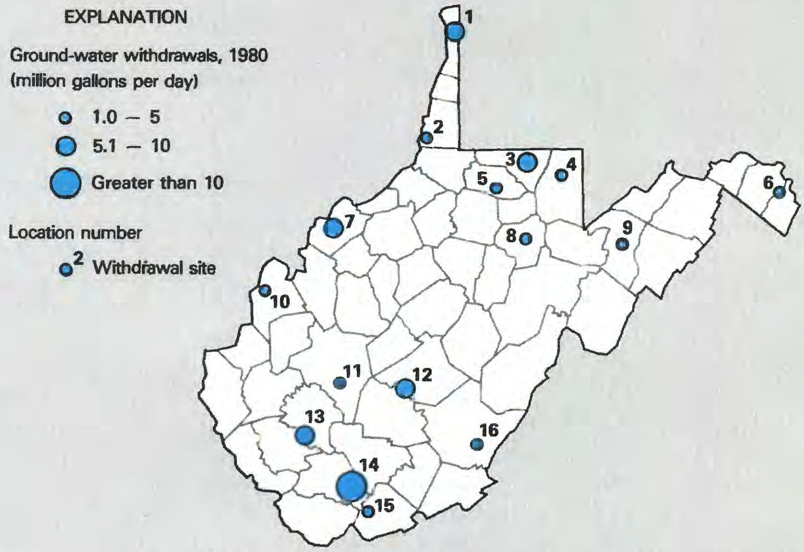
Table 2. Aquifer and well characteristics for West Virginia—Continued

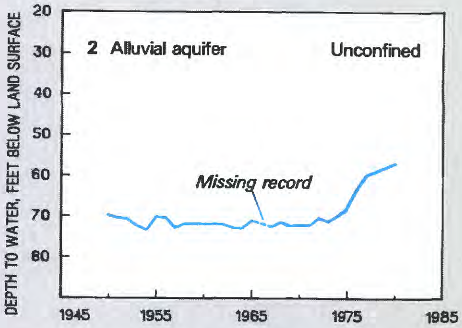
[Ft = feet; gal/min = gallons per minute. Sources: Reports of the U.S. Geological Survey, the West Virginia Geological and Economic Survey, and the West Virginia Department of Natural Resources, Division of Water Resources]

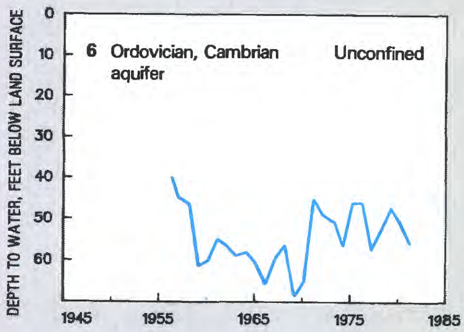
Aquifer name and description	Well characteristics				Remarks
	Depth (ft)		Yield (gal/min)		
	Common range	May exceed	Common range	May exceed	
Silurian aquifers:					
Tonoloway Formation, Wills Creek Formation, Williamsport Sandstone: Very folded, predominantly limestone and sandstone with shale. Generally unconfined at shallow depth to confined at greater depth.	50 - 300	400	1 - 100	200	Yields adequate for domestic, farm and small to moderate industrial and public supplies. Units are source of large springs that yield from 10 to 1,000 gal/min. Water generally suitable for most uses but hard to very hard. Water in Tonoloway and Wills Creek Formations may have large sulfate concentrations because of presence of anhydrite. Units very susceptible to pollution from surface sources.
McKenzie Formation, Clinton Group, Tuscarora Sandstone: Very folded, sandstone, shale, and some limestone. Generally unconfined at shallow depth to confined at greater depth.	40 - 250	300	1 - 25	50	Yields adequate for domestic and farm supplies where units crop out in valley areas. Water suitable for most uses but hard to very hard and has large iron concentrations locally.
Ordovician aquifers:					
Juniata Formation, Oswego Formation, Martinsburg Formation: Very folded, sandstone with some shale and limestone. Generally unconfined at shallow depth to confined at greater depth.	50 - 200	250	1 - 30	50	Yields adequate for domestic and farm, and moderately large industrial and public supplies. Water generally suitable for most uses but hard to very hard and has large iron and sulfate concentrations locally.
Trenton Group, Black River Group, St. Paul Group, Beekmantown Group: Very folded, predominantly limestone with some sandstone and shale. Generally unconfined at shallow depth and confined at greater depth.	75 - 400	500	5 - 400	600	Yields adequate for domestic, farm, and moderate to large industrial and public supplies. Units are source of large springs that yield from 50 to 5,000 gal/min. Water generally suitable for most uses but hard to very hard. Units very susceptible to pollution from surface sources.
Cambrian aquifers:					
Conococheaque Formation, Elbrook Formation, Waynesboro Formation, Tomstown Dolomite: Very folded, predominantly limestone with some sandstone and shale. Generally unconfined at shallow depth and confined at greater depth.	100 - 400	500	2 - 200	300	Yields adequate for domestic, farm, and moderate to large industrial and public supplies. Large springs from these units generally yield from 50 to 2,300 gal/min. Water hard to very hard but suitable for most uses. Units very susceptible to pollution from surface sources.
Chilhowee Group: Very folded, predominantly shale and sandstone. Generally unconfined at shallow depth and confined at greater depth.	50 - 200	250	1 - 25	50	Yields adequate for domestic and farm use. Generally slightly acidic, soft to moderately hard, and suitable for most uses.

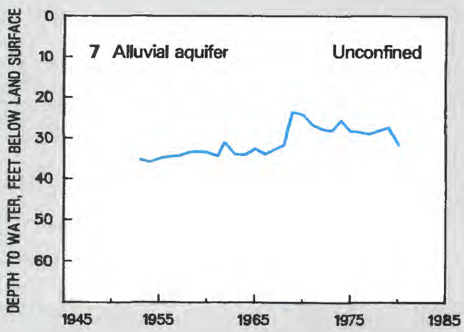
Alluvial Aquifers

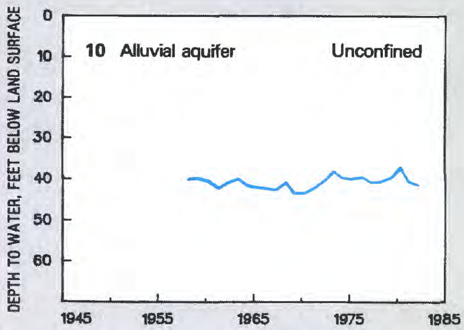
The unconsolidated alluvial aquifers along the Ohio and Kanawha Rivers in the western part of the State are the best sources of ground water for public-supply and industrial use in the State (fig. 1). Well yields depend upon the permeability, areal extent, and saturated thickness of the sand and gravel materials and the proximity of wells to rivers, where properly constructed wells can induce the infiltration of large quantities of streamflow. The quality of water in the alluvial aquifers generally is suitable for most uses, but the water commonly is hard to very hard; concentrations of calcium carbonate exceeding 120 milligrams per liter (mg/L) are common. In places where waste from chemical and industrial plants has contaminated the local ground water, the water has large concentrations of iron (as much as 87 mg/L), sulfate (as much as 2,400 mg/L), chloride (as much as 2,200 mg/L) (Shultz, 1984), manganese (as much as 5.3 mg/L), and organic compounds, such as phenols (as much as 6,600 mg/L) (M. V. Mathes, U.S. Geological Survey, oral commun., 1984).

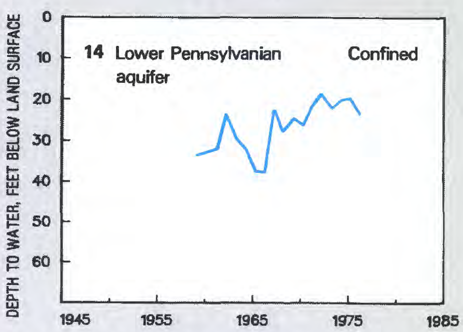












WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Weirton area.	Alluvial.	Public supply.
2	Moundsville-New Martinsville area.	. . . .do	Public supply, industrial.
3	Morgantown area . .	Upper Pennsylvanian . .	Industrial.
4	Kingwood area . . .	Lower Pennsylvanian . .	Industrial, public supply.
5	Fairmont area	Upper Pennsylvanian . .	Industrial.
6	Martinsburg-Charles Town area.	Ordovician, Cambrian.	Public supply.
7	Parkersburg area. . .	Alluvial.	Public supply.
8	Philippi area	Lower Pennsylvanian . .	Industrial.
9	Henry area	. . . .do	Do.
10	Point Pleasant area.	Alluvial.	Public supply.
11	Montgomery area . .	Lower Pennsylvanian . .	Industrial.
12	Oak Hill-Summersville area.	. . . .do	Industrial, public supply.
13	Logan-Peytona area.	. . . .do	Do.
14	War-Beckley area . .	. . . .do	Do.
15	Matoaka area	. . . .do	Industrial.
16	White Sulphur Springs area.	Mississippian.	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in West Virginia. (Sources: Withdrawal data from Stevens and Lessing, 1982; water-level data from U.S. Geological Survey files.)

SEDIMENTARY BEDROCK AQUIFERS

Upper and Lower Pennsylvanian Aquifers

Major sources of ground water in the Appalachian Plateaus province in the western and central parts of the State are the Upper and Lower Pennsylvanian aquifers (fig. 1). The Upper Pennsylvanian aquifers consist of the Dunkard, Monongahela, and Conemaugh Groups of Permian and Pennsylvanian age. These geologic units are composed mostly of nearly horizontal layers of shale with thin interbeds of fine-grained sandstone, siltstone, limestone, and coal. The Lower Pennsylvanian aquifers, which consist of the Allegheny Formation and the Pottsville Group, are composed mostly of massive coarse-grained sandstone with interbeds of shale, siltstone, coal, and limestone.

The primary permeability of the Pennsylvanian bedrock aquifers generally is negligible. Water in these aquifers flows through and is stored in joint systems, fractures, bedding planes, and, in carbonates, solution channels. These aquifers commonly are very local in extent. In some areas, these local aquifers are perched and isolated under individual hilltops (section A–A′, fig. 1C).

Because rocks in valley areas generally are more fractured and receive more recharge from streams, hillsides, and hilltop areas, wells in valleys commonly yield more water than wells on hills. Although the Upper Pennsylvanian aquifers yield less water to wells than the Lower Pennsylvanian aquifers, they are an important source of water in rural areas.

The quality of water in the Upper and Lower Pennsylvanian aquifers is similar and generally suitable for most uses. Dissolved-solids concentrations range from 150 to 400 mg/L, iron ranges from 0.2 to 3 mg/L, and sulfate is less than 50 mg/L; pH ranges from 6 to 8. However, the water is moderately hard (61–120 mg/L as calcium carbonate) to very hard (as much as 300 mg/L as calcium carbonate). In places where coal-mine drainage is a source of recharge to underlying aquifers, ground water may be acidic (pH less than 3.5) and may contain large concentrations of iron (as much as 180 mg/L), manganese (as much as 9.9 mg/L), sulfate (as much as 2,500 mg/L), hardness (as much as 1,300 mg/L as calcium carbonate), and chloride (as much as 2,200 mg/L) (Bader, 1984). Brine underlies freshwater in most areas of the Appalachian Plateaus (generally below 300 feet in valley areas).

