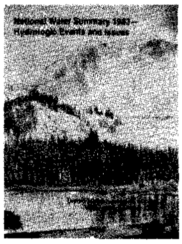
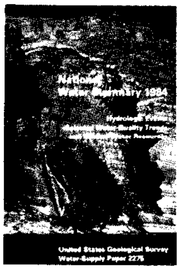
NATIONAL WATER SUMMARY 1985—
Hydrologic Events and Surface-Water Resources

United States Geological Survey
Water-Supply Paper 2300

NATIONAL WATER SUMMARY—



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



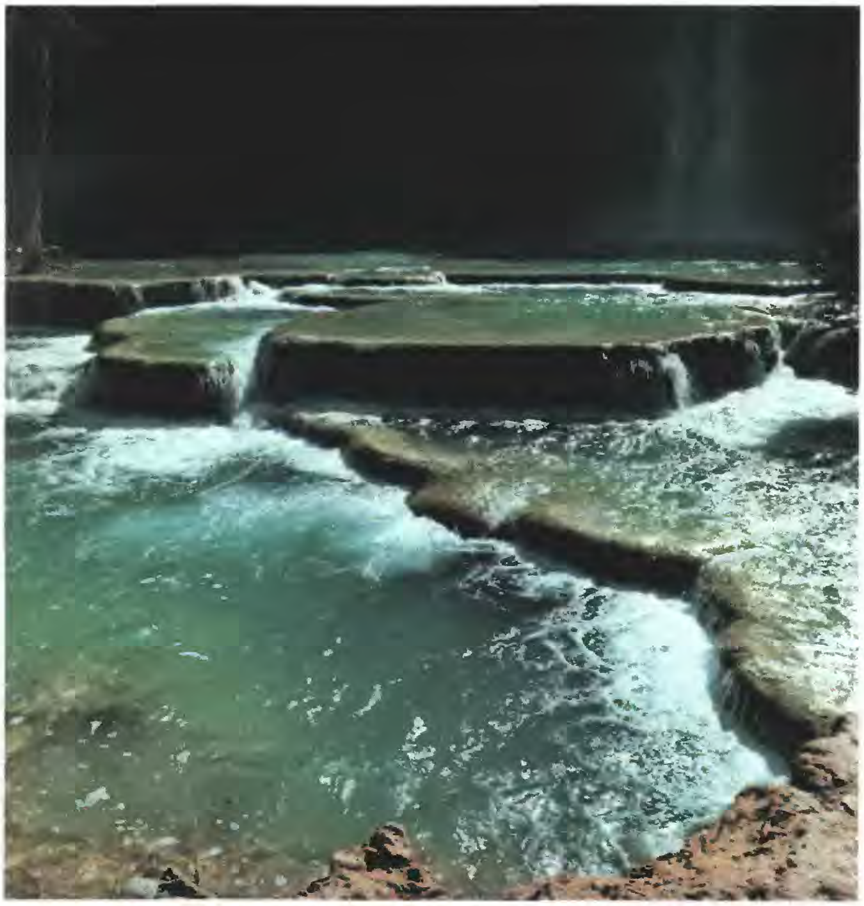
1984—Hydrologic Events, Selected Water-Quality Trends, and Ground-Water Resources (U.S. Geological Survey Water-Supply Paper 2275)

COVER

Havasu Falls descends 110 feet in a 20-foot broad lacey veil to a series of travertine-rimmed pools at its base. The falls, also known as Bridal Veil Falls, are located on Havasu Creek, a tributary to the Colorado River near mile point 157 below Lees Ferry, Arizona. (Photograph by D. E. Reed, U.S. Geological Survey.)

NATIONAL WATER SUMMARY 1985—

Hydrologic Events and Surface-Water Resources



By U.S. Geological Survey
David W. Moody, Edith B. Chase, and David A. Aronson, Compilers

United States Geological Survey
Water-Supply Paper 2300

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

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

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FOREWORD

National Water Summary 1985—Hydrologic Events and Surface-Water Resources is the third in a series of annual reports that describe the conditions, trends, availability, quality, and use of the Nation's water resources. This year's report presents an overview of the occurrence, distribution, and use of surface-water resources in each State, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, the Trust Territories of the Pacific Islands, Saipan, Guam, and American Samoa.

Surface-water resources have played a central role in the history, culture, and economic development of the United States. Rivers carried the first explorers into the interior of the continent and continue to serve as a major means of transportation for various commodities. Today, surface water provides 65 percent of the freshwater withdrawn for municipal water supplies, 3 percent of rural drinking water, 60 percent of irrigation water, and 74 percent of the water used by industry, excluding thermoelectric power uses. If the water used for thermoelectric power generation is included, the percentage of water withdrawn from surface water directly by industry increases to 94 percent. In addition to offstream uses of water, surface water serves a variety of instream uses such as the support of riverine wildlife habitat, sport and commercial fishing, navigation, recreation, and hydroelectric power generation. At present, hydroelectric power generation is the only instream use for which information is readily available. Hydroelectric powerplants often are located downstream of one another; consequently, the same water is reused a number of times as the water flows to the ocean. The aggregate amount of water that passes through these plants is over 2 1/2 times the entire flow of the conterminous United States.

The factors that presently control and regulate the flow of the Nation's rivers and the effects of water use and development on surface-water resources are emphasized in the report. Also discussed are trends in some institutional and management practices that may dramatically change the ways in which water is allocated and lead to the more efficient use of available resources.

The 1985 *National Water Summary* contains several items of particular interest. First, a map of average precipitation in the United States for the 30-year period 1951–80 (fig. 27) was prepared by the National Weather Service to update previous maps. A companion map that shows average runoff for the same 30-year period (fig. 28) was prepared by the Geological Survey; this map also updates previous maps. Both maps have been digitized by the Office of National Water Summary. Parts of these maps, locally modified and adjusted, are included in the State summaries of surface-water resources. The State outlines, river-basin boundaries, and hydrography on the maps in each State summary are examples of computer graphics prepared from files in the Geological Survey's 1:2,000,000 National Digital Cartographic Data Base.

A second item of interest is the increased use in this third *National Water Summary* of other agency expertise to assist in the synthesis and presentation of available information and knowledge about particular aspects of water resources. For example, the table of significant hydrologic and water-related events (table 1) draws on reports from the U.S. Coast Guard National Response Center, the U.S. Environmental Protection Agency, and the National Oceanic and Atmospheric Administration to supplement material gathered by Geological Survey offices in each State. Agencies represented by authors in this year's report include the National Oceanic and Atmospheric Administration, the U.S. Coast Guard, the Department of the Interior's Office of Environmental Project Review and Office of Policy Analysis, and the Interstate Commission on the Potomac River Basin. We plan to draw upon contributions from other agencies in future reports.

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

Dallas L. Peck

Director

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    2. Selected streamflow characteristics of principal river basins.

PHOTOGRAPHIC CREDITS:

All photographs are by U.S. Geological survey personnel unless otherwise identified. Photographs not identified within the book are:

Page 1, Stream-gaging station, Royal River at Yarmouth, Maine (W. B. Higgins)
Page 5, Alatna River in Alaska (H. C. Riggs)
Page 7, Lake Malheur in Oregon (L. D. Burnett)
Page 28, (left) Stream-gaging station at Boundary Creek near Bechler Ranger Station, Yellowstone National Park (W. B. Higgins); (bottom) Big Cabin Creek near Big Cabin, Okla., in flood, February 23, 1985 (D. J. Pruitt)
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Page 49, Stream gager measuring water velocity in the Gunpowder Falls, Glencoe, Md. (K. R. Taylor)
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OVERVIEW AND INTRODUCTION

OVERVIEW OF NATIONAL WATER SUMMARY 1985

The surface-water resources of the United States, the focal point for this *National Water Summary*, are extensively developed and managed to provide water supplies, hydroelectric power, navigation, recreational opportunities, and sufficient instream flows to maintain fish and wildlife habitats and adequate water quality. Surface water represents 77 percent of the Nation's total freshwater withdrawals, 65 percent of public supplies, 74 percent of self-supplied industries, excluding thermoelectric power generation, and 60 percent of irrigation. In only 10 States does surface water provide less than half of the total withdrawals.

Are we running out of water? Certainly not on a national level. Total annual renewable supply for the conterminous United States is about 1,380 bgd (billion gallons per day) or enough to cover the land to an average depth of 8.5 inches each year. Of that enormous quantity of water, only about 8 percent or 117 bgd is consumed or not available for immediate reuse downstream. The spatial and temporal distribution of this water, however, is very uneven. In the New England Water-Resources Region, for example, less than 1 percent of the annual renewable water supply is consumed. In contrast, nearly the entire annual renewable supply is consumed in the Colorado River basin.

Precipitation is the source of essentially all freshwater, and it is the single most important factor controlling the variability and availability of surface-water resources. Average annual precipitation in the United States is about 30 inches per year and ranges from a few tenths of an inch per year in desert areas of the Southwest to about 400 inches per year at some locations in Hawaii. In any given year, however, departures from average conditions may be extreme.

The 1985 water year presented several examples of the effects of the variability of precipitation on surface water. Below-normal precipitation resulted in deficient streamflows and drought along much of the West Coast, the northern Rocky Mountains and northern High Plains, central Texas, and most notably, along the entire East Coast. These hydrologic conditions marked a significant change from the normal to above-normal pattern of precipitation and streamflows that prevailed during the previous two water years. Above-normal precipitation and streamflow patterns did persist in some parts of the country, causing, for example, a continuation of record high water levels in Great Salt Lake. Record high monthly mean water levels in Lakes Michigan, Huron, St. Clair, and Erie also were recorded. Coupled with spring and fall storms common to the Great Lakes area, the high water levels exacerbated flooding and erosion along shorelines. Despite the acute dryness in some areas, the combined yearly average flow of the Nation's three largest rivers—the Mississippi, the St. Lawrence, and the Columbia—was 9 percent above normal.

During the 1985 hurricane season, six hurricanes struck the United States mainland, the largest number to make landfall since 1916. Although socially and economically costly, these hurricanes provided considerable relief to the drought-plagued East Coast by replenishing soil moisture, increasing runoff, and restoring reservoir levels. For example, in September 1985, Hurricane Gloria contributed sufficient precipitation to bring Delaware River basin reservoirs to near-normal levels and to end water-use restrictions and the reduced diversions for the New York City and northern New Jersey area that had been in effect since May 1985.

Ice and climate are closely related. Sea level is rising globally at an average rate of 4 to 8 inches per century, but it is not clear whether the present rise in sea level is caused by ice wastage. Climate models, however, indicate that a predicted doubling of carbon dioxide concentrations in the atmosphere during the next century may increase global air temperature from 3 to 8 °F, which would increase glacial recession and melting. The resulting global sea-level rise is likely to be in the range of 0.6 to 2.7 feet by the year 2100. Such a rise in sea level will have an appreciable impact on low-lying coastal regions, such as the Southeastern United States.

Events having long-term implications for the world's climate continued in water year 1985. Columbia Glacier, for example, in south-central Alaska continued its rapid retreat begun in 1983, the onset and rate of disintegration of which had been predicted by U.S. Geological Survey computer models. Those who live and work along the world's coastlines should have special interest in what is happening to the ice masses in high elevations and in the polar regions.

Snowmelt runoff is a major component of surface-water supply in many parts of the United States. Management of snowpack can assist agriculture by optimizing soil moisture and minimizing frost penetration. Forecasts of snowmelt runoff are especially important in the mountainous West, where most runoff is provided by snowmelt. Floods, as a result of rapid snowmelt, can cause major economic losses as well. To improve forecasting, emphasis is being given to developing improved techniques for large-scale, all-weather determination of snow mass by remote sensing.

Not all significant hydrologic events are caused by nature. The grounding on a rocky shoal of the tanker *Grand Eagle* in the Delaware River on September 28, 1985, spilled more than 435,000 gallons of crude oil that spread over a 25-mile stretch of the river, impacting wetlands, waterfowl, recreational facilities, boat docks, and commercial traffic. Containment and cleanup of the oil spill cost an estimated $4.5 million and involved a multitude of Federal, State, private, and volunteer resources.

Surface-water reservoirs, a major water-supply source in many parts of the country, are used to provide reliable water supplies and to help smooth out the seasonal or annual variations in streamflows. In the United States, 2,654 reservoirs and controlled natural lakes with capacities over 5,000 acre-feet provide about 480 million acre-feet of storage. Storage capacity is dominated by large reservoirs—the 574 largest reservoirs account for almost 90 percent of the total. In addition there are perhaps as many as 50,000 smaller reservoirs with capacities ranging from 50 to 5,000 acre-feet and about 2 million smaller farm ponds. Reservoirs also help reduce the size of floods and increase the amount of water in river channels during low flow; they also trap the sediment carried by the rivers. Consequently, river channels downstream from dams will change in response to new patterns of streamflow imposed by releases from the reservoirs. A good example of changes that occur as a result of water development is provided by the Platte River basin in Colorado, Wyoming, and Nebraska, which has 130 large reservoirs. Since reservoir construction, there has been both an increase in the magnitude of low-flow discharges, a result of reservoir releases during periods of low flow, and a decrease in the magnitude of high flows, a result of reservoir storage during periods of flooding.

The high cost of construction for major water projects, environmental concerns, legal constraints, economic considerations, and increasing competition for water all point to an urgent need for better management of existing water supplies. New projects generally are designed and developed independently of existing projects, with limited attempts at operating water-supply projects as integrated regional systems. Water-supply systems in several parts of the country have been improved by implementing coordinated management techniques.

In the Washington, D.C., metropolitan area, water supplies were increased by implementing better management procedures instead of major new construction. The suppliers coordinated operation by adopting new flexible operating rules, which provide that when Potomac River flows are high, withdrawals from local reservoirs are reduced well below their safe yield. The "saved" water is stored to support withdrawals from the reservoirs at rates well above safe yields when the Potomac flows are low. The joint operation of supplies solved a water-supply problem of almost 30 years standing and was between $200 million and $1 billion less expensive than previously evaluated alternatives.

Computer simulations of coordinated operation of three water-supply reservoirs with ground-water pumping in the Houston, Texas, area indicated that, if the coordinated management techniques were used, the total system yield could be increased by over 18 percent. In the North Platte River basin, another computer simulation showed that if substantial changes in operating policy were adopted and water-supply facilities were jointly operated, the total annual shortages could be reduced threefold each year. These simulations demonstrate that the reliability of an existing water right can be substantially increased or additional water rights can be allocated without affecting the reliability of existing rights. Doing so, however, involves the difficult task of institutionalizing a substantial change in operating policy.

Water is becoming increasingly a valuable economic commodity. Water transactions, which can be a change in the location of, or in the type of, water use that is undertaken voluntarily to the mutual benefit of the involved parties, are becoming more commonplace. Water previously used for irrigation in the U.S. Bureau of Reclamation's Emery County Project in Utah, for example, has been leased by the Utah Power and Light Company for use in a coal-fired thermoelectric powerplant for cooling purposes.

Water banks also are becoming more common. During the 1976–77 drought in California, 42,544 acre-feet of water was sold, with an average price of $61 per acre-foot. Idaho's Water Supply Bank leased 276,167 acre-feet on the upper Snake River in 1984. Members of the Northern Colorado Water Conservancy District frequently trade water at fair market prices.

Water transactions are easier when suppliers and buyers have accurate estimates of the amount of water available. Likewise, timely knowledge of hydrologic conditions is a key element in improving water management. Data on floods and other extreme hydrologic events must be collected and transmitted without delay. Some water-resources agencies have begun to implement very sophisticated communications and data-processing technologies to collect and analyze up-to-date hydrologic data so that management decisions can be made on a day-by-day or even hour-by-hour basis. Hydrologic data-collection instruments automatically collect and communicate data from hydrologic gaging stations to the Geostationary Operational Environmental Satellites (GOES). Relay of environmental data via these satellites can be accomplished at any time from virtually any point in the Western Hemisphere. In 1985, about 1,500 hydrologic stations reported through GOES. These stations are connected together through the U.S. Geological Survey's network of approximately 70 minicomputers.

These improvements in the timely communication of information on hydrologic conditions should enable water managers to increase the efficiency of water-supply system operations and more closely match water supply and water demand. A major challenge in the future will be to overcome the institutional and legal barriers that prevent managers from taking full advantage of new water-management technologies.

The State summaries of surface-water resources, which comprise the final part of the 1985 *National Water Summary*, reinforce the importance of surface water to the Nation by portraying the availability, use, and development of surface-water resources and related management activities 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. These State summaries point out the many similarities as well as the differences among the States regarding their surface-water resources.

The future availability of the Nation's water supplies depends, in large part, on future demands and the legal and institutional arrangements that are used by the States to manage and allocate water. But whatever specific techniques are adopted by each State to manage and develop its water resources, increasing competition for available supplies will increase the demand and underscore the need for water information and knowledge about the hydrologic processes that control the availability, quantity, and quality of the Nation's water supplies.

INTRODUCTION TO

NATIONAL WATER SUMMARY 1985

The general theme of *National Water Summary 1985—Hydrologic Events and Surface-Water Resources* is the availability, use, and management of surface-water resources. This volume continues the chronology of water-related events begun in 1983 and presents additional information on several water issues discussed in the two previous volumes of this annual series of reports on the Nation's water resources (U.S. Geological Survey, 1984, 1985).

The 1985 *National Water Summary* is organized in three parts. The first part, "Hydrologic Conditions and Water-Related Events, Water Year 1985," provides a synopsis of the hydrologic conditions and water-related events that occurred during the 1985 water year (October 1, 1984–September 30, 1985). 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. Specific events described include drought in the Delaware River basin, record high levels of the Great Lakes, summer flooding in Cheyenne, Wyo., the retreat of the Columbia Glacier in Alaska, and an oil spill in the Delaware River.

The second part, "Hydrologic Perspectives on Water Issues," is divided into two sections. The section entitled "Water-Availability Issues," stresses the role of rainfall and runoff in the hydrologic cycle and documents the significance of snow and ice in some parts of the country in providing seasonal storage of water. This information provides background and examples of how the information presented in the "State Summaries of Surface-Water Resources" (the third part of the report) can be interpreted to characterize the surface-water supply of a particular area. Articles on the hydrology of rivers and on snow and ice provide additional information about the major factors that determine water availability and control the variation of surface-water resources across the country. These articles are followed by a description, with examples, of the hydrologic and physical changes that take place downstream after the construction of dams and reservoirs. Consideration of such effects is of prime importance in the planning of new reservoir construction.

The section entitled "Institutional and Management Issues" begins with an article about the growing availability of real-time hydrologic data and the development of communications systems to distribute the data to water managers. Real-time data provide a foundation for advances in the management of water resources by improving the reliability and accuracy of short-term water-supply forecasts and by providing information for water accounting and the integrated management of regional water-supply systems. The remaining two articles elaborate on themes presented in the 1983 *National Water Summary*. One discusses the potential yields from water-resources projects by jointly operating the individual projects as a regional water-supply system. The other describes voluntary transfers of water and water rights as means of meeting increased water demands and reducing the probability of water shortages. Both articles focus on the scarcity of water in a number of places in the country as a result of the increasing competition for water, and identify some of the modifications taking place in existing legal and institutional structures.

The third and final part of the report, "State Summaries of Surface-Water Resources," summarizes for each State, the District of Columbia (combined with Maryland), Puerto Rico, the U.S. Virgin Islands, the Trust Territories of the Pacific Islands, Saipan, Guam, and American Samoa, the distribution, characteristics, uses, and management of surface-water resources. (The term "State" as used throughout the report is all-inclusive of these geographic areas.) Each summary contains maps and graphs that portray the average annual runoff and precipitation for the period 1951 to 1980; the average annual discharge of principal rivers; the location of principal river basins, rivers, reservoirs, and hydropower plants; trends in average annual discharges at selected sites; and average seasonal variations in precipitation and runoff. A table provides streamflow statistics for representative gaging stations in each principal river basin. These descriptions of surface-water resources were prepared by the U.S. Geological Survey office in each State in cooperation with State agencies.

Although water-quality issues are mentioned only in a very general way in the State summaries, it should be noted that water quality is intimately related to water quantity. The river-basin information presented in this report provides the basis for consideration of water-quality issues in future *National Water Summary* volumes. With regard to water-quality issues, several reports sponsored by the U.S. Environmental Protection Agency (EPA) are of particular interest. The 1984 *National Water Quality Inventory* reviews progress being made by the States in cleaning up the Nation's rivers, lakes, and estuaries and includes a section on ground water (U.S. Environmental Protection Agency, 1985). The report, required by Section 305(b) of the Clean Water Act of 1972 (Public Law 92-500) and its 1977 amendments, is the fifth in the series that began in 1975 and is based on submissions from each of the States. EPA also sponsored an assessment of nonpoint sources of pollution prepared by the Association of State and Interstate Water Pollution Control Administrators (1985). Both reports include State-by-State summaries of water-quality information.

A national perspective on current trends in water management is provided by a recent publication of the Freshwater Society (1985), *Water Management in Transition 1985*. This publication contains articles by and interviews with a diverse mix of lawyers, economists, politicians, policymakers, and other knowledgeable observers of the water scene.

Most technical terms used in this volume are defined in the Glossary. References are given at the end of each article and State summary to supplement the information provided. Numerous references are made throughout the text to cubic feet per second (ft^3/s), millions of gallons per day (Mgal/d), and acre-feet per year (acre-ft/yr). All are measures of the rate of movement of water volumes. In the United States, cubic feet per second is the conventional unit used by hydrologists to measure streamflow. Water managers in the East generally discuss water use in terms of millions of gallons per day. In the West, where irrigated agriculture has traditionally been the dominant water use, acre-feet per year commonly is used to measure amounts of water used. To assist readers from both regions of the country, a conversion table of measurement units follows the Glossary. Maps of water-resources regions and subregions of the United States, Puerto Rico, and the U.S. Virgin Islands and a listing of their names are included to assist readers in locating major river basins discussed in the articles. The report is concluded with a table of statistics on selected rivers in the conterminous United States and Alaska.

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Preparation and publication of the *National Water Summary* report involves contributions by many individuals from the U.S. Geological Survey and from various Federal and State agencies. The 1985 *National Water Summary* was conceived and prepared under the administrative supervision of Philip Cohen, Chief Hydrologist, U.S. Geological Survey. The report compilers gratefully acknowledge the assistance of water-resources agencies in each State in preparing and reviewing the State summaries of surface-water resources. The following Federal agencies provided data, advice, and review of parts of this report:

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  Bureau of Land Management
  Bureau of Reclamation
  Fish and Wildlife Service
  Office of Environmental Project Review
  Office of Policy Analysis
U.S. Department of Transportation, Coast Guard, National Response Center
U.S. Environmental Protection Agency

The authors of individual articles and State surface-water summaries are identified within the report. Henry C. Riggs provided many of the examples used to illustrate the relative importance of factors controlling streamflow throughout the country. Byron N. Aldridge, David A. Aronson, James F. Bailey, Jerry E. Carr, Vernon B. Sauer, and Kenneth L. Wahl coordinated the preparation of the State summaries. Roz D. Czajkoski, Jack H. Green, Eugene R. Hampton, George A. Irwin, Robert S. Roberts, Wayne B. Solley, and Katherine A. Wolf provided editorial assistance. Joan M. Rubin, Gregory J. Allord, Wendy J. Danchuk, James O. Whitmer, Kenneth J. Lanfear, and Kerie J. Hitt assisted with the design of the report and the preparation of illustrations. Janet N. Arneson and Sherron D. Flagg coordinated the preparation of the manuscript. Although individual credit is not feasible for all reviewers, graphics specialists, and typists who contributed to the preparation and publication of this report, their cooperation and many contributions made the timely production of this report possible. Overall preparation of the 1985 *National Water Summary* was directed by David W. Moody, Edith B. Chase, and John N. Fischer.

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HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS, WATER YEAR 1985

REVIEW OF WATER YEAR 1985 HYDROLOGIC CONDITIONS AND WATER-RELATED EVENTS

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

Hydrologic conditions and extreme events such as floods and droughts are most directly influenced by meteorologic and climatic factors. To understand fully why and how a particular hydrologic event occurred, it is necessary to describe the atmospheric conditions prevailing at the time of the event's occurrence. Thus, the following annual and seasonal summaries of hydrologic conditions for water year 1985 are described in a climatic context.

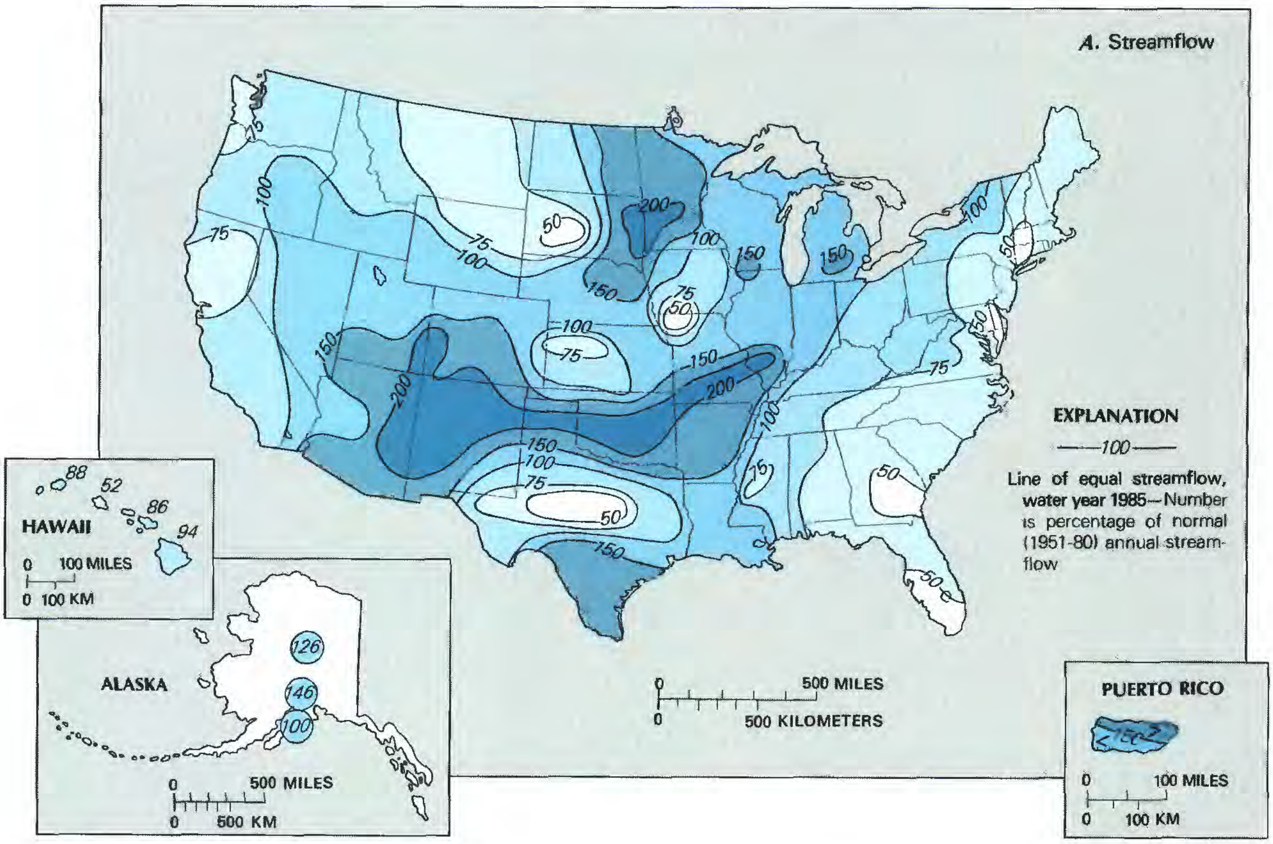
In this annual review, maps of streamflow and precipitation depicting conditions as a percentage of annual normals for 1951–80 are presented. In the seasonal summaries, maps of streamflow and precipitation are supplemented by maps showing temperature and atmospheric circulation near 10,000 feet. These seasonal or quarterly maps depict each variable as a departure from its respective average seasonal conditions. The characterization of atmospheric circulation at about 10,000 feet, recorded in terms of the 700-millibar pressure surface, is included because wind flow at that level is a primary determinant of surface temperature, precipitation and, consequently, streamflow. Typically, hydrologic extremes (floods and droughts) that persist through an entire season will do so in conjunction with persistent low- or high-pressure (troughing or ridging) conditions in the upper atmosphere. Because these maps depict conditions averaged over a 3-month period, ephemeral events, such as flooding that results from a localized brief but intense convective storm, may not be associated easily with the general upper-level circulation.

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

Hydrologic conditions across the United States during the 1985 water year marked a change in the annual pattern that prevailed during the previous two water years. In both 1983 and 1984 the conterminous United States was largely dominated by normal to above-normal streamflow (Lins and others, 1985). Only in southern and central Texas were flows persistently deficient. In 1985, however, deficient streamflows and drought conditions were widespread along much of the West Coast, the northern Rocky Mountains and northern High Plains, central Texas, and, most notably, along the entire East Coast (fig. 1*A*). A broad band of abundant streamflows spread from the Southwest across the southern Rocky Mountains and central Great Plains into the middle Mississippi River valley. Another region of above-normal streamflow engulfed parts of the northern Great Plains and upper Mississippi valley. Not surprisingly the pattern of precipitation departures during the 1985 water year (fig. 1*B*) agrees closely with that of streamflow: below normal in the West, northern High Plains, and East; above normal in the Southwest and central parts of the country. In general, precipitation exhibited less spatial variability during the year than did streamflow with lower departure magnitudes.

The synoptic as well as regional and local patterns of hydrologic conditions can be seen more specifically in the graphs of monthly discharges for selected rivers and month-end storage of selected reservoirs (figs. 2, 3). For example, the relatively dry conditions along the West Coast are apparent in the below-median monthly flows observed along the Columbia and the Sacramento Rivers in nearly all months of the 1985 water year. Similarly, the contents of Franklin D. Roosevelt Lake in Washington remained below its long-term median month-end value in all but one month. The intense drought along much of the East Coast is quite obvious in the much-below-median monthly flows on Florida's Apalachicola River and in the unusually reduced contents of the New York City reservoir system. At the other extreme, the abundant moisture conditions stretching from the Four Corners area (Colorado, Utah, New Mexico, Arizona) eastward to the middle Mississippi River valley is reflected in the graph of monthly flows of the Missouri River at Hermann, Mo., where streamflow was in the above-median to much-above-median range during most of 1985. Reservoir contents in western Colorado also were in the much-above-median range in all months, continuing a pattern begun two years earlier, whereas in New Mexico's Conchas Lake, a steady recovery from below-median contents in 1984 to above-median contents occurred by the spring of 1985.

An unusual aspect of the atmospheric-hydrologic system in the United States during 1985



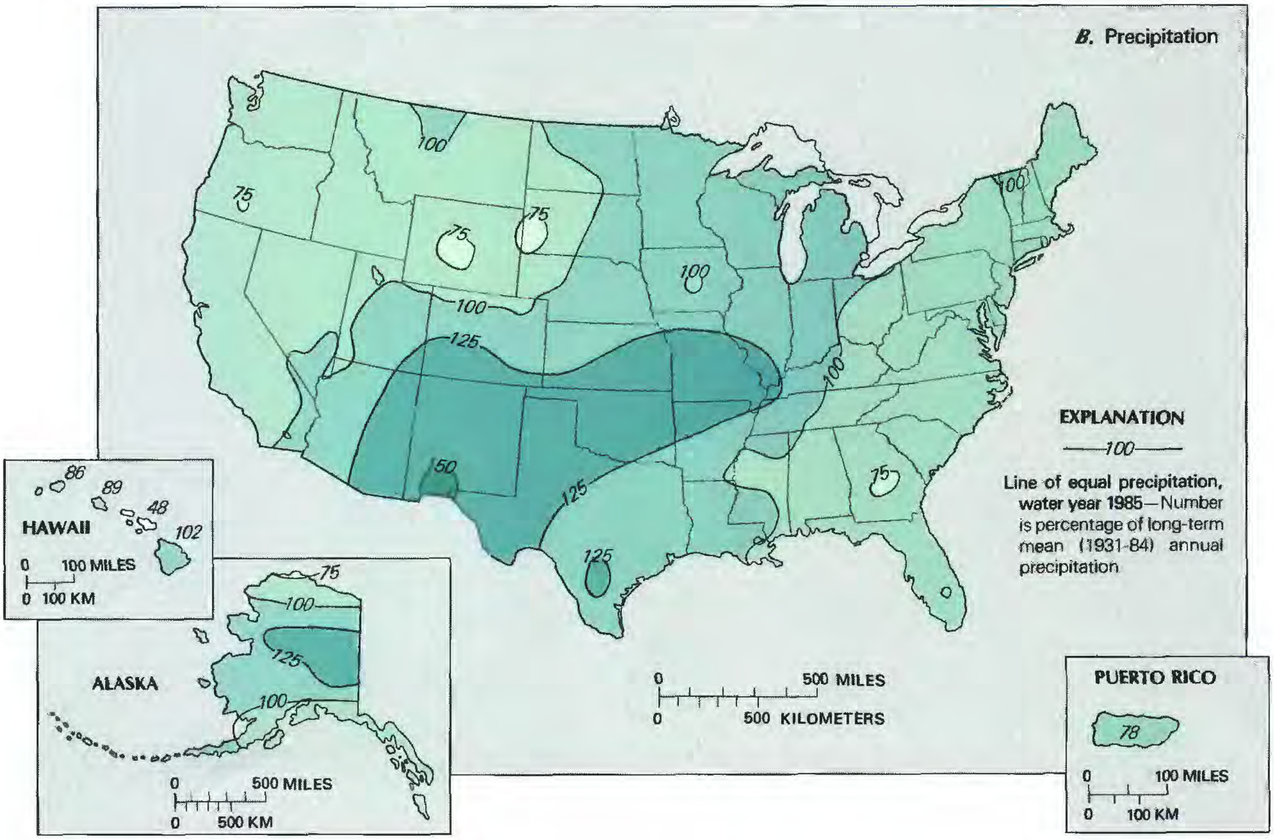


Figure 1. Streamflow (*A*) and precipitation (*B*) in the United States and Puerto Rico in water year 1985. Streamflow is shown as a percentage of normal (1951–80) annual streamflow, precipitation is shown as a percentage of long-term mean (1931–84). (Source: Data from *A*, U.S. Geological Survey, *B*, National Oceanic and Atmospheric Administration, National Climatic Data Center.)

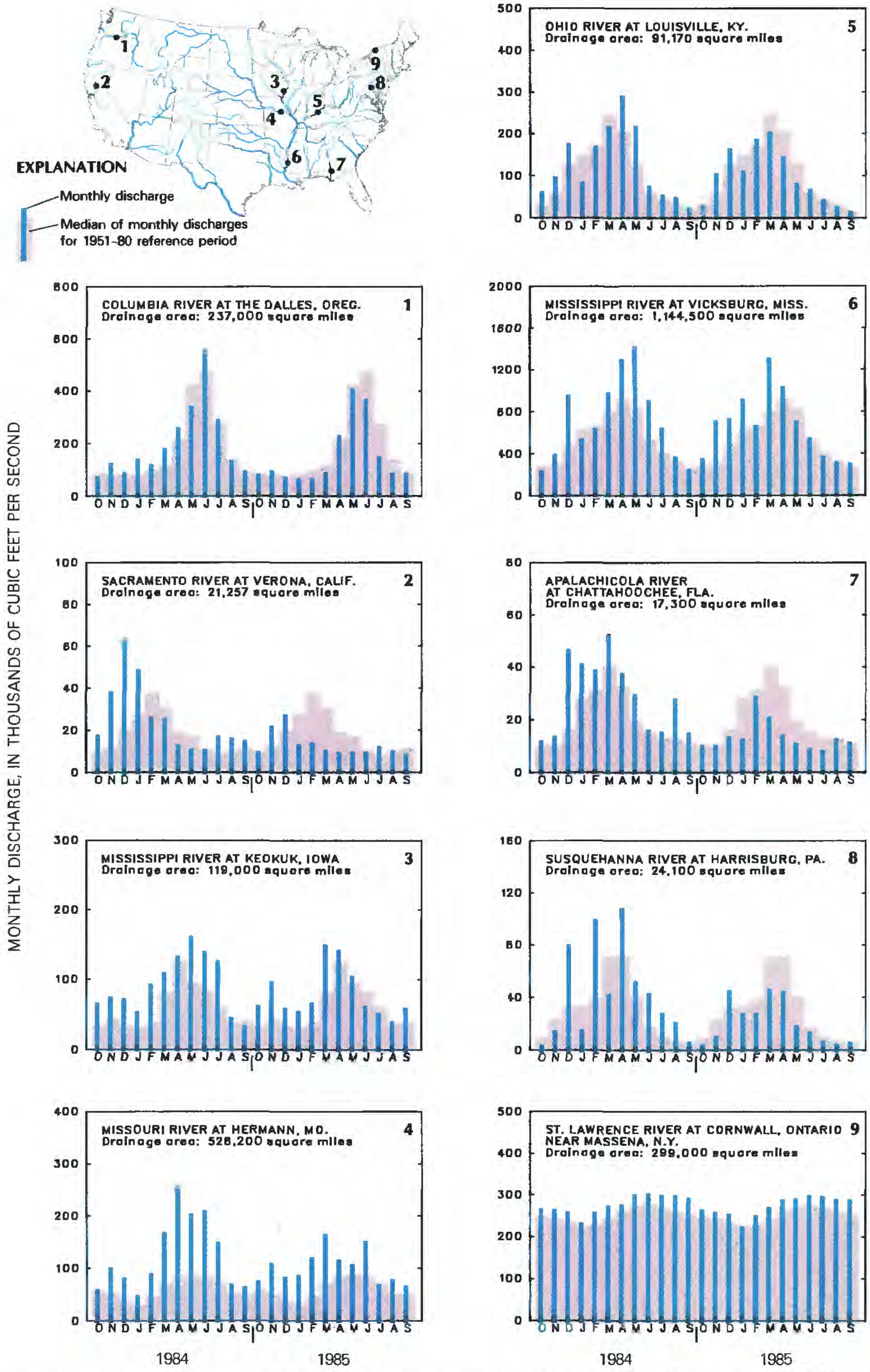


Figure 2. Monthly discharges for selected major rivers of the United States for water years 1984 and 1985 compared with monthly median discharges for the reference period water years 1951 to 1980. (Source: Data from U.S. Geological Survey.)

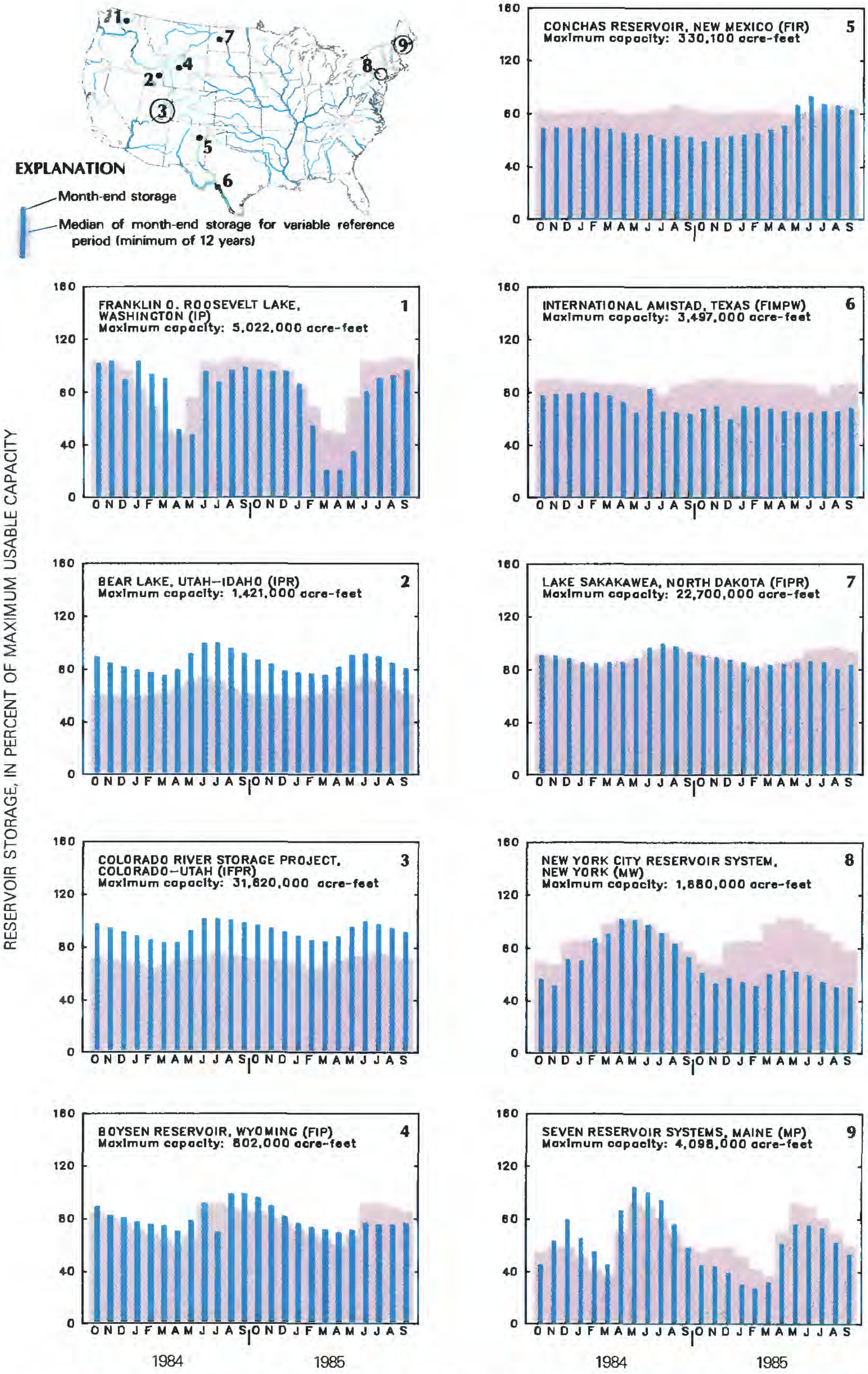


Figure 3. **Month-end storage of selected reservoirs in the United States for water years 1984 and 1985 compared with median of month-end storage for reference period.** Reference period varies but is a minimum of 12 water years. The location of individual reservoirs is shown on the map by a black dot; the general location of reservoir systems (multi-reservoirs) is shown by an open circle. Principal reservoir and water uses: F, flood control; I, irrigation; M, municipal; P, power; R, recreation; and W, industrial. (Source: Data from U.S. Geological Survey.)

was the large number of hurricanes to affect the mainland. Between June 1 and November 30 (the official hurricane season), six hurricanes struck the Nation, the most since 1916. Although the effects of these storms were more socio-economic than hydrologic, there were some important hydrologic consequences, which in many instances were of a positive nature. For example, Hurricane Bob, the first of the season, moved across south Florida and into South Carolina during late July. Flooding from Bob, although serious in a small region of northeastern Alabama (table 1, event 67), was largely minor elsewhere. A more important consequence of the rains produced by the storm was the replenishment of seriously depleted soil moisture in the Southeastern and Middle Atlantic coastal areas. Hurricane Elena, in late August and early September, caused extensive coastal and small-stream flooding from west Florida to Mississippi. Elena, however, broke the persistent pattern of dryness and below-normal streamflows that had plagued central Florida since September 1984 (table 1, event 80). Finally, Hurricane Gloria, which spread extensive damage along the eastern seaboard from North Carolina to New York in late September, also was responsible for breaking the year-long drought in the Delaware River basin. (See article in this volume "Drought in the Delaware River Basin, 1984–85.") Thus, given the pervasive and persistent dryness that affected most of the East Coast during the 1985 water year, the active hurricane season, although socially and economically costly (35 people dead and $3 to $4 billion in damage), produced distinct hydrologic benefits. It has been suggested that hydrologic benefits also have clear social and economic value and should be balanced against losses in assessing hurricane damage (Sugg, 1968).

In looking broadly across the country, despite the moderate dryness along the West Coast and the acute dryness in some areas along the East Coast, the Nation's overall streamflow condition for water year 1985 was slightly above normal. The combined yearly average flow of the Nation's three largest rivers—the Mississippi, the St. Lawrence, and the Columbia—was more than 1.12 million cubic feet per second, or 9 percent above normal.

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

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985

[The events described below are representative examples of hydrologic and water-related events that occurred during water year 1985. Toxic-spill data were provided by the U.S. Coast Guard National Response Center. Fishkill data were provided by the U.S. Environmental Protection Agency on the basis of reports transmitted by State agencies. Meteorological data mostly are from reports of the National Oceanic and Atmospheric Administration. Abbreviations used: Mgal/d = million gallons per day; ft³/s = cubic feet per second; mi² = square miles]

No. (fig. 4)	EVENT
	OCTOBER 1984
1	On October 6 in Obion County in northwestern Tennessee, flash flooding from 10 inches of rain occurred in the Union City and Fulton areas. County roads and bridges were damaged, and in South Fulton about 100 homes and several businesses were flooded, especially along Harris Fork Creek (Obion River basin).
2	Near the Indiana-Illinois border in west-central Indiana, about 15 miles north-northwest of Terre Haute, xylene (an industrial solvent) that had leaked from a chemical pipeline killed about 25,000 fish on October 11 in Brouillettes Creek, a tributary of the Wabash River.
3	A series of storms October 11 to 27 caused severe flooding in Texas, Louisiana, and Arkansas. Estimated overall damage, including that from wind and hail, was $190 million; more than $6 million was flood-related. Eleven persons died, and more than 1,000 people evacuated their homes as floodwater inundated many areas. Although the intense rains raised the low water levels in streams and lakes in the region, water restrictions continued in most of Texas. Three of the especially severe storm events occurred in southeastern Texas: (a) intense rains and flooding south of Houston on October 20 and 21 with nearly 10 inches of rain along the Gulf Coast between Freeport and Galveston; (b) intense rains (as much as 15.5 inches) and flooding in northern Houston on October 25 and 26 inundated about 650 homes and caused one drowning; and (c) on October 19, extremely intense rain and a flash flood at Odem, 15 miles north of Corpus Christi. Odem was deluged with a reported total of 25 inches of rain in 3½ hours (one of the maximum rainfalls of record in the United States), forcing about 600 people from their homes. As a result of the Houston storm on October 25, the highest peak discharge in the 32-year period of record on Greens Bayou (drainage area, 69.6 mi²), 12,000 ft³/s, was recorded. In southern Louisiana, intense rains and consequent flooding on October 22 to 23 were especially severe and were centered on New Iberia and included Vermilion, Iberia, Lafayette, and St. Martin Parishes (west of Baton Rouge). Rains of 10 to 15 inches fell in a 24-hour period, causing one death, forcing evacuation of hundreds of people, and flooding almost 1,000 structures. The peak streamflows had 10- to 25-year recurrence intervals. About 70 miles northwest of New Iberia, the peak flow of the Calcasieu River near Oberlin on October 23 was the highest for October in 48 years of record.

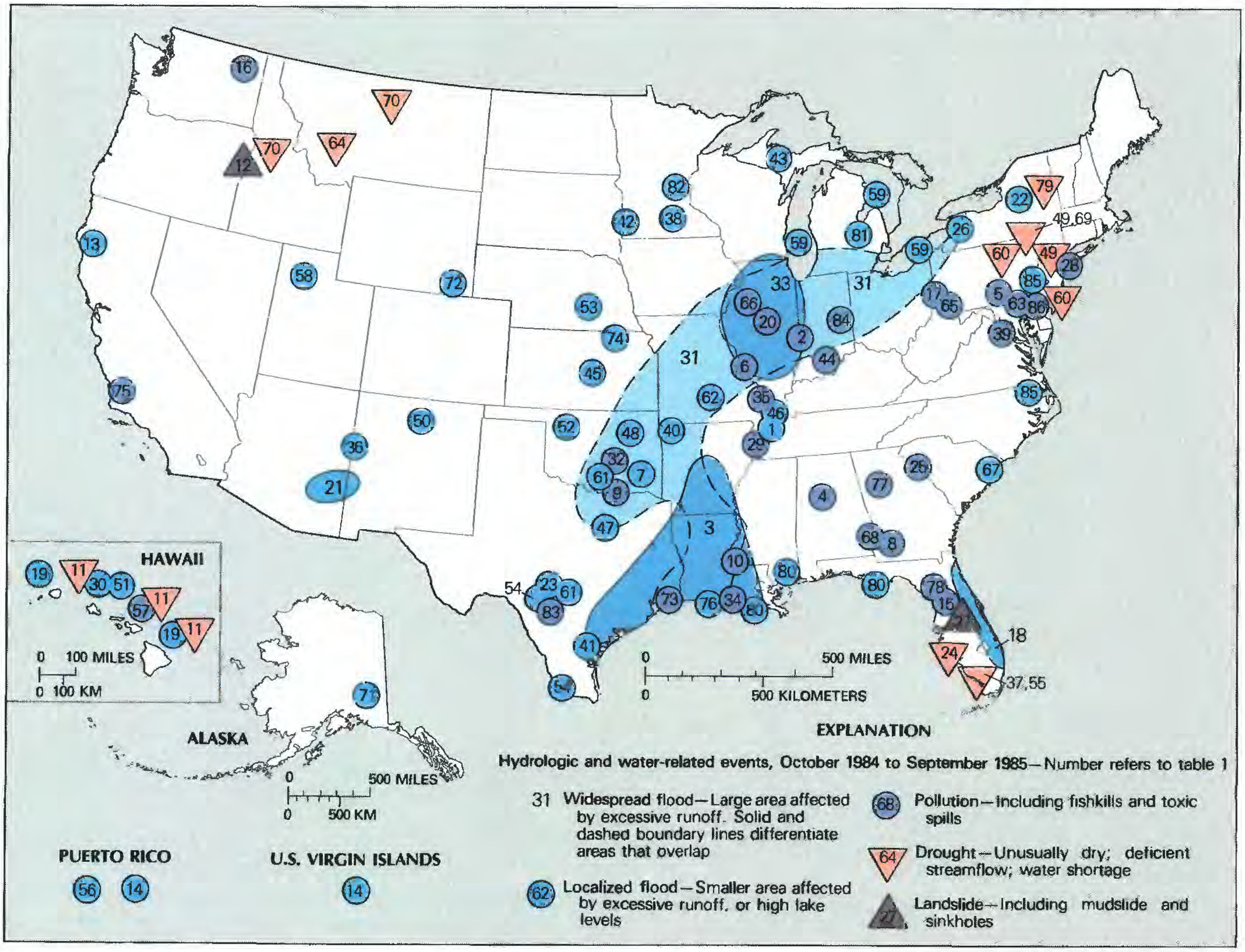


Figure 4. Location or extent of significant hydrologic and water-related events in the United States, Puerto Rico, and U.S. Virgin Islands, October 1984 through September 1985.

Tabla 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT — OCTOBER 1984
3 (con.)	In Arkansas, some of the most severe flooding occurred on October 18 and 19 in the west-central part of the State in parts of Pulaski, Garland, and Conway Counties. At Morrilton, 30 miles northwest of Little Rock, 6-inch rains in 3 to 4 hours on October 18 caused widespread flash flooding; several persons were rescued from trees they had clung to after abandoning their vehicles. Ten bridges were washed out in the Hot Springs area of Garland County, southwest of Little Rock. In Pulaski County, flooding occurred primarily along Rock, Coleman, and Fourche Creeks in western Little Rock.
4	Along several miles of Village Creek (tributary to Black Warrior River via Locust Fork), northwest of Birmingham, Ala., nearly 9,000 fish were killed on October 13 by a release of untreated sewage from a metals plant. About one quarter of the fish was game fish.
5	About 10,600 fish (10 percent game fish) were killed on October 15 along 2.5 miles of Little Chickies Creek, a tributary of the Susquehanna River in southeastern Pennsylvania 10 miles west of Lancaster. The source of pollution was manure drainage from feedlot operations.
6	A barge grounding and collision on the Mississippi River near St. Louis, Mo., on October 20 caused a spill of about 100,000 gallons of fuel oil into the river. Most of the oil was carried downstream within 45 minutes after the collision because of rain and the current of the river. About 9,000 gallons was recovered by the completion of cleanup on October 22.
7	In southeastern Oklahoma on October 20 and 21, rains of 10 to 14 inches (as much as 13 inches in 24 hours) caused damages estimated at more than $400,000 in Latimer and Pushmataha Counties, including extensive damage to buildings, bridges, and highways.
8	On October 22 in an airport drainage ditch southwest of Albany in southwestern Georgia (draining to a tributary of the Flint River), washings from a food-processing plant lowered the dissolved oxygen of the water, killing

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT
	OCTOBER 1984
8 (con.)	nearly 19,000 fish (about 70 percent game fish) along 3.5 miles of the drainage channel.
9	Two pipelines broken by earth movement that resulted from heavy rains in south-central Oklahoma spilled about 60,000 gallons of crude oil on October 27. The oil traveled downstream in Caddo Creek near Fox, Carter County, entered the Washita River and Lake Texoma, and created a light sheen on parts of the Tishomingo Wildlife Refuge north of the lake.
10	In southwestern Mississippi, about 25 miles south of Natchez, an estimated 17,000 fish (60 percent game fish) died on October 30 and 31 along 7 miles of Homochitto River, a tributary of the Mississippi River. The fishkill apparently was caused by depletion of dissolved oxygen in the river by debris from soybean and cotton fields that had been defoliated.
11	In Hawaii, drought conditions worsened during October. Flows at key stream-measurement sites on the islands of Oahu, Maui, and Hawaii, were the lowest for the month in more than 50 years of record.
12	Near the end of October, a large landslide, which covered more than 40 acres, blocked Powder River canyon about 25 miles east of Baker in northeastern Oregon and threatened to impound a lake in the narrow mountain gorge. The landslide became active in September, dammed the main river channel, and pushed the Powder River out of its banks onto an ancient river terrace. Moving debris enlarged the landslide dam. Oregon officials closed a dam on the Powder River above the landslide, reducing flow to about 50 percent of normal at the landslide barrier. As a result of the landslide, a major relocation of Oregon Highway 86 onto the canyon rim, 400 feet above the river, is planned.
	NOVEMBER 1984
13	Along the northern California coast, winds and rain associated with a Pacific cold front blew down power lines and uprooted trees on November 2. A 24-hour rainfall of 13.7 inches was reported by an unofficial observer at Wilder Ridge, 40 miles south of Eureka. Wind speeds as much as 58 miles per hour were measured in Eureka.
14	On November 3, extremely intense rains on Puerto Rico—ranging from 3 to 5 inches in 3 hours to 6 to 8 inches in 24 hours—triggered evacuations, numerous landslides, and one drowning. Toa Baja-Dorado, at the mouth of the Río de la Plata, was inundated by as much as 4 feet of water. On November 6 and 7, tropical storm Klaus battered eastern Puerto Rico and the U.S. Virgin Islands. St. Thomas and St. John, V.I., received 8 to 12 inches of rain.
15	In Lake Catherine, about 30 miles west of Orlando, Fla., on November 12 and 13 a fishkill of 15,000 to 20,000 shad occurred in an area of about 1 acre. The fishkill was caused by a severe drop in water temperature in an isolated area of the lake in which aquatic weeds prevented thermal mixing with the main body of the lake.
16	In northeastern Washington, 50 miles north-northwest of Spokane, an estimated 5,000 fish (80 percent game fish) died on November 16 and 17 along 4 miles of Stranger Creek, a tributary of the Columbia River, as a result of discharge of dairy waste.
17	On November 21, at Freedom, Pa., 30 miles northwest of Pittsburgh, 17,400 gallons of lubricating oil was spilled from a ruptured transfer line as the oil was being unloaded from a barge on the Ohio River. Recovery efforts accounted for 16,000 gallons; about 1,400 gallons were lost to the river.
18	Along the east coast of Florida on November 22 and 23, a strong coastal storm that produced flooding, gale-force winds, and high tides caused extensive damage, beach erosion, and evacuation of about 1,000 people. As much as 7 inches of rain accompanied the storm over the southern half of the State. In the north, only about 200 feet of St. Augustine's new 1,100-foot pier survived the storm. Several northeast Florida rivers rose to flood levels as high tides backed up the flow of fresh water.
19	In Hawaii, intense rains (on November 26 and 27) associated with a stalled cold front caused flooding mainly over windward portions of the islands of Kauai and Oahu. Rainfall generally was in the 6- to 15-inch range, and flooding was most severe in the Lanikai area of windward Oahu. The rains gave at least temporary relief to drought-stricken areas.
20	A fishkill of some 30,000 fish (nearly all nongame fish) occurred on November 30 in central Illinois near Heyworth (10 miles south of Bloomington) along 2.5 miles of Short Point Creek, a tributary of the Illinois River (via Kickapoo and Salt Creeks and Sangamon River). Cause of the fishkill was discharge into the stream of water having a high content of ammonia.
	DECEMBER 1984
21	A storm system with considerable inflow of subtropical moisture produced 1 to 3 inches of rain on December 27 and 28 over much of Arizona and southwestern New Mexico. In southwestern New Mexico (Catron, Grant, Hidalgo, and Luna Counties), runoff from snowmelt and the warm rains that began the evening of the 27th caused the Gila, the San Francisco, and the Mimbres Rivers to reach flood stages in the early hours of the next day. Damages reportedly totaled more than $15 million. Bridges, crops, and public works were destroyed. The high flood flows along the Gila River had a 75-year recurrence interval. In Arizona, flood damage was mostly confined to the southeastern part of the State (Greenlee, Graham, and Pima Counties), especially along the Gila and the San Francisco Rivers, which have their headwaters in southwestern New Mexico. At Duncan, Ariz., near the State border and east of Safford, 125 homes were evacuated before a dike broke along the Gila River, sending waters as much as 3 feet deep surging through the town. Homes and businesses sustained major damage, and estimates of damage to public structures alone was more than $200,000.
22	In northwestern New York, intense rain fell on December 28 and 29, and in central New York again on the morning of December 31. The eastern Lake Ontario counties of Oswego, Lewis, and Jefferson received from 3 to 6 inches of rain. About 1,000 persons were evacuated from their homes along the Salmon River in Oswego County. On the 31st, the Black River at Watertown (near the east end of Lake Ontario) crested at its highest stage in the 64-year period of record; and this stage and that on several other tributaries of the lake represented recurrence intervals of about 100 years. Flood damages from these storms were estimated to be more than $14 million.

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT
	DECEMBER 1984
23	In southern Texas on December 31, as much as 6 inches of rain fell in Kimble and Kerr Counties and as much as 9 inches in Real and Uvalde Counties. These rains caused widespread flash flooding and accompanying damages along tributaries of the Llano River and the headwaters of the Guadalupe, the Frio, and the Sabinal Rivers. The city of Kerrville, northwest of San Antonio, lost portions of a dam as water undermined a part of the spillway.
24	Much of southwestern Florida remained especially dry during December—the area received 10 percent or less of normal precipitation for the month. This dryness was reflected in the low flows of the Peace River at Arcadia (about 40 miles east of Sarasota) where the stream discharge on December 16 was only 63 ft^3/s (41 Mgal/d; drainage area, 1,367 mi^2), the lowest for any December day in the 53 years of measurement at that site.
	JANUARY 1985
25	On the western border of South Carolina, south of the town of Calhoun Falls, Abbeville County, some 200,000 to 500,000 bass and herring died on January 8 and 9 along 22 miles of shoreline of Clark Hill Lake (reservoir). The lake is a continuation of the Savannah River and is a source of municipal water supply. Cause of the fishkill is not known.
26	On January 22, gale-force winds caused ice jams along the Niagara River in western New York. More than 50 persons were evacuated from the town of Wheatfield and from Cayuga and Grand Islands (upstream from Niagara Falls) because of the flooding from unprecedented ice buildups. The winds and ice were part of an extremely severe storm from January 19 to 23 that reached blizzard proportions on the 21st and 22d and blanketed eastern Lake Ontario counties with as much as 5 feet of snow.
27	About 20 sinkholes developed in the Dover area of southern Florida (15 miles east of Tampa) after heavy pumping for frost protection temporarily lowered ground-water levels 19 feet on January 22. Damages to highways, homes, and other structures were estimated to exceed $300,000, and wells for over 100 homes temporarily went dry as a result of the drop in water level.
	FEBRUARY 1985
28	On February 10 at a powerplant in southern Nassau County, Long Island, N.Y., a valve failure on a 450,000-gallon storage tank and subsequent failure of a diked area resulted in spillage of 100,000 gallons of fuel oil into Barnums Channel. The channel separates Oceanside and Island Park, N.Y., and is 2 miles north of coastal Long Beach. Booms held much of the oil in a small area during cleanup.
29	Accidental grounding of two tank barges on a dike on the Mississippi River, about 50 miles north of Memphis, Tenn., on February 12 caused a spill into the river of more than 200,000 gallons of fuel oil and jet fuel. The site was near river mile 792 and the hamlet of Golddust, Lauderdale County. A heavy sheen was visible for 20 miles downstream. Cleanup was not feasible.
30	On the island of Oahu, Hawaii, on February 14 flooding occurred in many areas along the northeastern coast from Waimanalo to Kahuku as a result of 5- to 10-inch rains on and east of the adjacent Koolau Range. The thunderstorm rains developed over the mountains during the early morning hours and again during the late afternoon and evening. The rains resulted in lifting of water restrictions imposed because of predominantly dry conditions of prior months.
31	Between February 21 and 25, warm temperatures, as high as 12^0 above normal and accompanied by intense rains, caused serious flooding from the central Great Plains to upper New York. Snow cover was rapidly depleted except in northern parts of the Great Lakes. The storm systems produced the most rainfall over parts of Oklahoma (totals of 5 to 7 inches were common) and Arkansas on February 22 and 23 and continued into Louisiana. Widespread flash flooding occurred, causing one death and driving many people from their homes. Some rivers peaked at 10 feet above flood stage. The most serious flooding in southeastern Kansas was along the Marais des Cygnes River downstream from Osawatomie and along the Neosho River downstream from Parsons. Severe flooding occurred in southern Missouri where a few streams had peak discharges exceeding those estimated to have 100-year recurrence intervals. In parts of Michigan and Indiana, rapid snowmelt and about 2 inches of rain combined to produce peak stream discharges with recurrence intervals equal to or in excess of 100 years, such as on the Tippecanoe River (tributary to the Wabash River) in Indiana. Locally severe flooding occurred along the Illinois, Wabash, and Kankakee Rivers in Illinois and Indiana. Ice jamming contributed to the flooding, particularly in Vermilion, Ohio, where ice borne by the floodwaters caused $10 million in damages to the city. In Defiance, Ohio, 200 persons were evacuated and damages were estimated at $2 million. Ice jams also worsened the flooding and damages in western New York State. The areas affected most severely were in Erie, Chautauqua, and Genesee Counties, and western parts of Monroe County. The flood along Ellicott Creek in Erie County caused a massive evacuation, with many fleeing by boat. In northern Chautauqua County at the mouth of Cattaraugus Creek, residents claimed to have suffered the worst ice-jam flooding since 1963. Flood damages in New York were estimated to be about $12 million. The Governor of New York declared six northwestern counties adjacent to Lake Erie and the Niagara River a disaster area.
32	In eastern Oklahoma on February 25, a faulty valve on an oil and water separator at an oil- and gas-storage facility caused nearly 9,000 gallons of crude oil to enter an unnamed stream tributary to the Canadian River. The spill affected about 150 yards of the tributary and 5 miles of the Canadian River. Containment and cleanup prevented some of the oil from entering the river. The spill occurred near Sasakwa in Seminole County.
	MARCH 1985
33	A severe weather system marked mainly by high winds and drifting snows from March 3 to 5 affected at least eight States from northern Texas to southern Michigan and was partly concurrent with massive snows blanketing the northern Great Plains States. The storms in Illinois, however, were characterized mainly by rain instead of snow, resulting in major flooding of several rivers. The

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT
	MARCH 1985
33 (con.)	rains fell on ground saturated from snowmelt and from rains of the previous week, with the most intense added rainfall (more than 5 inches at La Harpe, Hancock County) occurring in west-central Illinois in the headwaters of the La Moine River. Peak discharge of that river at Colmar (drainage area 655 mi²) was estimated to have a recurrence interval greater than 100 years. The major flooding along the Illinois River was at near-record levels: second highest since 1943 from La Salle (80 miles west-southwest of Chicago) to Peoria and the worst since 1943 further downstream, from Havana to Meredosia. Fifty houses along the Illinois River were destroyed, and more than 1,200 others were damaged. By the end of the month, rivers in northern Illinois were below flood stage, but in the southern part of the State intense rains near the end of March kept rivers above flood stage. Many rivers in and bordering Illinois were flooding at some time during the month (mostly during the first week) including the Pecatonica, Rock, Des Plaines, Fox, Sangamon (lower reaches), Spoon, Kaskaskia, Big Muddy, and Wabash Rivers.
34	On March 5, an estimated 21,000 gallons of light crude oil discharged into the Atchafalaya River near Morgan City in southern Louisiana (70 miles west of New Orleans) when a barge tank was ruptured by a submerged object. Week-long cleanup operations recovered 75 percent of the oil.
35	On March 11 in the Mississippi River near Cairo, Ill., a barge cargo tank cracked after striking a highway bridge. About 3,000 gallons of oil spilled into the river. Cleanup operations along the shoreline were completed in 3 days, but only 20 gallons of oil was recovered.
36	Day-long rains on March 12 in northwestern New Mexico on the snowpack above Ramah and Zuni in the Zuni Mountains caused flooding along the Zuni River west of the Continental Divide. The water came through the spillway at Ramah Reservoir causing estimated damages of $200,000.
37	Rainfall on March 17 and 21 on much of Florida provided a temporary respite to the prevailing very dry conditions in much of that State, but the drought conditions returned and persisted, especially in the southwestern part of the State.
38	In southeastern Minnesota, as a result of saturated soil conditions in late winter, above-average precipitation, and much-above-normal early spring temperatures, the highest daily flow for March during 51 years of record occurred on March 19 on the Minnesota River near Jordan (drainage area 16,200 mi²). Jordan is about 20 miles southwest of Minneapolis. In the west-central part of the State, monthly mean flows were the highest of record for March on the Pomme de Terre River, Chippewa River, and Minnesota River (at Montevideo). Monthly mean flows of these streams were highest of record (48 to 70 years of record) also for the 4 months October through January—a result of excessive late summer-early autumn precipitation in west-central Minnesota.
39	Southwest of Alexandria in northern Virginia on March 24, leakage of fuel oil killed about 3,400 fish along 3 miles of Dogue Creek. The creek enters the Potomac River between the Fort Belvoir military reservation and the Mount Vernon area of Fairfax County.
40	In northwestern Arkansas on March 30, rains of 4.5 to 7.5 inches fell on Boone, Carroll, Marion, Newton, and Searcy Counties. Four low-water bridges were washed out in Boone County, and many road beds and low-water bridges were eroded in the other counties.
	APRIL 1985
41	On April 10 and 11 in southern Texas, the second severe flood to hit San Patricio County (near Corpus Christi) in 6 months occurred as intense rains fell, with amounts ranging up to nearly 10 inches, mainly between 4 p.m. and midnight on the 10th. Some 200 rural homes in the Sinton-St. Paul-Papalote area were flooded and marooned by the high water. Intense rains of more than 6 inches fell on parts of adjacent Neches County.
42	On April 21, intense rains associated with thunderstorms washed out crops in parts of southwestern Minnesota and some county roads in Lincoln County. Rainfall of 6.5 inches in a 2-hour period was reported at Lake Benton in southern Lincoln County, about 55 miles north-northeast of Sioux Falls, S. Dak. A few miles west of Sioux Falls near Brandon, flash flooding occurred as more than 3 inches of rain fell in less than 2 hours onto already saturated ground, washing out some roads in the area.
43	South of Lake Superior on Michigan's Upper Peninsula, rain and rapid snowmelt caused flooding along many streams in Marquette County from April 20 to 24. At eight stream-measurement sites, the flows had recurrence intervals equaling or exceeding 100 years.
44	In southern Indiana on April 22, more than 5,000 fish died along 5 miles of Brock Creek in Washington County, apparently as a result of pollution by fertilizers from agricultural operations. Brock Creek enters West Fork Blue River at Salem. The Blue River is a tributary of the Ohio River about 70 miles east of Evansville.
45	In central Kansas on April 26 and 27, intense rainfall at Durham in western Marion County 50 miles north of Wichita, measured 7.45 inches in 12 hours. The downpour washed out a quarter-mile section of railroad track near the town.
46	As much as 6 inches of rain on April 26 and 27 in western Kentucky caused flooding of homes and businesses in Hickman, Fulton County, in the extreme southwestern part of the State near the Mississippi River. About 25 miles to the north near Wickliffe (Ballard County), a culvert collapsed on Kentucky State Highway 121 about 10 miles southeast of Cairo, Ill.
47	Intense thunderstorm rains blanketed most of northern Texas in the late evening of April 27 and early morning of April 28. About 10 inches of rain fell between 9 and 11 p.m. near Rockwall in Rockwall County a few miles northeast of Dallas. Other areas received less rainfall, but overflowing of creeks and rivers was common. Eight people drowned as a result of driving cars into high water.
48	In parts of central and western Oklahoma, intense rains of 2 to 6 inches on April 29 and 30 caused flooding in many areas. Damage estimated at $500,000 occurred on the 30th at Skiatook (north of Tulsa) in Tulsa County from floodwaters overflowing Bird Creek. About 40 miles south of Tulsa in Henryetta, Okmulgee County, 4 to 5 inches of rain caused flooding of Coal Creek and the evacuation of many residents.
49	Below-average precipitation conditions persisted during April in much of the northeastern and middle-Atlantic parts of

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT
	APRIL 1985
49 (con.)	the country. Pennsylvania, New Jersey, and New York City declared drought emergencies affecting more than 20 million people. Streamflow and contents of reservoirs in the Delaware River basin were the lowest for April in many years of record. (See article in this volume, "Drought in the Delaware River Basin, 1984-85.") Much of the Southeast also was unusually dry for this time of year.
	MAY 1985
50	During the period of May 5 to 15, rapid runoff from above-normal snowpack in north-central New Mexico damaged roads, bridges, and irrigation ditches from the Taos area to below Pilar in Taos and Rio Arriba Counties north of Santa Fe.
51	On May 6 on the island of Oahu, Hawaii, 8 to 10 inches of rain from eastward-moving thunderstorms (mostly between 2 and 4 a.m.) fell on the Koolau Range causing flash flooding and many rock and mud slides. Although some roads were blocked temporarily, the rains were welcome because of low water levels in reservoirs dependent upon runoff from mountain streams.
52	In Woodward County, Okla., 100 miles northwest of Oklahoma City, rains of up to 6 inches on May 6 and 7, as well as hail, caused flooding and an estimated $750,000 damage to roads, bridges, farm machinery, and crops, including complete destruction of an area of crops 0.5-mile wide and 15 miles long.
53	On May 14, in south-central Nebraska, 4 to 7 inches of rain caused flash flooding along School Creek in Clay County from east of Harvard through Sutton, damaging a number of homes, businesses, bridges, and farms. The area is about 70 miles west of Lincoln, Nebr.
54	In extreme southern Texas, between 5 and 10 inches of rain fell on May 15, causing extensive flooding in and around the town of Mission, Hidalgo County, and forcing the evacuation of 150 persons. Rainfall at Rio Grande City (30 miles west of Mission) was measured at nearly 8 inches for May 15 and 16. Some flooding occurred along the nearby Rio Grande. Northwest of San Antonio, as much as 6 inches of rain fell on May 16 and 17 and caused flash flooding in parts of four counties—Bandera, Kerr, Kimble, and Real. Substantial rises in water level occurred along the Medina and the Guadalupe Rivers.
55	Dry conditions continued in much of the Southeast. Forest fires plagued some areas, especially Florida, where 150,000 acres burned from May 17 to 20 with damages estimated to exceed $30 million. Mandatory water restrictions were in effect in eight southwestern counties of Florida.
56	Puerto Rico was deluged by as much as 25 inches of rain from May 15 to 19. The greatest rainfall occurred in the western interior and about 14 inches fell in the eastern interior, lessening to about 4 inches along coastal areas. The most significant floods occurred in the Río Grande de Arecibo, Río Tanama, Río Grande de Manatí, Río Grande de Jayuya, Río Orocovis, Río Turabo, upper Río Grande de Loíza, Río Cibuco, Río de la Plata, and Río Grande de Añasco basins. Peak flows along some of these streams had recurrence intervals of once in 50 years. The severe flooding resulted in at least two deaths and more than $50 million in property damage. About 3,500 to 4,000 persons were evacuated from the affected towns, including Manati, Arecibo, Barceloneta, Jayuya, and
	MAY 1985
56 (con.)	Utuado. Major damage was sustained by coffee, citrus, and other crops.
57	On May 18 in the Kahului industrial area on the island of Maui, Hawaii, about 175,000 fish (nearly all Tilapia) died in a settling pond contaminated by 10 percent ammonia solution. Kahului is the port city on the northern coast of Maui, about 12 miles east of the west end of the island.
58	On May 21, Great Salt Lake, northeast of Salt Lake City, Utah, reached its seasonal peak for the year of 4,209.95 feet above sea level. This high level is 0.7 foot above the 1984 peak and only 1.65 feet below the all-time high elevation for the 139 years during which such measurements have been made. The high level is the result of a series of years of above-average precipitation—principally occurring as snowfall—in the region that drains into the lake.
59	Water levels of Lakes Michigan, Huron, and Erie equaled or exceeded the highest monthly levels of record for March, April, and May as a result of above-average precipitation in the Great Lakes basin from autumn 1984 to spring 1985. (See article in this volume, "Great Lakes Set Record High Water Levels.")
60	Occasional rains on May 2, 12, 16 to 18, and 30 to 31, temporarily relieved the drought situation in some areas of the Northeast, but water supplies were still far below normal for this time of year. Water rationing remained in effect in New York City and in 93 New Jersey communities. The Governor of New Jersey declared a drought emergency for the remainder of the State. An example of low streamflow in New York State was the Susquehanna River where the flow as measured at Conklin, N.Y., and draining an area of more than 2,200 mi^2, was the lowest May flow in the entire 73 years of record.
	JUNE 1985
61	Runoff from as much as 5 inches of rain on June 5 and 6 caused severe flooding in parts of south-central and northeastern Oklahoma and southern Missouri. On June 6 the flow of Washita River near Dickson in the northeastern part of Carter County, Okla., and draining more than 7,200 mi^2, was the highest daily June discharge in the entire 57 years of record at that site. Four lives were lost as a result of floods in Ardmore, Carter County, 90 miles south of Oklahoma City. On June 7, as much as 8 inches of rain fell in localized areas around San Antonio in southern Texas.
62	On June 17 in south-central Missouri, flooding of streams caused by as much as 7 inches of rain in the Rolla area, Phelps County, forced evacuation of many residents of that area. Local flooding also occurred in southern Arkansas on the 17th and in southeastern Texas on the 18th. Monthly mean streamflow for June in Missouri showed a wide variation from one part of the State to another. In the south-central part of the State, for example, the June discharge of the Gasconade River at Jerome (Phelps County), 10 miles west of Rolla, Mo., (drainage area 2,840 mi^2), was nearly 10 times the median flow for June and the second highest for the month in 65 years of record. This high flow was in sharp contrast to the discharge of the Grand River near Gallatin (Davies County) in northwestern Missouri (drainage area 2,250 mi^2), where the flow was only 15 percent of median and the sixth lowest flow for June in 64 years.

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT
	JUNE 1985
63	In southeastern Pennsylvania on June 28, more than 6,000 fish (35 percent game fish) were killed along several miles of an unnamed tributary to Big Beaver Creek near Quarryville in Lancaster County. The fishkill resulted from chemicals washed into the stream by water used to put out a fire at a Quarryville industrial site. Big Beaver Creek is a tributary of Pequea Creek, which in turn flows into Lake Aldred (part of the Susquehanna River) about 10 miles north of the Pennsylvania-Maryland State line.
64	Below-average precipitation and streamflow conditions persisted in many areas of the northern Great Plains States, especially in Montana. In Helena, Mont., for example, the month was the driest June in the 106 years of record and was the eighth consecutive month with below-average precipitation. In the East, dry conditions were eased somewhat, but drought warnings remained in effect in the New York City area, and forest fires continued to be a problem in parts of the Southeast. Florida received some welcome rains on June 12 and 13.
	JULY 1985
65	On July 9 in the Lawrenceville area of Pittsburgh, Pa., vandalism to a storage tank caused 2,500 gallons of fuel oil to discharge into the Allegheny River. Cleanup operations recovered 1,800 gallons of the oil by the next day. Lawrenceville is on the southeast side of the river about 3 miles upstream from where the Allegheny joins the Monongahela River to form the Ohio River.
66	In northwestern Illinois on July 21 and 22, drainage from agricultural operations killed about 19,000 fish (26 percent game fish) along 3.8 miles of Brandywine Creek near Williamsfield, Knox County. In that vicinity, the creek flows south into Spoon River, a tributary of the Illinois River. Williamsfield is 25 miles northwest of Peoria.
67	Tropical storm Bob, after moving eastward from the Gulf and crossing southern Florida with rains of 8 to 10 inches on July 23, moved northward and then inland (as a hurricane) at South Carolina on July 25. Runoff from rains associated with the storm caused minor flooding in central and coastal South Carolina, but on July 24 in northeastern Alabama, rains of 6.5 to 8 inches on the periphery of the storm system caused extensive, damaging floods in Cherokee and DeKalb Counties. The estimated peak discharge of 50,000 ft^3/s on Little River near Blue Pond (drainage area, 199 mi^2), tributary to the Coosa River via the Weiss Reservoir, was the highest flow for the 27-year period of record and had a recurrence interval greater than 100 years. This stream-measurement site is in Cherokee County about 85 miles northeast of Birmingham. The storm system caused intense rains from Virginia to New York as it continued up the East Coast.
68	In southwestern Georgia on July 30 and 31 on the Chattahoochee River (about 60 miles south of Columbus, Ga.), about 30,000 fish died from low dissolved-oxygen conditions resulting from release of deoxygenated water (hypolimnion water) from the dam holding the waters of the Walter F. George Reservoir along the Chattahoochee River. About 28 miles of the river were affected by the fishkill (mostly of nongame fish).
69	Near-normal rainfall in July reduced the severity of the long-term dry conditions on the East Coast. Water-rationing restrictions in New Jersey were removed on July 11. New York City remained under a drought-warning alert and restarted its Chelsea pumping station (as a source of supplemental water supply) on the Hudson River for the first time since the 1966 drought. The contents of the city's reservoirs continued to decline and remained far below average. In southern Florida, water-use restrictions imposed by various water management districts were lifted as a result of normal or above-normal rainfall in July in most counties.
70	Dry conditions persisted in many parts of western and northern Great Plains States. Streamflow was far below normal for July in much of Idaho and Montana.
71	In Alaska, intense rains and flash flooding in the Alaska Range on July 30 and 31 caused damage to bridges and culverts and washed out the highway near Tok, 180 miles southeast of Fairbanks. Several streams near Tok had peak flows with recurrence intervals of 50 years or greater.
	AUGUST 1985
72	Powerful thunderstorms over Cheyenne in southeastern Wyoming on August 1 caused severe flooding. A total of 6.06 inches of rain fell in less than 4 hours (a new record for the State); winds as much as 70 miles per hour were noted; and hail accumulated in drifts several feet deep in some places. Twelve lives were lost, and property damage reportedly exceeded $61 million. (See article in this volume, "Storm and Flood of August 1, 1985, in Cheyenne, Wyo.")
73	At Port Neches near the Gulf Coast of southeastern Texas on August 6, about 20,000 gallons of light crude oil was spilled into the Neches River through a faulty valve system during the transfer of cargo. More than 4,000 gallons were recovered, and cleanup was completed by August 13. Port Neches is 5 miles upstream from the junction of the Neches River and the Sabine River and 10 miles downstream from Beaumont, Tex.
74	Unseasonably frequent or intense rains in parts of eastern Kansas and southeastern Nebraska in July and early August caused unusually high flows in some streams for this time of year. In northeastern Kansas, for example, the daily discharge of Little Blue River near Barnes (drainage area 3,324 mi^2), Washington County, on August 7 was nearly 20,000 ft^3/s, more than twice the highest daily flow for August in the preceding 58 years of record.
75	On August 12 a pipeline rupture south of San Luis Obispo near the coast of southern California discharged about 2,500 gallons of crude oil into San Luis Obispo Creek. The creek enters the ocean at Avila Beach about 10 miles south-southwest of San Luis Obispo and 150 miles northwest of Los Angeles. Spill cleanup operations included containment by a sorbent boom, berming of the creek in several locations, and removal of contaminated soil.
76	Hurricane Danny came ashore in Louisiana on August 15, was downgraded to a tropical storm, and moved northeastward through Mississippi and northern and western parts of Georgia and the Carolinas and southern Virginia before moving out to sea. Major damages were generally limited to the Gulf Coast and were the result of the high winds and tidal flooding. Between August 15 and 18, up to 8 inches of rain (but generally less than 5 inches) fell over the lower Mississippi valley and from

Table 1. Chronology of significant hydrologic and water-related events, October 1984 through September 1985—continued

No. (fig. 4)	EVENT
	AUGUST 1985
76 (con.)	2 to 5 inches of rain from the southern Appalachian Mountains to southern Virginia. In northern North Carolina, the peak discharge of the Dan River (a tributary of the Roanoke River) near Francisco, exceeded the 100-year flood-recurrence interval.
77	On August 26 in northwestern Georgia, drainage from hog manure killed about 18,000 fish (24 percent game fish) along 5.6 miles of Canton Creek south of Buffington in Cherokee County. Canton Creek flows into the Etowah River at Canton and is tributary to the Coosa—Alabama—Mobile Rivers system. Buffington is about 30 miles north of Atlanta, Ga.
78	In late August in north-central Florida (30 miles northeast of Ocala, Marion County) more than 8 million fish (77 percent game fish) died in Rodman Pool—the part of Oklawaha Lake immediately upstream from Rodman Dam several miles west-southwest of Rodman, Putnam County. Oklawaha Lake is on the Oklawaha River, a tributary of St. Johns River. The cause of the several massive fishkills between August 22 and 30, was a combination of sequential circumstances that greatly magnified the severity of the event. Prolonged dry conditions prior to August were accompanied by a series of forest fires that destroyed trees and undergrowth in the Oklawaha River basin, leaving a heavy residue of organic material on the forest floor. Above-normal rainfall in August caused surface runoff to deposit large amounts of organic material from the floor of the forest into Oklawaha Lake. The fishkills resulted from the interrelated effects of the overload of organic material, prolonged cloud cover, high temperatures, low oxygen levels, and an abundance of water hyacinths (hydrilla).
79	In the East, August rains generally alleviated previously dry conditions. However, reservoir storage (including the New York City system) remained below average in some areas as was also true of the flow of some streams. For example, the discharge of the upper Hudson River at Hadley, N.Y. (45 miles north of Albany), drainage area 1,664 mi^2, was the lowest August monthly flow in the 64 years of record. In the West, abnormally dry conditions continued and were especially persistent in northern and southeastern California, east-central Washington, and large areas of Montana and Wyoming.
	SEPTEMBER 1985
80	Tropical storm Elena formed on August 28 over central Cuba, reached hurricane level the next day, moved northwest, then east, stalled August 31 within 50 miles of the Florida Keys, then moved north and made landfall at Biloxi, Miss., on September 2 as the first major hurricane of 1985. Hurricane-spawned rains were reportedly as high as 12 inches in 3 days at Apalachicola, Fla. Rainfall on September 3 at Biloxi, Miss., was reported to be 3.53 inches in 24 hours. The hurricane caused damages estimated at hundreds of millions of dollars from Florida to Louisiana and forced over 1 million people to evacuate affected areas—actually two evacuations occurred, each involving more than 500,000 people. Although five people died, timely forecasting and evacuation probably kept the death toll at a relatively modest level for a storm of this magnitude. Some flash flooding was reported. The President declared 38 counties in Florida, Alabama, Mississippi, and Louisiana eligible for Federal disaster aid. The rains of Elena did benefit what had been water-short parts of the Southeast, especially Florida.
81	In the Flint area of southeastern Michigan, rainfall of up to 12 inches during an 8-hour period caused extensive flooding with estimated damages of at least $10 million. The peak discharges of the Flint River near Flint and of Kearsley Creek near Davison (east of Flint) had recurrence intervals of about 25 years. Peak stage of the Flint river was 0.6 foot higher than the previous maximum, reached in 1947.
82	Discharge of the upper Mississippi River near Anoka, Minn. (drainage area 19,600 mi^2), on September 10 was the highest daily flow for September during 53 years of record at the site. The unseasonably high flow resulted from above-normal rainfall in the headwaters during August and early September. Anoka is about 10 miles north-northwest of Minneapolis, Minn.
83	On September 14, a train derailed while crossing the Medina River about 10 miles southwest of San Antonio in southern Texas and discharged a large but unknown quantity of sulfuric acid into and near the river. Of the 29 derailed tank cars, 21 contained a total of 300,000 gallons of the acid. People were evacuated from over a 1-mile radius of the accident site. In order to neutralize the acid, 950 tons of lime were dumped into the river thereby averting a greater magnitude of an already large fishkill. Vacuum trucks had recovered 55,000 gallons of the acid from along the river banks by September 18.
84	In east-central Indiana near Muncie, effluent from a combined storm sewer overflowed into the White River (a tributary of the Wabash River) on September 24, causing 61,000 fish to die along a 5-mile reach of the river.
85	Hurricane Gloria, moving northward off the coast of the Carolinas, caused high winds and intense rains on coastal areas of North Carolina beginning on September 26 and continued to spread these effects through the coastal States to New England during the next 2 days, passing over Cape Hatteras, N.C., and moving inland at low tide on Long Island, N.Y., on September 27. The strongest winds remained over the ocean. Coastal and small-stream flooding was common from North Carolina to New England, September 26 to 28. The most extensive damaging effects of the hurricane were along the immediate coastline, including beach erosion and power outages. Substantial evacuations were made from exposed areas. Sixteen deaths were attributed to the hurricane. On the positive side, Gloria's rains helped reduce the problems of below-average water supplies in the Northeast. Although the storm provided 3 to 5 inches of rain to New York City reservoirs, the reservoir contents had still not reached normal levels, and water-use restrictions remained in effect.
86	On September 28 on the Delaware River near Chester in southeastern Pennsylvania, an oil tanker grounded and ruptured, discharging more than 435,000 gallons of crude oil. Parts of the spill spread downstream during cleanup and recovery operations. The spill was in the estuarine part of the river about 10 miles northeast of Wilmington, Del. (See article in this volume, "Major Oil Spill on the Delaware River, September 1985.")

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SEASONAL SUMMARIES OF HYDROLOGIC CONDITIONS, WATER YEAR 1985

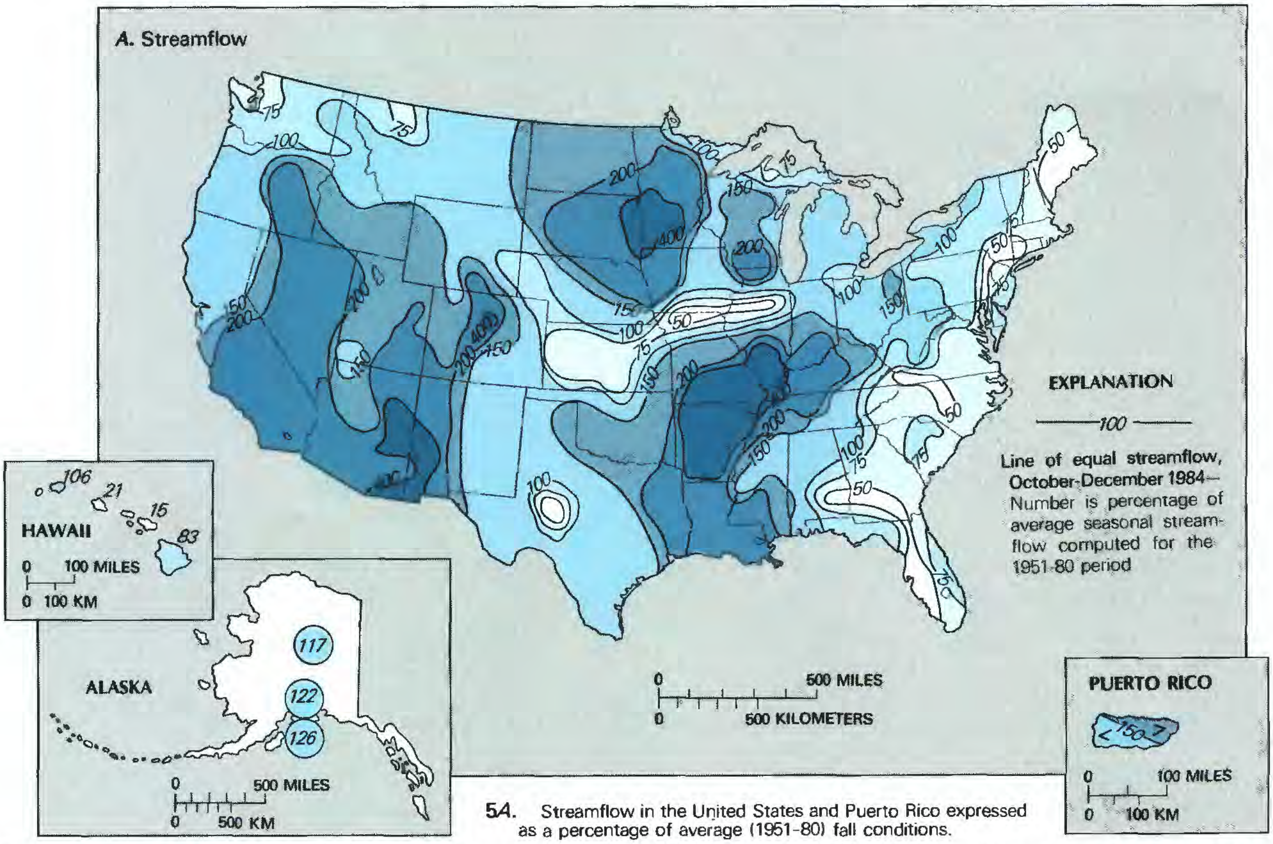
By Harry F. Lins[1] and Thomas R. Karl[2]

FALL 1984

The fall (October–December 1984) of water year 1985 was characterized by two notable changes from hydrologic conditions that had persisted during the spring and summer seasons (April–September 1984) of water year 1984. First, in the southern Great Plains the area of below-normal streamflow was significantly reduced by unusually abundant precipitation. Second, in the Eastern United States, especially in coastal areas from Maine to Florida, streamflow patterns shifted dramatically from mostly above normal to largely below normal. Throughout much of Maine, and in parts of Connecticut, New York, Pennsylvania, Maryland, Virginia, North Carolina, Alabama, Georgia, and Florida, streamflows averaged less than one-half their normal fall values. Across the rest of the Nation, above-normal streamflows persisted in the Great Basin, central Rockies, the Southwest, and the northern Great Plains regions. Above-normal flows also occurred in the middle and lower Mississippi River valley. (See fig. *5A*.)

This particular distribution of streamflows nationwide resulted largely from abundant precipitation with normal to below-normal temperatures associated with an upper-level atmospheric trough over the Western United States and from very warm and dry conditions associated with an upper-level atmospheric ridge over the Eastern United States (figs. *5B*, *5C*, *5D*). The active and well-developed 700-mb (millibar) low-pressure trough formed unusually early in the fall season and resulted in abundant precipitation in an area that extended from the Pacific coast and Southwest regions, across the central and southern Rocky Mountains, into the southern and central Great Plains, and to the upper Great Lakes. Several early season winter-like storms, which produced intense rains, snow, and floods, were associated with the trough (table 1, events 3, 7). Storm tracks were pushed far to the south of their normal position in the western two-thirds of the Nation during October, and as these storms tried to advance eastward, the strong upper-level ridge halted their progress, generating an unusually dry month in the East.

During November, a more zonal upper-air flow across the country gave the West a respite from the strong storms of October but at the same time produced substantial rainfalls in the middle Mississippi and Ohio River valleys. Flood stages were exceeded on many rivers and small streams in the lower Mississippi and Ohio River basins throughout the month. The mean flow of the Mississippi River at Vicksburg, Miss., increased sharply to 229 percent of its long-term median value and registered the se-



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

Figure 5. Hydrologic conditions during the fall (October-December 1984) of water year 1985. (Sources: Meteorological data–National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data–U.S. Geological Survey.)

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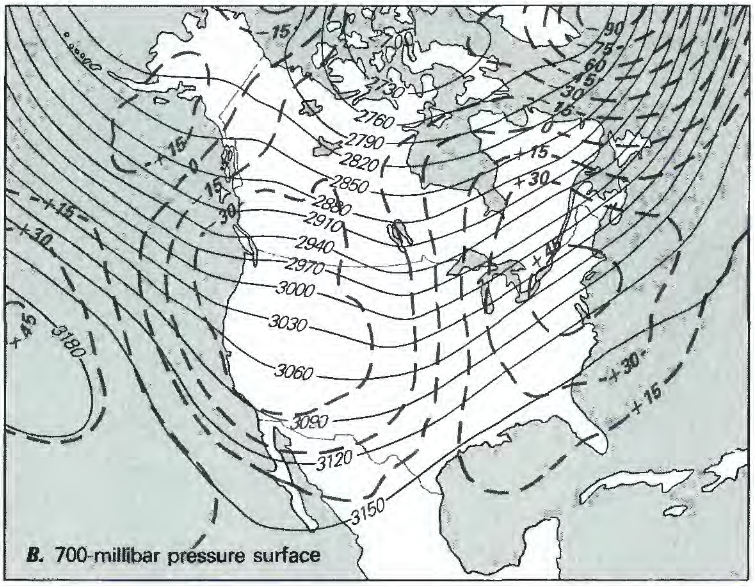
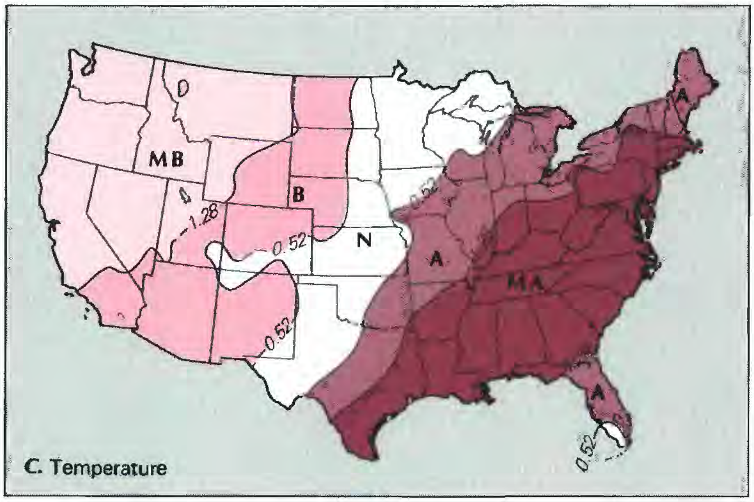
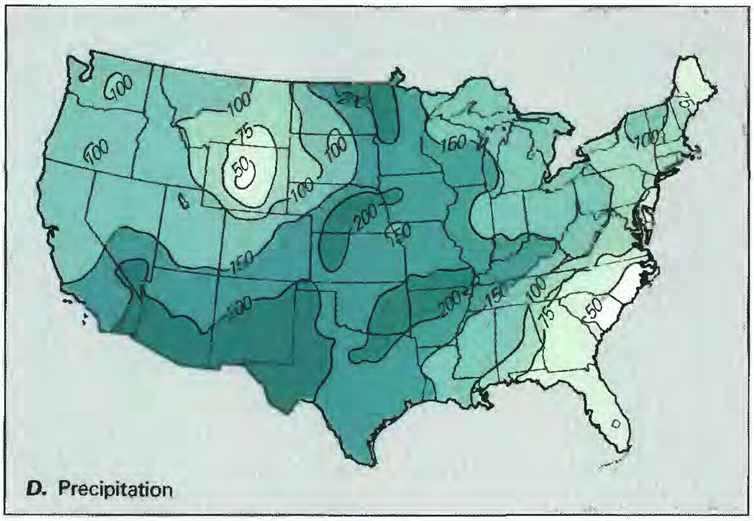
[1] U.S. Geological Survey. [2] National Oceanic and Atmospheric Administration, National Climatic Data Center.

cond highest flow for November in 56 years of record. Over Thanksgiving, a small but intense storm that developed along Florida's eastern coast caused floods, high winds, high tides, and much of the precipitation received by the State during the entire fall season (table 1, event 18). By mid-December, a return to a deep atmospheric trough in the West and a strong atmospheric ridge in the East produced considerable cold weather and snow across much of the West, especially across the Northwest, and record warmth and dry weather in most Eastern States. Near the end of December, a large low-pressure system moved onshore across southern California and into the desert Southwest. It generated intense precipitation over Arizona and southwestern New Mexico and produced floods along the Gila River with recurrence intervals in excess of 75 years (table 1, event 21).

Despite the storminess in the western parts of the northern Rocky Mountains, much of Wyoming and Montana received below-normal precipitation. In fact, central areas of Wyoming, which were bypassed by rainstorms that moved to the south, had their driest fall season of record. Streamflows in central Wyoming, however, remained mostly in the near-normal range through the season.







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

5*C*. Temperature in the conterminous United States expressed as a departure from average (1931-84) fall conditions. (MA=much above, at least 1.28 standard deviations above the mean; A=above, between 0.52 and 1.28 standard deviations above the mean; N=near normal, between −0.52 and 0.52 standard deviations from the mean; B=below, between 0.52 and 1.28 standard deviation below the mean; MB=much below, at least 1.28 standard deviations below the mean.)

5*D*. Precipitation in the conterminous United States expressed as a percentage of average (1931-84) fall total precipitation.

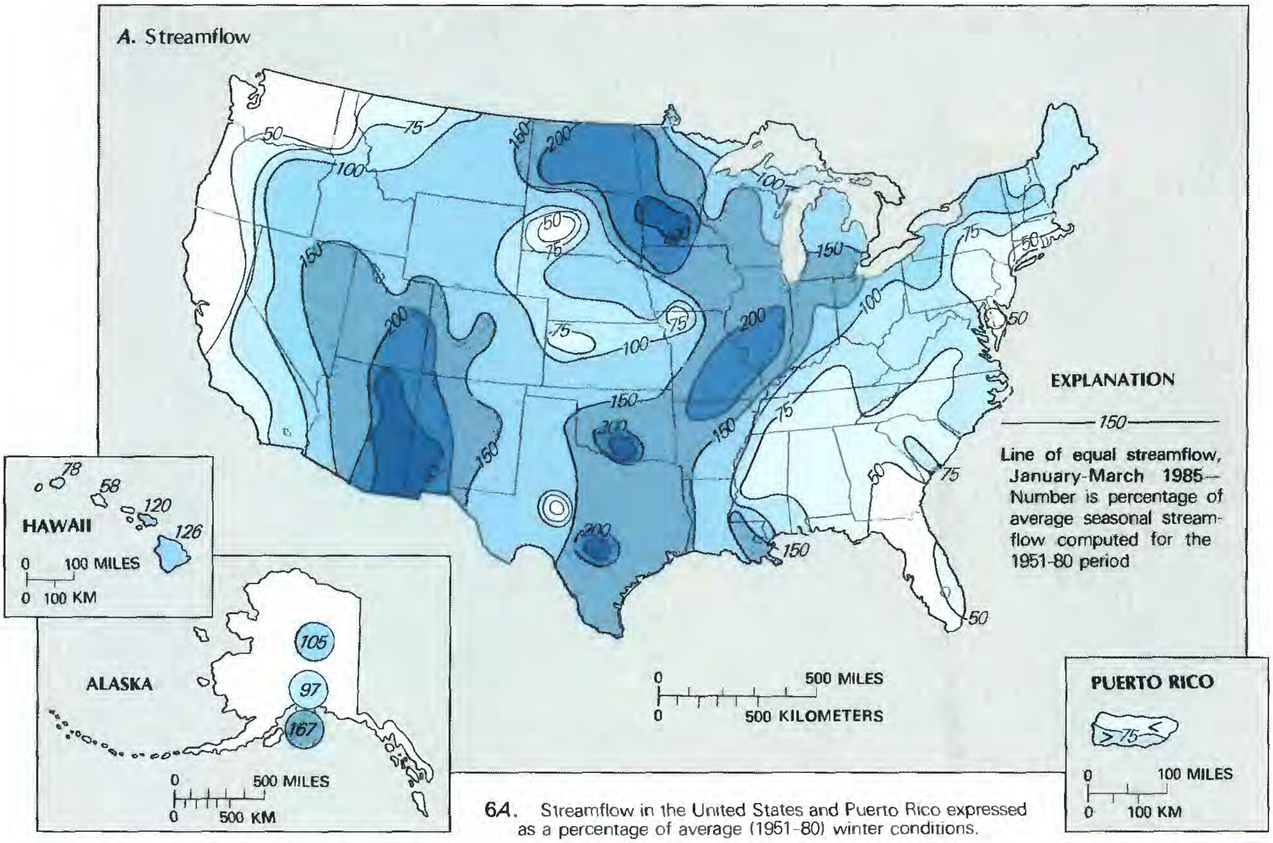
Figure 5. Continued.

WINTER 1985

Streamflow during the winter (January–March 1985) of water year 1985 was characterized by a notable persistence of the fall patterns. Very high seasonal flows continued in the Southwest, northern Great Plains, and middle Mississippi River valley, whereas low-flow areas on the East and West Coasts expanded and, in some instances, intensified (fig. 6*A*). Despite the similarities in surface hydrologic conditions, 700-mb circulation was quite different during the fall and winter of water year 1985 (fig. 6*B*). A semipermanent upper-air ridge of high pressure over the Pacific Northwest inhibited the typical movement of winter storms onto the West Coast throughout the winter. The ridge also brought unusually cold temperatures from the Northwest into the Great Basin (fig. 6*C*). The dry weather along the East Coast was caused principally by a marked reduction in the number of coastal storms in the Gulf of Mexico and the Atlantic Ocean. Much of coastal New England and the Southeastern States experienced the driest winter since 1931 (fig. 6*D*).

The winter season began on New Year's Day with a major storm that moved through the Ohio River valley and produced heavy snows and rains from the southern Plains to the Great Lakes. The track followed by this storm was typical during the season as heavy precipitation north and west of storms moving up the Ohio River valley produced record seasonal precipitation totals in parts of Oklahoma, Illinois, and Michigan. Bands of intense precipitation associated with the New Year's storm produced record-high January streamflows on the Washita and the Guadalupe Rivers in Oklahoma and Texas, respectively. Later in the month, an extraordinary blast of frigid air dropped temperatures 30° to 50° during one 24-hour period and froze many lakes deep into the south. By the end of the month, a strong upper-level atmospheric trough over the Western United States produced a broad frontal disturbance that stretched from the Southwest to the Great Lakes. As the front pushed eastward during the first few days of February, it produced one of the few heavy rainfalls of the winter along the southern Appalachians and Middle Atlantic States, (table 1, event 31). Although the remnants of this frontal system brought some of the most abundant rains of the season to Florida, the rains were not nearly enough to break the drought-like conditions that were becoming firmly established throughout much of the region. Florida's Peace River had its second lowest February flow in 54 years of record, which, although severe, actually broke a consecutive 5-month string of lowest-ever recorded monthly flows.

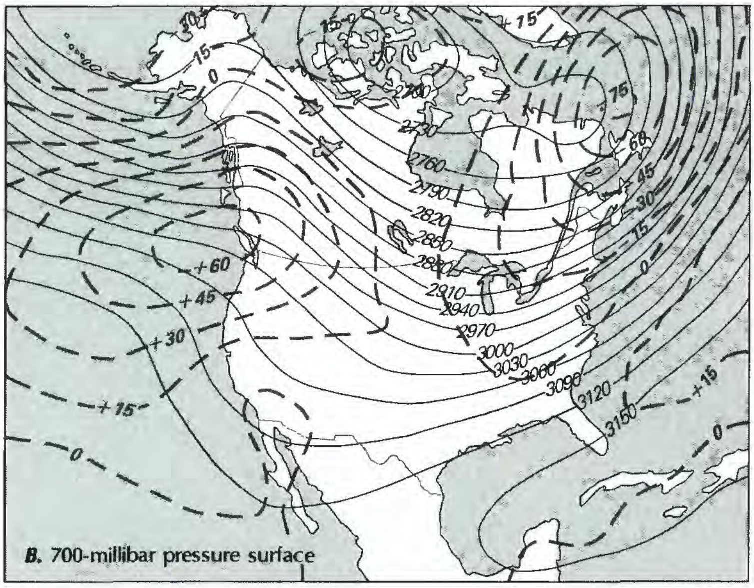
Despite the general pattern of dryness along the east coast and southeastern States during the winter, flood stages were exceeded on many rivers and small streams during the last week in February in most States east of a line running from central Nebraska and Texas to the Atlantic coast and also in the central part of the Great Lakes region. The most severe flooding, however, occurred in Michigan, Indiana, Ohio, and New York where peak discharges on nearly a dozen streams had recurrence intervals of 50 to greater than 100 years (table 1, event 33). These high flows were generated by a series of weak storms from a front that stretched from Texas to southeastern Canada and brought about 2 inches of rain to the Great Lakes area.



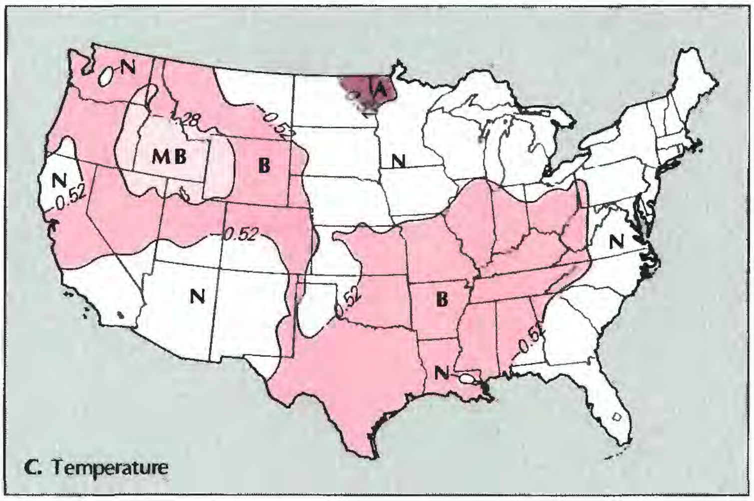
6*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951-80) winter conditions.

Figure 6. Hydrologic conditions during the winter (January-March 1985) of water year 1985. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

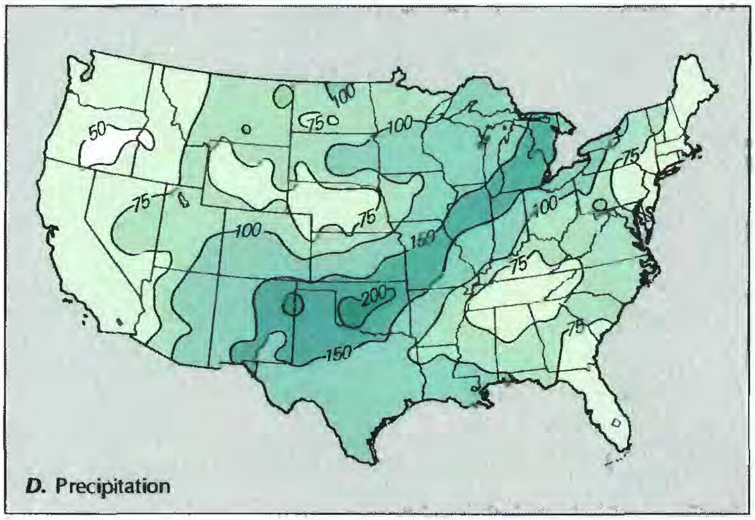
During March, intense rains continued in the southern Great Plains, the middle Mississippi River valley, and the Ohio River valley. These rains produced widespread late-winter flooding throughout the Nation's midsection. The tracks of the storms responsible for this abundant precipitation continued to remain primarily west of the Appalachians. The persistent lack of normal amounts of rainfall in the East during March contributed to decreased streamflow in Connecticut and New Jersey and all States south of Pennsylvania and the Ohio River and east of the Mississippi River. Many parts of North Carolina, South Carolina, Virginia, and Georgia had their driest March of the century. The monthly mean flow on the Delaware River at Trenton, N.J., was only 48 percent of the long-term median and was below normal for the fifth consecutive month at that site. Consequently, the New York City reservoir system, much of which is located in the Delaware River basin, was at 59 percent of normal maximum contents, well below the March long-term-average of 96 percent.



B. 700-millibar pressure surface



C. Temperature



D. Precipitation

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

6C. Temperature in the conterminous United States expressed as a departure from average (1931-84) winter conditions. (MA=much above, at least 1.28 standard deviations above the mean; A=above, between 0.52 and 1.28 standard deviations above the mean; N=near normal, between −0.52 and 0.52 standard deviations from the mean; B=below, between 0.52 and 1.28 standard deviation below the mean; MB=much below, at least 1.28 standard deviations below the mean.)

6D. Precipitation in the conterminous United States expressed as a percentage of average (1931-84) winter total precipitation.

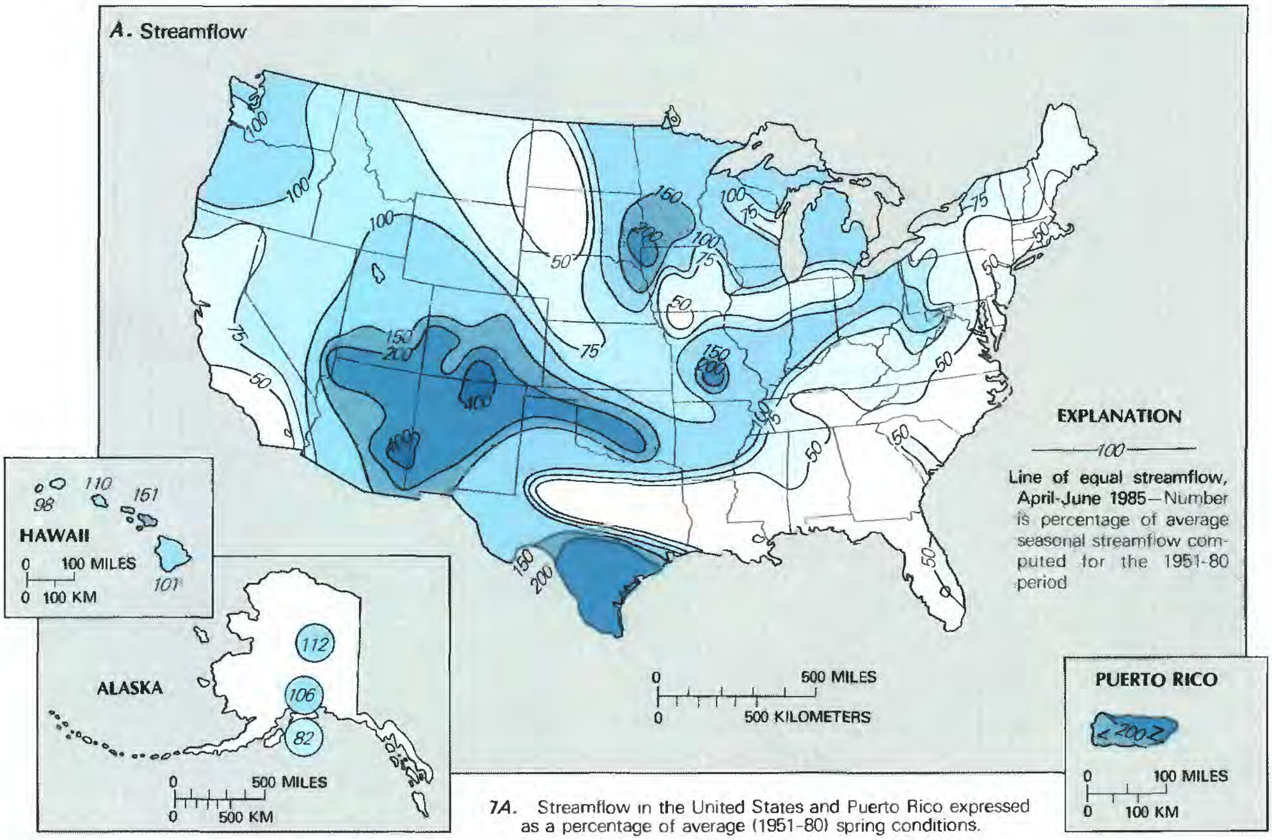
Figure 6. Continued.

SPRING 1985

Spring (April–June 1985) streamflow across the Nation maintained many of the characteristics exhibited during the winter season (fig. 7*A*). There were, however, some notable changes in magnitude. The below-normal flows, which affected most of the Southeast and Middle Atlantic States in the winter, for example, decreased further during the spring and this condition spread westward and northward into Texas, the Ohio River valley, and from the upper Mississippi River valley across to the lower Great Lakes. Flows along most of the Gulf and Atlantic coastal regions were less than half of normal. In the northern Rocky Mountains and northern Great Plains, a major expansion in the area affected by below-normal streamflow occurred. Along much of the Pacific coast, however, where winter season flows had been much below normal, the situation moderated considerably. In Washington and Oregon, for example, flows returned to near-normal levels. Although there was some improvement in conditions in northern California, the flows continued below normal. Southern California, in contrast, experienced a reduction in flow during the spring. The only broad region of the Nation with abundant streamflow was the Southwest where, for the fourth consecutive season, flows were in the above-normal to much-above-normal range.

The mean circulation during the spring (fig. 7*B*) provides some hints regarding the explanation for the observed patterns of streamflow as well as the associated temperature and precipitation departures from normal (figs. 7*C* and 7*D*, respectively). Much of the Nation received below-normal precipitation at least partially attributable to a semipermanent ridge of high pressure in the upper levels of the atmosphere along the West Coast, especially during the first half of the season. As a result, when upper-level disturbances passed through this semipermanent feature they were prevented from maturing into fully developed cyclonic storms. For this reason many parts of California and Nevada had their driest spring in recent record (previous 55 years). By the end of June, for example, the content of Shasta Lake was 76 percent of normal for the month and 71 percent of what it had been in June 1984. The ridge also contributed to the warmth in much of the western half of the Nation. During the latter part of the season the ridge broke down and a few storms penetrated the West Coast, but by this late in the season the jetstream (or steering currents) had moved northward, and only the Pacific Northwest managed to receive enough moisture to compensate for the dry start to the season.

Only the middle sections of the Nation received near-normal or above-normal precipitation. In the southern Rocky Mountains, ample precipitation combined with a heavy snowpack and plenty of soil moisture from the previous season to produce one of the few areas with excessively high streamflow. During April, the monthly mean flow on the Colorado River at Cisco, Utah, was the second highest for the month in 73 years of record, while a record (80-year) high flow was recorded on the Animas River at Durango, Colo. In May, which was a particularly wet month in parts of Utah, the Great Salt Lake reached a peak elevation of 4,209.95 feet above sea level. This was the second highest recorded level of Great Salt Lake since records were begun in 1847, just 1.65 feet below the maximum which occurred in 1872. Once



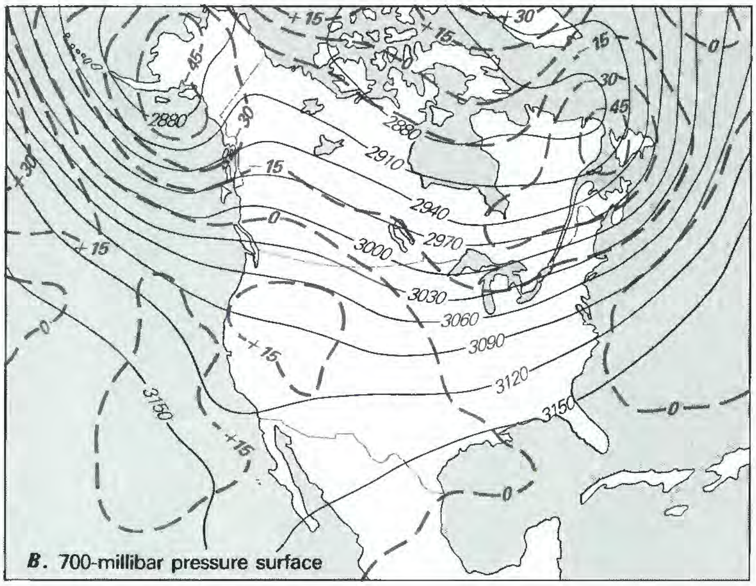
7*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951-80) spring conditions.

Figure 7. Hydrologic conditions during the spring (April-June 1985) of water year 1985. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

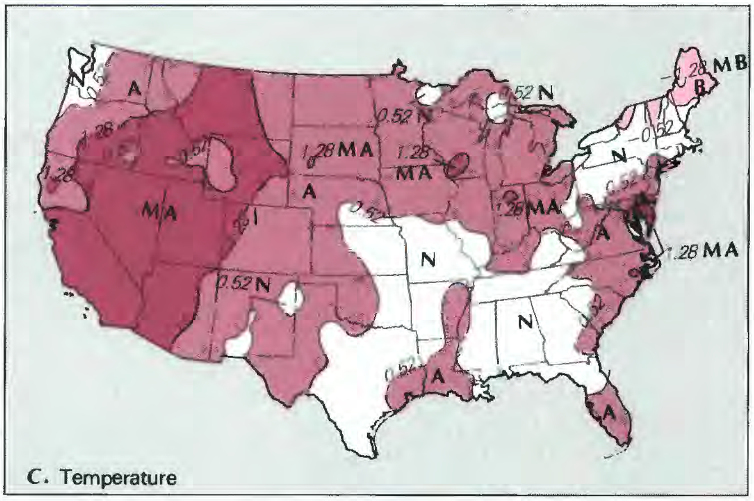
past the ridge along the West Coast, several eastward-propagating disturbances matured and developed into surface cyclones contributing to the near-normal or above-normal precipitation in these areas. Unfortunately for the dry Southeast, the storms were often steered to the North as they moved out of the region.

The mean 700-mb circulation in the Southeastern United States belies the atmospheric characteristics responsible for the scarcity of precipitation and depressed streamflow in that area. During a significant part of the season, a strong dry northwesterly flow, associated with deep upper-level low pressure, prevailed over the area. During the times of active cyclonic activity in the middle parts of the Nation, this pattern often broke down. It was replaced by an anticyclonic high-pressure blocking condition that prevented storm systems from penetrating into the southeastern States. As a result, many parts of the area, from Louisiana to Virginia, had one of their driest spring seasons of recent record. This lack of precipitation, combined with the low moisture supply from previous seasons, contributed to the occurrence of at least nine record-low monthly stream discharges between April and June in North Carolina, South Carolina, Georgia, and Louisiana. The alternating patterns of cold northwesterly flow and warm anticyclonic activity produced near-normal seasonal temperatures over most of the Southeast.

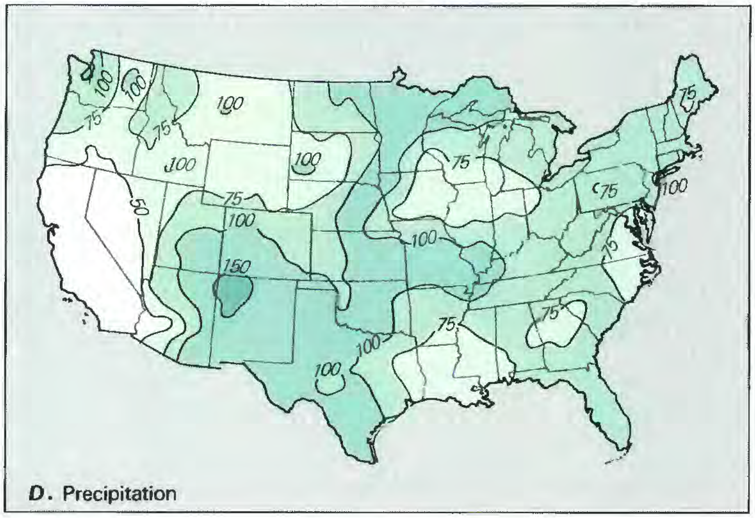
In the Northeast, conditions remained quite dry, but beneficial rains during May and June prevented a more extreme deficiency in the water supply. Record April low flows occurred at nine index stations in the Northeast, and numerous reservoirs in the region reported below-average contents for the month. For example, both the monthly mean and daily mean flows, on April 30, for the Delaware River at Trenton, N.J., were the lowest for April in 73 years of record. New York City's reservoirs in the Delaware River basin were at 62 percent of capacity at the end of the month, a record April low. This compares to the long-term average for April of 100 percent of capacity. Stream inflows to the reservoir system were 40 percent of the long-term average. Drought emergencies were declared during the month in New Jersey, Pennsylvania, and New York City. At the end of May, despite receiving normal monthly precipitation, contents of the New York City reservoir system declined to 60.8 percent of capacity, while reservoir inflows dropped to 39 percent of average. The decline was due largely to above-normal temperatures during May and the associated increased evapotranspiration. In June, near-normal precipitation brought reservoir inflows up to 55 percent of their long-term average.



B. 700-millibar pressure surface



C. Temperature



D. Precipitation

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

7C. Temperature in the conterminous United States expressed as a departure from average (1931-84) spring conditions. (MA=much above, at least 1.28 standard deviations above the mean; A=above, between 0.52 and 1.28 standard deviations above the mean; N=near normal, between −0.52 and 0.52 standard deviations from the mean; B=below, between 0.52 and 1.28 standard deviation below the mean; MB=much below, at least 1.28 standard deviations below the mean.)

7D. Precipitation in the conterminous United States expressed as a percentage of average (1931-84) spring total precipitation.

Figure 7. Continued.

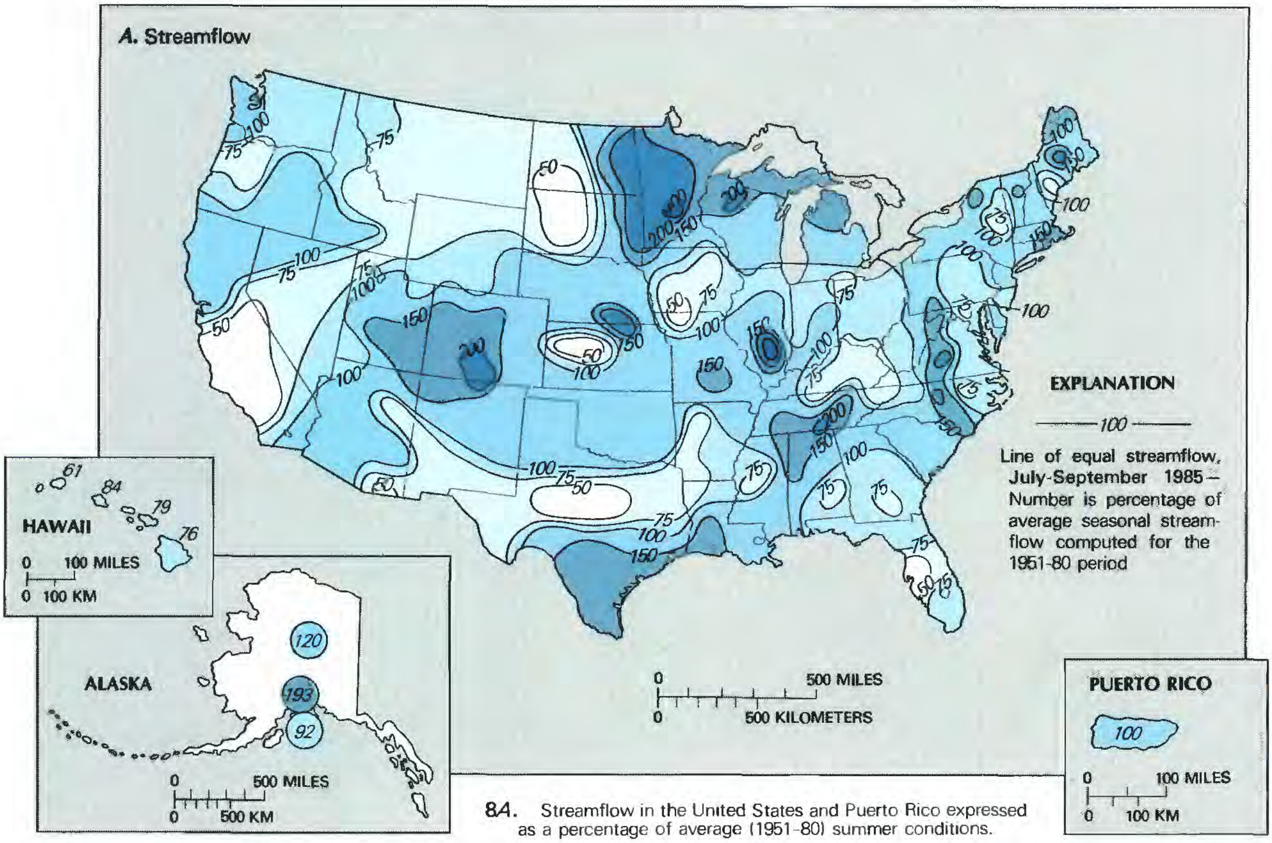
SUMMER 1985

As often occurs, the streamflow pattern for the summer (July-September 1985) had more spatial variability than for the other seasons (fig. 8*A*). Some of the larger areas with much below normal streamflow (less than 50 percent of normal) included much of southern and central California, parts of the upper and lower Missouri River valley, and part of central Texas. The unusually low streamflow east of the Appalachians that persisted through the spring quarter was ameliorated somewhat during the summer by the remnants of several hurricanes and the lack of a strong North Atlantic subtropical high (fig. 8*B*), although widespread deficient flows remained. Just to the west of the Appalachians, streamflow continued below normal. In the northern Great Plains, along the Red River valley and the headwaters of the Mississippi River, cool weather (fig. 8*C*) and copious precipitation (fig. 8*D*) were significant factors in producing abnormally high streamflow in these areas. August and September mean flows along parts of the Red River, for example, were their highest in more than 100 years of record. Similarly, the mean September flow of the Mississippi River near Anoka, Minn., was the highest in more than 50 years of record.

The atmospheric conditions that contribute to streamflow abnormalities during the summer are sometimes difficult to detect. During summer the circulation across North America generally weakens in response to a more even distribution of the Sun's energy from the pole to the tropics. (See figs. 5*B*, 6*B*, 7*B*, 8*B*.) As a result, the important dynamic features of the jetstream, which often produce coherent patterns of precipitation, frequently are replaced by rainfall patterns driven primarily by thermodynamic convective forces that have less spatial coherence. For this reason the streamflow patterns often look more chaotic during the summer than at other times of the year.

Some important large-scale features that occurred during the summer season can be briefly summarized. A southward dip in the jetstream helped produce beneficial rains in the East during July, but a ridge of high pressure in the West during a substantial part of the month inhibited significant rainfall in the parched area from the northern Rocky Mountains to the Pacific Northwest. An unusual exception to this pattern occurred during the evening and early morning hours of August 1 and 2 at Cheyenne, Wyo.—about 7 inches of rain (and considerable hail) fell and caused severe floods in the city. Local thermodynamic forcing was instrumental in producing this cloudburst. (See article in this volume, "Storm and Flood of August 1, 1985, in Cheyenne, Wyoming.") By the second week in August, however, an unusually persistent pattern of upper-level disturbances and their associated surface weather tracked southeast across the United States from the Pacific Northwest to the East Coast and brought ample rains to many parts of the United States. During September, a deep upper-level low-pressure system in the Pacific Northwest generated heavy rains from the Pacific Northwest to the Great Plains. In the eastern half of the United States, however, a strong upper-level ridge of high pressure during much of September provided the mechanism for dry weather across much of the east-central United States.

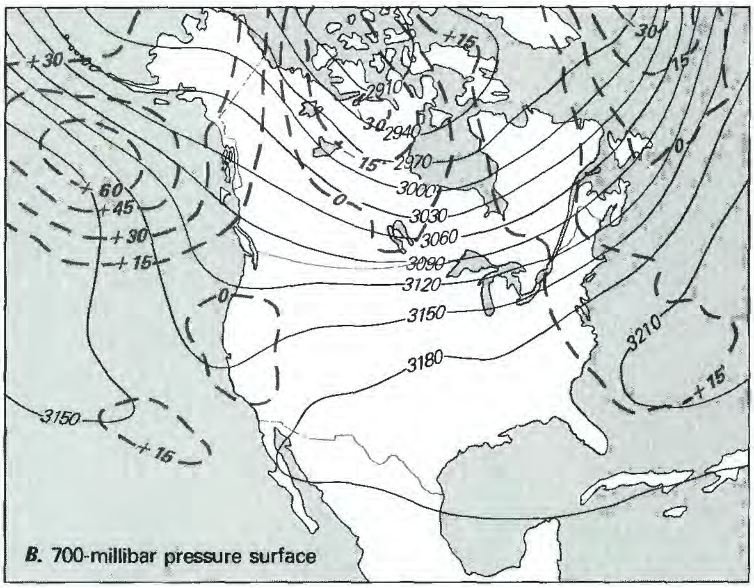
The summer of water year 1985 was an active hurricane period. Between July and September four



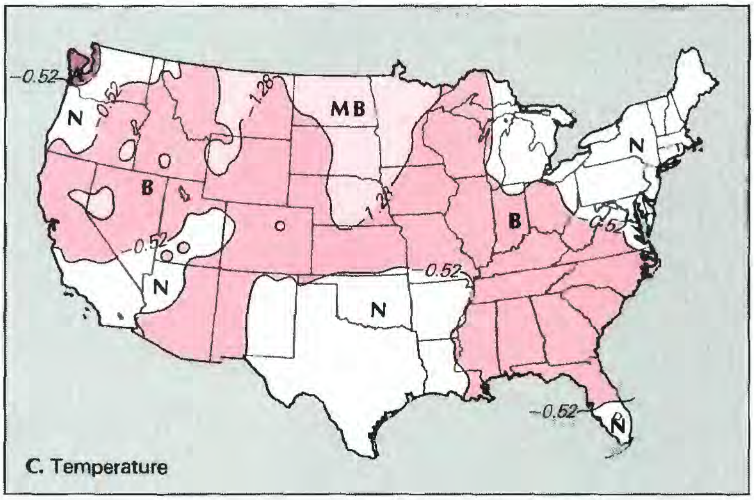
8*A*. Streamflow in the United States and Puerto Rico expressed as a percentage of average (1951-80) summer conditions.

Figure 8. Hydrologic conditions during the summer (July-September 1985) of water year 1985. (Sources: Meteorological data—National Oceanic and Atmospheric Administration, Climate Analysis Center and National Climatic Data Center; streamflow data—U.S. Geological Survey.)

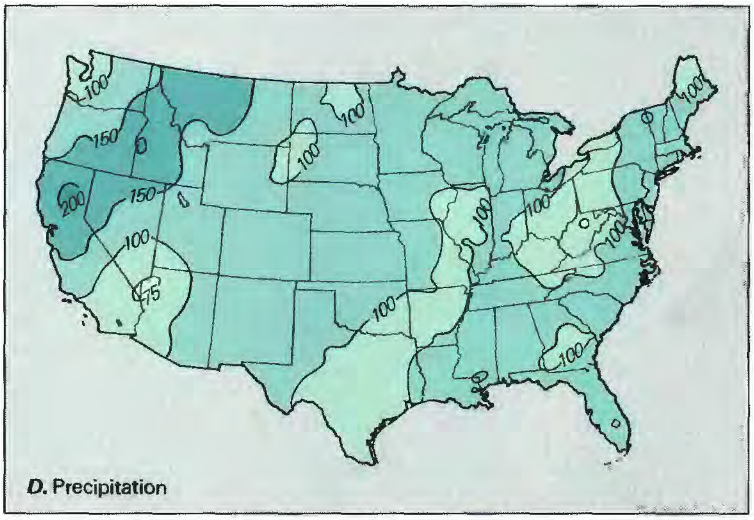
hurricanes affected many parts of the U.S. Gulf and Atlantic coasts. Near the end of July, Hurricane Bob moved from the Gulf of Mexico across Florida into the Atlantic Ocean. As Bob moved northward, heavy rains fell from Florida to the Carolinas. More than 3 inches fell in many areas, and parts of Florida received more than 10 inches of rain. Minor flooding occurred in central and coastal regions of South Carolina. Tropical moisture from Bob eventually became entrained in a cold front moving through the Appalachian Mountains, and precipitation from this system provided some relief from the continuing drought in many parts of New England and the Middle Atlantic States. In the middle of August, Hurricane Danny came ashore along the Louisiana coast. The remnants of Danny moved northeast from Louisiana and brought very heavy rains. Along Danny's trek to the Middle Atlantic States, 4 to 7 inches of rain was common. Over Labor Day weekend, Elena, the fourth costliest hurricane on record, produced torrential rains—as much as 10 inches in some areas—along the Gulf Coast from Florida to Louisiana. Once ashore on the Mississippi coastline, Elena produced heavy rains in northeast Louisiana and southwest Mississippi but then rapidly dissipated. In late September, Hurricane Gloria triggered heavy rains from the Carolinas to New England, as it hugged the coastline along the Middle Atlantic region before making landfall on Long Island, N.Y. The rainfall from Gloria effectively ended the drought that had plagued the East since the previous autumn.



B. 700-millibar pressure surface



C. Temperature



D. Precipitation

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

8C. Temperature in the conterminous United States expressed as a departure from average (1931-84) summer conditions. (MA = much above, at least 1.28 standard deviations above the mean; A = above, between 0.52 and 1.28 standard deviations above the mean; N = near normal, between −0.52 and 0.52 standard deviations from the mean; B = below, between 0.52 and 1.28 standard deviation below the mean; MB = much below, at least 1.28 standard deviations below the mean.)

8D. Precipitation in the conterminous United States expressed as a percentage of average (1931-84) summer total precipitation.

Figure 8. Continued.

SELECTED HYDROLOGIC EVENTS, WATER YEAR 1985

As documented in the previous section of this report ("Review of Water Year 1985 Hydrologic Conditions and Water-Related Events"), many examples of floods, droughts, rising lake levels, and other water-related events occurred during water year 1985. In this section, several of these events are described in some detail. They were selected to illustrate a range of events that affected large numbers of people, required a variety of management actions to mitigate their effects, or were just exciting from a scientific perspective. Weather-related events, for example, caused over $3.5 billion in economic losses in water year 1985. Of this amount, flood damages were less than $500 million, the lowest amount of damages incurred since 1971 (U.S. Army Corps of Engineers, 1986). Although flood fatalities were well below the national average of 200 lives per year, flash floods accounted for more than 90 percent of the death toll. Such a flash flood occurred in Cheyenne, Wyo., on August 1, 1985. It was the most destructive flood in 120 years of record in Wyoming and received nationwide attention. The effects of droughts are more difficult to estimate, but they can be documented through reports of crop losses, forest fires, and mandatory restrictions on water use. An article in this section describes the hydrologic effects of drought in the Delaware River basin, which directly or indirectly touched the lives of some 24 million people who depend upon the basin for all or part of their water supply.

What is not reflected in the events listed in table 1 or described in this section is some of the good news. For example, the U.S. Army Corps of Engineers' dams, levees, and flood protection projects prevented an estimated $10.8 billion in economic losses in water year 1985 (U.S. Army Corps of Engineers, 1986), and the vast majority of water suppliers met the water demands of their customers without interruption.

Rising lake levels continue to cause flooding problems in parts of the country. For example, Great Salt Lake in Utah continued its rise, and on May 21, 1985, it reached a seasonal peak of 4,209.95 feet above sea level—0.7 foot above the 1984 peak and only 1.65 feet below the all-time high observed over the past 139 years of record. The causes and effects of the rise of Great Salt Lake were documented in the 1984 *National Water Summary* (Arnow, 1985). During 1985 record high water levels occurred in all five of the Great Lakes, and this hydrologic situation is described in this section.

Finally, two other events are included in this section—"Disintegration of Columbia Glacier, Alaska, Continues Unabated" and "Major Oil Spill on the Delaware River, September 1985"—to provide an example of a scientifically exciting event that eventually may provide insight into the effects of climatic change on the world's glaciers and an example of procedures used to cope with an oil spill.

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DROUGHT IN THE DELAWARE RIVER BASIN, 1984–85

By William E. Harkness, Harry F. Lins, and William M. Alley

Dry conditions prevailed over much of the northeastern United States during 1984 and 1985. In particular, drought conditions in the upper Delaware River basin adversely affected the water supplies of New York City and northern New Jersey. This article examines the climatological and hydrological conditions that were associated with the drought from June 1984 through October 1985 and describes the management actions taken in response to the drought.

BACKGROUND

The Delaware River basin comprises a 12,765-square-mile area in New York, New Jersey, Pennsylvania, Delaware, and a very small part of northeastern Maryland (fig. 9). The river originates as the East and West Branches of the Delaware River in the Catskill Mountains of New York and flows generally south-southeast to a point between Cape May, N.J., and Cape Henlopen, Del. The basin lies between the Susquehanna River basin on the west and the Hudson, the Passaic, and the Raritan River basins on the east. For the purpose of managing the basin's water resources, the drainage area upstream of Montague, N.J., is referred to as the upper Delaware River basin, and the drainage area downstream of Montague is referred to as the lower Delaware River basin.

In addition to providing water for municipal and industrial use for about 7 million basin residents, the Delaware River also supplies water to about 17 million persons in parts of New York and New Jersey that lie outside the basin. New York City, for example, obtains about one-half of its total water supply from three reservoirs in the upper Delaware River basin—Pepacton, Cannonsville, and Neversink. Water from these reservoirs is diverted from the basin via three tunnels to Rondout Reservoir in the Hudson River basin. From Rondout Reservoir the water flows through the Delaware Aqueduct to the New York City water-distribution system.

The New York City diversions are regulated by the 1954 U.S. Supreme Court Decree in New Jersey vs. New York, 347 U.S. 995 (hereafter referred to as the decree). The decree authorizes diversions of as much as 800 Mgal/d (million gallons per day) from the Delaware River basin to New York City. It also authorizes the State of New Jersey to divert as much as 100 Mgal/d out of the basin. New Jersey diverts water from the Delaware River via the Delaware and Raritan Canal to supply water systems in central and northern New Jersey. In addition to authorizing the above diversions from the basin, the decree requires New York City to make downstream releases of water to the river at rates designed to maintain a flow of 1,750 ft^3/s (cubic feet per second) at the U.S. Geological Survey streamflow-gaging station at Montague, N.J. This commonly is referred to as the "streamflow objective" at Montague. The terms and conditions of the decree are administered by the U.S. Geological Survey through the Office of the Delaware River Master.

In November 1982, following 4 years of deliberations, the Governors of the four basin States and the Mayor of New York City agreed to the "Interstate Water Management Recommendations of the Parties to the U.S. Supreme Court Decree of 1954." These recommendations, commonly referred to as the "Good Faith Agreement," provide alternative operating procedures to those specified by the decree for implementation during water-supply shortages. The agreement also specifies that the combined storage levels in the three Delaware River basin reservoirs serving New York City would be used to trigger the declaration and termination of drought warnings and emergencies. These levels, which vary from month to month, define the operating curves for the reservoirs (fig. 10). The schedule of reductions in diversions and streamflow objectives to be implemented at different reservoir storage conditions is shown in tables 2 and 3*A*. The agreement also specifies that during drought warning and drought, minimum required releases from each reservoir (conservation releases) will be reduced.

The three Delaware River basin reservoirs serving New York City compose about 75 percent of the available reservoir storage in the basin. The remaining 25 percent is split about evenly between power company reservoirs in the upper basin and four reservoirs in the lower basin. The power company reservoirs in the upper basin—Lake Wallenpaupack and the Mongaup River system—are upstream from Montague. Therefore, releases from these reservoirs are considered in the design of releases to be made from the New York City reservoirs to meet the Montague streamflow objective. Releases from the lower basin reservoirs—Francis E. Walter, Blue Marsh, Beltzville, and Nockamixon—are used to meet the Trenton flow objective (see tables 2, 3*A*) and to maintain streamflow and water quality in the Lehigh and Schuylkill Rivers.

CLIMATOLOGICAL CONDITIONS ASSOCIATED WITH THE DROUGHT

Although in retrospect it is often easy to associate established drought conditions with features of the general atmospheric circulation, identifying the onset of drought (especially in a real-time sense) generally is very difficult. This difficulty was particularly true in the northeastern United States during the summer and early fall months of 1984. At that time, the monthly pattern of upper-air flow at the 700-mb (millibar) level (approximately 10,000 feet), which strongly influences the distribution of surface precipitation and temperature, was quite variable over North America. In June, for example, a weak upper-air ridge of high pressure over the eastern United States brought hot and dry conditions to the upper Delaware River basin. In July, however, this ridge was replaced with a shallow but persistent trough that brought above-normal amounts of precipitation to the upper basin. By August, the trough was replaced by a more zonal (east-west) upper-air flow, again resulting in dry conditions over the Northeast. Dryness continued in

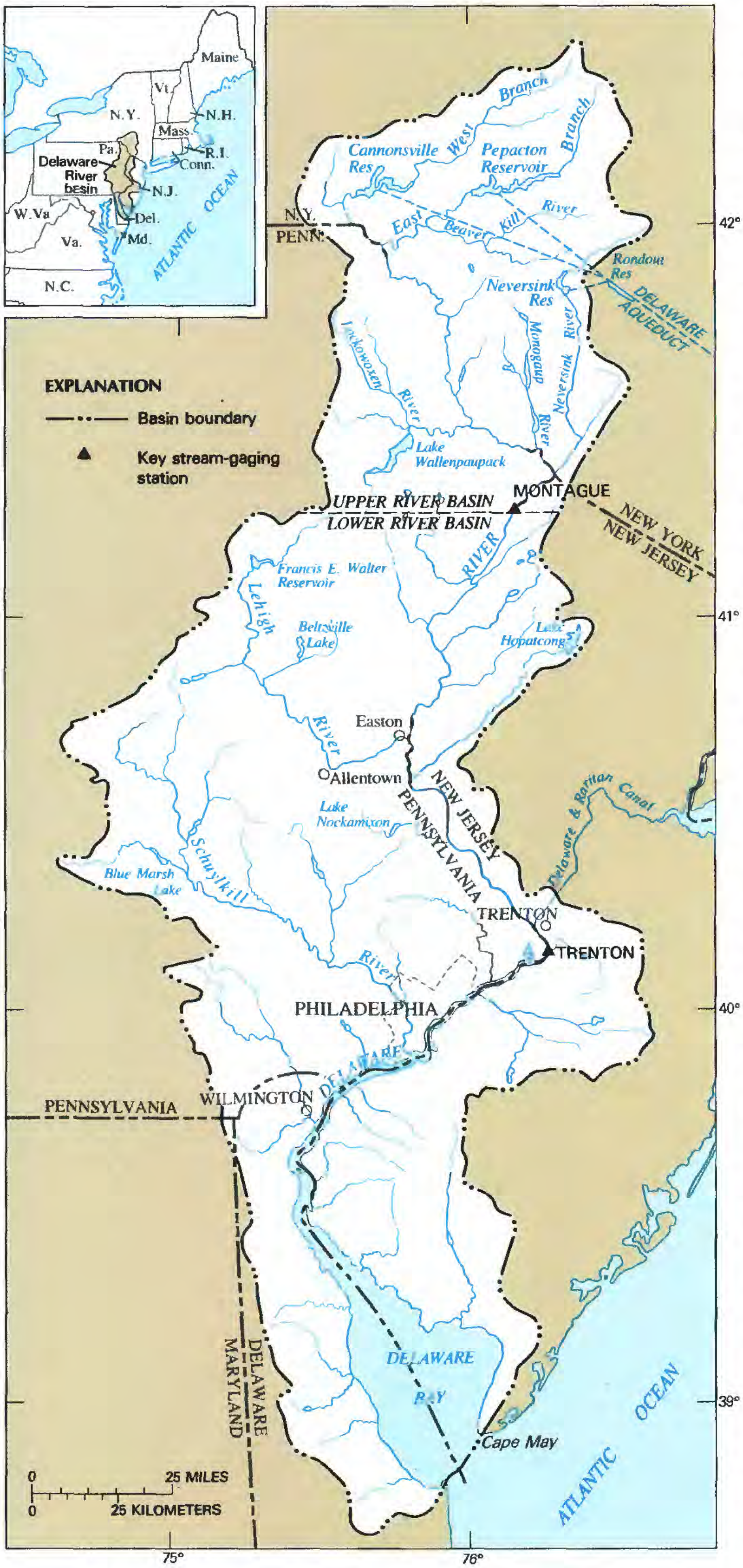

Figure 9. Delaware River basin.

September, but this time it was due to a strong upper-level ridge that stretched from Louisiana to the lower Great Lakes. Precipitation in the upper basin was less than half the monthly normal, whereas in parts of northern New England it was in the lowest 10th percentile. Thus, at the end of the summer of 1984, the telltale climatological signs of drought, which generally manifest themselves in characteristic and persistent month-to-month atmospheric patterns, were not present.

This situation changed, however, after September 1984 as the dryness continued in association with two distinct upper-level wind patterns. Recent droughts in the Northeast, generally have been associated with the occurrence of one or the other of these two patterns (Namias, 1983). The first pattern, which is characterized by a recurrent or persistent displacement of the jetstream and westerlies north of their normal position with subsidence prevailing south of the jet, typically gives rise to a relatively warm drought. The second type occurs in conjunction with recurrent upper-level trough activity and cyclonic surface activity just off the Atlantic seaboard. Under these conditions, New England and the Middle Atlantic region are dominated by northerly wind components driving cyclonic systems out to sea off the Southeast coast, thereby depriving the Northeast of moisture. The prevailing advection of dry air from the north also results in cooler than normal temperatures, thus producing what could be called a relatively cool drought. This type of cool drought occurred during the springs and summers of 1962–65.

During the 1985 water year, a combination of these two patterns, occurring in sequence, accounted for the persistence of drought conditions. Beginning in October 1984, circulation at the 700-mb level took on characteristics of a warm drought; that is, ridging in the Eastern United States with a northward displacement of the jetstream and westerlies. (See figure 5*B*.) This pattern continued into early January 1985. During this period, precipitation for the entire Delaware River basin was less than the fall median (50th percentile value), and in the southern and eastern parts of the basin, it was below the 30th percentile. Temperatures were much above normal across the basin.

In mid-January an upper-level trough developed over the Canadian Maritime Provinces and with it a brief shift to the cool drought pattern. With the trough centered over Newfoundland, a frigid northerly arctic airflow prevailed over the Eastern United States. This cold drought pattern, which lasted only until early February, was largely responsible for making January the driest month of the 1985 water year in the upper Delaware River basin.

By mid-February, the 700-mb flow returned to the warm and dry pattern, with recurrent ridging dominating the East Coast States. Throughout the winter season (January-March), temperatures averaged near normal in most parts of the Delaware River basin, although this average included rather dramatic positive and negative extremes. Most parts of the basin received one-half to three-quarters the normal winter season precipitation.

During mid-spring, an important change occurred in the drought pattern. The upper-air flow over

North America became dominated by ridging in the West and troughing in the East, a pattern that generally means more moisture along the Atlantic coast. Indeed, in May and June precipitation amounts returned to the normal range for the upper basin while parts of the lower basin received nearly twice the normal amounts. Near-normal conditions continued through the summer season when a rather weak zonal 700-mb flow prevailed over the conterminous United States.

At the close of the 1985 water year (in September), the upper-level flow pattern across the United States had returned to a pattern similar to that of the previous September and October. The deficient water-resource conditions in much of the basin likely would have continued had not Hurricane Gloria occurred, which brought unusually heavy amounts of precipitation to most of the Delaware River basin and (at least for awhile) ended the hydrologic drought.

HYDROLOGIC CONDITIONS ASSOCIATED WITH THE DROUGHT

Precipitation falling on the upper Delaware River basin generally is distributed evenly throughout the year. During the warmer months, however, much of the precipitation is returned to the atmosphere through evapotranspiration whereas during the cooler months evapotranspiration is greatly reduced. Precipitation occurring as snowfall is stored temporarily on the drainage basin. These factors contribute to a seasonal pattern of runoff in which about 45 percent of the streamflow typically occurs during March, April, and May and about 80 percent occurs between November and May.

Values of monthly precipitation and monthly combined inflow to the three reservoirs are illustrated in figure 11. As shown, precipitation was below normal from August 1984 through April 1985. This deficiency resulted in well-below-normal streamflow in the basin for all months of this period other than December. The December streamflow was near average because much of the precipitation that occurred during November fell near the end of the month. During the critical reservoir-filling months of November through May, streamflow was about 55 percent of normal.

The climatic situation changed in late May when near-normal precipitation occurred and continued through August. During this period, however, streamflow remained below normal, except for July when normal flows occurred. The return to normal streamflow conditions was delayed because much of the precipitation in May and June contributed to making up a soil-moisture deficit in the basin.

Only about 2.2 inches of precipitation fell during the first 24 days of September 1985, and streamflow conditions for the month had returned to well below normal. At the end of September, Hurricane Gloria and a frontal system moving through the area combined to provide about 5 inches of precipitation, resulting in above-average precipitation and streamflow for the month. The effects of this end-of-month precipitation carried over into October.

Precipitation and streamflow conditions provide only a partial indicator of drought conditions within the basin, because they do not account for the capability of reservoirs to store water or for seasonal differences in release requirements. The actual storage conditions of the three Delaware River basin reservoirs that supply New York City are described later in this article. First, however, it may be useful to place the water-supply conditions of the recent drought in historical perspective.

Several factors make it difficult to compare 1985 water-supply conditions with those during previous droughts. Neversink and Pepacton Reservoirs have been in operation only since the early 1950's and Cannonsville since 1967 and there have been several changes in the operating policies for these reservoirs. In addition, the demands for water from the reservoirs have changed over time. To obtain a historical perspective on the severity of the current drought compared to earlier droughts, a hypothetical history of reservoir storages was constructed by simulating the combined storage of water in the three reservoirs from August 1927 through October 1985 using the historical records of streamflow, the present-day water demands, and the current operating rules for the reservoirs. A water-supply index for each month was computed as the number of times that the combined contents of the 3 reservoirs would have been lower during that month of the year. (See figure 11*C*.) Thus, the index of 3 at the end of April suggests that reservoir conditions would have been worse at the end of April during only 3 of the past 58 years (1927–85).

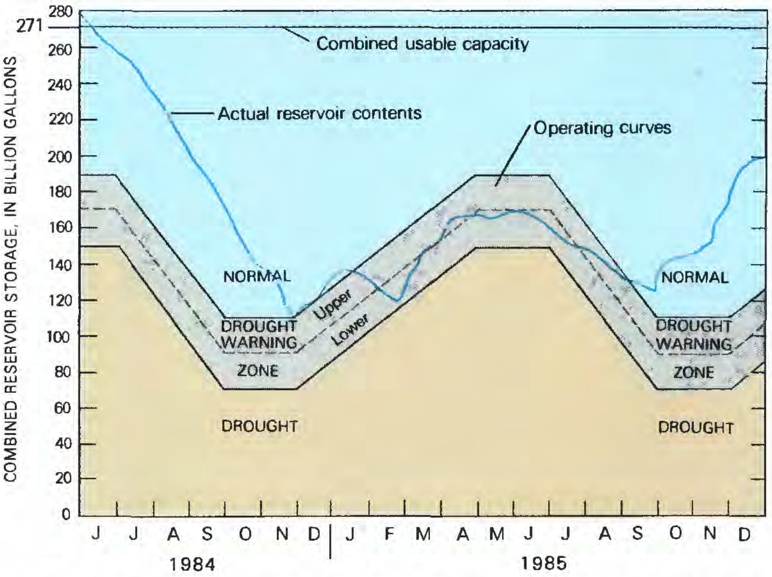

Figure 10. **Operating curves for New York City reservoirs in the Delaware River basin compared with the actual contents of the reservoirs, June 1984 to December 1985.** (Sources: Operating curves from Interstate Water Management Recommendations of the Parties to the U.S. Supreme Court Decree of 1954; reservoir contents compiled by W. E. Harkness from New York City, Bureau of Water Supply data.)

The water-supply index shown in figure 11 indicates a worsening of water-supply conditions from August 1984 through June 1985. By the end of June the water-supply index was 2, indicating that June water-supply conditions had been worse only twice (1965 and 1966) during the past 58 years. The 4 months of near-normal precipitation resulted in good

Table 2. Diversions and streamflow objectives during different combined storage conditions of the three Delaware River basin reservoirs serving New York City

[Mgal/d = million gallons per day; ft³/s = cubic feet per second. Source: Interstate Water Management Recommendations of the Parties to the U.S. Supreme Court Decree of 1954]

Reservoir storage condition (see fig. 10)	Diversions (Mgal/d)		Streamflow objective at streamflow-gaging stations in New Jersey (ft³/s)	
	New York City	New Jersey	Montague	Trenton
Normal	800	100	1,750	3,000
Drought-warning zone:				
Upper half	680	85	1,655	2,700
Lower half	560	70	1,550	2,700
Drought	520	65	[1]1,000–1,650	[1]2,500–2,900
Severe drought	To be negotiated on the basis of conditions.			

[1] Varies with time of year and location of "salt front" as shown in table 3.

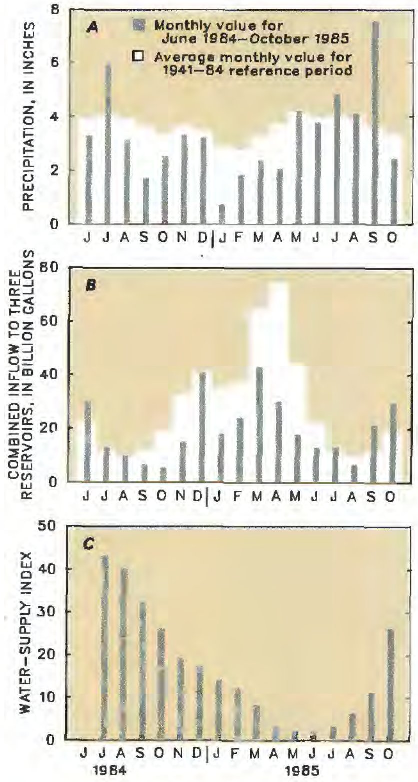

Figure 11. Precipitation (*A*), combined New York City reservoir inflows (*B*), and water-supply index (*C*) for the upper Delaware River basin, June 1984 through October 1985. The water-supply index gives for each month the number of times that the combined contents of the three Delaware River basin reservoirs would have been lower during that month, if all the reservoirs had been in place and had been operated using the "Good Faith Agreement" operating rules beginning in August 1927. For example, an index of 3 for June indicates that only three times during the past 58 years June reservoir contents would have been lower than in 1985. No water-supply index is shown for June 1984 because the reservoirs were filled and spilling. (Source: Compiled by W. M. Alley and W. E. Harkness using data obtained from the National Weather Service, New York City Department of Environmental Conservation, and U.S. Geological Survey.)

Teble 3. Streamflow objectives for controlling salinity in the Delaware River during drought

[River miles (R.M.) are measured in statute miles along the navigation channel from the mouth of the Delaware Bay. ft³/s = cubic feet per second]

7-day average location of "salt front"[1]	Streamflow objective at streamflow-gaging stations in New Jersey (ft³/s)					
	Montague			Trenton		
	Dec.–April	May–Aug.	Sept.–Nov.	Dec.–April	May–Aug.	Sept.–Nov.
A. Interstate Water Management Recommendations of the Parties to the U.S. Supreme Court Decree of 1954						
Upstream of R.M. 92.5	1,600	1,650	1,650	2,700	2,900	2,900
Between R.M. 87.0 and R.M. 92.5	1,350	1,600	1,500	2,700	2,700	2,700
Between R.M. 82.9 and R.M. 87.0	1,350	1,600	1,500	2,500	2,500	2,500
Downstream of R.M. 82.9	1,100	1,100	1,100	2,500	2,500	2,500
B. July 25 to October 2, 1985—during periods of reservoir storage within the drought-warning zone (*Delaware River Basin Commission Resolution* No. 85-21 (Revised) Conservation Order No. 6)						
Upstream of R.M. 92.5	1,600	1,650	1,650	2,700	2,900	2,900
Between R.M. 87.0 and R.M. 92.5	1,350	1,600	1,500	2,700	2,700	2,700
Between R.M. 82.9 and R.M. 87.0	1,350	1,600	1,500	2,600	2,600	2,600
Downstream of R.M. 82.9	1,300	1,350	1,300	2,600	2,600	2,600

[1] The location of water containing chloride concentrations of 250 milligrams per liter. This "salt front" is a result of the movement of salt water upstream in the Delaware estuary. Its average location is controlled by the inflow of fresh water to the estuary.

summer growing conditions in the upper Delaware River basin and near-normal streamflow by mid to late summer. These summer rains had little effect on reservoir conditions within the basin, however, because they occurred during the period of high evapotranspiration and relatively low streamflow. By the end of August, the water-supply index was 6 indicating that water-supply conditions were worse in only 6 out of the last 58 years. As a result of late-September precipitation, the water-supply index had risen to 11 by the end of September. At the end of October the water-supply index was 26, suggesting close to median conditions.

Although in a meteorological sense the Delaware River basin drought was broken by the return to normal precipitation conditions in May and June, the hydrologic drought continued late into the summer season. This dichotomy arose from several factors. First, after 9 consecutive months of below-normal precipitation, reservoir reserves had been severely depleted. (See figure 12.) Second, a period of above-normal precipitation was needed to restore depleted soil moisture and ground-water resources. Finally, the difference in time between the ending of the meteorologic drought and hydrologic drought in this particular instance had to do with seasonality. The restoration of reservoir levels in response to normal amounts of precipitation was slow owing to the high summer rates of evapotranspiration. Had the return to normal precipitation occurred at almost any other time of year, the lag in the ending of the hydrologic drought probably would have been less.

MANAGEMENT ACTIVITIES IN RESPONSE TO THE DROUGHT

At the beginning of the water-supply operation year, June 1, 1984, the three Delaware River basin reservoirs, which have a combined capacity of 271 billion gallons, were spilling (fig. 10). The below-normal precipitation beginning in August 1984, coupled with normal releases to maintain the Montague flow objective and the New York City diversion rates specified by the decree, caused the storage to decline rapidly reaching the drought-warning level on November 27, 1984. Heavy rainfall, averaging almost 2 inches over the upper basin, occurred on November 29 to 30 causing the storage to increase above the drought-warning zone. This increase averted the need to impose restrictions on diversions and releases at that time, but the delay was short lived, and the storage again declined to the drought-warning level on January 18, 1985.

On January 23, 1985, per the "Good Faith Agreement," the streamflow objective at the U.S. Geological Survey streamflow-gaging station at Montague, N.J., was reduced from 1,750 ft^3/s to 1,655 ft^3/s. In addition, maximum allowable diversions to the New York City water-supply system were reduced from 800 Mgal/d to 680 Mgal/d; allowable diversions from the Delaware basin to the State of New Jersey were reduced from 100 Mgal/d to 85 Mgal/d; and conservation releases from each of the reservoirs serving New York City were reduced.

On February 7, 1985, combined reservoir storage declined into the lower half of the drought-warning zone. In response, the streamflow objective at Montague, N.J., was reduced to 1,550 ft^3/s, New York City diversions were reduced to 560 Mgal/d, and New Jersey diversions were reduced to 70 Mgal/d.

During the next 5 months, from February to June 1985, the water-supply situation worsened. The 5-month precipitation was about 4 inches below average, bringing the total shortage since August 1984 to almost 11 inches. Reservoir storage continued in the drought-warning zone of the rule curve (fig. 10). On May 13, 1985, the Delaware River Basin Commission declared a state of water-supply emergency which, in addition to instituting restrictions on nonessential water uses in the basin, temporarily placed all stored waters in the basin including the power company reservoirs in the upper basin under Commission control. In effect, this action put the operating schedules of the hydroelectric facilities under Commission control to help augment river flows and conserve reservoir storage. In addition, the Commission reduced conservation releases from all reservoirs and entered into a contract with the U.S. Army Corps of Engineers to store additional water in Francis E. Walter Reservoir for use at a later time if the drought worsened. The restrictions on nonessential water uses included a ban on car washing, lawn watering, golf-course irrigation, and street and driveway cleaning.

On July 5, 1985, the Executive Director of the Delaware River Basin Commission, with the consent of the parties to the U.S. Supreme Court decree, set aside 1.29 billion gallons (2,000 ft^3/s-day) of stored water for release by the New York State Department of Environmental Conservation to control water temperatures and prevent possible fishkills downstream from the reservoirs. This volume was increased subsequently by Commission action on July 24, 1985, to 2.26 billion gallons (3,500 ft^3/s-day). This water was released from the New York City reservoirs in addition to amounts released according to the Montague formula, during the period July 9 to August 15, 1985. Also on July 24, 1985, the Delaware River Basin Commission, with the consent of the parties to the decree, passed a resolution to temporarily amend the schedule of reductions in diversions and streamflow objectives contained in the "Good Faith Agreement" for periods of reservoir storage in the drought-warning zone (table 3*B*). The amended schedule was placed in effect as of July 25, 1985, and immediately reduced allowable diversions to New York City and New Jersey to 540 and 68 Mgal/d, respectively.

The amended schedule also adjusted the flow objectives for the Delaware River at Montague and Trenton, N.J., to be contingent on time of the year and location of the 7-day average 250 mg/L (milligrams per liter) chloride concentration in the Delaware estuary (table 3*B*). The 7-day average chloride concentration ("salt front") was located downstream of river mile 82.9. Therefore, the streamflow objective at Montague, N.J., was reduced to 1,350 ft^3/s and to 2,600 ft^3/s at Trenton, N.J., as required by the amended schedule. On September 1, 1985, the "salt front" was still located downstream of river mile 82.9 so that the Montague streamflow objective was further reduced to 1,300 ft^3/s. On

Figure 12. Pepacton Reservoir, New York, on May 19, 1985. Reservoir storage on that day was 263,040 acre-feet (85.7 billion gallons), which was about 61 percent of capacity; water-level elevation was 1,246.65 feet above sea level. By mid-September just before Hurricane Gloria, the reservoir level had dropped to 1,217.8 feet and the reservoir storage was 153,440 acre-feet (50.0 billion gallons), which was 36 percent of capacity. The spillway level (treeline on photograph) is 1,280 feet. (Photograph courtesy of Alison Peck Smith, *The River Reporter*, Narrowsburg, N.Y.)

September 13, 1985, the "salt front" migrated upstream of river mile 82.9, and the Montague streamflow objective according to the amended schedule (table 3*B*) should have been increased to 1,500 ft^3/s. Part of the agreement to release the additional 3,500 ft^3/s-day (2.26 billion gallons of water during July and August required, however, that during periods when thermal stress was not expected, the Montague streamflow objective would be reduced by an amount ranging from 125 to 250 ft^3/s until the 3,500 ft^3/s-day were paid back. Therefore, the thermal release payback agreement resulted in a streamflow objective at Montague of 1,375 ft^3/s until the thermal releases were paid back on September 27, 1985.

On October 2, with reservoir storage 28 billion gallons above the upper drought-warning curve, the amended schedule was dropped, and the original "Good Faith Agreement" schedules (tables 2, 3*A*) were restored. Water-use restrictions and reservoir operations continued, however, as though the combined storage was still in the drought-warning zone.

On October 30, the Delaware River Basin Commission lifted the mandatory water-use restrictions, but the parties to the decree agreed to continue a reduced level of operations of the reservoirs serving New York City until February 1, 1986, or until further modified by unanimous agreement. As a result of the mandatory water-use restrictions and voluntary conservation measures, water use in New York City was reduced by about 20 percent. Effective November 1, the Montague streamflow objective was increased from 1,655 to 1,700 ft^3/s and allowable diversions to New York City were increased from 680 to 740 Mgal/d. The allowable New Jersey diversions and the streamflow objective for Trenton were returned to normal levels.

In addition to the above actions, which were taken within the Delaware River basin to combat the drought, New York City also acted to conserve water supplies. In January 1985, the city began pumping from its reservoirs in the Croton watershed of the Hudson River basin to increase the amount of water that the city normally gets by gravity from that part of the system. On February 25, the Mayor of New York City declared a "drought watch," which is the first step in the city's drought-management plan, and requested residents to begin voluntary conservation measures. The drought watch was upgraded to a drought warning on April 3 and additional voluntary conservation measures were imposed. On April 26, a drought emergency was declared and mandatory conservation measures were imposed banning nonessential water use within the city in an attempt to reduce water consumption by 15 percent. The emergency was upgraded to a Stage II drought emergency on June 5; further restrictions were imposed which mandated an additional 5 percent reduction in water consumption. A Stage III drought emergency was declared on July 10, and allowable water use was reduced by an additional 5 percent. On the same day, the city reactivated the Hudson River pumping station at Chelsea (60 miles north of New York City and 10 miles south of Poughkeepsie) to provide up to 100 Mgal/day of water to the city; this action allowed the city to reduce the consumption of water from the reservoirs. The Chelsea pumping station was operated for 155 days, from July 10 to December 11, and provided an average of 83 Mgal/day of water to the city.

Precipitation in the upper Delaware River basin during November 1985 was 6.23 inches—167 percent of the long-term average for November. Runoff from this above-normal precipitation maintained streamflow at above-normal levels and significantly increased reservoir storage as shown in figure 10. On November 27, in response to the much improved hydrologic conditions and increased storage in the reservoirs, the city reduced the drought emergency to drought-warning status. On December 18, 1985, the Delaware River Basin Commission declared an end to the drought emergency. The following day, diversions and releases from New York City reservoirs were returned to normal levels specified by the decree. On February 25, 1986, the Mayor declared an end to the drought.

At the height of the drought in July 1985, the Mayor convened an Intergovernmental Task Force on New York City Water Supply Needs. The purpose of this task force was to make recommendations that the city could take to increase the dependability of its water supply and, thus, reduce its vulnerability to a drought similar to the one experienced in 1984–85 (New York City Intergovernmental Task Force on New York City Water Supply Needs, 1986).

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GREAT LAKES SET RECORD HIGH WATER LEVELS

By Kerie J. Hitt and John B. Miller

Record high monthly mean water levels in Lakes Michigan, Huron, St. Clair, and Erie during calendar year 1985 prompted the International Joint Commission to reduce outflows from Lake Superior beginning on May 2, 1985. Such an emergency action has been deemed necessary only once before since 1921 when the control structures were completed at the outlet of the lake. Coupled with spring and fall storms common to the Great Lakes area, the high water levels exacerbated flooding and erosion along shorelines.

PROFILE OF THE GREAT LAKES SYSTEM

The Great Lakes system is comprised of the Great Lakes—Superior, Michigan, Huron, Erie, and Ontario—and their connecting waterways—St. Marys River, Straits of Mackinac, St. Clair River, Lake St. Clair, Detroit River, Niagara River and Welland Canal, and St. Lawrence River (fig. 13). For the purposes of this article, Lake St. Clair is considered to be one of the Great Lakes. The volume of water stored in the Great Lakes, about 6,020 trillion gallons or 5,472 cubic miles, represents 20 percent of the world's and 95 percent of North America's fresh surface water (table 4). These surface-water resources and their role in commerce have attracted 40 million people to live in the Great Lakes basin—about one-seventh of the total population of the United States and about one-third of the total population of Canada. As a result, over 20 percent of the Great Lakes shoreline has been developed as residential property (International Joint Commission, 1985a, p. 5-6).

Water in the Great Lakes system flows from Lake Superior (elevation 600.59 feet) to Lake Michigan and Lake Huron (elevation 578.27 feet). From a hydrologic point of view, Lakes Michigan and Huron are considered to be one lake because the elevation of their water surfaces is the same (fig. 13). From Lakes Michigan-Huron, water flows through Lake St. Clair to Lake Erie. Leaving Lake Erie, water plummets over Niagara Falls into Lake Ontario (elevation 244.71 feet). The outflow of Lake Ontario moves down the St. Lawrence River and ultimately empties into the Atlantic Ocean. Niagara Falls, between Lake Erie and Lake Ontario, precludes changes in the water level of Lake Ontario from influencing the level of the upstream lakes. On the other hand, the small difference in elevation between Lakes Michigan-Huron and Lake Erie allows changes in the water levels of Lakes St. Clair and Erie to be transmitted to Lakes Michigan-Huron (International Joint Commission, 1985b, p. 3).

REGULATION OF THE GREAT LAKES

To provide adequate water depths for navigation and to assure dependable flows for the production of hydroelectric power, the outflows of Lakes Superior and Ontario are regulated by control structures at their outlets. These structures are operated in accordance with rules established by the International Joint Commission, an organization set up by the Boundary Waters Treaty of 1909 between the United States and Canada.

Control works in the St. Marys River near Sault Ste. Marie, Mich., have regulated outflows from Lake Superior since 1921. These flows through the St. Marys River represent, on the average, 40 percent of the total inflow to Lakes Michigan and Huron. The works are operated under the International Joint Commission's Regulation Plan 1977, whose overall goal is balancing the levels between Lake Superior and Lakes Michigan-Huron. Plan 1977 has the following objectives (International Joint Commission, 1985b, p. 27):

- The monthly mean level of Lake Superior shall not exceed an elevation of 602.0 feet.
- The monthly mean level of Lake Superior shall not fall below 598.4 feet and impair navigation.
- When the level of Lake Superior is less than 600.5 feet, the outflow of the Lake shall not be greater than flows before the regulating works were constructed.
- The maximum outflow of Lake Superior in the winter shall be 85,000 ft^3/s (cubic feet per second) [54,945 Mgal/d (million gallons per day)] to minimize ice jams on the St. Marys River.

The International Lake Superior Board of Control monitors and reports the flows of the St. Marys River and the levels of Lakes Superior, Michigan, and Huron.

Lake Ontario has been regulated since 1960 by control structures in the St. Lawrence River near Ogdensburg, N.Y. These structures have no effect on the upper Great Lakes because of Niagara Falls. The control structures are operated under the International Joint Commission's Regulation Plan 1958-D. Plan 1958-D outlines the following objectives (International Joint Commission, 1985b, p. 35):

- Provide adequate depths and acceptable velocities for navigation.
- Provide dependable flow for hydroelectric power generation.
- Reduce ranges of levels on Lake Ontario.

The International St. Lawrence River Board of Control monitors and reports outflows from Lake Ontario.

Levels and outflows of the middle lakes—Michigan-Huron, St. Clair, and Lake Erie—are determined by the discharge capacities of the rivers that drain them. These are the lakes that experienced the brunt of the high water levels during 1985.

DIVERSIONS OF WATER

Five major diversions transfer water into, out of, or between the Great Lakes and the connecting waterways (fig. 13). The first two, Long Lac (completed in 1941) and Ogoki (completed in 1943), take

Figure 13. The Great Lakes system showing lake profiles and average monthly water-level elevations, 1900–84. Elevations are in feet and are referenced to International Great Lakes Datum 1955. Zero Great Lakes datum ranges from about 0.7 foot to about 2 feet below sea level. (Sources: Great Lakes system modified from U.S. Army Corps of Engineers, 1985a, and International Joint Commission, 1985a; lake profiles from U.S. Army Corps of Engineers, 1985a; lake-level data from National Oceanic and Atmospheric Administration, National Ocean Service.)

water from rivers in Canada, which under natural conditions would flow into the Hudson Bay drainage basin, and divert it into Lake Superior for hydroelectric power generation downstream. The combined diversion, which averaged about 5,600 ft³/s (3,600 Mgal/d) from July 1943 to December 1979, has a net effect of increasing the supply of water to the Great Lakes and increasing mean lake levels (International Joint Commission, 1985a, p. 13).

The third diversion is a canal system at Chicago that takes water from Lake Michigan for water supply and other uses and then transfers it to the upper Mississippi River basin. The total authorized annual diversion is 3,200 ft³/s (2,100 Mgal/d), and the net effect is a decrease in the water supply of Lake Michigan and a consequent reduction in average lake levels (International Joint Commission, 1985a, p. 15).

The Welland Canal, the fourth diversion, connects Lake Erie and Lake Ontario, bypassing Niagara Falls. The 1980 annual rate of diversion was 9,200 ft³/s (5,900 Mgal/d). The net effect is an increase in the outflow capacity of Lake Erie and a consequent reduction in the average level of Lakes Erie, Michigan-Huron, and Superior (International Joint Commission, 1985a, p. 16–18).

The last major diversion is the New York State Barge Canal, which takes water from the Niagara River for navigation. The water eventually returns to Lake Ontario via tributaries and canals; the Barge Canal has virtually no effect on the Great Lakes. The estimated current (1985) diversion averages 700 ft³/s (450 Mgal/day) with a maximum of 1,100 ft³/s (700 Mgal/day) (International Joint Commission, 1985a, p. 20).

FLUCTUATING WATER LEVELS

Long-term water-level fluctuations in the Great Lakes generally are caused by variations in the total

Table 4. Selected facts about the Great Lakes system

[Abbreviations: mi = miles; mi^2 = square miles; mi^3 = cubic miles. Source: International Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1977]

Lake	Volume (mi^3)	Water surface area (mi^2)	Drainage area (mi^2)	Shoreline length (includes islands) (mi)	Outlet	Remarks
Superior	2,900	31,700	49,300	2,726	St. Marys River to Lake Huron.	Largest surface area of all the freshwater lakes in the world. Outflow controlled by St. Marys River Compensating works.
Michigan	1,180	22,300	45,600	1,638	Straits of Mackinac to Lake Huron.	Sixth largest surface area of world's freshwater lakes.
Huron	850	23,000	51,700	3,827	St. Clair River to Lake St. Clair.	Fifth largest surface area of world's freshwater lakes.
St. Clair	1	430	4,800	257	Detroit River to Lake Erie.	Shallowest lake in the Great Lakes system.
Erie	116	9,910	22,720	871	Niagara River and Falls to Lake Ontario.	Eleventh largest surface area of world's freshwater lakes.
Ontario	393	7,340	23,400	712	St. Lawrence River to Atlantic Ocean.	Outflow controlled by St. Lawrence Seaway and Power Project.
Total	5,440	94,680	197,520	10,031		

water supply, which depends on inflow to and outflow from the system. Inflow to the system is from precipitation falling on the surface of the lakes, runoff from the Great Lakes drainage basin, inflow from ground water, and artificial diversions into the system. Outflow from the system occurs by evaporation from lake surfaces, by the discharge of the St. Lawrence River, and by diversions from the system.

The enormous storage capacity of the Great Lakes generally absorbs most of the variations in water supply; however, the water levels of the lakes do fluctuate from year to year and from season to season. Normally, the range in water levels is only a few feet with the overall range in annual levels about 6 feet (table 5; figs. 14, 15). In the early 1950's and early 1970's, the mean annual levels of the Great Lakes reached record highs after periods of record low levels in the mid-1930's and the mid-1960's (International Joint Commission, 1985b, p. 8).

The lakes usually are at their lowest seasonal levels in the winter (fig. 14). As precipitation and snowmelt increase runoff in late winter and spring, the lake levels rise. Smaller lakes, such as Erie and Ontario, usually reach their highest levels in June. Lake Superior generally reaches its maximum level in September. The lake levels begin their seasonal decline when high evaporation and low runoff cause the net inflow to the system to become negative (International Joint Commission, 1985b, p. 9).

The precipitation and air temperature regimes prevailing over the Great Lakes basin strongly influence the levels of the lakes. Lower air temperatures, for example, result in more runoff for a given amount of precipitation because evaporation and transpiration are less. Since 1940, precipitation generally has been above average, although below-average precipitation in the early 1960's led to record low lake levels (fig. 15). From the late 1960's to the present, the combination of above-average precipitation and below-average air temperatures has caused lake levels generally to rise (International Joint Commission, 1985b, p. 13-18).

RECENT HIGH WATER LEVELS

At the beginning of water year 1985 (October 1984), monthly mean water levels of Lakes Superior, Michigan-Huron, St. Clair, and Erie were above their respective long-term (1900-84) monthly averages for October (fig. 14). The October 1984 monthly mean water levels for Lakes Michigan-Huron and Erie were about 1.5 feet above their long-term average levels.

Table 5. Water levels of the Great Lakes, 1900-84

[Levels are referenced to International Great Lakes Datum 1955. Source: National Oceanic and Atmospheric Administration, National Ocean Service]

Lake	Lake surface elevation, in feet					
	Monthly mean			Monthly range (from winter low to summer high)		
	Average	Maximum	Minimum	Average	Maximum	Minimum
Superior	600.59	602.02	598.23	1.2	2.1	0.4
Michigan-Huron	578.27	581.04	575.35	1.2	2.1	.4
St. Clair	573.34	576.23	569.86	1.7	3.3	.6
Erie	570.44	573.51	567.49	1.6	2.8	.9
Ontario	244.71	248.06	241.45	2.0	3.6	.7

Above-average precipitation from December 1984 to March 1985 coupled with a major snowmelt during February caused April and May monthly mean water levels in Lakes Michigan-Huron and Erie to exceed their previous record high levels. Lake St. Clair also set new record highs in March, April, and May 1985. The monthly mean water levels of Lakes Michigan-Huron and Erie were more than 2 feet above their respective long-term averages for April and May.