Mississippian Aquifers

In the southeastern part of the State, the mostly noncarbonate strata (Mauch Chunk Group, Maccrady Formation, and the Pocono Group) within the Mississippian aquifers are similar in lithology and permeability to the Pennsylvanian aquifers in the Appalachian Plateaus. The Mississippian aquifers, however, are gently to moderately folded (section B–B′, in fig. 1C). In this area, parts of the sandstones are saturated and confined by overlying and underlying shales. Under these conditions, the aquifers can yield moderate to large amounts of water.

The predominantly carbonate Greenbrier Group of the Mississippian aquifers has good potential for large-scale withdrawal of ground water. Fracture openings in these strata generally are enlarged by solution; springs, and wells that penetrate enlarged openings, may have large yields. However, in limestone areas where wells penetrate few fractures, it is possible to drill a dry well only a few feet away from a well that produces enough water to supply a small city (Landers, 1976).

Water quality of the Mississippian aquifers generally is suitable for most uses. Hardness and locally large iron concentrations (more than 0.3 mg/L) are common problems. Because of sinkholes and large solution openings that may be in direct hydraulic connection with sources of contamination in outcrop areas, the carbonate unit (Greenbrier Group) is very susceptible to biological and chemical pollution.

Devonian to Cambrian Aquifers

Farther to the east, in the Valley and Ridge province, the aquifers are faulted and compressed into steep folds, which greatly affect the occurrence and movement of ground water (section C–C′, fig. 1C). In these areas, ground-water conditions are more variable than in the rest of the State. The principal carbonate units, such as the Helderberg Group of the Devonian aquifers, the Beekmantown Group of the Ordovician aquifers, and some of the massive sandstone units, such as the Oriskany Sandstone of the Devonian aquifers, have potential for providing large amounts of ground water. The carbonate units in this part of the State also are a source of springs with large yields [as much as 15,000 gallons per minute (gal/min)] that supply small water-supply systems and light industry (Hobba and others, 1972).

The water-bearing properties of minor carbonate units, such as the Tonoloway Formation of the Silurian aquifers, the Conococheaque, Elbrook, and Waynesboro Formations, and the Tomstown Dolomite of the Cambrian aquifers, generally are comparable to those of the major carbonate units of the Mississippian, the Devonian, and the Ordovician aquifers. Because of small areal extent, water storage in the minor carbonate units generally is small (Bieber, 1961). The water quality is very hard but is suitable for most uses. Many shallow wells that tap the carbonate units have large concentrations of nitrate (as much as 108 mg/L as nitrate) and chloride (as much as 8,300 mg/L), which may indicate pollution from surface sources.

The noncarbonate units within the Devonian, the Silurian, the Ordovician, and the Cambrian aquifer systems generally provide small amounts of water (less than 30 gal/min) to wells. The quality of water generally is suitable for most uses; hardness ranges from soft (less than 60 mg/L) to very hard (more than 180 mg/L as calcium carbonate), and local areas have large concentrations of iron (as much as 18 mg/L) and sulfate (as much as 2,150 mg/L) (Friel and others, 1975).

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

The distribution of major ground-water withdrawals and trends of water levels near selected withdrawal areas are shown in figure 2. Ground-water pumpage for small public-supply and rural domestic uses generally ranges from 0.1 to 1 Mgal/d for most counties in the State. Withdrawal areas that produce more than 1 Mgal/d for public and industrial supply generally overlie the alluvial aquifers along the Ohio River, the coal fields of southern West Virginia, and the carbonate aquifers in the eastern part of the State. Well fields near some of the larger cities along the Ohio River (Parkersburg and Weirton) produce from 5 to 10 Mgal/d, principally for public supply.

Hydrographs from wells near Moundsville (location 2, fig. 2), Parkersburg (location 7, fig. 2) and Point Pleasant (location 10, figure 2) are representative of ground-water levels in the alluvial aquifers along the Ohio River. Little change in the long-term trends of water levels is apparent in the hydrographs, indicating that ground-water storage in these areas is relatively stable. The nearly steady rise in water levels (after 1975) near Moundsville is due, in part, to the Ohio River lock-and-dam construction in 1975 and 1976, which raised the elevation of the river in the area.

The hydrograph from a well near Beckley (Raleigh County, location 14, fig. 2) is representative of valley wells that tap the Lower Pennsylvanian aquifers in unmined areas; the hydrograph from a well near Martinsburg (location 6, fig. 2) is representative of the Ordovician and Cambrian carbonate aquifers in the eastern part of the State. Overall, the long-term water-level trends in both wells indicate little change in ground-water storage in these parts of the State. The sharp water-level declines in the well near Martinsburg during 1959, 1966, and 1969 probably reflect increased pumpage, and the cumulative effect of several deficits in annual ground-water recharge because of decreased precipitation.

Abandoned underground mines in the coal fields of West Virginia are an important source of ground water for public supply and industrial use. If the mines do not drain freely, the mine voids act as large "drains" for overlying ground water and permit the accumulation of large volumes of water (Landers, 1976). If the mines drain freely from their openings, overlying ground-water supplies can be severely depleted and water levels can decline sharply.

GROUND-WATER MANAGEMENT

Water law in West Virginia is based on a modification of the riparian doctrine. State-level 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 State Geological and Economic Survey, implement most of the regulatory, planning, and research programs for the protection and management of ground water in the State (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 Water Resources Division administers and enforces all laws relating to the conservation, development, protection, and use of the ground-water resources of the State. Further revision by 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, corporations, institutions, and county and municipal governments. Through its Division of Sanitary Engineering and the State Board of Health, the Department of Health regulates installation of public-supply systems and adherence to water-quality standards.

Permit applications for drilling of 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 State Geological and Economic Survey examines the geology of formations (which include the aquifers) and the physical features of the State, with special reference to their economic products. The State Geological and Economic Survey, in cooperation with the U.S. Geological Survey, maintains a statewide water-data 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 ground-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 ground-water resources.

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Prepared by Celso Puente

For additional information contact District Chief, U.S. Geological Survey, 603 Morris Street, Charleston, WV 25301

WISCONSIN
Ground-Water Resources

Ground water provides about half of the water used in Wisconsin, excluding water used for cooling thermoelectric-power generating plants. Ground water supplies 70 percent of Wisconsin's population. All rural-domestic supplies and 94 percent of the municipalities use ground water (Lawrence and Ellefson, 1982, p. 9). Most water for irrigation and stock watering is ground water.

Ground water is used throughout Wisconsin, but withdrawals do not exceed 30 Mgal/d at any location. The largest withdrawals are for irrigation in central Wisconsin and for municipal supplies at Eau Claire, Janesville, La Crosse, and Madison (fig. 2). Ground-water withdrawals in 1980 for various uses and related statistics are given in table 1.

The natural chemical quality of ground water in the State is suitable for human consumption and most other uses. The major dissolved components are calcium, magnesium, and bicarbonate derived from dolomite bedrock (Kammerer, 1981, p. 12). The smallest dissolved-solids concentrations are in water from the unconsolidated sand and gravel aquifer in north-central Wisconsin where dolomite bedrock is absent.

GENERAL SETTING

Wisconsin is underlain by three principal types of rocks. The deepest and oldest rocks that form the basement consist primarily of crystalline igneous and metamorphic rocks of Precambrian age. A series of layered sedimentary rocks that consist largely of sandstone and dolomite overlie the basement rocks in all but north-central and northwest Wisconsin. Unconsolidated glacial deposits overlie these older rocks in most of the State except in southwestern Wisconsin. The principal aquifers in Wisconsin consist of glacial deposits and the sedimentary sandstones and dolomites.

Ground-water recharge in Wisconsin is from precipitation that averages 31 inches (in.) annually. Of this amount, 21 in. is lost to evapotranspiration and 10 inches either runs off or infiltrates the soil. Some of the water that infiltrates is stored in the soil, but most percolates downward to recharge the ground-water reservoir. Annual ground-water recharge in Wisconsin is estimated to average 6 in. (16,000 Mgal/d), although it may be as much as 10 in. in the sandy outwash deposits of central and northern Wisconsin.

PRINCIPAL AQUIFERS

Principal aquifers in Wisconsin are grouped into three major types—the unconsolidated sand and gravel aquifer, the Silurian dolomite aquifer, and the sandstone aquifer. The aquifers are described below and in table 2, from youngest to oldest; their areal distribution is shown in figure 1.

Table 1. Ground-water facts for Wisconsin

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Lawrence and Ellefson, 1982]

Population Served by Ground Water, 1980	
Number (thousands)	3,280
Percentage of total population	70
From public water-supply systems:	
Number (thousands)	1,620
Percentage of total population	35
From rural self-supplied systems:	
Number (thousands)	1,660
Percentage of total population	35
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	5,900
Ground water only (Mgal/d)	580
Percentage of total	10
Percentage of total excluding withdrawals for thermoelectric power	46
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	290
Percentage of total ground water	50
Percentage of total public supply	48
Per capita (gal/d)	177
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	72
Percentage of total ground water	13
Percentage of total rural domestic	100
Per capita (gal/d)	43
Livestock:	
Ground water (Mgal/d)	72
Percentage of total ground water	12
Percentage of total livestock	96
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	61
Percentage of total ground water	11
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	1
Excluding withdrawals for thermoelectric power	15
Irrigation withdrawals:	
Ground water (Mgal/d)	82
Percentage of total ground water	14
Percentage of total irrigation	97

UNCONSOLIDATED SAND AND GRAVEL AQUIFER

The sand and gravel aquifer consists of the more permeable unconsolidated sediments in stream-valley alluvium and in the glacial deposits that underlie much of the State. The aquifer consists of numerous discontinuous layers, lenses, terraces, and valley fillings of sand and gravel. The aquifer is not well mapped, but is known to be as thick as 600 feet. Figure 1 shows the area where the glacial deposits probably contain this aquifer. Wells in this aquifer are generally not

Table 2. Aquifer and well characteristics in Wisconsin

[Ft = feet; gal/min = gallons per minute; mg/L = milligrams per liter. Source: Reports of the U.S. Geological Survey and Wisconsin Geological and Natural History Survey; Kammerer, 1981]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Principal aquifers:					
Sand and gravel aquifer: Unconsolidated sand and gravel; variable amounts of silt, clay, and organic materials. Thickness 0-600 ft; commonly 50-200 ft. Generally unconfined.	30 - 100	400	10 - 100	2,000	A well in Janesville was pumped at more than 5,000 gal/min. The water is very hard except in north-central Wisconsin. The median dissolved-solids concentration is 219 mg/L.
Silurian dolomite aquifer: Dolomite; some shale. Thickness 0-700 ft; thickest along Lake Michigan. Generally unconfined where shallow; confined where deep or overlain by clay sediments.	50 - 180	450	5 - 50	200	Important aquifer because it underlies the most densely populated part of Wisconsin. The water is commonly very hard. The median dissolved-solids concentration is 377 mg/L.
Sandstone aquifer: Sandstone, dolomitic sandstone, and dolomite; some siltstone. Thickness 0-2,700 ft thick in south; thickest in southwest. Confined in eastern Wisconsin by Maquoketa Shale; locally confined elsewhere.	50 - 1,000	2,000	10 - 500	1,000	Yields are commonly proportional to thickness of aquifer open to the well. The water is commonly very hard. The median dissolved-solids concentration is 307 mg/L.
Other aquifers:					
Precambrian igneous and metamorphic rocks; sandstone in northwest. Thickness unknown, but in thousands of feet. Generally unconfined where shallow; confined where deep or overlain by clay sediments.	50 - 100	400	0.5 - 10	50	Sandstone in northwest may yield 300 gal/min. Elsewhere yields generally do not exceed 50 gal/min.

deep; depths of less than 100 feet are common. Because of the high permeability of some sand and gravel beds, shallow wells may yield more than 2,000 gal/min. In some areas, the glacial deposits yield little water.