To mitigate flooding and erosion due to high water levels in the middle lakes, several management actions were taken. The International Joint Commission ordered outflows from Lake Superior reduced by 30 percent below the normal flow prescribed by Plan 1977 beginning on May 2, 1985. This reduction was intended to last until October 1985. The purpose of this action was to reduce inflows into Lakes Michigan-Huron—and thus reduce their levels—without raising

Landsat multispectral imagery of the Great Lakes, obtained during 1972–74. (From the Canadian National Air Photo Library with permission of Energy, Mines and Resources Canada. Roll number EMG 1303, copyright 1975, Her Majesty the Queen in Right of Canada.)

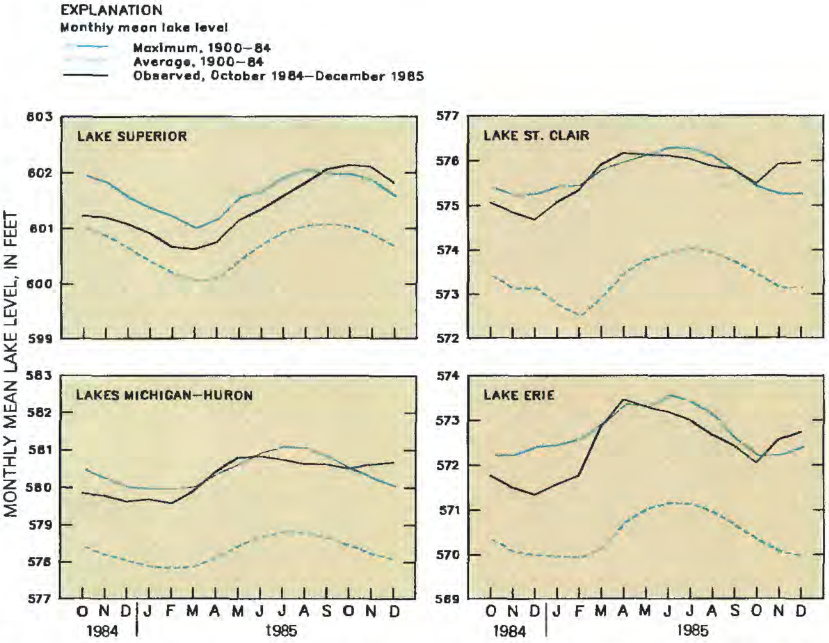

Figure 14. Monthly mean lake levels, October 1984–December 1985, compared with the long-term average and maximum monthly levels, 1900–84. Lake Ontario is not included because it did not set any record monthly highs during the period. Levels are referenced to International Great Lakes Datum 1955. (Source: Compiled by K. J. Hitt from data in U.S. Army Corps of Engineers, 1985b, and from data from Ron Wilshaw, U.S. Army Corps of Engineers, oral commun., January 1986.)

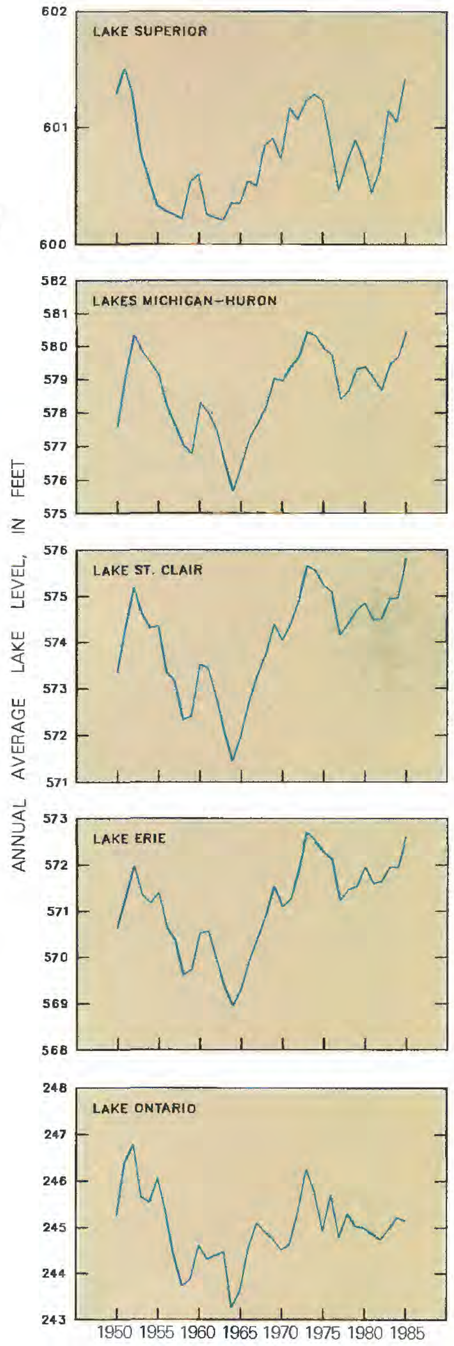

Figure 15. Long-term fluctuations in the water levels of the Great Lakes, 1950–85. Levels are referenced to International Great Lakes Datum 1955. (Source: Compiled by K. J. Hitt from data collected by National Oceanic and Atmospheric Administration, National Ocean Service.)

the level of Lake Superior above the 602-foot monthly mean limit specified by Plan 1977. The action was in keeping with the objective of "systematic regulation" of the lakes to balance the level of Lake Superior with the level of Lakes Michigan-Huron (International Joint Commission, 1985c). On June 28, 1985, in response to a request by the U.S. Department of State, Canada began withholding 4,000 ft³/s (2,586 Mgal/d) of outflow from the Ogoki diversion, which normally diverts water from the Hudson Bay drainage basin into Lake Superior (U.S. Army Corps of Engineers, 1985c).

Between April and July 1985, precipitation was below average. Despite this, levels of all the Great Lakes remained above their long-term monthly averages, but they did not set new record monthly highs for June or July. The International Joint Commission specified that the June outflow from Lake Superior should average less than 69,000 ft³/s (44,602 Mgal/d) (International Joint Commission, 1985d).

Above-average precipitation during August and September, however, caused water levels of Lakes Michigan-Huron, St. Clair, and Erie to again rise to record monthly highs. Lakes Michigan-Huron exceeded previous record monthly levels for October, November, and December. Lake Erie broke record highs for November and December, and Lake St. Clair reached new record high levels for September, October, November, and December. The December 1985 levels of Lakes Michigan-Huron and Erie were about 2.69 feet and 2.82 feet, respectively, above their long-term December averages.

In the Lake Superior basin, rainfall was above average in August, September, and October (35, 90, and 19 percent, respectively). During those months the International Joint Commission, which had kept the outflow for Lake Superior below normal to the extent possible, had to increase the outflows to avoid raising the lake level above the 602.0-foot level required by Plan 1977 (U.S. Army Corps of Engineers, 1985e). In spite of this action, during September the monthly mean level of Lake Superior rose to a new record of 602.06 feet.

Lake Superior continued to rise during October and then began to fall during November and December. The lake level reached a new all-time record high of 602.24 feet both in October and November and exceeded the previous monthly high for December. The December level was 1.2 feet above the long-term average for that month (U.S. Army Corps of Engineers, 1986). This increase in lake level occurred despite the fact that from mid-October until mid-December the outflow from the lake averaged a record rate of about 133,000 ft³/s (85,973 Mgal/d). Although the outflow from Lake Superior was reduced for most of the summer by closing the control gates at Sault Ste. Marie in an attempt to lower the levels of the middle lakes, by the end of November, the levels of Lakes Michigan-Huron had been lowered by only 1 inch, Lake St. Clair by 1.25 inches, and Lake Erie by 1.25 inches (U.S. Army Corps of Engineers, 1985f).

EFFECTS OF HIGH LAKE LEVELS

High water levels in lakes are not necessarily damaging by themselves, but when the wind produces large waves on top of the high waters, flooding and erosion can result, as illustrated in figure 16. During a storm, the difference between the level at one end of a lake and the level at the opposite end of the lake can be as great as 16 feet. The shoreline of western Lake Erie, for example, is especially prone to flooding caused by storm surges because the shoreline is gently sloping. Moreover, the lake's long axis is alined northeast to southwest. Storm-generated winds from the northeast can cause water levels to rise as much as 8 feet in a few hours. Fluctuations in lake levels caused by storm surge cause the most damage (International Joint Commission, 1985b, p. 10).

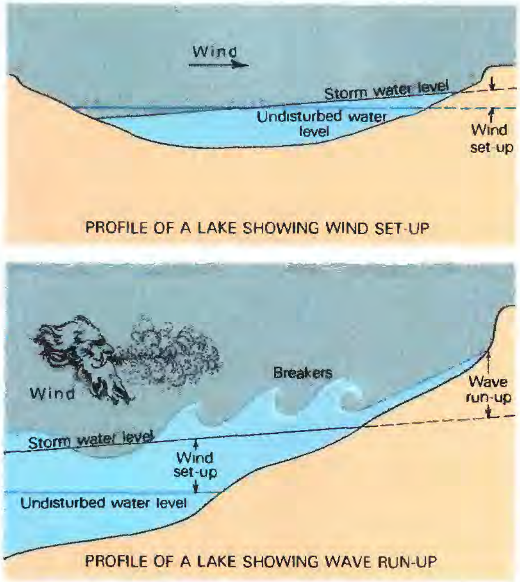

Figure 16. Effects of wind on lake water levels. (Source: Modified from U.S. Army Corps of Engineers, 1985a, fig. 10.)

In areas with gently sloping beaches, only a few inches of wind-driven water can diminish the shoreline by several feet. On steep shorelines with easily eroded soils, such as the highly unstable clay bluffs along parts of Lake Superior in northwestern Wisconsin, the waves undercut the bluffs and cause them to fall. In these areas, the shoreline may lose as much as 15 to 20 feet in 1 day (John Wolf, U.S. Army Corps of Engineers, oral commun., November 1985).

Although existing diversions of water may be used as temporary measures to alleviate problems caused by extreme lake levels, fluctuations of the Great Lakes will recur in response to climatic factors. Control structures at the outlets of Lakes Superior and Ontario have only minimal effects on lake levels. Although the amount of outflows can be controlled partially, the amount of inflow to the lakes cannot be controlled. Consequently, flooding and erosion of the shoreline by storm surges may be expected to continue despite attempts to manipulate lake levels.

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STORM AND FLOOD OF AUGUST 1, 1985, IN CHEYENNE, WYOMING

By H. W. Lowham and Stanley A. Druse

Twelve deaths, 70 injuries, and $61.1 million in damage to homes and personal property, government properties, businesses, utilities, and agriculture were the result of flooding, precipitated by the massive thunderstorm that drenched Cheyenne with 7 inches of rain and hail the evening of August 1, 1985 (J. D. Swanson, Federal Emergency Management Agency, written commun., 1985). Three and one-half inches of rain fell in 1 hour initiating the most damaging flood in Wyoming in over 120 years. The city was declared a major disaster area by the President.

Thursday, August 1, 1985, began with fog blanketing much of southeastern Wyoming during the early morning hours (W. T. Parker, National Weather Service, Cheyenne, Wyo., written commun., 1985). A moist air mass and an unstable atmosphere created favorable conditions for severe weather, and radar imagery indicated that large thunderstorms were developing during the afternoon. The storm that caused the damage developed as a cell of only moderate intensity southeast of the city. About 6 p.m., the storm cell increased in intensity and moved over Cheyenne (fig. 18). Analysis later showed that several secondary cells merged with the larger storm cell, creating severe in-

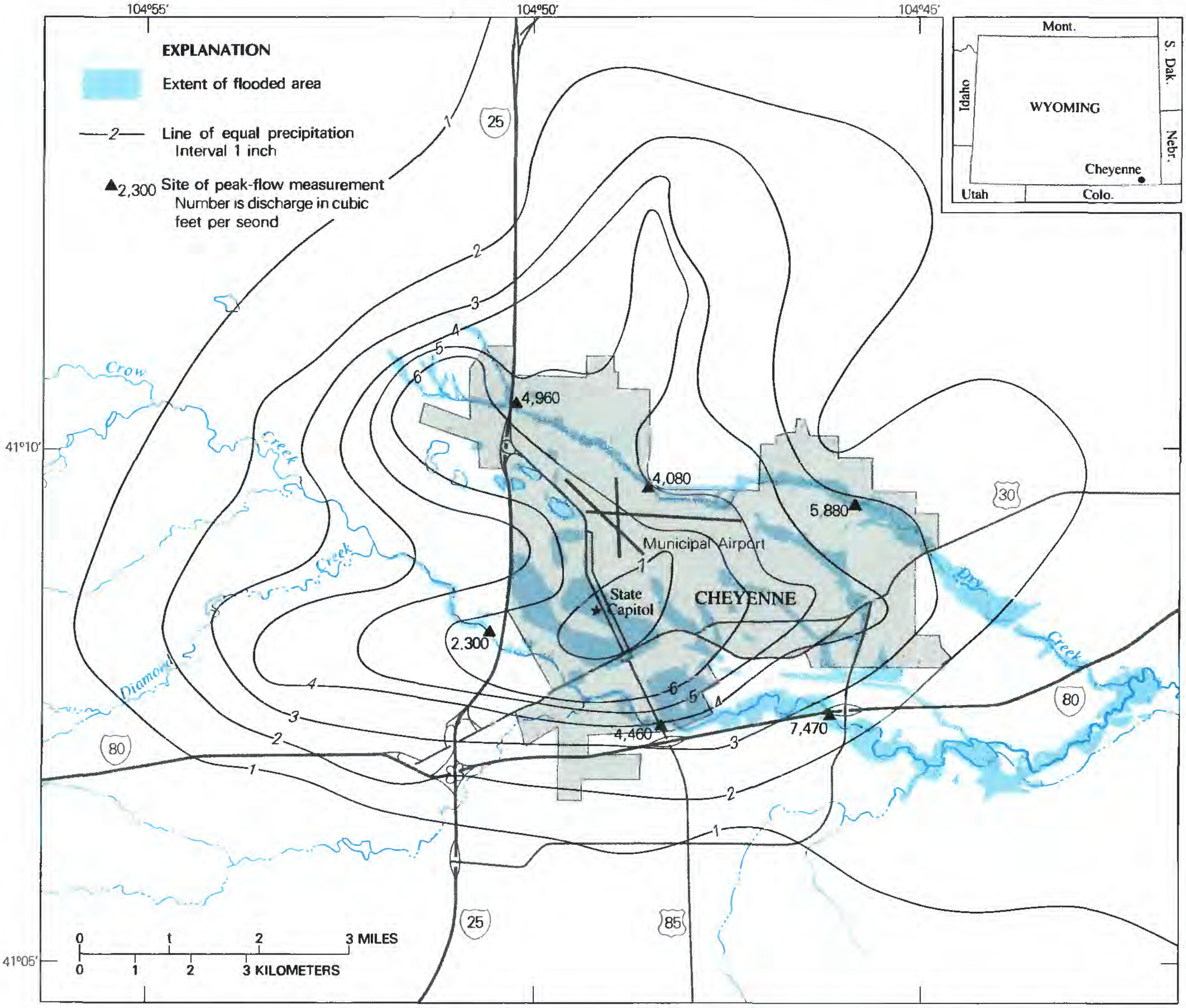

Figure 17. Precipitation and selected peak flows of Dry Creek and Crow Creek resulting from the storm of August 1, 1985, Cheyenne, Wyo. (Source: Precipitation data compiled by National Weather Service on U.S. Geological Survey base map, Cheyenne, 1981, 1:100,000; peak-flow data from U.S. Geological Survey files.)

tensity while the storm remained fairly stationary over the city. The top of the storm reached an altitude of more than 60,000 feet above sea level.

Torrential rain, hail as large as 2 inches in diameter, and 70 mile-per-hour winds prevailed when the storm was at the height of its fury. New 1-hour and 24-hour rainfall records were set for both Wyoming and Cheyenne as 3.51 inches of rain were recorded between 8:00 p.m. and 9:00 p.m., and 6.06 inches between 6:20 p.m. and 9:45 p.m. at the National Weather Service station at the municipal airport.

The intense rainfall caused severe flooding on Dry Creek and Crow Creek, two streams that drain most of Cheyenne (fig. 17). Dry Creek is an ephemeral stream that originates just northwest of the city. Its main channel trends in a southeasterly direction through newly developed neighborhoods and commercial areas. Crow Creek is a perennial stream that originates about 30 miles to the west. It drains about 250 mi^2 (square miles) upstream from Cheyenne. Crow Creek flows southeasterly through the southern section of the city.

Figure 18. Thunderhead over Cheyenne, Wyo., during evening of August 1, 1985, as viewed from location 40 miles south. (Photograph courtesy of Mike Mussetter, Simons, Li & Associates, Inc.)

Figure 19. Hail was deposited in low-lying areas of Cheyenne, Wyo., to depths of 3 feet and greater. (Photograph courtesy of Michael Mee, Federal Emergency Management Agency, Region VIII.)

The flooding along Dry Creek was much more destructive than that along Crow Creek, even though the Crow Creek drainage area is larger and received the greatest amount of precipitation. Although Dry Creek is a relatively small drainage, its headwater tributaries merge in a tree-branch pattern, which is very efficient in draining runoff quickly from the area. Flows from the individual tributaries combined in the main channel to create a peak discharge of 4,960 ft^3/s (cubic feet per second) where the stream crosses Interstate 25 (Druse and others, 1986). A recurrence frequency was not determined for this discharge; however, it greatly exceeded the theoretical 100-year flood of 850 ft^3/s estimated for this site in a flood-insurance study of Dry Creek (Federal Emergency Management Agency, 1982). The drainage area of this site is 1.88 mi^2, which resulted in a peak-flow yield of 2,640 ft^3/s per square mile.

In the central and southern areas of the city, overland flows and street flows were 2 feet or more in depth. Many storm drains and culverts were clogged with debris, and the backwater contributed to flooding in many areas (fig. 19). The severity of the storm claimed the lives of 12 people. Nine drownings were attributed to attempts made to drive across roads flooded by Dry Creek. The road crossings were dark, and the victims obviously were unaware of the force of rapidly moving water.

The residents of Cheyenne demonstrated a spirit of helpfulness following the flood. Volunteers from Warren Air Force Base, businesses, service organizations, and neighboring communities quickly responded to assist those most severely affected by the flood.

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DISINTEGRATION OF COLUMBIA GLACIER, ALASKA, CONTINUES UNABATED

By Mark F. Meier

The Columbia Glacier is a large, grounded, iceberg-calving glacier located in south-central Alaska (fig. 20). It has an area of about 400 mi^2 (square miles) and extends 40 miles along its main branch to the terminus in Columbia Bay (fig. 21). The terminus of Columbia Glacier has been retreating landward since about 1976, but the rate of retreat began to accelerate in 1983 (Meier and others, 1985). The retreat, which

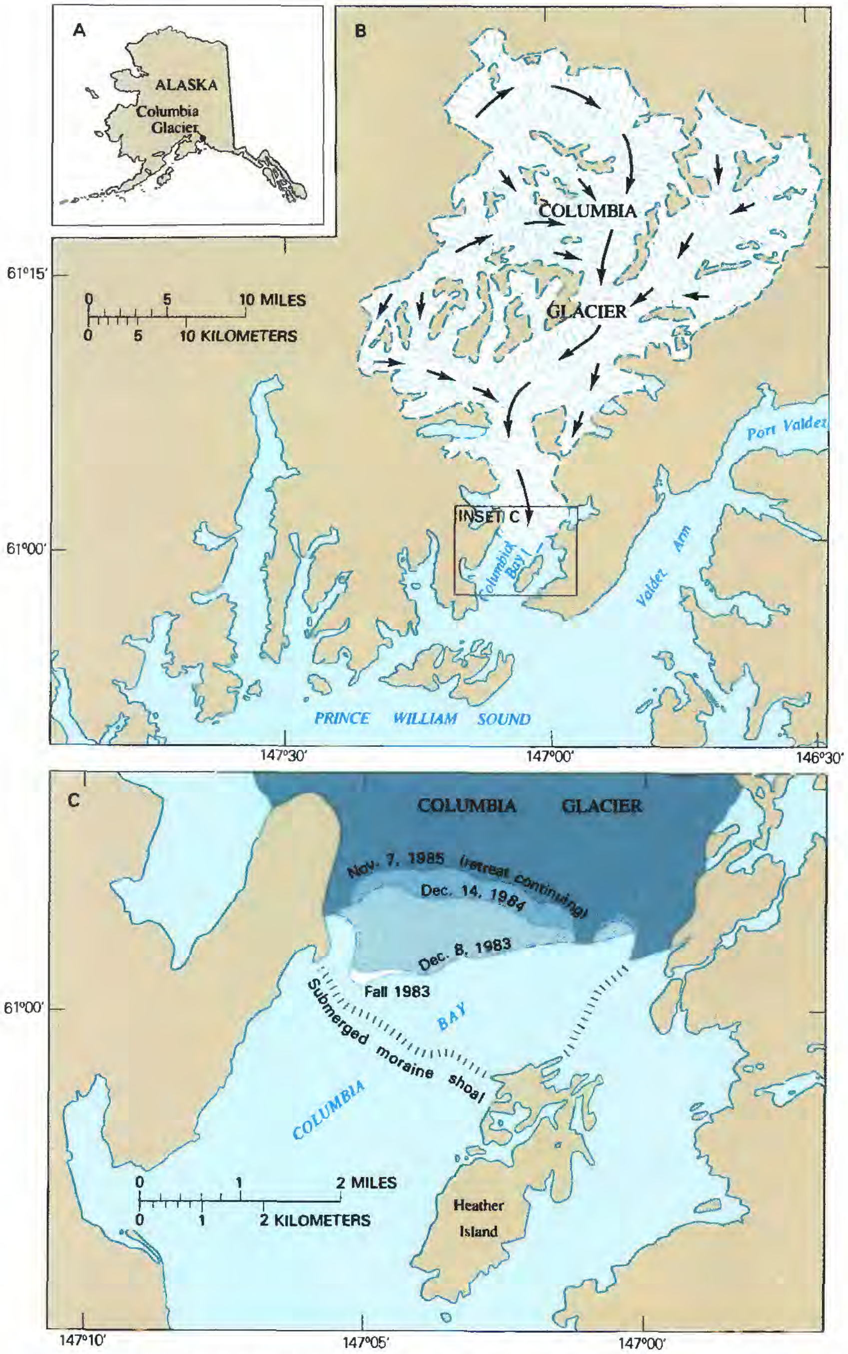

Figure 20. Columbia Glacier, Alaska, showing (*A*) location of glacier, (*B*) direction of movement of the glacier, and (*C*) the change in position of terminus of the glacier, from the fall of 1983 to November 7, 1985. (Sources: *A*-*B*, modified from Rasmussen and Meier, 1982; *C*, modified from Meier and others, 1985.)

Figure 21. Aerial view of the 3.7-mile-wide terminus of Columbia Glacier, Alaska, August 14, 1984. In front of the glacier, icebergs and smaller ice blocks are confined by a submerged moraine shoal. Beyond the shoal, icebergs drift southward along the western side of Heather Island (left center), and then occasionally to the east into Valdez Arm and Prince William Sound (in distance in left of photograph). (Photograph by M. F. Meier, U.S. Geological Survey.)

Figure 22. Typical small iceberg calved from Columbia Glacier, Alaska. (Photograph by M. F. Meier, U.S. Geological Survey.)

caused by disintegration of the terminus at a rate faster than that of the seaward flow of the glacier, is significant because, until recently, such a hydrologic event had never been documented. The event is exciting scientifically because the onset and rate of disintegration had been predicted by computer models (Meier and others, 1980; Rasmussen and Meier, 1982; Sikonia, 1982; Bindschadler and Rasmussen, 1983), which were based on the observations and hypothesis of Post (1975). After the Columbia Glacier began to disintegrate, the accuracy of the predictive models was confirmed. (The predicted date of the onset of disintegration was off by less than 2 years; the predicted rate of disintegration was close to the measured value.) The event also is of practical interest, because the rapid disintegration of a glacier such as Columbia is accomplished by a greatly increased discharge of icebergs, and icebergs from Columbia Glacier (fig. 22) sometimes drift into the shipping lanes of tankers that carry oil from Valdez, Alaska, to the lower 48 States.

The reason why such a rapid disintegration might abruptly "switch on" is related to the stability of iceberg-calving glaciers. Post (1975) surmised that the rate of iceberg calving depends on the water depth at the grounded terminus of these glaciers; if the glacier terminates in shallow water, the rate of calving will be low, and the loss of ice mass can be balanced by the replenishment of ice from glacier flow. On the other hand, if the glacier terminates in deep water, the loss of mass from iceberg calving will be so great that glacier flow cannot replenish the loss, and the glacier will be in an unbalanced condition. In this situation, retreat will be rapid and irreversible until the terminus retreats to a point where it rests in shallow water.

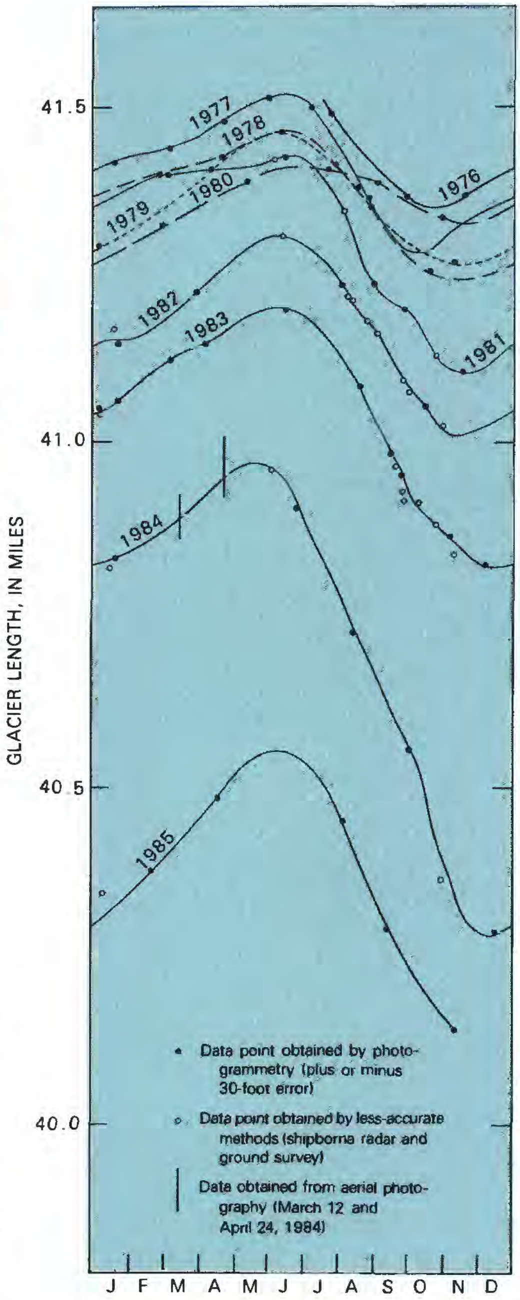

Figure 23. Seasonal advance and retreat of Columbia Glacier during 1976–85. Data obtained from aerial photography of March 12 and April 24, 1984, are plotted as vertical lines because of the difficulty in differentiating the low, irregular ice cliff from floating ice. Values are averaged over the width of the active part of the terminus. (Source: Modified from Meier and others, 1985, fig. 3.)

The terminus of Columbia Glacier was relatively stable from the time of the first scientific studies of it in 1899 until the late 1970's. During this period, the glacier terminated partly on Heather Island and partly on a submerged moraine shoal. In December 1978, the glacier terminus retreated from Heather Island, and retreat has accelerated since then.

Although the glacier has not terminated on Heather Island since 1978, part of the terminus remained on the crest of the submerged moraine shoal until the fall of 1983. By December 8, 1983, that part of the terminus (which then consisted only of a narrow ridge of ice) had receded more than 0.2 mile from the crest of the shoal and by December 14, 1984, had disappeared completely, leaving most of the terminus more than 1.2 miles behind the crest of the shoal (fig. 20*C*).

The terminus of Columbia Glacier shows a seasonal pattern of fluctuation superimposed on a long-term trend of retreat; this fluctuation is marked by an advance during the winter followed by a large amount of retreat during the summer (fig. 23). Seasonal changes in the position of the terminus are the result of seasonal changes in the rate of iceberg calving. The 0.7-mile retreat during 1984 (through December 14) was far greater than in any previous year; the next greatest retreat had been 0.4 mile in 1983. Spring and summer of 1985 in the area of Columbia Glacier were wet and cool, which may have delayed the onset of rapid iceberg calving. By mid-August, however, Columbia Glacier had already retreated 0.3 mile from its position at that time in 1984 (fig. 23), and retreat was proceeding at the same rate through mid-September 1985. By November 7, 1985, the front had receded 0.15 mile further than the farthest retreat of 1984 and was still actively receding.

The speed of calving (equal to volume of ice calved per unit time —calving discharge—divided by the area of the calving face) seems to be proportional to water depth at the front (Brown and others, 1982), or to the reciprocal, squared, of the ice thickness unsupported by buoyancy (Sikonia, 1982). Because of the channel configuration, water depth at the front has increased with the retreat of the glacier, and the ice thickness unsupported by buoyancy has decreased. This situation has resulted in an increase in calving rate and discharge. The calving discharge in 1977–78 averaged 3.3 million tons per day; by September 1, 1984, the discharge had reached 12 million tons per day.

The increased calving has caused retreat of the glacier; however, the rate of flow of the glacier near the terminus has increased in response to the retreat because removal of ice at the terminus, among other effects, decreases the longitudinal compressive stress on the ice upstream from the terminus and, consequently, increases the rate of ice flow. The velocity at the terminus averaged 13 ft/d (feet per day) in 1977–78 but had increased to 47 ft/d by August 1984. (See figure 24.)

This increase in the rate of glacier flow has caused a thinning of the glacier upstream (fig. 25). One important consequence of this thinning, in addition to the fact that the glacier now terminates where the seabed is as much as 800 feet below sea level, is that the ice thickness unsupported by buoyancy at the terminus is becoming very low. On August 8, 1985, the average thickness unsupported by buoyancy along the active terminus was only 19 feet, and at three loca-

Figure 24. Three laser distance-measuring devices used by U.S. Geological Survey scientists to measure the movement of Columbia Glacier, Alaska. These devices are programmed to take readings automatically every 10 minutes. The results are revealing new information on glacier flow. Glacier flow, which is caused by sliding at the bed of the glacier, responds to additions of liquid water from rain or ice melt and to changing water depth at the terminus caused by tides at the calving ice face. (Photograph by R. M. Krimmel, U.S. Geological Survey, August 6, 1985.)

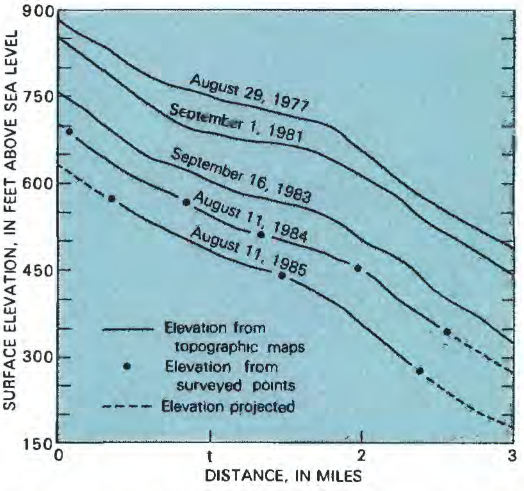

Figure 25. Elevation of surface of Columbia Glacier along a central flow line, in late summer of 1977, 1981, 1983, 1984, and 1985. The horizontal scale is not referenced to the terminus of the glacier; a fixed reference point off the glacier was used for each survey. (Source: Compiled by M. F. Meier from U.S. Geological Survey data.)

tions it was negative. (The ice would float if it had broken loose.) This thinning implies not only high rates of iceberg calving, but also high rates of ice flow according to our current understanding of basal ice sliding. The high rate of ice flow means that further reduction in ice thickness will occur and that the reduction will lead to further increases in calving and rate of ice flow. Thus, in spite of this increase in rate of ice flow caused by the rapid drawdown (thinning) of its ice reserves, increasing iceberg discharge is causing the terminus of the Columbia Glacier to retreat.

Columbia Glacier is the first opportunity for scientists to observe and study a rapidly moving, rapidly disintegrating glacier. A controversial scenario has suggested that the West Antarctic Ice Sheet might disintegrate as a result of higher air and water temperatures caused by the ''greenhouse effect'' induced by increases in atmospheric carbon dioxide concentrations (See article in this volume ''Snow, Ice, and Climate—Their Contribution to Water Supply.'') If this disintegration were to happen, the effect on global sea level would be major (National Academy of Sciences, Committee on Glaciology, 1985). Iceberg calving and rapid glacier flow, necessary for the hypothesized ice-sheet disintegration, unfortunately, are not well understood. However, observation of the disintegrating Columbia Glacier should add to basic knowledge of these processes and provide a basis for an improved evaluation of the global consequences of glacier retreat.

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MAJOR OIL SPILL ON THE DELAWARE RIVER, SEPTEMBER 1985

By Anita J. Miller[1] and Gary L. Ott[2]

At nearly midnight on September 28, 1985, at high tide, the 751-foot tanker *Grand Eagle* ran aground on a rocky shoal in the Delaware River near Claymont, Del. (See figure 26.) More than 435,000 gal (gallons) of crude oil was spilled into the water and ultimately spread over a 25-mile stretch of the river, impacting wetlands, waterfowl, recreational facilities, boat docks, and commercial river traffic. The ensuing containment and cleanup activities involved a multitude of Federal, State, private, and volunteer resources, at an estimated cost of more than $4.5 million.

The *Grand Eagle* was carrying a cargo of 22 million gal of crude oil from the Shetland Islands off Scotland to an oil-storage facility in Marcus Hook, Pa. As the tanker grounded, the rocky shoal tore a hole in the hull and ruptured the number one starboard tank that contained approximately 2.3 million gal of oil. During the first hours of the accident, the tanker was pulled from the shoal and escorted to the docks of the oil-storage facility, where several floating containment booms were deployed around the vessel in an attempt to capture the still-leaking oil. During these first few hours, the U.S. Coast Guard (USCG) notified emergency response personnel in many Federal and State agencies.

The tri-State area of Delaware, New Jersey, and Pennsylvania had just experienced the effects of Hurricane Gloria. Although the weather was clear and pleasant in the aftermath of the storm, runoff had swollen streams and rivers, and flood-cleanup operations were underway. Emergency-response personnel just finishing up with one emergency had to gear up for another.

During the night, the USCG surveyed the spill, but it was not until after helicopter overflights the following day that the extent of the emergency became obvious. By afternoon, the oil was visible on the river and shoreline from the Commodore Barry Bridge at Chester, Pa., to the Delaware Memorial Bridge near New Castle, Del.

A computer program specifically designed for such incidents was used by the National Oceanic and Atmospheric Administration (NOAA) to prepare initial trajectories for the movement of the oil. Based on current river flow, tides, winds, weather, and other data, the oil was projected to move down the Delaware River, mainly under the influence of the tides. For the first 2 days after the spill, a minor contribution to the movement of the oil came from increased streamflow associated with Hurricane Gloria rains. The leading edge of the spill was expected to advance 8 to 10 miles downstream per day.

The Delaware River at the spill site has numerous marshes and wetlands that provide important habitat for over-wintering birds, as well as feeding and resting areas for migrating ducks, geese, and other waterfowl. These habitats are considered to be very sensitive to spilled oil. Commercial shipping facilities, recreational beaches and docks, and water-supply intakes also are within the affected area. Because of tidal fluctuations, tributaries to the Delaware also were likely to be affected.

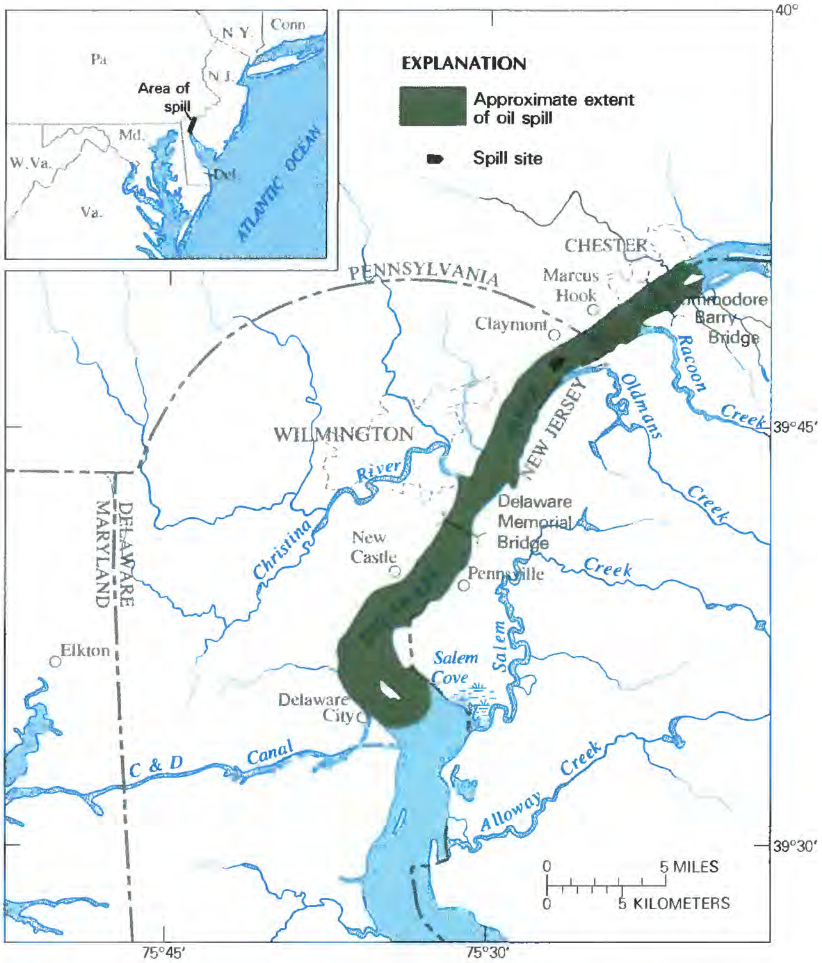

Figure 26. Area affected by oil spill in the Delaware River, September 28, 1985.

During the first day of the spill, floating containment booms were deployed in the Christina River. However, strong currents, improper deployment configurations, and inadequate surveillance and maintenance of the booms made their use ineffective. Oil was deposited along the shoreline of the Christina River, including the Port of Wilmington, for 6 miles upriver from its confluence with the Delaware. Similar problems occurred in Racoon Creek, Oldmans Creek, and other tributaries as the oil moved with the incoming tide.

Private cleanup contractors hired by the ship's owners attempted to contain and mop up the oil in the river stretch between the Commodore Barry Bridge and the Delaware Memorial Bridge. Meanwhile, the USCG directed a significant part of its effort toward cleanup and prevention of additional oil impacts

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downstream from the Delaware Memorial Bridge, deploying protective booms at key locations in an attempt to prevent oil from entering numerous creeks and wetlands, including Federal and State wildlife refuges.

In theory, protective actions taken during an oil spill may appear to be clear cut and relatively simple. In real life, the effectiveness of such actions is tempered by the river currents, number of booms available, wind direction, properties of the oil, and many other variables. For example, for some areas such as the Salem Cove and Salem River area, it proved difficult to devise a protective strategy because of the configuration of the marshlands at the mouth of the river. In addition to the use of containment and protective booming, several skimmers (vessels designed specifically to remove floating oil from the water) were deployed in the Delaware and Christina Rivers. The efforts of the skimmers met with limited success.

In addition to protective actions by the ship's owners, the USCG, and local governments, several industries, including two powerplants and a chemical company, set out their own floating booms to help protect their water intakes from the oil. No public water-supply intakes were threatened by the spill.

By September 30, considerable volumes of oil floated in uncontrolled slicks from the oil facility at Marcus Hook downstream to New Castle, Del., and to Pennsville, N.J. The slicks were described as ribbons of oil as much as 20 feet wide and 1 to 2 miles long. By October 1, the oil had reached Delaware City, near the Chesapeake and Delaware Canal that links the Delaware River with Chesapeake Bay.

Twelve days after the accident, it appeared that all of the free-floating oil had washed ashore and would stay there. Much of the oil, which had been deposited during the initial high flow caused by the Hurricane Gloria rainfall, remained stranded on the shoreline as the water receded. Between October 10 and November 7, when the USCG and State officials determined that cleanup actions had been adequate, private contractors spent many hours raking up and disposing of oiled debris and sand, and using water jets or steam to remove oil from seawalls, riprap, and other artificial structures.

Damages caused by this oil spill came in a variety of forms. A total of 78.5 acres of wetlands along the river received a moderate to heavy deposition of oil. The most severely affected area was along the State of Delaware shoreline between Deemers Beach and Edgemoor, including the city of New Castle. More than 90 cormorants, ducks, and geese affected by the oil were captured by the U.S. Fish and Wildlife Service, by the New Jersey Division of Fish, Game, and Wildlife, and by the Delaware Division of Fish and Wildlife and taken to an emergency center staffed by trained volunteers to be cleaned of the oil and nursed back to health. About 40 percent of the birds survived. As many as 200 additional birds may have been affected by the oil but were not brought to the rescue center, either because they could not be captured or because the effects of the oil had already been fatal. Battery Park, a high-use recreational area in New Castle, received heavy oil deposition. Numerous recreational and commercial vessels were affected by the oil, and river traffic was restricted during the cleanup operations.

Although spill-response efforts began immediately after the incident, there were inevitable damages. It is virtually impossible to completely prevent impacts during a spill of this magnitude on a river that sustains commerce, recreational uses, and significant fish and wildlife habitats. However, the environmental impacts of the oil spill were mitigated by the dry, sunny weather during the first 2 days of the spill, which hastened the evaporation of the more toxic hydrocarbons and reduced the total volume of oil by an estimated one-third. The fall bird migrations that would bring thousands of waterfowl and shorebirds into the area had not yet begun, and it was almost the end of the growing season for the marsh grasses and other wetland plants. Compared to losses that could conceivably have accompanied a 435,000-gal oil spill, the actual losses were relatively small. As a follow-up to the spill, three research studies were initiated by Rutgers University, the State of Delaware, and NOAA. The studies are to determine the effects of oil spills on downstream Delaware Bay oyster beds, on aquatic habitat and fish populations in the Wilmington, Del., area, and on Delaware River wetlands.

HYDROLOGIC PERSPECTIVES ON WATER ISSUES

INTRODUCTION TO

HYDROLOGIC PERSPECTIVES ON WATER ISSUES

The articles in "Hydrologic Perspectives on Water Issues" of the 1985 *National Water Summary* are grouped under the headings "Water-Availability Issues" and "Institutional and Management Issues." The first article under "Water-Availability Issues" focuses on the factors that control the spatial and temporal distribution of the Nation's surface-water resources and, by the use of examples, provides information that can be used to interpret the monthly and annual hydrographs, precipitation maps, and runoff maps presented in the State summaries. This is followed by an overview of the role of snow and ice as natural forms of water storage. Of particular concern, in the longer term, is the issue of climatic change and its impact on sea level and water resources. There now appears to be a consensus among scientists that fossil-fuel combustion and other human activities are releasing large enough quantities of carbon dioxide and other gases into the atmosphere to increase global air temperature over the next 50 years. The projected warming is expected to lead to higher sea level and probably will alter future precipitation and runoff patterns. Such changes could have significant economic and social ramifications and are the topic of increased research by Federal and academic scientists.

The storage and consumptive use of water in a river basin can significantly affect the streamflow characteristics, channel stability, water quality, and wildlife habitat downstream. The third article illustrates these changes by examples drawn from an examination of 29 dams in the Central and Western United States. The fourth article describes similar changes in the Platte River basin.

Water management is undergoing major changes (Freshwater Society, 1985). These changes are driven by several factors: increasing water demands, a fixed but renewable resource base whose physical limit is being approached in a number of areas of the country, the increasing costs of adding additional water-supply capacity, and limited budgetary resources to fund capacity expansion. A search for solutions to these problems has led to the emergence of water-management strategies based on (1) demand management through water conservation measures, water prices, and withdrawal permits; (2) management of water supplies by reuse or recycling of existing water supplies, by increasing system yield through the conjunctive use of ground water and surface water, and by the operation of individual projects in the same region or river basin as a single system; (3) the reallocation of water through the development of water markets, negotiated water transfers, or other voluntary transactions in water. The increased emphasis on water-resources management has increased the need for hydrologic data for management purposes.

The first article under the "Institutional and Management Issues" heading describes the growing availability of real-time data and the related communications system used to distribute the data to water managers and provides some examples of applications. The final two articles present several innovative approaches to some of the water-management issues facing the States. These approaches will intensify the demand for water information and the need to obtain greater understanding of the hydrology of the water-resources systems being managed.

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WATER-AVAILABILITY ISSUES

NATIONAL PERSPECTIVE ON SURFACE-WATER RESOURCES

By Bruce L. Foxworthy and David W. Moody

INTRODUCTION

Rivers have played a vital role in the development of North America. Throughout history, they have served as routes of exploration and commerce and have been a source of food and drinking water. As settlement proceeded, rivers met the Nation's demand for transportation, waterpower, and water supplies. Today the surface-water resources of the United States are extensively developed and managed to provide water supplies for industry, irrigated agriculture, hydroelectric-power generation, and navigation, to provide recreational opportunities, and to regulate instream flows for the maintenance of fish and wildlife habitats and water quality. Although water is still readily available, increasing water demands have led to competition and conflicts between users of existing supplies in some areas. This article summarizes some of the natural and human influences on the quantity of the Nation's surface waters and presents some implications for the future.

ANNUAL PRECIPITATION AND RUNOFF

Precipitation is the source of essentially all freshwater resources, and the amount of precipitation falling on the land is the most important factor controlling the variability and availability of surface water. Average annual precipitation in the United States ranges from a few tenths of an inch per year in desert areas of the Southwest to about 400 inches per year at some locations in Hawaii (fig. 27). Nationwide, average precipitation is quite abundant—about 30 inches per year. However, about one-third of the conterminous United States, mostly in the West and Midwest, receives less than 20 inches of precipitation during an average year.

Precipitation that falls on land and eventually reaches stream channels, lakes, ponds, or wetlands is termed "runoff." The amount of runoff from an area is always less than the amount of precipitation because approximately two-thirds of the precipitation either evaporates directly or is intercepted by vegetation and transpired back to the atmosphere. The remainder flows directly to local stream channels or infiltrates soil and rocks to recharge the ground-water reservoirs (aquifers).

Average annual runoff from a drainage basin commonly is calculated by dividing the average total flow volume—measured at a stream-gaging site—by the area of the drainage basin upstream from that site. The result, reported in inches per year, can then be compared directly to precipitation over the same area for the same period.

The highest runoff rates in the United States occur in southeastern Alaska and western Washington, where the annual runoff of many streams exceeds 60 inches and for a few streams is as much as 240 inches (fig. 28). Runoff from some small basins in the northern and central Rocky Mountains and in northern New York and western North Carolina exceeds 40 inches. Large areas west of 100° longitude and away from mountain ranges have runoff of only 1 inch or less; however, runoff from mountainous basins is greater. In Alaska, Hawaii, and Puerto Rico, runoff varies widely within relatively short distances.

A comparison of figures 27 and 28 shows an obvious similarity in the map patterns. That is, the areas of the conterminous United States that have large amounts of precipitation also have large amounts of runoff. A graph depicting the relation between annual average runoff and annual average precipitation for selected river basins east of about 100° W longitude shows that annual runoff is very small from basins having 20 inches or less of annual precipitation (fig. 29). Significant differences exist between figures 27 and 28, however. These disparities, which would be even larger if greater detail were shown, are caused by differences in evapotranspiration rates (water losses from evaporation plus transpiration) among the different river basins. Differences in the rates of evapotranspiration, in turn, are mainly a result of three interrelated factors—climate, topography, and geology.

In semiarid regions, major evaporation losses occur shortly after precipitation. Consequently, the only persistent sources of water available for evaporation are stream channels and lakes. Although the potential evapotranspiration rate in semiarid regions may exceed 70 inches, the lack of water available for evaporation and transpiration limits the actual rates to much smaller amounts. These actual amounts, however, nearly equal the precipitation rates in some areas, and, therefore, runoff is very small. In contrast, humid regions usually have water available for evaporation and transpiration. The annual evapotranspiration from river basins in the Eastern United States ranges from about 20 to 40 inches, depending on the latitude. Thus, evapotranspiration losses and the effects of these losses on runoff differ from basin to basin and from year to year within a basin.

The runoff from a given amount of annual precipitation also can vary considerably depending on whether the precipitation is associated with a few large storms or with many small ones. Storms with small amounts of precipitation tend to produce little or no runoff. Runoff from an annual precipitation of 25 inches, for example, will be greater if that precipitation occurs in a few large storms than if it occurs in many storms of a half inch or less. Although most of the differences in runoff shown in figure 28 are the result of differences in annual precipitation, runoff is affected to some extent by the season in which the major precipitation occurs and by the time-distribution of the precipitation.

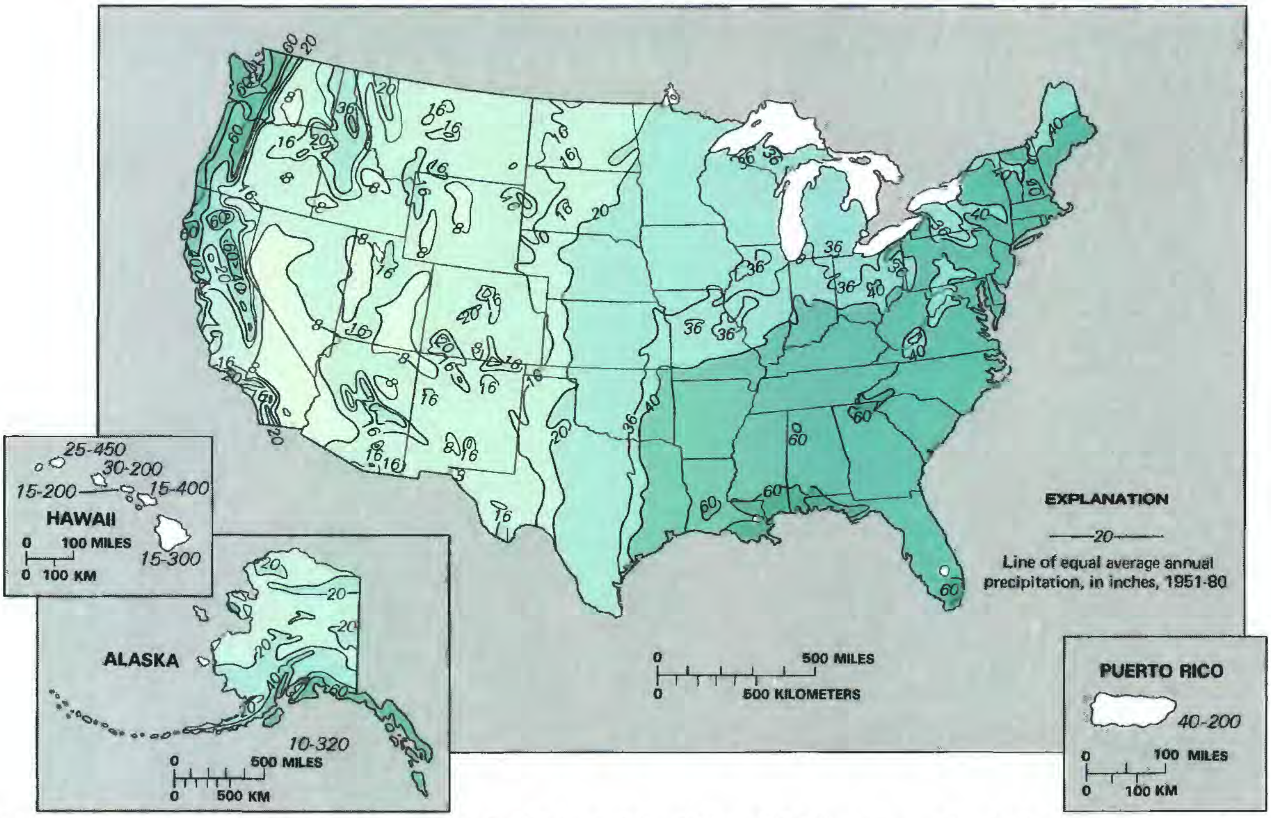

Figure 27. Average annual precipitation in the United States and Puerto Rico, 1951-80. (Source: Data for the conterminous United States from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration, 1985; data for Alaska, Hawaii, and Puerto Rico from National Oceanic and Atmospheric Administration files.)

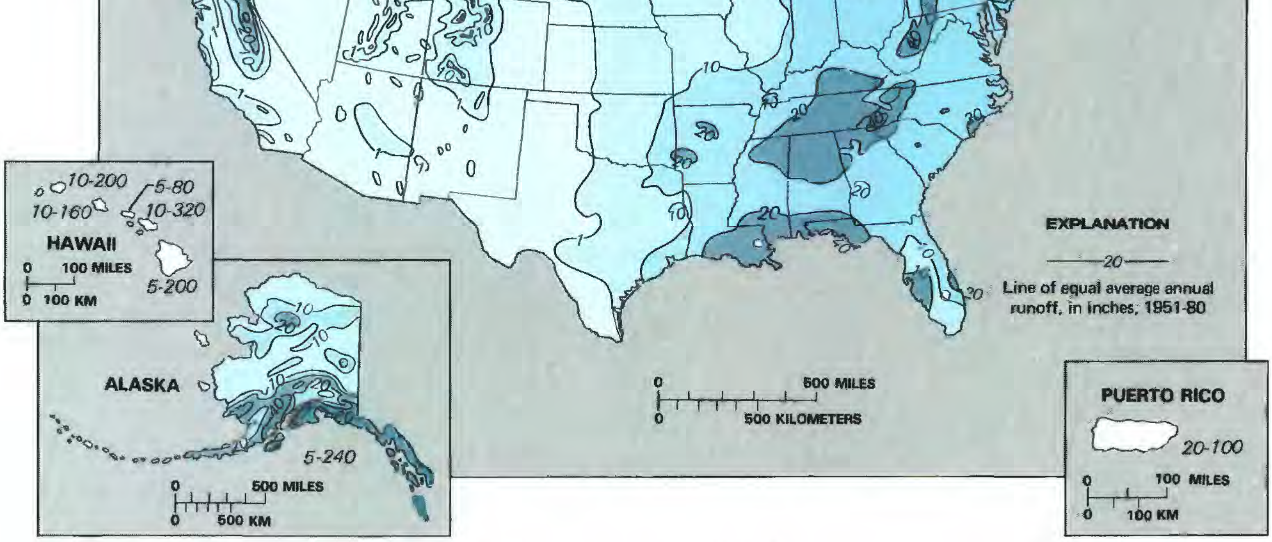

Figure 28. Average annual runoff in the United States and Puerto Rico, 1951-80. (Source: Gebert and others, 1985.)

The topographic setting of a river basin also may significantly affect the amount and character of runoff. If a river basin of high relief and steep slopes receives the same amount of precipitation as a basin of low relief, the total runoff from the steeper basin generally is greater. One reason is that the steeper slopes allow the water to flow rapidly through the basin, so that the water is subjected to evaporation losses for a shorter time than is water flowing through the low-relief basin. Another reason is that the steep basins generally are at higher altitudes where average air temperatures, and therefore evapotranspiration losses, are lower.

The principal influence of topography on runoff, however, comes from its relation to precipitation. Precipitation usually is greater at high elevations than on lowlands. The position of mountain ranges with respect to prevailing storm paths is another topographic influence on precipitation that may greatly affect the amount of runoff. As a storm crosses a mountain range, most of its precipitation falls on the side facing the approaching storm. The lee side is said to be in the "rain shadow." For example, storms usually approach the Olympic Mountains in Washington from the west. Figure 30 compares the runoff from two rivers that flow from the Olympic Mountains to the ocean—the Quinault River, which drains the western slopes, and the Dungeness River, which drains the northeastern slopes. The centers of these basins are only about 30 miles apart, and the elevations are quite similar. However, the average annual runoff from the windward basin generally is more than four times that from the leeward basin.

Geology influences annual runoff largely through its control of topography. Rock characteristics, such as permeability, also affect the amount of precipitation that infiltrates into the ground. The temporary storage of the water in shallow aquifers has its greatest effect on the seasonal rather than the annual runoff.

Annual runoff from a river basin is the net result of all these natural influences as well as human influences to be discussed later. Average flows of major rivers in the conterminous United States and Alaska are shown in figure 31. For basins where the natural influences far outweigh human influences, the average discharge over a long period of years is a reliable index of the long-term renewable water supply.

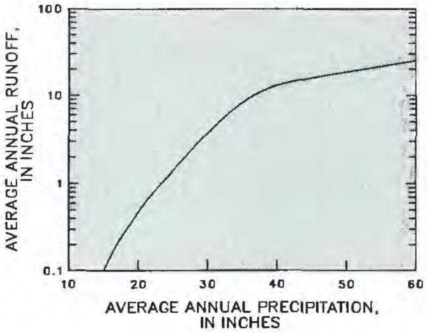

Figure 29. **General relation between average annual runoff and average annual precipitation for about 200 river basins in the eastern conterminous United States.** To adequately portray the relation for the lower part of the curve, it was necessary to plot runoff on a logarithmic scale. (Source: Data from Williams and others, 1940.)

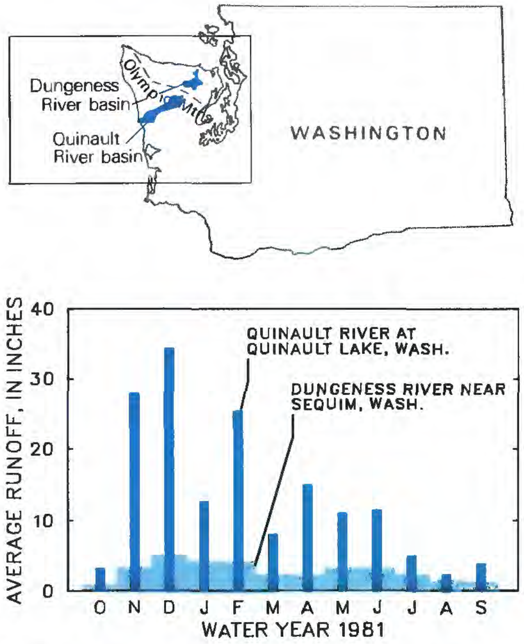

Figure 30. **Effect of the Olympic Mountains in Washington on runoff, water year 1981.** Quinault River is windward and Dungeness River is leeward of the mountain range. (Source: Data from U.S. Geological Survey, 1981.)

SEASONAL FLOW VARIATION AND NATURAL STORAGE

Streamflows vary within regions as well as among regions. Considerable variation with time occurs at most stream sites. Probably the most obvious is the flow variation from season to season.

Most rivers have distinct periods of high flow followed by periods of low flow within a given year. High flows result from storm runoff and snowmelt; low flows result from periods of low precipitation and high evapotranspiration. The times of high and low flows differ from basin to basin, and also from year to year, depending on the aforementioned climatic factors. Each geographic region, however, has a characteristic pattern of seasonal streamflow, called the stream regimen, which can be represented by the long-term average flows for each of the 12 months. Figure 32 shows the differences from place to place in the usual months of highest and lowest average flows.

At places where temperatures seldom fall below freezing, or do so only for short periods, the monthly distribution of streamflow (runoff) corresponds closely in time to the monthly distribution of precipitation. For example, both major precipitation and runoff occur in the winter for streams along the Pacific coast. (See figure 32, sites 1 and 2.) Conversely, most of the precipitation and runoff occur in summer on the San Pedro River in Arizona (site 6) and in late summer on Fisheating Creek in Florida (site 10). In most

Figure 31. Flow of major rivers in the conterminous United States and Alaska. Rivers shown are those that have an average discharge of more than 35,000 cubic feet per second. (Sources: Data for conterminous United States modified from Iseri and Langbein, 1974; data for Alaska from Graczyk and others, 1986.)

of the eastern part of the United States, streamflows generally are higher in the winter and early spring when evapotranspiration losses are small. (See figure 32, site 11.)

The monthly flows of northern streams or those that drain mountain areas do not closely follow the monthly distribution of precipitation. Low temperatures in the basins of such streams delay runoff by holding the precipitation as snow or ice until later release by melting during periods of higher temperatures. In the conterminous United States, the period of snow storage in a basin and the rate of melting vary. In the southern basins, snow melts quickly, and its effect on monthly runoff is small. Similarly, if snow is stored for extended periods on only a small part of a basin, or if the snow on most of the basin melts occasionally during the winter, the amount available for melting in the spring is small and the snow-storage effect is slight.

In basins having little difference in elevation, the winter accumulation of snow is fairly uniform throughout the basin, as is the air temperature at ground level. Consequently, the snow melts almost simultaneously throughout the basin, and the meltwater runoff is concentrated in a short period. Basins in the North-Central United States have this characteristic. Goose River in North Dakota is an extreme example; more than one-half of its annual runoff usually occurs during April (fig. 32, site 7).

The snow-storage effect is most pronounced where temperatures remain below freezing for several months and winter precipitation is relatively abundant.

This situation results in very low winter flows followed by high runoff when the snow and ice melt. Examples are the Boise River in Idaho and Clarks Fork Yellowstone River in Montana (fig. 32, sites 4 and 5). *The monthly distribution of flow in arctic streams* is similar, except that small streams there usually cease to flow during winter.

If seasonal snow packs were the only type of water storage in a drainage basin, streams would cease to flow between times of snowmelt and storm runoff. For most streams, however, other types of natural storage, such as meltwater from perennial snowfields and glaciers, drainage from lakes and swamps, and springflow and seepage from ground-water systems, sustain streamflows during periods of low flow.

In some basins of the Western United States, especially in Alaska and Washington, glaciers strongly influence the dry-season water supply and provide natural regulation of the streamflow to balance the seasonal and year-to-year variations in precipitation. The effects of ice and snow are discussed in greater detail in another article in this volume entitled "Snow, Ice, and Climate—Their Contribution to Water Supply."

Wetlands and lakes also regulate local streamflows in the short term by storing water during periods of high flow and releasing it during periods of low flow. The degree of regulation depends largely upon the volume of water that can be stored temporarily in relation to the rate of inflow and the degree to which evapotranspiration losses deplete the stored water.

The natural freshwater storage that has by far the greatest effect on streams in most of the Nation is the ground-water system. Ground-water reservoirs (aquifers) are replenished, or recharged, mainly by infiltration of part of the precipitation and by seepage from stream channels whenever stream levels are higher than ground-water levels. When stream levels drop lower than ground-water levels, ground water seeps into the channels and becomes part of the streamflow. This storage effect of ground-water reservoirs is so great that ground water seeping into stream channels may provide an average of 40 percent of the annual streamflow in some areas and nearly all the streamflow during periods of lowest flow (base flow).

Whether the response of streamflow to rainfall is prompt or prolonged, therefore, depends partly on the character of the soil and the underlying rocks. Water falling on impervious soil or rock runs off quickly to stream channels with little loss to infiltration and evaporation. In moderate climates, average monthly runoff closely follows the time distribution of precipitation. Also, the magnitude of runoff relative to the precipitation is greater than that from a basin having a more pervious soil. Conversely, when most of the precipitation soaks into the ground, its appearance as streamflow is considerably delayed, and the variation among average monthly runoffs is moderated. Some basins in which most of the precipitation passes through the ground before appearing as streamflow are those in the Delmarva Peninsula of Maryland and Delaware, in the Sandhills region of Nebraska, and in the volcanic regions of Idaho, Oregon, California, and Hawaii.

Inasmuch as low flows usually occur at times when the only contribution to streamflow is ground water and when evapotranspiration is high, the amount of an annual low flow depends on the amount of ground water stored and on the rate at which it moves to the stream; both of these factors are functions of *the topographic and geologic characteristics of the* basin. Streams sustained by large and permeable aquifers tend to have relatively higher low flows and also to be less variable from year to year than those streams supplied by smaller aquifers or those that are less permeable. For example, the flow of the Dismal River in the Sandhills region of Nebraska is supplied almost entirely from ground water that enters more or less uniformly along the stream channel. Monthly flows are very evenly distributed throughout the year.

Streamflow from limestone regions may show large seasonal variation, or it may be unusually uniform, depending on the extent and character of fractures and solution channels in the limy rocks. Most of the large springs issuing from limestone are concentrated in Florida, the Ozark region of Missouri and Arkansas, and in the Balcones Fault belt in Texas. Silver Springs in Florida, with an average discharge of 813 ft^3/s (cubic feet per second), probably is the largest limestone spring in the United States (Vineyard and Feder, 1974). Silver Springs and other springs in Florida have relatively constant flows, whereas those in the Ozark region fluctuate considerably. Big Spring in Missouri, for example, has an average flow of 438 ft^3/s, but daily flows ranged from 294 ft^3/s on March 2, 1984, to 1,500 ft^3/s on March 20, 1984, in response to heavy rains (U.S. Geological Survey, 1984a).

In arid and semiarid regions, ephemeral streams—those having no flow for some period during most years—are typical. Exceptions in such regions usually are large streams that head in mountainous areas and that are fed by perennial snow and ice storage or that are fed by a large ground-water system.

ANNUAL FLOW VARIATION, DROUGHT, AND FLOODS

NATURAL INFLUENCES AND FLOW FREQUENCIES

Year-to-year variations in runoff from a drainage basin are caused by changes in weather patterns and precipitation. Such variations are greatest in arid and semiarid regions where a small change in precipitation has a large effect on runoff. For example, a 20-percent increase in annual precipitation in a river basin with an average of 20 inches might increase runoff by about 150 percent (fig. 29), whereas the same percentage increase in a basin with an average precipitation of 50 inches might increase runoff by about 30 percent.

In some regions, the variability in the size of storms results in high variability among annual discharges. The average discharge of the Middle Concho River in Texas for 1931–68 was 34.9 ft^3/s, but for 1962–68 it was only 8.8 ft^3/s (fig. 33). The principal cause of the unusually low runoff during the 1962–68 period was the lack of long-duration, high-intensity rainfall (Sauer, 1972).

Average monthly mean flows, discussed previously, are even more variable than annual mean flows. The precipitation and temperature for a

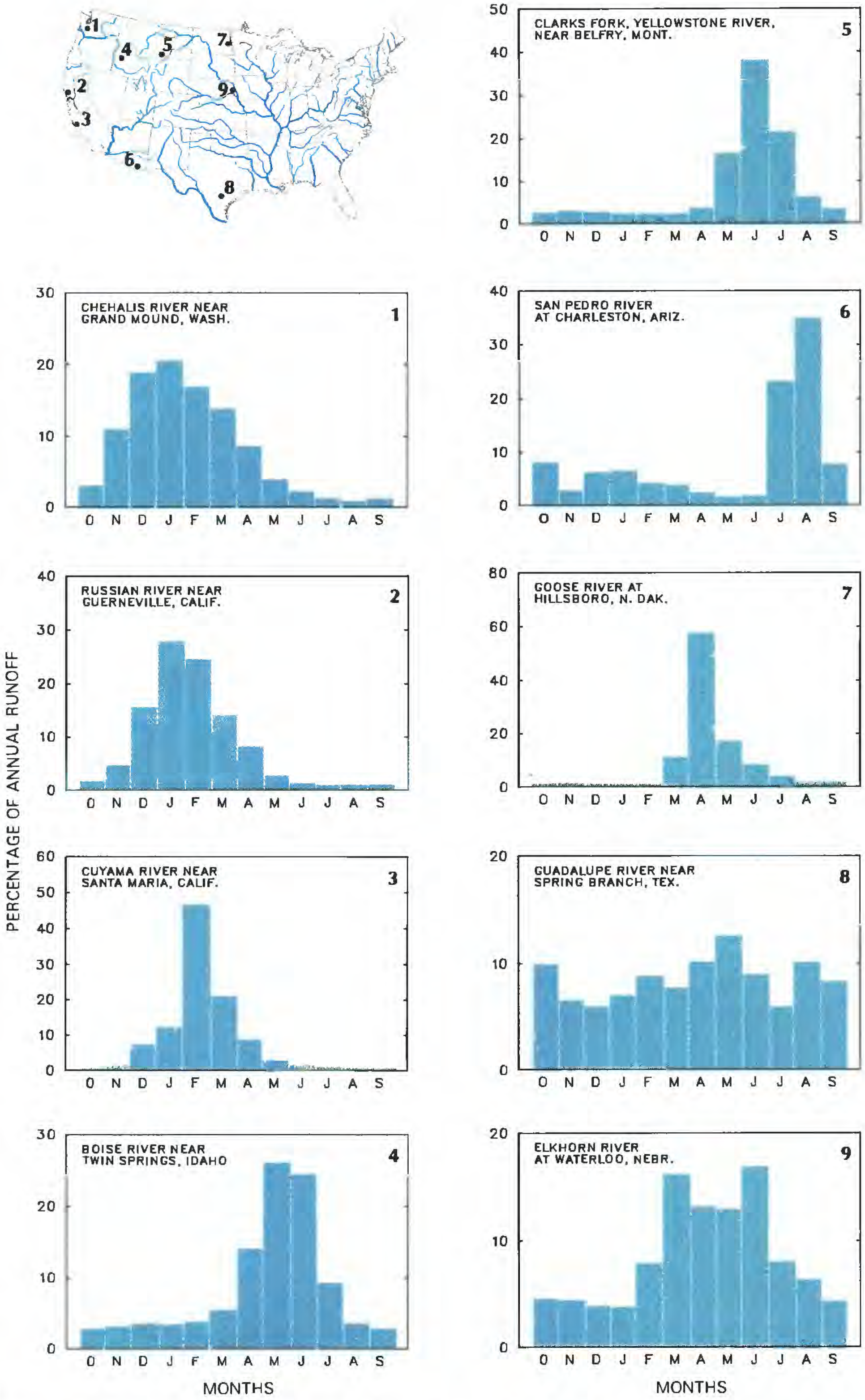

Figure 32. Average monthly distribution of runoff as a percentage of annual runoff at diverse locations in the United States and Puerto Rico. Data are for 1951-80, except for sites 3 (1960-80), 16 (1952-80), and 17 (1964-80). (Source: Compiled by K. J. Hitt from U.S. Geological Survey data.)

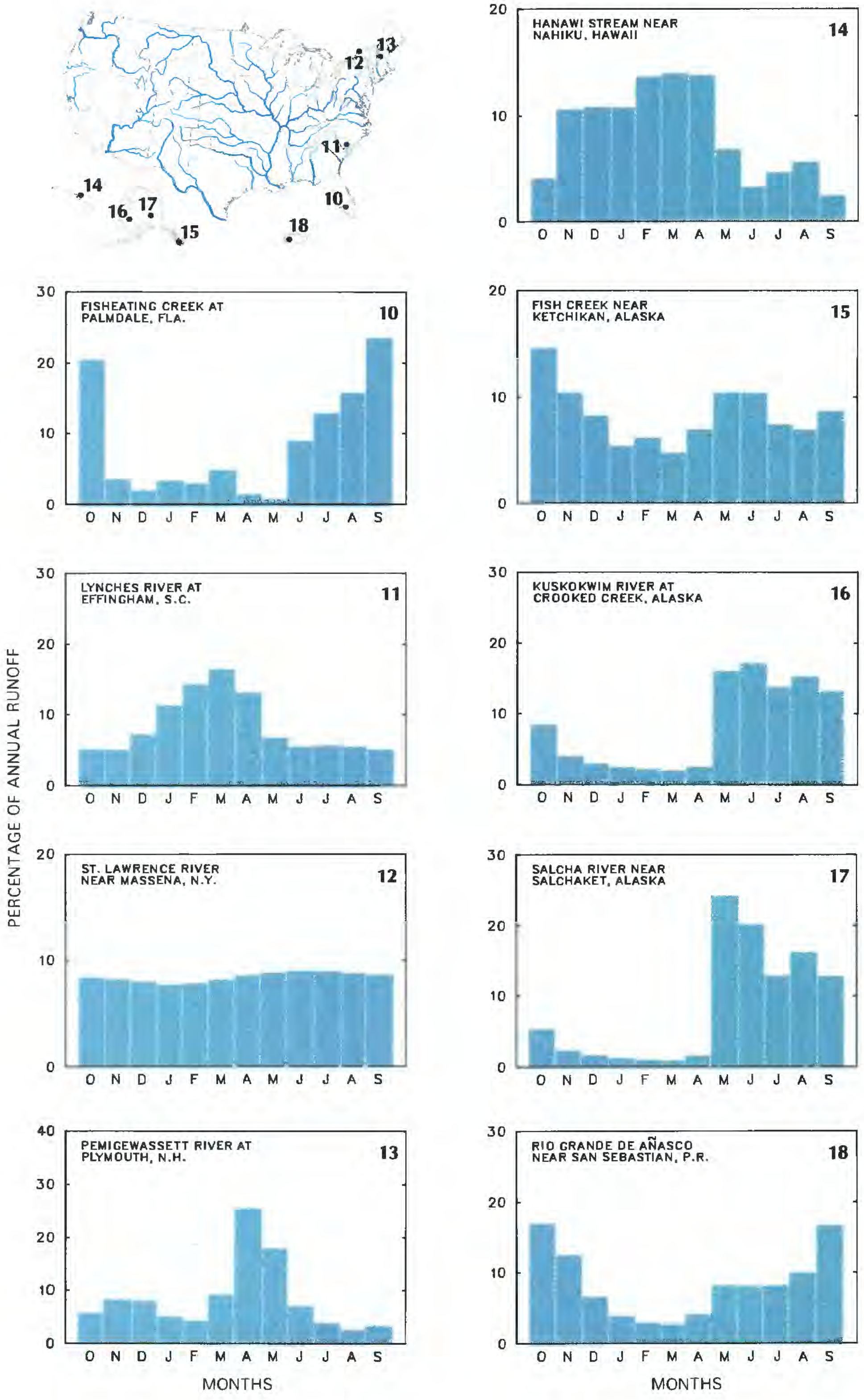

Figure 32. Continued.

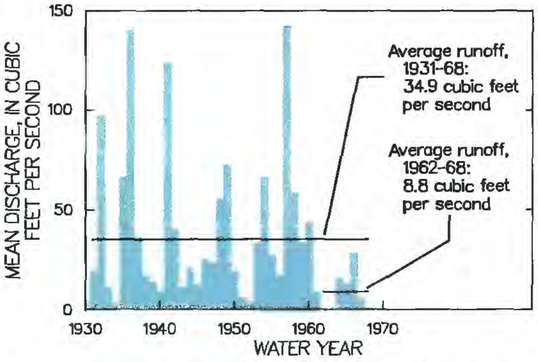

Figure 33. **Annual mean discharge of the Middle Concho River in Texas, 1931–68.** The large range, from practically no flow in 1962 and 1963 to more than 140 cubic feet per second in 1936 and 1957, illustrates the high variability of runoff in a semiarid region. (Source: Data from Sauer, 1972.)

particular calendar month may vary widely from year to year. Also, the heaviest precipitation on the basin may occur in different months from year to year. Thus, the flow regimen for an individual year may be quite different from the average regimens shown in figure 32.

Low streamflows at a site differ from year to year, primarily in response to weather conditions, ground-water inflow, and snowmelt. The variation in annual low flows commonly is described by a "low-flow frequency curve" (fig. 34), which is a convenient way to show how frequently different rates of streamflow can be expected to recur on the average. Low-flow frequency curves also are used to define (mainly for water management) "dependable flow." The dependable flow of a stream is a low rate of its flow, which commonly is defined as the average minimum flow for some period of successive days in a year. In figure 34, for example, the 30-day average low flow of Ichawaynochaway Creek in Georgia is expected to be less than 170 ft³/s during only 10 percent of the years on the average (30-day, 10-year low flow). This also may be referred to as the 90-percent dependable flow because the flow of 170 ft³/s can be depended upon during any successive 30 days in 9 out of 10 years. For Spring Creek in Georgia (fig. 34), the 30-day, 90-percent dependable flow is only about 22 ft³/s, or only 13 percent of that for Ichawaynochaway Creek. The drainage area above the Ichawaynochaway stream-gaging station is considerably larger than the drainage area above the Spring Creek station, and indications are that the rate of ground-water inflow per unit area is also much larger for Ichawaynochaway Creek than for Spring Creek.

DROUGHTS

A drought is an unusually long, dry period that can be defined in various ways. Generally speaking, a drought is a deficiency in precipitation that affects human activities and interests. The effects of a drought depend, in part, on the severity, duration, and geographical extent of the precipitation deficiency, and on whether precipitation is used directly (for example to maintain soil moisture) or whether affected water supplies are drawn from streams, from reservoirs, or from ground water.

In nonirrigated agriculture, lack of rain for a few weeks during the growing season will reduce crop yield and perhaps destroy the crop. Also residential or municipal water supplies that depend on runoff and involve limited storage will not be adequate unless they are replenished every few weeks. In semiarid regions, water for livestock often is provided by reservoirs, called stock ponds, on small ephemeral streams. Maintenance of water in these ponds requires rain at relatively frequent intervals. Users of water in these situations would consider a relatively short period without rainfall to be a drought.

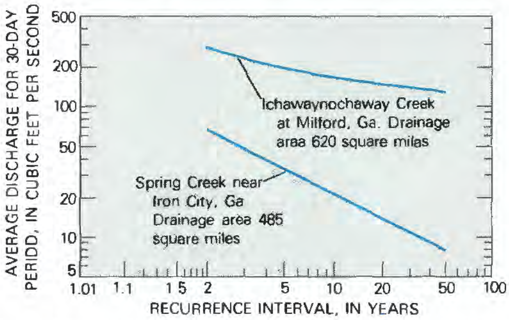

Figure 34. **Low-flow frequency curves for two nearby streams in southwestern Georgia.** The rate of ground-water inflow per unit area is larger for Ichawaynochaway Creek than for Spring Creek. (Source: Compiled by H. C. Riggs from U.S. Geological Survey data.)

Lack of rain for a few weeks or a month may have no appreciable effect on a water supply derived from a large stream; however, if the rate of demand is high, lack of appreciable rain for an extended period might result in streamflow dropping below that rate. For example, during the summer, 2 months with no storms large enough to produce runoff will cause the Potomac River flow to recede to less than the amount required for municipal supplies in the Washington, D.C., metropolitan area. As stated previously, the effects of precipitation deficiencies are delayed because low flows are sustained by ground water. The extent of the delay depends on the amount of water in aquifers at the beginning of the period of deficient precipitation and on the rate at which that stored water drains to the stream.

In regions where water supplies are drawn from sizable surface- or ground-water reservoirs, a critical drought is caused only by deficient precipitation for several successive years. Over the drought period, usable water in storage, both surface and underground, becomes progressively depleted until the usual rates of water withdrawals cannot be made. The 1976–77 drought in California is an example. The water supply there is derived largely from snowpack accumulated in the Sierra Nevada during winter. In 1976, the Sierra Nevada snowpack at many sites was the lowest ever recorded, and in 1977 it was even lower. Consequently, storage in surface reservoirs was depleted, streamflow became inadequate for irrigation and other supplies, and the reduced river flow into San Francisco Bay allowed saltwater to move upstream in the Sacramento River delta. In addition, the water table was lowered as much as 30 feet as ground water was pumped to augment the reduced supplies from the usual sources (Matthai, 1979, p. 61-62).

The perceived severity of a multiyear drought usually is based on the deficiency in the runoff and on the human-related consequences of that deficiency. The actual deficiency depends on the amount of storage available from the preceding year and on the desired withdrawal rate, as well as on the natural flow during the drought period. Thus, two streams affected by the same deficiency in precipitation over several years would show different degrees of drought impact, unless they happen to have the same storage capacities and water demands relative to their average flows. Drought has, in fact, been defined also by its effect on streamflow. A streamflow drought is said to exist when streamflow for a month or more in 1 year, or for a period of successive years, is unusually deficient. The severity of a within-year drought can be expressed in terms of probability determined from a low-flow frequency curve. Monthly mean flows of the Ohoopee River in southern Georgia during the notable drought of 1954 and 1955 are shown in figure 35 in comparison to median monthly flows for the period 1938-60. Low-flow frequency analysis of annual minimum flows for successive days show that the 1954 flows at this site had a probability of 2 percent (50-year recurrence interval); that is, the probability of experiencing lower flows at this site in any given year is about 1 in 50.

The effects of major droughts, especially multiyear droughts, include a reduction in streamflow, the lowering of ground-water levels, and the many consequences of these changes. Notable multiyear droughts occurred in the 1930's, the 1950's, and the 1970's. These are described in detail by Hoyt (1936, 1938), Thomas and others (1962-63), Nace and Pluhowski (1965), Barksdale and others (1966), and Matthai (1979). Several of these droughts affected the annual flows of the Red River of the North in North Dakota and Minnesota, as indicated in figure 36.

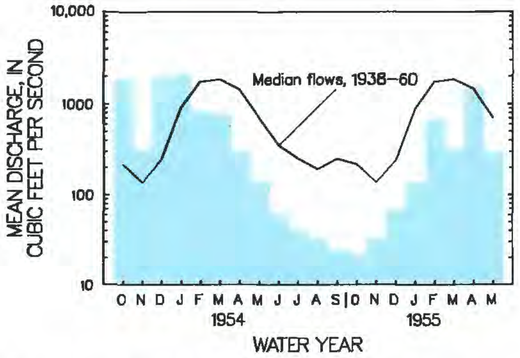

Figure 35. Monthly mean discharges of Ohoopee River in Georgia, during the drought of 1954 and 1955, in comparison to median monthly flows for the period 1938-60. (Source: Compiled by H. C. Riggs from data in U.S. Geological Survey files.)

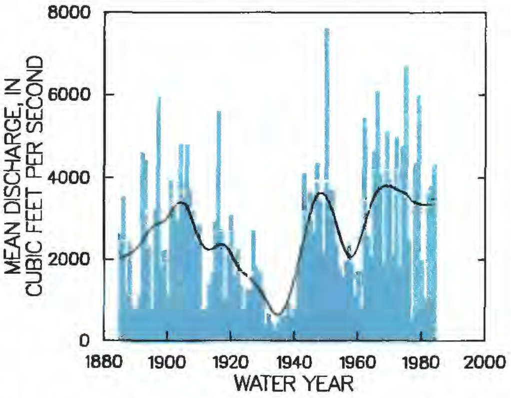

Figure 36. Annual mean discharges of the Red River of the North at Grand Forks, N. Dak., for the period 1885-1984, indicating major multiyear droughts. Curved line is 15-year weighted moving average. (Source: Compiled by H. C. Riggs from U.S. Geological Survey data.)

FLOODS

A flood can be defined as any relatively high flow that overtops a stream's natural channel or artificial confines (levees or dikes) in any reach of the stream. Floods range from fairly common high flows that barely overtop the natural stream banks and have only local effects to rare flows that crest well above the stream's confines and have extensive and severe impacts. Floods usually are compared according to the heights of their flood crests (highest water) or the probability with which large flows of various magnitudes can be expected to be equaled or exceeded. The same frequency analyses applied to low flows also are applied to flood flows but are adapted to the special overbank flow conditions during flooding. Floods are described in terms of their probability or likelihood of a flood flow being equaled or exceeded in any 1-year period. For example, if a flood flow has a 1-percent chance of being equaled or exceeded in a given year, one such flood will occur every 100 years on the average. Such a flow is often termed the "100-year flood." The floods with the smallest probability (longest recurrence interval) are the rarest, highest, and most disruptive.

Floods (excluding coastal flooding from high tides and storm surges) result from intense rains, rapid snowmelt, or a combination of the two. The larger floods often are caused by intense rainfall in one or more tributary basins. The peak runoff from different basins may arrive simultaneously at the confluence of tributaries downstream, creating very high water stages. The other most common cause of major floods is the combination of rapid snowmelt and heavy rainfall. For a stream that heads in high mountains and accumulates considerable snowpack during the winter, snowmelt is the major runoff event of the year. Such is true for Clarks Fork (fig. 32, site 5). The runoff from melting snow usually increases gradually with seasonal temperature rise, although a particular sequence of weather conditions can produce unusually large rates of runoff. Such a situation occurred in the Colorado River basin in 1984 (U.S. Geological Survey, 1985, p. 42) when abnormally heavy snowpack followed by unseasonably warm temperatures caused near-record runoff that began about May 20, 1984. Heavy rains in parts of the basin led to peak flows more than 1.5 times the estimated 100-year flood on the Uncompahgre River at Delta, Colo.

Certain other characteristics of a basin also can contribute to floods and, in fact, have contributed to some of the most disastrous floods in history. Mountain glaciers, a potential for landslides on steep unstable land, the occurrence of earthquakes, and the presence of lakes and reservoirs in conjunction with these other potentially hazardous factors provide a setting for catastrophic flooding. For example, the sudden failure of a dam impounding a sizable reservoir, or the sudden displacement of water in a lake or reservoir by a landslide or mudflow, can create a flood of disastrous proportions for downstream areas.

The greatest likelihood for catastrophic flooding probably exists for rivers that drain large mountain glaciers on active volcanoes. For such streams, the possibility exists for occasional floods and mudflows from outbursts of glacier meltwater (Richardson, 1968) or even mudflows of huge proportions that are caused by an increase in volcanic activity. Mudflows can be especially dangerous because of their possible large size, their ability to travel long distances, and their relatively high speed (some reported at 20 to 55 miles per hour). Not only do they constitute a special type of flooding, but they can severely damage dams, fill reservoirs, and cause catastrophic floods farther downstream by displacing reservoir water, causing it to overspill a dam (Crandell, 1973). Mudflows also can make certain areas flood prone by reducing the carrying capacity of stream channels. Mudflows that resulted from the eruption of Mount St. Helens in Washington in May 1980 produced in-channel deposits so extensive and voluminous that they obstructed the shipping channel of the Columbia River about 70 river miles from the volcano. Even after it receded, the main volcanic mudflow left a residual flood hazard along the channels of the Toutle and the lower Cowlitz Rivers in Washington, which were so choked with mudflow deposits that even normal wet-season runoff could have caused severe overbank flooding (Foxworthy and Hill, 1982, p. 68, 115).

Floods are among the most destructive natural hazards. About 6 percent of the land area of the conterminous United States is prone to flooding and nearly 21,000 low-lying communities have flood problems. Floods cause about 10 times more deaths, on the average, than any other natural hazard. During water year 1985, however, estimated economic loss from flood damage in the United States was about $500 million, the lowest amount since 1971 (U.S. Army Corps of Engineers, 1986).

Flood flows at various exceedance probabilities (frequencies of recurrence) are determined from streamflow records and from historical flood heights. Also, for places where weather-station data may be available for periods longer than the streamflow record, the magnitude of flooding may be estimated from the amount of runoff likely to be produced by a storm of a certain frequency, or from the most intense foreseeable storm. The extent of flooding (inundated land) for various flood flows can be determined from historical evidence (high-water marks and observations of residents) or can be estimated by indirect methods that may include surveying the channel dimensions and slope and then mathematically modeling floods of various magnitudes.

Sufficient streamflow records have been obtained by the U.S. Geological Survey, in cooperation with various State and other Federal agencies, to provide reliable flood-frequency estimates for nearly all major rivers in the United States. In addition, regional analyses of the flood-flow records and of natural features that control the flows have produced methods for estimating the magnitude and frequency of floods at any site on a natural (unregulated) stream. Similarly, maps of flood-prone areas (mostly related to the 100-year or 1-percent-chance flood) along most major rivers have been prepared and are available from the U.S. Geological Survey District Offices and other agencies such as the Federal Emergency Management Agency, U.S. Army Corps of Engineers, U.S. Soil Conservation Service, and various State agencies.

Of course, the estimated exceedance probabilities imply that it is entirely possible for two or more major floods to occur within a period of a few years or even within the same year. Conversely, a major flood may not occur for several decades—long enough for flood-plain residents to forget that a flood hazard exists.

Intensive use has significantly modified flood plains and streamflow characteristics from their natural (predevelopment) condition. Almost every conceivable land use occurs on the Nation's flood plains. It is now clearly established that virtually every change in land use (conversion of open land to urban areas, for example) alters, to some extent, the water quality and the flow regimen of a stream system.

Flow conditions have been artificially modified by dredging and mining of channel deposits, rerouting and lining of channels, construction of locks, dikes and levees, and dams and reservoirs, and by encroachment onto the flood plains. The purpose of the locks and much of the dredging is to maintain and improve navigation on the rivers. Many of the dams and reservoirs were constructed to store water supplies. Other dams and reservoirs and most other channel modifications, such as levees, were constructed to provide flood protection to low-lying lands.

Because of obvious shortcomings, undesirable side effects, and high costs of physical flood-control measures, the emphasis in flood protection has shifted to nonstructural measures. These measures include improving flood forecasts, installing community flood-warning systems, zoning or limiting land uses in flood-prone areas, and delineating flood hazards. In the last effort, interpretations of flood-frequency and the mapping of flood-prone areas are continuing by the U.S. Geological Survey and other agencies and are being refined through ongoing programs of data collection and research.

Despite these measures and the significant benefits provided by existing flood-control projects, average annual flood damages generally continue to rise, although water year 1985 was an exception. Much of the increase in economic losses can be attributed to continuing encroachment onto the flood plain.

People are attracted to the flood plain by its obvious advantages—the flat land, desirability for transportation routes, access to water, and, commonly, the best agricultural soils. Once people are established on the flood plain, governments have characteristically tried to control the damages from flooding by means of dikes, dams, reservoirs, and other flood-control works. Often, these flood-control measures successfully reduce damage from small and moderately sized floods and, in so doing, provide incentives for additional development on the flood plain. Thus, when a flood occurs that is greater than the capacity of the flood-control works, losses often are much greater than if development had been limited by periodic small-scale flooding. Moreover, the dikes and modified channels that partially protect adjacent lowlands may worsen flood problems in downstream areas (Dunne and Leopold, 1978, p. 403–404). Even the presence of buildings in the flood channels tends to constrict flood flow and raise flood crests; and urban development, which increases runoff via the paving and storm-sewering of a substantial part of a stream's drainage basin, can cause a drastic increase in the frequency and intensity of flooding (Leopold, 1968). These effects of urbanization alone can largely offset the benefits derived from expensive flood-control construction.

Although floods are a hazard, the storms that cause floods replenish soil moisture and recharge the ground-water systems, which in turn discharge to streams between storms. Because a large part of the annual runoff of some streams occurs during floods, floods play a major role in replenishing reservoirs and are important elements in the management of water supplies.

USE AND MODIFICATION OF SURFACE-WATER RESOURCES

OFFSTREAM AND INSTREAM USES

Uses of water are characterized as instream uses and offstream or diversion uses. Each use has an impact on the streams, although for some uses, principally certain instream uses, the impact may be small and not necessarily undesirable.

Principal offstream uses of surface water are for supplies for irrigation, industrial, municipal, and energy-production purposes. For all but irrigation diversions, most of the water, following its use, eventually returns to the stream system, usually with some aspect of its quality (such as temperature, chemical quality, or sediment load) changed. The part of the diverted water that does not return to streams is consumed, mostly by vegetation, or evaporated during use; this is referred to as "consumptive use."

The diverted water sometimes is used in a drainage basin other than the one in which it originates; typically, water is transferred from regions with large supplies to others with smaller supplies or larger water demands. For example, waters from streams in northern and central California and from the Colorado River currently are transferred to and used in southern California. Such interbasin transfers of water, of course, are equivalent to a totally consumptive use within the originating basin.

Intensive withdrawal of ground water also can divert water from streams. In the fairly common situation where an aquifer system is in hydraulic contact with a stream, pumping from the aquifer not only can intercept ground water that otherwise would seep into the stream channel but also can (if ground-water levels are lowered below stream levels) induce water to flow from the stream channel into the aquifer. Flow-reduction effects of ground-water pumping, however, occur some time after the onset of pumping and, unless the wells are very near the stream, usually do not coincide with times of maximum direct diversions from the stream.

Instream uses of water include navigation, fish and wildlife propagation, waste transport, hydropower generation, and recreational activities. They usually require some minimum flow rate and are largely competitive with diversion uses, which reduce the flow. For example, streamflows must not fall below some minimum rate if navigation is to continue, if fish habitat is to be preserved, or if waste loads are to be adequately assimilated. Flows needed for hydropower generation may change hourly, daily, and seasonally. Flows that are optimum for recreational activities depend on the particular activity; they range from some minimum for fishing and esthetics to higher flow for white-water canoeing and rafting.

ARTIFICIAL STORAGE

The amounts of water needed for each of the major uses of stream water change throughout the year, but rarely do periods of high demand occur at times of high streamflow. Consequently, when the demand for water is greater than the dependable flow of the stream, the flow regimen commonly is modified by constructing reservoirs for storing water during high flows and releasing it later as needed. At present there are 2,654 reservoirs and controlled natural lakes with capacities of 5,000 acre-ft (acre-feet) or more in the United States and Puerto Rico. These have a combined normal storage capacity of more than 479 million acre-ft (table 6), and the 574 largest reservoirs account for almost 90 percent of the total storage. In addition there are least 50,000 smaller reservoirs with capacities ranging from 50 to 5,000 acre-ft and about 2 million smaller farm ponds used for storage (U.S. Army Corps of Engineers, 1981).

The change in flow regimen by operation of a storage reservoir for irrigation is shown in figure 37 by the monthly flows of the Crooked River in Oregon, above and below Prineville Reservoir. The effect of reservoir operation also can be shown by comparing the distributions of daily flows for periods of years before and after the reservoir was established. Usually, reservoir operation increases minimum flows and reduces maximum flows, as indicated by the duration curves for periods before and after construction of a reservoir. For example, figure 38 shows that, before construction of a reservoir on the East Fork Clarion River in Pennsylvania, a daily mean flow of about 350 ft³/s or greater could be expected 10 percent of the time, whereas after reservoir construction a daily mean flow of only 230 ft³/s or greater could be expected 10 percent of the time. The lower parts of the curves show that, before construction, the daily mean flow that could be expected 90 percent of the time was only about 12 ft³/s, but the comparable value after construction increased to about 23 ft³/s. That is, the low flows nearly doubled. The character and extent of changes in the flow regimen due to reservoir operation depend on the capacity of the reservoir relative to the annual flow and on the purposes of the flow regulation.

Table 6. Summary of reservoir storage, including controlled natural lakes, in the United States and Puerto Rico

[Reservoir storage is expressed as normal capacity, which is the total storage space in a reservoir below the normal retention level, including dead storage and inactive storage, and excluding any flood-control or surcharge storage. Source: U.S. Army Corps of Engineers, 1981]

Reservoir storage (range, in acre-feet)	Number of reservoirs	Total reservoir storage	
		Acre-feet	Percentage of total
Greater than 10,000,000	5	107,655,000	22.4
100,000–10,000,000	569	322,852,000	67.3
50,000–100,000	295	20,557,000	4.3
25,000–50,000	374	13,092,000	2.7
5,000–25,000	1,411	15,632,000	3.3
Total[1]	2,654	479,788,000	100.0

[1] In addition, there are perhaps at least 50,000 reservoirs with capacities ranging from 50 to 5,000 acre-feet, and about 2 million smaller farm ponds used for storage.

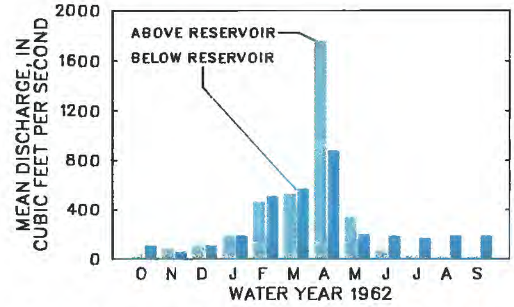

Figure 37. Modification of the natural flow regimen of Crooked River by Prineville Reservoir in Oregon, as shown by monthly mean flows upstream and downstream of the reservoir during water year 1962. (Source: Compiled by H. C. Riggs from U.S. Geological Survey data.)

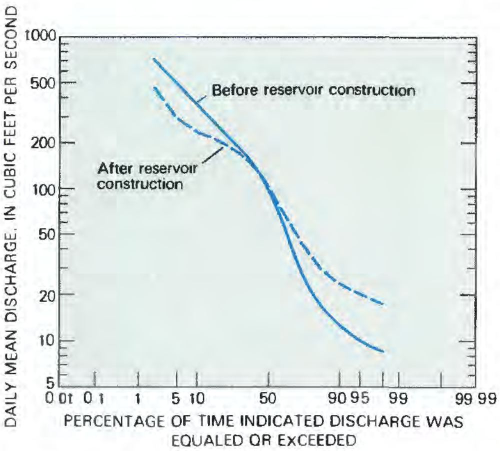

Figure 38. Change in duration of daily flow of East Fork Clarion River in Pennsylvania as a result of reservoir construction and operation. (Source: Compiled by H. C. Riggs from U.S. Geological Survey data.)

Flow regimens can be adjusted by the use of surface storage to be more suitable for various instream uses, but compromises must be made where many uses of water, both instream and offstream, are sought. Successful operation of a multipurpose reservoir, which may provide water for inherently conflicting purposes, is especially complicated and difficult. Such multipurpose reservoirs may be operated to provide hydropower generation, irrigation supplies, flood control, recreation, and maintenance of low flows for fisheries enhancement, water-temperature control, and waste assimilation.

Besides altering the flow regimen, reservoirs have other effects that may involve sediment deposition and the growth of aquatic vegetation within the reservoir and may involve water-quality and channel changes downstream. Many of these effects are indirect and only become apparent after a reservoir has been in operation for some years. (See, for example, articles in this volume "Effects of Dams and Reservoirs on Surface-Water Hydrology—Changes in Rivers Downstream from Dams" and "Effects of Dams and Reservoirs on Surface-Water Hydrology—Changes in the Platte River Basin.")

DEVELOPMENT IN WATER-RESOURCES REGIONS

Generalized water budgets for each of the Nation's 21 water-resources regions are presented in table 7. The approach used in developing these budgets was the same as that used in the 1983 *National Water Summary* (U.S. Geological Survey, 1984b, p. 23–28). Annual renewable supply is defined as the flow potentially available for use in the region. Because there commonly are minimum streamflow requirements for instream uses (such as navigation, hydropower generation, recreation, and fisheries) or to provide water for downstream withdrawals, the renewable supply represents a theorectical upper limit for long-term water use.

Average annual stream outflows from each of the water-resources regions (first column of table 7) are estimated from streamflow records for the period 1951–80 (Graczyk and others, 1986). For most regions, however, the annual renewable supply is somewhat different from the observed outflows. Because water obtained from mining ground water cannot be depended upon as a long-term supply, the regional outflows were reduced by the estimated depletion of ground-water storage. On the other hand, water losses resulting from offstream consumption and net reservoir evaporation in each region were added to the regional outflows, as these are part of the renewable supply.

Outflows from the Lower Mississippi and the Lower Colorado Regions reflect an integration of conditions in both the upstream and downstream parts of those extensive river basins. For this reason, the amounts given in tables 7 and 8 for these regions represent conditions in the entire river basin.

One measure of the degree to which the available water resources of a region have already been developed is the percentage of the annual renewable supply of a region that is consumptively used. (As used in table 8, consumptive use is the sum of offstream

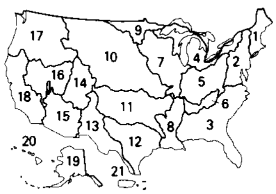

Table 7. Generalized water budgets for 1980, by water-resources region

[Data in billions of gallons per day. Sources: Average annual stream outflows from Graczyk and others, 1986; annual depletion of ground-water storage estimates from U.S. Geological Survey, 1984b; offstream consumptive use from Solley, Chase, and Mann, 1983; net reservoir evaporation estimates based on data from Hardison, 1972, and U.S. Army Corps of Engineers, 1981]

Water-resources region and no.	Average annual stream outflows	Annual depletion of ground-water storage (estimated)	Offstream consumptive use	Net reservoir evaporation (estimated)	Annual renewable supply
New England (1)	76.7	0.0	0.4	0.2	77.3
Mid-Atlantic (2)	94.6	.0	1.7	.2	96.5
South Atlantic–Gulf (3)	207	.0	5.1	.5	213
Great Lakes (4)	75.2	.0	1.3	.3	76.8
Ohio (5) (exclusive of outflows from region 6)	138	.0	1.7	.4	140
Tennessee (6)	42.9	.0	.4	.0	43.3
Upper Mississippi (7) (exclusive of outflows from region 10)	77.6	.0	1.5	.6	79.7
Lower Mississippi (8) (represents conditions in regions 5, 6, 7, 8, 10, 11)	433	5.8	36.3	6.0	470
Souris–Red–Rainy (9)	7.2	.0	.1	.4	7.7
Missouri (10)	50.2	2.2	16.0	3.3	67.3
Arkansas–White–Red (11)	56.3	3.6	9.6	1.4	63.7
Texas–Gulf (12)	30.7	3.1	6.5	1.8	35.9
Rio Grande (13)	1.8	.0	2.4	.8	5.0
Upper Colorado (14)	8.3	.0	2.3	1.7	12.3
Lower Colorado (15) (represents conditions in regions 14 and 15)	2.5	2.1	7.2	3.6	11.2
Great Basin (16)	4.2	.0	3.9	.2	8.3
Pacific Northwest (17)	278	.0	12.0	.6	291
California (18)	62.8	1.4	25.0	.5	86.9
Alaska (19)	921	.0	.04	.0	921
Hawaii (20)	13.6	.0	.7	.0	14.3
Caribbean (21)	4.8	.0	.3	.0	5.1

consumptive use and net reservoir evaporation from table 7). This consumptive use ranges from less than 1 percent of the renewable supply in the New England, Tennessee, and Alaska Regions to nearly 100 percent in the Colorado basin, where virtually the entire renewable supply is used. About 30 percent of the renewable supply in the Missouri, Upper Colorado, and California Regions, 49 percent in the Great Basin Region, and 64 percent in the Rio Grande Region is consumptively used. Even in regions where consumptive use is a small percentage of renewable supply, the regional aggregation of consumptive use and water-supply estimates may mask local areas where the percentage is high. Conversely, in regions where consumptive use is a large percentage of renewable supply, there may be river basins where the available water resources are underutilized. Nonetheless, for most of the country, consumption is a relatively small percentage of supply and, aside from institutional and distribution constraints, considerable increases in consumptive use could be sustained. Exceptions are the Great Plains and the Southwest, where the high percentages of renewable water supply that are consumptively used (table 8) clearly show that additional consumptive use will be constrained by water availability.

The intensity of surface-water development in a region can be determined by comparing normal reservoir capacity to annual renewable supply, adjusted for interregion water imports and exports. The adjustment, which is made by subtracting imports and adding exports to the renewable supply, reflects the fact that most large interbasin transfers are made from reservoir storage located in the exporting basin. The net imports and exports shown in table 8 depict 1980 interbasin transfers (Mooty and Jeffcoat, 1986; Petsch, 1985).

Reservoirs often are characterized as having a "safe yield," which represents the amount of water that can be continuously withdrawn from storage with an acceptably small risk of interrupting the supply. Hardison (1972) found that the safe yield of reservoirs in water-resources regions of the conterminous United States reaches a maximum when storage represents 160 to 460 percent of the average annual renewable water supply of the region. Further additions to reservoir capacity actually will decrease the net safe yield because evaporation losses associated with the increased reservoir surface area exceed increases in safe yield associated with increased reservoir capacity.

Reservoir storage as a percentage of annual renewable supply (table 8) is greatest in the entire Colorado River basin (421 percent), followed by the Upper Colorado (261 percent), the Rio Grande (189 percent), the Missouri (112 percent), the Souris–Red–Rainy (93 percent), and the Texas–Gulf (61 percent) regions. According to Hardison (1972) the maximum safe yield of a region falls within the range of 160 to 460 percent of the annual renewable supply. Hence, the data shown in table 8 suggest that there may be considerable potential for increasing basin safe yields by expanding reservoir capacity in most regions. On the other hand, environmental constraints, economic considerations, and a lack of good reservoir sites may hinder future expansion of reservoir capacity.

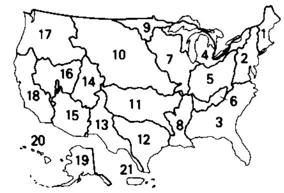

Table 8. Comparison of surface-water resources development criteria, by water-resources region

[Bgd = billion gallons per day. Sources: Annual renewable supply from table 7; net imports and exports from Petsch, 1985, and Mooty and Jeffcoat; 1986, normal reservoir storage capacity from U.S. Army Corps of Engineers, 1981, and U.S. Geological Survey, 1984b]

Water-resources region and no.	Annual renewable supply (bgd)	Net imports or exports (-), 1980 (bgd)	Consumptive use			Normal reservoir storage capacity		
			Bgd[1]	Percent of renewable supply	Rank	Million acre-feet	Percent of adjusted renewable supply[2]	Rank
New England (1)	77.3	0.0	0.6	0.8	20	13.0	15	14
Mid-Atlantic (2)	96.5	−.7	1.9	2.0	17	10.3	9.5	17
South Atlantic–Gulf (3)	213	.0	5.6	2.6	14	38.7	16	13
Great Lakes (4)	76.8	−1.3	1.6	2.1	16	6.9	7.9	18
Ohio (5) (exclusive of outflows from region 6)	140	.0	2.1	1.5	18	19.6	12	16
Tennessee (6)	43.3	.0	.4	.9	19	11.2	23	11
Upper Mississippi (7) (exclusive of outflows from region 10)	79.7	2.0	2.1	2.6	15	12.2	14	15
Lower Mississippi (8) (represents conditions in regions 5, 6, 7, 8, 10, 11)	470	.0	42.3	9.0	9	164.8	31	10
Souris–Red–Rainy (9)	7.7	.0	.5	6.5	10	8.0	93	5
Missouri (10)	67.3	.2	19.3	29	5	84.3	112	4
Arkansas–White–Red (11)	63.7	.1	11.0	17	8	31.8	45	7
Texas–Gulf (12)	35.9	.0	8.3	23	7	24.7	61	6
Rio Grande (13)	5.0	.1	3.2	64	2	10.4	189	3
Upper Colorado (14)	12.3	−.6	4.0	33	4	37.7	261	2
Lower Colorado (15) (represents conditions in regions 14 and 15)	11.2	−3.7	10.8	96	1	70.4	422	1
Great Basin (16)	8.3	.0	4.1	49	3	3.3	35	9
Pacific Northwest (17)	291	.0	12.6	4.3	13	60.9	19	12
California (18)	86.9	3.7	25.5	29	6	38.8	42	8
Alaska (19)	921	.0	.04	0	21	1.5	.1	20
Hawaii (20)	14.3	.0	.7	5	12	.0	.0	21
Caribbean (21)	5.1	.0	.3	6	11	.3	5.2	19

[1] Sum of offstream consumptive use and net reservoir evaporation shown in table 7.

[2] Annual renewable supply adjusted by subtracting net imports to, or adding net exports from, the water-resources region.

OUTLOOK FOR THE FUTURE

The adequacy of available stream supplies to meet future demands depends on the following factors:

- quantities of available surface water,
- future demands and types of water use,
- water-quality constraints on future stream uses,
- legal, institutional, and management influences on future water supplies and demands.

SUPPLY AND DEMAND

The renewable water supply of the conterminous United States amounts to about 1,380 billion gallons per day. Even though the total offstream withdrawals of surface water more than doubled during 1950-80 (fig. 39), withdrawals still remained less than 21 percent of the renewable supply in 1980. Despite major droughts, such as the one in the Eastern United States in 1985, and chronic water shortages in some localities, the Nation is not "running out" of water. Periods of drought will be followed by periods of above-normal precipitation and runoff in the future as in the past. Many of the concerns about water shortages arise because of uneven distribution of water in relation to the regional and seasonal distribution of water demands; concerns also arise because of increasing demand for existing supplies and related difficulties in distribution. In some situations, changes in engineering, management, or institutional procedures can improve the situation.

Information about historical climates and speculation about the possibility of future climatic changes related to human activities allow interesting conjecture, but provide no real guidance to water-resources planners as to the future availability of water. Knowledge about past climatic conditions has been extended by means of tree-ring data and, more recently, by the study of ice cores from the thick ice sheets of Greenland and Antarctica. The data indicate that swings in climatic conditions (and, therefore, in runoff conditions) in North America were greater in the past than any measured in the past 100 years or so. However, these data have not yet provided the basis for helping to predict the onset of significant climatic changes. Similarly, widely publicized hypotheses about climatic changes that may result from pollution of the upper atmosphere, from a thinning of the ozone layer, or from the increase in the concentration of carbon dioxide in the atmosphere (the "greenhouse effect"), are controversial and somewhat contradictory. (See article in this volume, "Snow, Ice, and Climate—Their Contribution to Water Supply.") Therefore, pending more definitive guidance from ongoing research, a reasonable assumption about future availability of stream supplies is that the present average renewable supplies can be expected to remain relatively unchanged over the next several decades. However, major changes in runoff conditions and amount are a long-term possibility.

Although the available supply appears unlikely to change appreciably in the near future, estimates of that supply may not be very accurate because there is no objective way of selecting a representative period of record that includes the full range of possible variations. Moreover, even if the long-term average supply could be closely estimated, the actual supply over a specific future period probably will deviate from that average. One of the problems facing water-resources planners is the inability to define accurately the amount of water available, and this uncertainty should be considered in developing and allocating water resources.

Even without a change in the total renewable supply, a larger percentage total can be made available for human use by intercepting surface runoff during periods of abundant flow and storing it for use during periods of low flow. Opportunities exist for increasing reservoir storage in many parts of the country, but the future emphasis on large surface-storage reservoirs will be less than in the past. This is because most of the remaining sites for surface reservoirs are already preempted by other land uses or have shortcomings such as construction problems, legal constraints, shallow storage, excessive land inundation, or excessive evaporation loss. In addition to these factors and in part because of them, large-scale water-resources projects are increasingly difficult to justify economically. Other methods available for increasing the beneficial use of available runoff include conservation, reuse of water of impaired quality, reduction of evapotranspiration loss, improved water-system management, and greater utilization of ground-water reservoirs through conjunctive use of ground-water and surface-water resources. (See article in this volume, "Managing Water Supplies to Increase Water Availability.")

The adequacy of water supplies in the future depends, in large part, on future demands and the legal and institutional arrangements used by the States to allocate water. Even though the projection of future water demands is at best an uncertain exercise (Osborn and others, 1986), an examination of trends in water use provides a historical perspective.

Trends in estimated water withdrawals (ground-water pumpage and surface-water diversions) for five major water-use categories during 1950–80 are shown in figure 39. Also shown is the trend in hydroelectric power generation, an instream use of surface water. Surface-water diversions have consistently exceeded ground-water withdrawals (290 bgd as compared to 88 bgd of freshwater in 1980; see Solley and others, 1983, p. 32). In the foreseeable future, surface water will continue to be the primary source of the Nation's water supplies but ground-water withdrawals probably will continue to increase at a faster rate than surface-water diversions. Ground water is being used increasingly in many areas as the preferred source of additional water supplies because of its general availability and high quality, as well as its reliability, at least in the short term, during periods of drought.

In 1980, about 90 bgd of fresh surface water was withdrawn for irrigation, of which an average of 55 percent (about 50 bgd) was consumed. Irrigation currently accounts for 81 percent of all water consumption in the United States. Obviously, even improvements of a few percent in the efficiency of use could result in water savings that are equivalent to sizable new supplies. The Federal Interagency Task Force on Irrigation Efficiencies (1979, p. 6) estimated that $5 billion in public and private expenditures on water conservation over the next 30 years could reduce withdrawals by 13 bgd to 18 bgd and, thereby, make 1.7 bgd to 4.5 bgd available for new uses.

Reduction in conveyance losses between storage reservoirs or diversions and the fields being irrigated, more efficient water-application methods, irrigation scheduling based on plant requirements, improved crops, and several other structural and nonstructural methods can increase agricultural production without increasing total water use. Therefore, water withdrawals for irrigated agriculture may peak within the next decade even though total irrigated acreage may continue to increase into the first decade of the next century (Frederick, 1982, p. 227). Undoubtedly, future expansion of irrigated agriculture will take place in a quite different economic and institutional environment than in the past.

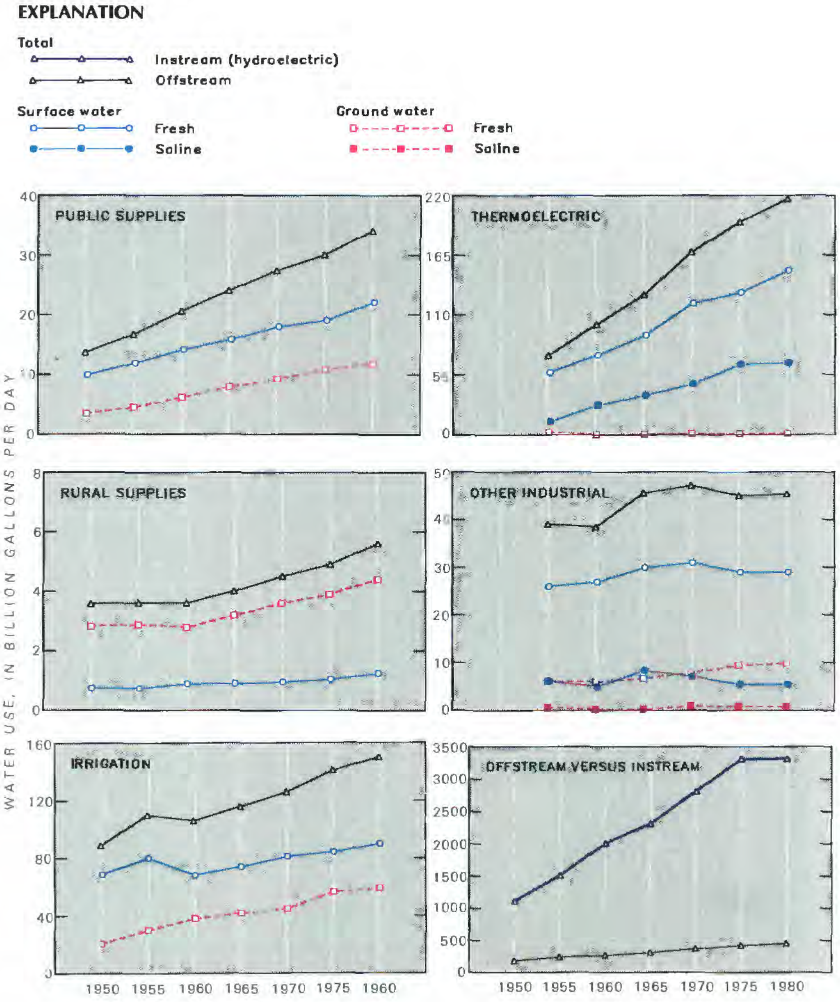

Figure 39. Trends in offstream (withdrawal) and instream (nonwithdrawal) water use at 5-year intervals, 1950–80. Data for 1950 not available for thermoelectric and other industrial water use. (Source: Data from Solley and others, 1983, p. 46–52.)

In the industrial sector, conservation measures associated with pollution-control measures under the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) probably accounted for much of a 4-percent decline in the "other industrial withdrawals" between 1970 and 1975 and for a lack of change in withdrawals between 1975 and 1980 (fig. 39), despite a doubling of manufacturing income (expressed in constant dollars) (U.S. Bureau of the Census, 1984, p. 744). Many industries that used large amounts of process water simply increased the recycling of water in their plants to reduce the volume of waste discharges and the associated costs of treating the discharges (David, 1984). A similar trend seems to be present in the use of water for thermoelectric generation. The percentage increase in that water use between 1970-75 and 1975-80 declined from 18 percent to 9 percent, whereas the percentage increase in electrical power production declined only from 25 percent to 20 percent for the same time periods (U.S. Bureau of the Census, 1984, p. 564). Some of the slowing in the growth of water-use withdrawals for thermoelectric use is related to a reduction in once-through cooling, largely to reduce the discharge of waste heat to streams. Further increases in recycling of cooling water for powerplants by using cooling towers should further slow the growth of withdrawals but probably will increase consumptive use.

Demands for public water supplies are increasing (fig. 39), reflecting the continued growth of population. Many factors, however, will influence the future per-capita demand for water. Overall, the increased use of water-conserving appliances and fixtures over the next few decades, expected increases in the cost of water, and a general awareness of the need to conserve water should stabilize or reduce future per-capita use rates.

It should be noted that development of water resources to the full extent of their normal availability increases the probability of failure to meet demands during droughts. Alternative, temporary supplies should be identified unless demands can be reduced during drought periods. For example, domestic water use generally can be reduced with minimal inconvenience for short periods of time by eliminating lawn watering and car washing. During the 1976-77 drought in California, surface-water supplies were supplemented by ground water, and the use of water for irrigation was greatly curtailed (Matthai, 1979, p. 71-72). For some areas, an increase in water use may be possible only if additional supplies can be obtained by interbasin transfers.

WATER QUALITY

Water-quality degradation has been widely publicized but has not become a major limitation on water availability nationwide. Actually, the Nation is blessed with a relative abundance of good-quality surface water. Although serious water-quality problems have developed in some stream reaches and although some streams do not always maintain a quality suitable for all desired uses, quality problems have not imposed extensive limitations on water use nationwide or even in most regions.

Growing perceptions of water-quality problems in the United States during the 1960's led to the passage of several water-quality-related pieces of Federal legislation in the 1970's, including the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500; amended in 1977 and 1981) and the Safe Drinking Water Act of 1974 (Public Law 93-523). In support of this legislation, billions of dollars have been spent by the public and private sectors on different types of pollution-abatement programs designed mainly to reduce point-source pollution and improve stream-water quality. For example, more than $100 billion was spent for pollution control between 1974 and 1981 (U.S. Environmental Protection Agency, 1984). In the decade following passage of the Federal Water Pollution Control Act of 1972, total biological oxygen demand (BOD) loads from municipal discharges reportedly decreased an estimated 46 percent, and industrial loads decreased at least 71 percent (Association of State and Interstate Water Pollution Control Administrators, 1984; U.S. Environmental Protection Agency, 1982) despite increases in population and real Gross National Product of 10 percent and 27 percent respectively.

In general, significant improvements apparently have been made in the quality of the Nation's waters (U.S. Environmental Protection Agency, 1985, p. 1). Observed trends at 294 National Stream Quality Accounting Network (NASQAN) stations (operated by the U.S. Geological Survey) and 94 National Stream Quality Surveillance System (NWQSS) stations (operated by the U.S. Environmental Protection Agency) between October 1974 and October 1984 showed widespread decreases in fecal bacteria concentration and, to a lesser degree, in phosphorus downstream of large point-source discharges (Smith and others, 1986). These trends provide some evidence of the beneficial effects of improved treatment of point-source effluents on water quality. However, similar relationships between trends in dissolved-oxygen deficit and changes in point-source BOD loads were not observed.

In many regions, nonpoint sources of pollution contribute significantly to water-quality problems. Widespread increases in chloride, nitrate, and, to a lesser extent, sulfate are thought to be related to nonpoint sources. Increases in the use of salt (chloride) on highways and of nitrogen fertilizer, and regionally variable trends in coal composition (sulfate) and production appear to be reflected in water-quality changes at the NASQAN and NWQSS stations. Of particular interest is evidence that atmospheric deposition of a variety of substances has played a large role in water-quality changes of surface water (Smith and others, 1986). The off-farm effects of cropland erosion also are a concern in many parts of the country (Clark and others, 1985). Thus, water-quality programs that formerly emphasized control of point-source pollution are now shifting to programs that emphasize the control of nonpoint sources of pollution, the protection of ground-water quality, and the cleanup of toxic-waste disposal sites.

The protection of ground-water quality is particularly important, not only because ground water supplies much of the Nation's drinking water, but also because it is the source of about 40 percent of the Nation's streamflow. This hydraulic connection between streams and aquifers implies that if a pollutant gets into an aquifer and is not adsorbed or degraded by chemical, physical, or biological processes, the pollutant will eventually be discharged to a surface-water body.

As yet, surface-water quality has not greatly affected offstream water uses. Most water can be treated to remove contaminants, although there is some concern about the effectiveness of conventional water-treatment processes in removing synthetic organic substances.

In terms of instream uses, water quality, including sediment content, significantly affects fish and wildlife. The impact of water quality on the capability of streams to support sport fish does not seem to have changed appreciably over the past 5 years. About 67 percent of the Nation's stream miles are reported to be capable of supporting sport fisheries (Judy and others, 1984, p. 52-53). Nonpoint-source pollution from agricultural lands, however, is a major constraint to improving stream-habitat conditions for fish (resident and migratory) and other wildlife.

A particularly difficult problem is the reuse of irrigation return flows which may be contaminated by pesticides and fertilizers. Because of the high consumptive use in irrigation, the mineral content of the return flows often is increased substantially. Subsequent reuse of irrigation water may not be possible unless the return flow is diluted with fresher water to lower these salt concentrations. Such salt buildups have affected a number of western rivers, most notably the Colorado and the Arkansas Rivers (U.S. Geological Survey, 1985, p. 74-84). The salinity of irrigation return flows always has been a major problem in irrigation management. Recently new concerns have arisen about toxic substances, such as selenium, in waters associated with agricultural drainages, and the possibility that such substances may accumulate in the aquatic food chain to the point where they are toxic to fish and wildlife (U.S. Geological Survey, 1985, p. 45-46; Presser and Barnes, 1985).

It is obvious from the foregoing that improving or even maintaining stream water quality, in the face of population growth and more intensive use and reuse of the water, will be one of the major challenges of the coming decades. These challenges are only part, however, of the overall challenge of meeting future water demands in the context of evolving legal and institutional arrangements, and of resolving the competing and often conflicting demands for limited supplies of water.

MANAGEMENT INFLUENCES

Water management is undergoing major changes (Freshwater Society, 1985). These changes are driven by several factors: increasing water demands; a fixed but renewable resource base whose physical limit is being approached in some river basins; increased costs of expanding water-supply capacity; and a changing view of the Federal role in water-resources development. Several strategies appear to be emerging as a means of coping with these factors.

- Demand management—use of water-conservation measures, water pricing, and withdrawal permits to match demands to available supplies.
- Supply management—use of recycling and reuse of existing supplies, conjunctive use of surface and ground water, and the joint operation of individual water projects in a river basin as a system in order to increase the beneficial use of existing supplies.
- Water reallocation—use of water markets, negotiated water transfers, and other voluntary transfers to set priorities for meeting competing water demands.

The existing institutions, water laws, and conventions evolved during a period in history when water demands generally could be met by allocations from a relatively abundant supply. State water-rights systems originally were designed to preserve a static pattern of use, once that pattern was established (Brown and others, 1980). The new challenge to State water managers is to facilitate the transfer of existing water rights to new users while also protecting other water-right holders. Innovative approaches already have been used by several Western States as described by the article in this volume, "Voluntary Transfers of Water in the West." Recognition of water rights or the access to water supplies as a negotiable and transferable property right that may be sold or leased in the market place seems to be one of the keys to resolving many of today's "water crises" (U.S. Council on Environmental Quality, 1986, p. 312).

Regardless of the management techniques adopted by each State to manage its water resources, the development and management of water resources in the face of increasingly competitive water demands are likely to increase the demand for water information and knowledge about hydrologic systems.

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SNOW, ICE, AND CLIMATE—THEIR CONTRIBUTION TO WATER SUPPLY

By Mark F. Meier

INTRODUCTION

The surface-water components of the hydrologic cycle usually are considered to be rainfall and subsequent runoff. Yet, in many parts of the United States and the world, for a major part of the year, the more appropriate concept is precipitation and storage (as snow and ice), followed by melting, followed by runoff. The timing involved in these two concepts is very different: Runoff follows rainfall almost immediately, whereas the time between snowfall and melt can range from days to months for seasonal snow covers and from years to millenia for glaciers. The predictive analysis of runoff also is very different: Prediction of runoff from rainfall requires knowledge of the precipitation pattern in time and space, whereas the prediction of runoff from snow and ice melt requires (for seasonal snow) knowledge of the amount of snow in storage (measurable) and the meteorological conditions that cause melt. The fact that snow and ice accumulate and melt to produce runoff in a very different way than does rainfall commonly is ignored in simple hydrologic analyses. This article discusses the nature of global snow and ice, the role of snow and ice in the hydrologic cycle, possible consequences to global sea level of large-scale melting of snow and ice, the concept of snow and ice as a water resource, and the influence of snow and ice on human activities.

Although the Sun is the energy source that drives the global hydrologic cycle and the circulation of the atmosphere and oceans, our planet's present climate would not be possible without snow and ice to help maintain energy equilibrium. In the tropical lower latitudes, more radiant energy is received than is lost; the opposite situation must exist in other areas of the world in order to maintain equilibrium and to help drive the atmospheric and oceanic circulation. This compensatory loss is provided in the high latitudes, where ice and snow dominate the environment. Snow has the highest reflectivity of solar radiation (in visible-light wavelengths) of any widely distributed natural material on the Earth's surface, yet it is an almost perfect radiator of energy at infrared and longer wavelengths. Thus, snow absorbs little solar energy, and it radiates heat to outer space.

Sea ice on the polar oceans plays a similar role in radiating energy and also greatly inhibits the transfer of water mass and energy between air and ocean. In polar regions, the seawater, which is more saline than seawater in other regions, spreads throughout the world oceans, with the result that 75 percent of the world's ocean water has properties determined by processes that take place at the surface in very narrow zones in the high latitudes. Atmospheric and oceanic circulation are driven by the contrasts between heat gain at low latitudes and radiative heat loss at high latitudes.

The amount of ice on Earth is immense, greatly exceeding the amount of liquid freshwater on the surface and in soil, in ground-water reservoirs, and in the atmosphere (table 9). If the ice were to melt, global sea level would rise by about 250 feet, and the oceans would inundate about 600,000 mi^2 (square miles) of land. Even very small changes in the mass of ice on Earth could cause changes in sea level capable of affecting the habitation of coastal areas. Sea level is rising globally at an average rate of 4 to 8 inches per century. The cause and rate of sea-level rise are questions of vital importance to present and future generations.

Table 9. Freshwater of the Earth

[Sources: Meier, 1983; UNESCO, 1971; and Shumskiy and others, 1964]

Water source	Mass (water equivalent, cubic miles)	Approximate residence time
Glaciers and ice sheets	7,000,000	Hundreds to tens of thousands of years.
Ground ice	50,000–120,000	Hundreds to thousands of years.
Seasonal snow	2,500	Months.
Icebergs	1,800	One year.
Lakes, reservoirs, swamps	31,000	Years to tens of years.
Rivers	400	Weeks.
Ground water	[1]1,000,000	Days to tens of thousands of years.
Soil moisture	16,000	Weeks to several years.
Water in the atmosphere	3,100	One week.

[1] Mass estimates, including the water deep within the Earth that does not actively participate in the hydrologic cycle, range to as much as 14,000,000 cubic miles.

Ice and climate are closely related. Glaciers and ice sheets, which contain most of the world's ice (and freshwater), grow and shrink as the climate changes. It is not clear, however, whether the present rise in sea level is caused by ice wastage or not. The largest ice mass—the Antarctic Ice Sheet—is thought by most glaciologists to be growing, thereby taking water out of the ocean (National Academy of Sciences, Committee on Glaciology, 1985). The volume of the second-largest ice mass—the Greenland Ice Sheet— seems to be stable under present climatic conditions. However, the remaining 3 percent of Earth's glacier ice, consisting of mountain glaciers and the small ice caps, clearly has been wasting away since the beginning of this century. Although small in comparison with the two huge ice sheets, this glacier ice has lost a thickness equivalent to about 1.2 feet of water per year, averaged over its total area of 211,000 mi^2. This water, lost from the frozen reserves, augmented streamflow during the first part of this century and has caused between one-fourth and one-half of the observed rise in sea level (fig. 40). The cause of the remainder of the global sea-level rise is

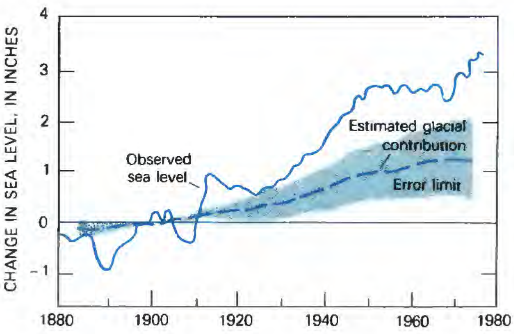

Figure 40. Global sea-level change as observed (1880-1979) compared to the change contributed by the wastage of the world's small glaciers (1884-1974). The higher observed sea-level change may be the result of glacier wastage and thermal expansion of ocean water due to the warming trend of the past century, although this has not yet been proved. The error limit indicates possible range in sea level estimated from glacier-wastage data. (Sources: Observed sea-level data from Gornitz and others, 1982; estimated glacier data from Meier, 1984.)

not clearly understood; it may be caused, at least in part, by thermal expansion of ocean water because of slight warming over the last century.

What will happen to climate and sea level in the future? Climate is being changed by fossil-fuel combustion and other human activities that add CO_2 (carbon dioxide), methane, chlorofluorocarbons, and other so-called "greenhouse" gases to the atmosphere. Fossil air, trapped in bubbles in glacier ice from times before the industrial revolution, has a CO_2 concentration of about 260 ppmv (parts per million by volume) (Raynaud and Barnola, 1985). In 1985, the concentration of CO_2 in air was about 345 ppmv, and during the next century this concentration is expected to exceed 600 ppmv. Climate models indicate that this doubling in CO_2 concentration may cause an increase in global air temperature from 1.5 to 4.5 °C (3 to 8 °F); other "greenhouse" gases may cause an additional increment of warming, and the expected warming will be accentuated at high latitudes (National Academy of Sciences, Carbon Dioxide Assessment Committee, 1983). Moreover, there is little that can now be done to delay this warming appreciably (Hoffman and others, 1983, p. 8–9). Thus, the question of whether this "greenhouse" warming will cause large amounts of ice to melt, which will raise global sea level and cause extensive damage to coastal and low-lying regions, is of vital concern.

The amount of sea-level rise by the time CO_2 reaches 600 ppmv, which is expected before the year 2100, could be large enough to cause major societal dislocations (Hoffman and others, 1983). Most of the world's major cities and much of its population are in low-lying areas near shorelines, and even very small rises in sea level, which can cause coastal inundation, beach erosion, storm-surge damage, and saltwater intrusion into coastal aquifers, can have significant social and economic impacts. The repeated disasters in Bangaladesh, including the major loss of life in May 1985, that were caused by flooding of low-lying islands by storm surges, show how vulnerable humans are to even slight variations in sea level.

A recent study by the National Academy of Sciences, Committee on Glaciology (1985) analyzed the present state of knowledge on the cause of present-day changes in sea level and also analyzed possible future changes that could be expected because of glacier wastage from a CO_2-induced change in climate. The following conclusions were reached:

- Local changes in sea level relative to the land may result from global sea-level changes plus local geologic processes, such as compaction of sediments (Mississippi Delta), or from a continuing adjustment of the Earth to the loss of the Ice Age ice sheets (in parts of the Atlantic coast), or to vertical tectonic displacements (in parts of the Pacific coast).
- Global average sea-level rise is caused in part by the wastage of small glaciers, but the contribution by the immense ice sheets is not clear.
- Part of the current sea-level rise may be caused by thermal expansion of ocean water, but this has not been proved by observational evidence.

There are great unknowns in almost all major components of the current world water balance and in the exchanges (fluxes) of water between the land and sea. The most critical uncertainties, in view of the known sea-level trends, are the roles of thermal expansion of ocean water and the mass balance of the great ice sheets.

Looking to the future, it is likely that small-glacier wastage will accelerate, adding more water to the ocean. But it is more difficult to predict what will happen in Antarctica, where melting of surface snow and ice is likely to be negligible in the next 100 years in spite of the predicted higher temperatures (National Academy of Sciences, Committee on Glaciology, 1985). According to the Committee, the higher temperatures and ensuing decrease of sea-ice cover may result, instead, in increased snow accumulation, which will add mass to the ice sheet. It must be kept in mind, however, that warmer ocean water likely will penetrate under the floating ice shelves along the margins of Antarctica and cause increased melting of the underside of these shelves. This subsurface melting, in itself, will not affect sea level, but the ice shelves, by becoming thinner, will exert less back pressure on ice streams (outlet glaciers) that flow outward from the ice sheet onto the shelves. This, in turn, would cause the ice streams to flow faster and to drain ice more rapidly from the land into the sea. One scenario suggests that this process could cause the disintegration of the entire West Antarctic Ice Sheet in a century or so, which would result in a 16- to 23-foot rise in global sea level. Two recent reports (National Academy of Sciences, Carbon Dioxide Assessment Committee, 1983; National Academy of Sciences, Committee on Glaciology, 1985) suggest, however, that a much more modest rise is likely, although a 3-foot rise by the year 2100 from disintegration of the West Antarctic Ice Sheet alone cannot be ruled out (table 10).

The estimated global sea-level rise as a result of wastage of the world's glacier ice is likely to be in the range of 0.6 to 2.7 feet by the year 2100; additional sea-level rise, however, will be caused by thermal expansion of the ocean water, associated with atmospheric warming. This sea-level rise will have an appreciable, but probably not catastrophic, impact on low-lying coastal regions, such as those in the Southeastern United States. Other studies (Hoffman and others, 1983; Barth and Titus, 1984) have suggested somewhat more extreme scenarios and have projected severe economic impacts to areas such as Galveston, Tex., and Charleston, S.C.

Those who live and work along the world's coastlines should have special interest in what is happening to the ice masses at high elevations and in the polar regions. Changes are afoot, and they will have global consequences within a few generations.

The expected rise in atmospheric CO_2 and the ensuing climatic change also will have other effects on surface-water supplies. A rise in air temperature generally will cause increased evaporation and also can cause precipitation to increase in some areas and decrease in others, which in turn will effect runoff. Langbein and others (1949), in a study of the drainage basins of the Western United States, developed a simple relation between runoff and annual precipitation and temperature. Revelle and Waggoner (1983), using this relation, estimated that, for a typical western basin with an initial air temperature of 39 °F and an annual precipitation of 12 inches, a 3 °F rise in temperature would result in a 35-percent decrease in runoff. Rind and Lebedeff (1984), using the atmospheric general-circulation model developed by Hansen and others (1983), estimated the effects of doubling of the CO_2 on runoff in the conterminous United States. Their results, which are on a coarse grid so that all or parts of 23 grid cells cover the conterminous United States, suggest changes in runoff that range from a 66-percent decrease (north Texas, Oklahoma, and adjacent areas) to a 58-percent increase (Oregon and adjacent areas). They stated that these are preliminary results, set forth for study purposes, and that such models are still in their infancy. Other general circulation models produce different patterns of surface air temperature and precipitation changes. Consequently, runoff patterns might also be different. These models, unlike the model by Hansen and others (1983), do not include the effect of CO_2 on plantlife and, therefore, on transpiration.

A study by the National Academy of Sciences, Panel on Water and Climate (1977) points out that future water shortages may be exacerbated by climate change. However, this study indicates that existing climatic forecasts are not yet sufficiently precise in predicting the area affected and the magnitude of the effect to be useful for the design of future water-resources systems. But this may change in the near future.

Table 10. Estimated sea-level change by year 2100, as a result of ice wastage in a carbon dioxide-enhanced environment

[Source: National Academy of Sciences, Committee on Glaciology, 1985]

Ice mass contributing to sea-level change	Estimated sea-level change (range, in feet)
Glaciers and small ice caps	+0.3 to 1.0
Greenland Ice Sheet	+0.3 to 1.0
Antarctic Ice Sheet	[1]−0.3 to +3

[1] Most likely the change will range from 0 to 0.7 foot.

Figure 41. Snow in the mountains—an object of beauty; an opportunity for recreation; and a principal source of water for irrigation, hydroelectric power, industrial and public supplies, aquatic habitats, navigation, and dilution of salinity and pollution in rivers. (Photograph by M. F. Meier, U.S. Geological Survey.)

SEASONAL SNOW COVER

Snow is a pervasive element of the environment in the northern-tier States of the conterminous United States, in Alaska, and in the higher elevations of the western States and Hawaii; snow also occasionally affects most other parts of the country (figs. 41, 42). Globally, the seasonal snow cover of the northern hemisphere is an important factor in the heat budget and, therefore, in Earth's climate. Snow is such an efficient reflector of radiation that if the Earth were to become completely snow covered, the mean temperature of the Earth would drop to −89 °C (−128 °F) and remain that way (Budyko and Kondratiev, 1964).

Both globally and regionally, the presence of snow cover causes a positive feedback to climate. With snow on the ground, more solar radiation is reflected, causing cooling and preservation or augmentation of the snow. Snow cools the overlying atmosphere and significantly modifies local atmospheric circulation. The resulting high-pressure atmospheric cells that form in the snowbelts can generate anticyclonic winds that export the cold, dry air into the middle latitudes.

The effect of snow on humans and on the hydrologic cycle, however, is not limited to climate. For example, snowmelt runoff in the United States supplies water for virtually all types of offstream and instream uses; snowpack management can optimize soil moisture and minimize frost penetration for agriculture; and snowmelt floods can cause major economic losses. Snow also has major effects on transportation, construction, recreation, and other activities (Colbeck and others, 1979).

SNOW, SNOW, AND SNOW

Snow types and methods for managing snow and snowmelt water are diverse. The Eskimos recognize about two dozen different kinds of snow;

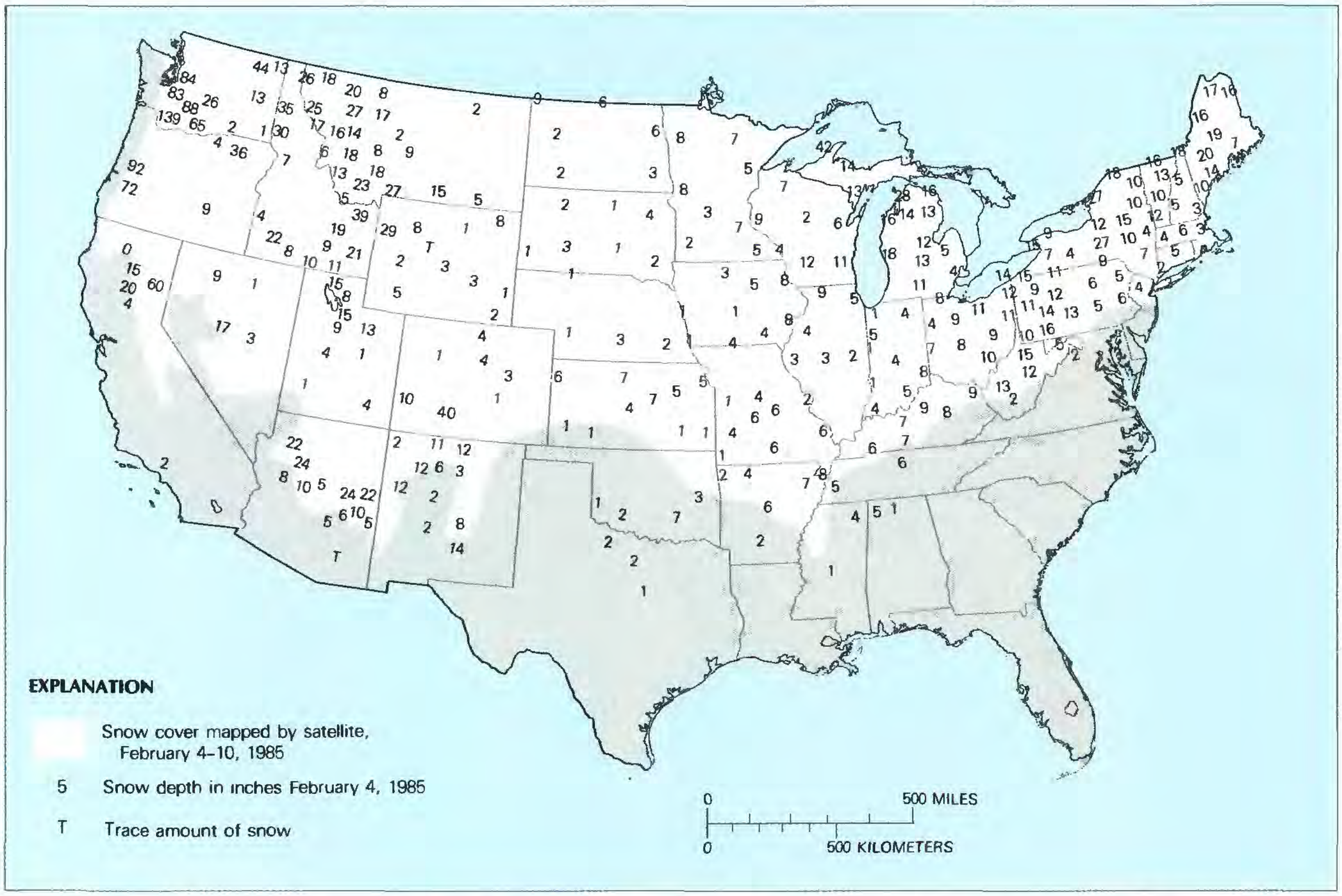

Figure 42. Typical snowpack distribution in winter in the conterminous United States. The snow measurements were made at established stations that generally are at low elevation; in the mountains, snowpack usually is much thicker than that at lower elevations. The area of snow cover is based on data from images acquired by Geostationary Observational Environmental Satellite. (Sources: Snow-depth data—from Weekly Weather and Crop Bulletin, prepared jointly by National Oceanic and Atmospheric Administration and U.S. Department of Agriculture; areal snow-coverage data—National Oceanic and Atmospheric Administration.)

certainly "Api" (snow not yet picked up and reworked by the wind) is different from "Upsik" (snow that has been reworked by wind and deposited as a firm mass), and neither should be confused with "Siqoq" (snow blown along the ground by the wind) (Kirk, 1980, p. 27). The problems and benefits associated with snow, and the methods for its management, differ greatly from region to region. These differences can be illustrated by considering snow in three contrasting regions of the conterminous United States: the northern Great Plains, the Cascade Range of the Pacific Northwest, and the Rocky Mountains.

Northern Great Plains.—In the northern Great Plains, snowpacks typically are thin (2 to 5 inches of water equivalent) and, because snow is blown into swales or gullies or into the lee of vegetation, snowpacks are extremely variable areally. The snow usually is dry, and initially has low density but becomes dense where it is windpacked ("Api" to "Upsik" in Eskimo terms); the snow crystals may fragment and evaporate as they are blown along the ground. Horizontal-transport studies are important for understanding the distribution, management, and hydrology of snow. In this region, snowpacks although small in amount are important economically because they supply critical soil moisture at the beginning of the crop-growing season and because they insulate plants from frost damage. Snow deposition is managed by the use of agricultural cropping practices, such as controlling the height of stubble, and by the construction of windbreaks that concentrate the snow and delay melting until the ground thaws. Snowmelt floods, exacerbated by frozen ground, occasionally occur in some areas. Snow data are used for soil-moisture-conservation studies and other purposes; a major problem in hydrologic modeling for this region is related to an incomplete understanding of evaporation from the snowpack.

Cascade Range, Pacific Northwest.—Snowpacks in the Cascade Range of the Pacific Northwest (fig. 43) are very thick (more than 30 feet in places with more than 15 feet of liquid-water equivalent) and are almost never far below the freezing point. The amount and distribution of the snow are strongly dependent on elevation because of the importance of temperature during storms and because of a marked increase in precipitation in the mountains with increasing elevation. The distribution of snow also relates, to a lesser extent, on a west-to-east decrease in precipitation across the range. The snowpack is coarsely crystalline, very dense, and usually wet throughout. Evaporation from snow is negligible compared to snow loss caused by melting. The snowpack is not managed except in a very minor way through forestry practices. Because of extensive hydroelectric development in the region and the relatively low ratio of reservoir storage to annual streamflow, accurate predictions of snowmelt runoff are essential for meeting energy needs economically and for managing multiple uses of the river systems. Several complex runoff-forecasting schemes, supported by an extensive network of real-time data-acquisition sensors and telemetry and snow-course observations, are used to help predict snowmelt runoff. (See article in this volume, "Real-Time Hydrologic Data for Water Management.") However, because of extensive forest cover, remote-sensing techniques are of limited value. Snow avalanches commonly damage property and occasionally cause fatalities. Rain-on-snow events can occur at any time of the year but are most likely to cause flooding in the fall when the snowpacks are widespread but relatively thin.

Rocky Mountains.—In the Rocky Mountains, snowpacks are moderate in thickness, are relatively cold, and are extremely variable areally. Redistribution of the snow by wind causes the snow to be concentrated in cornices along ridge crests, in valleys, and in openings in timber stands. Evaporation, usually unknown in amount, often occurs when plumes of snow are blown from high ridges. The snow generally is dry and powdery when it falls but increases in density because of metamorphism and compaction over time. A form of snow termed "depth hoar" (fragile crystals that develop within a snowpack because of vapor transfer) is common. Snow avalanches are serious hazards in many areas. Snowmelt runoff is used mainly to irrigate crops throughout the intermountain West and Southwest; other major uses include power generation, supply of municipal water, and mitigation of river salinity. In spite of a relatively high ratio of reservoir storage to annual streamflow, the water is so valuable and is so intensively utilized that complex data networks and runoff-forecasting schemes are employed. Several remote-sensing techniques are in use to inventory the snow resource, and much effort has gone into studies of snow management. Management options include cloud seeding to increase snow accumulation, construction of wind fences on ridges to concentrate the snow into drifts so as to minimize evaporation and extend the runoff period, and forest-cutting practices designed to maximize the trapping of snow and reduce snowmelt-runoff peaks.

Other parts of the United States.—In other parts of the United States, snowpacks have different properties and uses. For instance, on Alaska's North Slope, snow is used to build roads, to protect construction sites, and to provide local water supplies. In the Sierra Nevada Mountains of California, the snow itself is similar to that of the Northwest, but the meltwater is far more intensively used to support agriculture. In the Northeastern United States, as in Scandinavia, snow exacerbates the problem of acid precipitation by capturing and storing pollutants during the winter and releasing them to lakes and streams in a sudden rush of spring-time runoff (Johannessen and others, 1977). (See figure 44.)

These descriptions of various snowpacks in the United States show the riskiness of generalizing about snow as a water resource as well as the uncertainty in applying snow-research results broadly without considering the local characteristics of snow accumulation, snowpack properties, and snowmelt processes. We can all learn from the Eskimos.

PREDICTING SNOWMELT RUNOFF

One of the most propitious, and economically valuable, aspects of snow as a water resource is that it can be measured as it lies on the ground. From this information, the volume of subsequent runoff can thus be predicted. In turn, knowledge of snowmelt runoff facilitates the management of reservoirs and permits management of rivers for multiple uses. Forecasts of snowmelt runoff are especially important in the mountainous West, where most runoff is provided by snowmelt. The U.S. Soil Conservation Service, the National Weather Service, U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and many other Federal, State, and local agencies, including the U.S. Geological Survey, participate in a Cooperative Snow Survey Program and in projects that forecast river flows from snow surveys.

A major difficulty in providing accurate forecasts of snowmelt runoff is the areal and temporal variability of snow in the mountains. This variability stems in part from the variability of precipitation in the mountains and in part from the redistribution of snow by wind and avalanches after it falls. Snow measurements are determined from precipitation gages, from measurements made at snow courses, from snow pillows, and from techniques that measure electrical properties or the absorption of radioactivity. Remote sensing also is becoming a useful technique in some areas. Precipitation gages alone are not adequate because the catches are often deficient at times of blowing snow (fig. 45). At snow courses, measurements are made by extracting and weighing cores from snow on the ground four to six times each winter; this technique accurately measures the snowpack at a specific place, but it is labor intensive, costly, sometimes dangerous, weather dependent, and is not adaptable to telemetry and real-time data collection. Snow pillows, which measure the weight of snow on the ground, have been integrated into automatic data-collection networks. On occasion, pillows can give suspect readings because of "bridging," whereby snow on the pillow is supported partly by ice lenses or buried crusts. Although snow pillows generally are reliable, they can provide only a limited sample of the variable snow resource because of the cost of installation and maintenance.

Remote sensing eventually may overcome the spatial sampling problem, but this technique is still in the experimental phase. Four methods have been actively investigated: (1) Repeated aircraft flights along a designated path over relatively flat terrain to detect the attenuation of natural Earth radioactivity, whereby the degree of attenuation is proportional to the mass of snow on the ground; (2) aircraft flights in the mountains to note the position of the snowline or the fraction of the area covered by snow (commonly used to check runoff-model calculations); (3) satellite images made with visible-to infrared-light sensors that are used to monitor snow-covered areas (fig. 46); and (4) satellite images made with passive-microwave sensors, which can provide information on snowpack mass (assuming that no liquid water is present). The first

Figure 43. **Snowpacks in the Cascade Range of Washington, which commonly are very thick, provide abundant water but make snow measurement, and especially pit digging, difficult.** U.S. Geological Survey scientists are shown measuring the percolation of liquid water through a snowpack that is about 33 feet thick (note person at bottom of pit). (Photograph by M. F. Meier, U.S. Geological Survey.)

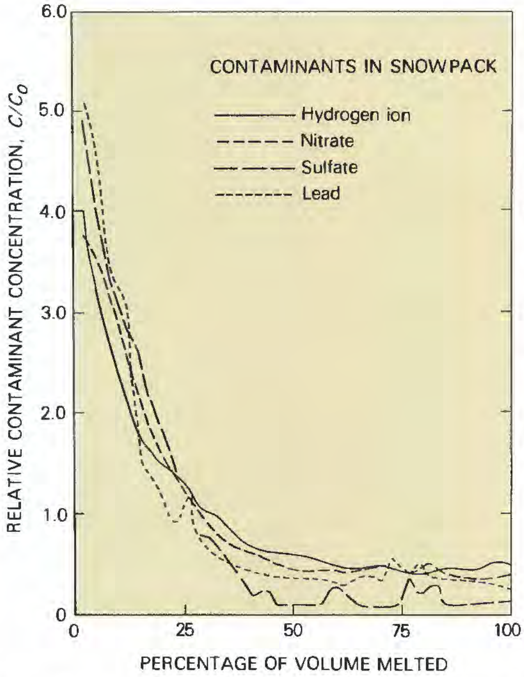

Figure 44. Contaminants in snowpack shown as the ratio of concentration, *C*, of selected contaminants in a meltwater fraction to the average concentration, C_0 as a function of the fraction melted. Soluble impurities such as acid droplets may be accumulated and stored in a cold snowpack for about 3 to 6 months. When the snowpack warms up and liquid water moves through it, the solutes at the grain boundaries are suddenly flushed out. This flushing causes a rapid acidification or contamination of the meltwater, with possible resultant damage to downstream ecosystems. This typical melt curve shows that the greatest concentration of contaminants is in the initial meltwater. Source: Modified from Johannessen and others, 1977, fig. 2.)

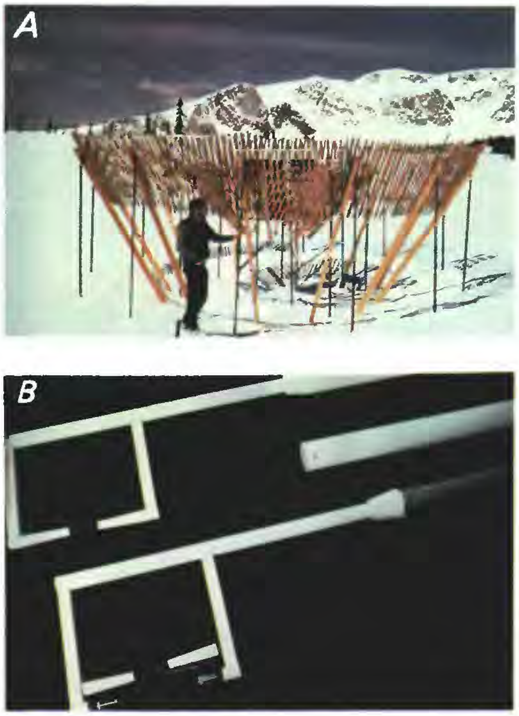

Figure 45. Large and small approaches to the problem of measuring blowing snow, of which conventional precipitation gages may catch only a fraction, depending on local windspeed, snow crystal type, and other factors. *A*, the Wyoming gage—a precipitation gage inside a complex arrangement of snow fencing. This gage has been successfully used in Wyoming, on the North Slope of Alaska, and in other windswept locations. *B*, A tiny optical device that counts snow particles as they pass between a light source and detector. (Photographs courtesy of (*A*) R. D. Tabler, U.S. Forest Service, Laramie, Wyo.; (*B*) R. A. Schmidt, U.S. Forest Service, Fort Collins, Colo.)

two methods are labor intensive and expensive, and the last two have numerous drawbacks, including infrequency of coverage (using Landsat high-resolution sensors), low resolution and obscuration by clouds (using meteorological satellites with visible-and infrared-light sensors), and ambiguity of interpretation (using satellite active and passive microwave sensors). Thus, improvement in understanding remotely sensed properties of natural snowpacks and in developing improved techniques for the large-scale, all-weather determination of snow mass by satellite remote sensing have been given a high priority for research (National Academy of Sciences, Committee on Glaciology, 1983).

Volume forecasts are based on measurements of the amount of snow on the ground at a fixed date (such as April 1) as an index to the total amount of water likely to be produced by snowmelt after that date, usually in terms of what the river flow will be in relation to a specified "normal" flow. These forecasts are useful in managing reservoirs to optimize allocations for competing water uses and to minimize the amount of water or hydroelectric power wasted because of uncertainty in the forecasts. Forecasts, however, at frequent intervals, including daily forecasts of inflows to many reservoirs, often are required when monitoring river systems that are extensively developed. Volume forecasts can be updated when runoff begins, and new forecasts can be made using new measurements of snow mass at monthly or bimonthly intervals. These volume forecasts generally are developed by use of a statistical regression analysis of snow mass versus subsequent runoff as a percentage of "normal" runoff. The accuracy of the result depends in part on the statistical population of past snowmelt-runoff scenarios used in the regression analysis.

Accurate prediction of extreme or unusual events, which are not represented in the historical record, sometimes is not possible. This can be illustrated by noting the unusual conditions in the upper Colorado River basin in 1983—conditions that occurred in many drainages in the West that year. The flow of the Colorado River at Lees Ferry, Ariz., is dominated by snowmelt runoff that generally peaks in June (fig. 47). During the 1983 water year, precipitation was only slightly (about 6 percent) higher than normal, yet the runoff volume for the year was more than twice normal (corresponding to a recurrence interval of 100 years), and the June-July flow was even more exceptional (corresponding to a 200-year event) (Shafer and others, 1984). Predictions made on May 1 at many forecast sites were substantially low.

Air temperature during the snow-accumulation season and through the normal time of low-elevation melting was unusually low; snow continued to accumulate at all elevations in the mountains until about May 21. Then, with the weather very warm and the Sun high in the sky, melt occurred at all elevations very rapidly in late May and June. This melt pattern was in marked contrast to the usual melting period of April through June (fig. 48). Because of the previous cool temperatures, the extent of the snow-covered area in late May also was larger than usual—a factor not yet included in most operational forecast models. Soil moisture had been high all year, and the shortening of the melt season into about half of its normal length reduced the opportunity for meltwater infiltration and evapotranspiration. The rate of runoff, therefore, was large, and major flooding resulted. No precedent for that scenario was found in the historical data sets used in forecasts made by statistical regression analysis. Furthermore, differences between forecast and actual runoff were uncharacteristic, based on previous experience and on evaluations of the accuracy of past forecast performance (Shafer and others, 1984). Physically based conceptual models offer a better framework for understanding and predicting such events (Shafer and others, 1984).

SNOWMELT PROCESS

Understanding the snowmelt process requires consideration of the energy fluxes that produce melt. Snow receives energy from the Sun (short-wavelength radiation), from radiation emitted by water vapor and clouds in the air (long-wavelength radiation), from warm air, from the heat of condensation, from rainfall, and from heat conducted from the underlying ground. As previously mentioned, much of the incoming solar radiation is reflected back from the snow surface because of its high reflectivity or albedo; the snow also emits long-wave radiation. The radiation balance of a snowpack depends not only on the algebraic sum of these components but also on atmospheric conditions, snow temperature, and other factors that vary with time. Heat energy also is gained or lost from the snow by evaporation or condensation and by the transfer of heat from the air by eddy convection; these processes depend primarily on the wind, humidity, and temperature gradients in the air just above the snow surface.

The effects of these various energy components vary with time of day and time of year, and with elevation, latitude, and vegetation cover. In general, net radiation increases in relative importance with increasing elevation and as the season advances from winter to summer. Male and Granger (1981) summarized the different contributions to the total melt in 24 separate studies at diverse locations. They found that net radiation accounted for 17 to 100 percent of the melt, heat transfer (from air) for −42 to 79 percent, and latent-heat (evaporation-condensation) transfer for −74 to 36 percent. (The minus sign indicates that the snow cooled rather than melted.)

Even simple generalizations, such as that a clear day implies the highest net radiation balance, are not always true. Hubley (1957) found that the net short-wave radiation on snow near Juneau, Alaska, on a clear day in June, was 247 ly (1 langley (ly) = 1 calorie per square centimeter; 200 ly absorbed by ice at 32 °F produces 1 inch of meltwater), and that the net long-wave radiation was −122 ly, leading to a net radiation balance of 125 ly. On a totally overcast day with cloud temperatures of about 41 °F, the net short-wave radiation was reduced to 124 ly, but the net long-wave radiation balance was +50 ly, leading to a net radiation balance of 174 ly, which was 40 percent greater than it was on a clear day.

Clearly, the measurement or prediction of all the energy fluxes that determine the rate of snowmelt is impossible for operational use at most locations. Therefore, attempts are made to relate snowmelt to one or a very few simple variables that are easily measured.

Air temperature is used widely to estimate melt rate, usually by an empirical formula such as

$$M = k\,(T - To),$$

where

M = melt rate, in inches of water per day;
T = air temperature;
To = reference temperature (usually 32 °F);

and

k = melt factor.

T can be the average or maximum daily temperature, depending on the model. (See figure 49.)

This approach, although commonly applied, is not sufficiently precise for modern water-resources management purposes for several reasons. Air temperature is not involved directly in the energy-balance components but is correlated with several components, such as incoming short-wave radiation. These correlations make temperature, in effect, a nonlinear function of the combination of these fluxes, and therefore the average daily temperature may not reflect the daily average of the combination of these fluxes. Also, other important factors, such as the wind gradient near the snow surface, may not correlate with air temperature. Another problem with the simple air-temperature formula is the need to use a wide range of values for the empirical melt factor, *k*, when applying the formula to contrasting areas (Gray and others, 1979.)

Air temperature also commonly is used to distinguish precipitation that falls as rain or snow. This

Figure 46. Landsat image showing the changing snow-covered area during one melt season in northwestern Washington and adjacent British Columbia (a temporal composite). The white area was snow-covered on April 7, 1973, and the red area was still snow-covered on September 16, 1973. The yellow and brown areas generally were snow-free on both dates, but snow was hidden in some areas under heavy forest. For instance, in the lower right, numerous white spots indicate snow cover in April and areas where timber has been harvested; this snow undoubtedly extended under the adjacent timber stands. (Source: Landsat images E-1258-18322 and E-1420-18303, temporal composite prepared by Morris Deutsch, U.S. Geological Survey.)

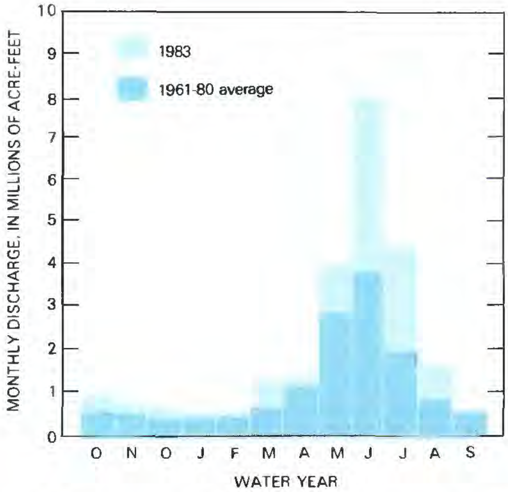

Figure 47. Monthly discharge for 1983 compared with the average monthly discharge for 1961-80, for the Colorado River at Lees Ferry, Ariz. Discharges have been corrected for artificial diversions and impoundments. (Source: Modified from Shafer and others, 1984, fig. 2.)

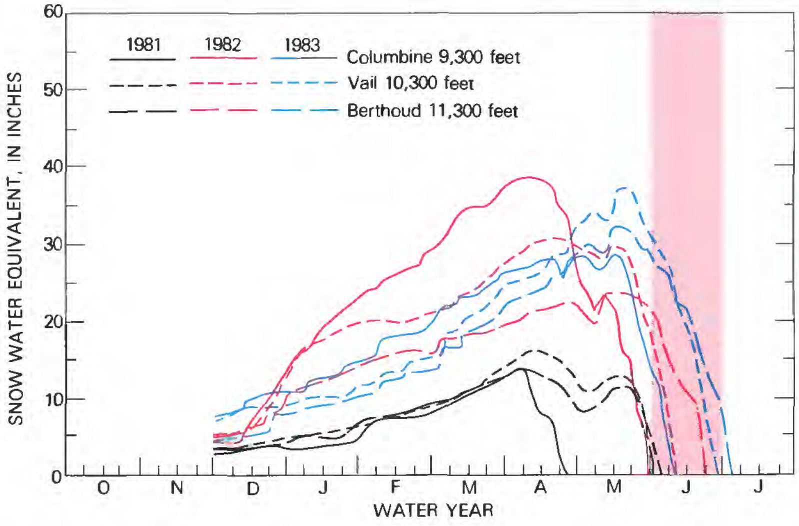

Figure 48. Variation in snow water equivalent during 1981, 1982, and 1983. Snow depth was measured by snow pillows at three representative snow courses in the upper Colorado River basin for typical thick- and thin-snowpack years (1982 and 1981, respectively) and for 1983. *The month of June is shaded to emphasize the different conditions. Note that in 1983* the maximum snowpack was reached in late May (in contrast to the earlier years) and that the decline in June was rapid and nearly simultaneous at all elevations. (Source: Modified from Shafer and others, 1984, fig. 9.)

relation is reasonably accurate when applied instantaneously, but it is very poor when used with averages for weeks or months (fig. 50).

Many snowmelt models now reflect a compromise between simple temperature indices and complete energy-balance indices. Empirical or physical relations are used to estimate each of the important heat fluxes from the air. Of these, the most difficult to estimate include the heat transfer by eddy convection and from the incoming long-wave radiation from water vapor and clouds. Recent studies have shown that under some circumstances these fluxes may be estimated just as well from gross air-mass properties as from local measurements near the surface. For instance, Male and Granger (1981) show that the eddy-convection transfer of heat in a snow-covered area of large extent (unbroken by forests or mountains) is related to the air temperature at the 850-millibar air-pressure level—a variable that characterizes individual air masses and one that is measured routinely several times daily at many locations. As Male and Granger point out, air-mass characteristics are more predictable than the temperature at a point near the snow surface; consequently, research at an air-mass scale should give improved insight into the exchange of heat and mass with the snow surface because such studies will be considering the causes of the exchange and not just the effects. Clearly, snowmelt modeling can be improved. Especially important are new models that will predict reliable melt rates from elementary meteorologic variables.

GLACIERS

Although an enormous reserve of water, equivalent to all the precipitation over the entire globe for about 60 years, is stored in the form of glacier ice, most of this ice is in relatively uninhabited polar and subpolar regions. In North America alone, however, the volume of water stored as snow and ice in glaciers exceeds that stored in all of the lakes, ponds, rivers, and reservoirs on the continent.

Glaciers have a profound effect on the residents of Alaska. About 3 percent, or 29,000 mi², of that State is covered by glaciers (fig. 51), and much of this ice is in mountains not far from population centers. Most of the major rivers originate at glaciers, and the unique characteristics of glacier runoff (discussed later in this article) have a pronounced effect on the society and economy of Alaska.

The effect of glaciers on water-resource development also is appreciable in the Pacific Northwest and the middle and northern Rocky Mountain States (fig. 52). The glaciers there are small—almost inconsequential in comparison to Alaskan or arctic glaciers—but they are an important source of streamflow.

The general location of glaciers in the United States is shown in figure 51, and the numbers and the areas of these glaciers are summarized in table 11. These data are approximate only; many glaciers are present in relatively inaccessible and poorly mapped areas, and it is likely that the total numbers and areas of glaciers shown in table 11 are conservative.

The glaciers in the conterminous United States are small but numerous, contain a considerable equivalent volume of water, and release an appreciable *amount of water during the summer months.* (See table 11.) In Washington, water stored as glacier ice (about 40 million acre-feet) is equivalent to the amount of water in all the reservoirs and lakes in the State, and water released to summertime streamflow (870,000 acre-feet) is as much as the annual ground-water withdrawals (840,000 acre-feet in 1980; Solley and others, 1983).

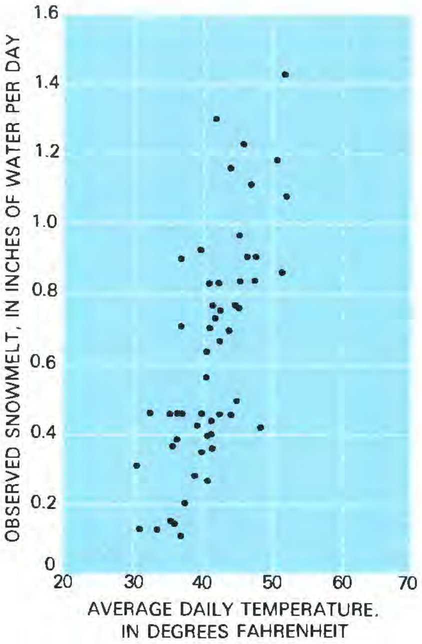

Figure 49. Observed snowmelt, as a function of average daily air temperature (1973-77), for the Marmot Creek drainage basin in Alberta, Canada. Several subbasins and different time intervals are included for each year. (Source: Modified from Barnaby, 1980, fig. 3.)

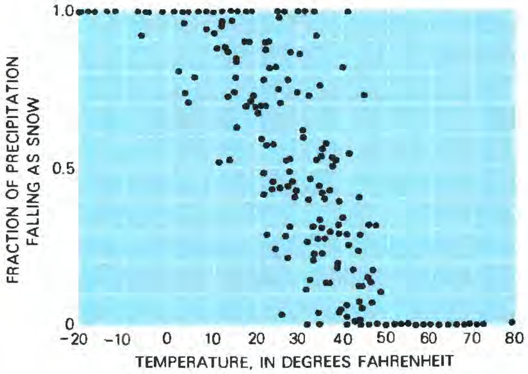

Figure 50. Relation of the fraction of monthly precipitation that fell as snow as a function of the average monthly air temperature in Canada in 1975. (Source: Modified from Ledley, 1985, fig. 2.)

HYDROLOGIC CHARACTERISTICS OF GLACIER RUNOFF

The importance of glacier ice to water-resource development in the conterminous United States stems largely from seasonal and long-term natural regulation of meltwater. Water is stored as ice and snow in winter when the need for water is low and becomes available during the warm weather when it is most needed for irrigation and other purposes.

Most glaciers in the United States are located at high elevations—areas where precipitation occurs mainly as winter snow. Winter runoff, therefore, is negligible; no appreciable runoff can begin until part of the winter snowpack has warmed to the melting point. At high elevations or at moderate elevations at high latitudes, the snow remains below freezing throughout the year, and "runoff" occurs only as the solid ice flows slowly to lower elevations.

The rate of meltwater production during the summer is determined primarily by two factors: (1) incoming solar radiation and (2) albedo (ratio of the light reflected from a surface to the total light falling on that surface) of the snow or ice surface. In May and June, the incoming radiation is intense, but the snow albedo also is high; inasmuch as snow covers most of the glacier, only moderate melt rates are possible. By July and early August, the albedo of the snow has dropped, the snow-covered area has become smaller, and considerable glacier ice with comparatively low albedo is exposed. Thus high melt rates occur even though the incoming radiation has decreased slightly. By September and October, the incident radiation has decreased markedly so that, in spite of low-albedo surfaces, the melt rates are only moderate (fig. 53).

The amount and distribution of glacier runoff is quite different from the runoff resulting from a lowland seasonal snow cover at the same latitude. Three effects related to runoff can be noted:

Elevation effect—At high elevations, precipitation is greater than at low elevations, more precipitation occurs in the form of snow, water losses to evaporation are negligible, and lower temperatures cause snowmelt to occur later in the year than at low elevations.

Topographic effect—In rugged mountains, snow blows from ridge crests or from the sides of steep slopes and forms thick accumulations in hollows or basins. Some snow lies on slopes that face the Sun, whereas other snow lies on shadowed slopes. Thus, snowmelt on some slopes begins a little earlier than on flat lands, and as a result the peak of meltwater runoff may be subdued and floods may be rare. The runoff peak occurs much later during the year, and the runoff season is sustained for a much longer time in rugged terrain than in flat terrain.

Unlimited reservoir effect—When a seasonal snow cover melts, the runoff is approximately equal to the water-equivalent volume of the snow. Glacier runoff, on the other hand, can be much less or much more than the water equivalent of the winter snow and can continue late into the summer, even if all traces of winter snow have disappeared.

The unlimited-reservoir effect, coupled with the dependence of snow and ice melt on heat balance rather than on the amount of snow or ice available, produces a remarkable natural regulation of streamflow from year to year (Meier, 1969). The effect of an unusually hot summer is obvious. Very warm air normally is associated with highly positive radiation balances, which cause rapid melting and unusually large runoff volumes. Conversely, cool summers normally are accompanied by lower radiation balances and unusually low volumes of summer runoff from glaciers.

Figure 51. Location of glaciers in the western conterminous United States and Alaska. (Source: Modified from Meier, 1961, fig. 1.)

Tabla 11. Glacier statistics, by State

[Source: Modified from Meier, 1961]

State	Approximate number of glaciers	Total glaciated area (square miles)	Glacier contribution to July—August streamflow (estimated)	
			Thousand acre-feet	Million gallons
Alaska	(unknown)	29,000	150,000	49,000,000
Washington	950	160	870	280,000
California	290	19	65	21,000
Wyoming	100	19	80	26,000
Montana	200	16	65	21,000
Oregon	60	8	40	13,000
Colorado	25	.6	2	650
Idaho	20	.6	2	650
Nevada	5	.1	.4	130
Utah	1	.04	.1	33

The effect of precipitation is less obvious. Higher-than-normal snowfall on glaciers produces less-than-normal runoff because of the reflective (high-albedo) properties of fresh snow. Snow in summer immediately raises the albedo of a glacier-ice surface from about 0.35 to about 0.75, causing a twofold to threefold drop in the amount of solar radiation absorbed. Usually, thick winter snow means that the high albedo of snow will persist over a larger area of the glacier's basin for a longer period into the summer, thereby greatly decreasing the possible melt.

When glacier runoff is combined with nonglacier runoff, the effects of abnormal temperature or precipitation on the total runoff tend to balance out and produce a more stable and even flow. Thus, runoff tends to be fairly uniform in regions with some glaciated basins (fig. 54). This natural regulation has an important economic benefit; river systems can be operated more efficiently with a given amount of reservoir storage. The economic importance of this streamflow-stabilization effect is difficult to measure, but certainly is very large in regions such as the Pacific Northwest, where dependable supplies of water for hydroelectric power and irrigation are an important commodity. Glacier runoff, however, cannot be forecasted by ordinary procedures. Techniques based on streamflow records unaffected by glacier runoff will lead to inaccurate answers because the causes of the variabilities in flow are so different from those for streams carrying glacier runoff. Volume-type forecasts lead to entirely wrong answers, because the runoff volume from glaciers is inversely, not directly, related to the magnitude of the spring snowpack. New techniques need to be developed to cope with this problem.

Management of glacier runoff is possible by applying to the surface a material such as soot, which modifies the albedo, and by enhancing snow drifting. These techniques have been practiced in China and in the Soviet Union. Tampering with the natural processes that affect glaciers, however, may have long-term undesirable effects on the hydrologic environment and may have a detrimental effect on the wilderness. Glaciers are important elements of the scenery in many of the mountainous areas of the United States. More than nine-tenths of the glaciated areas in the conterminous United States are included in the National Wilderness Preservation System. Management of glacier runoff cannot be accomplished without affecting these wilderness areas.

GLACIER FLUCTUATIONS

Glaciers advance and retreat in response to subtle, persistent changes in climate. Thus, glaciers are indicators—perhaps the most sensitive in nature—of climatic change. The response, however, is slow; at any instant in time, the position of the terminus of a glacier is dependent on the climate of the previous year and, to an ever-lessening degree, the climatic history extending back several centuries (Nye, 1963).

Whenever glaciers grow and advance, water is added to storage as ice, and glacier runoff is less than precipitation. Whenever glaciers retreat, water is released from storage, and glacier runoff exceeds precipitation. The effect can be appreciable; for example, South Cascade Glacier is now retreating very slowly, but runoff averages 18 percent more than precipitation. During the period 1900 to 1945, most glaciers in western North America were shrinking. As a consequence, the average flow of all glacier streams during the last half century was abnormally high, and runoff exceeded precipitation. This cannot continue long, however; either the glaciers will disappear, or the climate will change so as to put water back into storage as ice, while, at the same time, decreasing the runoff.

Because glacier runoff affects streamflow, the recession or advance of glaciers has important consequences for long-range water-resources planning. The present period of glacier recession happens to coincide with the "base" or "normal" period of record for many important hydrologic data. About 15 percent of the present summer flow of the Columbia River at the United States–Canada border is derived from about 1,000 mi^2 of glaciers in Canada, and perhaps a third of this flow is from glacier wastage (Tangborn, 1980). Glacier wastage has been extreme in the Susitna River basin of Alaska, where a major hydroelectric development is planned (Harrison and others, 1983). In this and similar areas, plans for future development should be based on consideration of potential loss of water and ice storage.

GLACIER SURGES, OUTBURST FLOODS, AND DEBRIS FLOWS

The physics of the movement of the melt phase (water) through the solid phase (ice) of glaciers is interesting, in that several kinds of instabilities can produce large changes in the ice mass and great hazards to people. These hazards include sudden glacier advances, or surges; floods caused by the rapid release of water from within or alongside a glacier; and rapid melting of ice, which produces mudflows and debris flows, on active volcanoes.

Surges

Most glaciers flow slowly and steadily, varying their flow rate gradually in response to climatic changes. Some glaciers, however, have alternating phases of very rapid flow, or surges, and normal slow flow, or quiescence. The duration of the surge phase typically is from less than 1 to about 3 years, and the duration of the quiescent phase typically is from 10 to 100 years. During the surge, a 10- to 1,000-fold increase in flow rate may occur, and large ice displacements and increases in glacier length may result (Meier and Post, 1969).

The changes that occur during a glacier surge can be spectacular (fig. 55). Surges may destroy transportation lines and structures; they also may block rivers and impound lakes and may cause major floods when these blockages open.

The cause of the alternating cycle of surge and quiescence, and the mechanisms of rapid flow, have long puzzled glaciologists. The 1983 surge of Variegated Glacier in Alaska, which ended abruptly when meltwater drained out and caused a flood, was carefully observed by a team of scientists. It is now clear that the rapid acceleration of motion leading to a surge is caused by the blockage of drainage conduits under the glacier; this blockage results in a thick layer of water at the sole of the glacier and consequent rapid sliding of the glacier over its bed (Kamb and others, 1985). Many aspects of glacier surging still need explanation, however; for example, how can the buildup of water and its effect on sliding be modeled?; what causes the cyclic alternation of rapid and normal behavior?; why do surge-type glaciers occur in some areas (for example, in the St. Elias Mountains) and not in other areas (for example, adjacent Chugach Mountains)?; and could parts of the Antarctic Ice Sheet surge and cause sudden rises in sea level?

Outburst Floods and Debris Flows

Even in normal glaciers, the internal "plumbing"(englacial drainage channels) may become plugged, probably as a result of the movement of the ice, which causes water to be stored in or behind the glacier. Later, this water may be released as a sudden "outburst" flood, which is commonly known by the Icelandic term "jökulhlaup."

Figure 52. A tributary arm of Dinwoody Glacier, Wind River Range, Wyo. (Photograph by M. F. Meier, U.S. Geological Survey.)

Outburst floods can be large (for example, about 70,000 ft^3/s (cubic feet per second) on Nisqually River at Mount Rainier, Wash., in 1955), or even catastrophic in areas where large glaciers are present. Outburst floods at Lake George (Knik Glacier) near Anchorage and at Tulsequah Lake (Tulsequah Glacier) near Juneau, Alaska; and Summit Lake (Salmon Glacier) near Hyder, British Columbia, are well known (Post and Mayo, 1971). One of the largest glacier floods on record is the 1922 jökulhlaup from Grimsvotn, Iceland, which discharged about 1.7 cubic miles of water in a 4-day period, producing a flood discharge estimated to be almost 2,000,000 ft^3/s at its peak.