The water quality is acceptable for most uses. Dissolved solids, consisting mainly of hardness-forming minerals, have a median concentration of 219 mg/L (Kammerer, 1981). Dissolved solids (and hardness) are lowest in north-central Wisconsin, where the aquifer rests on Precambrian crystalline rock.

Silurian Dolomite Aquifer

The Silurian dolomite aquifer is restricted to the eastern coast of Wisconsin where it directly underlies the sand and gravel aquifer. The aquifer consists of dolomite strata that dip to the east beneath Lake Michigan. The aquifer's permeabilitity depends on the size, number, and interconnection of rock fractures and solution channels; well yields depend on how many of these fractures and channels are intersected by the well. Yields differ greatly over short distances but generally do not exceed a few hundred gallons per minute. Although the dolomite may be as much as 700 feet thick (table 2), the deeper parts of the aquifer commonly do not yield significant quantities of water, and most wells do not exceed a depth of 180 feet. The Silurian dolomite aquifer is underlain in its entirety by the sandstone aquifer.

The water quality is acceptable for most uses, although the water has the greatest hardness of the major aquifers (median hardness of 333 mg/L as calcium carbonate). Dissolved solids, which consist largely of calcium, magnesium, and bicarbonate from the dolomite aquifer, have a median concentration of 377 mg/L (Kammerer, 1981).

Sandstone Aquifer

The sandstone aquifer underlies the southern two-thirds of the State and includes many rock formations—mostly sandstone and dolomite. The aquifer also includes beds of siltstone and dolomitic sandstone. From north-central Wisconsin these formations dip and thicken to the east, south, and west. In extreme southeastern Wisconsin, the sandstone aquifer is about 2,700 feet thick. Aquifer permeability depends on fractures and solution channels in the dolomite and dolomitic sandstone and on intergranular pore space in sandstone. Yields from this aquifer depend on the type of rock penetrated by the well and on the total thickness penetrated. Large-yield wells commonly are open to hundreds of feet of this aquifer. Many wells in eastern Wisconsin yield more than 1,000 gal/min.

The water quality is acceptable for most uses, although the water is commonly very hard (median hardness of 290 mg/L as calcium carbonate). Dissolved solids, which consist largely of hardness-forming minerals dissolved from dolomite

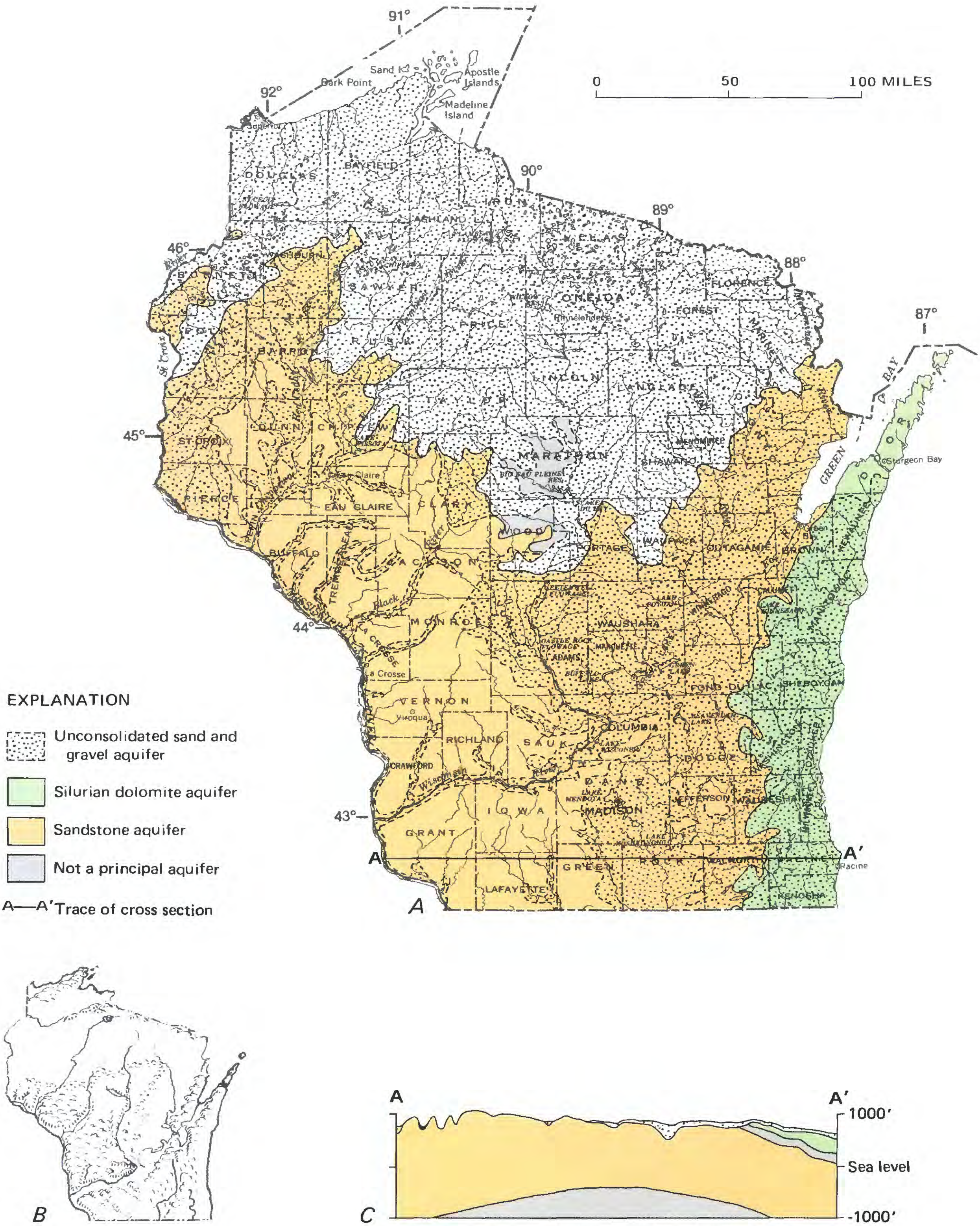


Figure 1. Principal aquifers in Wisconsin. *A*, Geographic distribution. *B*, Physiographic diagram. *C*, Generalized cross section (A-A'). (See table 2 for a more detailed description of the aquifers. Sources: *A*, Cotter, 1976. *B*, Raisz, 1954. *C*, Hanson, 1971.)

contained in the bedrock, have a median concentration of 307 mg/L (Kammerer, 1981) and are highest in eastern Wisconsin.

OTHER AQUIFERS

Other aquifers have been described in Wisconsin. Some of these are subdivisions of the major aquifers, and others, like the Maquoketa Shale and the Precambrian aquifer, are separate but less important sources of water. The Precambrian aquifer is the most important of these, based on its areal extent. The Precambrian aquifer includes all rocks of Precambrian age that underlie Wisconsin. In most of the State, they consist of crystalline igneous and metamorphic rocks that have very little permeability but yield some water from fractures and crevices. In northwestern Wisconsin, a series of very thick Precambrian sandstones yield larger quantities of water (table 2).

GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

More than 150 pumping centers in Wisconsin each produce more than 1 Mgal/d. Locations where more than 3 Mgal/d of ground water is withdrawn are shown in figure 2, and a description of the major locations is included in the accompanying table.

The water table in the unconfined sand and gravel aquifer is commonly within 50 feet of the land surface. Water levels in confined aquifers in eastern Wisconsin commonly stand above the water table unless drawn down by pumping. The natural fluctuations in the water table are an annual spring rise followed by a fall and winter decline. Hydrographs from shallow wells (less than 35 feet deep) in the sand and gravel aquifer (fig. 2, two northernmost locations) illustrate these fluctuations.

Water levels generally decline in response to pumping and recover as pumping is reduced. In southeastern and northeastern Wisconsin, ground-water levels have declined significantly because of pumping (Erickson and Cotter, 1983, p. 14). In both areas, water levels in the sandstone aquifer have been drawn down by public-supply and industrial pumpage.

In southeasten Wisconsin, where the sandstone aquifer is confined beneath shale, water levels have been drawn down over hundreds of square miles by pumping in the Milwaukee-Waukesha (fig. 2, locations 8, 9, and 10) and Chicago areas. The hydrograph in southeastern Wisconsin from a well in the sandstone aquifer shows a uniform annual decline of 5 to 6 feet over a 20-year period. The slight downward trend in water levels in the Silurian dolomite aquifer (near Milwaukee) is possibly a result of downward leakage throught the Maquoketa Shale induced by pumping from the sandstone aquifer.