These floods may be caused by the release of water that had been contained within or under the glacier (the flood at Nisqually Glacier), by the release of a lake dammed by ice (the floods at Knik, Tulsequah, and Salmon Glaciers), or by the outburst of accumulated meltwater because of volcanic heating (the floods at Grimsvotn). The impounded water, once it finds a miniscule channel, enlarges the channel at an ever-increasing rate as the heat produced by the loss of potential energy melts the channel walls. The flow increases at an exponential or near-exponential rate until nearly all the water is drained. One of the most ominous aspects of glacier outburst floods is that they cannot be predicted with the present state of knowledge.

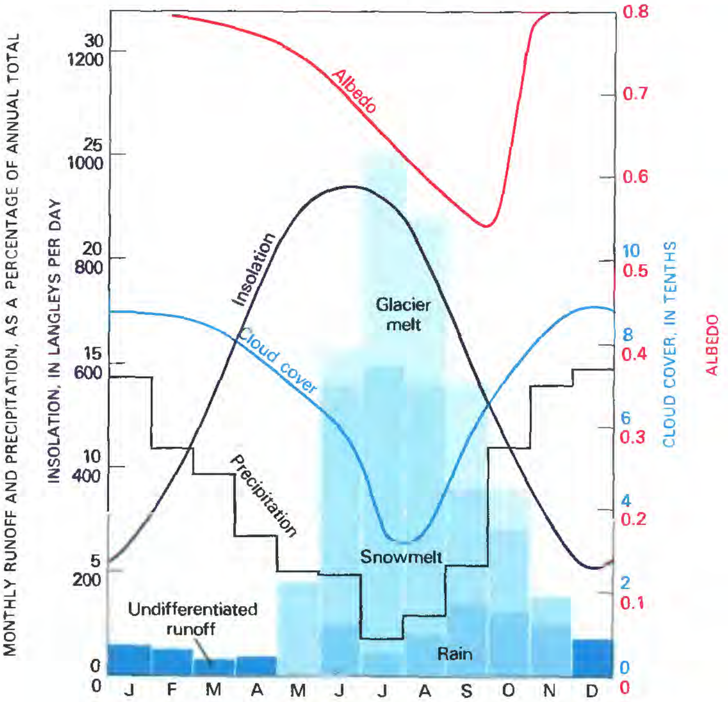

Figure 53. Average monthly runoff for the South Cascade Glacier in Washington, showing variation of some important heat-balance components, 1957-67. Insolation is the incoming radiation at the top of the atmosphere. Albedo, which is averaged over the whole glacier surface, was not measured in winter (December- February) but is assumed to remain fairly constant between 0.75-0.85; cloud cover was measured in daytime only. Source: Meier, 1969, fig. 2.)

Snow and ice on volcanos can be useful to other scientific studies by acting as a natural calorimeter—changes in the ice can be used to monitor or measure the rate of heat released (fig. 56). Ice melts rapidly when there is an actual eruption. The resulting flood may mobilize silt, sand, gravel, and larger objects and rush downvalley as a mudflow or debris flow. The source of water that mobilized mudflows of the May 18, 1980, eruption of Mount St. Helens, Wash., has not been clearly identified, but enough water was contained in the glaciers to cause mudflows of disastrous proportions (Brugman and Meier, 1981). To assess these debris-flow hazards, attention is now being given to measuring the ice volume on active volcanos in Alaska, Washington, Oregon, and California (Driedger and Kennard, 1984).

CONCLUSIONS

In a broad context, snow and ice are important to the global circulation of the atmosphere and ocean as well as to the global hydrologic cycle. If the amount and distribution of snow and ice were steady and unchanging, it would be a simple matter to ignore the role of snow and ice in the less-accessible high elevations and latitudes. But the ratio of the amount of liquid to solid water on Earth is ever changing, partly because of human activity, and the changes in these ratios may have important societal consequences. We cannot understand what is happening or what is going to happen to the Earth's climate and hydrologic cycle without understanding the dynamics of snow and ice.

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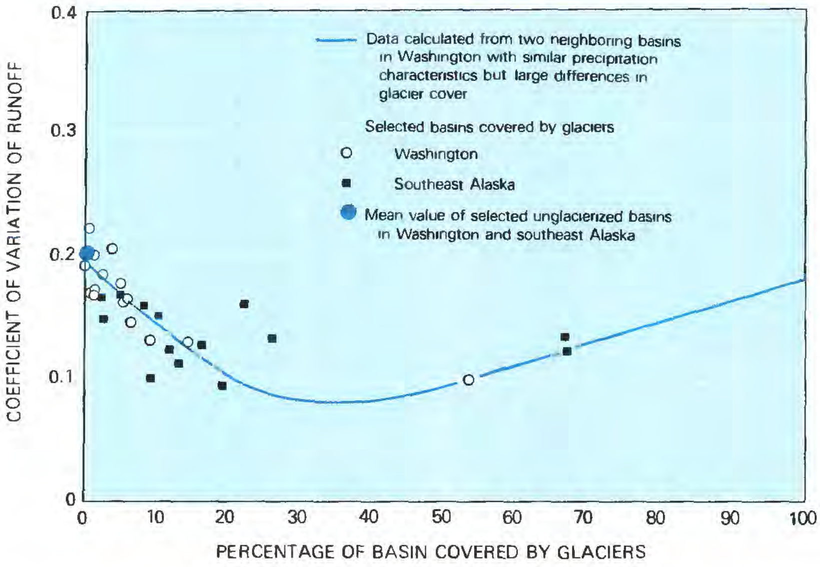

Figure 54. Variation of annual runoff as a function of the percentage of the drainage basin covered by glaciers in Washington and southeastern Alaska. The coefficient of variation is equal to the standard deviation divided by the mean. (Source: Modified from Fountain and Tangborn, 1985, fig. 5.)

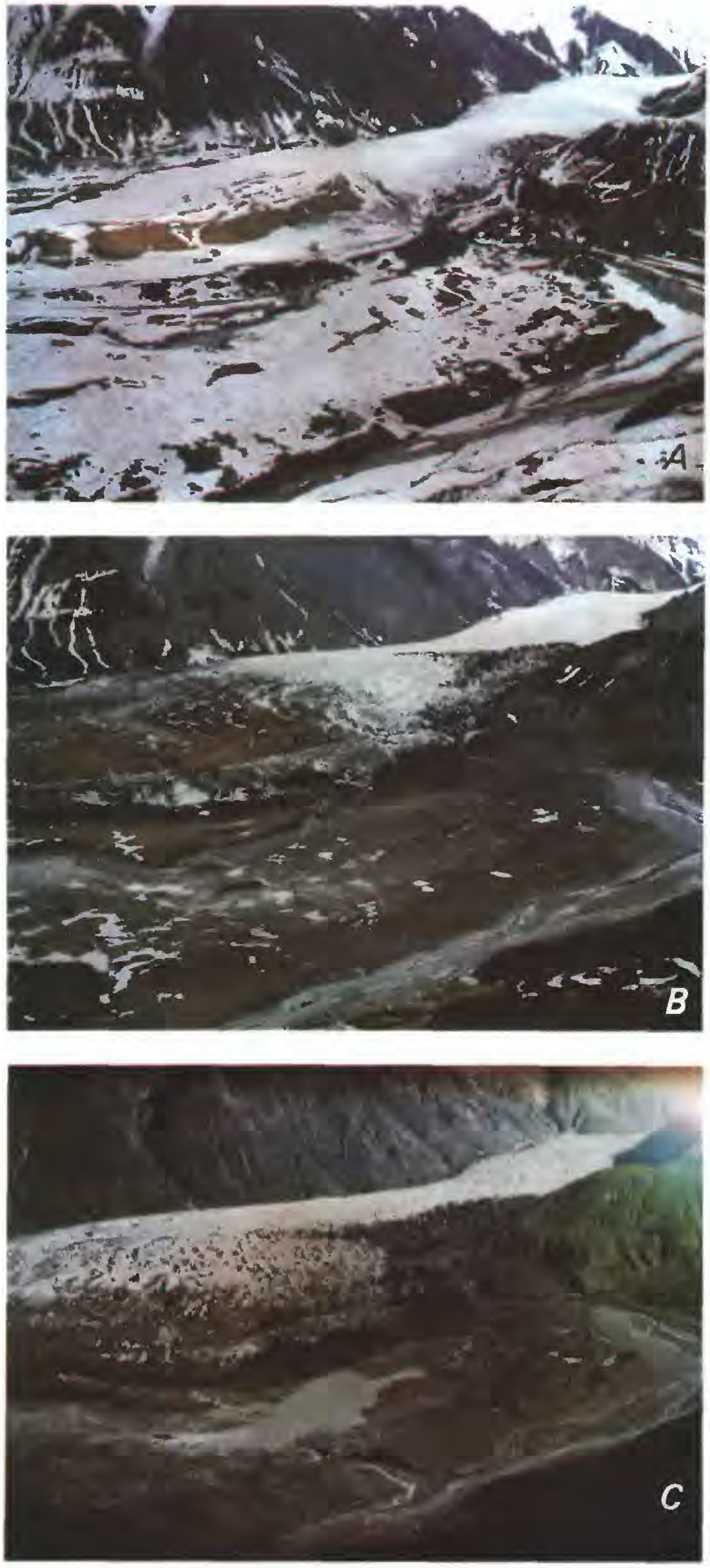

Figure 55. Three views of the 1983 surge of Variegated Glacier, Alaska. *A*, May 2; *B*, June 18; *C*, August 28. Most of the surge activity ended on July 4. Ice-flow velocity during the surge exceeded 200 feet per day. (Time-lapse photographs by R. M. Krimmel, U.S. Geological Survey.)

Figure 56. Ice and fire. Heat output from Sherman Crater, Mount Baker, Wash., abruptly increased in March 1975 and led to the formation of new fumaroles and rapid ice melt. The change in heat output could be measured from the rate of ice removal. (Photograph by David Frank, U.S. Geological Survey, spring 1985.)

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EFFECTS OF DAMS AND RESERVOIRS ON SURFACE-WATER HYDROLOGY—CHANGES IN RIVERS DOWNSTREAM FROM DAMS

By Garnett P. Williams[1] and M. Gordon Wolman[2]

INTRODUCTION

Dams are constructed and rivers are impounded to provide many benefits to society. At the same time, dams typically bring about changes in the downstream environment. These downstream changes—discharge of water and sediment and size, shape, and habitat of the river channel—may have positive or negative effects, depending on the location and interests of those affected. An understanding of the factors contributing to these changes can help anticipate many of the changes and can permit an evaluation of the associated potential damages or benefits. This article presents a hydrologic perspective on changes in river channels downstream from dams.

Dams and reservoirs are built to store water for many purposes—to control flood waters, to generate power, and to provide water for irrigation, water supply, navigation, and recreation. The timing and amounts of water released from a reservoir depend on how the water is to be used. For example, if the water is used for irrigation, the water usually is stored during most of the year and is released to the river downstream from the reservoir only during the irrigation season. At some dams, enough water is withdrawn directly from the reservoir—for example, for municipal water supply—so that releases to the downstream channel almost never are made, and only dam-face and ground-water seepage and rare floods provide water to the reach immediately downstream from the dam. Water releases from hydropower dams are likely to be varied throughout the day (that is, high in the morning and afternoon and low at night) to meet peak demands for electricity.

Dams and reservoirs, then, regulate the irregular pattern of flows provided by nature and permit the release of water to meet specific needs. In general, reservoirs tend to even out the flow, reducing the size of floods and often increasing water in the channel during low flow. Moreover, sediment carried by the rivers may be trapped in the reservoirs.

Normally, the size and shape of river channels adjust to the quantities of water and sediment provided by precipitation and runoff from the drainage basin. Therefore, river channels downstream from dams will change in reaction to new patterns of streamflow imposed by releases from the reservoir.

The magnitude of these changes generally is greatest nearest the dam and diminishes with distance downstream. For example, changes such as bed lowering, modification of channel width, and increases in riparian vegetation commonly occur in the reach nearest the dam. This can vary, however, because the pattern of flow releases from each dam, which depends on the purpose of the dam and the frequency and magnitude of arriving flood flows, is unique. Moreover, each channel has its own characteristics, such as sizes of sediment particles in the bed and banks, locations of bedrock outcrops, types and distribution of vegetation, and channel configuration. Differences among these characteristics, combined with the variability in the frequency and magnitude of flow releases from a dam, make it difficult to predict the precise changes that will occur or to generalize about expected future effects of a newly built dam. Despite these uncertainties, experience suggests that changes in downstream river channels will occur and should be anticipated. Although channels change naturally even without the influence of upstream dams, the changes described below have been found to be largely attributable to dams (Williams and Wolman, 1984).

CHANGES IN RIVERS DOWNSTREAM FROM DAMS

WATER DISCHARGE

The construction of dams and reservoirs modifies the magnitude, duration, and timing of downstream flows. One such modification is the decrease in the magnitude and frequency of downstream floods (Petts and Lewin, 1979; Williams and Wolman, 1984; Harrison and Mellema, 1984). In the Central and Western United States, for example, average annual peak flows downstream from 29 dams range from about 3 percent to about 90 percent, and average 40 percent, of pre-dam values (Williams and Wolman, 1984, p. 8). Other characteristics of downstream flows, such as average discharge, may also change after a dam has been built.

SEDIMENT LOADS

Rivers customarily transport large amounts of sediment. Large reservoirs generally trap most of this sediment load—in some instances, more than 99 percent. Hoover Dam on the Colorado River in Arizona is a good example (fig. 57). Suspended-sediment loads on the Colorado River were measured upstream (Grand Canyon station) and downstream (Topock station) from Hoover Dam, both before and after dam construction (fig. 58). Before closure of Hoover Dam in 1936, annual loads at the two stations were similar. After closure, sediment inflow, represented by the data for the upstream (Grand Canyon) station, continued to be large and variable. Downstream from the dam at Topock, both the amount and the annual variations of sediment load were markedly decreased by the dam. Although a few dams have provisions for sluicing some of the trapped sediment downstream, the downstream reach even in these instances usually receives much less sediment than it formerly did.

Aside from observable changes in channel size (described below), trapping of sediment in major reservoirs may significantly deplete the amount of sediment carried by a river for hundreds of miles

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Figure 57. Location map of dams and rivers cited in this article. (Source: Adapted from Williams and Wolman, 1984, fig. 1.)

downstream. For example, three major Missouri River dams—Garrison in North Dakota, Fort Randall in South Dakota, and Gavins Point in South Dakota (listed in downstream order)—were closed between 1952 and 1955. The post-dam annual suspended-sediment load 5 miles downstream from Gavins Point Dam was less than 1 percent of the pre-dam load; 710 miles downstream, the load was only 30 percent of the pre-dam load. River channels react to such large, imposed changes in water discharge and sediment load in several ways.

LOWERING OF THE STREAMBED

The slope, cross-sectional size and shape, and other features of alluvial channels depend on the prevailing water discharges and sediment loads. Radical changes in either water discharge or sediment load trigger changes in the channel. For example, a river whose sediment load abruptly is removed tries to regain its normal load by picking up sediment from its bed and banks. Curtailment of sediment supply from upstream, combined with the stream's newly acquired tendency to remove additional sediment from its bed and banks, result in erosion (lowering or degradation) of the streambed downstream from the dam.

The extent of streambed lowering and the rate at which it progresses vary considerably from one river to another, although both the extent and the rate tend to be most pronounced near the dam and less pronounced long distances away. In a study of 23 of the 29 dams noted earlier, primarily on rivers in the Western United States (Williams and Wolman, 1984), maximum streambed lowering ranged from a negligible amount to as much as 25 feet. Although streambed lowering was variable from river to river, maximum lowering at any one site averaged about 6 or 7 feet. On many rivers in the Great Plains, a lowering of only 2 or 3 feet can be significant hydraulically, because the gradients of many large rivers in that region are only 2 to 5 feet per mile.

An example of streambed degradation is shown in figure 59. These photographs were taken about 0.8 mile downstream from Jemez Canyon Dam on the Jemez River in New Mexico. They show dramatically the effect that the dam had on the streambed. The bed lowering at this site is about 9 feet.

Degradation typically occurs most rapidly just after dam closure. Initially, rates of degradation for the 23 cases studied ranged from negligible to about 2 feet per month. (These high rates generally do not last for more than a few months.) With time, the rates become slower and slower (fig. 60*A*). Some rates taper off in a smooth, progressive fashion; however, degradation at a site can vary considerably with time and can occur in no systematic way (fig. 60*B*). Degradation rates are influenced by the controlled releases of water from the reservoir, the location of bedrock under the stream channel, particle sizes of the streambed sediment and their variation with depth, and the presence of a large tributary that may control the bed elevation downstream, among other factors. Thus, different sites along a river may have unique features that lead to different responses.

Where several years of measurement indicate a rather smooth progression of degradation over time, the trend of subsequent degradation over time can be predicted with a simple equation, assuming no significant change in controlling factors such as those noted in the previous paragraph (Williams and Wolman, 1984, p. 19). Observations at 111 sites on various rivers in the conterminous United States indicated that most of the degradation occurred during the first few years after dam construction. The average number of years needed for the bed to lower to half its estimated eventual total degradation was 7 years. If degradation were to continue, one or two centuries (on the average) might be required for all of the predicted degradation to occur. However, degradation may be limited by the factors mentioned previously.

In the first year or two after dam closure, degradation may not have occurred, or it may extend over as much as 20 to 30 miles. In some instances, bed degradation may not occur for two or three decades after dam closure. Bed erosion in the Colorado River progressed downstream from Hoover Dam to a point more than 75 miles downstream from the dam within 12 years after dam closure. On the Hanjiang River in China, the degraded reach extended 290 miles downstream during the first 4 years after dam closure and extended 400 miles downstream 14 years after dam closure (Han and Tong, 1982, p. 191). The rate at which the leading edge of the degraded reach migrates downstream can be very steady to highly variable.

SIZE AND SHAPE OF THE RIVER CHANNEL

Following dam closure, the new flow and sediment regimen may alter the size and cross-sectional shape of the channel. Flow releases and bank materials are two key factors that influence these responses. Channels not only may deepen through degradation, as discussed earlier, but also may become wider, or even shrink in size, depending on flow releases from the reservoir and on local geologic controls.

Erosive, periodic floods tend to maintain a channel wide enough to convey such floods. Elimination or marked curtailment of high flows by a dam, especially if accompanied by a considerable reduction in lower flows, means that the post-dam discharges may not maintain as wide a channel (fig. 61). Many post-dam channels are only about one-fifth to one-half as wide as the pre-dam channel. In the extreme case, where virtually no water is released and only a trickle seeps into the downstream channel, a channel that was thousands of feet wide before dam construction may be only a few feet wide afterward, as in the case on the Canadian River downstream from Sanford Dam in Texas.

Where channel narrowing occurs, several other features also change. As shown in in figure 61, vegetation commonly becomes established on lesser used parts of the old streambed. When plant growth traps sediment during inundations, the vegetated zone builds up to become a new flood plain. The old flood plain, having become a terrace, may be rarely, if ever, flooded. In this manner, the stream "channelizes" itself, commonly within more stable banks because of the binding properties of the vegetation.

Flow releases at some dams have been large enough and frequent enough to cause channel widening downstream. Although a definitive study has not been made, widening seems to occur mostly where degradation is inhibited, such as by bedrock or armoring. Widening can also occur in conjunction with degradation, where bank failure results from increasing bank height, removal of toe support, or exposure of seepage planes. Where widening occurs, it

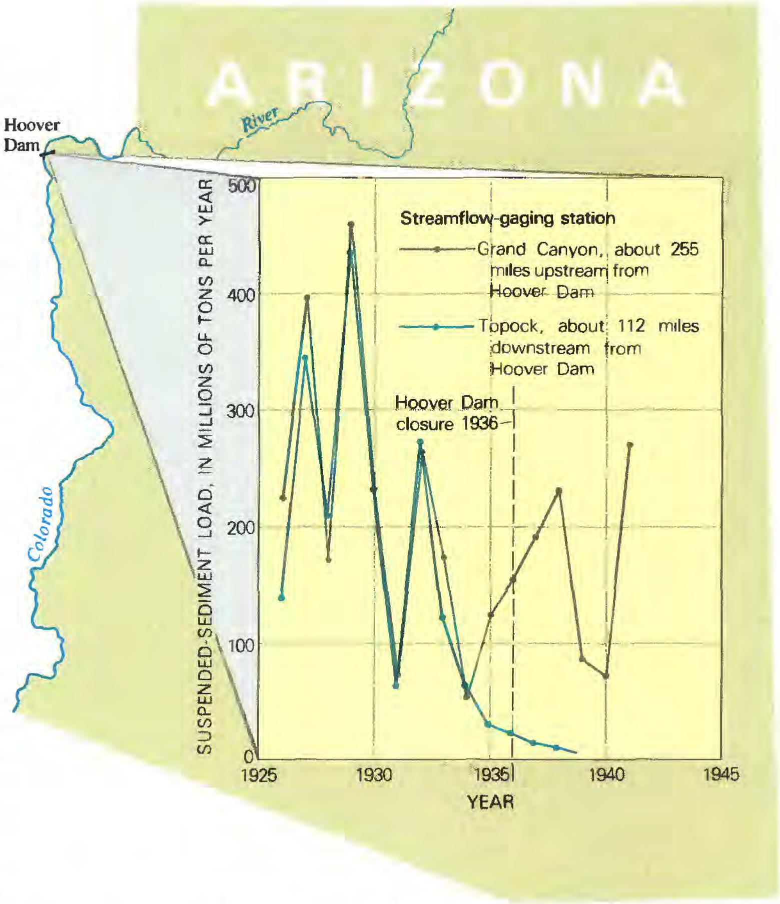


Figure 58. Variation in annual suspended-sediment loads before and after closure of Hoover Dam on the Colorado River in Arizona, at stations upstream and downstream from the dam. Sediment load becomes very small after dam construction, and variability in annual loads almost is eliminated. (Source: Data from Howard, 1947, p. 8-9.)

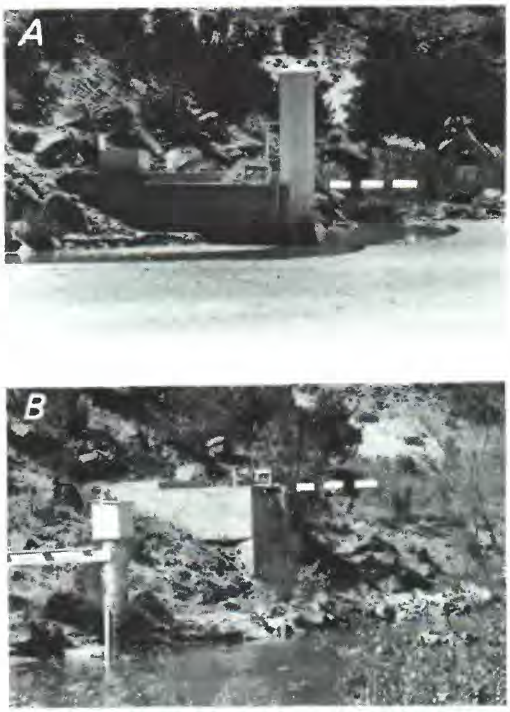


Figure 59. Effects of closure of Jemez Canyon Dam, Jemez River in New Mexico, on streambed about 0.8 mile downstream. *A*, 1952 (1 year before dam closure); *B*, 1980 (27 years after dam closure). The same concrete abutment appears in both photographs and the white dashed line is at the same elevation. Approximate bed lowering is 9 feet. (Photographs by (*A*) U.S. Geological Survey; (*B*) J. P. Borland, U.S. Geological Survey.)

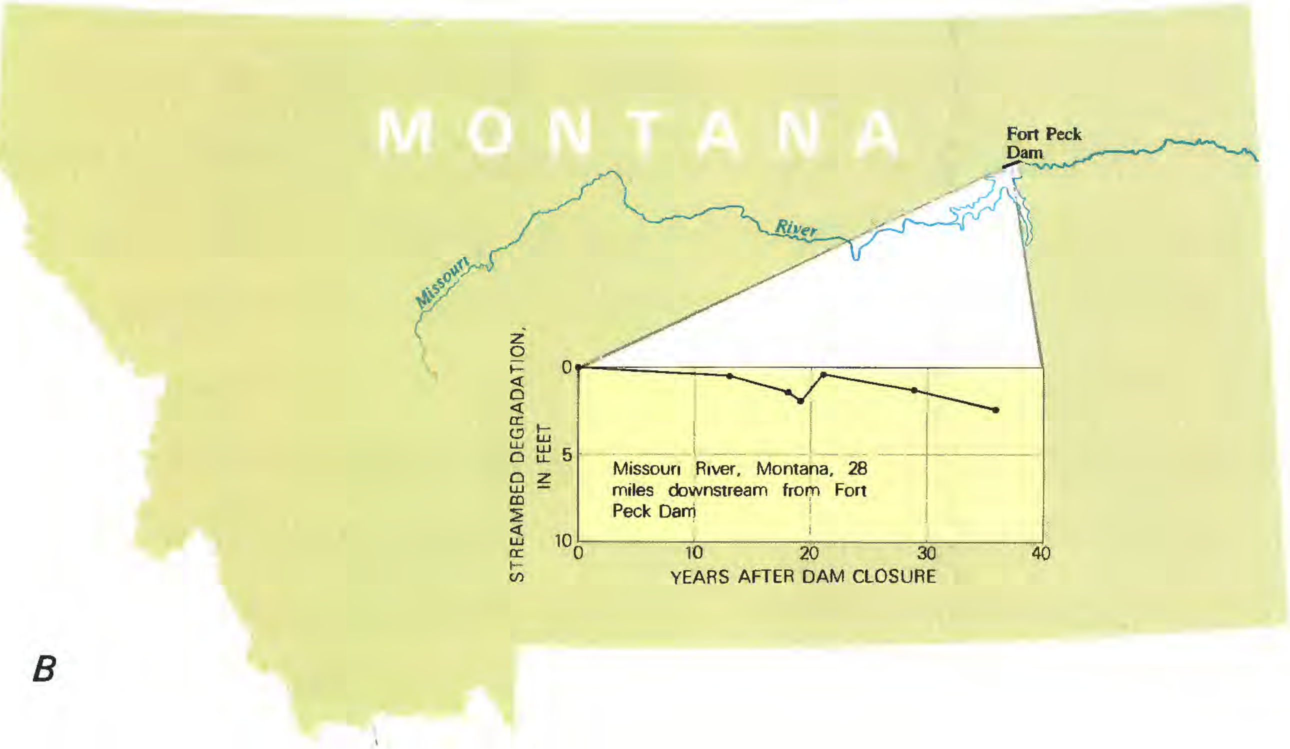
averages about 10 percent of pre-dam channel width and rarely exceeds 50 percent. Actual magnitudes can be considerable, however; some channels have eroded 100 to 200 feet laterally in 1 year, with losses of tens of acres of farmland (Rahn, 1977).

On channels that widen, the magnitude of widening varies considerably and irregularly from place to place and may not occur at all at some cross sections. Particular locations where widening occurs may change from one year to the next (Harrison and Mellema, 1984). Bank materials at some sites may be especially prone to erosion at specific flows, so that widening might be anticipated. In general, however, it is not yet possible to predict, with confidence, whether and how much channel widening will occur, at any selected site downstream from a dam.

At some locations, the channel at different times has widened, narrowed, and remained constant over the decades following dam construction. Such variations are relatively uncommon; they probably are associated with variations in the pattern of flow releases from the reservoir.

Widening or narrowing of the channel can proceed irregularly with time, at any particular cross section undergoing such changes. However, at roughly half of 164 sites where widening or narrowing occurred (Williams and Wolman, 1984), the rates were systematic enough that they could be described by a simple equation.

Figure 60. Examples of streambed degradation with time following dam closure. *A*, Colorado River, Arizona, 0.7 mile downstream from Davis Dam; *B*, Missouri River, Montana, 28 miles downstream from Fort Peck Dam. The gradually declining rate of bed lowering shown in *B* is characteristic of a number of rivers that have sandy and gravelly beds. (Source: Measured cross-section data from (*A*) U.S. Bureau of Reclamation, (*B*) U.S. Army Corps of Engineers.)



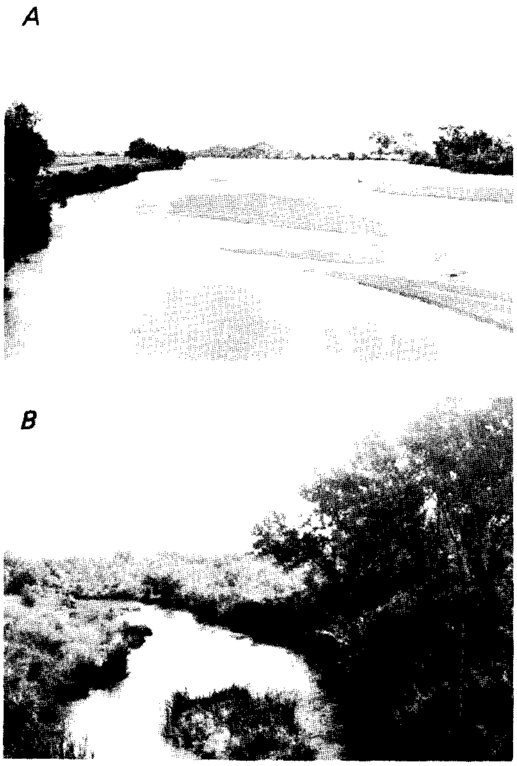


Figure 61. Width of channel of the Republican River at Culbertson, Nebr., 12 miles downstream from Trenton Dam, before and after the 1953 dam closure. (*A*) July 1932; (*B*) July 1980. Note man in lower right corner of *B* for scale. The broad, sandy channel shown in *A* is characteristic of many rivers on the Great Plains. Following control of high flows, the channel contracted, a process enhanced by encroaching vegetation. (Photographs by (*A*) U.S. Geological Survey, (*B*) C. R. Liggett, U.S. Geological Survey.)

Where changes in channel width occur, the process may proceed for many decades. However, as with bed degradation, most of the changes take place soon after the dam has been built. Half of the estimated total widening or narrowing typically happens within 1 or 2 years after dam closure; occasionally, much of the eventual total change may take place within the first few months.

VEGETATION

Changes in flow and sediment regimen commonly have resulted in major changes in the distribution and density of downstream riparian vegetation after construction of some dams. These vegetation changes are especially evident where the channel has narrowed (figs. 61, 62). The new vegetation may be distributed in a relatively thin strip along each bank (Turner and Karpiscak, 1980), particularly in narrow, rocky valleys; in extensive stands on bottomlands that cover most of the former streambed (figs. 61, 62); or in higher parts or shifting sand bars of the former streambed that become stable islands (fig. 63).

Two factors appear to encourage the growth of vegetation in channels downstream from dams: Elimination of most floods that periodically would erode the channel bed and banks and remove seedlings; and a regulated increase in low flows that may enhance the survival and development of plants.

In addition to changing the appearance of the channel, the increase in vegetation that commonly occurs downstream from a dam may block parts of the channel and impede the flow of water. This vegetation reduces—in some instances very significantly—the ability of the channel to convey water. An example of this phenomenon is the Republican River in Nebraska downstream from Trenton and Harlan County Dams (Northrop, 1965). The result of such channel blockage could be overbank flooding, at least where the released flows are too large for the new channel capacity.

A potential effect of more vegetation, although not well documented, is a possible increase in water losses by evapotranspiration. Another effect involves the binding properties of the new roots which may enhance the stability of the channel bed and banks.

CONSEQUENCES OF CHANGES

The changes downstream from a dam may be favorable, unfavorable, or insignificant from an environmental standpoint, depending on the proximity and interests of the people affected. Bed degradation, for example, when accurately predicted, can be used to increase the fall or head of water available for hydropower. Similarly, degradation on some rivers can improve navigation capability. On the other hand, degradation may undermine bridges, railroad piers, and retaining walls, and may require the abandonment of water intakes. Along the Missouri River, lowering of the river bed (and, hence, of the water table) apparently eliminated a number of lakes on adjacent bot-

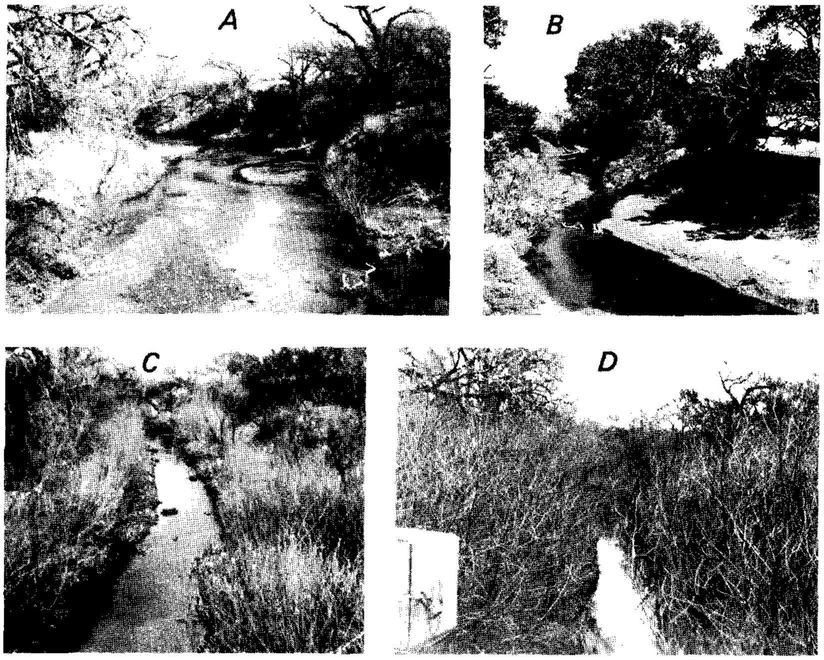


Figure 62. Vegetation along the Washita River in Oklahoma, about 0.9 mile downstream from Foss Dam, before and after the 1961 dam closure: *A*, February 1958; *B*, May 1962; *C*, March 1967; *D*, February 1970. These photographs show the progressive encroachment of vegetation associated with narrowing of the channel. In *A* (pre-dam), the channel is an estimated 15 feet wide, whereas in *D*, 9 years after closure of the dam, the channel is an estimated 3 feet wide. (Photographs by U.S. Geological Survey.)

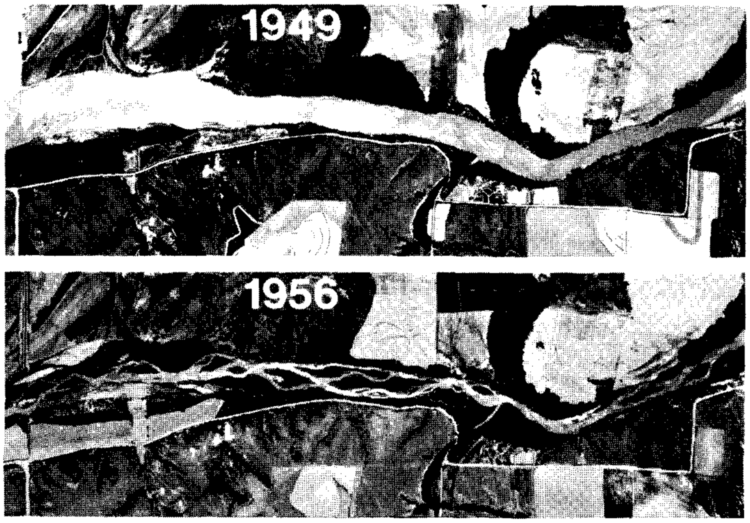


Figure 63. Republican River, about 10 miles downstream from Harlan County Dam in Nebraska, before and after the 1952 dam closure. White reach in 1949 photograph is the full width of the sandy channel; white reaches in 1956 photograph are threads of the channel, braided around vegetated islands. (Photographs courtesy of U.S. Department of Agriculture.)

tomlands. Moreover, in some places sediment is scoured from reaches downstream from dams and is deposited at a downstream site of flatter gradient, thereby raising the streambed and waterlogging adjacent farmlands. The same effects on dammed rivers can result from the deposition of sediment from tributaries, as has occurred on the Rio Grande. Channel widening in some regions may be of no consequence; in others, it may destroy homes and farmlands. Channel narrowing might provide increased acreage for farming in formerly unused bottomlands.

Dams also tend to alter stream habitat. For example, the decrease in peak flows and marked reduction in sediment loads downstream from a dam commonly change the character of the streambed. Finer particle sizes gradually are removed from the bed, commonly leaving only an armor of larger sizes (fig. 59). Water released from the reservoir may not only have less sediment but also may have a different temperature, usually a higher one, than the water of pre-dam flows. These changes may mean that fish that formerly occupied the reach downstream from the dam no longer can survive in the new environment. At the same time, a species that formerly was incompatible may move in or may be stocked to provide prime fishery, such as downstream from Glen Canyon and Hoover Dams on the Colorado River in Arizona.

A more noticeable change in habitat can occur in the riparian environment as a whole. Commonly, at least in semiarid regions, a wide, shallow channel with little riparian vegetation is changed to a narrow, heavily vegetated channel (figs. 61, 62). Wildlife species at home in the former habitat may not be able to live in the latter one. Where important or endangered species are involved, mitigation measures may be required to assure maintenance of the species. As with the fish, a new variety of wildlife may move into the new environment.

CONCLUSIONS

Changes in the characteristics of the river and in the environment downstream from dams are inevitable. The magnitude and significance of such changes vary from place to place, depending upon the climate and geology of the region and upon the purposes and mode of operation of the dam and reservoir. Changes in river channels also can occur from variations associated with natural events, such as floods, droughts, and climatic changes—that is, some of the channel changes observed downstream from dams might occur regardless of construction of the dam. Nevertheless, several characteristics are common in connection with dam construction:

- Frequently, major changes in a channel occur immediately after dam closure.
- The greatest changes occur, in many instances, just downstream from the dam, with progressive decrease or recovery with distance downstream.
- Progressive change toward an apparent new stability at a site occurs in the years after dam closure.
- The changes at many locations are continuous or do not reverse themselves.
- The climatic and physiographic regions in which these features have been observed are diverse.

These characteristics all point to the alteration of the flow regimen of rivers by water-regulating dams and reservoirs, along with the virtual elimination of sediment into downstream reaches, as primary causes of channel changes on many rivers. Even given the uncertainties of prediction of the changes, change can and should be anticipated.

Should new dams be constructed in the United States, attendant changes will occur in the regime of water and sediment in the river channels downstream. In large parts of the Midwest and the Great Plains, dams and reservoirs have altered permanently the hydrologic systems of large and small rivers. An awareness of these changes and of potential future changes can provide a useful framework for developing and managing our Nation's surface-water resources.

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EFFECTS OF DAMS AND RESERVOIRS ON SURFACE-WATER HYDROLOGY—CHANGES IN THE PLATTE RIVER BASIN

By James E. Kircher

INTRODUCTION

Water-resources development, such as construction of dams and reservoirs and irrigation diversions, affects the hydrologic system in many ways. For example, reservoirs alter streamflow characteristics, including the magnitude of average and peak flows and their timing, and this alteration in turn can affect the sediment-transport characteristics downstream from the reservoirs (Meade and Parker, 1985; also see article in this volume, "Effects of Dams and Reservoirs on Surface-Water Hydrology—Changes in Rivers Downstream from Dams"). Irrigation diversions and return flows, which alter the recharge rates to the stream, can affect the magnitude of low flows in the hydrologic system. These and other processes can occur simultaneously. Many of the processes and changes that can occur as a result of water development have taken place in the Platte River basin, which comprises the South Platte, the North Platte, and the Platte River basins in Colorado, Wyoming, and Nebraska (fig. 64).

The total drainage area of the Platte River basin is 85,000 mi² (square miles). The Platte River, which begins at the convergence of the North Platte and the South Platte Rivers near the city of North Platte, Nebr. (fig. 64), flows eastward 310 miles and empties into the Missouri River near Omaha, Nebr., draining 29,800 mi². The South Platte River originates as snowmelt streams in north-central Colorado at about 12,500 feet above sea level (fig. 64). By the time the South Platte River meets the North Platte River, it has flowed 450 miles and drained about 24,300 mi².

The North Platte River also is fed by snowmelt streams in the mountains of north-central Colorado at about 11,000 feet above sea level. From its source to its confluence with the South Platte River, the North Platte River traverses about 665 miles and drains an area of 30,900 mi².

Storage reservoirs are located throughout the Platte River basin, and large reservoirs are on or adjacent to the two major tributaries. As of 1983, there

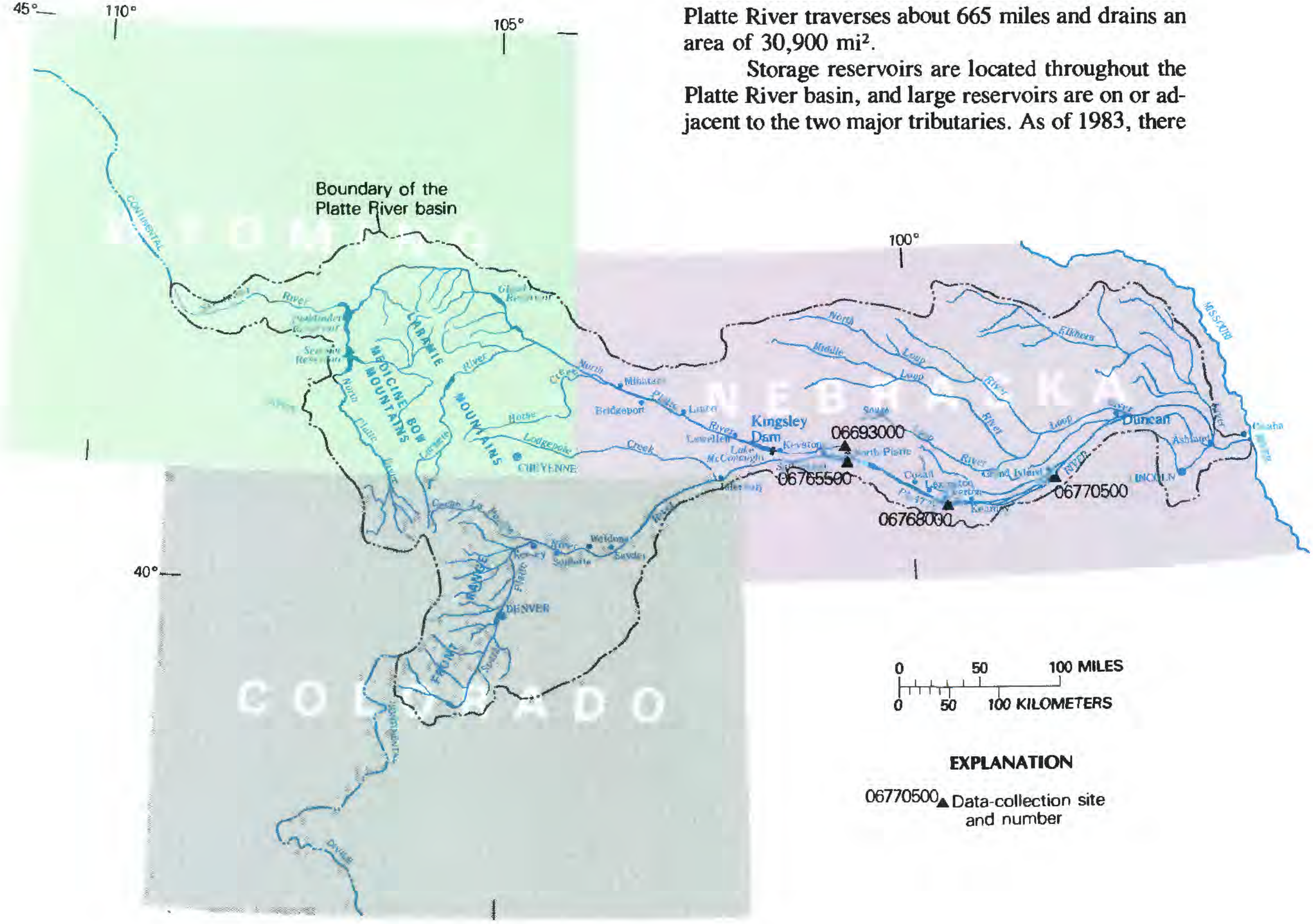


Figure 64. The Platte River basin of Colorado, Wyoming, and Nebraska.

were 194 reservoirs in the Platte River basin with storage capacities greater than 500 acre-ft (acre-feet), and 130 of these have storage capacities greater than 5,000 acre-ft. The combined usable storage capacity of the 130 larger reservoirs is almost 7 million acre-ft [2,281,000 Mgal (million gallons)] (Kircher and Karlinger, 1983). (See figure 65.) The principal purpose of most of these reservoirs is to store water for irrigation; hydroelectric-power generation ranks second; flood control and storage for municipal and industrial use are the other major uses. Nearly all the reservoirs provide recreational opportunities and fish and wildlife habitats.

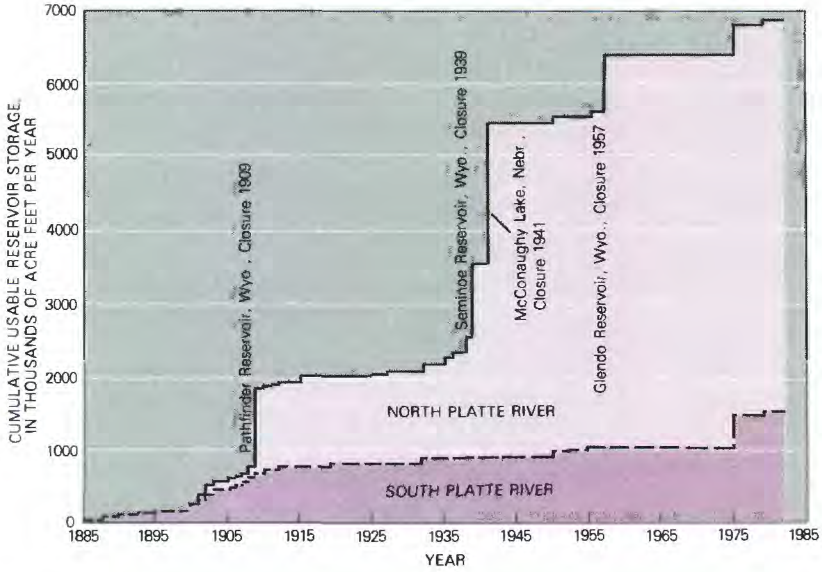


Figure 65. Cumulative usable storage of reservoirs in the Platte River basin, 1885-1983. Only reservoirs with at least 5,000 acre-feet of storage are included. (Source: Modified by J. E. Kircher from Bentall, 1975.)

To meet the needs of irrigation and municipal and industrial users in the South Platte River basin, several major transmountain and transbasin diversions, which are located in Colorado, divert water from the North Platte River and the Colorado River basins to the South Platte basin. Annual transmountain and transbasin diversions generally were less than about 100,000 acre-ft before construction of the Colorado–Big Thompson Project in northeastern Colorado and have not been less than 300,000 acre-ft since completion of the project in 1953. (See figure 66.)

Because of the many changes to the natural streamflow regime, the Platte River basin provides a good example for illustrating the effects of water development on surface-water hydrology. This article traces the history of water development in the Platte River basin, the historical effects of water development on streamflow, and the effects of changes in hydrology on the stream channels.

DEVELOPMENT IN THE PLATTE RIVER BASIN

Settlers first moved into the Platte River basin during the early 1800's; however, the supply of water was not dependable for large-scale settlement and

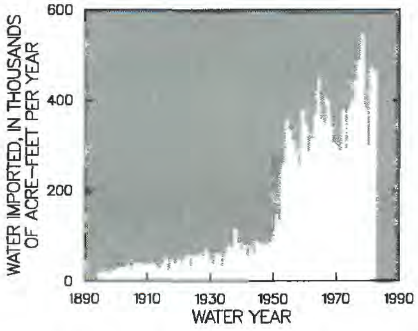


Figure 66. Total yearly imports of water to the South Platte River basin from the North Platte and the Colorado River basins, 1895-1982. (Source: Modified by J. E. Kircher from Gerlek, 1977.)

agriculture. By the late 1800's, irrigation began to develop the great potential in vast expanses of land that had been too dry to be cultivated effectively. The subsequent growth of irrigation in the Platte River basin has affected significantly the hydrology of the river. The earliest streamflow records date from 1891, and systematic flow records date from 1930.

Irrigation development along the Platte River and its tributaries followed four general stages. The first stage represents the earliest period of irrigation and was characterized by the construction of small, crude ditches to irrigate irregular patches of land on the flood plain. In the second stage, larger and more sophisticated canals and ditches were constructed to irrigate lands on benches above the valley floor. The amount of water appropriated to these canals usually exceeded the summer flows of the river, and many times canals that had junior water rights were unable to divert water throughout the irrigation season. Consequently, many canals were abandoned, and few new water appropriations were granted (U.S. Bureau of Reclamation and others, 1983; Eschner and others, 1983).

During the third stage of development, reservoirs were constructed to store water from snowmelt runoff. Many of the canals previously abandoned were reopened, new canals were constructed, and existing canals enlarged. Summer flows still were overappropriated during most of the third stage, and new demands for water each year exceeded the amount of water available in the basin.

The fourth stage began at the end of canal construction in the basin. Dam construction continued, but at a slower rate. The stored water was used to satisfy existing water rights and new municipal demands for water and power. This stage also was the beginning of large-scale ground-water withdrawals in the basin to satisfy new demands for irrigation water (Eschner and others, 1983; U.S. Bureau of Reclamation and others, 1983).

EFFECTS OF WATER DEVELOPMENT ON STREAMFLOW

Diversion and storage of surface water have changed the patterns of streamflow in some reaches of the Platte River basin. These changes are not

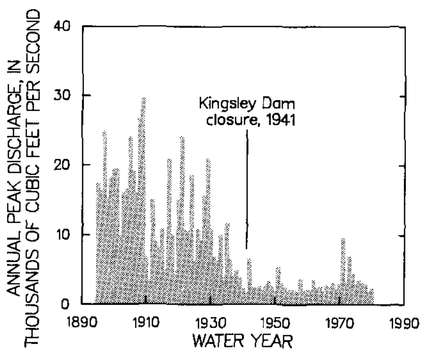
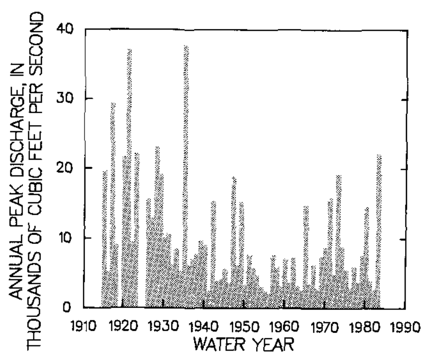


Figure 67.



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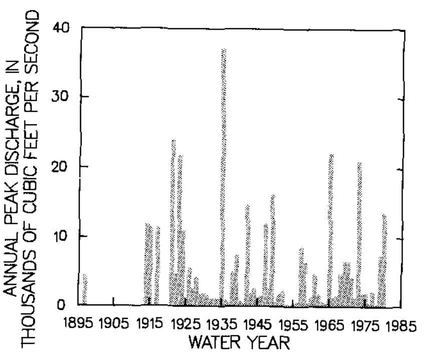

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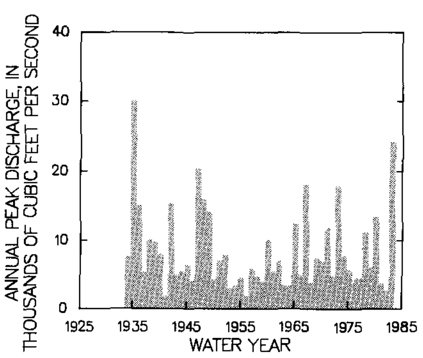
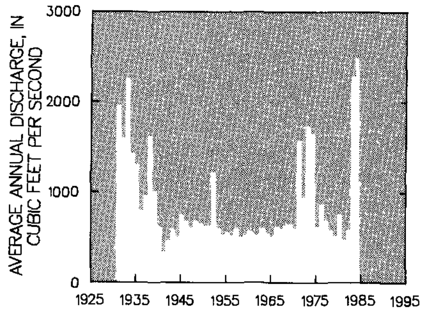


Figure 70.

Figures 67-70. Annual peak discharge at—
67. North Platte River at North Platte, Nebr., 1895-1980.
68. South Platte River at North Platte, Nebr., 1897, 1914-15, 1917, and 1921-80.
69. Platte River at Overton, Nebr., 1915-18, 1920-23, and 1926-83.
70. Platte River near Grand Island, Nebr., 1934-83.
(Source: Compiled by J. E. Kircher from U.S. Geological Survey data.)



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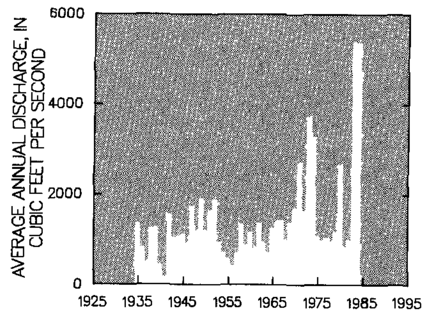

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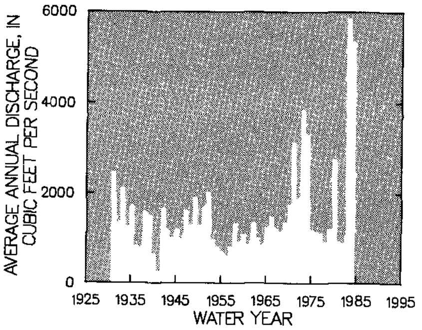

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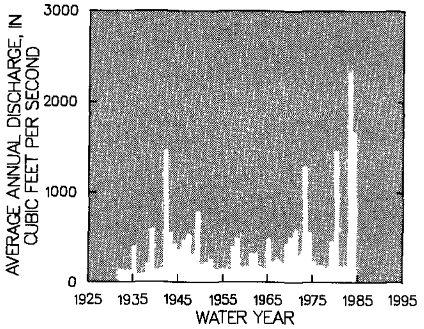
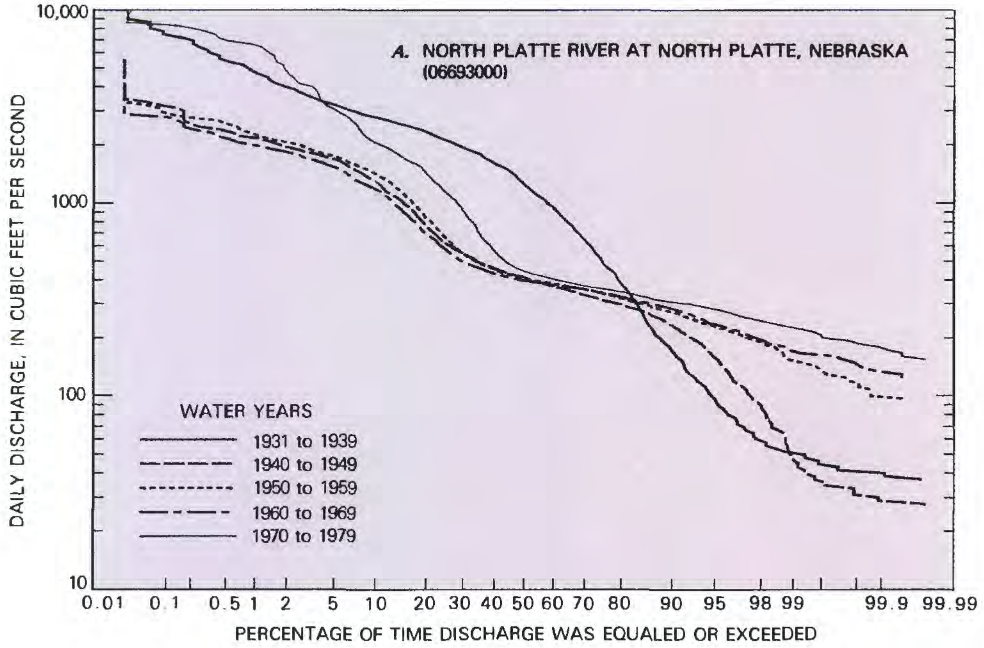


Figure 74.

Figures 71-74. Average annual discharge at—
71. North Platte River at North Platte, Nebr., 1931-84.
72. Platte River near Overton, Nebr., 1931-84.
73. Platte River near Grand Island, Nebr., 1935-84.
74. South Platte River at North Platte, Nebr., 1932-84.
(Source: Compiled by J. E. Kircher from U.S. Geological Survey data.)



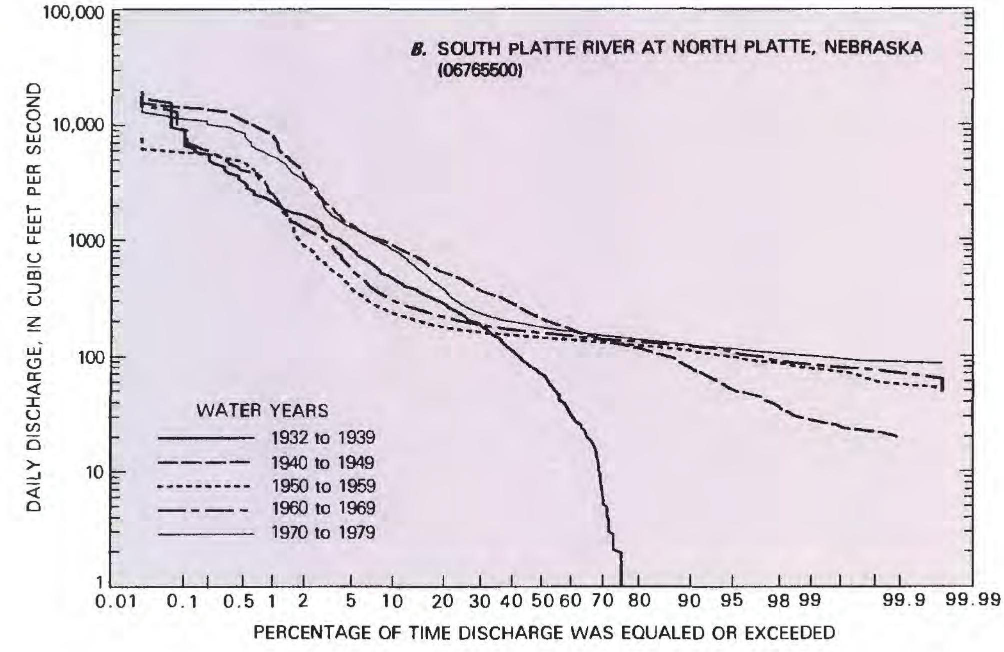
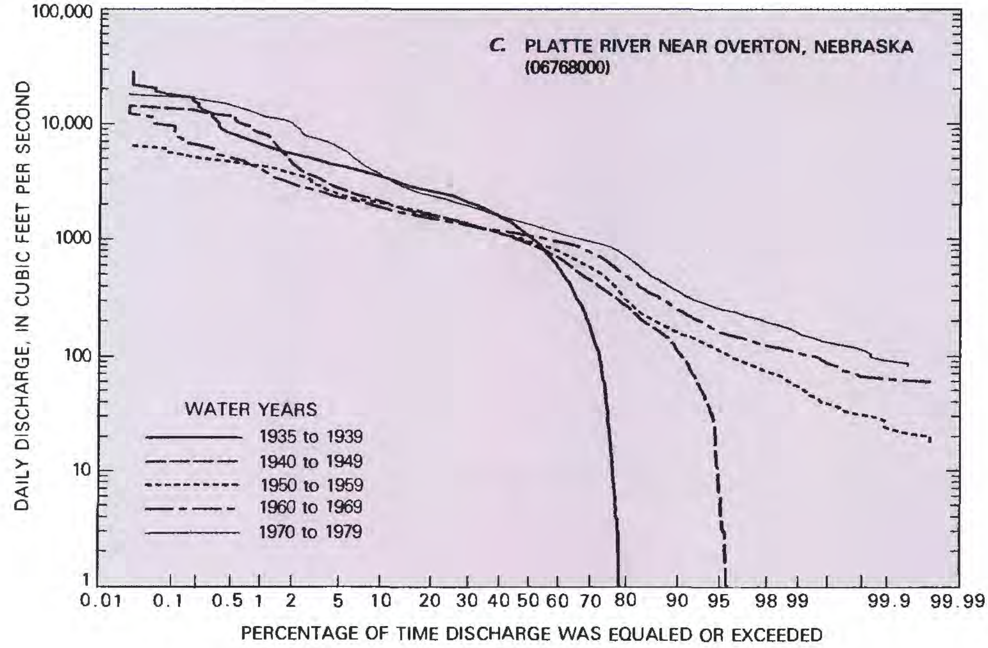


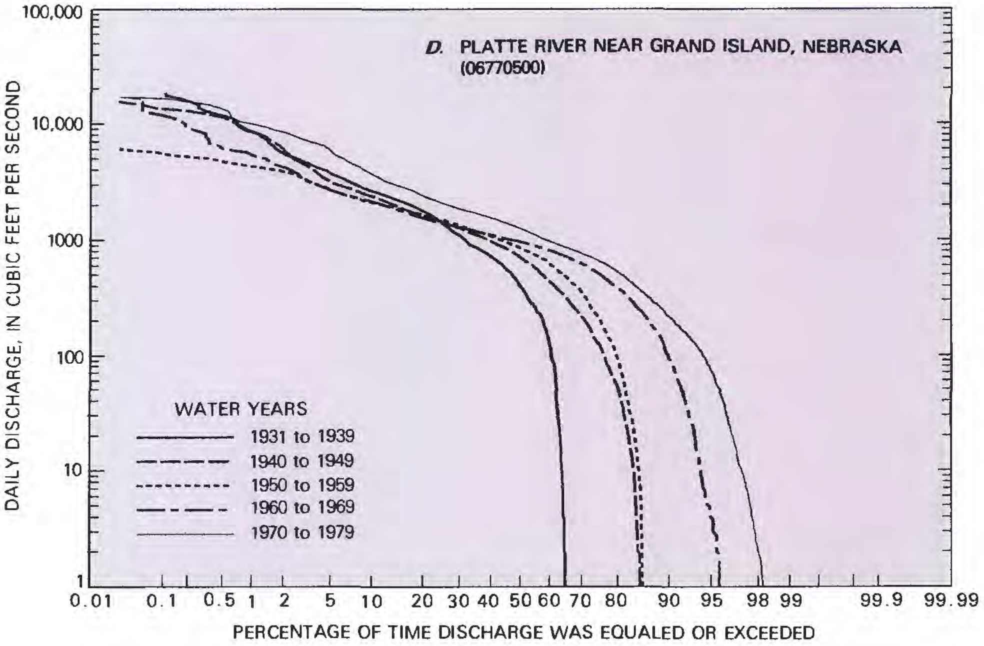
Figure 75. Selected flow-duration curves at four stream-gaging stations near the downstream end of the Platte River basin in Nebraska. See figure 64 for location of stations. (Source: Compiled by J. E. Kircher from U.S. Geological Survey data.)

uniform throughout the Platte River basin because development of water resources has progressed differently along the North Platte, the South Platte, and the Platte Rivers. The effects on hydrology vary in different reaches of the basin, and the changes in flood peaks, average annual discharge, and shape of flow-duration curves have been recorded (Kircher and Karlinger, 1983; Williams, 1978).

Construction of large onstream reservoirs in Wyoming and Nebraska has decreased flood magnitudes of the North Platte River. Four streamflow-gaging stations on the North Platte River that have long periods of record show that peak discharge decreased progressively after the closure of each of four major dams (Williams, 1978). Since 1941, after completion of Kingsley Dam, peak flows have not changed significantly (fig. 67).

Reservoir development has been less extensive in the South Platte River basin than in the North Platte. Total reservoir storage in the South Platte River basin





has doubled from 1915 to the present, primarily from the construction of offstream reservoirs. Peak flows of the South Platte River near Kersey and Julesburg, Colo., have not changed significantly since 1902 (Kircher and Karlinger, 1983); however, a significant decrease in peak flows with time was detected for the period of record on the South Platte River at North Platte, Nebr., possibly due to surface-water diversions downstream from Julesburg (fig. 68).

Peak flows of the Platte River are affected by flows from both the North Platte and the South Platte Rivers. Since the reduction of flood peaks on the North Platte River, flood peaks on the South Platte River have become the main influence on peak flows in the Platte River (Kircher and Karlinger, 1983). There is a statistically significant overall downward trend in peak flows of the Platte River near Overton, Nebr., from 1915 to 1979, but no significant decrease is evident since the 1941 construction of Kingsley Dam in Nebraska (fig. 69). No long-term change is apparent in peak flows near Grand Island, Nebr., since the record began during 1934 (fig. 70).

From 1935 to 1979, the North Platte River at North Platte, Nebr. (fig. 71), and the Platte River near Overton, Nebr. (fig. 72), showed no significant change in average annual mean discharge. Average annual discharge of the Platte River near Grand Island, Nebr. (fig. 73), shows a slight increase since 1935; although the analysis of the streamflow data shows a statistically significant difference, the actual difference is very slight (Kircher and Karlinger, 1983). No long-term change is apparent in the average annual discharge of the South Platte River (fig. 74). Importation of water into the South Platte River basin apparently has compensated for the effects of water development within the basin, in regard to average annual discharge; however, over a period of time, the distribution of flows probably has been affected.

Flow-duration curves can be used to show the relative frequency at which high flows, intermediate flows, and low flows occur at a stream location. By definition, a flow-duration curve is a cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded. When flow-duration curves are determined for different time intervals at the same location, a change in the shape of the curve illustrates how the flow regime of the stream is changing with time. As an example, in the Platte River basin in general, the curves show a rise in the low-flow end of the curve over a period of time, indicating an increase in the magnitude of low-flow discharges.

Flow-duration curves for 10-year intervals within the period of record at each of four stations illustrate the progression of hydrologic change within the basin (fig. 75).

Over a period of time, the only station showing any major change in the upper end of the flow-duration curve (high flows) is the North Platte River at North Platte, Nebr. (fig. 75*A*). A comparison of curves for the 10-year periods shows that from 1940 through 1969 flows of high magnitudes occurred on fewer days, or a smaller percentage of the time, than for the periods of 1931–39 and 1970–79. This flattening of the flow-duration curves after 1931–39 indicates a decrease in the magnitude of high flows resulting from flow regulation occurring along the North Platte River. The remainder of the stations show very little change in the high-flow section of the flow-duration curves, indicating no or very little change in the high flows.

The changes in the flow-duration curve sequences indicate the decrease in flow variability progressively downstream. The North Platte River at North Platte, Nebr. (fig. 75*A*), the South Platte River at North Platte, Nebr. (fig. 75*B*), and the Platte River near Overton, Nebr. (fig. 75*C*), show a flattening in the lower end of flow-duration curves beginning about 1940 and continuing to 1979. This flattening usually is caused by either irrigation return flows or by controlled release from reservoirs that maintain streamflow during low-flow periods. The flow-duration curve for the Platte River near Grand Island, Nebr. (fig. 75*D*), currently is flattening progressively at the low-flow end.

EFFECTS OF CHANGES IN HYDROLOGY ON THE CHANNEL MORPHOLOGY

Changes in channel morphology of the Platte River can be documented by comparison of maps and aerial photographs. Measurements of channel width were made from General Land Office maps surveyed onsite between approximately 1859 and 1867 (Eschner and others, 1983). Six sets of aerial photographs were made of four 3.1-mile reaches of the Platte River from 1938 to 1980. To illustrate the comparative change in channel width, the widths are plotted in figure 76 as percentages of the General Land Office map widths (Eschner and others, 1983). For convenience, the map widths are called "1860 width."

In general, the width of the Platte River channel has decreased consistently for most of the reaches since 1860. Width changes in the Cozad, Overton, Grand Island, and Duncan reaches are similar in character. The greatest reduction in channel width for Cozad and Overton occurred from 1938 to 1950. At these two locations, the rate of width reduction has decreased since 1940. The magnitude of change in channel width decreases downstream. For the four stations shown, Cozad has the greatest width reduction and is the most upstream reach. Overton is next downstream, with the second greatest width reduction, followed by Grand Island. Duncan is the reach furthest downstream and shows the least reduction.

Changes of North Platte River morphology have been similar to changes that occurred on the Platte River. Channel width in 1965 ranged from 5 to 40 percent of the channel width mapped in 1860 and probably averaged about 15 percent. Width of the South

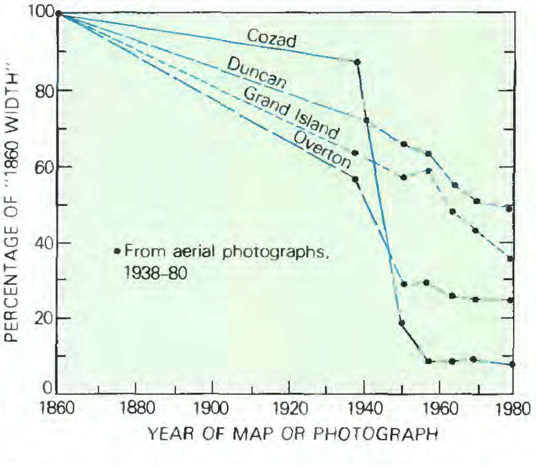


Figure 76. Changes in channel width of the Platte River in Nebraska from 1860 to 1980, for selected stations. (Source: Modified by J. E. Kircher from Eschner and others, 1983.)

Platte River also has changed. Channel width in 1952 averaged only about 15 percent of channel width in 1867.

The overall morphology of the channel in the Platte River system changed with time from broad channels interspersed with numerous small islands to a series of relatively narrow, well-defined channels intertwining among large islands. This change is effected by the processes of island formation and subsequent attachment of islands to either the flood plain or to other islands (Eschner and others, 1983).

By 1938, width of the Platte River system was decreased by the formation of islands in the channel. In addition, the banks of the rivers had shifted toward the center of the channels, as a result of island formation and attachment to the flood plain. Island attachment resulted from channel abandonment rather than from a migration of the river course. Most of the small islands have the same form as the adjacent sandbars, and it is concluded that the majority of the islands in the Platte River formed when vegetation established itself on these sandbars and stabilized them (Eschner and others, 1983). Once an island formed, it tended to perpetuate itself. The presence of vegetation promoted further aggradation by increasing roughness and decreasing flood-water velocity over the bar when the island was submerged. Thus, island elevation increased until it was at or above high-water stage.

Sets of maps and photographs made after 1938 show similar, continued development of islands. Although the number of islands diminished, over time the size of the islands increased. Islands merge as the channels between islands gradually lose their water- and sediment-carrying capabilities.

CONCLUSIONS

Flow in the Platte River basin is affected by transmountain diversions in the headwaters, by dams that create onstream reservoirs, by structures that divert water to offstream reservoirs, by ground-water pumpage from lands bordering rivers, by return of water to channels from irrigation and hydropower releases, by possible gain or loss of water by seepage, and by water demands of an increasing population. These human activities in the Platte River system probably explain the observed changes in flow as illustrated by the flow-duration curves.

Channel widths along the Platte and the North Platte Rivers have decreased primarily because of a change in river regime since about 1940. The 1979 channel width at Cozad, Nebr., was only 8 percent of the 1860 channel width. The magnitude of channel-width reduction decreases downstream. At Grand Island in Nebraska, the 1979 channel width was 35 percent of the 1860 channel width.

Hydrologic and channel changes have occurred in such a manner that the upstream reaches were affected earliest during the period of record. Observing the 10-year flow-duration curves and low flows at the sites studied indicates that stations upstream of the Platte River near Overton, Nebr., are relatively stable whereas sites downstream from Overton still are being affected by changes in the hydrologic system upstream (Kircher and Karlinger, 1983) as demonstrated by the Platte River near Grand Island, Nebr., where it appears the flow and channel are still adjusting toward stability.

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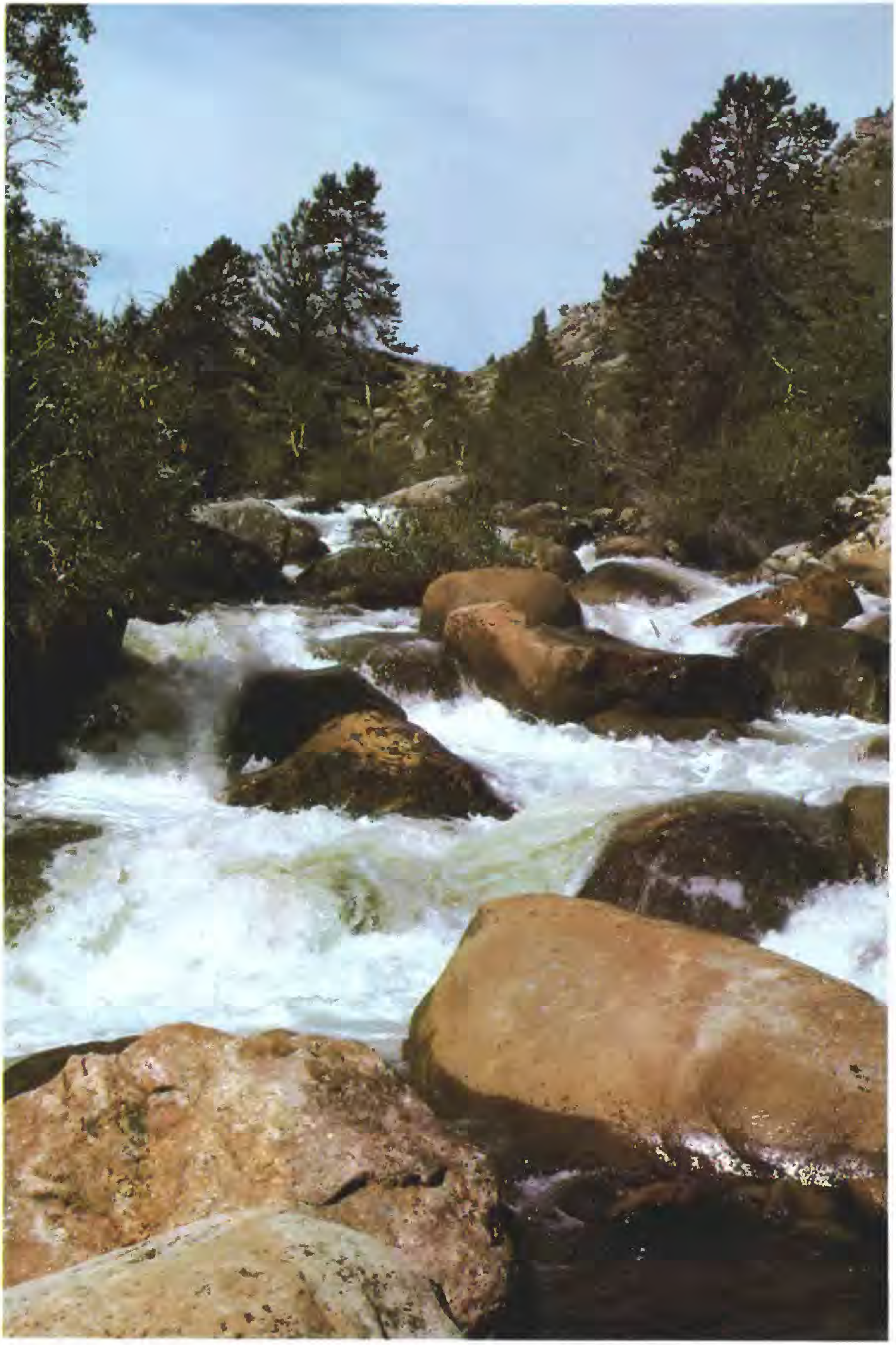

Popo Agie River in Wyoming. (Photograph by H. C. Riggs, U.S. Geological Survey)

INSTITUTIONAL AND MANAGEMENT ISSUES

REAL-TIME HYDROLOGIC DATA FOR WATER MANAGEMENT

By Richard W. Paulson

INTRODUCTION

Water is a natural resource whose distribution, availability, and quality vary geographically and temporally. An understanding of the resource requires the collection and analysis of hydrologic data.

Humans have gone to elaborate lengths to construct engineering works to transport and store water, to cope with hardships caused by droughts and floods, and to understand and control the distribution of water. Pressures of population growth, industrialization, stringent environmental regulations, and increasing standards of living have exacerbated the effects of natural variations in the availability of water. In response, methods for studying, controlling, and managing water resources continue to be developed.

Data on the quantity and quality of water at collection sites provide a basis for planning water-resources development; for operating and controlling engineering works, such as dams, aqueducts, and irrigation systems; and for issuing warnings during floods and other extreme hydrologic events. In recent years, some water-resources agencies have begun to implement very sophisticated communications and data-processing technologies to collect and analyze up-to-date hydrologic data so that water resources can be managed on a day-by-day or even hour-by-hour basis—an ability that was not possible just a few years ago.

REAL-TIME HYDROLOGIC-DATA-COLLECTION SYSTEM

DESCRIPTION OF SYSTEM

To collect hydrologic data in real time means that the data are collected (usually by automated instrumentation) and transmitted rapidly, generally in a few seconds to a central location in sufficient time to make a decision and take action (warn of a flood, or make operational changes in water control of dams—change gate settings—or an irrigation system), which could affect the impact of that hydrologic event. Mitigation of adverse effects of weather or human activities may be seriously impeded if up-to-date hydrologic data are not available.

A real-time hydrologic-data-collection system is composed of three basic elements: A network of hydrologic-data-collection stations, a communications subsystem, and a data-analysis and storage subsystem. Each of these elements is described below.

Hydrologic-data-collection stations—the first element of the real-time data-collection system—are sites on a stream, canal, lake or reservoir where systematic observations of hydrologic data are obtained with automated equipment that collect, record, and periodically transmit hydrologic data by radio or telephone. The most common type of modern automated equipment for hydrologic-data collection is the Data-Collection Platform (DCP), which automatically collects and communicates data from hydrologic gaging stations to the Geostationary Operational Environmental Satellites (GOES) (fig. 77). Although several types of DCP's are manufactured by different commercial sources, they share many attributes. Most are battery operated, are designed to operate under a great range of environmental extremes, incorporate microcomputers for onsite data analysis, and are designed and constructed for reliability.

Figure 77. U.S. Geological Survey hydrologic-data station at Turkey Creek near Cleator, Ariz., equipped with a Data-Collection Platform aimed at one of the Geostationary Operational Environmental Satellites. (Photograph by John W. H. Blee, U.S. Geological Survey.)

Until recently, the communications subsystem —the second element in the system for real-time telemetry of hydrologic data—relied on highly vulnerable telephone lines and line-of-sight radio communication. At present (1985) many new hydrologic-data telemetry systems rely on GOES or on transient micrometeor trails (meteorbursts) to relay radio messages. The U.S. Soil Conservation Service (SCS) is the principal user of meteorburst technology, whereas most other Federal agencies have come to rely on GOES. Each technology has its strengths and weaknesses, and each has been selected by the user agency to satisfy its particular needs. These communications subsystems are described below.

The GOES system for the relay of environmental data began with the successful tests of two experimental Synchronous Meteorological Satellites that were developed and launched in 1974 and 1975 by the National Aeronautics and Space Administration (NASA) (Paulson and Shope, 1984). Numerous successor satellites of the operational GOES series have since been launched by NASA for the National Oceanic and Atmospheric Administration (NOAA). These satellites, two of which are planned to be operational at any given time, provide imagery of cloud cover over the Western Hemisphere for weather monitoring and also provide a relay capability for the telemetry of environmental data. Because the satellites are in geostationary orbits, which have a period of 24 hours and coincide with the equatorial plane of the Earth, they are motionless in space relative to the Earth's surface.

NOAA operates a master Earth station, which receives data from the satellites and transmits the data to subordinate users. The master Earth station at Wallops Island, Va., allows many DCP's to relay data simultaneously through one of the satellites, each of which operates on a unique radio frequency. Relay of environmental data via these satellites can be accomplished at any time from virtually any point in the Western Hemisphere.

Currently, about 3,000 DCP's communicate through the two operational GOES; most of these DCP's are dedicated to relaying hydrologic data. The number of DCP's has reached the master Earth station's limit of data acquisition and transmission, and growth of the number of DCP's will be limited until NOAA expands the equipment's capacity. Most of the DCP's are programmed to collect hydrologic data every few minutes and to transmit accumulated data on conditions within a "normal" range at 4-hour intervals; the system reports data on extraordinary conditions, such as floods, immediately.

Meteorburst technology, used by the SCS, depends on transient micrometeor trails in the upper atmosphere to relay radio transmissions of hydrologic data between master central stations and networks of remote data stations. Because the reflection of a radio transmission from a micrometeor trail is directional and short lived, the establishment of radio communication in the SCS system between a master station and a remote site is random and transient. Typically, such a micrometeor trail persists for approximately 1 second. Thus, the amount of hydrologic data that can be conveyed is limited. This system is most ideally used for transmitting short bursts of data, and often requires repeated attempts by the master station to interrogate a remote data station.

The third element in a real-time hydrologic-data-collection system is a data-analysis and storage subsystem. This subsystem generally is computer based, is connected to the communications subsystem, and provides access to the hydrologic data through telephone lines. Users of the GOES system initially relied on NOAA's master Earth station to acquire their data. In recent years, a proliferation of Direct-Readout Ground Stations (DRGS), an example of which is shown in figure 78, has enabled users to receive messages directly from the satellites through the DRGS with relatively low-cost equipment. The location of DRGS's and DCP's, which are operated by Federal and State agencies, as shown in table 12 and figure 79, indicate where satellite-based technology is being most heavily used for water-resources monitoring.

Figure 78. Antenna of a Direct-Readout Ground Station operated by the U.S. Geological Survey in Harrisburg, Pa. (Photograph by Ennio V. Giusti, U.S. Geological Survey.)

The SCS data-analysis and storage subsystem is located at their Western Regional Technical Support Center in Portland, Oreg. This subsystem maintains communications with the master stations located in Boise, Idaho, and Ogden, Utah; these stations, in turn, maintain daily communications with slightly more than 500 stations where sensors monitor the snowpack and temperature in the high, mountainous regions in the Western United States. The snow telemetry (SNOTEL) subsystem has been in operation since the late 1970's. Under control of the central computer in Portland, there is daily communication with each remote site. Most of the remote sites are virtually inaccessible in the winter and spring, and manual collection of data is very difficult and costly. Data collected by SNOTEL are made available in real time to SCS snow supervisors in 10 conterminous States and Alaska. These data allow the SCS to assess the amount of water stored in the snowpack and to monitor the release of meltwater to streams. Such assessments provide a basis for forecasting runoff of snowmelt, which is the source of most runoff in many of the Western States. Such forecasts are vital for the day-by-day operation of dams and for the irrigation of crops during the growing season in the spring and summer. Data that are incomplete or otherwise of poor quality may not be adequate for preparing accurate runoff forecasts; water may be wasted or not used fully if the forecast is too low, or the water may not be adequate to meet demands if the forecast is too high.

APPLICATIONS OF SYSTEM

The use of the GOES for the telemetry of environmental data has grown significantly over the last 10 years, and most of the growth has been in the collection of hydrologic data. The hydrologic-data-collection programs of the U.S. Geological Survey, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the National Weather Service, and the Tennessee Valley Authority account for most of the DCP's in service. These programs and other activities are briefly described below.

The U.S. Geological Survey, in cooperation with more than 900 Federal, State, and local agencies, operates the basic hydrologic-data-collection network in the United States. This network includes about 6,800 continuously recording stream-gaging stations, nearly 800 continuously recording lake-level and reservoir-level gaging stations, and about 750 continuously recording surface-water-quality stations. These stations provide valuable data for planning and managing water supplies, monitoring compliance with environmental standards, and estimating flood and drought frequencies. In 1985, about 1,500 of these hydrologic stations, which were equipped with a DCP under agreements with Federal, State, and local agencies, reported through the GOES. The U.S. Army Corps of Engineers has equipped the largest number of these stations for real-time data collection. The U.S. Geological Survey has established DRGS's at its offices in Harrisburg, Pa.; Denver, Colo.; Tucson, Ariz.; Tacoma, Wash.; Anchorage, Alaska; and Columbia, S.C. (See table 21.) The U.S. Geological Survey also operates a station in Texas for the U.S. Army Corps of Engineers.

These stations are connected together as a network through the U.S. Geological Survey's Distributed Information System (DIS)—a nationwide telecommunications network of approximately 70 minicomputers. This network enables the Geological Survey to receive data from any Survey DRGS and route the data through the DIS to any Survey office for real-time distribution to cooperating agencies; those agencies use the data for flow forecasting, project operation, and water management. For example, up-to-date information on flows of streams that enter Salt River Project reservoirs in Arizona are needed to plan reservoir operation. These reservoirs are used for flood prevention, electric-power generation, and irrigation. If the reservoirs are kept full or nearly so for irrigation and electric-power generation, their ability to prevent floods will be minimal. Since the flood-control storage of the reservoirs is small, real-time data is very valuable in the management of the reservoir system.

Another example of the value of real-time hydrologic-data collection are stations in the vicinity of Mount St. Helens volcano, which provide data on floods or mudflows that can be triggered at any time by seismic or volcanic activity. The rapid analysis of the data can provide early warning to residents near these streams and, thus, minimize the loss of life and property. Real-time hydrologic-data collection improves the operational efficiency of the Geological Survey's network of hydrologic-data stations and enables the Survey to monitor the performance of remote site equipment, to schedule maintenance, and to minimize data loss (Paulson and Shope, 1984).

The U.S. Army Corps of Engineers plans, constructs, and operates projects to minimize floods, generate hydroelectric power, improve river navigation, provide water supplies, ensure compliance with environmental standards, provide recreational opportunities, and protect wildlife. The Corps uses DRGS's to obtain up-to-date hydrologic data on the quality and quantity of precipitation and surface water in project watersheds. These systems are being used by Corps Divisions to acquire data in their project-operating areas to assure effective project management and increase economic benefits to the many private and public organizations that rely on the management of Corps projects.

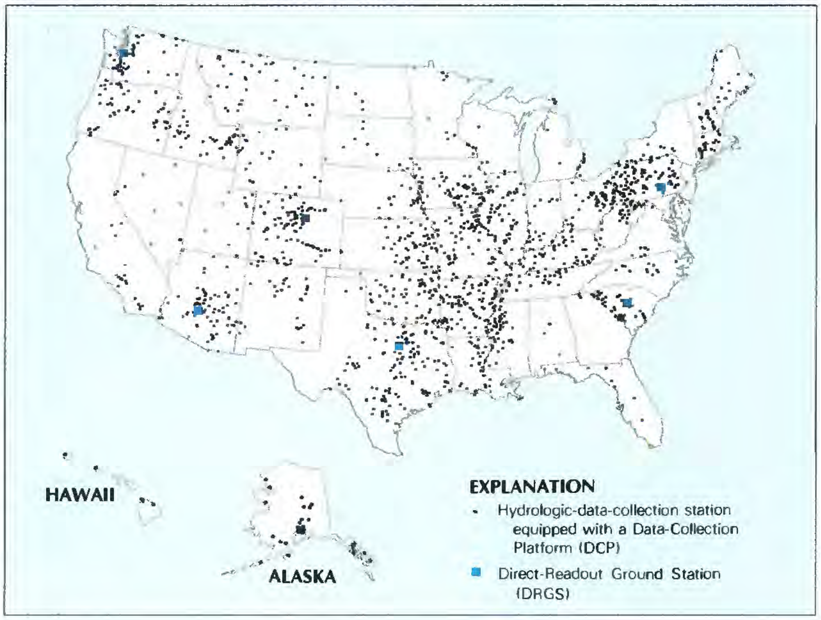

Figure 79. Location of U.S. Geological Survey hydrologic-data stations that transmit data through the Geostationary Operational Environmental Satellites, as of November 14, 1985.

Teble 12. Location of Direct-Readout Ground Stations (DRGS) operated by Federal agencies for hydrologic-data collection via the Geostationary Operational Environmental Satellites

Location of DRGS	General service area
U.S. Geological Survey	
Anchorage, Alaska	Alaska
Tuscon, Ariz	Southwestern States
Denver, Colo	Eastern Rocky Mountains and Great Plains
Harrisburg, Pa	Northeastern States
Columbia, S.C. (Two DRGS)	Southeastern States
Fort Worth, Tex[1]	South-Central States
Tacoma, Wash	Pacific Northwest
U.S. Army Corps of Engineers	
Rock Island, Ill	Upper Mississippi River
Omaha, Nebr	Missouri River
Cincinnati, Ohio	Ohio River
Waltham, Mass	New England
Vicksburg, Miss	Lower Mississippi River
Fort Worth, Tex[1]	Southwestern United States
Portland, Oreg	Pacific Northwest
U.S. Bureau of Reclamation	
Boise, Idaho	Snake River basin
Denver, Colo	Colorado River basin
Tennessee Valley Authority	
Knoxville, Tenn	Tennessee Valley

[1] DRGS is owned by the U.S. Army Corps of Engineers but operated by the U.S. Geological Survey.

The U.S. Bureau of Reclamation operates DRGS's in Boise, Idaho, and Denver, Colo. The Boise station is used principally for monitoring the Snake River system and various control structures on the system. The Bureau also cooperates with the U.S. Geological Survey and with the National Weather Service to increase significantly the number of real-time hydrologic-data and weather-data stations in the drainage area of the Colorado River in order to improve the reliability of precipitation monitoring in the basin and to forecast the extent of the snowmelt and meltwater runoff to its reservoirs. If reservoir capacity is not adequate for flows expected within days or weeks, the Bureau can begin releasing water before river flows reach the reservoirs; thereby minimizing flooding hazards. On the other hand, unnecessary releases can reduce the amount of water available in the summer for other uses, such as electric-power generation and irrigation.

The Tennessee Valley Authority (TVA) operates one DRGS in Knoxville, Tenn., that monitors a network of hydrologic stations in the drainage area of the Blue Ridge Dam and Reservoir. Real-time streamflow data from the reservoir's drainage area allow TVA to issue flood warnings and to manage releases from the reservoir when streamflows are large. TVA also is considering using the DRGS to monitor precipitation and streamflow throughout its operating area, to monitor air quality, and to assess the impact of emissions from fossil-fuel electric-power generating stations.

The National Weather Service (NWS) collects data automatically from all streamflow-gaging stations that report through GOES. Data from more than 2,000

GOES DCP's are forwarded to the NWS from NOAA's master Earth station. These data are used for streamflow forecasting by 12 NWS River Forecast Centers across the United States; these centers are responsible for making several daily forecasts of streamflow in virtually every major river and stream in the United States. In times of high flows and potential flooding, these forecasts are particularly important to private citizens; to local, State, and Federal civil-defense organizations; and to private industry. Accurate, plentiful, and up-to-date hydrologic data provide the information needed for timely issuance of flood warnings.

Other countries also are users of GOES. Of these countries, Canada is the greatest user; the Water Survey of Canada and the Province of Quebec use GOES to gather hydrologic data. The Canadians have found that the use of satellite technology is particularly suitable for collecting data from remote stations, particularly during the spring when many rivers thaw and flows increase. This information is critical to commercial interests who need to know when rivers become navigable. Many Canadian rivers have a relatively short navigable period in the summer; vessels may be trapped in ice-prone areas by traveling too soon or too late, and the delay of shipping when rivers are ice free or the cessation of shipping too soon can result in economic losses.

FUTURE PROSPECTS

During the last 10 years, the use of advanced meteorburst and satellite-communications technologies by water-resources agencies has evolved from experimental to operational. Many agencies now have direct access to advanced communications techniques that support telemetry of hydrologic data from virtually any area in the Western Hemisphere. Data on streamflow, some surface-water-quality characteristics, lake and reservoir levels, and precipitation characteristics can be measured and telemetered in real time by reliable and relatively inexpensive electronic systems.

The applications briefly described here demonstrate the tremendous potential of future real-time data-collection and telemetry systems. Major improvements will be made in the cost, efficiency, reliability, and flexibility of the electronics, communications, and computer technologies used by these systems. Eventually real-time applications will monitor on a continuous basis the characteristics and distribution of water resources throughout the entire United States. Many technical problems must be solved before such a system can be realized. The reliability of water-quality and water-quantity sensors must be improved and new measurement technologies developed. In addition, more advanced analytical approaches and institutional mechanisms must be developed. Nevertheless, great progress has been made in recent years, and technologies that are being implemented now can be expanded to collect and analyze hydrologic data from the Nation's present network of thousands of data-collection stations.

There is reason to believe that eventually we will be able to monitor our water resources and our water-management activities almost as efficiently as a modern industry monitors and controls its manufacturing processes, and to treat the natural and managed water resources of the United States as an integrated process-control system that can be used to maximize economic benefits and protect the environment. We are challenged to alter our traditional ways of thinking on the local and regional level into perspectives that are national in scope and to take advantage of the opportunities presented by new technologies.

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MANAGING WATER SUPPLIES TO INCREASE WATER AVAILABILITY

By Daniel P. Sheer[1]

INTRODUCTION

In the past, water managers generally met increasing water demands by building additional storage reservoirs or by drilling more wells. Today, it is increasingly difficult to find additional sources of water suitable for development. The best sites for surface-water storage are already in use, and the costs per unit storage at the remaining sites are high. In addition, environmental concerns may inhibit new storage projects, and construction funds may not be available.

Although much attention has been given to water conservation and other techniques to balance water demands with available supplies, at least over the short-term, few attempts have been made to operate water-supply projects as integrated systems. There are many reasons for this situation. Reservoirs, often hundreds of miles apart, may be viewed as individual projects, each with its own set of objectives and operating rules. The independent operation of water-management projects also is due to their ownership by different organizations and their location in different States.

The developers of new projects generally tend to avoid the legal complications that might arise if the new projects have adverse effects on the operations of the existing projects. Therefore, the developers design and operate the new projects as if no changes will be made in the operation of existing projects. Joint management of water supplies may never be seriously examined as an option because of the institutional and legal obstacles surrounding such proposals.

The three cases described in this article have been chosen to represent a variety of water-supply situations. The Potomac River case study deals with water supplies in the humid East where reservoir development is less extensive than in the West and where cities depend to a great extent on direct withdrawal of water from rivers whose flows may be highly variable at times. Joint management of the supplies under the jurisdiction of three agencies can increase water yields by over 30 percent as shown in the Potomac River example. The Houston, Tex., case study describes a situation where the conjunctive use of surface- and ground-water supplies might increase system yields by 20 percent even though both water sources are highly developed. Finally, the North Platte River study shows how joint management of supplies might reduce water shortages by about 30 percent in a semiarid region with extensive irrigated agriculture, even if additional water withdrawals are permitted.

The procedures described in the Potomac River case study are already implemented (Sheer and Meredith, 1984). The Houston, Tex., and North Platte River examples, however, are hypothetical. These exploratory analyses were sponsored by the U.S. Bureau of Reclamation to assess the potential of joint operations to improve the yield of existing water systems and to identify problems that might arise if procedures similar to those developed for the Potomac River were implemented elsewhere (Sheer, 1985a,b). None of the examples use highly sophisticated techniques to manage water supplies. They show that by improving communications between management agencies and by applying simple, commonsense guidelines to the management of systems of reservoirs, substantial benefits for all parties can be obtained. They also show how questions of equity, water-rights ownership, and responsibility can present obstacles to the consideration of such guidelines to the management of water-supply systems. Yet, as demonstrated by the Potomac River case study, problems associated with institutional constraints can be overcome. Although the arrival at mutually beneficial solutions takes persistance and patience, the rewards are enormous.

POTOMAC RIVER AND WASHINGTON, D.C., METROPOLITAN AREA

WATER-SUPPLY FACILITIES AND ANTICIPATED DEMANDS

The Washington metropolitan area and the Nation's Capital sit astride the Potomac River at its transition from a free-flowing river to an estuary. Three million people, 75 percent of the population of the entire Potomac River basin, live in the metropolitan region. Nearly all the water-supply needs of the Washington area are provided by three suppliers: the Washington Suburban Sanitary Commission (WSSC), which provides water for suburban Maryland; the Fairfax County Water Authority (FCWA), which provides water for most of the Fairfax and northeastern Prince William Counties in Virginia; and the Washington Aqueduct Division, U.S. Army Corps of Engineers (WAD), which wholesales finished water to the District of Columbia and to Arlington County and the city of Falls Church in Virginia (fig. 80).

The Washington area has three primary sources of raw water—the Potomac River, the Occoquan River, and the Patuxent River. Prior to 1982, the FCWA relied almost entirely on the Occoquan Reservoir near the mouth of the Occoquan River to meet water demands. The reservoir, which has about 11,000 Mgal (million gallons) of usable storage and a safe yield of 55 Mgal/d (million gallons per day) delivers water to two treatment plants that have a combined peak capacity of 112 Mgal/d. In 1982, to augment this supply, FCWA tapped the Potomac River through a new 200-Mgal/d intake and a 50-Mgal/d treatment plant.

The WSSC takes most of its supply from the Potomac River through a 400-Mgal/d intake and 240-Mgal/d peak-capacity treatment plant located just downstream of the new FCWA intake. In addition, the WSSC has the Duckett and the Triadelphia Reservoirs on the Patuxent River; these reservoirs have a combined usable storage of about 10,000 Mgal and a combined safe yield of 45 Mgal/d of which 10 Mgal/d is committed to maintaining flow below the downstream dam. The Patuxent treatment plant, which

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[1] The Interstate Commission on the Potomac River Basin.

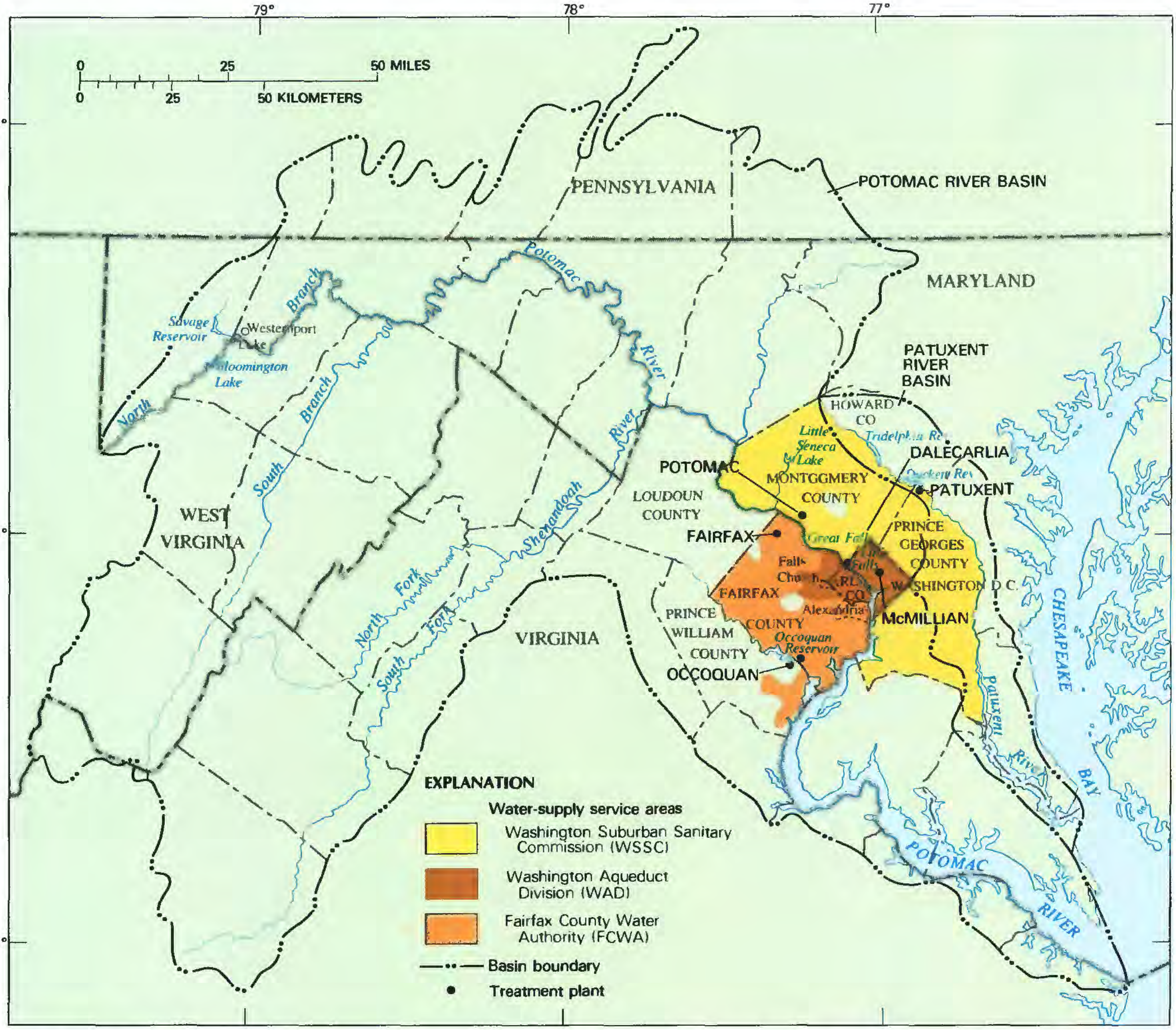


Figure 80. Potomac River basin and Patuxent River basin, water-supply reservoirs, and service areas of water-supply systems that serve the Washington, D.C., metropolitan area. (Source: Modified from U.S. Army Corps of Engineers, 1979.)

serves the Triadelphia and Duckett Reservoirs, has a peak capacity of 65 Mgal/d.

The WAD, which depends entirely on the Potomac River for supply, has two intakes—a 200-Mgal/d gravity intake at Great Falls and a 400-Mgal/d pumping station at Little Falls—just upstream of the Washington, D.C., boundary. These intakes are the farthest downstream of the three major suppliers. (See table 13.)

The Potomac River at Little Falls drains over 11,000 mi^2 (square miles) and has an average flow of about 7,500 Mgal/d. Daily river flows are quite variable ranging over almost three orders of magnitude from floods of 200,000 Mgal/d to drought flows of less than 400 Mgal/d. The drainage is almost entirely uncontrolled by reservoirs. The only sizable reservoirs in the basin are Savage River and Bloomington, which are located more than 200 miles upstream of Washington, D.C., in the headwaters of the North Branch Potomac River in western Maryland and West Virginia.

Savage River Reservoir was completed in the early 1950's. It regulates a drainage area of about 130 mi^2 and can store about 12,000 Mgal for purposes of flood control or water-quality flow maintenance. The reservoir has been used to provide a reliable flow of 60 Mgal/d in the North Branch Potomac River for use by the towns of Luke and Westernport, Md. The Savage River Reservoir was in operation on September 13, 1966, when a minimum 1-day flow of 388 Mgal/d was recorded at the U.S. Geological Survey's gaging station on the Potomac River near Washington, D.C. (Little Falls gaging station). Since that record low flow, the dependable flow of the Potomac for water supply, including contributions from Savage River Reservoir, commonly has been taken as 388 Mgal/d.

Bloomington Lake, on the North Branch Potomac River, controls a drainage area of 210 mi^2.

It is the third highest dam east of the Mississippi, yet, because of the steep gradient of the stream, the reservoir impounds only 31,000 Mgal of water for purposes of flood control, recreation, and conservation storage. Of the conservation storage, 55 percent is allocated for water-quality control in the North Branch and 45 percent is purchased by Washington metropolitan area water companies. The safe yield of Bloomington is 135 Mgal/d (table 14).

The total water available to the Washington metropolitan area is the sum of the independent operational supplies listed in table 14. Wastewater collected from the customers of all three water suppliers is discharged to the tidal Potomac below Little Falls and, consequently, is not available for reuse.

The combined safe yield of Bloomington Lake and the Potomac River provides 523 Mgal/d. From this total, a required minimum Potomac instream flow of 100 Mgal/d must be subtracted. This leaves 423 Mgal/d of Potomac flow for water supply. Adding the safe yields of the reservoirs on the Patuxent River and the Occoquan River gives a yield of 513 Mgal/d for the Washington metropolitan area's water supply.

In 1977, average demands for the summer months were often in the range of 450 to 470 Mgal/d. Peak day demands had well exceeded the sum of the safe yields, even counting water from Bloomington Lake, which was 4 years from completion. The U.S. Army Corps of Engineers (1975) predicted the possibility of regional shortages as large as 80 Mgal/d by 1980 and 365 Mgal/d by the turn of the century. The FCWA, as yet without a Potomac intake, nearly emptied the Occoquan Reservoir that year, and Fairfax County considered closing schools and businesses in a desperate attempt to save water.

SEARCH FOR SOLUTIONS

In the late spring of 1977, the Interstate Commission on the Potomac River Basin (ICPRB) realized that altering operations of existing water-supply facilities had not been adequately considered in previous regional water-supply planning efforts. Consequently, it performed an analysis that concentrated on the maximum yield that could be derived if reservoirs on the Patuxent and the Occoquan Rivers were operated in concert with the free-flowing Potomac. This analysis abandoned the concept of "safe yield" operation of these reservoirs, which generally is defined as not exceeding that constant rate of withdrawal that will just empty the reservoir given a repeat of the worst drought in the historical record.

ICPRB estimated total water requirements in the Washington area in the year 2000 to be 750 Mgal/d. The 90-day, 50-year recurrence interval low flow in the Potomac River was 580 Mgal/d. This 90-day duration flow was used to estimate the worst-case water-supply deficit. The total water deficit over the 90-day period is the difference between demand and supply:

Demand (750 Mgal/d × 90 days =)	67,500 Mgal
Supply (580 Mgal/d × 90 days =)	52,200 Mgal
Deficit	15,300 Mgal

However, reservoir storage on the Occoquan and the Patuxent Rivers totals 21,000 Mgal. Conclusion: the Washington metropolitan area was not short of water if a way could be found to efficiently use the existing local storage.

One way to make the water in the local reservoirs more accessable was to improve the existing distribution system (finished-water interconnections). An ICPRB study of the finished-water interconnections, which involved modeling the major distribution systems in the Washington area, was based on the concept that when Potomac River flows were high, withdrawals from local reservoirs would be reduced well below their safe yield. The water thus "saved" would be stored to support withdrawals from the reservoirs at rates well above safe yield when the Potomac flows were low.

The conclusions of the finished-water interconnections study were unexpected. Construction of new distribution lines would not improve yield as a result of altering operations of the water system. To the contrary, the existing distribution systems, with proposed improvements required for normal non-drought operations, could be operated to ensure the availability of water to support the peak capacity of the reservoir treatment plants whenever the Potomac

Table 13. Capacities of local water-supply facilities in the Washington, D.C., metropolitan area

[Mgal/d = million gallons per day; - - - = not applicable]

Facilities	Capacity (Mgal/d)	Yield (Mgal/d)	Peak capacity of treatment plants (Mgal/d)
Reservoirs			
Triadelphia and Duckett (Patuxent River)	10,000	[1]35	65
Occoquan (Occoquan Creek)	11,000	55	112
Little Seneca	4,000	24	- - -
Potomac River Intakes			
Fairfax County Water Authority	200	200	50
Washington Suburban Sanitary Commission	400	400	240
Washington Aqueduct Division:			
Great Falls	200	200	([2])
Little Falls	400	400	([2])

[1] Yield is 45 Mgal/d but 10 Mgal/d are required for instream flows and water-quality maintenance.

[2] Peak capacity of treatment plants is more than sufficient to meet projected peak demands. Therefore, the treatment plant capacity is not a limiting factor.

Table 14. Summary of the safe yields of independently operated water supplies in the Washington, D.C., metropolitan area

[Mgal/d = million gallons per day]

Source of water	Safe yield (Mgal/d)
Potomac River (including Savage River Reservoir)	388
Bloomington Lake	135
Potomac River minimum instream-flow requirement	−100
Subtotal	423
Triadelphia and Duckett Reservoirs	35
Occoquan Reservoir	55
Total	513

was low. In fact, simulation of operations during the worst drought of record using year 2030 demands failed to lower the local reservoirs below 40 percent of capacity.

Existing system capacity was underutilized. Major parts of the distribution system are designed to handle peak demands (160 percent of the Washington area's average demand), which occur quite infrequently. Smaller system components are designed to accommodate fire-fighting requirements, which proportionally are even larger than the peak demands. This excess capacity is available nearly all the time to accommodate flexible operating rules designed to maximize system yield.

Another reason for the flexibility of the existing water-supply system is that minimum flows in the Potomac River generally occur in the fall and do not coincide with peak demands which occur in July and August. Consequently, more water than might be expected from just considering minimum Potomac flows will be available to meet peak demands most of the time.

The reason for the availability of water in the Patuxent River and Occoquan River reservoirs to support withdrawals over and above the safe yield, given a flexible operating rule, is a result of assumptions made in the design of the reservoirs. The critical period used for safe-yield analysis of the local reservoirs is approximately 9 months. The critical period of low flows in the Potomac River is much shorter, about 4 months; it is a much larger river than those that feed the local reservoirs, and the demands on it are a much smaller percentage of the average flow. Therefore, the flexible operating rules called for the "saving" of water in the local reservoirs when Potomac flows were sufficient to meet demands and the taking of water from the local reservoirs at a higher rate than allowed under a safe-yield constraint on withdrawals, but only for short periods of time, during low Potomac flows. The total volume of water taken from the reservoirs is still the same as under previous rules, but the timing of withdrawals is different.

The flexible operating rules were called "reregulation," and the WSSC and FCWA immediately indicated that they would implement such procedures. The rules increased the yield of the Patuxent River for water supply from 35 Mgal/d to 65 Mgal/d (the capacity of the Patuxent treatment plant). The Occoquan Reservoir yield increased from 55 Mgal/d to 112 Mgal/d. The combined increase in yield is nearly 90 Mgal/d, or 100 percent.

The increase in system yield through greater use of the Potomac River is nearly cost free. Pumping costs for the FCWA are lower inasmuch as its Potomac intake is at a higher elevation than the Occoquan intake. These savings are offset by a small increase in operating costs for the WSSC because pumping costs from the Patuxent River are somewhat less than from the Potomac.

Another opportunity to improve the management of the region's water supply was to integrate the operations of the upstream reservoirs to meet downstream demands. In late 1977, the Department of Geography and Environmental Engineering at the Johns Hopkins University, in cooperation with ICPRB, received grants from the Maryland Department of Natural Resources, the Virginia State Water Control Board, and the Maryland Water Resources Research Center (through the U.S. Office of Water Research and Technology) to investigate future operating rules for Bloomington Lake that would increase its water-supply yield. The first work used linear programming, an optimization technique, to establish upper bounds on reservoir yield. Assuming perfect forecasting of demand and flow on a weekly average basis, and perfectly coordinated operation of upstream and downstream reservoirs, the study evaluated the tradeoffs between safe-yield operation and upstream operations to meet downstream demands.

The results were surprising. The upper bound on yield was over 1,000 Mgal/d, far in excess of projected demands. Moreover, this yield could be achieved while still meeting upstream demands of more than twice that predicted.

To aid in explaining the results of the study, the Johns Hopkins University team developed the Potomac River Interactive Simulation Model (PRISM). At the heart of PRISM was a reasonably realistic weekly simulation model of reservoir and utility raw-water operations. The computer provided the water-system operators with the information that they would have during a real drought and asked them to make operational decisions. The effects of those decisions were then simulated, and the results were provided as information upon which to base the next round of decisions. Good decisions and good luck (the forecasts were not always right) were needed to keep water shortages from occurring and to minimize the amount of water wasted.

The main cause of shortages and wasted water was the long travel time between the upstream reservoirs and the Washington area. Releases made a week in advance and based on a forecast of no rain were almost always too large. The elimination of unnecessary reservoir releases required that the local water suppliers formally coordinate their operations. In 1979, the water suppliers asked the ICPRB to establish a Cooperative Water Supply Operations Section (CO-OP) to develop, integrate, and formalize the tools and techniques required for joint daily operations of Washington metropolitan area water systems during droughts.

CO-OP completely revamped the PRISM model to develop daily operating rules. The simulation of daily operations was necessary because (a) of the daily nature of utility operations, (b) the latest information from the U.S. Geological Survey indicated that travel times from the upstream reservoirs were not 7 but 4 to 5 days, (c) forecasts changed from day to day, and (d) water use varied substantially from day to day. The first two factors were incorporated easily into the new daily model.

CO-OP next entered into an agreement with the National Weather Service to attack the forecast problem. Working closely together, the two agencies calibrated the National Weather Service River Forecast System (NWSRFS) for the entire Potomac basin, and modified the computer programs to produce the output necessary for risk analysis.

CO-OP, the water suppliers, the Johns Hopkins University, and the National Weather Service all contributed to the development of techniques for producing synthesized records of water demand. The records had to preserve not only the variability of daily demand, but also the cross-correlation of demand between the water suppliers and the tendency of demands to increase substantially during hot, dry weather. The latest 10 years of demand and meteorological data were analyzed using statistical techniques to build the forecast model. The forecast model was then used to simulate demands that varied much more, on a day-to-day basis, than historical demands and, thus, provided a greater challenge to the operators of the water-supply systems to coordinate their operations successfully.

In February 1980, the Washington Metropolitan Area Water-Supply Task Force, comprised of one member each from the Montgomery and Prince Georges County Councils, the Fairfax County Board of Supervisors, and the District of Columbia City Council, had its first meeting. It approved a work plan that included the following tasks:

- Definition of the demands to be met
- Determination of the available supply
- Evaluation of alternatives for additional supply
- Selection of the most desirable alternatives

To assist the task force, two committees were formed: a citizens advisory committee, with members appointed by the executives of each of the jurisdictions represented on the task force, and a technical advisory committee, which consisted of the chief operating officer of the WSSC, WAD, and FCWA. The General Manager of the WSSC chaired both the task force and the technical advisory committee. The first task was completed when the committees quickly agreed to use the U.S. Army Corps of Engineer's (1979) water-demand projections for the Washington area.

CO-OP was asked to help determine the available supply, using the new CO-OP model. The first review of the model results made it clear that close cooperation between CO-OP and the water-system staffs was necessary to refine the CO-OP model to accurately reflect all the constraints on daily water-system operations. This effort resulted in increased credibility for the model.

The Technical Advisory Committee and CO-OP then began experimenting with different forms of operating rules. One of the best, called the "difference rule," also is one of the simplest. To determine upstream releases under this rule, the natural flow in the Potomac River at Washington on the date of the release is subtracted from the total demand (including required instream flow) from all sources expected on the day the release will arrive in the Washington area. The difference represents the total additional water that will be needed to meet demands if the natural flow remains constant. It is adjusted by subtracting the amount to be taken from the local reservoirs and by adding a safety factor.

The difference rule was used to evaluate the supply capabilities of existing and proposed projects. The rule was simple and practical. There was no operational experience with the NWSRFS, then being calibrated for the Potomac by CO-OP and the National Weather Service. Any improvement in operations made possible by more accurate short-range (5–7 day) forecasts would provide a margin of safety in the estimates of system reliability. Because of the large drainage area, low flows in the Potomac are relatively stable, and thus, the assumption that flow would not change over the time it took upstream reservoir releases to reach Washington produced generally reasonable forecasts for use in simulation.

The simulations demonstrated that it was possible to meet the Washington area water requirements, including a 100 Mgal/d instream flow, through the year 2000—without the additional pipeline and small reservoir (cost $100 million) recommended by the Corps in their 1979 interim report on the Washington area's water supply (U.S. Army Corps of Engineers, 1979). A critical examination of the simulation results by the technical advisory committee, however, revealed that if the existing system was not upgraded, there would be undesirable consequences.

Several of the simulated droughts drew the reservoirs down significantly during the late summer. Such drawdowns might call into question the ability of the water systems to meet their commitments during those droughts. The reason for the drawdowns was not lack of water but a lack of local operational flexibility.

Reregulation provided the flexibility. When releases from the upstream reservoirs (made 5–7 days ahead) turned out to be inadequate, withdrawals from the local reservoirs could be increased to take up the slack. The increase was limited by the capacity (about 180 Mgal/d) of the treatment plants on the local reservoirs. Given the minimum withdrawals required from the reservoirs, about 30 Mgal/d, the amount available to augment Potomac flows, was on the order of 150 Mgal/d.

Unfortunately, 5- to 7-day flow forecasts are not that accurate. To ensure enough water reaches downstream intakes, the margin of safety in the upstream releases must be about 100 Mgal/d. Most of this water (almost 70 percent of the water released from the upstream reservoirs) flowed by the intakes unused. Further, because the extra release was in the Potomac, the average use of the local reservoirs was undesirably low. The local reservoirs stayed full, whereas the upstream reservoirs dropped precipitously.

A proposed small local reservoir eliminated the operational problems. Simulations showed that the ability to correct for errors in streamflow forecasts by making releases directly to the Potomac River from a small local reservoir would eliminate the need for a large margin of safety in the upstream release, reduce the unused portion of the releases from 70 percent to about 10 percent, and allow full utilization of the storage in the existing local reservoirs. The additional water made available was sufficient to meet Washington area water requirements through the year 2030, based on Corps projections (U.S. Army Corps of Engineers, 1979). The utilities decided to build the reservoir on Little Seneca Creek in Montgomery County, Md.

IMPLEMENTATION OF JOINT OPERATIONS

The implementation of the joint operating scheme is designed to minimize interference with normal water-system operations. Joint scheduling of operations does not begin until drought conditions exist. Drought conditions are defined in two ways: flow in the Potomac River drops below 200 percent of expected withdrawals, or the probability of meeting all water requirements and refilling all reservoirs by the following June falls below 98 percent. The probabilities are defined using the NWSRFS and risk analysis.

When drought conditions exist, releases from Bloomington Lake are scheduled using the difference rule explained above. The CO-OP demand model is used to forecast demand. Desired withdrawals from the Patuxent and the Occoquan reservoirs are set at the safe yields, and, until Little Seneca Lake became available, a margin of safety of 100 Mgal/d was used. Little Seneca Lake was completed in the summer of 1985, and the 100 Mgal/d margin of safety is no longer required.

Downstream operations strive to balance storage between the Patuxent and the Occoquan reservoirs. Each morning, target Potomac withdrawals are set for the WSSC and FCWA. Both suppliers attempt to meet their remaining requirements from their local reservoirs. Mid-day reports are analyzed in the afternoon, and modest corrections in withdrawals are made to further balance the systems.

A convincing demonstration that the procedures developed by CO-OP actually work took the form of a drought exercise in 1981. The NWSRFS was used to produce a "quasi-historical drought" using artifically set antecedent soil-moisture conditions and the actual meteorological data from a year of deficient rainfall. Because the drought was based on a historical meteorological record, actual weather forecasts, complete with inherent uncertainty, were available for use by system's managers.

The 1981 exercise also established lines of communications, and tested operating procedures. Problems were corrected as the exercise progressed. Not only did the exercise establish beyond doubt that coordinated operations were feasible and could provide adequate water, but they also prepared all parties for dealing with an actual drought. A second drought exercise, held in October 1982, tested the reliability of the improved demand forecasting model. Annual drought exercises have been held in subsequent years.

Writing the contracts to implement the joint operations and the sharing of the costs for the operation of Bloomington Lake, Savage Reservoir, and Little Seneca Lake was a formidable task. The interstate nature of the agreements, the unique character of the government of the District of Columbia, and the congressionally mandated responsibilities of the Corps of Engineers created an extraordinarily complex situation. In large part due to their familiarity with the situation gained through the simulations and the drought exercise, the negotiators (the system managers) were absolutely convinced of the feasibility and desirability of joint operations. Eight separate but interlocking contracts were executed on July 22, 1982 (table 15).

Table 15. Water-supply agreements signed by Maryland, Virginia, Washington, D.C., and the U.S. Army Corps of Engineers on July 22, 1982

[Source: Interstate Commission on the Potomac River Basin]

1. Water-Supply Coordination Agreement.
    Binds all parties to joint operations during drought, assigns responsibility for scheduling release withdrawals to Interstate Commission on the Potomac River Basin Cooperative Water Supply Operations Section.
2. Contract for Future Water Supply Storage in the Bloomington Lake.
3. Novation Agreement for Initial Water Supply, Bloomington Lake.
    Reassigns ownership from Maryland Potomac Water Authority to Washington Suburban Sanitary Commission, Fairfax County Water Authority, and District of Columbia.
4. Novation Agreement Regarding District of Columbia's Payment to the Potomac Water Authority.
    (Cancels a previous contract.)
5. Bloomington Lake Payment Agreement.
    (Provides for legal remady in case of nonpayment.)
6. Little Seneca Lake Cost-Sharing Agreement.
7. Modification No. 1 Potomac River Low Flow Allocation Agreement.
    (Removes "1988 Freeze" provision.)
8. Savage Reservoir Maintenance and Operation Cost-Sharing Agreement.
    (Provides for Washington Suburban Sanitary Commission, Fairfax County Water Authority, Washington Aqueduct Division, and Allegany County, Md., cost sharing.)

CONCLUSIONS

Providing the Washington area with an adequate water supply was a complex engineering, social, economic, environmental, and institutional problem. Large-scale structural solutions had been proposed and found wanting. A fresh approach was required.

Joint operation of supplies, developed and tested using new computerized techniques, provided the solution to a problem of almost 30 years standing. Between $200 million and $1 billion was saved compared to previously evaluated alternatives. Moreover, the solution was not achieved at great environmental expense. In fact, the environmental benefits of increased minimum instream flow and the recreational opportunities provided by Little Seneca Lake may outweigh any other environmental impacts.

SAN JACINTO RIVER BASIN AND THE HOUSTON, TEXAS, AREA

WATER-SUPPLY FACILITIES AND ANTICIPATED DEMANDS

The city of Houston and its surrounding areas historically have relied on ground-water supplies. Growth in the area, explosive at times, has led to pumping ground water in excess of natural recharge. This depletion in turn has caused dramatic subsidence with loss of land along the coast (Gabrysch, 1982). Ground-water withdrawals peaked in the early 1970's but fell to 463,000 acre-ft/yr (acre-feet per year) in 1980 (U.S. Bureau of Reclamation, 1984b). This figure still represents some 38 percent more than the estimated average annual recharge capacity of the aquifer, which is 337,000 acre-ft/yr.

In addition to ground water, the area has three major reservoirs for water supply—Lake Houston and Lake Conroe on the San Jacinto River and Lake Livingston on the Trinity River (fig. 81). Lake Houston

Figure 81. **Source of water supply for Houston, Texas, and surrounding areas.** Ground water, mostly in the Gulf Coast aquifer, underlies the entire area. Surface water is from three major reservoirs—Lakes Houston, Conroe, Livingston.

is the oldest of the three, with storage capacity of 100,000 acre-ft and a yield of 145,000 acre-ft/yr. Lake Conroe, owned by the San Jacinto Authority, has 430,000 acre-ft of storage and a yield of 98,000 acre-ft/yr. Releases from Lake Conroe flow into Lake Houston where they are withdrawn for treatment. Lake Livingston on the Trinity River has a storage of 1,750,000 acre-ft and a yield of 1,290,000 acre-ft/yr (Houston Chamber of Commerce, 1983).

The Houston area currently (1985) uses about 822,000 acre-ft/yr (730 Mgal/d) of water annually. Demands are expected to grow substantially in the first quarter of the 21st century to perhaps more than 2,000,000 acre-ft/yr (1,790 Mgal/d) (U.S. Bureau of Reclamation, 1984b). Facilities for conveying, treating, and distributing the requisite amount of surface water to meet such demands simply do not yet exist in the Houston area. In fact, conveyance of water from Lake Livingston to the Houston area is limited to about one quarter of the safe yield. Because the simulation of operating schemes in this article deal with future demands that are so much larger than current (1985) demands, existing conveyance, treatment, and distribution system constraints are ignored. It is assumed that these will be provided as needed.

ANALYSIS OF OPERATING RULES

The objective of the analyses herein is not to precisely define a rule for the joint operation of the sources available in the San Jacinto River basin and the Houston area nor to precisely define yields under any operating scheme. Rather, approximate yields under "reasonable" independent and joint rules were compared to demonstrate the potential for increasing yield by coordinating the operations of all sources. This approach is particularly important because two recent reports on water supply in the area have used the sum of the independent yields of the facilities to determine water-supply needs for the area (Houston Chamber of Commerce, 1983; U.S. Bureau of Reclamation, 1984b).

The analysis began by running single reservoir safe-yield analyses of Lakes Houston, Conroe, and Livingston to establish their independent yields. Monthly inflows (1941–79) were supplied by the U.S. Bureau of Reclamation, from their 1984–85 San

Jacinto study (U.S. Bureau of Reclamation, 1984a). Data on reservoir storage and monthly evaporation also were supplied by the Bureau. Evaporation was computed as the monthly rate times the reservoir surface area. Evaporation was limited to 8 percent of storage to avoid negative storages when the reservoirs were nearly empty; this constraint had no significant effect on the results.

To avoid questions of storage space and water rights in all the reservoirs, the analysis considered the yield of the source for all users. The independent safe yields were in excellent agreement with the yields published in the preliminary findings of the San Jacinto study (U.S. Bureau of Reclamation, 1984b), and are given in table 16. The sum of the independent yields of the surface supplies is 1,533,000 acre-feet/yr.

An estimate of withdrawal rates that do not exceed recharge rates for the Gulf Coast aquifer within the San Jacinto basin has been estimated as 337,000 acre-ft/yr (U.S. Bureau of Reclamation, 1984b). In this case, the task of estimating is confounded by the extension of the aquifer into developed areas beyond the boundaries of the study area. Nonetheless, 337,000 acre-ft/yr was used as a basis for comparing joint and independent yields in an internally consistent manner as described below. The sum of the independent yields of surface- and ground-water supplies is 1,870,000 acre-ft/yr.

The joint operation of the surface-water reservoirs was simulated using the same inflows, evaporation, and reservoir storages as were used in the independent safe yield analysis. However, where the independent-yield analysis assumed constant withdrawals from each reservoir, the new simulation released water first from Lake Houston, then from Lake Livingston, and finally from Lake Conroe. This order of releases was based on the relative probability that each reservoir would refill and spill before the others, thus "losing" water downstream.

The simulation also varied monthly withdrawals from the reservoirs. The percent of average annual demand used in each month was supplied by the U.S. Bureau of Reclamation. A small amount of capacity in each reservoir was allocated to meet local demands. Small minimum withdrawals also were set for each reservoir. Neither the local demands nor percentage variation in monthly demands have a significant impact on the multi-reservoir system yield. The simulation indicated that Lakes Houston, Conroe, and Livingston, when operated as a system, could yield 1,660,000 acre-ft/yr, an increase in water supply of 127,000 acre-ft/yr or 8 percent (table 16).

The difference in yields is due, in large part, to the disparity in the length of the critical periods used for safe-yield analysis of Lake Houston (1 year) and Lake Livingston (4 years). Because of its size, Lake Livingston dominates the joint operating scheme. Its storage is more than large enough to augment flows to Lake Houston during its one critical year of low inflows. As a result, the critical period on Lake Houston changes from 1 year to 4 years. The average flow in the basin during the 4-year period is substantially larger than the minimum 1-year flow, accounting for the difference in system yields between individual and joint operations.

Next a provision for incorporating a ground-water pumping rule was made in the model. Again, instead of pumping at constant rate, equal to the safe yield, the pumping rate was based on levels of reservoir storage. A minimum pumping rate of 150,000 acre-ft/yr arbitrarily was set to provide water for those who could not be economically served by surface water. A maximum pumping rate of 600,000 acre-ft/yr also was set. This maximum corresponds approximately to the historical maximum pumping that occurred in the early 1970's. (It has no other basis.) Finally, the average pumping over any consecutive 10-year period was constrained to be less than 337,000 acre-ft/yr, the estimated aquifer-recharge rate. This limit was imposed to keep pumping from causing subsidence due to aquifer compaction caused by water-level drawdown.

Table 16. Summary of yields of water-supply facilities in the San Jacinto River area near Houston, Tex.

[acre-ft/yr=acre-feet per year; - - - =not applicable]

Source of water	Yield (acre-ft/yr)	Increase (acre-ft/yr)
Independent-Yield Summary		
Surface water only:		
Lake Houston	145,000	- - -
Lake Conroe	98,000	- - -
Lake Livingston	1,290,000	- - -
Total surface-water	1,533,000	- - -
Ground water only	337,000	- - -
Total surface- and ground-water sources	1,870,000	- - -
Joint-Yield Summary		
Combined surface-water sources (Lakes Houston, Conroe, Livingston)	1,660,000	127,000
Surface water plus ground water	2,220,000	350,000
Brazos River flow-skimming facility	120,000 to 180,000 (50–75 percent of capacity of 240,000 acre-ft/yr or 20,000 acre-ft/month)	

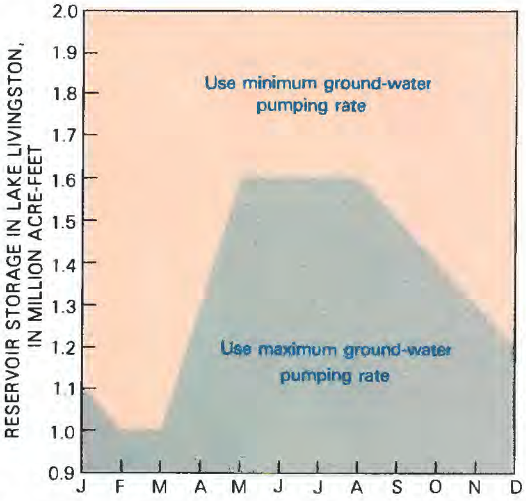


Figure 82. Rule curve for pumping ground water in the Houston, Tex., area based on storage in Lake Livingston. If reservoir storage, for example, fell below 1.6 million acre-feet in June, then the maximum ground-water pumping rate would be used.

The simulation set the aquifer pumping rate on the basis of storage in Lake Livingston. Simulated storage in Lake Livingston was tested against a target storage for a certain month (fig. 82). If simulated storage fell below the curve, ground-water pumping was increased from minimum to maximum. When storage rose above the curve, ground-water pumping was again set to the minimum level. The rule curve is set to balance (a) the desire to minimize pumping during noncritical droughts, and (b) the need to start pumping early enough during critical droughts to maximize total pumping during the drought without exceeding the maximum monthly pumping rate.

Inclusion of ground water in the joint operating scheme raised the total system yield to 2,220,000 acre-ft/yr, compared to 1,870,000 acre-ft/yr for independent operations—an increase of over 18 percent. Viewed another way, including ground water in independent operations increased total yield by 337,000 acre-ft/yr, but including ground water in joint operations increased total yield by 560,000 acre-ft/yr. This represents an increase of more than 60 percent for the effective yield of the ground-water component.

Average ground water pumping over the 39-year record is only 245,000 acre-feet (less than three-quarters of the independent yield). But the rule curve is successful in pumping at the maximum rate of 600,000 acre-ft/yr during nearly the entire critical period without violating the constraint that average pumping not exceed the safe yield for any consecutive 10-year period.

Finally, provision for augmenting the Houston area water supply by withdrawals from the Brazos River at times when flows are above minimum flows (flow skimming) was added to the simulation model. Historical flows for the Brazos River at Richmond, Tex., were used as the basis for the simulation. These flows do not account for planned depletions, however. In a coarse attempt to account for such depletions, minimum flows were set before pumping could occur. These minimum flows varied month by month as follows: 25,000 acre-ft/month for October to April and 75,000 acre-ft/month for May to September. A maximum pumping rate also was arbitrarily set at 20,000 acre-ft/month (240,000 acre-ft/yr) to obtain the simulation results described below.

The operating rule for flow skimming was quite simple. Water was pumped (up to the maximum rate) whenever it was available in the river (flows in excess of minimums), unless inflows to the reservoirs were sufficient to (a) meet all demands with minimum ground-water pumping and (b) fill all the reservoirs.

The availability of a 20,000 acre-ft/month flow-skimming facility, operated as described, could increase the system yield by 180,000 acre-ft/yr, some 75 percent of the facility size. Because the reservoirs are often full, and because there are periods during which excess flows are not available in the Brazos River, average pumping over the period was only 108,000 acre-ft/yr. Increasing the minimum flows to 75,000 acre-ft/month year round decreased the additional yield to the system by about 50 percent of the capacity of the facility (120,000 acre-ft/yr). Whereas the ground-water pumping rule attempts to use reservoir storage in order to leave water in the ground for later use when reservoir inflows are small, pumping from the Brazos River makes additional water available by reducing the draft on the reservoirs, thus, making water available when flows in the Brazos River are too low for pumping.

Because of the approximate nature of the assumptions on flows, demands, and particularly on ground-water yields, this exploratory analysis does not provide firm estimates of the yield, or increases in yield, that might be had from joint operations of supplies available to the San Jacinto basin near Houston, Tex. It does, however, suggest that relatively large increases in yields are possible to meet the future water demands of the region. Joint system operations should be a major concern in the planning, design, construction, and operation of all future water-supply facilities in the San Jacinto River basin.

The operating rules presented herein must be modified before they can be implemented. In particular, the constraints imposed by local demands and existing facilities must be taken into account, and the operation of water-supply facilities must be simulated in greater detail than presented above, especially with regard to the response of the aquifer to pumping.

The potential for increasing yield from the joint operation of water-supply facilities far exceeds the potential for increasing the yield by adding more surface-water storage in the San Jacinto River basin. Because the length of the critical period is 4 years and because Lake Livingston will continue to dominate the system, 4,000 acre-ft of additional storage will provide less than 1,000 acre-ft of additional yield. If evaporation losses are considered, the ratio of storage to yield is likely to be closer to 5 to 1. The same is true for storage in the Trinity River basin above Lake Livingston.

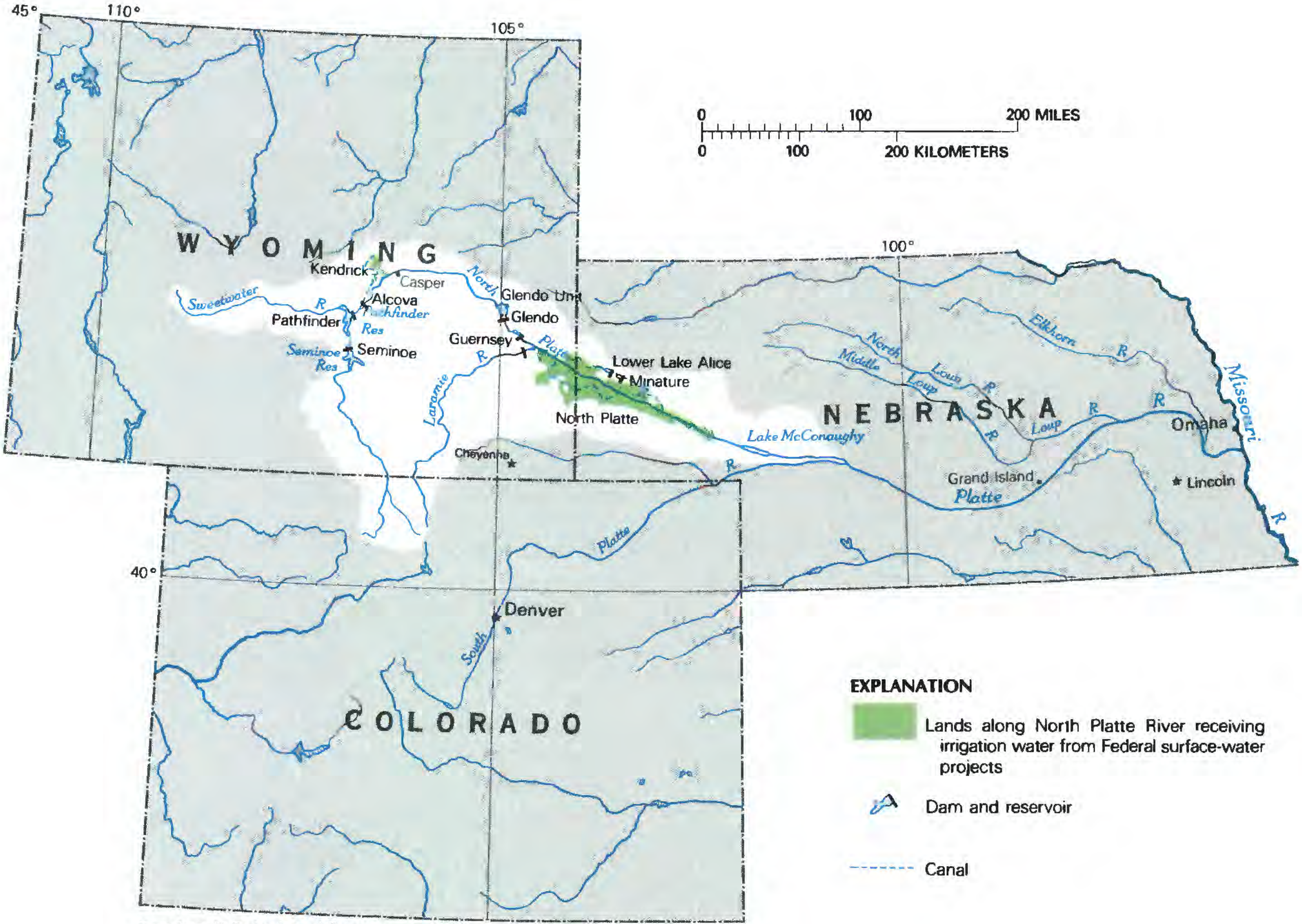
It should not be concluded, however, that additional storage in the San Jacinto River basin is unnecessary. A reservoir in the basin might serve as a reregulating lake for pumpage from the Brazos River or as a source for a new treatment plant located at an elevation where the plant could serve much of the area by gravity, a decided advantage. Flood-control benefits also may accrue. The water-supply benefits from new projects in the San Jacinto River basin will depend heavily on how such projects can improve system operations rather than on their independent yield.

In conclusion, the water-supply facilities already available in the San Jacinto basin can reliably supply substantially more than the sum of their independent safe yields. This supply can only be realized, however, if the necessary conveyance, treatment, and distribution facilities are planned and designed to take full advantage of the potential for joint operation.

NORTH PLATTE RIVER BASIN, WYOMING

WATER-SUPPLY FACILITIES, IRRIGATION DEMANDS, AND WATER RIGHTS

The North Platte River rises in north-central Colorado and flows nearly due north into Wyoming. There it turns to the east-southeast and flows to its confluence with the South Platte River, west of Grand Island, Nebr. The U.S. Bureau of Reclamation has constructed and operates three major reservoirs—



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

Figure 83. Major water-supply facilities in the North Platte River basin. (Source: Modified from Hitt, 1985.)

Seminoe, Pathfinder, and Glendo—and several smaller reservoirs on the North Platte in Wyoming for purposes of irrigation, flood control, and power generation. Lands irrigated by water from the reservoirs are mainly in Wyoming and Nebraska downstream of Guernsey Reservoir. Additional irrigated lands lie near Casper, Wyo. (fig. 83).

Seminoe Reservoir is the major feature of the U.S. Bureau of Reclamation Kendrick project and is the farthest upstream of the three reservoirs. Completed in the mid-1950's, its conservation pool is 985,000 acre-ft. Authorized purposes are irrigation and power generation.

Pathfinder Reservoir, which is one of the oldest of the Bureau of Reclamation facilities, is the major feature of the Bureau's North Platte Project. It has a conservation pool of 986,000 acre-ft and, like Seminoe, is authorized for irrigation and power generation. Inflow in the reach between the Seminoe and Pathfinder Reservoirs primarily is from the flow of the Sweetwater River.

Glendo Reservoir is the major feature of the Bureau's Glendo Unit of the Pick-Sloan Missouri River Basin Project. It is the only reservoir on the North Platte River in Wyoming that has dedicated flood-control storage (220,000 acre-ft). Glendo's conservation storage is 514,000 acre-ft, but use of that water is limited by the U.S. Supreme Court (1952) adjudication of the waters of the North Platte between Colorado, Wyoming, and Nebraska. Flood control, irrigation, and hydroelectric power generation are authorized as project purposes.

About 95 percent of the irrigation water supplied by the North Platte River in Wyoming is used by the owners of storage in the Bureau of Reclamation projects. This amounts to an average of 1,120,000 acre-ft/yr for irrigation. In addition, some 50,000 acre-ft/yr of irrigation water is used by irrigators with rights senior to any of the Bureau's project rights. Their water withdrawals are reflected in the hydrologic records used in the simulation of various operating proposals.

Each irrigator with storage rights in Bureau projects also has direct-flow rights to water from the North Platte River. Seven water rights explicitly were considered in this analysis; in order of priority these rights were–

- Direct-flow irrigation rights for North Platte Project irrigators.
- Storage rights in Pathfinder Reservoir for North Platte Project irrigators.
- Storage rights in Guernsey Reservoir for North Platte Project irrigators.
- Direct-flow irrigation rights for Kendrick Project irrigators.
- Storage rights in Seminoe Reservoir for Kendrick Project irrigators.
- Direct-flow irrigation rights for Glendo Unit irrigators.
- Storage rights in Glendo Reservoir for Glendo Unit irrigators.

In addition, 46,000 acre-ft are diverted from Guernsey Reservoir each March and April to refill Lakes Alice and Minitare.

ANALYSIS OF OPERATING RULES

A monthly simulation model was used to establish the performance of the reservoir system if operated strictly in accordance with ownership priorities and to meet existing water rights. The results were then compared with simulations based on operating rules that attempted to increase reservoir yield and decrease periods of water shortages.

The details of the simulation, and simplifying assumptions made about reservoir system operation, are presented in recent reports to the U.S. Bureau of Reclamation (Sheer, 1985a,b). Obviously, the multiple purposes authorized for the reservoirs and the system of water rights add considerable complexity to the simulation. As with the study of water supplies in the San Jacinto River basin near Houston, Tex., this exploratory analysis does not provide firm estimates of the increases in yield or decreases in shortages that might be derived from implementation of joint operating rules for the existing water-supply facilities in the North Platte River basin. The results, however, do suggest that there are considerable benefits to be derived from further study of joint operations.

Water rights define quantity of water delivered, and the seniority of the right defines the reliability of water delivery. Rights define an operating rule that is the basis of the ownership simulations. Water demands in the ownership simulation averaged 1,154,000 acre-ft/yr while shortages averaged 38,100 acre-ft/yr.

A different operating rule based on the physical characteristics of the system was incorporated into a second simulation of the North Platte River system. Its basic premise is that in order to increase yield, water should be stored as far upstream as possible, and that to have maximum use of existing storage, all water should be treated uniformly and allocated to meet any and all demands.

Simulation of joint-operation of water-supply facilities significantly reduced total shortages from an average of 38,100 acre-ft/yr to 12,300 acre-ft/yr. Demands in both runs averaged 1,154,000 acre-ft/yr. The joint-operation simulation demonstrates that the reliability of an existing right can be substantially increased. Doing so, however, involves the difficult task of institutionalizing a substantial change in operating policy.

Other runs of the joint-operation simulation were made that met increased water demands without increasing shortages over those experienced in the ownership simulation. Demands of 1,240,000 acre-ft/yr, a 7.5 percent increase, produced average shortages of 37,000 acre-ft/yr in the joint-operation simulation, an increase in yield of over 80,000 acre-ft/yr. This demonstrates that additional quantities of water could be allocated without affecting the reliability of existing rights. Once again, doing so involves the difficult task of institutionalizing a substantial change in operating policy.

The simple rules in the joint-operation simulation are not meant to be fully practical operating rules. Before they can be implemented, they must be modified to account for daily operations, availability of flow forecasts, and impacts on the multiple objectives of the water-resources projects in the basin. Distribution of shortages, hydropower, flood control, and recreation may be positively or negatively influenced by changing operating rules. There is reason to believe, however, that these impacts will be small.

SUMMARY

The three studies discussed in this article show that substantial increases in water yields may be obtained by operating existing facilities as systems rather than as independent projects. The Potomac River example shows that the implementation of new operating procedures requires substantial and lengthy negotiations, whereas, the initial analysis of the water-supply system requires a relatively small amount of work. However, a substantial shift in perspective is needed to recognize opportunities to improve system operations.

Improving the management of existing projects should be seen as a complement to, rather than a substitute for, building new projects. New projects may be built to provide water in new locations not served by existing projects. However, the benefits attributable to new projects may be greatly enhanced by operating them in full coordination with existing projects. For example, the effective yield of Bloomington Lake on the Potomac River almost doubled when it was operated to augment supplies in downstream reservoirs. In contrast, proposed flow skimming from the Brazos River near Houston, Tex., has no safe yield at all unless it is considered in the context of the larger supply system.

Improved water-resources management cannot supply all our future water-supply demands. It can, however, make a substantial contribution. Expenditures on improved management probably will be the most cost-effective water-supply investment possible over the next decade.

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VOLUNTARY TRANSFERS OF WATER IN THE WEST

By Richard W. Wahl[1] and Frank H. Osterhoudt[1]

INTRODUCTION

Competition for water increases with population and economic growth, and it is further influenced by technological changes, by preferences of water users, and by governmental policies. Because of the increasing demands for water, institutional and management issues related to the allocation of available water supplies are a concern, in varying degrees, throughout the Nation. One method of allocating water to meet increasing demands is the transfer of water or water rights (U.S. Geological Survey, 1984, p. 3, 72–73). Several representative examples of such transfers are presented in this article. As used here, the terms "water transaction" and "water exchanges" mean a change in the location of, or in the type of, water use that is undertaken voluntarily for the mutual benefit of the involved parties.

The "prior appropriation" system of water law, which predominates in the Western States, has proved to be the most conducive to voluntary exchanges of water. In the Eastern States, most of which use the "riparian" system, the possibilities for exchanges in water are just emerging. Thus, the case studies presented here are from the Western States where most transactions have taken place. These transactions, which have occurred in a variety of situations, are identified as follows: isolated, negotiated transactions; short-term exchanges to alleviate drought; transfers to and withdrawals from organized water banks; and transactions involving established water markets. Examples of each type of transaction are described below. The general location of the case studies is shown in figure 84.

ISOLATED, NEGOTIATED TRANSACTIONS

When the difference in the value of water to two water users is large, an "isolated, negotiated transaction" may occur. As used here, the term refers to the transfer of water as worked out by two or more major water users, even though no established, organized market exists. Such transactions commonly involve a change in water use. In each case discussed, the substantial difference in the value of water to the parties involved made it worth the time and effort to investigate the procedural requirements for a transfer (requirements that may be far from standardized) and to undertake what often are protracted negotiations. Also, because of the costliness of the negotiation process, isolated, negotiated transactions usually involve fairly large amounts of water. In addition to the parties exchanging the water, other parties may be involved, such as the U.S. Bureau of Reclamation, which has constructed major water-supply facilities in the Western States, or State agencies that regulate water use.

The representative cases of isolated, negotiated transactions discussed in this article are an exchange between the Emery Water Conservancy District of Utah and the Utah Power and Light Company, the purchase of water by the Intermountain Power Project in Utah from several water-rights holders, a transfer between the Casper–Alcova Irrigation District and the city of Casper, Wyo., and the ongoing negotiations regarding a transfer of water between the Imperial Irrigation District and urban water wholesalers on the southern California coast.

SHORT-TERM WATER EXCHANGES TO ALLEVIATE DROUGHT

Drought can be an impetus for short-term water exchanges, because it can abruptly force an examination of water-conservation measures and the identification of water uses that might be temporarily foregone with the least economic loss. Voluntary market transactions are one way of allocating water to areas of greatest need during a drought. For example, during the 1976–77 drought in the Western States, a Federal water bank operated in California to facilitate transfers within the agricultural sector. The bank, which in effect acted as a water broker, was authorized to spend funds to make purchases from those willing to reduce their own use temporarily. It then resold this water to irrigators who wanted to protect long-term investments in perennial crops, such as orchards. Without the bank, some isolated, negotiated water transfers undoubtedly would have occurred. However, the bank facilitated exchanges because it had funds to purchase water, and it also provided a central location where trades between potential purchasers and sellers could be consummated. In brief, the bank made short-term water exchanges easier than isolated, negotiated transactions.

ORGANIZED WATER BANKS AND EXCHANGES

During nondrought conditions, some formally organized water banks and exchange pools have developed on a more permanent basis. The term "water banking" is used loosely to cover a variety of organized forms of water trading. As the name implies, a water bank involves a clearinghouse between the seller and the buyer of water, where the seller can advertise the quantity of water he has for sale. The rules governing water-banking operations differ among the case studies. In California, the price paid for water in the Arvin–Edison Water Storage District exchange pool is limited to the district's water

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[1] U.S. Department of the Interior, Office of Policy Analysis.

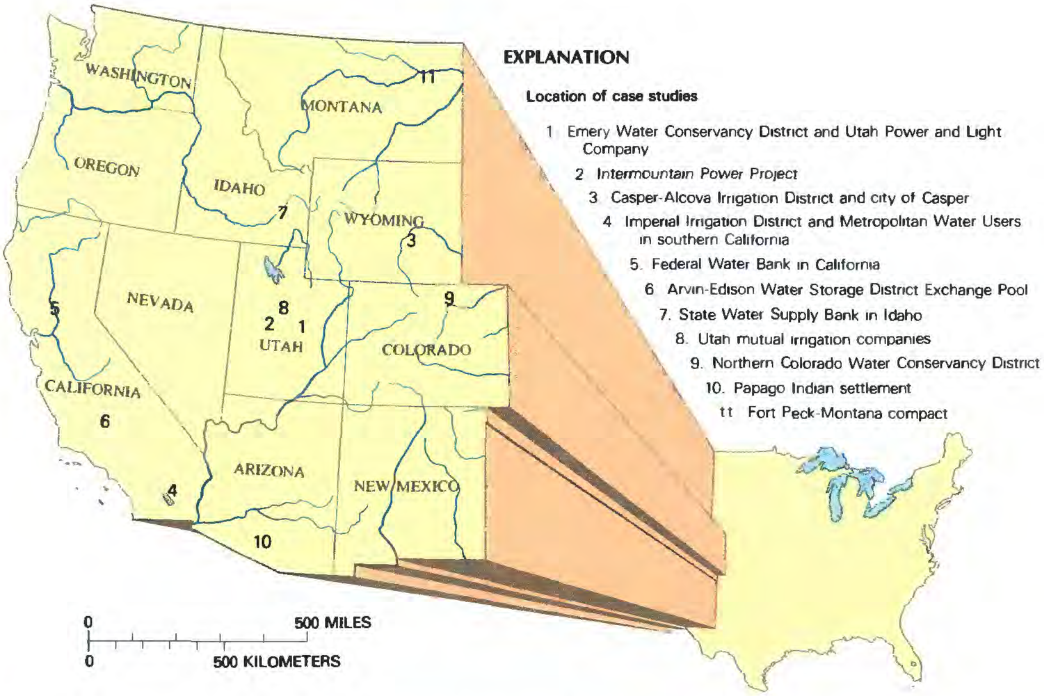

Figure 84. Location of case studies of voluntary transfers of water.

rate. In the water bank that operates on the upper Snake River in Idaho, a uniform price for the sale of water is established each year. Irrigators who offer to sell specific quantities of water through the bank before the start of the irrigation season share proportionally in the proceeds from bank water sales.

ESTABLISHED WATER MARKETS

Established water markets, where prices are determined by the market rather than by a managing entity, have developed in some locations. In one case study involving mutual irrigation companies in Utah, individual irrigators own a share of the district's water supply—each share can be leased or sold. The Northern Colorado Water Conservancy District, which encompasses a large agricultural area and several towns, imports water across the Continental Divide from the Colorado River basin. The district owns the rights to the return flows, a factor that has facilitated trades among agricultural interests and between agricultural interests and municipalities. Trading is not organized through a banking operation but occurs regularly, sometimes with the assistance of private water brokers.

In established water markets, as well as in water banks, the large number of water sales and leases is made possible because little effort is required of potential buyers and sellers to complete a transaction, compared to the comparatively large effort required to complete an isolated, negotiated transaction. Because of the relative ease of entering an established, organized market, it is not uncommon for the exchanges to involve small amounts of water and relatively small difference in the value of water to buyers and sellers. Several factors facilitate transactions, depending on the particular market:

- Clear property rights to water increase the incentive to seek out mutually beneficial transactions.
- Well-established rules governing trades reduce the uncertainty associated with the procedures for completing an exchange and increase the ability to anticipate the responses by water officials that regulate exchanges. Such rules can eliminate the need to negotiate a complex set of conditions for each exchange.
- Public knowledge of buying and selling prices in a water bank or established market also facilitates transactions by providing important information about the value of water to potential buyers and sellers.

CASE STUDIES

WATER TRANSACTIONS BETWEEN THE EMERY WATER CONSERVANCY DISTRICT AND THE UTAH POWER AND LIGHT COMPANY

In 1972, the Utah Power and Light Company obtained the equivalent of a 40-year lease on 6,000 acre-ft (acre-feet) of water from the U.S. Bureau of Reclamation's Emery County Project. This water, formerly used for irrigation, has since been used in a coal-fired thermoelectric powerplant, principally for cooling purposes. The plant lies in Huntington Canyon, about 150 miles southeast of Salt Lake City, Utah (fig. 84, site 1; fig. 85).

The transaction entailed a cooperative effort by officials of several organizations, including individual water-rights holders, the power company, two irrigation companies, a water-conservancy district, and the U.S. Bureau of Reclamation. The water transfer also involved a change in water use, which complicated the transfer. Before contacting the Bureau of Reclamation, the Utah Power and Light Company had purchased primary water rights from several individual landowners who were shareholders in irrigation companies operating within the Emery Water Conservancy District. The original contract (1962) between the United States (via the U.S. Bureau of Reclamation) and the Conservancy District covered use of water for irrigation only. However, the Emery County Project of the Bureau of Reclamation is a unit of the Colorado River Storage Project, which had been established by the Congress for irrigation and for broader purposes. A 1972 amendatory contract between the Conservancy District and the United States, which holds the storage rights, expanded project purposes to include water for municipal and industrial uses. Two irrigation companies in the Conservancy District contractually agreed to reduce their allotments of project water in order to enable the Conservancy District to allocate project water to the power company. In turn, the power company agreed to assume payment of the irrigation companies' corresponding share of project costs.

The shift of water from irrigation use to industrial use resulted in a reduction in irrigated land. The U.S. Bureau of Reclamation had designated 18,755 acres of land in the district as irrigable. This acreage was reduced by 4,604 acres as a result of the water transaction, and since 1976, the actual acreage irrigated by project water has decreased by a like amount. More than 90 percent of the irrigated acreage produces hay and grain, which support the local livestock industry. The local economy also depends heavily on coal production, the coal-fired thermoelectric plant in the district, and associated economic activity. An environmental impact statement (EIS) on the proposed powerplant discussed the water transfer. Public comments on the EIS generally indicated no concern over the loss of agricultural production. Rather, most comments supported construction of the power company's facilities.

Both the private sector and the Federal Government benefited from this transaction, as well as the trading parties. The United States received $120,000 a year from the power company for the 6,000 acre-ft of water transferred—$20.00 per acre-ft/yr (acre-feet per year)—plus a proportionate share of the annual operation and maintenance costs. Although the 1972 amendatory contract reduced the irrigation repayment obligation from $2,935,000 to $2,433,600, it added $4,440,000 for industrial water—a net increase in the total repayment obligation of $3,938,600. The revenues to the United States have increased because, under reclamation law, municipal and industrial users must repay capital costs with interest, whereas irrigation repayments bear no interest charges. The payment made by the Utah Power and Light Company to the other parties involved is not known. At the end of the 40-year period, the contract may be renegotiated with the Bureau of Reclamation. As of 1985, Utah Power and Light was purchasing options to buy land in order to acquire additional water for increasing its electric-generation capacity (Deborah Linke, U.S. Bureau of Reclamation, oral commun., 1985).

PURCHASE OF WATER BY THE INTERMOUNTAIN POWER PROJECT

In 1980, the Intermountain Power Project (IPP) agreed to pay $1,750 per acre-ft for permanent water rights to 45,000 acre-ft of water near Delta, Utah, about 125 miles southwest of Salt Lake City (fig. 84, site 2). The water—about 39,500 acre-ft of surface-water rights from five irrigation companies, together with about 5,500 acre-ft of ground-water rights from 20 water-rights holders—supports a coal-fired thermoelectric powerplant. The project, planned at 3,000 megawatts, was to have been the largest coal-fired plant in the United States. However, because of a reduction in electric power demand forecasts, the four units were reduced to two with a total capacity of 1,500 megawatts, and the plant is expected to use only 18,500 acre-ft of water annually; the remaining water is available for lease. Unit 1 is scheduled to begin power production in July 1986 and Unit 2 in July 1987 (Manuel F. Perez, Intermountain Power Project, oral commun., 1985).

Previous experience had acquainted the power companies participating in IPP with the water-purchase process. When the present site was selected, the quantity of available water was recognized as the key siting factor. There was no surplus water in the area, and it appeared that sufficient water could be obtained only by transfers of water from agricultural uses. Those responsible for the water acquisition were hesitant to act, but when local farmers discovered IPP's preferred site and its need for water, they took the initiative in anticipation of the high income that water sales might bring. In response, the water buyers established a set of rules to govern subsequent transactions (Clark, 1980, p. 102):

> (1) IPP will negotiate only with established water entities or their representatives; we will not go behind anyone's back. (2) The existing water users will all have equal opportunities to sell their water rights to IPP. (3) Impacts on nonsellers will be minimized. If you don't want to sell, you don't have to and we will see that you are protected. (4) Acquisition will be conducted so as to minimize the effect on agricultural production. (5) IPP will endeavor not to become a water broker because of excess water accumulated in high water years.

These rules were published in the local newspaper and stated in all water purchase contracts. Following these rules, all negotiations were conducted with interested irrigators as a group—not separately. However, inasmuch as water rights were held by individuals, contracts were made with individuals and the transactions were covered by warranty deeds.

The initial sale offer of the irrigation companies to IPP was $3,400 per acre-ft for permanent water rights, and IPP responded with an offer of $550 per acre-ft. The price at which the transaction finally took place—$1,750 per acre-ft—was about 2 percent of the original estimated cost of the powerplant (Abbey and Lucero, 1980, p. 8) and is equivalent to an annual cost of $175 per acre-ft assuming a discount rate of 10 percent.

TRANSACTION BETWEEN THE CASPER-ALCOVA IRRIGATION DISTRICT AND THE CITY OF CASPER, WYO.

Increasing urban demands for water in the city of Casper, Wyo. (fig. 84, site 3), led to a mutually beneficial transaction with the Casper-Alcova Irrigation District. Under the agreement, the city is paying for rehabilitation and lining of parts of the district's 59-mile-long canal and its 190-mile-long lateral systems in order to reduce seepage. The reduction in canal seepage reduces water loss and therefore the quantity of water diverted for agricultural use, while maintaining the same quantity of water delivered to crops. This arrangement has provided Casper with an additional water supply of 7,000 acre-ft/yr from the North Platte River. The United States, in whose reservoirs the water is stored, received repayment in full for the debt outstanding on its facilities. Inasmuch as only the amount of conserved water is transferred, the reassignment is not considered to be a change of use under Wyoming law. Rather, a "secondary supply permit" was used to reassign storage rights from the U.S. Bureau of Reclamation's Seminoe and Alcova Reservoirs, which are the sources of supply for the irrigation district. During the Federal environmental impact review process, there was some concern that the proposed rehabilitation and improvement project would eliminate the wetlands that existed due to canal seepage. As a result of public concern, four of the larger seepage areas (out of some 100) were maintained.

NEGOTIATIONS REGARDING A TRANSFER OF WATER BETWEEN THE IMPERIAL IRRIGATION DISTRICT AND METROPOLITAN WATER USERS IN SOUTHERN CALIFORNIA

A proposal similar in effect to the Casper-Alcova arrangement presently (1986) is under negotiation in southern California (fig. 84, site 4). The Metropolitan Water District of Southern California (MWD), which supplies water to 27 member agencies on the Pacific coastal plain, has held discussions with the Imperial Irrigation District (IID) about funding conservation improvements in exchange for receiving the conserved water. (See figure 86.)

The IID diverts about 2.9 million acre-ft/yr of water from the Colorado River (nearly one-fifth of the average flow) through the All-American Canal (a U.S. Bureau of Reclamation project) and 1,627 miles of main canals and laterals to irrigate 450,000 acres of farmland. In 1980, one of the district's farmers, whose lands were being threatened by the increasing levels of the Salton Sea, filed a complaint with the State alleging that wasteful use of water by the district was a contributing factor to the flooding. In accordance with State law, the California Department of Water Resources investigated and estimated that as much as 437,000 acre-ft of water could be conserved in IID by various means, including canal lining, spill-interceptor canals, tailwater recovery systems, system automation, an increased number of regulatory reservoirs, and a more flexible system of deliveries. The annual costs of these various measures were estimated to range from $8 to $115 per acre-ft of water conserved (California Department of Water Resources, 1981; and U.S. Bureau of Reclamation, 1983). In June 1984, the State Water Resources Control Board used the California Department of Water Resources report in reaching its decision that IID's use of water was

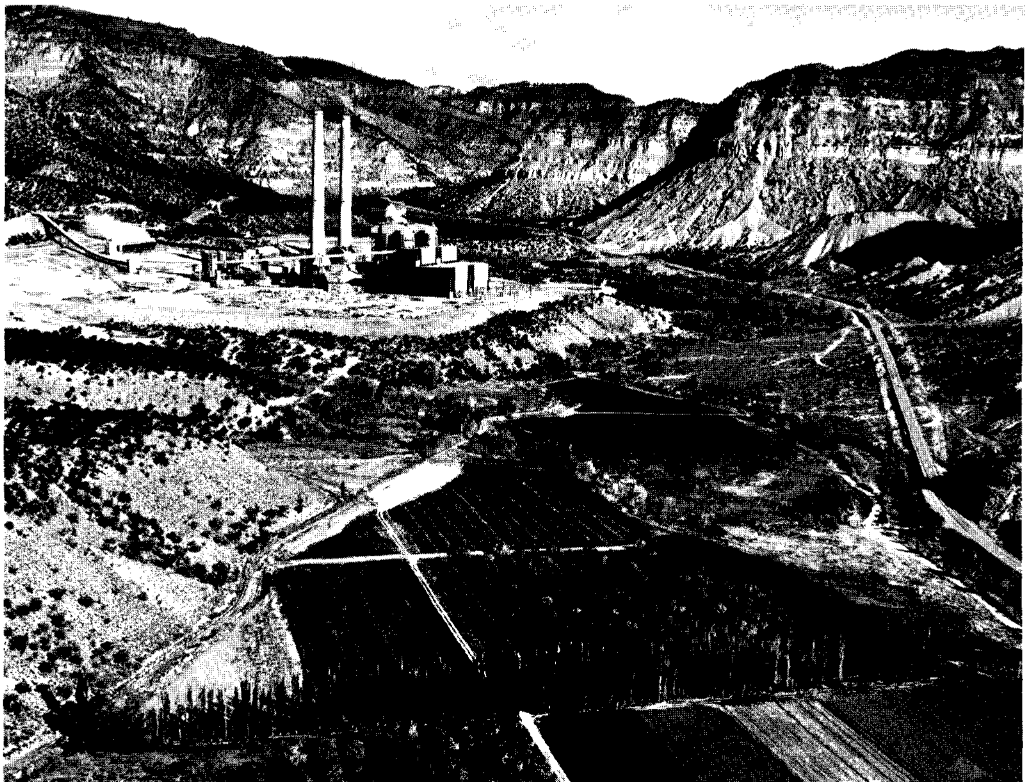

Figure 85. Huntington Unit of the Utah Power and Light Company. Water formerly used for irrigation of lands similar to those in the foreground has been transferred for use by the coal-fired thermoelectric powerplant. Most of the water is used for evaporative cooling; note the water vapor rising from the cooling tower. (Photograph courtesy of Utah Power & Light Co., May 1978.)

"unreasonable" and that conservation measures should be implemented.

The MWD is interested in the water conserved by IID because MWD has been taking Colorado River water allocated to, but unused by, Arizona. Under the set of priorities governing use of the Colorado River, MWD began losing these deliveries when the Central Arizona Project began operation on November 15, 1985. A decrease in agricultural diversions to IID from the river via the All-American Canal would allow a corresponding increase in MWD diversions upstream at the Colorado River Aqueduct.

Financing the conservation measures in IID would appear to provide water to MWD at less cost than would several other prospective alternatives available to MWD (Stavins and Willey, 1983; Wahl and Davis, 1986). In 1985, IID held discussions with an engineering firm that may plan the conservation improvements and arrange for sale of the water to MWD or to other metropolitan water users. The details of any transfer are yet to be worked out. In this case, however, the successful completion of a water transaction would appear to be facilitated by the following factors:

- Irrigation return flows are contributing to increased costs to some farmers.
- The State Water Resources Control Board's order to IID would require the financing of certain improvements to increase water conservation.
- A high value is placed on the water by potential urban wholesalers such as MWD.
- The IID holds perfected rights to Colorado River deliveries, and the State legislation encourages water transfers.
- Water conveyance facilities of adequate capacity are already in place.

FEDERAL WATER BANK IN CALIFORNIA DURING THE 1976-77 DROUGHT

Drought can intensify interest in water exchange. Water users who would suffer the greatest damage as a result of a water shortage may be able to purchase water from those willing to reduce water use temporarily for sufficient compensation. In California, 1976 was the fourth-driest year in more than 100 years, and 1977 was the driest year of record. Statewide precipitation was 65 percent of normal in 1976 and 45 percent of normal in 1977. Runoff to rivers and streams during those 2 years amounted to 47 percent and 27 percent of normal, respectively.

The 1976-77 drought presented a challenge to the capability of the major water systems serving California to distribute limited water supplies in a manner that would minimize the adverse effects of water scarcity (U.S. Bureau of Reclamation, 1978; California Department of Water Resources, 1978). The most severe water shortages were experienced in the northern two-thirds of the State (fig. 84, site 5). Much of this area lies in the Central Valley Basin of California, which is served by the U.S. Bureau of Reclamation's Central Valley Project and by the California State Water Project. The Federal Central Valley Project is a multipurpose, integrated water-management system comprising 16 storage dams, 3 diversion dams, and about 600 miles of canals and appurtenant works. It was through the facilities of the Central Valley Project that a Federal water-banking program operated in California to facilitate the transfer of scarce water supplies from willing sellers to willing buyers.

Following the severe drought of 1976 and the worsening situation developing for 1977, the Congress enacted Public Law 96-18 on April 7, 1977, which authorized the operation of Federal water banks during the drought. To implement the law, rules and regulations were published in the Federal Register on April 16, 1977. The Secretary of the Interior was to to assist willing sellers in transferring water to willing irrigation-water buyers. The program was to be carried out so that no "undue benefit or profit" would accrue to water sellers. Toward that objective, the Secretary was directed to establish a price paid by the buyer that would recover all expenditures in acquiring the water, and the price paid to sellers was allowed to be high enough to cover not only the costs of water but also the estimated net income usually derived from the water. The rules also established allocation of the following priorities among purchasers: preservation of orchards and perennial crops, irrigation of support crops for dairy and beef-cattle herds and other breeding stock, and irrigation of all other crops. Funds made available through Public Law 96-18 provided for interest-free loans to irrigation purchasers for repayment over a period not to exceed 5 years.

The bank that operated in California during the 1976-77 drought was established under this legislative authority. The prices for the water exchanged in the bank ranged from $15 to about $85 per acre-ft (table 17). Various methods were used to establish the price paid for water. For example, the price of $25 per acre-ft paid to Reclamation District No. 108 represented the estimated cost to the district of pumping ground water in lieu of its usual diversions from the Sacramento River. The price of $70 per acre-ft for Pleasant Grove-Verona Mutual Water Company's supply was intended to compensate farmers for foregoing rice production (valued at $60 per acre-ft), as well as to compensate those landowners who would lease the associated tailwater (valued at $10 per acre-ft). The price of $85 per acre-ft paid to the State of California was based on State Water Project rates for operation, maintenance, and capital repayment, plus the power costs associated with compensatory water diversions from the Colorado River to southern California.

The Federal water bank spent a total of $2,251,714 to purchase 46,438 acre-ft both from the State Water Project and from the U.S. Bureau of Reclamation's Central Valley Project water contractors (table 17). Of the 46,438 acre-ft purchased by the Federal water bank, 42,544 acre-ft was sold (table 18). The balance of 3,894 acre-ft represented deductions for return-flow losses and conveyance losses. The average price for water paid by purchasers was about $61 per acre-ft, with prices ranging from about $55 to about $142 per acre-ft. The high end of the price range reflected significant conveyance and pumping costs necessary to get the water to the purchaser.

The U.S. Bureau of Reclamation, which operated the water bank, also provided loans totaling

Table 17. Sources of water sold to the Federal water bank in California during the 1976-77 drought

[Source: U.S. Bureau of Reclamation records]

Seller	Water sales		
	Amount (acre-feet)	Cost	
		Total	Per acre-foot
California Department of Water Resources	8,185	$691,729	$84.51
Chaplin-Lewis-Lewis	1,279	44,765	35.00
Pelger Mutual Water Company	4,425	110,625	25.00
Pleasant Grove–Verona Mutual Water Company	15,752	1,102,640	70.00
Natomas Central Mutual Water Company	6,000	90,000	15.00
Reclamation District No. 108	5,000	125,000	25.00
Sacramento River Water Contractors' Association	5,797	86,955	15.00
Total	46,438	$2,251,714	

$2,444,000 to water districts, so that they could purchase water supplies directly from other entities. This latter program resulted in the transfer of an additional 107,497 acre-ft outside of the federally operated water bank. In addition, the State of California facilitated a series of water exchanges among various entities during the drought.

ARVIN-EDISON DISTRICT EXCHANGE POOL

Water "banking" or exchange operations also have developed under nondrought conditions to facilitate more efficient use of available supplies. The Arvin–Edison Water Storage District, located on the eastern side of the San Joaquin Valley in California (fig. 84, site 6), operates a "water-exchange pool" among its contractors (Davis, 1985). The pool is activated each year with offers and requests for water received by December 15. If there is a surplus of offers to sell water, then the pool is open to additional requests for water until February 1, after which time any surplus is made available on a first-come, first-served basis. On the other hand, if requests to purchase water exceed offers, then the exchange pool remains open until February 1 for additional water to be offered for sale. If requests still exceed offers by that date, then the available water is prorated among the requesters, as shown in table 19. As table 19 indicates, the water-deficient years of 1974 and 1977 showed the largest excess of demands over offers. Exchanges in the pool have been as much as 7.6 percent of the district's water supply of 128,300 acre-ft. Water purchasers pay for their allocation from the exchange pool at the district's normal water rate. Those offering water for sale receive refunds at the end of the year for water distributed by the pool. Water exchanges are limited to the boundaries of the district.

Water deliveries also can be exchanged after the District's water year begins on March 1. (Refer to the last column of table 19.) This is done by submitting written notice to the district requesting or offering water. The dispatcher's office serves as the clearinghouse for such "posted" transfers. In addition, water exchanges are worked out between individuals without the aid of the posting process, and the district subsequently is notified in writing. It is not surprising that in-season transfers are sometimes more heavily used than pre-season exchanges because of the risk involved in forecasting water needs several months in advance of the growing season.

STATE WATER SUPPLY BANK IN IDAHO

Idaho's Water Supply Bank was established in 1980 to facilitate the leasing or renting of water (Idaho Code, Section 42-1761 to 1765). In 1984, the bank leased 276,167 acre-ft on the upper Snake River at $2.50 per acre-ft to 13 lessees (table 20). Of this amount, the Idaho Power Company leased 275,000 acre-ft to control the timing of water releases for generation of hydroelectric power at its facilities.

The Water Supply Bank has legislative authority to operate statewide with either short-term or long-term leases, although not with permanent sales of water. As presently operated, however, the bank is confined to Water District No. 1 on the upper Snake River above Milner Dam (fig. 84, site 7), and leases are limited to 1-year duration. All the water in the water bank is stored in U.S. Bureau of Reclamation facilities—principally the American Falls, Jackson Lake, and Palisades Reservoirs (fig. 87). Although the Water Supply Bank in its present form is relatively new, it has its roots in water rentals that reach back into the 1930's, and the bank is still occasionally referred to as the "rental pool."

The State's Water Supply Bank functions under the jurisdiction of the Idaho Water Resources Board. Jurisdictional authority for the upper Snake water-supply bank has been delegated to a local committee called the "Committee of Nine." The Committee is formed of representatives from various jurisdictions within Water District No. 1, and, since 1919, the Committee has acted as advisor to the water master who operates the water bank. The water master is elected by the water users of the district and works closely with the U.S. Bureau of Reclamation's Minidoka Project superintendent. The Bureau currently requires the price set by the Committee of Nine to be based on space-owner costs and also requires leases to be restricted to a 1-year duration. The Committee of Nine has established the following priorities for leasing water: existing canal companies that own storage space, agricultural users that traditionally have used rental pool water, new agricultural users, and any other user (such as a power company). Water transfers are facilitated by the fact that one water user cannot gain rights to the return flows from stored water used by another water user and by the fact that the bank deals only with stored water (R. Carlson, Water Master, Idaho Water District No. 1, oral commun., 1985).

Water is made available to the water bank by individuals, corporations, irrigation companies, irrigation districts, and cities. In order to encourage early commitments of water to the bank, water made available before July 1 is sold first, and the contributors share proportionally in the revenues from the sales. Water made available after July 1 is sold on a first-come, first-served basis, and the water owners are reimbursed in a like manner.

The incentive to place water in the bank is that water users can recover the cost of some of the water they do not wish to use that year. Each year, the price for water from the bank is established on the basis of cost, and these prices have been relatively low. (See table 20.) Some space holders maintain large water holdings as insurance against water-short years and defray their costs by placing unneeded supplies in the bank. To increase the flexibility of the bank's operation and to provide a basis for long-term investments related to water use, there have been requests that the term of the leases be allowed to be longer than 1 year and that the price for water be established on a basis other than cost. The U.S. Bureau of Reclamation currently (1986) is considering contract amendments that would allow space holders to use longer lease terms, and in the future the Bureau may also allow the bank more flexibility in establishing the rental price of water.

WATER MARKET TRANSACTIONS IN UTAH'S MUTUAL IRRIGATION COMPANIES

The typical mutual irrigation company in Utah is a private, nonprofit corporation consisting of its member stockholders who use a common water source or facilities. Whether a company is incorporated or not depends mainly upon the size and complexity of its operations and membership. Management and policy decisions, including system operations, assessment rates, and intracompany transfers, remain with the stockholders and their elected board of directors.

Since 1853, when the first mutual irrigation company was incorporated by Utah's Territorial Legislature, mutual companies have provided a means for accommodating voluntary market exchanges of water among their shareholders. These private companies evolved around the informal water systems organized and constructed by Mormon pioneers to serve the domestic and irrigation needs of their settlements in the arid valleys of the Great Basin. Private water companies of this general type are found throughout the Western States, but their most notable concentration is within the State of Utah, where more than 900 companies provide water to irrigate about 1.1 million acres. In a 1964 survey of mutual companies in the Sevier River basin in Utah (fig. 84, site 8), 90 percent of the respondents reported voluntary purchase and sale of water, or rental of water on a seasonal basis (Fullerton, 1966). Extensive market activity has occurred since that time not only in the Sevier River basin, but throughout the State.

Market activity within these mutual companies has been facilitated by the convenience of private ownership of water and by the fact that, in Utah, water rights are not made appurtenant to an owner's land. Stock ownership in the mutual company provides entitlement to a proportionate share of the company's water—a share that can be used on any lands within the company's service area. Typically, water shares can be exchanged, bought, sold, rented, or otherwise transacted for the mutual benefit of individual stockholders. Some mutual companies require all transactions to be completed before the irrigation season begins. Others, principally those with water-storage facilities, have virtually no restrictions except to require a current record of ownership to assist in system operation and in assigning water assessments. Markets are most active in areas where water can be both rented seasonally or sold in perpetuity. The price in a water transaction is negotiated to the mutual

Figure 86. **Coachella Canal in southern California.** The heavy vegetation near the canal in the foreground indicates an area of leakage from this unlined section, which has been lined since this picture was taken. Similar water losses occur from facilities owned by the Imperial Irrigation District. (Photograph courtesy of U.S. Bureau of Reclamation.)