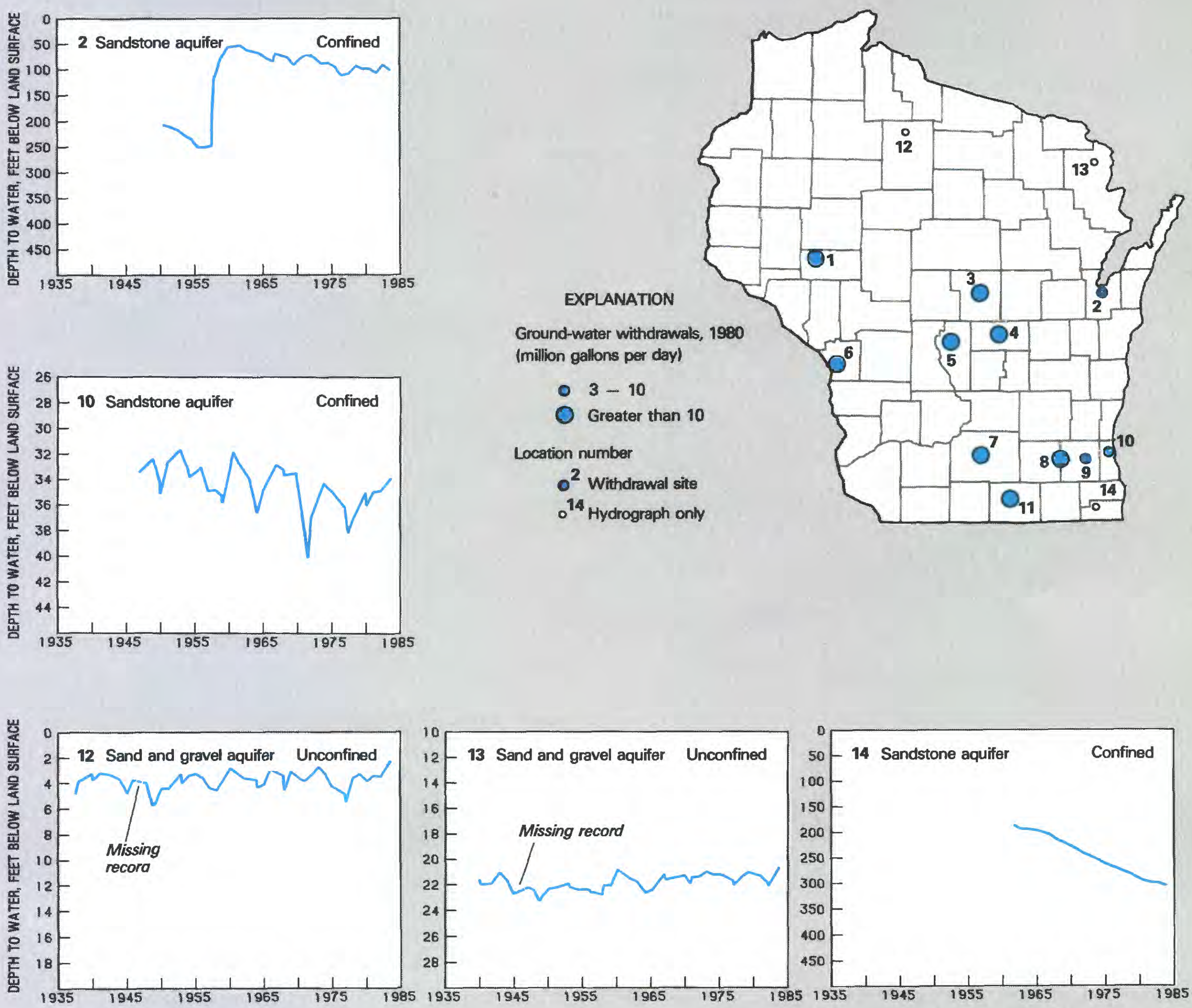
The hydrograph of a well in the city of Green Bay, in northeastern Wisconsin, shows a consistent decline until 1957 when the city stopped pumping ground water and began using Lake Michigan as a source of supply. When pumping from the sandstone aquifer stopped, the water level in this well recovered 200 feet. Subsequent industrial pumping in the Green Bay area (fig. 2, location 2) has caused the levels in the aquifer to decline 2 to 3 feet annually over the past 20 years.

GROUND-WATER MANAGEMENT

In 1984, Wisconsin passed ground-water legislation containing five main components designed to (1) set ground-water quality standards, (2) provide funds for replacement of contaminated water supplies, (3) provide an environmental repair fund, (4) develop a water-quality monitoring network, and (5) certify laboratories to be used to analyze ground-water quality (State of Wisconsin, 1984). The monitoring network includes the following four classifications: problem-assessment monitoring, regulatory monitoring, at-risk well monitoring, and management-practice monitoring. The details of these components are still being developed with the assistance of the newly created Ground-Water Coordinating Council of State Agencies.

Prior to passage of this legislation, Wisconsin had many regulations designed to protect ground water. Injection of wastes into wells was prohibited, septic system installers required licensing, well drillers required licensing, and large-capacity wells required permits. These and many other regulations are still in effect.

Several Wisconsin agencies are involved in developing and enforcing rules related to ground-water protection. The principal agency is the Department of Natural Resources.



WITHDRAWAL SITES

No. on map	Geographic area	Aquifer	Principal uses
1	Eau Claire	Sandstone	Public supply.
2	Allouez, Ashwaubenon, De Pere.	. . . .do	Do.
3	Portage County	Sand and gravel	Irrigation.
4	Waushara County	. . . .do	Do.
5	Adams County	. . . .do	Do.
6	La Crosse.	Sandstone	Public supply.
7	Madison	. . . .do	Do.
8	Waukesha County. . . .	Sand and gravel, Silurian dolomite, sandstone.	Industrial, rural-domestic.
9	Waukesha	Sandstone	Public supply.
10	Milwaukee County . . .	Silurian dolomite, sandstone.	Industrial.
11	Janesville.	Sand and gravel	Public supply.

Figure 2. Areal distribution of major ground-water withdrawals and graphs of annual greatest depth to water in selected wells in Wisconsin. (Sources: Withdrawal data from Lawrence and others, 1984; water-level data from U.S. Geological Survey files.)

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Prepared by R. Dale Cotter

For further information contact District Chief, U.S. Geological Survey, 1815 University Avenue, Madison, WI 53705.

WYOMING
Ground-Water Resources

Ground water has been vital to the development of Wyoming. Most early settlements and irrigated lands were developed along the widely spaced perennial streams in the plains areas. Efficient use of the intervening rangeland required the use of wells, springs, and stock ponds; thousands of wells have been drilled to provide water for irrigation and livestock. The development of Wyoming's abundant energy and mineral resources requires large quantities of water. In many places, ground water is an important source of supply because perennial surface-water supplies may be fully appropriated or remote from the area of mineral resource development.

Fresh ground water is used throughout Wyoming, although it accounted for only about 10 percent of all water used in 1980 (table 1). Most of the public-supply systems in the State use ground water; these systems, however, supply less than one-half of the water used for public supply because the larger towns and cities usually are supplied by surface water. Ground water supplied an estimated 90 percent of rural domestic water during 1980. Ground-water withdrawals in 1980 for various uses, and related statistics, are given in table 1.

Table 1. Ground-water facts for Wyoming

[Withdrawal data rounded to two significant figures and may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Solley, Chase, and Mann, 1983]

Population served by ground water, 1980	
Number (thousands)[1]	256
Percentage of total population	54
From public water-supply systems:	
Number (thousands)	122
Percentage of total population	26
From rural self-supplied systems:	
Number (thousands)[2]	134
Percentage of total population	28
Freshwater withdrawals, 1980	
Surface water and ground water, total (Mgal/d)	5,300
Ground water only (Mgal/d)	540
Percentage of total	10
Percentage of total excluding withdrawals for thermoelectric power	11
Category of use	
Public-supply withdrawals:	
Ground water (Mgal/d)	27
Percentage of total ground water	5
Percentage of total public supply	33
Per capita (gal/d)	221
Rural-supply withdrawals:	
Domestic:	
Ground water (Mgal/d)	8.8
Percentage of total ground water	2
Percentage of total rural domestic	92
Per capita (gal/d)	69
Livestock:	
Ground water (Mgal/d)	3.1
Percentage of total ground water	0.6
Percentage of total livestock	21
Industrial self-supplied withdrawals:	
Ground water (Mgal/d)	130
Percentage of total ground water	24
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	34
Excluding withdrawals for thermoelectric power	76
Irrigation withdrawals:	
Ground water (Mgal/d)	370
Percentage of total ground water	69
Percentage of total irrigation	8

[1] The sum of population served from public water-supply plus rural water-supply systems.

[2] Estimated as 90 percent of the difference between the total population of the State and the population served by public water-supply systems using ground water or surface water.

GENERAL SETTING

Landforms and geologic features define the major areas of ground-water occurrence in Wyoming. More than three-fourths of the State consists of semiarid high plains and intermontane basins (Great Plains, Wyoming Basin, and parts of the Middle Rocky Mountains physiographic provinces; fig. 1). The rocks that comprise the aquifers in these provinces vary from the flat-lying, generally unconsolidated Cenozoic rocks in southeastern Wyoming to the steeply dipping, consolidated Mesozoic or younger rocks in structural basins to the north and west. The remainder of the State consists of high mountains of the Southern and Middle Rocky Mountains provinces (fig. 1) that have Precambrian rock cores and tilted Paleozoic and Mesozoic rocks on the flanks.

Recharge to ground water is mainly from precipitation. Although annual precipitation in the mountains exceeds 30 inches (in.), almost 90 percent of the State receives less than 20 in. and nearly 50 percent receives less than 12 in. Morgan (1946, p. 19) estimated annual recharge from precipitation to be about 0.8 in. in the vicinity of Cheyenne, or about 5 percent of the average precipitation.

PRINCIPAL AQUIFERS

For the purpose of discussing and illustrating the ground-water resources of Wyoming, geologic units have been grouped into four principal aquifers. From youngest to oldest, these are the alluvial aquifer, the High Plains and equivalent aquifers, the structural basin aquifer, and the carbonate and sandstone aquifer. These aquifers are described below and in table 2; their areal distribution is shown in figure 1.

ALLUVIAL AQUIFER

The alluvial aquifer commonly is used for rural-domestic and public-water supplies and also is used for irrigation in many places. An equivalent aquifer along the Bear River in Utah is referred to as the valley-fill aquifer. The alluvial aquifer borders most of the larger streams of Wyoming. Only relatively extensive areas of this aquifer, where actual or potential well yields exceed 100 gallons per minute (gal/min), are shown on the map (fig. 1). However, many other alluvial aquifers along smaller streams in the plains and in the mountains and, in places, lithologically similar glacial deposits provide important local sources of ground water. In southeastern Wyoming, the alluvial aquifer usually is considered to be part of the High Plains aquifer (Luckey and others, 1981) but, in places, it is hydrologically differentiated from the High Plains aquifer, as shown in figure 1. In most places, the

Table 2. Aquifer and well characteristics in Wyoming

[ft = feet; gal/min = gallons per minute. Sources: Files of the U.S. Geological Survey and hydrologic reports listed in Selected References]

Aquifer name and description	Well characteristics: Depth (ft) Common range	Depth (ft) May exceed	Yield (gal/min) Common range	Yield (gal/min) May exceed	Remarks
Alluvial aquifer: Gravel, sand, silt, and clay. Unconfined.	10 - 100	300	50 - 100	3,000	Thickness commonly 10 to 100 ft; may be several hundreds of feet in Bear River and Snake River basins. Water generally suitable for most purposes.
High Plains and equivalent aquifers: Unconsolidated, heterogenous gravel, sand, and silt; very fine to medium-grained sandstone. Generally unconfined.	100 - 400	1,000	150 - 800	2,000	Thickness exceeds 1,000 ft in places but generally is less than 400 ft. Includes Ogallala and Arikaree Formations and also North Park Formation and underlying sandstone unit. High Plains aquifer used for supplemental supply for Cheyenne and primary supply for other communities in southeastern Wyoming. Water suitable for most purposes.
Structural basin aquifer: Lenticular beds of sandstone, shale, and coal. Generally confined.	40 - 300	3,000	1 - 50	1,000	In deeper basins thickness may exceed 5,000 ft. Wells open to several hundreds of feet may yield more than 100 gal/min. Flowing wells common. Includes Wasatch, Green River, Wind River, and Fort Union Formations, and Fox Hills Sandstone. Water suitable for most uses. Equivalent aquifer in Montana is the Cenozoic aquifer.
Carbonate and sandstone aquifer: Limestone, dolomite, and sandstone. Confined except in outcrop areas.	1,000 - 3,500	6,000	100 - 700	10,000	Several thousand feet of limestone, dolomite, and sandstone can produce yields in excess of 1,000 gal/min. Includes Madison Limestone and Tensleep Sandstone. Many of Wyoming's largest springs produce from this aquifer. Near mountains some wells yield thousands of gallons per minute—near Worland one reportedly flowed 14,000 gal/min. Water in outcrop areas suitable for most uses; where aquifer deeply buried, water likely to be unsuitable for some uses due to large concentration of dissolved solids. Equivalent to the Paleozoic aquifer in Montana.

alluvial aquifer is less than 50 feet (ft) thick, but much greater thicknesses are found in the Bear River and Snake River basins where recurrent faulting has accompanied deposition. Yields from the thicker parts of the aquifer may exceed 3,000 gal/min (table 2). In the North Platte River basin in Goshen County, some irrigation wells yield more than 1,000 gal/min.