Teble 18. **Purchasers of water from the Federal water bank in California during the 1976-77 drought**

[Source: U.S. Bureau of Reclamation records]

Purchaser	Water purchased		
	Amount (acre-feet)	Revenue	
		Total	Per acre-foot
	Irrigation District		
Delano-Earlimart	200	$27,294.09	$136.47
Glenn Colusa	22	1,208.46	54.93
Hills Valley	76	10,825.63	142.44
Hospital	1,389	85,269.35	61.39
Lindsay-Strathmore	300	40,545.50	135.15
Stone Corral	124	17,232.37	138.97
Terra Bella	503	67,452.91	134.10
	Water District		
Broadview	120	7,387.98	61.57
Centinella	329	19,404.67	58.98
Contra Costa	1,250	70,252.02	56.20
Davis	304	18,208.69	59.90
Del Puerto	1,326	76,986.73	58.06
Foothill	1,100	63,539.13	57.76
Kern Canon	605	36,894.35	60.98
Mustang	112	7,168.29	64.00
Drestimba	843	49,503.97	58.72
Panoche	891	49,859.16	55.96
Plain View	1,180	67,870.11	57.52
Quinto	435	25,310.10	58.18
Romero	120	7,482.57	62.35
Salado	500	29,538.97	59.08
San Luis:			
Delta-Mendota Canal	5,469	314,926.32	57.58
San Luis Canal	1,144	72,746.07	63.59
Sunflower	1,205	68,718.19	57.03
Tri-Valley	135	18,688.19	138.43
Westlands	22,362	1,295,098.78	57.92
	Water Storage District		
Arvin-Edison	500	30,356.38	60.71
Total	42,544	$2,579.769.53	

benefit of buyer and seller. Drought and increases in commodity prices tend to result in higher water prices. Alternatively, water prices may be depressed by reductions in commodity prices and by unusually high precipitation and frosts, which reduce or obviate the need to irrigate.

Figure 87. **Palisades Dam and Reservoir, located on the upper Snake River, Idaho.** The Palisades is one of the principal facilities providing storage space for the water available for transfer in Idaho's Water Supply Bank. (Photograph courtesy of U.S. Bureau of Reclamation, August 1976.)

Table 19. Pre-season water exchange pool and in-season transfers, Arvin-Edison Water Storage District, 1970–84

[Pre-season and in-season refer to the Arvin-Edison Water Storage District water year which begins on March 1. Prorated share is the percentage of the request that was received by the purchaser. - - - =not available. Source: Arvin-Edison Water Storage District records]

Year	Pre-season exchange pool			In-season transfers (acre-feet)
	Offers (acre-feet)	Requests (acre-feet)	Prorated share (percent)	
1970	9,725	9,720	100	- - -
1971	3,223	3,623	89	- - -
1972	2,212	3,147	70	- - -
1973	3,531	5,202	68	- - -
1974	1,071	7,631	14	- - -
1975	1,124	1,124	100	- - -
1976	2,953	2,953	100	- - -
1977	1,509	7,868	19	1,743
1978	3,788	3,788	100	2,644
1979	3,937	3,937	100	11,759
1980	4,604	7,872	58	7,940
1981	5,862	5,862	100	13,695
1982	3,165	5,591	57	5,730
1983	6,225	6,225	100	3,812
1984	7,814	3,192	100	- - -

Sale or rental of water for delivery outside a given company's service area, although allowed by a few companies, commonly is discouraged or explicitly forbidden. Some notable exceptions are found in areas of rapid residential and industrial expansion, such as in the counties along the Wasatch Front near Salt Lake City and in the lower Sevier River basin. In these areas, where more valuable uses have developed in close proximity to a given company's service area, sale or rental of irrigation water for delivery to municipal and industrial uses occurs with relative ease, subject to protection of third-party interests under State water law. Kennecott Copper and Geneva Steel, as well as several municipalities, have become large stockholders in mutual companies and purchase water stock as needed to meet increased demands. It is not uncommon for a growing municipality to require subdividers and developers to purchase and transfer stock in irrigation water to the city as a precondition for accepting a proposed subdivision or annexation.

Quantitative documentation of the extent and variety of market activity occurring within the State is not easily obtained because the transactions involve proprietary information, and in the case of mutual companies, formal documentation outside the company is minimal. One study (Fullerton, 1966), based on the records of four large mutual companies (Delta, Melville, Abraham, and Deseret) that supply water to 50,000 to 75,000 acres of land at the terminus of the Sevier River in Utah, indicate that the number of intercompany transactions ranged from 290 to 629 per irrigation season between 1951 and 1964. (These companies also were involved in the sale of water to the Intermountain Power Project, as described previously.) The water involved in these transactions ranged from 11 to 29 percent of the total surface-water supply for the area, which averaged about 80,000 acre-ft per season. The sale price for permanent ownership of mutual company shares (expressed in 1980 dollars) ranged from $250 to $336 per acre-ft. Rental rates ranged from $6 to $41 per acre-ft. Water-rental rates in the four companies typically stabilize early in the irrigation season, once the approximate water supply is known and crops are planted.

The procedures used by these mutual companies in accounting for water in a sale or rental resembles the accounting system of a bank. Prior to the irrigation season, a water credit—based on reservoir storage and anticipated runoff from snowpack less estimated system losses—is announced and credited to the company accounts and to the individual account of each shareholder in proportion to the amount of stock held. Each shareholder can then make plans to use, buy, sell, or lease his water. Withdrawals for one's own use and for transactions are reflected in both the individual accounts and those of the companies. The water credits of any one company may be transferred to the credit of any other, subject to the established "basis of exchange." This basis of exchange is an amount added to the face amount for water transferred between individuals to adjust for changes in return flow and system losses stemming from the trans-

Table 20. Transfers in Idaho's Water Supply Bank, 1980–84

[Source: Idaho Department of Water Resources records]

Year	Water (acre-feet)		Sale price (per acre-foot)
	Supplied	Released	
1980	71,570	14,575	$0.64
1981	168,691	148,925	2.30
1982	288,854	203,515	2.30
1983	540,507	353,840	2.40
1984	806,400	276,167	2.50

action. As such, establishing a basis of exchange facilitates transactions because it relieves individual buyers and sellers from the burden of developing information regarding the effects of the water exchange.

WATER MARKETS WITHIN THE NORTHERN COLORADO WATER CONSERVANCY DISTRICT

Water frequently is traded among members of the Northern Colorado Water Conservancy District (NCWCD) (fig. 84, site 9) at prices established by the market. Each year, about 65,000 acre-ft, or about 30 percent of the water delivered to the District by the Colorado-Big Thompson Project moves through the rental market (Howe and others, 1986). Annual rentals require no more than a postcard to the NCWCD in order to shift the water to a different use or location (Harrison, 1984). Sales of water on a permanent basis also are relatively frequent and straightforward. A number of realtors have begun to specialize in brokering these water transactions.

The NCWCD was founded in the 1930's to contract with the U.S. Bureau of Reclamation to serve the water demands on the eastern slope of the Front Range by using the more abundant water supplies of the western slope. The Bureau's Colorado-Big Thompson Project was constructed to divert water at the headwaters of the Colorado River and to transport it across the Continental Divide to supplement the water supplies of some 720,000 acres of irrigated land and of several east-slope cities, which are served by nearly 200 existing canal and reservoir systems. For 1957-82, the project provided an annual average of 220,000 acre-ft of water, or about 25 percent of the total 865,000 acre-ft of water used in the district (Northern Colorado Water Conservancy District, 1982).

Water is traded with relative ease and frequency in the NCWCD due to a combination of physical and institutional factors. There are three principal types of water rights in the NCWCD area: rights to Colorado-Big Thompson Project water imported from the western slope; rights to water stored in irrigation company reservoirs; and direct flow rights from eastern-slope streams. Water companies typically hold some or all three of these types of water rights.

Water from the Colorado-Big Thompson Project is the most easily marketed water in the NCWCD. This water is diverted under water rights filed for and owned by the U.S. Bureau of Reclamation and is sold under contract to the district. Each year, the NCWCD divides the amount of available project water proportionally among the owners of its 310,000 shares or units. These shares can be bought, sold, and leased within the district. The fact that project water is a supplemental supply probably has enhanced its marketability (Howe and others, 1986). Initially, different areas in the NCWCD had different demands for the additional water. It became clear that a mandatory, uniform assignment of water to land would not work: Farmers wanted freely transferable allotments so that they could recover water costs when the supplemental supply was not needed. Transfers are facilitated because return flows of project water belong to the district (a provision of the NCWCD contract with the U.S. Bureau of Reclamation). This arrangement was possible because Colorado-Big Thompson Project water is imported from the western slope: because the water was new to the region, no rights to return flows had developed (Howe and others, 1986). Because there is no legal basis for an objection by downstream parties, market transactions of project water within the district are greatly simplified.

Water held by mutual irrigation companies in local reservoirs in the region also is relatively easy to transfer. In Colorado, surface water is a property right that is legally separable from the land. Also, once water is captured by artifical means and reduced to physical possession, it may be transferred, subject to complaint of injury by third parties. Direct-flow rights are more difficult to transfer, in part because the effect of altering return flows on third parties must be considered. Transactions involving direct-flow rights occur less frequently than those involving other types of rights (Anderson, 1978).

Agriculture is a major industry in the NCWCD; 621,000 cropland acres were harvested in 1982. There are many transfers of water among agricultural and municipal and industrial uses in the NCWCD, and the transfers seem to occur with a minimum of friction. Several factors are responsible. Most municipal and industrial uses consume relatively small amounts of water. Thus, they return to the stream nearly as much as they withdraw. Within NCWCD, most agricultural lands are located downstream from urban areas and, therefore, are able to utilize return flows from municipal and industrial uses. Because of these factors, municipal and industrial withdrawals have only a small effect on irrigation use. In 1978, for example, the NCWCD manager estimated that with existing (1978) water supplies the population of the district could increase from 500,000 to 3,270,000 and farmers could still irrigate about 560,000 acres of cropland using return flows (Anderson, 1978). In addition, urban growth generally encroaches on irrigated land; when this change of land use occurs, water becomes available for irrigation use elsewhere (Anderson, 1984).

Another factor facilitating the transfer of water from agricultural to municipal uses may be recognition that, on the average, both direct and indirect economic benefits of water used in agriculture are less than the benefit realized from other uses (table 21). This is true also for employment. The same amount of water will support considerably more workers when used in nonagricultural industries than when used in irrigated agriculture (table 22) (Young, 1983).

The sales price of shares of Colorado-Big Thompson Project water has varied widely. The average price for permanent rights to project water (expressed in 1980 dollars) was $99 per acre-ft in 1961; $504 in 1970; $2,895 in 1980; $2,445 in 1981 (Gardner and Miller, 1983); about $1,600 in 1983 (adapted from Howe and others, 1986); and about $900 in 1985 (R. L. Anderson, U.S. Department of Agriculture, Economic Research Service, oral commun., 1985). A number of factors have contributed to the fluctuations in water prices, although their relative importance is unknown. Certainly, growth of the Front Range region's economy has increased water demands with a concomitant rise in water prices. However, urban development has slowed recently and economic conditions have been unfavorable for farming, which has decreased the price of water and agricultural land. Favorable growing conditions and an ample water supply also have contributed to the decline of water prices.

Rental rates rose slightly from 1961 to 1983, but less than the rate of inflation. The predominant annual rental price ranges from $5 to $7 per acre-ft. Prices are slightly lower in the early part of the irrigation season as compared to late in the season (Howe and others, 1986). Use of the rental market has been stimulated by the practice of cities in the district, which regularly acquire water in excess of present demands to ensure sufficient supplies for the future. For instance, the current development of the Windy Gap Project in the Colorado-Big Thompson Project—funded by municipal and industrial interests—will add 48,000 acre-ft of water annually to the Front Range. This water is expected to be available for lease to irrigators until needed by the expanding cities (Harrison, 1984).

PAPAGO INDIAN SETTLEMENT AND FORT PECK-MONTANA COMPACT

In a series of decisions dating from 1908, the U.S. Supreme Court has held that when Indian reservations are established, water is implicitly reserved from unappropriated sources appurtenant to the reservation in an amount necessary to fulfill the purpose for which the reservation was established. The priority of that reserved right is no later than the date on which the reservation was established, and the right is not subject to loss by nonuse. Determining the extent of such reserved rights is considered to be a major factor affecting future water use in these States, and in recent years, adjudications in many Western States have been filed expressly for the purpose of establishing the nature and extent of Indian reserved water rights. Two recent Indian water-rights settlements—those for the Papago Tribe in Arizona (fig. 84, site 10) and the Assiniboine and Sioux Tribes of the Fort Peck Indian Reservation in Montana (fig. 84, site 11)—include provisions for off-reservation marketing of Indian water, and other tribes may explore similar provisions in their settlements.

Papago Settlement.—The Papago Indian Water Rights Settlement, enacted by the Congress on October 12, 1982, provides a settlement of the Tribe's claims for the San Xavier Reservation and the Schuk Toak District of the Sells Papago Reservation in southern Arizona. The settlement provides for annual deliveries of 66,000 acre-ft of water to the Tribe. The Tribe's initial entitlement consists of water from the Central Arizona Project, as well as treated sewage effluent. Section 306(c)(1) of the Act provides that the Tribe may sell, exchange, or temporarily lease its water. However, sales are limited to the Tucson Active Management Area— one of four areas that the State has established for ground-water management. The marketing of this water also is limited to temporary exchanges, because the Tribe is prohibited from permanently selling or "alienating" its water rights.

Fort Peck-Montana Compact.—In May 1985, the Montana State Legislature ratified a compact settling the reserved-rights claims of the Assiniboine and Sioux Tribes of the Fort Peck Indian Reservation. The settlement provides for annual Indian diversions up to 950,000 acre-ft/yr of surface water from the Missouri River and its tributaries that traverse or border on the Reservation. Consumptive use of this water is limited to 475,000 acre-ft. Under the agreement, the Tribes are permitted to market as much as 50,000 acre-ft/yr off the Reservation, and greater amounts can be marketed if the State is able to sell more than 200,000 acre-ft/yr of its allocation. Congressional ratification of the Tribes' authority to market water off the Reservation will be necessary.

Table 21. Direct and direct-plus-indirect income per unit of water consumed for selected sectors, Colorado, 1980

[Direct agricultural income is income from the sale of farm products. Indirect agricultural income is income indirectly associated with agriculture, such as that from the sale of tractors to farmers and the processing of wheat into bread. The principle is the same for nonagricultural sectors. Source: Young, 1983. Price levels are 1980]

Sector	Consumptive use of water per dollar of output (gallons per dollar)	Income (dollars per acre-foot)	
		Direct	Direct-plus-indirect
Agriculture, irrigated ..	1,752.00	$184	$503
Nonagriculture:			
Coal mining	1.74	186,000	413,000
Electronics	.14	2,364,000	4,208,000

Tabla 22. Water use per direct and direct-plus-indirect worker employed in selected sectors, Colorado, 1980

[Water use per direct worker in irrigated agriculture consists of the water used in irrigation of crops. Indirect water use for that worker is the water employed in associated uses, such as the water used to make the steel of the tractor that the farmer drives. The principle is the same for nonagriculture sectors. Source: Young, 1983]

Sector	Water use per worker (acre-feet)	
	Direct	Direct-plus-indirect
Agriculture, irrigated	142.000	210.000
Nonagriculture:		
Coal mining	.280	.390
Electronics	.024	.031

CONCLUDING REMARKS

A number of examples of transactions in water have been discussed. Established markets, water banks, and pooling arrangements commonly operate under the auspices of a single district, such as in the

Northern Colorado Water Conservancy District, the Arvin-Edison Water Storage District exchange pool, and the water bank operating on the upper Snake River in Idaho; in some cases the district covers a substantial geographic area. Some of the examples of established markets are in areas where the water supply was supplemental (for example, Northern Colorado Water Conservancy District and the water bank on the upper Snake River) and where there was a clear realization that the water supply would not be needed every year or in a uniform amount by everyone within the district. Individual ownership of water has clearly facilitated trading, such as in the Utah mutual companies and in the NCWCD; however, other forms of tradable property in water have evolved, such as those specified by water contracts in the Idaho Water Supply Bank and in the Arvin-Edison Water Storage District exchange pool. Exchanges also are facilitated where the property rights to water are simplified by a district owning its return flows, such as Colorado-Big Thompson Project water in the NCWCD. This simplification also occurs where the return flows have little or no value, as in the case of four mutual companies on the Sevier River in Utah and in the Imperial Irrigation District in California.

Substantial transactions in water also have taken place between districts or other water-using entities under more difficult circumstances and where no established market exists. The impetus that overcomes these difficulties is the recognition, on the part of both the buyer and the seller, that the value of water may be substantially different between them. The result is an individually negotiated transaction. In the cases discussed here, these differences in value have arisen in situations of increasing urban demands (for example, in Casper, Wyo., and in southern California) and for powerplant cooling water (for example, purchase of water by the Intermountain Power Project in Utah and the transaction involving the Utah Power and Light Company).

The examples presented are diverse in their geographic location and in the manner in which the exchanges were implemented, illustrating the variety of circumstances under which water exchanges have proved useful. Various State legislatures are addressing ways in which to facilitate voluntary transfers. For example, in 1982 California amended its water code (through the Katz-Bates Bill) to establish that conservation and subsequent sale of water is a beneficial use and to direct all appropriate State agencies to encourage voluntary transfers of water and water rights. The Idaho legislature is considering (1986) House Bill No. 369, which would further the lease and sale of water. At the Federal level, the Bureau of Reclamation is working to streamline its response to transfer requests that involve Bureau projects, project operations, or Federal water contracts. In the future, voluntary water exchanges may be expected to become more routine as a means of using water efficiently to meet changing patterns of water demands.

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STATE SUMMARIES OF SURFACE-WATER RESOURCES

INTRODUCTION TO
STATE SUMMARIES OF SURFACE-WATER RESOURCES

The United States enjoys an abundance of surface-water resources. Total streamflow in the United States for 1951–80 averaged about 1,270 bgd (billion gallons per day), which is more than 7 times the present (1980), total fresh ground- and surface-water withdrawals of about 380 bgd and more than 28 times the consumptive use of freshwater (Graczyk and others, 1986). Considering only the overall supply of fresh surface water without regard to distribution or quality, there is no water shortage—the resource far exceeds the present level of use. However, streamflow varies areally and temporally, and there is no assurance that adequate supplies of surface water of an acceptable quality will be available where and when needed.

In the "State Summaries of Surface-Water Resources" part of the 1985 *National Water Summary*, the Nation's surface-water resources are described with emphasis on their occurrence, use, and development in 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. (Hereafter, the term "State" is used for all of these geographic areas.) Each State summary includes the following components:

- General setting—Highlights of the State's physiography, climate, hydrology, and other factors that control runoff patterns and a discussion of fresh surface-water withdrawals of various uses in relation to total use (table 1).
- Principal river basins—Description of the hydrologic setting, selected streamflow characteristics, degree of regulation, general surface-water quality where it constrains use, and various water-related issues in the principal river basins of the State. This component includes a tabulation of selected streamflow characteristics at representative gaging stations and the extent and effects of streamflow regulation within the drainage basins (table 2). Also included are two illustrations: one showing average annual precipitation and runoff and average monthly precipitation and streamflow at selected sites (fig. 1); and the other showing principal river basins, major reservoirs, hydroelectric powerplants, and long-term variations in stream discharge at selected sites (fig. 2).
- Surface-water management—Description of State laws and regulations related to surface water and the identification of State surface-water-management agencies and their functions.
- Selected references—Relevant reports on surface-water resources.

The State summaries use common hydrologic terms, and reference is made without explanation to basic hydrologic principles. Some of these principles, such as rainfall-runoff relations and the cause and significance of low flows, are discussed in the article in this volume, "National Perspective on Surface-Water Resources." Selected hydrologic terms are defined in the Glossary.

IMPORTANCE OF SURFACE WATER TO THE NATION

Surface-water resources have played an important role in the exploration and economic development of the North American continent. Native Americans and European explorers used rivers as principal transportation routes. The first settlements were established along rivers, which served as trade routes and sources of food, water supply, and power. Today, surface water continues to be the major source of water for public supplies, irrigation, and the generation of electricity. Some 25,000 miles of waterways handled 2.1 billion tons of cargo in 1979, and waterborne commerce is increasing (U.S. Army Corps of Engineers, 1981). Finally, rivers and lakes provide recreational opportunities for tens of millions of people each year and support fisheries and wildlife habitats.

Aside from recreation and fisheries, the largest direct or instream use of surface water is for hydroelectric power, primarily in the Pacific Northwest (Washington, Oregon, California, Idaho, and Montana), in the Tennessee Valley (Alabama, Tennessee, and Kentucky), and in the Northeast (New York, Pennsylvania, and Maine). In 1980, an estimated 3,300 bgd was used to generate about 277 billion kilowatt-hours of electricity (Solley and others, 1983, p. 28). The 11 States named above account for about 77 percent of the water used to generate hydroelectric power.

The relative importance of fresh surface water in meeting the Nation's demand for water may be shown by comparing surface-water withdrawals to total freshwater withdrawals from both surface-water and ground-water sources (table 23). In 1980, fresh surface water represented 77 percent of the Nation's total freshwater withdrawals. Surface water was the source of 3 percent of of rural-domestic supplies, 45 percent of rural-livestock supplies, 60 percent of irrigation supplies, 65 percent of public supplies, 74 percent of supplies for self-supplied industries (excluding thermoelectric-power generation), and 99 percent of supplies for thermoelectric-power generation—by far the largest offstream-withdrawal use of water. (Virtually all of the water withdrawn for thermoelectric-power generation is returned to a watercourse after use.) Withdrawals of fresh surface water in the United States, Puerto Rico, and the U.S. Virgin Islands are shown graphically in figure 88.

The importance of fresh surface water differs across the country and reflects the uneven distribution of precipitation and runoff. In 1980, fresh surface-water withdrawals for all categories of use ranged from 15 percent of total withdrawals in Kansas to virtually 100 percent in the District of Columbia (Solley and others, 1983). In only 10 States did surface water provide less than half of total withdrawals. Eleven States withdrew more than 10 bgd of surface water for all offstream uses and accounted for about 52 percent of the total surface-water withdrawals in the country. The largest withdrawals of surface water occurred in California (24 bgd), Illinois (16 bgd), Pennsylvania (15 bgd), and Michigan (14 bgd) (table 23).

In 1980, the largest offstream use of fresh surface water was for thermoelectric-power generation (150 bgd). Industrial uses other than thermoelectric-power generation accounted for 29 bgd, and the States with the largest use for this purpose were Louisiana, Pennsylvania, Indiana, and North Carolina. Because large amounts of cooling water are required by thermoelectric powerplants, many coastal States use saline water. As shown in Solley and others (1983, p. 26), States with the largest withdrawals of saline surface water for thermoelectric-power generation were Florida (14 bgd), California (9.2 bgd), New York (8.5 bgd), New Jersey (6.5 bgd), and Maryland (6.1 bgd).

The second largest use of fresh surface water was for irrigated agriculture (90 bgd). In the West where irrigation is a major activity, States with the largest surface-water withdrawals for irrigation were California (19 bgd), Idaho (12 bgd), Colorado (11 bgd), and Montana (10 bgd). In the East, Florida withdrew the largest amount (1.4 bgd) of fresh surface water for irrigation.

Table 23. Summary of fresh surface-water offstream (withdrawal) use, by category of use, and instream (nonwithdrawal) use for hydroelectric-power generation 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, 1985 *Nation Water Summary*; national totals and percentages from Solley and others, 1983]

State	Offstream use									Instream use
	Total fresh surface- and ground-water withdrawals per day (Mgal)	Percentage of population served by surface water	Fresh surface-water withdrawals per day (Mgal)	Fresh surface-water withdrawals as a percentage[1] of total fresh surface- and ground-water withdrawals for—						Surface water for hydroelectric-power generation per day (Mgal)
				All categories of use[2]	Specific categories of use					
					Public supply	Rural supply		Industrial self-supplied[2]	Irrigation	
						Domestic	Livestock			
Alabama	11,000	45	10,000	97 (81)	74	0	72	99 (92)	73	170,000
Alaska	220	32	170	77 (78)	57	1	50	91 (95)	100	770
Arizona	7,300	35	3,000	42 (40)	46	0	18	28 (12)	42	41,000
Arkansas	6,900	49	2,900	41 (56)	57	0	64	83 (9)	15	26,000
California	40,000	54	24,000	61 (58)	61	7	60	51 (40)	62	81,000
Colorado	16,000	84	13,000	81 (81)	92	63	78	98 (99)	79	5,500
Connecticut	*1,300*	*68*	*1,200*	*90 (80)*	*83*	*0*	*81*	*98 (93)*	*90*	*4,000*
Delaware	140	40	57	41 (41)	62	0	0	23 (29)	37	0
District of Columbia	340	100	340	100 (100)	100	0	0	100 (43)	0	8
Florida	7,300	10	3,600	49 (33)	13	0	34	73 (18)	47	15,000
Georgia	6,700	52	5,500	82 (48)	70	0	39	92 (49)	34	52,000
Hawaii	1,300	5	510	39 (41)	8	10	4	24 (80)	49	180
Idaho	18,000	13	12,000	67 (67)	10	4	59	5 (5)	74	76,000
Illinois	17,000	51	16,000	94 (64)	72	0	0	99 (71)	0	26,000
Indiana	14,000	38	13,000	93 (77)	53	6	45	95 (81)	9	9,500
Iowa	3,200	18	2,300	72 (19)	19	0	0	87 (29)	17	28,000
Kansas	6,600	37	980	15 (10)	52	0	57	64 (22)	8	570
Kentucky	4,600	58	4,400	96 (78)	87	10	95	98 (75)	94	98,000
Louisiana	12,000	31	11,000	86 (73)	56	0	29	95 (88)	59	1,400
Maine	850	43	770	91 (90)	81	2	41	94 (95)	97	75,000
Maryland	1,400	72	970	70 (58)	90	0	5	93 (80)	47	15,000
Massachusetts	2,500	68	2,100	84 (67)	76	0	42	94 (71)	74	25,000
Michigan	15,000	57	14,000	96 (75)	83	0	23	99 (96)	52	65,000
Minnesota	3,100	25	2,400	77 (50)	48	0	15	96 (80)	11	20,000
Mississippi	2,900	7	1,400	48 (17)	14	0	57	77 (22)	13	0
Missouri	6,900	66	6,400	93 (64)	78	26	74	98 (63)	23	13,000
Montana	11,000	46	11,000	98 (98)	63	2	68	81 (48)	99	66,000
Nebraska	12,000	18	5,200	42 (27)	22	0	20	97 (15)	28	5,900
Nevada	3,600	50	2,900	81 (80)	61	6	71	68 (53)	84	1,200
New Hampshire	380	40	320	84 (80)	52	2	65	95 (94)	100	26,000
New Jersey	2,900	54	2,100	72 (60)	56	0	33	90 (79)	27	140
New Mexico	3,900	7	2,100	53 (52)	10	3	50	75 (2)	56	430
New York	8,000	66	7,200	90 (81)	86	0	34	96 (89)	54	310,000
North Carolina	8,100	45	7,300	90 (79)	88	0	14	93 (83)	70	40,000
North Dakota	1,000	38	910	89 (13)	56	2	39	100 (75)	63	15,000
Ohio	14,000	58	13,000	93 (75)	71	10	40	98 (86)	64	380
Oklahoma	1,700	58	760	44 (39)	73	15	86	75 (63)	16	34,000
Oregon	6,800	36	5,700	84 (84)	70	13	73	85 (84)	85	490,000
Pennsylvania	16,000	56	15,000	94 (83)	87	0	11	96 (86)	88	81,000
Puerto Rico	720	73	480	67 (67)	80	42	50	0 (1)	64	440
Rhode Island	170	76	140	82 (82)	85	0	50	66 (66)	90	23
South Carolina	5,800	59	5,600	96 (85)	78	0	45	99 (95)	74	63,000
South Dakota	690	23	360	52 (52)	32	6	12	46 (45)	67	67,000
Tennessee	10,000	52	9,600	96 (82)	3	41	41	98 (89)	51	150,000
Texas	16,000	51	6,300	39 (38)	61	17	51	77 (76)	30	>9,800
Utah	4,100	37	3,400	81 (81)	34	11	22	89 (82)	86	3,400
U.S. Virgin Islands	6	58	5	82 (82)	88	70	100	0 (0)	0	0
Vermont	340	46	300	87 (51)	65	15	38	98 (65)	81	14,000
Virginia	5,600	59	5,200	93 (70)	83	0	90	98 (76)	71	26,000
Washington	*8,200*	*51*	*7,500*	*91 (91)*	*63*	*22*	*33*	*86 (86)*	*96*	*940,000*
West Virginia	5,600	47	5,400	96 (80)	72	1	87	98 (82)	92	21,000
Wisconsin	5,800	30	5,200	90 (54)	49	0	4	98 (78)	4	71,000
Wyoming	5,300	46	4,800	91 (90)	67	8	79	66 (24)	92	7,200
Total or percentage	380,000	49	290,000	77 (62)	65	3	45	94 (74)	60	3,300,000

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[1] Percentages calculated from unrounded numbers. [2] Number in parentheses was calculated excluding withdrawals for thermoelectric-power generation.

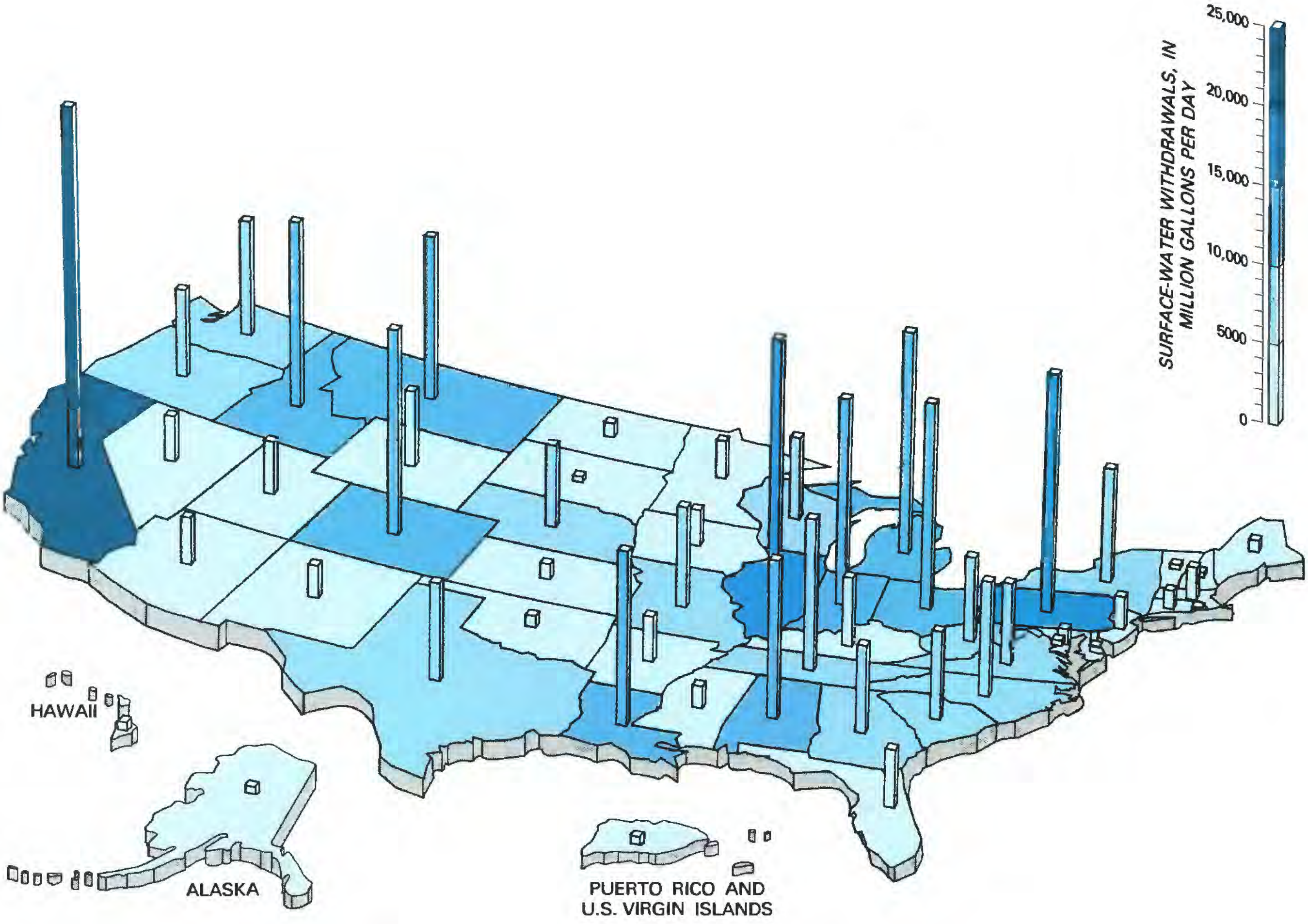

Figure 88. Fresh surface-water withdrawals in the United States, Puerto Rico, and U.S. Virgin Islands. (Source: Data from table 1 in respective State summary, 1985 *National Water Summary*.)

The third largest withdrawals of fresh surface water was for public supply (22 bgd). States with the largest withdrawals were Texas (2.9 bgd), California (2.7 bgd), New York (1.9 bgd), Illinois (1.3 bgd), Pennsylvania (1.3 bgd), and Ohio (1.0 bgd).

Surface-water withdrawals for rural use comprised only a small percentage of total freshwater withdrawals. The States with the largest rural withdrawals were Texas (0.17 bgd) and Colorado (0.15 bgd).

DELINEATION AND DESCRIPTION OF PRINCIPAL RIVER BASINS

The United States and its possessions are divided into hydrologic units—21 water-resources regions and 222 subregions. (See maps in "Glossary" part of report.) The boundaries of regions coincide with the natural drainage areas of major rivers, such as the Ohio Region, or with the combined drainage areas of several major rivers, such as the Arkansas–White–Red

Region. Eighteen of these regions are in the conterminous United States. Alaska, Hawaii, and Puerto Rico and the U.S. Virgin Islands comprise three additional regions. Because natural drainage divides and political boundaries usually do not coincide, some States may be located entirely within one region, whereas others may be located in several regions. A full description of these regions and subregions is given in Seaber and others (1984).

These hydrologic units provide a framework with which to describe the principal river basins in each State. In most States, principal river basins are either subregions, groups of subregions, or parts of subregions. A few States, however, have adopted their own schemes for defining principal river basins. River-basin boundaries in these States may differ from those shown on the maps in the Glossary.

Table 2 of each State summary presents data on average discharge, 7-day, 10-year low flow, discharge of the 100-year flood, and degree of regulation at representative streamflow-gaging stations in the principal river basins. The 7-day, 10-year low flow is the minimum 7-day average discharge that has a 10-percent chance of recurring in a given year or once in 10 years on the average. This statistic commonly is used by water-resources planners to estimate the reliability of a surface-water source for water supply or for use in diluting waste discharges. The "100-year flood" is the instantaneous peak discharge that has a 1-percent chance of being equaled or exceeded in a given year or once in 100 years on the average. The stage or height of the water surface of the 100-year flood is used to delineate "flood-prone areas" for flood-insurance purposes. Some State summaries discuss peak flows that exceed the 100-year flood discharge. The degree of regulation of stream indicates how much the natural flow of the stream is controlled by upstream reservoir storage. Additional information on the significance of some of these statistics is given in the article in this volume, "National Perspective on Surface-Water Resources."

Figure 2 in each State summary shows the locations of major reservoirs and hydroelectric powerplants, the principal river-basin boundaries, and the major rivers. Figure 2 also contains bar graphs that show year-to-year variations in annual discharge of principal rivers. The variations in streamflow are a result of variations in precipitation as well as changes in consumptive use, regulation within the basin, and interbasin imports or exports of water. Annual variations in streamflow tend to be smaller in the more humid eastern States, where streamflow is comparatively well sustained by ground-water discharge to streams, than in other parts of the country, where streamflow is derived largely from intermittent runoff or snowmelt.

Superimposed on the discharge bar graphs is a curve that shows the 15-year, weighted moving-average discharge. This curve illustrates long-term changes in streamflow that might otherwise be obscured by the natural variability of the data. Long-term variations that may influence trends in streamflow include variations in precipitation, consumptive water use, reservoir storage, water diversions and transfers, and discharge of wastewater. For example, cyclic variations in the curve are related to long-term changes in precipitation (see California, fig. 2, sites 2 and 16); a relatively rapid downward trend in the curve for the Canadian River is the result of increased consumptive use following reservoir construction (see New Mexico, fig. 2, site 1); and a rising trend in the curve for the South Platte River is the result of water imports from other river basins for irrigation and municipal supply (see Colorado, fig. 2, site 3). A discussion of the mathematics of weighted moving averages is given by Chambers and others (1983, p. 94–98).

SURFACE-WATER MANAGEMENT

Numerous pieces of legislation have been enacted and organizations created by the States to address a variety of land- and water-resource-related issues. Descriptions of key State surface-water-related laws and regulations and the management infrastructure established to implement and enforce them comprise the final section of each State summary. In addition to the State agencies mentioned in the summaries, a number of Federal agencies, such as the Bureau of Reclamation, Army Corps of Engineers, Soil Conservation Service, and Tennessee Valley Authority, have major responsibilities for water-resources management. The roles of these Federal agencies are not discussed in detail in the State summaries.

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Tributary (unnamed) to the Noatak River in Alaska. (Photograph by H. C. Riggs, U.S. Geological Survey)

ALABAMA
Surface-Water Resources

Alabama has abundant surface-water resources that are suitable for public and industrial water supplies, agriculture, industry, navigation, hydropower, and recreation. About 170,000 Mgal/d (million gallons per day) or 263,000 ft^3/s (cubic feet per second) of surface water is used to generate hydroelectric power at 20 operating facilities. Offstream use of surface water averaged 10,000 Mgal/d or 16,000 ft^3/s in 1980, or 97 percent of the total offstream water use in Alabama. Approximately 45 percent of the population relies on surface water for its freshwater needs. Surface water will continue to provide the majority of the water used in the State because of its low cost and availability. Surface-water withdrawals in Alabama in 1980 for various purposes, and related statistics, are given in table 1.

Principal issues related to surface water in Alabama generally concern the large variability of streamflows. At times, excessive flows cause floods, and at other times, low flows barely supply sufficient water for domestic, municipal, and industrial uses and for other uses, such as waste assimilation and recreation. In some highly developed industrialized areas, streamflow during droughts would not be sufficient for future industrial development.

GENERAL SETTING

Alabama has a total area of 51,600 mi^2 (square miles) about 500 mi^2 of which are inland water. The State is located in five physiographic provinces—Coastal Plain, Piedmont, Valley and Ridge, Appalachian Plateau, and Interior Lowland Plateaus (fig. 1). The area north of the Fall Line, which delineates the contact of the Coastal Plain with the other provinces, has a very diverse topography, with altitudes that range from 200 to 2,400 feet above sea level. In the Coastal Plain, altitudes range from sea level at the Gulf of Mexico to about 1,000 feet above sea level in the northwestern part of the State. The land surface slopes to the south and west.

Annual precipitation averages about 55 inches statewide, and ranges from about 50 inches in central and west-central Alabama to about 65 inches near the Gulf of Mexico (fig. 1). Rainfall in Alabama generally is associated with the movement of warm and cold fronts across the State during November through April and isolated summer thunderstorms from May through October. Occasionally, hurricanes, which usually enter the State along the gulf coast, produce unusually heavy rainfall, and have caused some of the more disastrous floods in Alabama.

Seasonal rainfall patterns, except near the gulf coast, are similar to those at Birmingham and Huntsville where more than half of the average rainfall occurs in the 6 months December through May; March is usually the wettest month. Rainfall patterns near the gulf coast are typically similar to those at Mobile, where more than half of the average rainfall occurs during April through September and July is the wettest month (fig. 1).

Runoff and precipitation vary areally and seasonally. With the exception of the extensively urbanized greater Birmingham area and the extreme northeastern part of Alabama where runoff is relatively high, runoff and precipitation decrease northward away from the Gulf of Mexico.

Flooding is common during March and April. Runoff typically decreases in response to a reduction in rainfall from September through November. Streamflows generally are greatest in February, March, and April, as shown by the average monthly discharges for Coosa River (site 3), Black Warrior River (site 8), and Choctawhatchee River near Newton (fig. 1).

Table 1. Surface-water facts for Alabama

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	1,740
Percentage of total population	45
From public water-supply systems:	
Number (thousands)	1,740
Percentage of total population	45
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980 **FRESHWATER WITHDRAWALS**	
Surface water and ground water, total (Mgal/d)	11,000
Surface water only (Mgal/d)	10,000
Percentage of total	97
Percentage of total excluding withdrawals for thermoelectric power	81
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	460
Percentage of total surface water	5
Percentage of total public supply	74
Per capita (gal/d)	264
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	63
Percentage of total surface water	1
Percentage of total livestock	72
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	9,700
Percentage of total surface water	97
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	99
Excluding withdrawals for thermoelectric power	92
Irrigation withdrawals:	
Surface water (Mgal/d)	24
Percentage of total surface water	<1
Percentage of total irrigation	73
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	170,000

PRINCIPAL RIVER BASINS

Alabama is in two water-resources regions—the South Atlantic-Gulf Region and the Tennessee Region (fig. 2). The South Atlantic-Gulf Region in Alabama includes four subregions—the Choctawhatchee-Escambia, the Alabama, the Mobile-Tombigbee, and the Apalachicola. Only the first three are described below; the Apalachicola, which occurs along the southeastern edge of the State, is discussed in the Florida Summary. The Tennessee Region in Alabama includes the Middle Tennessee-Elk and the Middle Tennessee-Hiwassee Subregions; (the Middle Tennessee-Hiwassee Subregion in the northeastern corner of the State is not discussed). These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

SOUTH ATLANTIC-GULF REGION

Choctawhatchee-Escambia Subregion

Rivers in Choctawhatchee Subregion rise in the Coastal Plain in southeastern Alabama and flow southward or southwestward to the Gulf of Mexico. Streams in these basins generally are similar in that they have low to moderate gradients and meander through broad swampy flood plains. Principal surface-water users in this primarily rural subregion are self-supplied industries and agriculture. Two small reservoirs on the Conecuh River have a combined capacity of 2,700 acre-ft (acre-feet) or about 880 Mgal (million gallons) and are used to generate hydroelectric power. Long-term variations in streamflow of the Choctawhatchee River (fig. 2, site 1) are highlighted by the damaging floods of 1929 and 1936 and the extremely dry years of 1954-55, 1968, and 1981. The general water quality in this subregion is good and is suitable for most uses.

Alabama Subregion

The Alabama River rises in northwestern Georgia from the headwaters of the Coosa and the Tallapoosa Rivers. From the northeastern corner of the State, the Coosa flows 286 miles in a general southwesterly direction and, near Montgomery, joins the Tallapoosa to form the Alabama River. The length of the Tallapoosa River in Alabama is 218 miles. Large dams and hydroelectric plants are located on both streams in the steep reaches near the Fall Line. The Alabama River meanders in a general westerly direction 100 miles to Selma and then 215 miles in a southwesterly direction to its confluence with the Tombigbee.

A principal tributary of the Alabama River is the Cahaba River, which rises northeast of Birmingham and flows 195 miles in a southerly direction to its confluence with the Alabama River, 17 miles below Selma.

The Coosa and the Alabama River systems have long been used for transportation as a link to Alabama's port at Mobile. During the Civil War era, steamboats transported goods from upstate Alabama to the gulf coast. Beginning in 1914, dams were constructed for hydroelectric-power generation, flood control, and navigation locks. Lay, Mitchell, and Jordan Dams, with a combined storage capacity of 671,000 acre-ft or 219,000 Mgal, were completed in the lower reaches of the Coosa River during 1914 to 1928. During the 1960's, four additional dams—Weiss, H. Neely Henry, Logan Martin, and Bouldin—were completed with a combined storage capacity of 745,000 acre-ft or 242,000 Mgal. These storage reservoirs, which dampen extremes in runoff, provide uniform flow for hydroelectric and industrial uses, the principal water users in the basin, and have increased recreational uses, primarily fishing and boating. Data on streamflow characteristics before and after regulation of the Coosa and the Alabama Rivers are given in table 2 (sites 3 and 5). The average annual discharge on the unregulated Tallapoosa River (site 4) is 2,594 ft^3/s or a runoff yield of 1.6 $(ft^3/s)/mi^2$ (cubic foot per second per square mile) compared with a runoff yield of 1.7 $(ft^3/s)/mi^2$ for the regulated Coosa River (site 3). The 15-year moving average of average annual discharge for the Coosa River (site 3) has gradually increased since the late 1950's and may reflect variations in regional precipitation (fig. 2).

As part of the Coosa-Alabama River development, three lock and dam projects with a combined storage capacity of 566,000 acre-ft or 184,000 Mgal were completed on the Alabama River between 1963 and 1970—a navigation lock and dam at Claiborne, a combination navigation lock and hydroelectric-power dam at Millers Ferry, and a combination navigation lock and hydroelectric power dam at Jones Bluff.

Mobile-Tombigbee Subregion

The Tombigbee River rises in northeastern Mississippi, enters Alabama near the center of the western boundary of the State, flows southward 254 miles, and joins the Alabama River 45 miles north of Mobile to form the Mobile River.

The principal tributary to the Tombigbee River is the Black Warrior River, which is formed by two smaller forks 20 miles west of Birmingham and flows southwestward 178 miles to the Tombigbee River at Demopolis. A series of locks and dams allows river transportation of industrial products, such as coal, lumber, and timber products, to Mobile. Although a few small hydroelectric powerplants are located at control structures on the upper Black Warrior, the primary use of the river is for navigation. The 15-year moving average of average annual daily discharge for the Black Warrior has gradually increased since the mid-1960's and has remained higher than the moving average for the previous years of record and may reflect variations in regional precipitation.

Activities associated with completion of the Tennessee-Tombigbee Waterway, which included construction of navigation locks and dams near Gainesville and Aliceville and channel improvements downstream, have altered the streamflow characteristics of the Tombigbee River in Alabama. The 15-year moving averages for average annual daily discharges of Black Warrior River (site 8) and Tombigbee River (site 9) indicate a general increase in streamflow since the mid-1960's compared to other sites in Alabama (fig. 2). Three of the five wettest years of record have occurred since the mid-1960's. The general water quality in this subregion is good and is suitable for most uses.

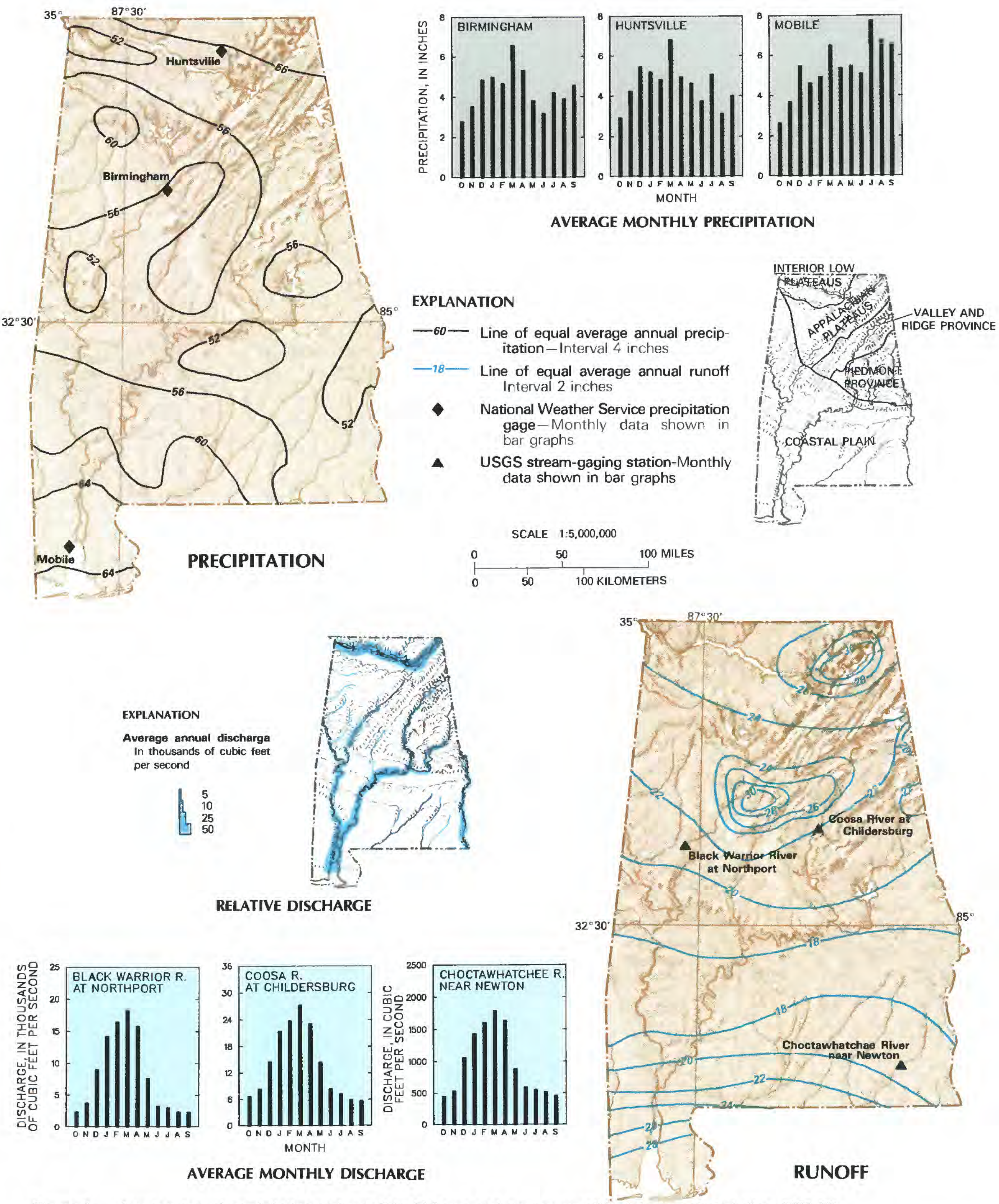

Figure 1. Average annual precipitation and runoff in Alabama and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954, divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Alabama

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest average discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of average annual discharges during the period of analysis. The 100-year flood is the peak flow that has a 1-percent chance of being equaled or exceeded in a given year. The degree of regulation is the effect of dams on the natural flow of the river. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Alabama State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				SOUTH ATLANTIC-GULF REGION **CHOCTAWHATCHEE-ESCAMBIA SUBREGION**				
1.	Choctawhatchee River near Newton (02361000).	686	1923-26 1937-83	88	983	40,900	Negligible	Major water use is agricultural.
2.	Conecuh River at Brantley (02371500).	500	1937-83	31	680	27,300	. . . do . .	
				ALABAMA SUBREGION				
3.	Coosa River at Childersburg (02407000).	8,392	1915-68 1969-78	2,000 1,330	13,860 13,860	157,600 144,900	Negligible Appreciable	Regulation by reservoirs upstream completed between 1949 and 1968. Major water uses are hydroelectric, recreation, and industrial supply.
4.	Tallapoosa River at Wadley (02414500)	1,675	1923-83	140	2,594	73,800	Negligible	Major water uses are hydroelectric and recreation.
5.	Alabama River near Montgomery (02420000).	15,087	1927-68 1969-83	5 240 3,860	24,260 24,260	317,000 219,500	. . . do . . . Appreciable	Regulation by reservoirs on Coosa and Tallapoosa Rivers completed between 1929 and 1968. Major water uses are industrial supply, hydroelectric, and recreation.
				MOBILE-TOMBIGBEE SUBREGION				
6.	Cahaba River at Centreville (02424000).	1,027	1902-07, 1931, 1937-83	143	1,633	117,000	Negligible	
7.	Mulberry Fork near Garden City (02450000).	365	1928-83	4.9	681	51,300	. . . do . . .	
8.	Black Warrior River at Northport (02465000).	4,820	1895-1902, 1929-60 1961-83	90 504	8,041 8,041	221,000 305,400	. . do . . . Appreciable	Some regulation by Lewis Smith Lake (completed 1960). Major water uses are navigation, hydroelectric, and industrial supply.
9.	Tombigbee River at Demopolis Lock and Dam near Coatopa (02467000).	15,385	1928-83	685	23,500		Negligible	Major water uses are navigation and industrial supply.
				TENNESSEE REGION **MIDDLE TENNESSEE-ELK SUBREGION**				
10.	Flint River near Chase (03575000).	342	1930-83	66	554	75,200	Negligible	
11.	Tennessee River at Florence (03589500)	30,810	1894-1983	7,490	51,900	. . . .	Appreciable	Flows regulated. Major water uses are navigation, hydroelectric, industrial supply, and recreation.

[1] Flood frequency information may be obtained from the U S Army Corps of Engineers.

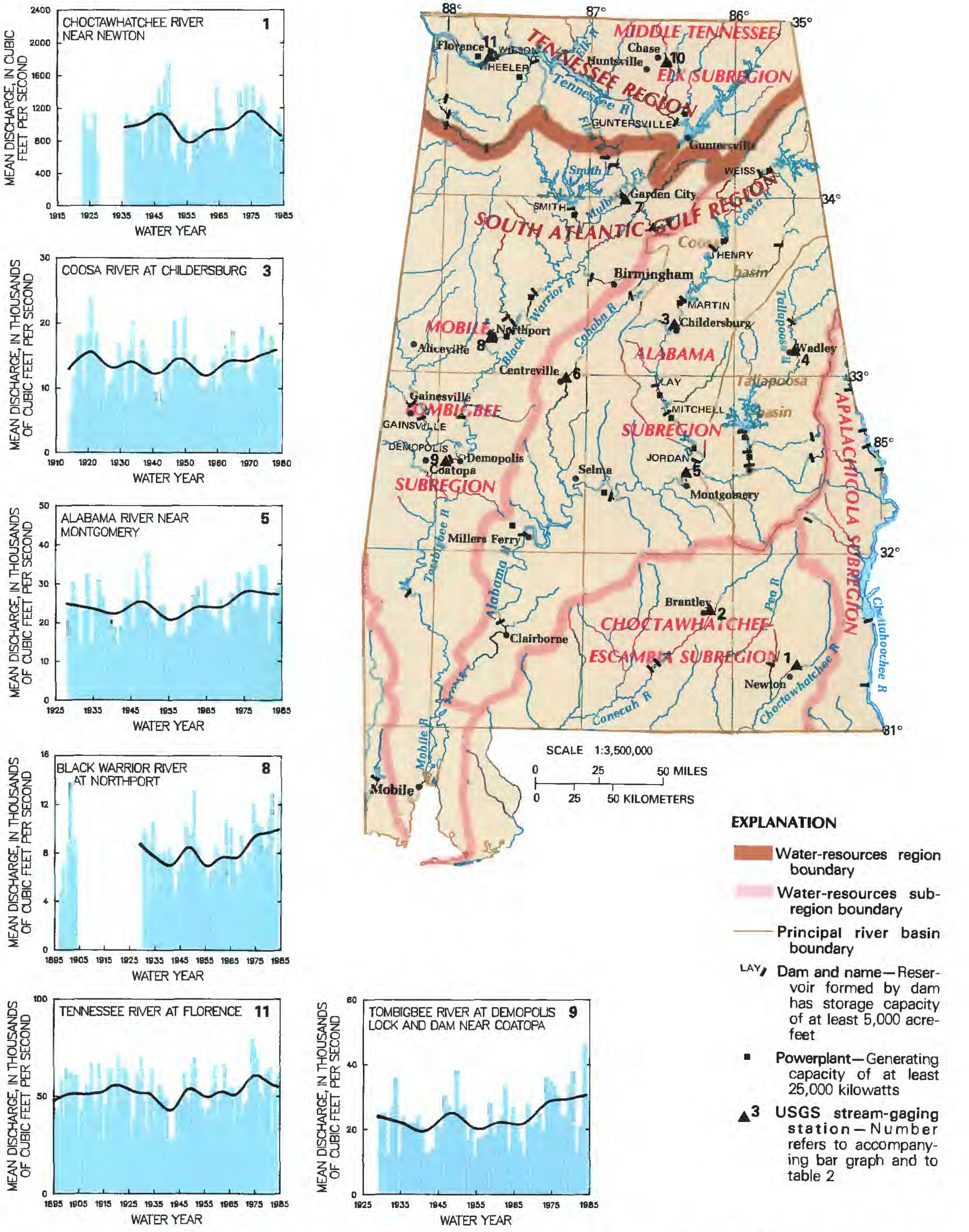

Figure 2. Principal river basins and related surface-water resources development in Alabama and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

TENNESSEE REGION

Middle Tennessee-Elk Subregion

The Tennessee River enters Alabama at the northeastern corner of the State, flows southwestward for about 60 miles to Guntersville, turns westward, and leaves the State at its northwestern corner. The drainage area of the Tennessee River at Florence is 30,810 mi^2 (22 percent of the State), approximately 6,700 mi^2 of which is in Alabama. The principal tributary—the Elk River—enters the State from Tennessee. A series of large dams regulate the Tennessee River but only three—Guntersville, Wheeler, and Wilson—are in Alabama. Combined storage capacity of these multipurpose reservoirs, which were completed in 1939, 1936, and 1924, respectively, is about 1,393,000 acre-ft or 454,000 Mgal. The flow of the unregulated Flint River near Chase (table 2, site 10) is characteristic of tributary flows in this subregion. The general water quality in this subregion is good and is suitable for most uses.

SURFACE-WATER MANAGEMENT

Surface-water resources of Alabama are managed by both public and private agencies. Because the State has enacted relatively few water-related statutes, the administrative responsibility for enforcing statutory water laws is divided among several agencies. The Alabama Department of Environmental Management (ADEM) is responsible for the quality of public drinking-water supplies and water-pollution control. Some streamflow requirements for river management often are established by the Federal Energy Regulatory Commission or State regulatory agencies through licensing procedures. The State Department of Conservation is responsible for the water quality in game management areas of the State.

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 surface-water management decisions can be made.

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FOR ADDITIONAL INFORMATION

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ALASKA
Surface-Water Resources

Alaska contains more than 40 percent of the Nation's surface-water resources, but most of the rivers and lakes are undeveloped and unaffected by humans. However, water is not always available where and when it is needed. For example, the most readily available and economical local water sources will be insufficient to meet projected demands at Anchorage and Juneau. Surface-water sources are not always dependable during the winter; some streams freeze completely or have periods of very low flows or no flow. Conversely, too much water occasionally is a problem. Ice-jam floods are common on many rivers during periods of snowmelt, and summer floods have caused extensive damage on other streams.

Generally, surface water is of suitable quality for most uses; but, in some areas, local degradation occurs from human activities or from natural causes. Suspended sediment in glacier-fed rivers makes the water unsuitable for most uses without some treatment. Alaska's principal surface-water issues are to maintain its good water quality, to minimize adverse effects on water resources when development occurs, and to improve conditions adversely affected by development.

Surface water supplies 32 percent of the State's population and 78 percent of the total water withdrawn for offstream use. Only 18 percent of this use is for public supply; the remainder is for fish processing, pulp mills, mining, and other industrial uses. In 1980, water used instream for hydropower generation was 3.5 times more than that used offstream. Surface-water withdrawals in Alaska in 1980 for various purposes and related statistics are given in table 1.

Table 1. Surface-water facts for Alaska

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	127
Percentage of total population	32
From public water-supply systems:	
Number (thousands)	113
Percentage of total population	28
From rural self-supplied systems:	
Number (thousands)	14
Percentage of total population	4
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	220
Surface water only (Mgal/d)	170
Percentage of total	77
Percentage of total excluding withdrawals for thermoelectric power	78
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	30
Percentage of total surface water	18
Percentage of total public supply	57
Per capita (gal/d)	265
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.1
Percentage of total surface water	<1
Percentage of total rural domestic	1
Per capita (gal/d)	10
Livestock:	
Surface water (Mgal/d)	0.1
Percentage of total surface water	<1
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	140
Percentage of total surface water	82
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	91
Excluding withdrawals for thermoelectric power	95
Irrigation withdrawals:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total irrigation	100
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	770

GENERAL SETTING

Wahrhaftig (1965) defined four major physiographic divisions—Pacific Mountain System, Intermontane Plateaus, Rocky Mountain System, and Arctic Coastal Plain (fig. 1). The Pacific Mountain System contains the Coast Mountains, Alaska Range, Aleutian Range, Aleutian Islands, and a parallel southern arc of lower elevation mountains in the islands of southeastern Alaska and along the Gulf of Alaska. The Intermontane Plateaus, which consist of dissected uplands, broad alluvial valleys, and lowland basins, lie between the Alaska Range and the Brooks Range of the Rocky Mountain System.

Alaska has four climatic zones (Hartman and Johnson, 1978, p. 59-61)—Maritime, Transition, Continental, and Arctic (fig. 1). The State's high mountain ranges, extensive ocean bounds, and vast size—one-sixth of the total area of the United States—are the principal causes of the great differences in climatic conditions and in the diverse patterns and amounts of runoff throughout the State. From the southern part of the Maritime Zone to the northern part of the Arctic Zone, average annual precipitation and temperature range from 320 to 5 inches and from 45 to 10 °F (degrees Fahrenheit), respectively. In the Maritime Zone, two-thirds of the annual precipitation occurs from September through March; October usually is the wettest month (fig. 1, bar graph for Annette). The driest period is from mid-May through July. In the Continental and Arctic Climatic Zones, about two-thirds of the precipitation falls from June through November and the driest months are March through May (fig. 1, bar graphs for Talkeetna and Barrow). In the Transition Zone, seasonal precipitation patterns are not sharply defined, fluctuate from year to year, and may resemble those of either the Maritime or Continental Zones. In low-elevation areas of the Maritime Zone, snow falls but usually melts fairly rapidly. Along the Arctic coast, snow generally falls from mid-September to mid-June but may occur in July and August. At higher elevations, snow falls throughout the year. Glaciers cover 5 percent of the State and are present mainly in the Coast Mountains, the Alaska Range, and the mountains bordering the Gulf of Alaska.

Average annual runoff for the State is about 25 inches, but the amount varies significantly depending on location (fig. 1). In southeastern Alaska, average runoff is about 150 inches, but locally it may be as much as 300 inches (not shown on map). At the other extreme, runoff averages about 8 inches north of the Brooks Range, but the average is only 4 inches in some Arctic coastal areas. No consistent statewide, long-term trend in streamflow is evident in the bar graphs of average annual discharges in figure 2.

Seasonal variations in streamflow result from precipitation and temperature fluctuations; ranges in basin elevation; and the effects of natural storage and release from the snowpack, glaciers, and lakes. Most streamflow patterns in the Maritime Climatic Zone are similar to those for Fish Creek (fig. 1); peak-flow periods occur

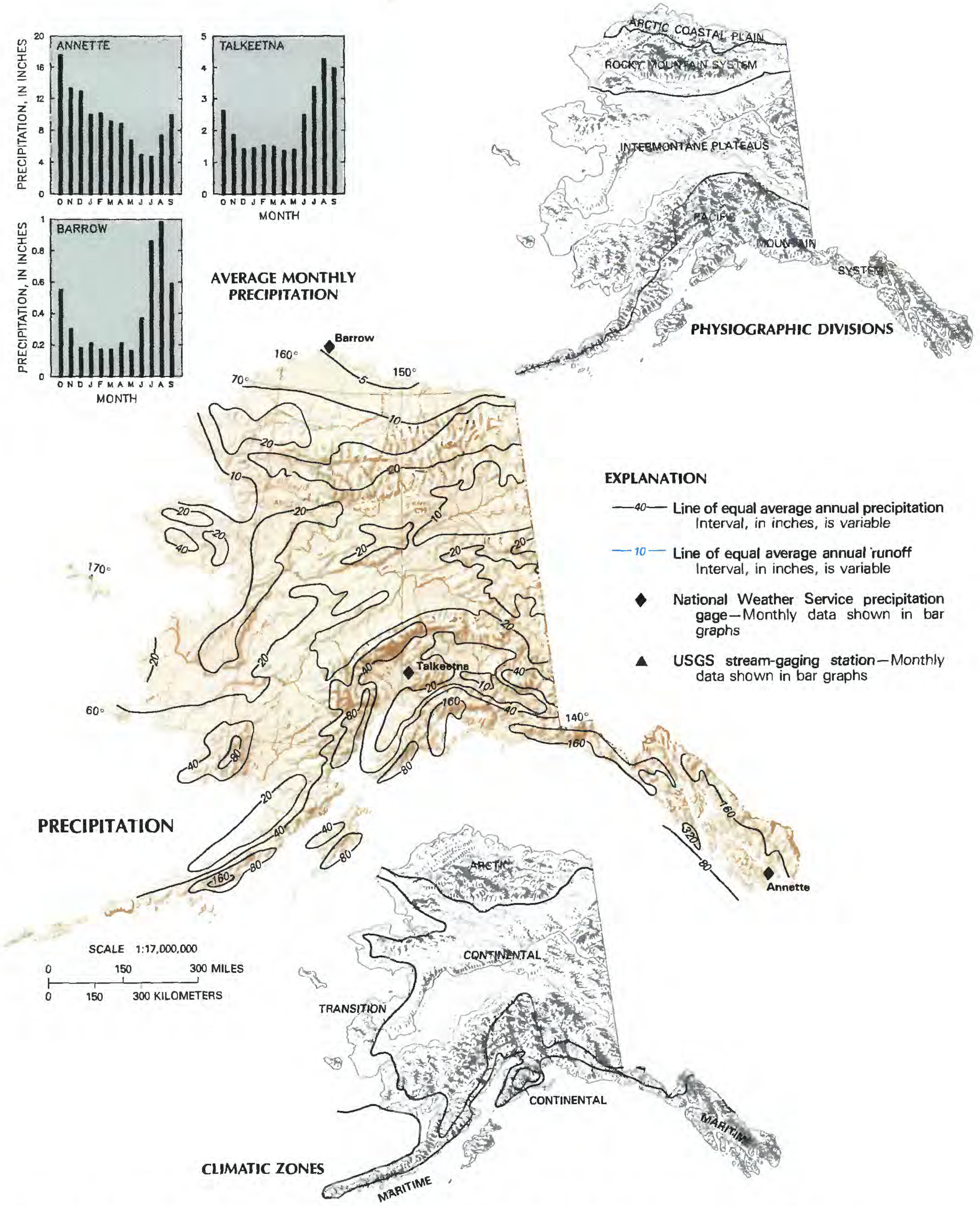
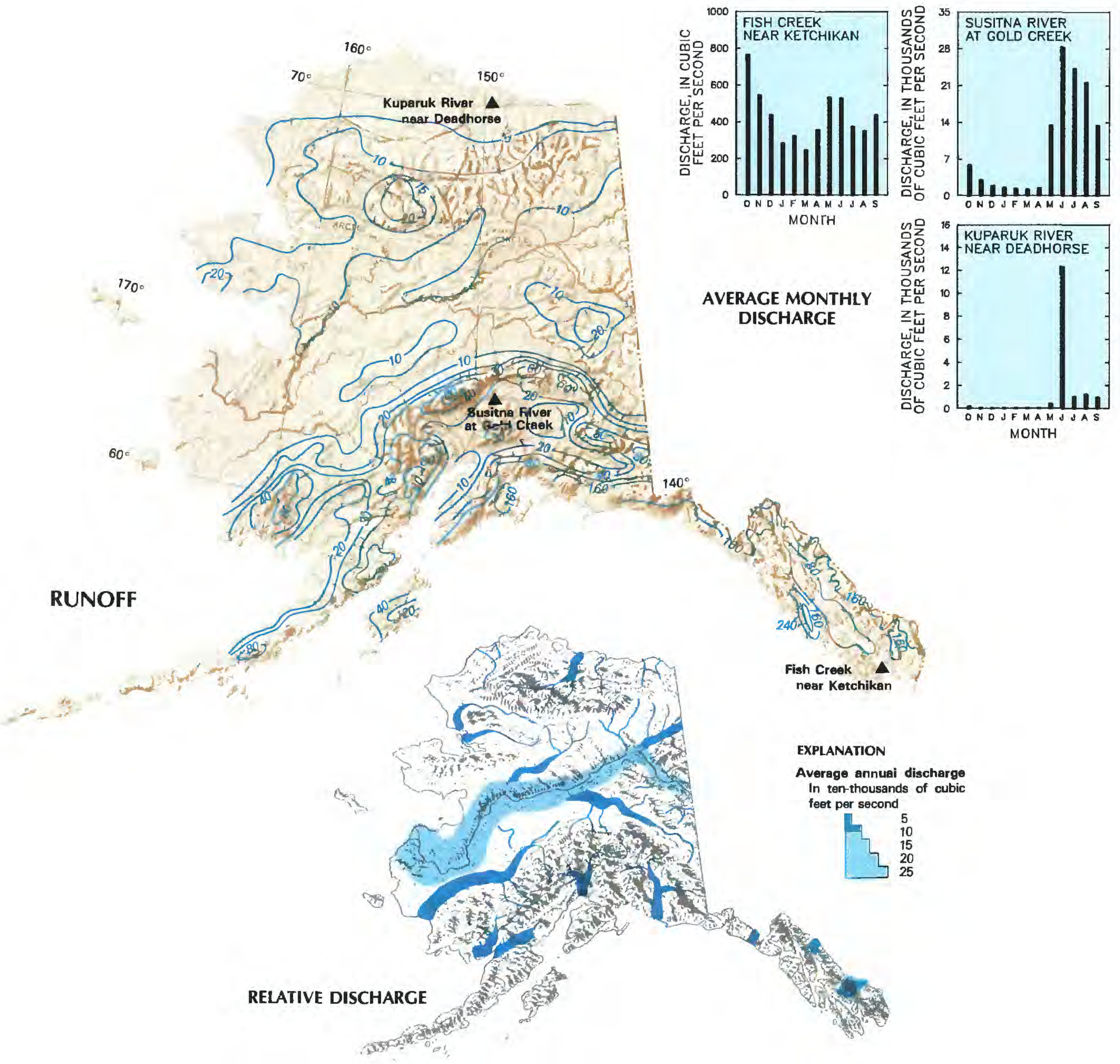


Figure 1. Average annual precipitation and runoff in Alaska and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data modified from National Weather Service, 1972; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data, and discharge data at mouth of principal rivers, from U.S. Geological Survey files. Physiographic diagram from Harrison, 1969; divisions from Wahrhaftig, 1965. Climatic zones from Hartman and Johnson, 1978.)


RUNOFF

AVERAGE MONTHLY DISCHARGE

RELATIVE DISCHARGE

AVERAGE DISCHARGE AT MOUTH OF PRINCIPAL RIVERS

[Units in thousands]

RIVER	AREA (mi²)	DIS-CHARGE (ft³/s)	RIVER	AREA (mi²)	DIS-CHARGE (ft³/s)
Stikine	20.0	56	Nushagak	b 12	b 32
Taku	6.6	a 20	Kuskokwim	48	67
Alsek	11	a 30	Yukon	328	225
Copper	24.4	59	Porcupine	45.1	23
Chitina	7.9	a 20	Tanana	44.5	41
Susitna	20.0	51	Koyukuk	32.4	22
Yentna	6.2	21	Kobuk	12.0	18
Kvichak	9.6	21	Colville	23,3	a 20

a—Approximate b—Does not include Wood River

Figure 1. Average annual precipitation and runoff in Alaska and average monthly data for selected sites, 1951-80—Continued.

(Sources: Precipitation—annual data modified from National Weather Service, 1972; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data, and discharge data at mouth of principal rivers, from U.S. Geological Survey files. Physiographic diagram from Harrison, 1989; divisions from Wahrhaftig, 1965. Climatic zones from Hartman and Johnson, 1978.)

in the fall and spring due to rainfall and snowmelt, respectively. However, the seasonal flow distribution in some southeastern-mainland streams, whose basins contain glaciers in their higher elevations, are similar to those for other high-elevation mountain streams throughout the State.

The seasonal flow pattern of the Susitna River (fig. 1) is characteristic of most large major rivers and of streams in the State's interior, but the temporal distribution in flow varies with basin elevation, latitude, and relative amounts of natural storage in lakes and glaciers. Discharge increases when snowmelt at lower elevations begins in late May or June, and it peaks in the following month; flow is sustained through the summer by rain, snowmelt at higher elevations, and runoff from glaciers. Most low-elevation basins have two high-flow periods—during the spring snowmelt period and a late-summer rainy period. The Kuparuk River (fig. 1) is characteristic of streams on the Arctic Coastal Plain that have short, intense, snowmelt-runoff periods but little response to summer rains.

According to Iseri and Langbein (1974), 16 rivers in Alaska qualify as "large" rivers because average annual discharge exceeds 17,000 ft^3/s (cubic feet per second) or 11,000 Mgal/d (million gallons per day). Estimated average discharges at the mouth of the 16 rivers are shown in figure 1.

Lakes cover about 1 percent of Alaska. Ninety-five lakes have a surface area larger than 10 mi^2 (square miles), eight are larger than 100 mi^2, and one (Iliamna Lake) has an area of 1,000 mi^2 (Bue, 1963). The State has an estimated 3 million lakes larger than "pond-size," mainly in lowland areas of the Yukon-Kuskokwim Delta, Yukon Flats, and Arctic Coastal Plain. Twenty-two reservoirs (fig. 2) have usable storage capacities of more than 5,000 acre-ft (acre-feet) or 1,600 Mgal (million gallons).

PRINCIPAL RIVER BASINS

The Alaska Water-Resources Region, which coincides with the State of Alaska, contains six subregions (fig. 2). The tabulation below (modified from Balding, 1976) summarizes runoff originating in each subregion. If part of the drainage area is in Canada, the drainage size and inflows to Alaska are given in parentheses.

[m^2 = square miles; ft^3/s = cubic feet per second]

Subregion	Drainage area (thousand mi^2)	Runoff (thousand ft^3/s)	Subregion	Drainage area (thousand mi^2)	Runoff (thousand ft^3/s)
Southeast.....	45 (35)	500 (120)	Yukon.....	210 (130)	154 (78)
South-Central	80 (1)	207 (5)	Northwest	67	78
Southwest....	108	224	Arctic.....	81	44

The location of the subregions, and long-term variations in streamflow at representative streamflow-gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2. The Hydrologic Unit Map for Alaska is being revised. Table 2 and figure 2 use provisional information from the proposed map. A few subregion boundaries and names were changed from the previous map.

ALASKA REGION

Southeast Alaska Subregion

The Southeast Alaska Subregion encompasses the mountainous, glaciated southeastern panhandle of Alaska and includes hundreds of islands, which comprise 37 percent of the subregion's area. Most drainage basins in the subregion are smaller than 200 mi^2; however, basins with headwaters in Canada are larger. Runoff from the subregion (including inflow from Canada) is almost as much as that of the Mississippi River.

Twelve hydroelectric reservoirs (mountain lakes that have been dammed at their outlets) have a total usable storage capacity of 624,000 acre-ft or 203,400 Mgal. Blue Lake (150,000 acre-ft or 48,900 Mgal) and Long Lake (140,000 acre-ft or 45,600 Mgal) have the largest usable storage capacities. The Snettisham Project (Long Lake) has 70,000 kW (kilowatts) of power generation capacity; the capacity of each of the other powerplants is less than 25,000 kW. The largest natural lake is Bering Lake (surface area about 17 mi^2) near Cordova. Offstream users are pulp mills at Ketchikan and Sitka, seafood processors, and public water-supply systems. The development of small, local streams to meet growing demands in outlying areas is being considered at Juneau.

South-Central Alaska Subregion

The South-Central Alaska Subregion lies between the crest of the Alaska and the Aleutian Ranges and the Gulf of Alaska and includes Kodiak Island (Alaska's largest island at 3,670 mi^2) and several smaller islands. The principal river basins—the Copper and the Susitna—comprise 56 percent of the subregion. Tustumena Lake (117 mi^2) is the largest lake, and 15 other lakes are 10 mi^2 or larger in area.

Four hydroelectric reservoirs have a total usable storage capacity of 380,500 acre-ft or 124,000 Mgal. Eklutna Lake, with 163,300 acre-ft or 53,220 Mgal of usable capacity, is the largest and supplies the Eklutna project (30,000 kW).

Offstream uses are for public water supply and industrial use, primarily seafood processing. The Municipality of Anchorage, home to half of Alaska's population, has begun construction of a pipeline to Eklutna Lake to augment the water supply in developed areas. Water from the glacier-fed lake will have to be treated to remove suspended sediment; also, an alternate means of power generation will be provided to compensate for power lost in the Eklutna project. The municipality recently has embarked on a program to reduce pollution of urban streams.

Southwest Alaska Subregion

The Southwest Alaska Subregion includes basins that drain to the southwest into Kuskokwim and Bristol Bays, the Aleutian Islands (6,820 mi^2), and many other islands. The principal river basins—the Kuskokwim, the Nushagak, and the Kvichak—comprise 64 percent of the subregion. Iliamna, Becharof, Naknek, Clark, and Dall Lakes have surface areas of 1,000, 458, 242, 110, and 100 mi^2, respectively; 50 more lakes are 10 mi^2 or larger. The interconnected stream and lake systems draining to Bristol Bay constitute the most productive area for salmon in Alaska. Floods, particularly those caused by recurrent ice jams, occur along the

Kuskokwim River and other large streams. Relatively small amounts of water are withdrawn for domestic supply, mining, and fish processing.

Yukon Subregion

The Yukon Subregion is virtually equivalent to the Yukon River basin, which extends across interior Alaska between the Alaska and the Brooks Ranges. Outflow at the mouth of the Yukon River is about 225,000 ft^3/s or 145,000 Mgal/d; inflow from Canada (table 2, site 10) is about 83,000 ft^3/s or 53,600 Mgal/d. Major tributaries are the Tanana, the Porcupine, and the Koyukuk Rivers. According to Bue (1963), the largest lakes in the subregion are Kgun Lake (31 mi^2) and Tetlin Lake (27 mi^2). Eight other lakes in the Yukon Delta and another farther upstream are 10 mi^2 or larger. Floods on the Yukon River and its major tributaries are caused by ice jams in May or early June and by rainstorms later in the year. The maximum recorded discharge (1,030,000 ft^3/s or 666,000 Mgal/d) on the Yukon River was at Kaltag (drainage area, 296,000 mi^2) on June 22, 1964. Extreme floods in the Tanana River basin occur in July or August from a combination of runoff caused by melting of snow and glacier ice at high elevations and areawide rainstorms. The State's most damaging flood occurred August 15, 1967, on the Chena River, when about 95 percent of Fairbanks was inundated. Floodwaters of the Chena River are temporarily stored (since 1981) in Moose Creek Reservoir, which has a capacity of 160,000 acre-ft or 52,000 Mgal, and may be diverted to the Tanana River when reservoir capacity is exceeded. Principal water uses are for cooling fossil-fuel powerplants, placer mining, and public water-supply systems. The principal surface-water issue in the subregion concerns placer mining and its effects on water quality; particularly, how to efficiently control the amount of sediment downstream from the mining area.

Northwest Alaska Subregion

The Northwest Alaska Subregion consists of the drainage basins of rivers that flow westward into Kotzebue and Norton Sounds. The principal rivers are the Kobuk and the Noatak; their basins comprise 36 percent of the subregion. Although their drainage areas are similar, flow in the Noatak is only about three-fourths that of the Kobuk River. Selawik Lake—a tidal, saline lake (400-mi^2)—is the largest in the subregion. The largest freshwater lakes are Imuruk Lake (26 mi^2) and Walker Lake (14 mi^2) (fig. 2). Surface water is used mainly for rural domestic purposes and for a few public water-supply systems.

Arctic Subregion

The streams in the Arctic Subregion flow northward from the Brooks Range into the Arctic Ocean. The Colville River—the subregion's largest—flows eastward for 200 miles before turning north; its basin comprises 29 percent of the subregion. Teshekpuk Lake has a surface area of 315 mi^2; two other lakes are larger than 10 mi^2. Because of the underlying permafrost, more than half of the flat, western parts of the coastal plain are covered by shallow lakes. Water is used mainly for domestic purposes and for petroleum development and production. The rivers, except for a few that are fed by springs, have no-flow periods during the winter. The larger deep lakes are a more dependable water-supply source. If water is withdrawn during the winter from shallow lakes or from rivers, the "overwintering" habitat of fish can be impaired or destroyed.

SURFACE-WATER MANAGEMENT

The "Alaska Water Use Act" (Alaska Statutes 46.15.010-270, enacted in 1966 and amended in 1980) defines the doctrine of prior appropriation authorized by the State Constitution, and it delegates administration of the act to the Alaska Department of Natural Resources (ADNR). The act states "Wherever occurring in a natural state, the waters are reserved to the people for common use and are subject to appropriation and beneficial use and to reservation of instream flows and levels of water, . . ." (Alaska Department of Natural Resources, 1985, p. 39). The regulations provide for certifying water rights for users prior to 1966 and for obtaining rights to appropriate surface and subsurface waters thereafter. ("Appropriate" means to divert, impound, or withdraw water or to reserve water for instream uses, including fisheries, navigation, recreation, and water-quality purposes (Alaska Department of Natural Resources, 1985, p. 48).) Dam safety is also covered in the act.

The Alaska Department of Environmental Conservation enforces Alaska's Water Quality Standards established in Title 18, Chapter 70 of Alaska Administrative Code. The standards identify limits to allowable pollution (Alaska Department of Environmental Conservation, 1979). The Alaska Department of Fish and Game, Alaska Statutes 16.05.840 and 16.05.870, has permit jurisdiction over activities that could affect fish (Alaska Department of Fish and Game, 1984).

Alaska has 25 rivers in the National Wild and Scenic Rivers System; 12 other rivers are being studied for possible inclusion. The designated rivers are administered by the following U.S. Department of the Interior agencies: National Park Service, Fish and Wildlife Service, and Bureau of Land Management. These agencies and the other Federal land-management agencies in Alaska—the Forest Service (Department of Agriculture) and the Department of Defense—also have water-related responsibilities. The U.S. Army Corps of Engineers, U.S. Coast Guard, U.S. Fish and Wildlife Service, National Marine Fisheries Service, and U.S. Environmental Protection Agency have review and permitting responsibilities for specific activities on navigable rivers, wetlands, anadromous fish streams, and other water bodies.

The Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys (DGGS), is the designated State agency responsible for water-data collection. Most long-term surface-water data are collected and interpreted by the U.S. Geological Survey in cooperation with other Federal, State, and municipal agencies. Short-term, special-purpose data are collected by the U.S. Geological Survey, DGGS, and other agencies. 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 studies in the State (U.S. Geological Survey and Alaska Department of Natural Resources, 1985).

Table 2. Selected streamflow characteristics of principal river basins in Alaska

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				ALASKA REGION SOUTHEAST ALASKA SUBREGION				
1.	Stikine River near Wrangell (15024800).	19,920	1976-83	[1]4,500	56,674	[1]299,600	Moderate	Flow crosses international boundary. Major tributary is regulated.
2.	Fish Creek near Ketchikan (15072000).	32.1	[2]1915-36 1936-83	31	421	5,420	None	Longest record in Alaska. Representative island stream.
				SOUTH-CENTRAL ALASKA SUBREGION				
3.	Copper River near Chitina (15212000).	20,600	1955-83	3,040	37,670	321,000	None	Large stream draining part of Alaska Range.
4.	Susitna River at Gold Creek (15292000).	6,160	1949-83	723	9,724	115,000	. . . do . . .	Drainage basin in Alaska Range. Proposed hydropower development. Long-term record.
5.	Susitna River at Susitna Station (15294350).	19,400	1974-63	[1]5,000	49,940	[1]230,000	. . . do . . .	Large stream draining part of Alaska Range.
				SOUTHWEST ALASKA SUBREGION				
6.	Kvichak River at Igiugig (15300500).	6,500	1967-83	7,380	18,060	65,500	None	Iliamna Lake and other smaller lakes total 1,100 mi^2.
7.	Nuyakuk River near Dillingham (15302000).	1,490	1953-83	1,100	6,156	36,200	. . . do . . .	Representative long-term record.
8.	Nushagak River at Ekwok (15302500)	9,850	1977-63	[1]6,000	23,840	[1]89,200	. . . do. . .	Large stream. Headwaters of main tributary drain Aleutian Range.
9.	Kuskokwim River at Crooked Creek (15304000).	31,100	1951-63	7,850	41,220	445,000	. . . do. . .	Large stream draining part of Alaska Range.
				YUKON SUBREGION				
10.	Yukon River at Eagle (15356000).	113,500	[2]1911-13, 1950-63	10,500	82,660	605,000	Negligible	Flow crosses international boundary.
11.	Porcupine River near Fort Yukon (15389000).	29,500	1964-79	[3]6	14,230	476,000	None	Headwaters in Canada.
12.	Chena River at Fairbanks (15514000).	1,980	1946-83	150	1,384	[4]38,800	Moderate	Some flood control by Moose Creek Dam since 1981.
13.	Tanana River at Nenana (15515500).	25,600	1962-83	4,740	23,550	[5]153,000	Negligible	Large river draining part of Alaska Range.
14.	Koyukuk River at Hughes (15564900).	16,700	1960-62,	267	14,540	332,000	None	Large river draining part of Brooks Range.
15.	Yukon River at Pilot Station (15565447).	321,000	1975-63	[1]37,000	219,600	[1]751,000	Negligible	Gaged at head of distributary delta. Largest river in Alaska.
				NORTHWEST ALASKA SUBREGION				
16.	Kobuk River near Kiana (15744500).	9,520	1976-83	[1]1,300	15,270	[1]152,000	None	Large river.
				ARCTIC SUBREGION				
17.	Kuparuk River near Deadhorse (15896000).	3,130	1971-83	No flow	1,367	218,000	. . . do . . .	Longest record in subregion. Representative stream.

[1] Less than 10 years of record. Minimum discharge and maximum instantaneous discharge for period of record are shown.

[2] Record interrupted.

[3] Adjusted for no-flow periods.

[4] Adjusted for high-outlier in period of record. Did not use 1981 peak because it was regulated.

[5] Adjusted for high-outlier in period of record.

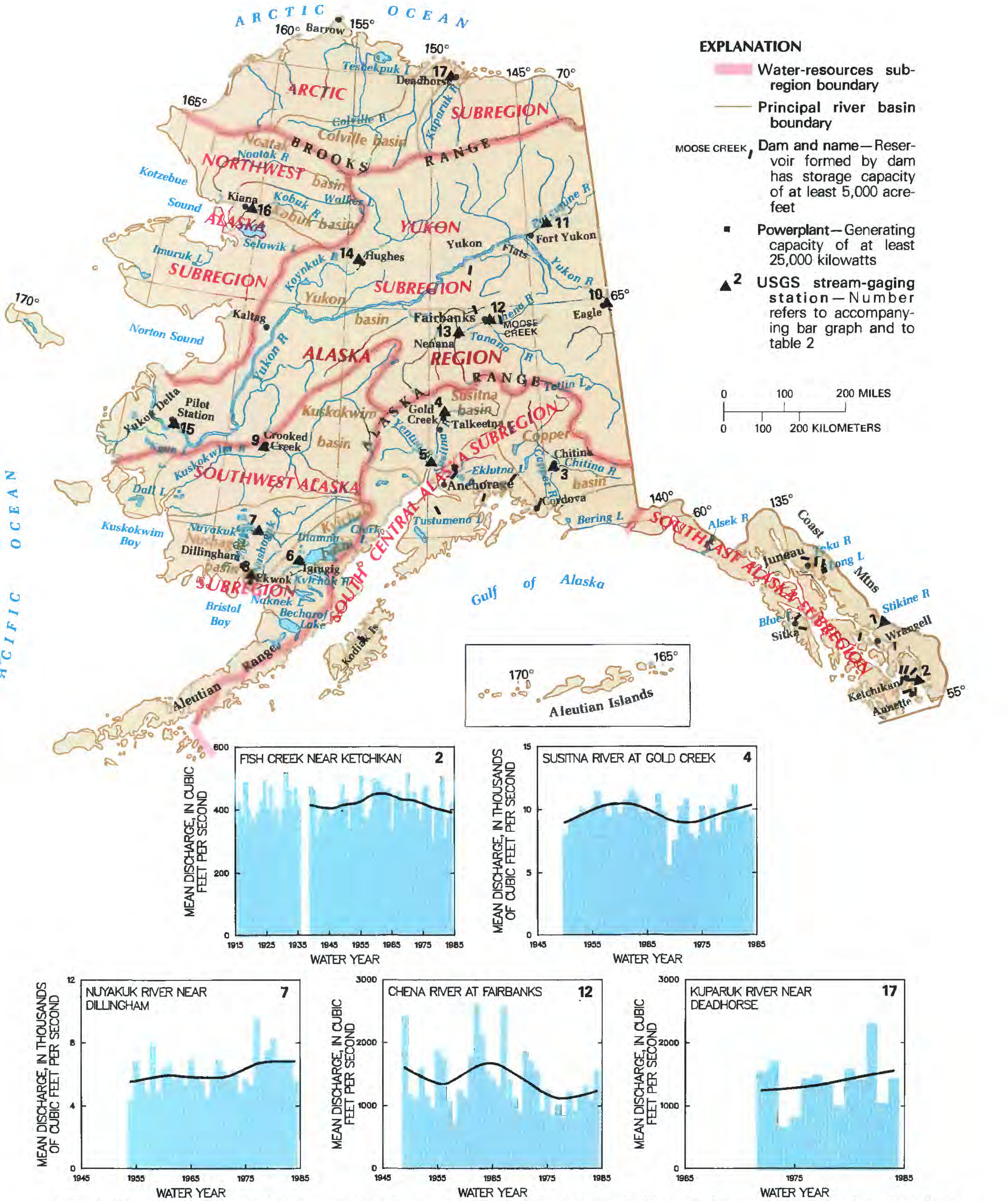


Figure 2. Principal river basins and related surface-water resources development in Alaska and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions modified from Seaber and others, 1984; surface-water-resources development from Alaska Department of Natural Resources, 1983, and from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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FOR ADDITIONAL INFORMATION

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ARIZONA
Surface-Water Resources

Surface water, which is a limited resource in Arizona, serves about 35 percent of the population of the State. The climate is arid throughout most of the State, and high evapotranspiration reduces the availability of surface-water resources. Virtually all surface water has been appropriated. Major surface-water issues in Arizona include flooding, quantification of Indian water rights, adjudication of water rights in the Gila and the Little Colorado River basins, and the interaction of surface-water and ground-water systems. Generally, surface water is of suitable quality for most uses.