In most places, water in the alluvial aquifer is suitable for most uses. However, in some areas, pollution of ground water by nitrate has occurred from nonpoint agricultural sources.

The alluvial aquifer is recharged from adjacent streams, underlying deposits, canals and surface-water irrigation, and infiltration from precipitation. In some places, recharge from surface-water irrigation exceeds the quantity of water that the deposits can transmit to discharge points. The results may be locally high water tables that discharge at the surface, sometimes causing bogs or "alkali patches" (residues of minerals from evaporated water). Most discharge is by wells, seepage to adjacent streams, and evapotranspiration.

High Plains and Equivalent Aquifers

The High Plains aquifer, which includes primarily the Arikaree Formation of early Miocene age and the Ogallala Formation of late Miocene age, underlies only the southeastern part of Wyoming. In central Wyoming, aquifers that comprise equivalent geologic units also include the Arikaree and the Ogallala Formations, and, in the south-central part of the State, the North Park Formation and the underlying sandstone unit of Miocene age.

Irrigation is the predominant use of the water from the High Plains aquifer in southeastern Wyoming and from the equivalent aquifer in southern Carbon County; more than 1,500 wells that supply water to more than 130,000 acres have been completed in these aquifers (R. M. Stockdale, Wyoming State Engineer's Office, written commun., 1980). Well yields commonly are from 150 to 800 gal/min, but some yields exceed 2,000 gal/min. In central Wyoming, the equivalent

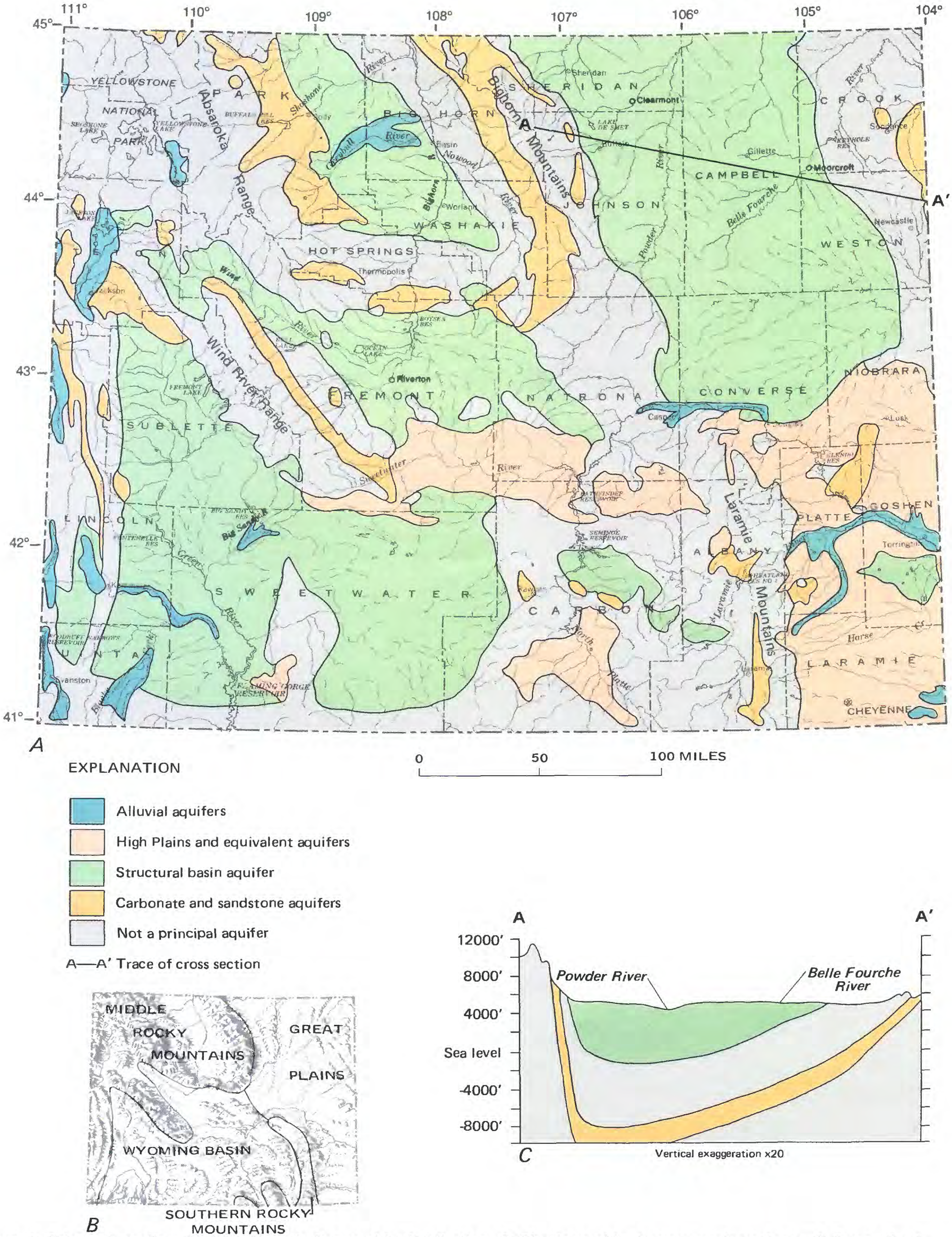


Figure 1. Principal aquifers in Wyoming. *A*, Geographic distribution. *B*, Physiographic diagram and provinces. *C*, Generalized cross section (A-A'), northeastern Wyoming. (See table 2 for more detailed description of the aquifers. Sources: *A*, Compiled by E. A. Zimmerman from U.S. Geological Survey files. *B*, Fenneman, 1931; Raisz, 1954. *C*, Modified from Renfro and Feray, 1972.)

aquifer currently supplies water primarily for stock and domestic use; however, potentially large supplies of water are available. Hydraulic characteristics of the equivalent aquifer are similar to those for the High Plains aquifer. In most of the area south of the Sweetwater River, saturated thickness ranges from about 200 to 3,000 ft. The water generally is suitable for most uses.

Precipitation on the outcrop is the principal source of recharge to the High Plains aquifer. Water levels have declined as a result of intensive withdrawals in areas underlain by the aquifer outside of Wyoming (Luckey and others, 1981); however, overall water-level declines in Wyoming have been negligible even though local declines have caused concern.

Structural Basin Aquifer

The structural basin aquifer underlies most of the major structural basins of Wyoming. A generally equivalent aquifer in Montana is referred to as the Cenozoic aquifer. The structural basin aquifer is composed mainly of lenticular sandstone, shale, and coal beds but may include conglomerate, arkose, and oil shale. The aquifer includes several major formations and their equivalents, including the Wasatch, the Green River, the Wind River, and the Fort Union Formations of Tertiary age, and the Fox Hills Sandstone of Cretaceous age.

Although this aquifer is very extensive and is more than 5,000 ft thick in places, it generally yields less than 50 gal/min. Permeability of individual beds generally is small; however, wells open to several hundreds of feet of saturated material may yield more than 100 gal/min, and, in the downstream parts of the basins, wells that tap confined beds are likely to flow. Coarser material, such as conglomerate and arkose, is present near the margins of some basins; yields of more than 1,000 gal/min are possible from wells that penetrate more than 1,000 ft of the aquifer.

Most of the wells yield water adequate in quality for domestic and livestock use. Suitability of water for these uses can be limited by sulfate concentrations exceeding 500 milligrams per liter (mg/L) and dissolved-solids concentrations exceeding 9,000 mg/L. Locally, ground water has been polluted by leachates from mine spoils and oil-field holding ponds.

Carbonate and Sandstone Aquifer

The carbonate and sandstone aquifer is comparatively little developed in Wyoming but includes geologic units, such as the Madison Limestone of Mississippian age and the Tensleep Sandstone of Pennsylvanian age, that either currently are being used or have potential for use. A generally equivalent aquifer in Montana is referred to as the Paleozoic aquifer and in South Dakota as the Inyan Kara, the Sundance, the Minnelusa, the Madison, the Red River, and the Deadwood aquifers. The carbonate and sandstone aquifer crops out in small areas of the State (fig. 1); much of the land is steep and consequently sparsely populated. The rocks generally dip steeply toward the basins and, within a few miles of the outcrops, are too deep to be economically accessible for most potential users (fig. 1). These rocks are characterized by secondary permeability (fractures, joints, and solution cavities).

The carbonate and sandstone aquifer is the source of water for many of the larger springs in Wyoming. Water that has circulated at great depth and returned to the surface may be very warm. Water flows from the large, hot (133°F) springs at Thermopolis at about 3,000 gal/min (Breckenridge and Hinckley, 1978, p. 35); this water is thought to be from the carbonate and sandstone aquifer.

Much of the water development of the carbonate and sandstone aquifer has occurred through the conversion to water wells of many holes drilled in search of petroleum. Irrigation wells along the flanks of the Bighorn Mountains flow at a rate of several hundreds of gallons per minute; static heads may exceed 100 ft above land surface (Cooley, 1985). A water well drilled for the city of Worland reportedly flowed at about 14,000 gal/min. Some public-supply and livestock wells in the northeastern corner of the State are open to this aquifer. Interest in industrial use of water has led to several studies of the aquifer's potential (Daddow, 1985, p. 92).

In outcrop areas, water quality is suitable for most uses. Where the aquifer is deeply buried, water quality may be unsuitable for most uses due to dissolved-solids concentrations ranging from 2,300 to 7,900 mg/L.

Much of the recharge to the carbonate and sandstone aquifer is from streams that traverse outcrops. Some streams lose much of their flow to caves and fractures in the rocks.

Other Aquifers

In addition to the principal aquifers, other aquifers are present in Wyoming that have small yields but are important locally. These aquifers consist of the igneous and metamorphic rocks of Precambrian to Cenozoic age and formations of predominantly Cretaceous age that contain a large percentage of marine shale and fine-grained sandstone.

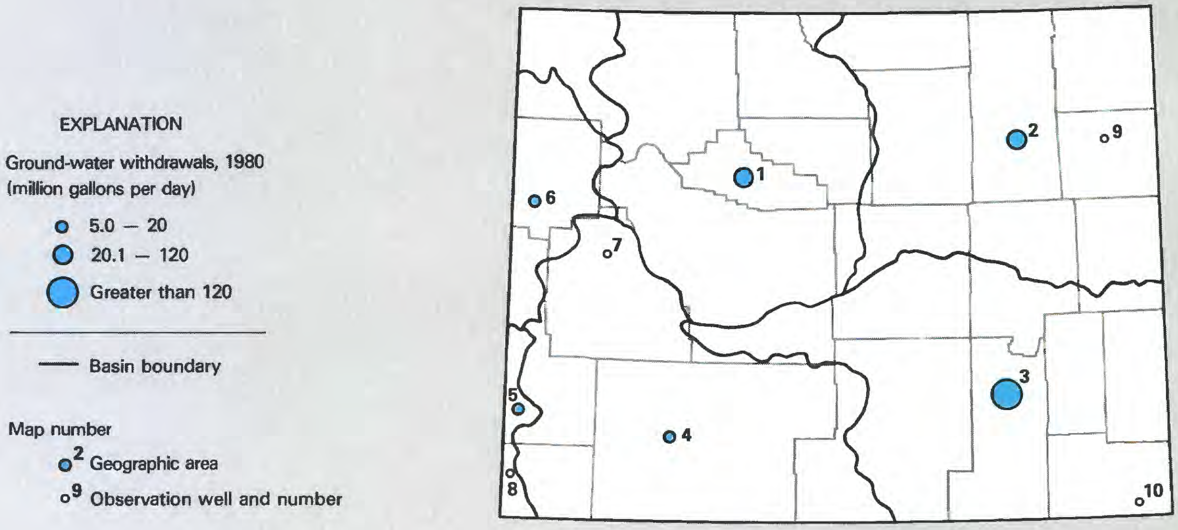
Most of the igneous and metamorphic rocks crop out in mountainous parts of the State. Well yields, commonly a few tens of gallons per minute, depend on the number of open interconnected fractures and joints or the thickness of the weathered zone penetrated by wells. Springs are abundant; yields from individual springs in northwestern Wyoming are as large as 200 gal/min, but most springs yield less than 10 gal/min. Most of the water is of excellent quality and is suitable for most uses.

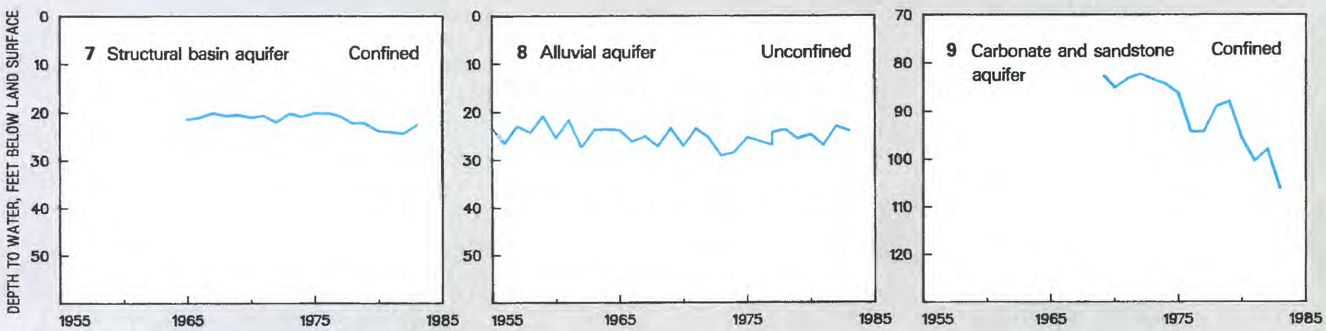
Shale and fine-grained sandstone comprise locally important aquifers occurring mostly along the margins of the structural basin aquifer. In western Wyoming, formations have a larger percentage of sandstone; in places, well yields may be larger than 300 gal/min. In eastern Wyoming, the Dakota Sandstone is the only notable aquifer in the shale and sandstone sequence. Wells commonly are more than 1,000 ft deep, drilled through the overlying shale to obtain a water supply suitable for livestock and domestic use. The water in shallower sandstone beds is sometimes used because of the drilling cost of deep wells, but that water generally contains concentrations of sulfates exceeding 500 mg/L and as much as 12,500 mg/L of dissolved solids.

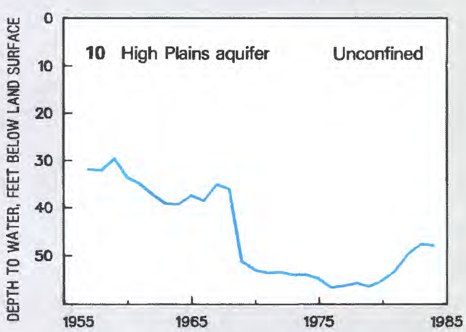
GROUND-WATER WITHDRAWALS AND WATER-LEVEL TRENDS

Irrigation, the largest use of ground water, accounted for about 69 percent of ground-water withdrawals in Wyoming during 1980 (Solley and others, 1983). Most ground-water irrigation is in the southeastern part of the State. Industrial supply is the second-largest use of ground water; much of the water is used by the petroleum industry for secondary recovery of oil. The distribution of ground-water withdrawals according to major drainage basins is shown in figure 2. Withdrawals indicated are for the entire basin. The symbols in figure 2 indicating withdrawal volumes are shown at the basin center for illustration purposes; they do not represent withdrawals at that particular point.

Water levels in Wyoming fluctuate primarily in response to changes in discharge from wells and to changes in recharge from precipitation or surface water (fig. 2). The effects of







WITHDRAWAL INFORMATION

No. on map	Geographic area	Aquifer	Principal uses
1	Wind River-Bighorn River basin.	Alluvial.	Irrigation.
		Carbonate and sandstone.	Industrial, irrigation.
2	Northeastern Wyoming. .	Structural basin . .	Industrial, public supply.
		Carbonate and sandstone.	Do.
3	Platte River basin	High Plains and equivalent.	Irrigation, public supply.
		Alluvial.	Irrigation, rural-domestic, and livestock.
4	Green River basin.	Structural basin . .	Industrial.
5	Bear River basin.	Alluvial.	Irrigation.
6	Snake River basin.	. . . .do	Public supply, rural-domestic, and livestock.

Figure 2. Ground-water withdrawals for major geographic areas and graphs of annual greatest depth to water in selected wells in Wyoming. (Sources: Withdrawal data estimated from Wyoming's Water Planning Program, 1973; water-level data from U.S. Geological Survey files.)

these factors commonly are superimposed on one another. For instance, abrupt seasonal water-level declines occur because of pumpage during the summer irrigation season and are followed by gradual water-level recovery until the next irrigation season. The seasonal water-level fluctuations do not show on the hydrograph for well 10 because only the annual low water levels were plotted. The plotting method also explains the apparent significant water-level decline in 1969. Irrigation wells installed near well 10 in 1969-70 caused annual low water-levels to become lower, but only slight water-level declines have occurred for the period of record as water levels recovered to about 35 ft below land surface each spring from 1969 to 1984. Declines in the water levels in observation well 9 (fig. 2) probably result from drought coupled with increased withdrawals in connection with petroleum production. The hydrograph for the well in the Bear River basin (observation well 8, fig. 2) reflects seasonal recharge from a nearby irrigation ditch and varying recharge from precipitation. The very slight downward trend in the hydrograph of the well in the Green River basin (observation well 7, fig. 2) is probably due to decreased recharge from precipitation.

GROUND-WATER MANAGEMENT

The Wyoming State Engineer administers the laws and regulations pertaining to ground water in Wyoming and is charged with providing for the orderly development of ground water and its protection from waste and contamination. The State Engineer issues permits for ground-water diversion and may recommend designation of an area as a ground-water-control area. After due process, new wells may be prohibited in the control area and withdrawals regulated. Three control areas have been designated, all of which are in southeastern Wyoming and have wells that withdraw water from the High Plains aquifer.

The State Department of Economic Planning and Development and the Farm Loan Board provide technical assistance and loans for ground-water development. This financial and technical assistance has provided considerable impetus to the use of ground water for irrigation. The Water Quality Division of the Wyoming Department of Environmental Quality is the primary agency for ground-water-quality protection.

The Oil and Gas Conservation Commission regulates the injection of ground water for secondary recovery of petroleum. The Commission also regulates the reinjection of water produced with the oil.

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Prepared by E. A. Zimmerman

For further information contact District Chief, U.S. Geological Survey, P.O. Box 1125, Cheyenne, WY 82003

Glossary, National Drinking-Water Regulations, Water Conversion Factors, and Geologic Age Chart

Glossary

Acre-foot Volume of water required to cover 1 acre of land (43,560 square feet) to a depth of 1 foot; equivalent to 325,851 gallons.

Absorption Process by which substances in gaseous, liquid, or solid form are assimilated or taken up by other substances.

Adsorption Adherence of gas molecules, ions, or molecules in solution to the surface of solids.

Alluvium A general term for deposits of clay, silt, sand, gravel, or other particulate rock material in a streambed, on a flood plain, on a delta, or at the base of a mountain.

Anion An ion that has a negative electrical charge; for example, nitrate and chloride ions are anions.

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. *See also* Confined aquifer and Unconfined aquifer.

Aquifer system A body of intercalated materials that acts as a water-yielding, hydraulic unit.

Artesian aquifer *See* Confined aquifer.

Artesian well A well tapping a confined aquifer in which the static water level is above the bottom of the upper confining unit; a flowing artesian well is a well in which the water level is above the land surface.

Atmospheric pressure The pressure exerted by the atmosphere on any surface beneath or within it; equal to 14.7 pounds per square inch.

Average discharge (surface water) As used by the U.S. Geological Survey, the arithmetic average of all complete water years of record of discharge whether consecutive or not.

Base flow Sustained low flow of a stream. In most places, base flow is ground-water inflow to the stream channel.

Basement Assemblage of metamorphic and (or) igneous rocks underlying stratified rocks.

Basal ground water or Basal lens A term that originated in Hawaii and refers to a major body of fresh ground water in contact with underlying saline water in the lowermost part of the flow system.

Bedload Sediment that moves on or near the stream bed and in almost continuous contact with the bed.

Bed material The sediment composing the stream bed.

Bedrock A general term for consolidated (solid) rock that underlies soils or other unconsolidated material.

Benthic organism Aquatic plants and animals living on the bottom or near the bottom of streams, lakes, or oceans.

Bolson An extensive, flat, saucer-shaped, alluvium-floored basin or depression, almost or completely surrounded by mountains from which drainage has no surface outlet; a term used in the desert regions of Southwestern United States.

Bolson plain A broad, intermontane plain in the central part of a bolson underlain by thick alluvial deposits washed into the basin from the surrounding mountains.

Brackish Water that contains from 1,000 to 10,000 milligrams per liter of dissolved solids. *See also* Saline water.

Brine Water that contains more than 35,000 milligrams per liter of dissolved solids. *See also* Saline water.

Capillary fringe Zone above the water table in which water is held by surface tension. The water is under pressure less than atmospheric.

Cation An ion that has a positive electrical charge; for example, sodium and calcium ions are cations.

Chert Any impure, flintlike rock, essentially of cryto-crystalline quartz or fibrous chalcedony, usually dark in color.

Commercial withdrawals Water for use by motels, hotels, restaurants, office buildings, commercial facilities, and civilian and military institutions. The water may be obtained from a public supply or it may be self supplied.

Cone of depression A depression in the potentiometric surface around a well, or group of wells, from which water is being withdrawn.

Confined aquifer An aquifer in which ground water is confined under pressure that is significantly greater than atmospheric pressure. Synonym: Artesian aquifer. *See also* Aquifer, Semiconfined aquifer, and Unconfined aquifer.

Confined ground water Water in an aquifer that is bounded by confining beds and is under pressure significantly greater than atmospheric.

Confining bed A layer or mass of rock having very low hydraulic conductivity that hampers the movement of water into and out of an adjoining aquifer.

Conjunctive use Combined use of ground and surface waters.

Connate water Water entrapped in the interstices of sedimentary rock at the time of its deposition.

Consumptive use Water that has been evaporated, transpired, or incorporated into products, plant tissue, or animal tissue and, therefore, is not available for immediate reuse. Also referred to as water consumption.

Cubic feet per second A unit of measurement for water discharge; 1 cubic foot per second is equal to the discharge of a stream at a rectangular cross section, 1 foot wide and 1 foot deep, flowing at an average velocity of 1 foot per second.

Cyclone A wind system in which the air motion is counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. Because cyclonic circulation usually occurs in conjunction with relatively low atmospheric pressure, the terms cyclone and low are used interchangeably.

Denitrification A process by which oxidized forms of nitrogen such as nitrate (NO_3^-) are reduced to form nitrites, nitrogen oxides, ammonia, or free nitrogen; commonly brought about by the action of denitrifying bacteria and usually resulting in the escape of nitrogen to the air.

Desorb To free from a sorbed state; to remove a sorbed substance by the reverse of adsorption or absorption. *See also* Absorption, Adsorption, and Sorb.

Discharge area (ground water) An area in which subsurface water, including ground water and water in the unsaturated zone, is discharged to the land surface, to surface water, or to the atmosphere.

Dissolved oxygen Oxygen dissolved in water.

Dissolved solids Minerals and organic matter dissolved in water.

Domestic withdrawals Water used for normal household purposes, such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, and watering lawns and gardens. Also called residential water use. The water may be obtained from a public supply or may be self supplied.

Drawdown The difference between the water level in a well before pumping and the water level in the well during pumping. Also, for flowing wells, the reduction of the pressure head as a result of the discharge of water. *See also* Pressure head.

Eutrophication The process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.

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.

Extratropical cyclone Any cyclonic storm that is not of tropical origin. Usually refers to the migratory cyclones that develop along air-mass or frontal boundaries in the middle and high latitudes. *See also* Cyclone.

Flow As used in this report, movement of water.

Fluvial Pertaining to a river or stream.

Freshwater Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids; generally more than 500 mg/L is undesirable for drinking and many industrial uses.

Glacial drift Rock material (clay, silt, sand, gravel, boulders) transported and deposited by a glacier.

Glaciofluvial Relates to the combined action of glaciers and streams.

Ground water In the broadest sense, all subsurface water, as distinct from surface water; as more commonly used, that part of the subsurface water in the saturated zone. *See also* Underground water.

Ground-water divide A ridge in the water table or other potentiometeric surface; ground water moves in both directions normal to the ridge line. *See also* Potentiometric surface *and* Water table.

Ground-water reservoir Permeable rocks in the zone of saturation. *See* Aquifer.

Ground-water system A ground-water reservoir and its contained water. Also, the collective hydrodynamical and geochemical processes at work in the reservoir.

Hardness (water) A property of water causing formation of an insoluble residue when the water is used with soap, and forming a scale in vessels in which water has been allowed to evaporate. It is due primarily to the presence of ions of calcium and magnesium. Generally expressed as milligrams per liter as calcium carbonate ($CaCO_3$). A general hardness scale is:

Description	Milligrams per liter as $CaCO_3$
Soft	0 - 60
Moderately hard	61 - 120
Hard	121 - 180
Very hard	More than 180

Hydraulic conductivity A measure of the ease with which a fluid will pass through a porous earth material, determined by the size and shape of the pore spaces in the material and their degree of interconnection as well as by the viscosity of the fluid; a term replacing "field coefficient of permeability." Hydraulic conductivity may be expressed as cubic feet per day per square foot or cubic meters per day per square meter; hydraulic conductivity is measured at the prevailing water temperature.

Hydraulic gradient In an aquifer, the rate of change of head per unit of distance in the direction of most rapid change. *See also* Pressure head.

Igneous rock A rock that solidified from molten or partly molten material; igneous rocks constitute one of the three main classes into which all rocks are divided (igneous, metamorphic, sedimentary).

Industrial withdrawals Water withdrawn for or used for thermoelectric power (electric utility generation) and other industrial uses such as steel, chemical and allied products, paper and allied products, mining, and petroleum refining. The water may be obtained from a public supply or may be self supplied.

Infiltration The movement of water into soil or porous rock.

Instream use Water use taking place within the stream channel. Examples are hydroelectric power generation, navigation, fish propagation, and recreational activities. Also called nonwithdrawal use and in-channel use.

Interface In hydrology, the contact zone between two fluids of different chemical or physical makeup.

Intermontane Situated between or surrounded by mountains, mountain ranges, or mountainous regions.

Ion A positively or negatively charged atom or group of atoms. *See also* Anion and Cation.

Ion exchange The reversible chemical replacement of an ion bonded at the liquid-solid interface by an ion in solution.

Irrigation return flow The part of artificially applied water that is not consumed by evapotranspiration and that migrates to an aquifer or surface-water body. *See also* Return flow.

Irrigation withdrawals Withdrawal of water for application on land to assist in the growing of crops and pastures or to maintain recreational lands

Karst A type of topography that results from dissolution and collapse of limestone, dolomite, or gypsum beds and characterized by closed depressions or sinkholes, caves, and underground drainage.

Liquefaction The process by which a solid is converted to the liquid phase by heat or the conversion of a gas into a liquid by increased pressure and cooling.

Livestock withdrawals Drinking and wash water for domesticated animals. *See also* Rural withdrawals.

Mean The arithmetic mean of a set of observations, unless otherwise specified.

Metamorphic rock Any rock derived from preexisting rocks in response to marked changes in temperature, pressure, shearing stress, and chemical environment at depth in the Earth's crust. Metamorphic rocks constitute one of the three main classes into which all rocks are divided (igneous, metamorphic, and sedimentary).

Metasedimentary rock Sedimentary rock that shows evidence of having been subjected to metamorphism.

Millibar A pressure unit of 100 pascals (newtons per square meter), convenient for reporting atmospheric pressure.

Mining of ground water Ground-water withdrawals in excess of recharge. *See also* Overdraft.

Nonpoint source of pollution Pollution from broad areas rather than from discrete points, such as areas of fertilizer and pesticide application and leaking sewer systems.

Normal Average (or mean) conditions over a specific period of time; usually the most recent 30-year period; for example, 1955 to 1984.

Offstream use Water withdrawn or diverted from a ground- or surface-water source for use. Also called withdrawal use and off-channel use.

Overdraft Withdrawals of ground water at rates perceived to be excessive. *See also* Mining of ground water.

Perched ground water Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.

Percolation Slow laminar movement of water through openings within a porous earth material.

Permafrost Any frozen soil, subsoil, surficial deposit, or bedrock in arctic or subarctic regions where below-freezing temperatures have existed continuously from two to tens of thousands of years.

Permeability The capacity of a rock, for transmitting a fluid; a measure of the relative ease of fluid flow in a porous medium.

Point source of pollution Pollution originating from any discrete source, such as the outflow from a pipe, ditch, tunnel, well, concentrated animal-feeding operation, or floating craft.

Pollution plume An area of a stream or aquifer containing degraded water resulting from migration of a pollutant.

Porosity The ratio of the volume of the voids in a rock to the total volume, expressed as a decimal fraction or as a percentage. The term "effective porosity" refers to the amount of interconnected pore spaces or voids in a rock or in soil; it is expressed as a percentage of the total volume occupied by the interconnecting pores.

Potable water Water that is safe and palatable for human use.

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.

Pressure head Hydrostatic pressure or force per unit area expressed as the height of a column of water that the pressure can support, relative to a specific datum such as land surface or sea level.

Prior appropriation A concept in water law under which users who demonstrate earlier use of water from a particular source are said to have rights over all later users of water from the same source.

Pyroclastic Rock material formed by volcanic explosion or aerial expulsion from a volcanic vent.

Public-supply withdrawals Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes such as domestic, commercial, industrial, and public water use.

Radionuclide A species of atom that emits alpha, beta, or gamma rays for a measurable length of time. Individual radionuclides are distinguished by their atomic weight and atomic number.

Reaeration The replenishment of oxygen in water from which oxygen had been removed.

Recharge (ground water) The process of addition of water to the zone of saturation. *See also* Saturated zone.

Recharge area (ground water) An area in which water infiltrates the ground and reaches the zone of saturation.

Recurrence interval The average interval of time within which the magnitude of a given event, such as a flood or storm, will be equaled or exceeded.

Regolith General term for the layer or mantle of fragmental and unconsolidated residual or transported rock material that nearly everywhere forms the surface of the land and overlies or covers the bedrock. It includes rock debris of all kinds.

Rem The dosage of an ionizing radiation that will cause the same biological effect as one roentgen of X-ray or gamma-ray dosage.

Renewable water supply The rate of supply of water (volume per unit time) potentially or theoretically available for use in a region on an essentially permanent basis.

Return flow The amount of water that reaches a ground- or surface-water source after release from the point of use and thus becomes available for further use. Also called return water. *See also* Irrigation return flow.

Riparian rights A concept of water law under which authorization to use water in a stream is based on ownership of the land adjacent to the stream.

Runoff That part of precipitation or snowmelt that reaches streams or surface-water bodies.

Rural withdrawals Water used in some suburban or farm areas for domestic and livestock needs. The water generally is self supplied and includes domestic use, drinking water for livestock, and other uses such as dairy sanitation, evaporation from stock-watering ponds, and cleaning and waste disposal.

Safe yield (ground water) Amount of water that can be withdrawn from an aquifer without producing an undesired effect.

Safe yield (surface water) Amount of water that can be withdrawn or released from a reservoir on an ongoing basis with an acceptably small risk of supply interruption.

Saline water Water that generally is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. Generally expressed as milligrams per liter (mg/L) of dissolved solids, with 35,000 mg/L defined as sea water. 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

Saprolite A soft, earthy, typically clay-rich, thoroughly decomposed rock formed in place by chemical weathering of igneous, sedimentary, and metamorphic rocks. *See also* Regolith.

Saturated zone A subsurface zone in which all the interstices or voids are filled with water under pressure greater than that of the atmosphere.

Sea level Refers to the National Geodetic Datum of 1929 (NGVD of 1929). The NGVD of 1929 is a geodetic datum derived from a general adjustment of the first-order level of nets of the United States and Canada; formerly called mean sea level.

Sea water *See* Saline water.

Sediment Particles derived from rocks or biological materials that have been transported by a fluid.

Sedimentary rock Rock resulting from the accumulation of loose sediment in layers either mechanically, by precipitation from solution, or from the remains or secretions of plants and animals. The term includes both consolidated and unconsolidated sediments. Sedimentary rocks constitute one of the three main classes into which all rocks are divided (igneous, metamorphic, and sedimentary).

Semiconfined aquifer An aquifer that is partially confined by a layer (or layers) of low permeability through which recharge and discharge nevertheless may occur. *See also* Aquifer, Confined aquifer, and Unconfined aquifer.

Shield volcano A volcano in the shape of a flattened dome (broad and low) built by flows of very fluid basaltic lava or by rhyolite ash flows. Synonymous with Lava dome.

Shut-in pressure Aquifer pressure recorded at the well head when the discharge valves are closed (the well is shut in).

Sinkhole topography *See* Karst.

Sole-source aquifer As defined by the U.S. Environmental Protection Agency, an aquifer that supplies 50 percent or more of the drinking water of an area.

Soft water *See* Hardness (water).

Sorb To take up and hold either by absorption or adsorption. *See also* Absorption and Adsorption.

Stage Height of the water surface in a river above a predetermined point that may be on or near the channel floor. This datum point often is expressed as altitude above sea level. Used interchangeably with gage height.

Suspended sediment Sediment that is transported in suspension by a stream.

Thermal loading The amount of waste heat discharged to a water body.

Thermoelectric power Electrical power generated by use of fossil-fuel (coal, oil, or natural gas), geothermal, or nuclear energy.

Transmissivity The rate at which water, at the prevailing temperature, is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity normally is expressed as foot squared per day or foot squared per second; it can be expressed as the number of cubic feet of water that will move during 1 day under a hydraulic gradient of 1 foot per foot through a vertical strip of aquifer 1 foot wide extending the full saturated height of the aquifer.

Transpiration The process by which water passes through living organisms, primarily plants, and into the atmosphere.

Trough In meteorology, an elongated area of relatively low atmospheric pressure; the opposite of a ridge. This term commonly is used to distinguish a feature from the closed circulation of a low (or cyclone). A large-scale trough, however, may include one or more lows, and an upper-air trough may be associated with a lower-level low. In ground water, an elongated depression in a potentiometric surface.

Turbidity The opaqueness or reduced clarity of a fluid due to the presence of suspended matter.

Unconfined aquifer An aquifer whose upper surface is a water table free to fluctuate under atmospheric pressure. *See also* Aquifer, Confined aquifer, and Semiconfined aquifer.

Underground water Subsurface water in the unsaturated and saturated zones. *See also* Ground water, Saturated zone, and Unsaturated zone.

Unsaturated zone A subsurface zone in which interstices are not all filled with water; includes water held by capillarity and openings containing air or gases generally under atmospheric pressure. Limited above by land surface and below by the water table.

Upconing Process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone as a result of pumping water from the freshwater zone.

Water budget An accounting of the inflow to, outflow from, and storage changes in a hydrologic unit.

Water table The top water surface of an unconfined aquifer at atmospheric pressure. The water levels in wells that penetrate the uppermost part of an unconfined aquifer mark the position of the water table.

Water-table aquifer *See* Unconfined aquifer.

Water year A continuous 12-month period selected to present data relative to hydrologic or meteorologic phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30.

Withdrawal Water removed from the ground or diverted from a surface-water source for use. Also refers to the use itself; for example, public supply withdrawals commonly refer additionally to public supply use. *See also* Offstream use.

National Drinking-Water Regulations

The U.S. Environmental Protection Agency's National Interim Primary Drinking-Water Regulations and National Secondary Drinking-Water Regulations are summarized below. The primary regulations, which specify the maximum permissible level of a contaminant in water at the tap, are health related and are legally enforceable. If these concentrations are exceeded or if required monitoring is not performed the public must be notified. The secondary drinking-water regulations control contaminants in drinking water that affect the esthetic qualities related to public acceptance of drinking water. These secondary regulations are intended to be guidelines for the States and are not federally enforceable.

As provided by the Safe Drinking Water Act of 1974, the U.S. Environmental Protection Agency has the primary responsibility for establishing and enforcing regulations. However, States may assume primacy if they adopt regulations that are at least as stringent as the Federal regulations in levels specified for protection of public health and in provision of surveillance and enforcement. The States may adopt more stringent regulations and may establish regulations for other constituents. As of January 1984, all States and territories have assumed primacy except Indiana, Oregon, Pennsylvania, Wyoming, and the District of Columbia.

National Interim Primary Drinking-Water Regulations

[Data from U.S. Environmental Protection Agency, 1982, Maximum contaminant levels (subpart B of part 141, National interim primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1982, p. 315-318. Data are given in milligrams per liter (mg/L) unless otherwise specified; mL = milliliters, tu = turbidity, pCi/L = picocurie per liter, mrem = millirem (one thousandths of a rem)]

Constituent	Maximum concentration
Arsenic	0.05
Barium	1
Cadmium	0.010
Chromium	0.05
Lead	0.05
Mercury	0.002
Nitrate (as N)	10
Selenium	0.01
Silver	0.05
Fluoride	1.4–2.4
Turbidity	1-5 tu
Coliform bacteria	1/100 mL (mean)
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Toxaphene	0.005
2,4-D	0.1
2,4,5-TP Silvex	0.01
Total trihalomethanes [the sum of the concentrations of bromodichloromethane, dibromochloromethane, tribromomethane (bromoform) and trichloromethane (chloroform)]	0.10
Radionuclides:	
Radium 226 and 228 (combined)	5 pCi/L
Gross alpha particle activity	15 pCi/L
Gross beta particle activity	4 mrem/yr

National Secondary Drinking-Water Regulations

[Data from U.S. Environmental Protection Agency, 1982, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1982, p. 374. Data are given in milligrams per liter (mg/L) unless otherwise specified]

Constituent	Maximum level
Chloride	250
Color	15 color units
Copper	1
Corrosivity	Noncorrosive
Dissolved solids	500
Foaming agents	0.5
Iron	0.3
Manganese	0.05
Odor	3 (threshold odor number)
pH	6.5–8.5 units
Sulfate	250
Zinc	5

Water Conversion Factors

Multiply	By	To obtain
	Area	
Acres	43,560	Square feet (ft^2)
	4,047	Square meters (m^2)
	0.001562	Square miles (mi^2)
	Flow	
Billion gallons per day (bgd)	1,000	Million gallons per day (Mgal/d)
	1,121	Thousand acre-feet per year (acre-ft/yr)
	1.547	Thousand cubic feet per second (ft^3/s)
	694.4	Thousand gallons per minute (gal/min)
	3.785	Million cubic meters per day (m^3/d)
Million gallons per day (Mgal/d)	0.001	Billion gallons per day (bgd
	1.121	Thousand acre-feet per year (acre-ft/yr)
	1.547	Cubic feet per second (ft^3/s)
	0.6944	Thousand gallons per minute (gal/m)
	0.003785	Million cubic meters per day (m^3/d)
Thousand acre-feet per year	0.0008921	Billion gallons per day (bgd)
	0.8921	Million gallons per day (Mgal/d)
	0.001380	Thousand cubic feet per second (ft^3/s)
	0.6195	Thousand gallons per minute (gal/min)
	0.003377	Million cubic meters per day (m^3/d)

Selected water relationships (approximations)

1 gallon	=	8.34 pounds
1 million gallons	=	3.07 acre-feet
1 cubic foot	=	62.4 pounds;
		7.48 gallons
1 acre-foot	=	325,851 gallons;
(1 acre covered by 1 foot of water)		43,560 cubic feet
1 cubic mile	=	1.1 trillion gallons;
		3,379,200 acre-feet
1 inch of rain	=	17.4 million gallons per square mile;
		27,200 gallons per acre;
		100 tons per acre

Geologic Age Chart

MAJOR GEOCHRONOLOGIC AND CHRONOSTRATIGRAPHIC UNITS

Subdivisions in use by the U.S. Geological Survey (map symbols)

Eon or Eonothem	Era or Erathem	Period or System		Epoch or Series		Age estimates of boundaries in million years [1, 5]
Phanerozoic	Cenozoic (Cz)	Quaternary (Q)		Holocene		0.010
				Pleistocene		2 (1.7–2.2)
		Tertiary (T)	Neogene Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene Subperiod or Subsystem (Pɛ)	Oligocene		38 (34–38)
				Eocene		55 (54–56)
				Paleocene		63 (63–66)
	Mesozoic (Mz)	Cretaceous (K)		Late	Upper	96 (95–97)
				Early	Lower	138 (135–141)
		Jurassic (J)		Late Middle Early	Upper Middle Lower	205 (200–215)
		Triassic (TR)		Late Middle Early	Upper Middle Lower	~240
	Paleozoic (Pz)	Permian (P)		Late Early	Upper Lower	290 (290–305)
		Carboniferous Periods or Systems (C)	Pennsylvanian (IP)	Late Middle Early	Upper Middle Lower	~330
			Mississippian (M)	Late Early	Upper Lower	360 (360–365)
		Devonian (D)		Late Middle Early	Upper Middle Lower	410 (405–415)
		Silurian (S)		Late Middle Early	Upper Middle Lower	435 (435–440)
		Ordovician (O)		Late Middle Early	Upper Middle Lower	500 (495–510)
		Cambrian (Є)		Late Middle Early	Upper Middle Lower	~570[2]
Proterozoic (P)	Late Proterozoic[3] (Z)					900
	Middle Proterozoic[3] (Y)					1600
	Early Proterozoic[3] (X)					2500
Archean (A)	Late Archean[3] (W)					3000
	Middle Archean[3] (V)					3400
	Early Archean[3] (U)					
			(3800?)			
pre-Archean[4] (pA)						4550

1 Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age of boundaries not closely bracketed by existing data shown by ~.

2 Rocks older than 570 Ma also called Precambrian (p€), a time term without specific rank.

3 Geochronometric units.

4 Informal time term without specific rank.

5 Age estimates for the Phanerozoic are by G. A. Izett, M. A. Lanphere, M. E. MacLachlan, C. W. Naeser, J. D. Obradovich, Z. E. Peterman, M. Rubin, T. W. Stern, and R. E. Zartman at the request of the Geologic Names Committee. Age estimates for the Precambrian are by International Union of Geological Sciences Working Group on the Precambrian for the United States and Mexico, J. E. Harrison, Chairman. The chart is intended for use by members of the U.S. Geological Survey and does not constitute a formal proposal for a geologic time scale. Estimates of ages of boundaries were made after reviewing published time scales and other data. Future modification of this chart will undoubtedly be required.

Geologic Names Committee, 1983

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