Ephemeral streams typify drainage in most of Arizona. However, the Colorado River, which provides about half of the surface water currently used in Arizona, contains perennial flow that represents runoff from the Upper Colorado River basin. Other perennial streams that drain the mountainous central part of the State provide the remaining half of the surface-water supply. Ten major storage reservoirs regulate flow in perennial streams such as the Little Colorado, the Gila, the Salt, the Verde, and the Agua Fria Rivers; other smaller reservoirs on small tributaries also regulate flow. Flow in the Colorado River is regulated by four storage reservoirs and three diversion dams. In a few places in the State, water is diverted from unregulated streamflow.

Of the total water withdrawals in 1980, about 42 percent—3,000 Mgal/d (million gallons per day) or 4,600 ft³/s (cubic feet per second)—was from surface-water sources (table 1). Of this amount, about 2,700 Mgal/d or 4,200 ft³/s or 90 percent, along with 88 percent of the ground-water withdrawal, was used for irrigation of 2 percent of the land area, which accounted for 7 percent of the income in the State in 1980 (Valley National Bank of Arizona, 1983, p. 2). The principal crop in the State is cotton, which represented 47 percent of the 1,343,000 acres of harvested land in 1980 (Arizona Crop and Livestock Reporting Service, 1981, p. 140); other major crops include alfalfa, grains, vegetables, and citrus. In parts of Arizona, ground water provides all or nearly all the useful supplies, and during the last several decades increased water demand has been met by increased withdrawals of ground water (U.S. Geological Survey, 1985, p. 135). Only 9 percent of the total surface-water supply was for public-supply use in 1980.

GENERAL SETTING

Arizona has been divided into three water provinces that are virtually synonymous with its physiography—the Plateau Uplands in the northern part of Arizona, the Basin and Range Lowlands in the southern part, and the Central Highlands (fig. 1). In each of these three water provinces, water conditions and problems are different because of the variety of geographic, geologic, and climatic conditions.

In the Plateau Uplands, flat-lying sedimentary rocks underlie the province, and, in places, volcanic mountain peaks rise to more than 8,000 feet above sea level. Annual precipitation ranges from less than 10 to more than 25 inches. The Basin and Range Lowlands province is characterized by broad alluvium-filled valleys bounded by steeply rising mountain ranges, and annual precipitation ranges from 4 to 12 inches. The Central Highlands province, which is mostly mountainous and contains rock types of both adjacent provinces, has annual precipitation that ranges from 15 to more than 25 inches.

Throughout Arizona, average annual precipitation varies widely both geographically and seasonally (fig. 1). In general, two seasons of precipitation are common. The summer season, particularly July and August, is the wettest, and precipitation occurs as intense thunderstorms of short duration. The second rainy season is December through mid-March. At the higher altitudes, much of the winter precipitation falls as snow, which contributes large amounts of spring runoff. May and June are the driest months.

More than 95 percent of the precipitation evaporates or is transpired by vegetation (Harshbarger and others, 1966, p. 5). The high evaporation rates have a large effect on storage reservoirs. For example, during the 1982 water year, evaporation from Lake Mead, which is the largest reservoir in the United States, was 787,600 acre-ft (acre-feet) or 257,000 Mgal (million gallons) (N. D. White, U.S. Geological Survey, written commun., 1985). Monthly evaporation rates vary significantly. Harbeck and others (1958, p. 37) show that evaporation from Lake Mead ranged from 4.0 to 11.7 inches or 41,300 to 140,200 acre-ft (13,500 to 46,000 Mgal) per month from March 1952 through September 1953.

Table 1. Surface-water facts for Arizona

[The published total withdrawal (Solley, Chase, and Mann, 1983) has been reduced by the amount of surface water that is returned to the Colorado River (U.S. Geological Survey, 1982). Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	945
Percentage of total population	35
From public water-supply systems:	
Number (thousands)	945
Percentage of total population	35
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	7,300
Surface water only (Mgal/d)	3,000
Percentage of total	42
Percentage of total excluding withdrawals for thermoelectric power	40
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	260
Percentage of total surface water	9
Percentage of total public supply	46
Per capita (gal/d)	275
Rural supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	1.8
Percentage of total surface water	0.1
Percentage of total livestock	18
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	69
Percentage of total surface water	2.3
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	28
Excluding withdrawals for thermoelectric power	12
Irrigation withdrawals:	
Surface water (Mgal/d)	2,700
Percentage of total surface water	90
Percentage of total irrigation	42
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	41,000

Runoff patterns in Arizona also vary greatly (fig. 1). In desert areas of the Basin and Range Lowlands and the Plateau Uplands, average annual runoff is less than 0.1 inch. In contrast, in the mountainous parts of these provinces and in most of the Central Highlands, the annual runoff is as much as 5 inches. Runoff from perennial streams in the Central Highlands is collected in storage reservoirs that provide water for use in the Basin and Range Lowlands. Some runoff infiltrates and recharges the ground-water reservoirs.

PRINCIPAL RIVER BASINS

The Colorado River Basin is divided into upper and lower parts, with the dividing point near Lees Ferry. Almost all of Arizona is in the lower part of the basin (the Lower Colorado Region). The Colorado River Compact of 1922 provides for the legal apportionment of water between the upper and lower basins. Nearly all streams in Arizona are tributary to the Colorado, although the amount of tributary inflow is small because of the intensive use and storage within the State. Major tributaries to the Colorado River that drain large parts of Arizona are the Little Colorado, the Bill Williams, and the Gila Rivers (table 2); a few small streams drain to Mexico. These river basins are described below; their location, and long-term variation in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

LOWER COLORADO REGION

Lower Colorado River basin

The Colorado River, which is completely regulated, enters Arizona at the State's north boundary, flows southwestward through the Grand Canyon, turns south and forms the western boundary of Arizona, and flows into Mexico. The average annual discharge of the Colorado River at Lees Ferry (fig. 2, site 1) varied significantly before regulation by Glen Canyon Dam, but is now about 12,000 ft^3/s or 7,800 Mgal/d. Before closure of the dam, the maximum discharge was 220,000 ft^3/s or 142,000 Mgal/d, but since regulation, it has been only 97,300 ft^3/s or 62,900 Mgal/d.

In Arizona, the uppermost regulation point of the Colorado River is Glen Canyon Dam (storage began in 1963). Other lakes include Lake Mead (1936), which is formed by Hoover Dam, Lake Mohave (1950), and Lake Havasu (1938). Total storage capacity of these reservoirs is about 59,200,000 acre-ft or 19,300,000 Mgal. Other dams downstream are used to divert water from the river for irrigation and municipal uses. Total diversion of water to Arizona from the Colorado River for all uses other than power development in water year 1984 was 1,663,000 acre-ft or 542,000 Mgal. Of this amount, about 779,000 acre-ft or 254,000 Mgal was returned to the river (N. D. White, U.S. Geological Survey, written commun., 1985). As of December 1985, operation of the Central Arizona Project to import Colorado River water to the central part of the State will allow for the use of the State's remaining entitlement. This increase in surface-water supply will help slow the rate of depletion of ground-water resources.

In 1983, high runoff from the Upper Colorado River basin necessitated flood-control releases at Glen Canyon and Hoover Dams. Some damage occurred in the floodway between Davis Dam and the international boundary. Although higher runoff occurred in 1984, fewer problems resulted. To a lesser degree, high flows and subsequent flood-control releases continued into 1985.

Little Colorado Subregion

The Little Colorado River, which heads in the mountains of east-central Arizona, drains the northeastern part of the State, flows generally north-northwestward, and joins the Colorado River upstream from the Grand Canyon (fig. 2). Most of the tributaries to the Little Colorado River are small ephemeral streams. The maximum discharge of the Little Colorado River near Cameron (fig. 2, site 5) for 1947-84 was 24,900 ft^3/s or 16,100 Mgal/d; the river has no flow at times each year (N. D. White, U.S. Geological Survey, written commun., 1985). Flow near Cameron is affected by reservoirs on the Little Colorado River and on tributaries.

Upper, Middle, and Lower Gila Subregions

The Gila River enters Arizona at the State's eastern boundary and generally flows westward across the southern part of the State. The river is perennial where it enters Arizona but becomes intermittent farther downstream because of seasonal variations in runoff and impoundment of runoff at Coolidge Dam. Major tributaries include the San Pedro, the Santa Cruz, and the Salt Rivers. In parts of its course, the Gila River can cause extensive flood damage. For example, in October 1983 a peak discharge of 132,000 ft^3/s or 85,300 Mgal/d occurred at the head of Safford Valley; damages to agriculture in Safford Valley amounted to about $14.5 million (Federal Emergency Management Agency, 1983).

The Gila River is regulated by Coolidge Dam. Upstream from this reservoir, the basin consists of extensive mountainous areas and limited grasslands. Water is diverted for irrigation in Duncan–Virden Valley (partly in New Mexico) and in Safford Valley. Coolidge Dam holds water for irrigation and power generation. Water for irrigation of the 100,000-acre San Carlos Project is diverted from the Gila River by the Florence-Casa Grande Canal at Ashurst-Hayden Dam. In the desert area farther downstream, Gillespie Dam diverts water for irrigation, and Painted Rock Dam, holds 2,492,000 acre-ft or 812,000 Mgal and stores water for flood control. Total diversions from the Gila River in the 1984 water year were 1,317,000 acre-ft or 429,000 Mgal (N. D. White, U.S. Geological Survey, written commun., 1985), which represented the entire flow from the basin. Only a small amount of flow from the Gila normally reaches the Colorado River.

The San Pedro River heads in Mexico and flows northward across the international boundary into Arizona about 4.5 miles upstream from the gaging station at Palominas (fig. 2, site 8). Its basin is long and narrow, and the landforms range from steep mountains to rolling plains. Although the San Pedro River is not regulated, its base flow is affected by ground-water pumping. It has no major tributaries and is intermittent throughout most of its course. The peak discharge in the San Pedro River near Mammoth was 135,000 ft^3/s or 87,300 Mgal/d in October 1983.

The Santa Cruz River is a typical desert stream that is dry much of each year but can flow at high rates in response to intense thunderstorms. The river flows through Tucson, the second largest city in Arizona. Flooding can cause extensive damage in Tucson as well as in smaller towns south and north of Tucson. Based on 75 years of data, the average annual discharge at Tucson (fig. 2, site 11) is less than 23 ft^3/s or 15 Mgal/d (U.S. Geological Survey, 1982, p. 276); however, a peak flow of 52,700 ft^3/s or 34,100 Mgal/d occurred in October 1983.

Salt Subregion

The Salt River basin includes more than 6,232 mi^2 (square miles) where it meets the Verde River east of Phoenix. The Salt River heads at the confluence of the Black (fig. 2, site 12) and the White (fig. 2, site 13) Rivers in the mountainous eastern part of Arizona (fig. 2). From its headwaters to Roosevelt Dam, which is the upstream regulation point, flow in the Salt River is perennial.

The flow of the Salt River is controlled by a series of four dams and reservoirs built during 1905 to 1930. The storage capacity of these reservoirs is 1,710,000 acre-ft or 557,000 Mgal. Downstream from the lakes, streamflow is dependent on releases from the reservoirs. Granite Reef Dam, about 25 miles east of Phoenix, diverts the entire normal flow of the Salt and the Verde Rivers for irrigation of about 250,000 acres in the Salt River Valley and for municipal use by the city of Phoenix and other municipalities in the valley. Average annual diversion at Granite Reef Dam during 1975-84 was 987,000 acre-ft or 322,000 Mgal (Salt River Project personnel, written commun., 1985).

Downstream from the reservoirs, the Salt River passes through metropolitan Phoenix, where the channel normally is dry. Severe flooding, however, can occur when it becomes necessary to release large volumes of water from the reservoirs. The reservoir system, which supplies water for irrigation and hydroelectric power, was not designed for flood-control purposes. Consequently, when storage in the reservoirs is near capacity and excessive precipitation occurs in the basin, large volumes of water may be

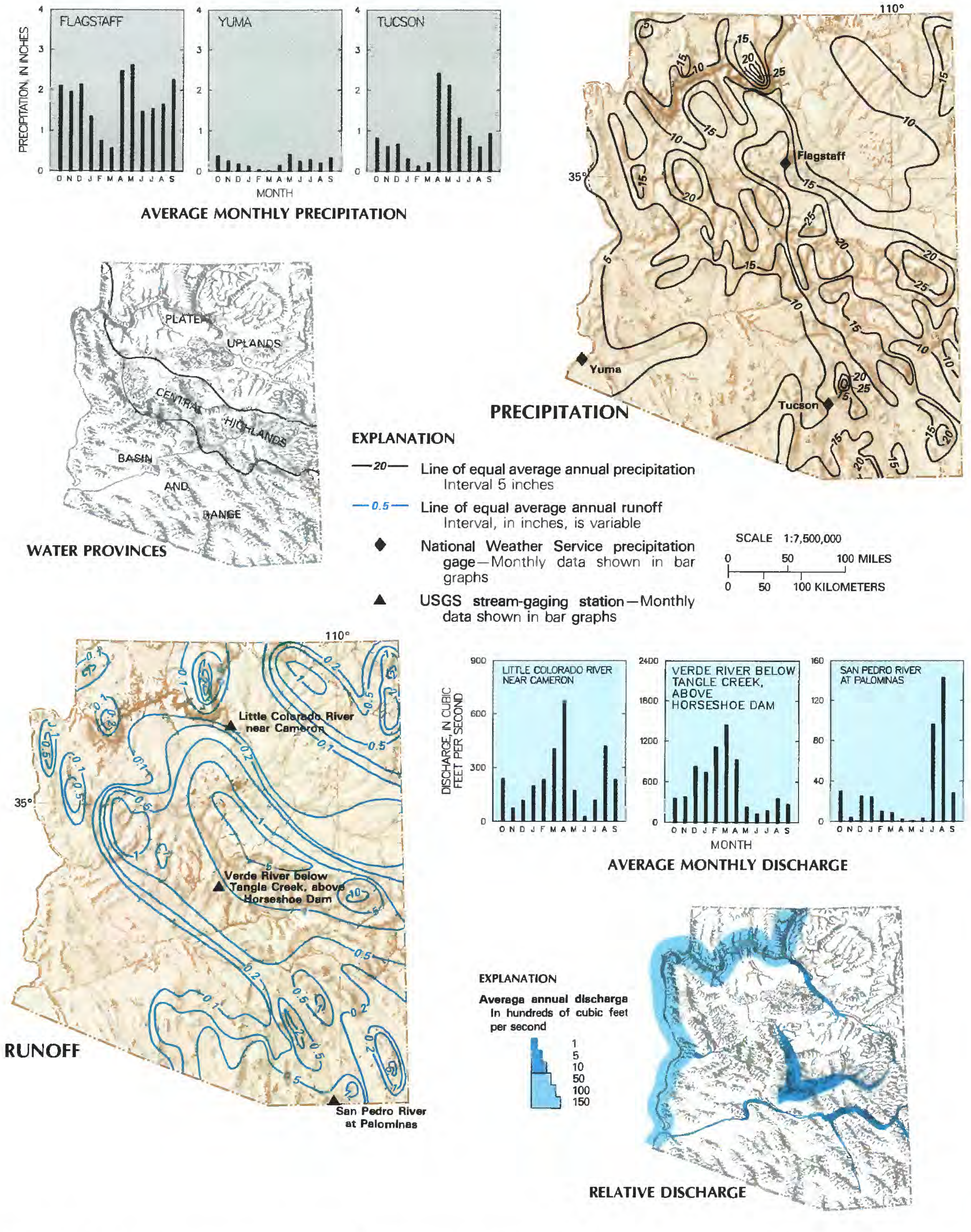

Figure 1. Average annual precipitation and runoff in Arizona and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from modified from Green and Sellers, 1964; monthly data from National Oceanic and Atmospheric Administration files. Runoff from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; Water-province diagram from U.S. Geological Survey, 1969.)

released. On three occasions in recent years, flooding occurred in Phoenix and surrounding communities. Peak discharges were 122,000 ft³/s or 78,900 Mgal/d in March 1978 (Aldridge and Eychaner, 1984, p. 50), 126,000 ft³/s or 81,400 Mgal/d in December 1978 (Aldridge and Hales, 1983, p. 40), and 170,000 ft³/s or 110,000 Mgal/d in February 1980 (N. D. White, U.S.

Table 2. Selected streamflow characteristics of principal river basins in Arizona

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				LOWER COLORADO REGION LOWER COLORADO RIVER BASIN				
1.	Colorado River at Lees Ferry (09380000).	111,800	1912–62 1965–84	1,670	17,850	189,500	None Appreciable	River unregulated at this point before March 15, 1963. Flow regulated by Lake Powell 16 miles upstream.
2.	Colorado River below Hoover Dam (09421500).	171,700	1935–84	2,550	13,590	. . . .	. . . do . . .	Unadjusted for storage in Lake Mead. Average dissolved solids in water was 1,980 mg/L during 1950–82.
3.	Bill Williams River below Alamo Dam (09426000).	4,730	1940–88	0.72	92.3	325,000	. . . do . . .	Storage behind Alamo Dam began March 1969.
4.	Colorado River at northerly international boundary, above Morelos Dam (09522000).	246,700	1950–84	541	. . . .	. . . .	. . . do . . .	Flow passing international boundary. Flow regulated. Average dissolved solids in water was 1,020 mg/L during 1950–82.
				LITTLE COLORADO SUBREGION				
5.	Little Colorado River near Cameron (09402000).	26,500	1947–84	. . . .	244	32,800	Negligible	Unusually high sediment load during high flow.
				UPPER GILA SUBREGION				
6.	Gila River near Clifton (09442000).	4,010	1928–84	8.15	192	30,600	None	
7.	Gila River at head of Safford Valley, near Solomon (09448500).	7,896	1914–84	22.0	468	86,800	. . . do . . .	
				MIDDLE GILA SUBREGION				
8.	San Pedro River at Palominas (09470500).	741	1950–81	0.03	32.1	21,800	None	Flow occasionally contaminated from mine-tailings pond spills in Mexico during high-flow events.
9.	San Pedro River at Winkelman (09473500).	4,471	1966–79	. . . .	57.1	. . . .	. . . do . . .	Ground water is main source.
10.	Gila River at Kelvin (09474000).	18,011	1912–84	0.82	494	244,000	Appreciable	Average discharge adjusted for storage. Flow regulated by San Carlos Reservoir 49 miles upstream since Nov. 15, 1928.
11.	Santa Cruz River at Tucson (09482500).	2,222	1915–81	. . . .	22.7	20,300	None	
				SALT SUBREGION				
12.	Black River near Fort Apache (09490500).	1,232	1958–84	16.7	412	58,100	None	
13.	White River near Fort Apache (09494000).	832	1958–84	4.80	201	11,900	. . . do . . .	
14.	Salt River near Roosevelt (09498500).	4,306	1925–84	81.9	888	164,000	. . . do . . .	Average dissolved solids in water was 1,140 mg/L during 1950–82.
15.	Verde River below Tangle Creek, above Horseshoe Dam (09508500).	5,872	1945–84	72.5	564	158,000	. . . do . . .	

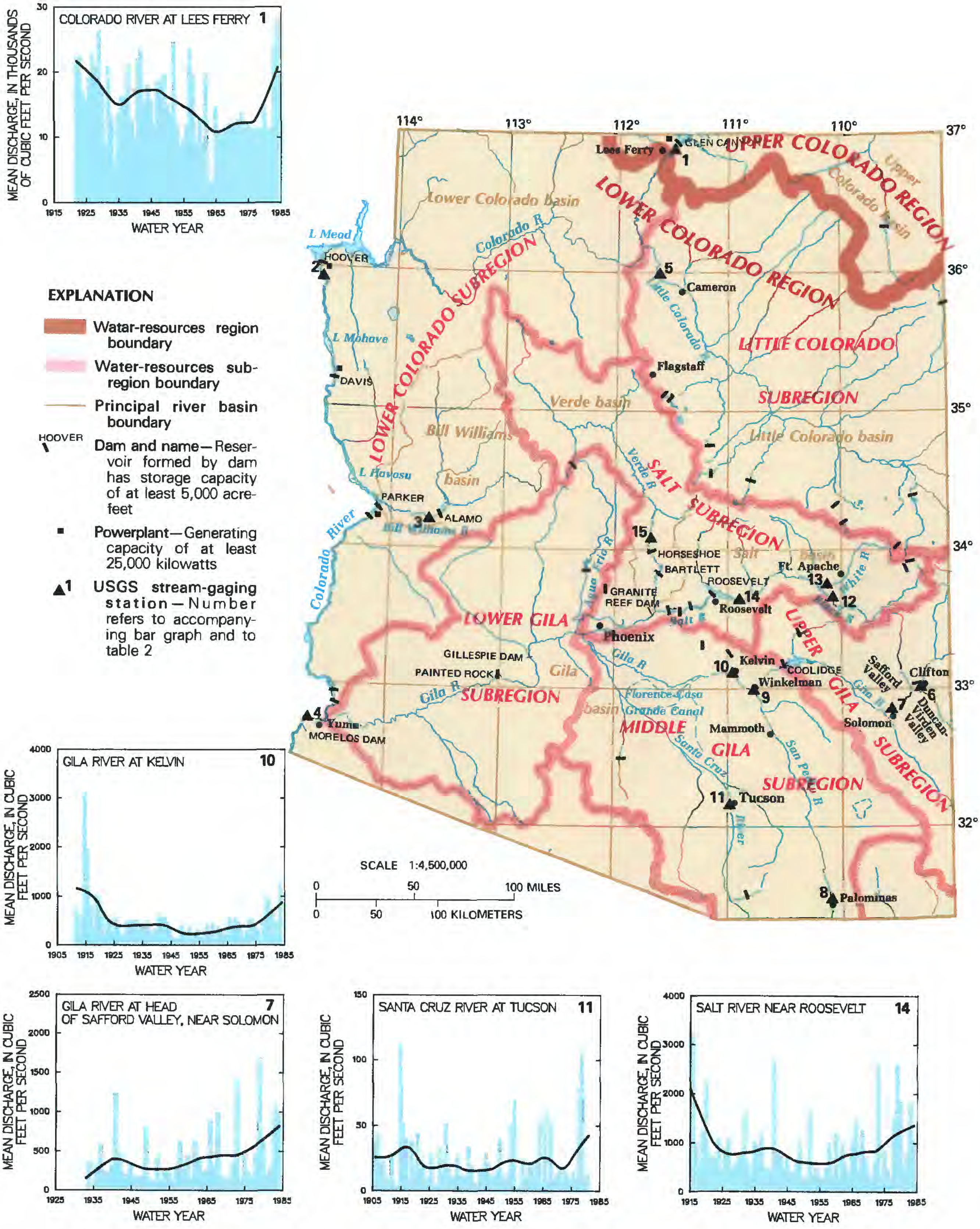

Figure 2. Principal river basins and related surface-water resources development in Arizona and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development modified from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Geological Survey, written commun., 1985). All three floods caused severe damage; however, the flood peaks were not nearly as large as they would have been without the upstream reservoirs.

The Verde River heads at Del Rio Springs about 40 miles southwest of Flagstaff in the Central Highlands province. Where the Verde River meets the Salt River east of Phoenix, the drainage area is about 6,600 mi². The Verde River flows through wide valleys and steep-sided canyons on its southeasterly course through the central part of the State. It contains perennial flow throughout its length to Horseshoe Dam (fig. 2). Downstream, the flow depends on releases from the reservoir. Horseshoe and Bartlett Dams hold a total storage capacity of 309,600 acre-ft or 101,000 Mgal. All the normal flow is diverted at Granite Reef Dam except during extreme flow events. The Verde River can cause severe flooding in and near Phoenix. Part of the peak flows in the Salt River is attributable to flow released at Bartlett Dam.

SURFACE-WATER MANAGEMENT

Surface-water resources available for use in Arizona can be broadly categorized as water from the Colorado River and water from other streams. The Colorado River Compact of 1922 and subsequent agreements and court decisions provide for the apportionment of water from the Colorado River to basin States and Mexico.

The Arizona Department of Water Resources (ADWR) is the legal administrator of water rights in Arizona. The Department began developing a State Water Plan in 1974 to provide information to State and local planners and legislators for decisions concerning water management. Arizona operates under a prior appropriation doctrine; thus, the earliest users of water have priority over other users. All water in Arizona belongs to the public and is subject to appropriation for beneficial purposes.

Surface water is administered or managed by many agencies. The U.S. Bureau of Reclamation is responsible for the control and management of the Colorado River. Water use from the upper Gila River basin above Coolidge Dam is administered by the Gila Water Commissioner. Below Coolidge Dam, water is diverted for irrigation on the San Carlos Irrigation Project, which includes Indian and non-Indian land, and is administered by the U.S. Bureau of Indian Affairs. Water from the Salt and the Verde River basins is managed by the Salt River Valley Water Users' Association. The ADWR has begun efforts toward comprehensive basinwide water-rights adjudication in the Gila River basin. The process is ongoing in the San Pedro River and the upper Salt River basins. The U.S. Geological Survey cooperates with many State, local, and other Federal agencies in the systematic collection of hydrologic data to document the quantity and quality of surface-water resources throughout the State.

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ARKANSAS
Surface-Water Resources

Arkansas has abundant surface-water resources. Forty-nine percent of the population uses surface water for public supply, which amounts to 2,900 Mgal/d (million gallons per day) or 4,490 ft^3/s (cubic feet per second). Ground water provides about 4,000 Mgal/d or 6,200 ft^3/s of freshwater needs in the State. The principal offstream use of surface water in Arkansas is for thermoelectric power generation. Nuclear One Powerplant near Russellville uses about 873 Mgal/d or 1,350 ft^3/s of surface water. The combined offstream withdrawals for all thermoelectric powerplants, including Nuclear One, is 1,780 Mgal/d or 2,750 ft^3/s. Surface-water withdrawals for various purposes in Arkansas in 1980 and related statistics are given in table 1.

Surface water in Arkansas is generally suitable for most uses, although treatment is required for some uses. Dissolved salts, sediment, and local contamination restrict use of surface water in some parts of the State. Degradation of water quality in some streams and surface-water bodies that receive municipal and industrial wastewater and nonpoint-source discharges is a concern in the State. These discharges have adversely affected the suitability of the water for drinking, recreation, and aquatic life.

Flooding of low areas, which sometimes destroys crops and buildings, is a major concern in the State. Much of the farmland in eastern Arkansas is in the flood plains of major streams. The last major flood in Arkansas occurred in December 1982, when peak discharges at 13 gaging stations exceeded the 100-year flood magnitude. Regulation of principal streams in Arkansas has reduced the frequency and severity of floods and has increased 7-day, 10-year low flows (table 2).

GENERAL SETTING

Arkansas has a diverse topography. The State is located in the Ozark Plateaus, Ouachita, and Coastal Plain physiographic provinces (fig. 1). The Ozark and Ouachita Mountains are as high as 2,700 feet above sea level. Streams in the Ozark Plateaus and in the southern half of the Ouachita Mountains tend to have sustained flows during dry seasons, whereas streams in the Arkansas Valley (fig. 1) and in the northern half of the Ouachita Mountains generally become dry. The Mississippi Alluvial Plain and the West Gulf Coastal Plain in the Coastal Plain province (fig. 1) comprise the southeastern part of the State; this area is relatively flat, with elevations that range from 55 to 500 feet above sea level, and is used for agriculture. The parts of the State with higher elevations are used mainly for raising cattle and poultry.

Arkansas has many springs, especially in the foothills of the Ouachita and Ozark Mountains. Thousands of people bathe in the water from Arkansas springs each year for therapeutic reasons. The Eureka Springs area in the Ozark Mountains contains approximately 65 springs. Mammoth Spring in the Ozarks is one of the largest springs in Arkansas, with an average discharge of 314 ft^3/s or 203 Mgal/d. In the Hot Springs area in the Ouachita Mountains, 51 springs yield about 1.5 ft^3/s or 1 Mgal/d.

The climate in Arkansas is mild and moderately humid. Average annual precipitation ranges from about 40 to about 58 inches (fig. 1). Monthly precipitation exhibits a pronounced seasonal pattern; May usually has the most precipitation and January and October the least. Runoff ranges from about 12 to 22 inches, depending on the precipitation pattern (fig. 1). Average annual evaporation from shallow lakes ranges from about 36 inches in the northeast to about 44 inches in the southwest.

PRINCIPAL RIVER BASINS

Arkansas is in the Lower Mississippi and Arkansas-White-Red Regions (Seaber and others, 1984). The Mississippi, the St. Francis, the White, the Arkansas, the Red, and the Ouachita Rivers are the principal rivers in these regions. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Arkansas

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Modified from Holland and Ludwig, 1981]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	790
Percentage of total population	49
From public water-supply systems:	
Number (thousands)	790
Percentage of total population	49
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	6,900
Surface water only (Mgal/d)	2,900
Percentage of total	41
Percentage of total excluding withdrawals for thermoelectric power	56
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	150
Percentage of total surface water	5
Percentage of total public supply	57
Per capita (gal/d)	190
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	39
Percentage of total surface water	1
Percentage of total livestock	64
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	2,100
Percentage of total surface water	75
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	83
Excluding withdrawals for thermoelectric power	9
Irrigation withdrawals:	
Surface water (Mgal/d)	600
Percentage of total surface water	21
Percentage of total irrigation	15
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	26,000

LOWER MISSISSIPPI REGION

Mississippi River Main Stem

The Mississippi River forms the eastern border of Arkansas. About two-thirds of the runoff from the State flows into the Mississippi through the Arkansas, the White, and the St. Francis Rivers. The U.S. Army Corps of Engineers has constructed levees along the western bank of the Mississippi River to protect fertile farmland in the St. Francis and the White River basins. The Mississippi River, which drains about 40 percent of the conterminous United States, has a drainage area of 932,800 mi^2 (square miles) at Memphis, Tenn. The average flow at Memphis (table 2, site 1) is 474,200 ft^3/s or 306,000 Mgal/d. The river has shown little change overall in water quality in recent years and remains suitable for most uses.

Lower Mississippi-St. Francis Subregion

St. Francis River Basin.—The St. Francis River originates in the hills of Missouri where it flows rapidly until it enters the flatlands and gradually becomes sluggish and meandering. The river enters the alluvial valley of the Mississippi River and flows into the Mississippi River near Helena. The St. Francis River is 475 miles long and has a drainage area of 8,416 mi², about 45 percent of which is in Arkansas. Originally, the stream channel was poorly defined as it flowed on the marshy and swampy flood plain of the alluvial valley for a distance of about 100 miles.

During the past 150 years, many manmade changes have occurred in the St. Francis River basin. Swamps have been drained, levees built, and millions of acres of land cleared for cultivation. Much of the fertile farmland is in the St. Francis River flood plain and is protected from flooding by levees. Accumulation of pesticides in bottom sediments of streams, lakes, and ponds, and the effects of these compounds on the food chain is a concern in the St. Francis River basin.

Part of the floodflows in the St. Francis River is diverted through the St. Francis River floodway at a diversion dam about 4.0 miles northwest of Marked Tree (fig. 2); the diverted flow is returned to the St. Francis River downstream from Marianna. The combined average discharge of the St. Francis River and the floodway is 8,020 ft³/s or 5,180 Mgal/d. Some regulation in Missouri has occurred since 1941. The capacity of Wappapello Lake is 625,000 acre-ft (acre-feet) or 203,700 Mgal (million gallons).

LOWER MISSISSIPPI REGION

Lower Red-Ouachita Subregion

Ouachita River Basin.—The Ouachita River is Arkansas' largest tributary to the Red River. The Ouachita River originates in the Ouachita Mountains in western Arkansas and flows to the southeast where it meanders as the gradient and rate of flow gradually decrease.

Tributaries of the lower Ouachita River continue to have water-quality problems, which, at times, limit use of the river for some purposes. These problems are related mainly to oil and gas production.

The average flow in the Ouachita River near Malvern (table 2, site 3) and at Camden (table 2, site 4) is 2,380 ft³/s or 1,540 Mgal/d and 7,490 ft³/s or 4,840 Mgal/d, respectively. Most of the streams in the upper part of the Ouachita basin have continuous flow (Hunrichs, 1983).

ARKANSAS-WHITE-RED REGION

Upper White Subregion

White River Basin.—The White River originates in the hills of northern Arkansas and southern Missouri and meanders through the steep hills and narrow valley flood plains to the Mississippi alluvial plain. The river continues southward becoming more sluggish as it flows through the alluvial plain and into the Mississippi River. Drainage area of the White River is 27,818 mi², about 65 percent of which is in Arkansas. The flow of the river has been regulated by Norfork Lake since 1943, Bull Shoals Lake since 1951, Table Rock Lake since 1956, Clearwater Lake since 1948, Greers Ferry Lake since 1962, and Beaver Lake since 1963. The total capacity of the six lakes is about 15.2 million acre-ft or 4,950,000 Mgal. Long-term average streamflow is decreasing slightly at Clarendon (fig. 2, site 13); this decrease is uniform along the river and may reflect increased withdrawals for irrigation. The average discharge at Calico Rock (table 2, site 9) and Clarendon (table 2, site 13) is 9,830 ft³/s or 6,360 Mgal/d and 29,510 ft³/s or 19,100 Mgal/d, respectively. Streams in the upper part of the White River basin are in the Ozark Plateaus province and have a high base flow. During the 1980 drought, the low flows in streams in the Ozark Plateaus province represented recurrence intervals of only 4 years, whereas the recurrence intervals for the remainder of the State were 20 or more years (Hunrichs, 1983).

Nutrients from point and nonpoint sources have occasionally resulted in the depletion of dissolved oxygen in the upper White River. This problem, along with a rapid growth in population, has caused concerns about the future water quality of Beaver Lake, into which the upper White River flows. Nutrients, pesticides, and silt from agricultural activities have slightly degraded the lower White River.

Lower Arkansas Subregion

Arkansas River Basin.—The Arkansas River flows southeastward across Arkansas and passes Fort Smith, Little Rock, and Pine Bluff before emptying into the Mississippi River. The drainage area as it enters the State is 149,977 mi² and at the mouth is 160,576 mi². The average flow during the last 56 years for the Arkansas River at Murray Dam (table 2, site 18) is 40,290 ft³/s or 26,000 Mgal/d. The Arkansas River has a length of 1,450 miles, 325 miles of which are in Arkansas.

The Arkansas River is regulated by many locks, dams, and reservoirs; eleven locks and dams are in Arkansas. Electrical power is generated by turbines at the Dardanelle and the Ozark Dams, which have a combined storage of 635,000 acre-ft or 207,000 Mgal. Water from the river is used for cooling at the nuclear powerplant at Russellville. The primary purpose of the locks and dams is for navigation. The locks and dams also help control low-magnitude floods; however, they have little effect in reducing peaks of large-magnitude floods. Most of the tributaries that flow into the Arkansas River go dry during dry periods (Hunrichs, 1983).

The Arkansas River is being considered as a source of water for public supply and irrigation. Seepage from natural salt deposits in upstream areas increases the salinity of the river, which may make the river unsuitable for some uses during low flow. Municipal and industrial discharges to the river may contribute wastes and chemicals that affect its potability. Impoundment of water by the Arkansas River Navigation System and tributary dams have moderated the effects of salinity and inflowing pollutants by maintaining larger volumes of water in the river thus diluting the concentration of contaminants.

Red-Sulphur Subregion

Red River Basin.—The Red River forms part of the boundary between Arkansas and Texas and flows southward into Louisiana. Although the main stem of the Red River is in Arkansas for only a relatively short distance, about one-third of the State's total streamflow eventually drains into the Red River in Louisiana. The total drainage area at Index (table 2, site 19) is 48,030 mi². The average flow at Index is 11,710 ft³/s or 7,570 Mgal/d. Flow of the river has been regulated upstream in Texas and Oklahoma since 1943, Pat Mayse Lake since 1967, Wright Patman Lake since 1956, Millwood Lake since 1966, and Hugo Lake since 1974. Total storage of the five lakes is about 11.1 million acre-ft or 3,620,000 Mgal. The Red River Compact signed by representatives of Arkansas, Louisiana, Oklahoma, and Texas in 1978, provides for the equitable apportionment of water in the Red River and its tributaries.

Water in the Red River is of poor quality. High concentrations of chloride, sulfate, and suspended sediment in the river as it enters Arkansas, along with the addition of municipal and industrial wastes discharged into the river in Arkansas, limit its use for domestic supplies. A relatively small amount of water is withdrawn from the river for irrigation.

SURFACE-WATER MANAGEMENT

Because Arkansas has abundant surface-water resources, there has not been a critical need to regulate surface-water use. The general attitude is that the water in a stream belongs to riparian land owners, subject to reasonable use.

Several State and local agencies have limited jurisdiction over surface water. The Arkansas Department of Health is responsible for protecting municipal and rural drinking supplies and

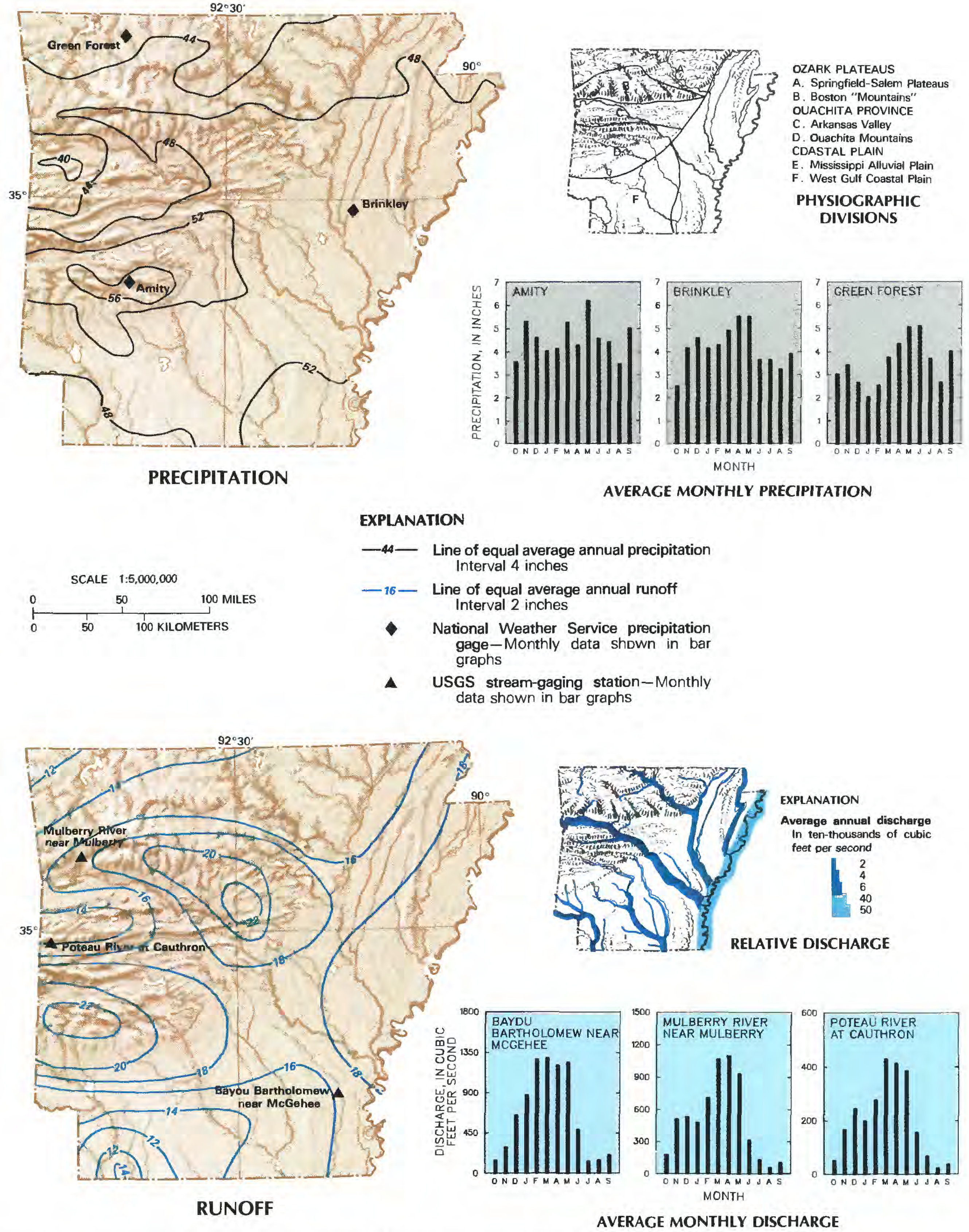

Figure 1. Average annual precipitation and runoff in Arkansas and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—from Freiwald, 1985. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Arkansas

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Arkansas State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				LOWER MISSISSIPPI REGION Mississippi River Main Stem				
1.	Mississippi River at Memphis, Tenn. (07032000).	932,800	1933-81	99,000	474,200	1,860,000	Appreciable	Flow regulated upstream by many locks, dams, and reservoirs.
				Lower Mississippi-St. Francis Subregion **St. Francis River basin**				
2.	St. Francis Bay at Riverfront (07047900).	. . . .	1936-75, 1978-81, 1944-75, 1978-81	57 83	5,274	. . . .	Appreciable	Total drainage area of St. Francis River and St. Francis Bay, 6,475 mi^2. Flow regulated by Weppapello Lake since 1941.
				Lower Red-Ouachita Subregion				
3.	Ouachita River near Malvern (07359500).	1,585	1928-84 1954-84	105 244	2,380	194,000	Appreciable	Flow regulated by one to four lakes since 1925.
4.	Ouachita River at Camden (07362000).	5,357	1928-84 1954-84	236 548	7,490	299,000	Moderate	Flow regulated by one to five lakes since 1925.
5.	Smackover Creek near Smackover (07362100).	385	1961-83	0.35	374	39,700	None	
6.	Saline River near Rye (07363500).	2,102	1937-83	12.6	2,590	102,000	. . . do . . .	
7.	Bayou Bartholomew near McGehee (07364150).	576	1939-42, 1946-84	6.5	676	6,930	. . . do . . .	
				ARKANSAS-WHITE-RED REGION Upper White Subregion **White River basin**				
8.	Buffalo River near St. Joe (07056000).	829	1939-84	16.5	1,027	176,000	None	
9.	White River at Calico Rock (07060500).	9,978	1939-83 1945-83 1958-83	894 973 1,120	9,830	352,000	Appreciable	Flow regulated by one to four lakes since 1943.
10.	Spring River at Imboden (07069500).	1,183	1936-83	279	1,360	163,000	None	
11.	Black River at Black Rock (07072500)	7,369	1929-31, 1939-83 1950-83	1,980 1,990	8,410	176,000	Moderate	Flow slightly regulated since 1948 by Clearwater Lake.
12.	Middle Fork Little Red River at Shirley (07075000).	302	1939-83	<0.19	467	140,000	None	
13.	White River at Clarendon (07077800).	25,555	1928-81 1945-81 1958-81	4,090 5,050 6,020	29,510	291,000	Appreciable	Flow regulated by one to six lakes since 1943.
				Lower Arkansas Subregion **Arkansas River basin**				
14.	Poteau River at Cauthron (07247000).	203	1939-83 1950-83	<0.1 <0.1	215	47,100	Appreciable	Since 1948 flow is regulated by 16 floodwater detention reservoirs.
15.	Mulberry River near Mulberry (07252000).	373	1938-83	<0.16	534	82,400	None	
16.	Big Piney Creek near Dover (07257000).	274	1950-83	0.15	398	112,000	. . . do . . .	
17.	Petit Jean River at Danville (07260500).	764	1916-84 1949-84	0.74 1.9	809	91,900	Appreciable	Flow regulated since 1947 by Blue Mountain Lake.
18.	Arkansas River at Murray Dam (07263450).	158,030	1927-84	1,230	40,290	588,000	. . . do . . .	Flow regulated upstream by many locks, dams, and reservoirs.
				Red-Sulphur Subregion **Red River basin**				
19.	Red River at Index (07337000).	48,030	1936-84 1945-84 1969-84	812 934 1,110	11,710	190,000	Appreciable	Flow regulated by three lakes in Oklahoma and Texas since 1943.

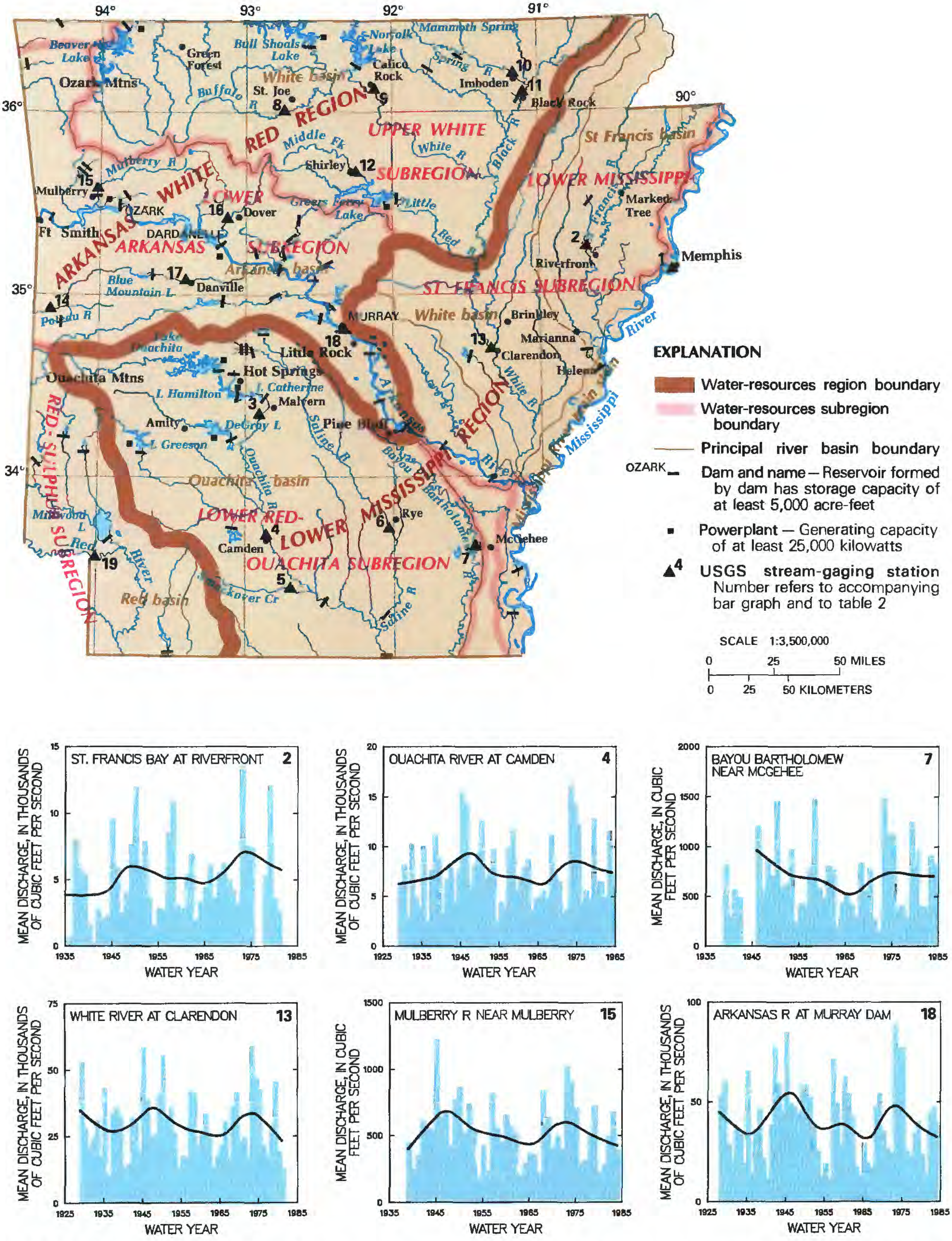

Figure 2. Principal river basins and related surface-water resources development in Arkansas and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

regulating construction and use of septic tanks. The Arkansas Soil and Water Conservation Commission is responsible for the Arkansas State Water Plan, which evaluates surface-water and ground-water resources, problems, and management strategies. The Commission also requires the reporting of surface-water withdrawals. The Arkansas Geological Commission provides geologic and hydrologic data for water-resources planning in the State. The Arkansas Department of Pollution Control and Ecology is responsible for controlling surface-water quality and implementing Federally delegated programs, such as the Resources Conservation and Recovery Act, the Clean Water Act, and construction-grant programs. The Arkansas Plant Board, the Forestry Commission, and the Cooperative Extension Service also have responsibilities that affect surface water. The U.S. Geological Survey works cooperatively with several of these State agencies to maintain a statewide water-data network and to investigate the State's water resources.

In 1972, the Arkansas River Compact was signed by representatives of Arkansas and Oklahoma to provide an equitable apportionment of the waters of the Arkansas River and its tributaries to the two States. The Arkansas River Compact is responsible for the development and protection of the water resources of the Arkansas River and its tributaries from pollution and for providing an equitable apportionment of these resources to Arkansas and Oklahoma. The U.S. Army Corps of Engineers is responsible for issuing permits for construction of all facilities on streams that have an average flow of 5 ft^3/s or 3.2 Mgal/d or more.

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FOR ADDITIONAL INFORMATION

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CALIFORNIA
Surface-Water Resources

In California, surface water provides about 60 percent of freshwater needs—more than 20,000 Mgal/d (million gallons per day) or 31,000 ft^3/s (cubic feet per second). About 54 percent of the population or 13 million people relies on surface water (table 1). Offstream uses of surface water include irrigation, industry, and municipal supply. Instream uses include hydroelectric power, sport fishing and recreation, and navigation in the lower Sacramento River and Sacramento-San Joaquin Delta. California has about 260 reservoirs that have a capacity of more than 5,000 acre-ft (acre-feet) or 1,630 Mgal (million gallons) and 40 reservoirs with capacities of more than 200,000 acre-ft or 65,200 Mgal. Many of the reservoirs are used to generate hydroelectric power. Selected reservoir and powerplant sites are shown in figure 2.

Most precipitation falls in the northern coastal region and the northern and central mountains of eastern California, which make up less than one-fourth of the State, but water use is heaviest in other parts of the State. Agriculture is concentrated in interior valleys, and population and manufacturing centers are principally in the Central Valley, in the San Francisco Bay area, and in the coastal region from Santa Barbara to San Diego. The water needs of agriculture are greatest from mid-April through October. Because of the geographic and seasonal mismatch between supply and demand, the storage and transfer of surface water is of great importance to the economy of the State.

Water quality in the State's upland streams generally is suitable for most uses, but some surface water has been degraded by human activities. Streams that pass through irrigated lowlands receive return flows containing organic substances and, in some places, minerals leached from irrigated arid-land soils. In many areas, industry has introduced chemical contaminants, and some waste-disposal sites contain toxic compounds that are reaching surface waters. Deterioration of water quality in California's lakes and streams is of great concern to water-use planners. Because continued economic development requires dependable supplies of usable water, water conservation and improvement of water quality are goals of the planning process.

Interbasin diversions have long been a source of controversy, as have been the merits of flow regulation and storage and the proper allocation of water-management authority among private, State, and Federal entities.

Tabla 1. Surface-water facts for California

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983; and California Department of Water Resources, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	12,860
Percentage of total population	54
From public water-supply systems:	
Number (thousands)	12,700
Percentage of total population	54
From rural self-supplied systems:	
Number (thousands)	160
Percentage of total population	0.7
OFFSTREAM USE, 1980 **FRESHWATER WITHDRAWALS**	
Surface water and ground water, total (Mgal/d)	40,000
Surface water only (Mgal/d)	24,000
Percentage of total	60
Percentage of total excluding withdrawals for thermoelectric power	58
Category of Use	
Public-supply withdrawals:	
Surface water (Mgal/d)	2,700
Percentage of total surface water	11
Percentage of total public supply	61
Per capita (gal/d)	213
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	6.0
Percentage of total surface water	<0.1
Percentage of total rural domestic	7
Per capita (gal/d)	38
Livestock:	
Surface water (Mgal/d)	54
Percentage of total surface water	0.2
Percentage of total livestock	60
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	1,400
Percentage of total surface water	6
Percentage of total industrial self supplied:	
Including withdrawals for thermoelectric power	51
Excluding withdrawals for thermoelectric power	40
Irrigation withdrawals:	
Surface water (Mgal/d)	20,000
Percentage of total surface water	83
Percentage of total irrigation	62
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	81,000

GENERAL SETTING

The three principal physiographic divisions in California are the Basin and Range province, the Cascade-Sierra Mountains province, and the Pacific Border province (fig. 1). Most of the Basin and Range province is desert. The only principal streams that head in that province are the Klamath and the Sacramento Rivers. All other principal rivers of the State are in the Cascade-Sierra Mountains or the Pacific Border provinces. In the eastern part of the Pacific Border province, the Central Valley extends for more than 400 miles along the western foot of the Sierra Nevada. This valley is one of the most productive agricultural regions of the world. The Imperial and Coachella Valleys, draining to the Salton Sea more than 200 feet below sea level in the southwestern part of the Basin and Range province, also are rich agricultural areas. They depend almost entirely on water from the Colorado River.

From early spring until early autumn, an area of high pressure typically forms off the California coast, giving California its dry summers. During the winter, storms occasionally move inland, bringing most of the annual precipitation, as shown in the bar graphs in figure 1. The northwest-to-southeast trend of the principal mountain ranges is almost perpendicular to the path of most storms, so that westward-facing slopes receive much heavier precipitation than the leeward slopes.

Average annual precipitation in California (fig. 1) ranges from about 4 inches in the desert areas in the southeastern part of the State to about 100 inches in the northwestern part (California State, 1979). Average annual precipitation on the floor of the Central Valley is less than 20 inches in the north and less than 10 inches in the south. Annual precipitation throughout California also varies greatly from year to year. Average annual potential evapotranspiration ranges from about 35 inches on the northwestern coast to about 120 inches in Death Valley in the southeast (California State, 1979, p. 13).

Much of the precipitation in the Sierra Nevada falls as snow at altitudes more than 4,000 feet above sea level, and it does not run off until late spring or early summer in most years. The snowpack is a natural reservoir that has a significant effect on management of the State's surface-water resources.

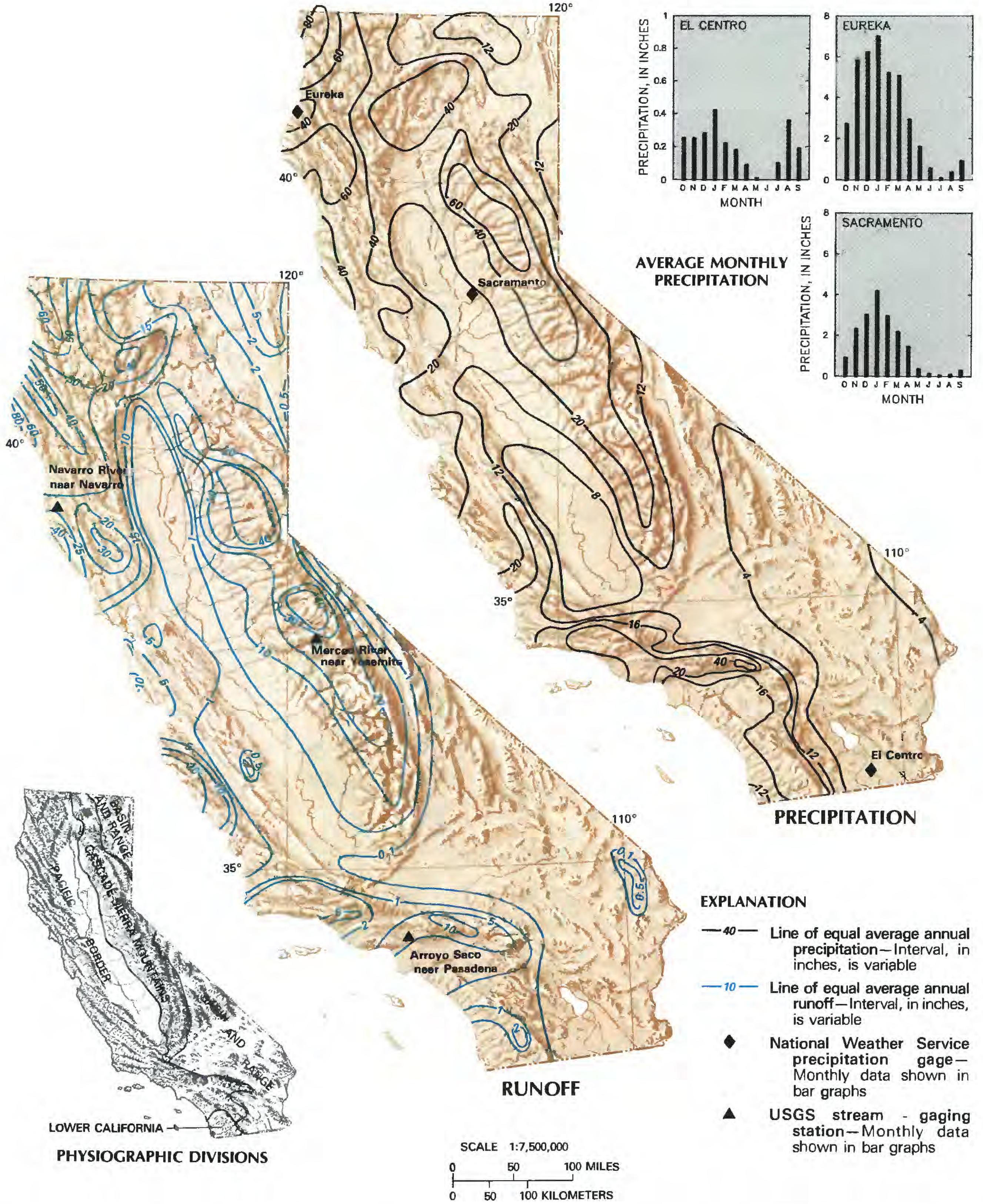

Figure 1. Average annual precipitation and runoff in California and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from California State, 1979, and unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from California State, 1979, and Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Average annual runoff statewide is about 8 inches (California State, 1979, p. 8), although runoff varies greatly with respect to location and season in California (fig. 1). Streamflow records show that long-term average runoff is more than 86 inches in the Smith River basin of northwestern California; however, many years of records show no runoff from small basins in southern California. The Basin and Range province in California includes many closed basins where runoff is usable only in small upland areas. Bar graphs in figure 1 show seasonal variations and typical regional differences in runoff.

Although damaging floods have occurred on most streams in parts of California at various times, major statewide flooding is rare. The greatest known major floods occurred throughout the Central Valley and coastal southern California during the winter of 1861–62. The Central Valley experienced severe flooding of similar intensity again in 1867–68. No floods of that magnitude have occurred since then. Recent flooding of large areas occurred in 1955, 1964, and 1969.

The most severe drought of record that affected the entire State was during 1976–77. The low flows of that period are evident in the bar graphs in figure 2. Rationing of water and (or) voluntary restrictions on water use occurred in most cities.

PRINCIPAL RIVER BASINS

California falls into four water-resources regions—the California, the Pacific Northwest, the Great Basin, and the Lower Colorado. The California Region (fig. 2) covers more than 95 percent of the State's area and includes more than 99 percent of its population. A small, almost unpopulated part of the State is in the Pacific Northwest Region. The Great Basin Region includes 1.6 percent of the State's area and about 0.3 percent of its population, principally in the vicinity of Lake Tahoe. The Lower Colorado Region includes 2.9 percent of California's area and less than 0.1 percent of its population. There are no significant streams in the Pacific Northwest Region in California; the only major stream in the Lower Colorado Region is the Colorado River main stem.

The principal river basins of the State are in six subregions (the Sacramento, the Tulare–Buena Vista Lakes and San Joaquin River, the Southern California Coastal, the Central California Coastal, and the Klamath–Northern California Coastal) of the California Region and in one subregion (Central Lahontan) of the Great Basin Region (Seaber and others, 1984) (fig. 2). The Sacramento River drains inland slopes of the Klamath Mountains and Coast Ranges and the western slopes of the northern Sierra Nevada. The valley of the lower Sacramento River constitutes the northern part of the Central Valley. The southern Central Valley includes the lowlands of the closed basin of Tulare–Buena Vista Lakes and the San Joaquin River basin. The confluence of the Sacramento and San Joaquin Rivers forms the Sacramento–San Joaquin Delta—an area of about 1,000 mi² (square miles) in which many channels meander among low-lying islands. The delta waterways are tidal, and the delta outflow constitutes an inland extension of the San Francisco Bay system.

The southwestern part of the State contains the southern California coastal basins, in which the large metropolitan areas of southern California are located. To the north, the central California coastal basins extend through the drainage to Monterey Bay. The Russian River basin and other stream basins south of the Oregon border constitute the northern California coastal basins. The Central Lahontan basins of the Great Basin Region are in the Basin and Range physiographic province east of the Sierra Nevada.

These river basins are described below; their location and long-term variations in streamflow at representative gaging stations are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

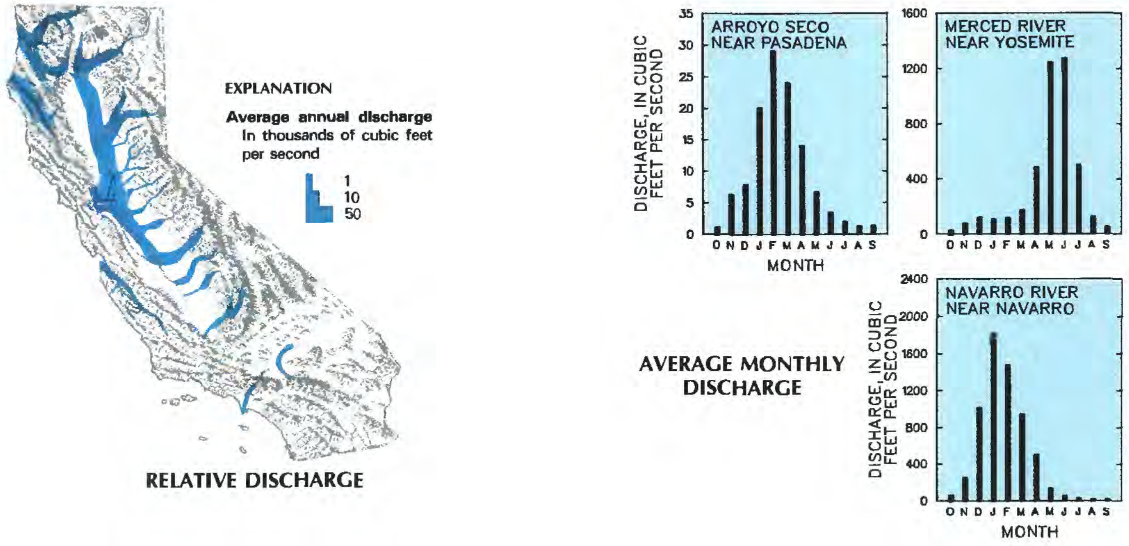

Figure 1. Average annual precipitation and runoff in California and average monthly data for selected sites, 1951–80—Continued.

(Sources: Precipitation—annual data from California State, 1979, and unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from California State, 1979, and Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in California

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				CALIFORNIA REGION SACRAMENTO SUBREGION				
1.	Feather River at Nicolaus (11425000).	5,921	1944–69	169	7,957	521,000	Appreciable	Irrigation diversions.
			1970–83	1,061	9,424	332,000	. . . do . . .	Regulated by Oroville Dam (1969).
2.	Sacramento River at Verona (11425500).	21,251	1930–69	1,618	18,240	[1]77,700	. . . do . . .	Regulated by Shasta (1949) and Oroville (1969) Dams.
			1970–83	5,732	22,680	[1]94,700	. . . do . . .	
3.	American River at Fair Oaks (11446500).	1,888	1906–55	64	3,735	257,000		
			1956–83	426	3,942	150,000	. . . do . . .	Diversions. Regulated by Folsom Dam (1955).
				TULARE—BUENA VISTA LAKES AND SAN JOAQUIN SUBREGIONS				
4.	Kern River near Kernville (11186000).	846	1912–84	104	762	45,800	Moderate	Diversion affects low flow.
5.	Kings River below North Fork, near Trimmer (11218500).	1,342	1953–83	111	2,177	135,000	Appreciable	
6.	Merced River near Stevinson (11272500).	1,273	1941–83	52	733	14,400	. . . do . . .	Much diversion at low flow.
7.	San Joaquin River near Vernalis (11303500).	13,536	1930–83	241	4,783	99,900	. . . do . . .	All flows affected by regulation. Quality affected by irrigation return flow.
				SOUTHERN CALIFORNIA COASTAL SUBREGION				
8.	San Diego River at Santee (11022500).	377	1914–43	0.1	42.3	54,900	Moderate	Some irrigation diversion.
			1944–82	1.0	13.7	5,400	Appreciable	Much diversion and regulation.
9.	Santa Margarita River at Ysidora (11046000).	740	1924–48	0	43.3	46,000	Negligible	After 1948, increased regulation and irrigation use.
			1949–83	0	31.0	32,000	Moderate	
10.	Santa Ana River at Santa Ana (11078000).	1,700	1942–84	0	52.8	33,800	Appreciable	Constantly increasing regulation, diversion, and wastewater inflow.
11.	Los Angeles River at Long Beach (11103000).	827	1930–40	.1	110	192,000	Negligible	Constantly increasing regulation, urban runoff, and imported water.
			1941–82	3.8	222	118,000	Appreciable	
12.	Santa Clara River at Los Angeles–Ventura County Line (11108500).	625	1953–71	.1	36.2	161,000	Moderate	Irrigation diversions.
			1972–84	2.9	67.8	58,500	Appreciable	After 1971, imported water and more regulation.
				CENTRAL CALIFORNIA COASTAL SUBREGION				
13.	Salinas River near Spreckels (11152500).	4,156	1930–41	0.1	659	[2]145,000	Negligible	Dams completed in 1941 and 1965. Heavy pumping in basin. Low flow mostly industrial and municipal waste.
			1942–65	.5	262	[2]145,000	Moderate	
			1966–84	.6	590	[2]145,000	Appreciable	
14.	San Lorenzo River at Big Trees (11160500).	106	1937–84	9.2	140	39,600	Negligible	Light irrigation use. Runoff 18 inches.

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[1] Sutter and Yolo Bypasses carry much of floodflow past Verona gage.

[2] Regulation has little effect on high floodflows.

Table 2. Selected streamflow characteristics of principal river basins in California—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				KLAMATH-NORTHERN CALIFORNIA COASTAL SUBREGION				
15.	Russian River near Guerneville (11467000).	1,338	1940–58 1959–83	77 40	2,230 2,435	108,000 93,400	Negligible Moderate	Irrigation diversions. After 1958, imported water.
16.	Eel River at Scotie (11477000).	3,113	1911–84	43	7,412	608,000	Negligible	Much sediment at high flow.
17.	Klamath River near Klamath (11477000).	12,100	1911–84	1,859	18,110	556,000	Appreciable	Flood flows slightly regulated.
18.	Smith River near Crescent City (11532500).	609	1932–84	191	3,891	231,000	None	More than 86 inches of runoff.
				GREAT BASIN REGION CENTRAL LAHONTAN SUBREGION				
19.	Truckee River at Tahoe City (10337500).	507	1910–84	2.4	240	2,830	Appreciable	Completely controlled at Lake Tahoe outlet, 500 feet upstream.

[1] Sutter and Yolo Bypasses carry much of floodflow past Verona gage.

[2] Regulation has little effect on high floodflows.

CALIFORNIA REGION
Sacramento Subregion

The principal source of surface water in California is the Sacramento River, which has a drainage area of 26,520 mi^2, excluding the closed basin of Goose Lake. The river carries an average annual outflow of more than 30,400 ft^3/s or 19,600 Mgal/d to San Francisco Bay; the outflow is more than 30 percent of the total flow of all rivers in the State. The headwaters of the Sacramento and its principal tributaries from the north—the Pit and the McCloud Rivers—are regulated by Shasta Dam and Lake (completed in 1949 with a capacity of 4,500,000 acre-ft or 1,470,000 Mgal). The Pit River is developed intensively for hydroelectric-power generation. There is little regulation of the main stem of the Sacramento River downstream from Shasta Dam, but a diversion from the headwaters of the Trinity River in the upper Klamath River basin enters the Sacramento River just downstream from Shasta Dam. The principal tributaries—the Feather and the American Rivers—and other smaller but important streams are heavily regulated by many reservoirs, which provide flood control and water for irrigation, power production, and recreation. Chief among these reservoirs are Lake Almanor (completed in 1927 with 1,300,000 acre-ft or 424,000 Mgal of storage) and Oroville Dam and Lake (completed in 1969 with 3,500,000 acre-ft or 1,140,000 Mgal of storage) in the Feather River basin; Folsom Lake (completed in 1956 with 1,000,000 acre-ft or 326,000 Mgal of storage) on the American River; and Clear Lake (completed in 1914 with 420,000 acre-ft or 137,000 Mgal of storage) and Lake Berryessa (completed in 1957 with 1,600,000 acre-ft or 521,000 Mgal of storage) on Cache Creek and Putah Creek, both of which are tributary to the Sacramento River from the west.

Flooding, which at times has covered wide areas of the lower Sacramento Valley, has been largely alleviated by upstream reservoirs and by the Sutter and Yolo Bypasses. During unusually wet years, the bypasses accommodate much of the floodflow from north of the Feather River to the northern part of the Sacramento-San Joaquin Delta, 25 miles southwest of Sacramento.

About 2.1 million acres are irrigated in the Sacramento River basin by surface-water and ground-water sources. Irrigation of field crops (including wheat, rice, and corn) and deciduous orchard crops depletes the main stem of the Sacramento River by diverting water from tributaries and withdrawing ground water that would seep into the river. Depletion of river flow for irrigation tends to coincide with the natural period of low flow. The need to maintain streamflow during low flow has significantly affected reservoir construction and water management.

In the Feather and American River basins, gold mining by hydraulic methods in the late 1800's produced large volumes of tailings in and near stream channels. Sediment washed from these tailings and large sediment yields from many steep tributaries occasionally impairs the quality of the rivers, especially during storms. Quantities of organic compounds and other chemical constituents in agricultural return flows are increasing in the lower reaches of the Sacramento River.

Shasta Dam is the keystone of the Central Valley Project, which was started by the State but was completed by the Federal Government when local funding failed during the economic depression of the 1930's. The project provides flood control, irrigation supply, maintenance of riverflows, and hydroelectric power for much of the Central Valley. Operation of Shasta Dam and Oroville Dam is coordinated by State and Federal authorities. Surface water in this subregion generally is of good quality and suitable for most uses. Water issues include regulation and possible diversion of flow from the lower Sacramento River for supply to the California Aqueduct.

Tulare-Buena Vista Lakes and San Joaquin River Subregions

The southern Central Valley includes the Tulare-Buena Vista Lakes and the San Joaquin River Subregions. The valley bottom is arid, but large-scale farming is practical because of the low topographic relief and an abundance of irrigation water from aquifers, runoff from the Sierra Nevada, and surface-water imports from the Sacramento-San Joaquin Delta. In 1980, more than 5 million acres in the valley were irrigated (California Department of Water Resources, 1983, p. 144).

Tulare-Buena Vista Lakes form a closed basin of about 16,200 mi^2. Irrigated lands in the basin total about 3.3 million acres. The principal irrigated crop is cotton on more than 1.4 million acres. Also important are grapes, grains, and alfalfa. In 1980, the Friant-Kern Canal (fig. 2) brought 1,200 Mgal/d or 1,860 ft^3/s of water from the San Joaquin River basin, and imports from the delta brought in about 2,590 Mgal/d or 4,000 ft^3/s. Principal rivers tributary to the basin are the Kings and the Kern; the Tule and the Kaweah Rivers also drain the western slopes of the Sierra Nevada. There is no drainage from the north, where a very low divide separates this basin from the San Joaquin basin, and runoff from the west and south is negligible. The chief reservoirs are Lake Isabella (completed in 1953 with 570,000 acre-ft or 186,000 Mgal of storage) on the Kern River and Pine Flat Lake (completed in 1954 with 1,000,000 acre-ft or 326,000 Mgal of storage) on the Kings River, both of which are managed by the U.S. Army Corps of Engineers.

The San Joaquin River basin (15,600 mi^2) has an average annual runoff of about 10,000 ft^3/s or 7,060 Mgal/d, almost entirely from the Sierra Nevada. Streamflow in the basin is affected by melting of mountain snowfields, reservoirs, water import and export, ground-water pumping, and irrigation return flow. The Delta-Mendota Canal (fig. 2) and the California Aqueduct traverse the western side of the basin, and the Friant-Kern Canal carries water from the upper San Joaquin River basin into the Tulare-Buena Vista Lakes basin. About 2.1 million acres in the San Joaquin River basin are irrigated; the chief crops are cotton, corn, grain, and grapes.

Irrigation return flow from the western part of the Central Valley in both the Tulare-Buena Vista Lakes and San Joaquin River basins has posed water-quality problems since the early 1900's. The San Luis Drain was authorized by Congress in 1960 to drain this area (more than 1,000,000 acres) and to prevent mixture of irrigation return flow with the San Joaquin River. The original plan was to run the drain northward to the Sacramento-San Joaquin Delta, but the project has been completed only as far as Kesterson National Wildlife Refuge (fig. 2), about 70 miles short of its goal. Small quantities of wastewater were released to Kesterson until 1978, when the quantity of subsurface drainage increased. In 1981, the inflow to Kesterson was found to contain excessive amounts of selenium salts (Presser and Barnes, 1984), which are toxic to most organisms in large concentrations (National Academy of Sciences, 1973).

Principal reservoirs in the San Joaquin River basin are Millerton Lake (completed in 1947 with 520,000 acre-ft or 169,000 Mgal of storage) on the San Joaquin River, Camanche Reservoir (completed in 1963 with 431,000 acre-ft or 140,000 Mgal of storage) on the Mokelumne River, and Hetch Hetchy Reservoir (completed in 1923 with 360,000 acre-ft or 117,000 Mgal of storage) on the Tuolumne River. Camanche and Hetch Hetchy Reservoirs provide the municipal water supplies of Oakland and San Francisco, respectively, as well as many of the cities' suburbs. The basin also contains the San Luis Reservoir (completed in 1962 with 2,039,000 acre-ft or 664,000 Mgal of storage)—a facility operated jointly by State and Federal authorities in managing the State Water Project and the Central Valley Project.

Water quality generally is excellent in the Sierra basins tributary to the Tulare-Buena Vista Lakes and San Joaquin River Subregions. Surface water in the lowlands receives runoff from agricultural areas and, during low flow, is often of poor quality and may be unsuitable for some uses. Water issues include controversy between those who desire flow regulation and others who favor preservation of natural conditions on Sierra streams; and differing views as to the manner of handling irrigation return flow of poor quality. The most significant concerns are the effect on wildlife of organic substances in the irrigation return flow and the composition and quality of inorganic salts being leached from westside soils.

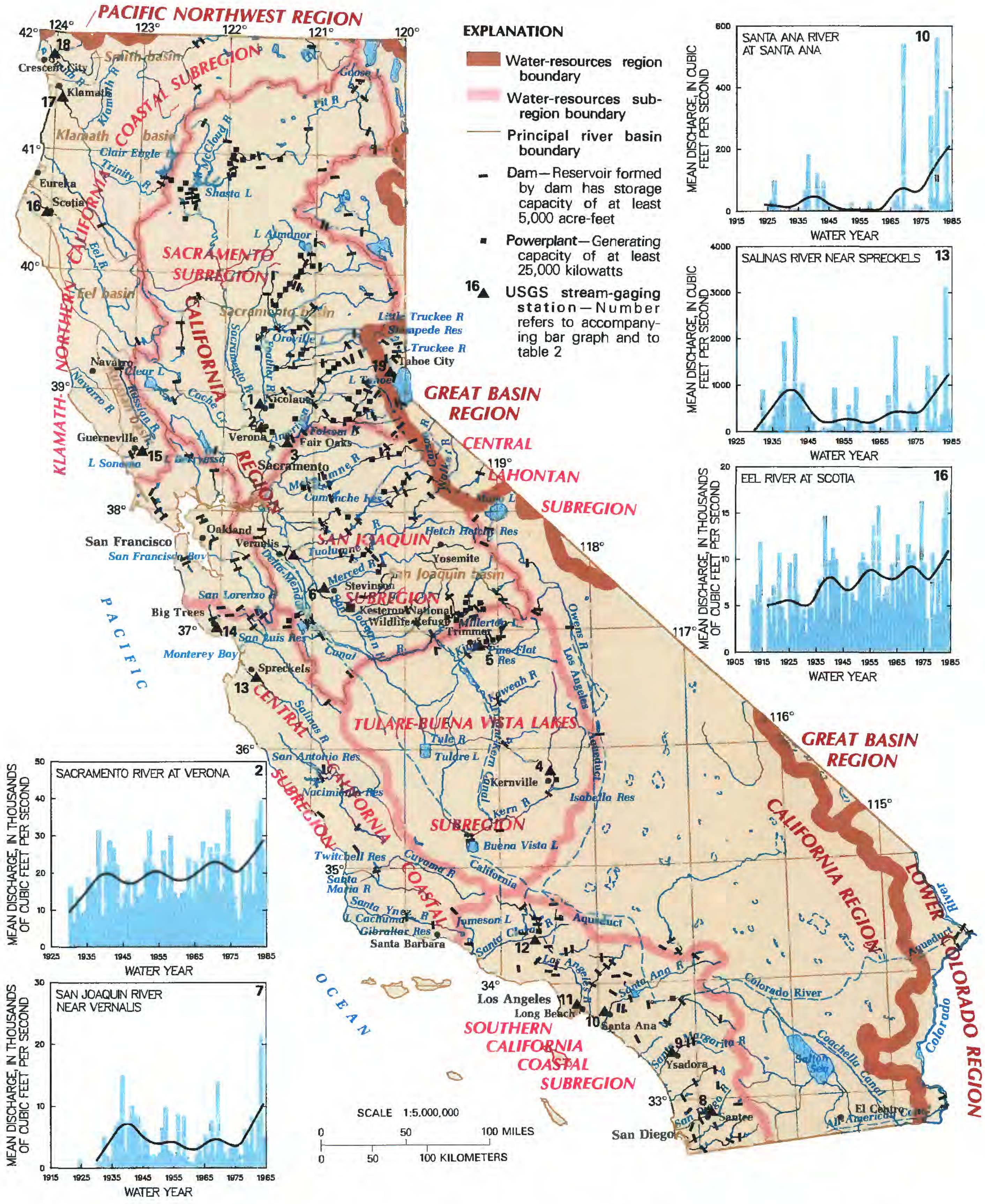

Figure 2. Principal river basins and related surface-water resources development in California and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Southern California Coastal Subregion

Although the southern California coastal basins encompass only about 10,900 mi^2, almost 13 million people or about 55 percent of the State's population resided there in 1980. Average annual outflow from these basins is about 1,660 ft^3/s or 1,070 Mgal/d, which is less than 2 percent of the statewide total. To meet this area's water needs, a total of 1,939 Mgal/d or 3,000 ft^3/s of water was imported in 1980 from the Colorado River, from the Sacramento–San Joaquin Delta through the California Aqueduct, and from the eastern slopes of the Sierra Nevada through the Los Angeles Aqueduct.

These basins were the first in California to be affected by human activities when diversions irrigated the crops of the Spanish missions starting about 1770. As the population of Los Angeles grew, so did the need for water, and, in 1913, the Los Angeles Aqueduct was completed. Increasing growth led to construction of the Colorado River Aqueduct, which began operation in 1941, and the California Aqueduct, which was extended into the area in 1972 (fig. 2). Many reservoirs in the region were constructed for storage and flood control, but their importance in meeting surface-water needs is negligible compared to surface-water imports. In this region, the conjunctive use of surface and ground water has been developed to a high degree. When excess water is available, it is used to recharge ground-water basins; when surface supplies run low, the recharged basins are pumped. In recent years, treated wastewater has been used for landscape irrigation, industry, and ground-water recharge.

About 365,000 acres in the basins are irrigated, principally for citrus, avocado, and truck crops. Streamflows (table 2) are highly regulated, especially in recent decades, and low flows are negligible unless supplemented by imported water. Public-water supplies throughout the area rely on imports. The bar graph of annual flows of the Santa Ana River (fig. 2, site 10) demonstrates the great variation of flow from year to year.

Except at times of low flow, from May to October, water quality generally is good in the streams that do not traverse densely populated or industrialized areas.

Water managers in the area are seeking ways to avoid shortages, which may occur when entitled Arizona users divert more water from the Colorado River (beginning in 1985).

Central California Coastal Subregion

The principal rivers of the central California coastal basins are the Santa Ynez River, the Santa Maria–Cuyama River system, and the Salinas River. By far the largest river in the basins, the Salinas flows northwestward, parallel to the trend of the San Andreas fault and the Coast Ranges. The Salinas River enters Monterey Bay from the south. The smaller San Lorenzo River enters Monterey Bay from the north, where runoff increases because of the more humid northern climate.

Lake Cachuma (completed in 1953 with 205,000 acre-ft or 66,800 Mgal of storage) and two small reservoirs in the Santa Ynez River basin—Jameson Lake and Gibraltar Reservoir—are used for flood control and municipal supply for Santa Barbara and nearby communities. In the Cuyama River basin, Twitchell Reservoir (completed in 1958 with 240,000 acre-ft or 78,200 Mgal of storage) regulates the flow of the lower Santa Maria River. Nacimiento Reservoir (completed in 1957 with 350,000 acre-ft or 114,000 Mgal of storage) and San Antonio Reservoir (completed in 1965 with 348,000 acre-ft or 113,000 Mgal of storage) are in the headwaters of the Salinas basin. Principal irrigated areas in the region include the lower Santa Maria and the lower Salinas Valleys. The Salinas Valley, for the 60 miles upstream from its mouth, is a productive source of truck crops, such as lettuce, cauliflower, and broccoli, and of grapes, tomatoes, and sugar beets. About 459,000 acres in the region are irrigated, mostly with ground water. However, the interchange of surface and ground water through the highly permeable soils of the valleys makes precise separation of ground water and surface water impossible. Water management in the region is based on conjunctive use. Water quality generally is good.

Klamath-Northern California Coastal Subregion

The Klamath and northern California coastal basins drain to the Pacific Ocean along the coastline for about 290 miles from the Golden Gate to the Oregon border. Outflow from the basins averages about 39,500 ft^3/s or 25,500 Mgal/d; about 75 percent of the total outflow is from the Russian, the Eel, the Klamath, and the Smith Rivers. Runoff in the northern coastal basins is about 40 percent of the statewide total. Headwaters of streams in this area are steep and carry large sediment loads, so that sediment deposition is a problem in some lower reaches. There is little regulation of streams in the area, although there is a small diversion from the upper Eel to the upper Russian River and, in the Russian River basin, Lake Sonoma (completed in 1983 with 381,000 acre-ft or 124,000 Mgal of storage) (California Department of Water Resources, 1984, p. 94), which provides flood control and flow augmentation. Since 1967, an average annual flow of about 1,520 ft^3/s or 982 Mgal/d has been diverted to the Sacramento River basin from Clair Engle Lake (completed in 1962 with 2,448,000 acre-ft or 798,000 Mgal of storage) on the Trinity River, tributary to the Klamath River. Most of the streams of the Eel, the lower Klamath, and the Smith River basins are protected under the State's Wild and Scenic Rivers Act of 1972 (California State, 1979, p. 92).

Ground water is the principal source for irrigation in the Russian River basin. Some fodder crops are irrigated by surface water in the lower Eel and the upper Klamath River basins, but the effect on streamflow is slight. Small reservoirs are used to generate hydroelectric power on the upper Klamath River. The Klamath River brings an average annual flow of about 1,930 ft^3/s or 1,250 Mgal/d to California from Oregon.

The streams of this region, particularly in the northern part, are used extensively for recreation and sport fishing. Water quality in the subregion generally is good, although in the downstream reaches of the Russian River it deteriorates during times of exceptionally low flow.

GREAT BASIN REGION

Central Lahontan Subregion

The Central Lahontan basins of the Truckee, the Walker, and the Carson Rivers are located east of the Sierra Nevada. The Truckee River (fig. 2, site 19) is of chief interest because it has the most flow and is associated with Lake Tahoe—the center of population and economic activity in the region. The three rivers head in the Sierra Nevada and flow into Nevada, carrying an average annual total flow of about 1,660 ft^3/s or 1,070 Mgal/d across the State line. Many small basins are north of the Truckee River basin; most are closed and none have appreciable flow.

Storage in the Truckee River basin in California includes Lake Tahoe (745,000 acre-ft or 243,000 Mgal of storage) and Stampede Reservoir (completed in 1970 with 225,000 acre-ft or 73,300 Mgal) on Little Truckee River, a downstream tributary. Some reaches of Truckee River are used intensively for recreation, and hydroelectric power is produced. The quality of water generally is excellent.

LOWER COLORADO REGION

The main stem of the Colorado River borders California for about 200 miles in a desert area from which there is no significant outflow. Water is diverted from the Colorado River in this reach for use in California. In 1983, the Colorado River Aqueduct provided 579 Mgal/d or 896 ft^3/s for municipal supply to southern California coastal cities, and the All-American and Coachella Canals and other facilities provided about 3,040 Mgal/d or 4,700 ft^3/s (Landsman, 1983, p. 2 and 6) for irrigation of grains, alfalfa, cotton, and truck crops. Litigation over rights to Colorado River water has involved several States and the Federal Governments of the United States and Mexico.

SURFACE-WATER MANAGEMENT

Surface-water management in California is perhaps as complex as its hydrology. At the State level are two major agencies and several ancillary ones. In addition, several Federal and hundreds of local agencies are responsible for water management and distribution.

All surface-water resources in California, except those on Federal lands, come under the purview of the California Department of Water Resources (DWR). The DWR's activities include (1) construction and operation of the State Water Project, (2) construction and operation of energy-producing facilities, and (3) statewide water-resources planning. The California State Water Resources Control Board, which establishes and enforces water-quality plans and standards and gives permits for certain uses of surface water, works with the DWR. Nine Regional Water Quality Control Boards grant permits for wastewater discharge and establish and enforce water-quality policy and standards for their regions. The State Departments of Health Services and Fish and Game also have responsibilities and authority in certain aspects of water-quality control, streamflow monitoring, and restrictions on water use. One other State group—the Colorado River Board—is concerned specifically with protection of California's interest in the Colorado River system.

The U.S. Bureau of Reclamation is the primary Federal agency for surface-water management. The Bureau manages the Central Valley Project and works in cooperation with State agencies in striving for optimum use of California's water resources. Water quality is a concern of the U.S. Environmental Protection Agency. The U.S. Army Corps of Engineers acts in matters pertaining to navigation, flood control, and wetlands. The Corps also is responsible for construction of certain federally owned facilities. The Federal Emergency Management Agency has a strong voice in flood-plain management. The U.S. Geological Survey maintains a cooperative program for data collection and hydrologic investigations with several State and numerous local agencies.

The management of water shared between California and its neighbors is the subject of three interstate agreements: (1) The 1922 Colorado River Compact (U.S. Congress, 1968) among Arizona, Nevada, and California; (2) the 1956 Klamath River Basin Compact (U.S. Congress, 1968) with Oregon; and (3) the California-Nevada Interstate Compact (Ralph G. Allison, California Department of Water Resources, oral commun., 1985), concerned with the waters of Lake Tahoe and the Truckee, Carson, and Walker River basins. The California-Nevada Interstate Compact has been approved by both State legislatures but not yet by the U.S. Congress.

A 1944 treaty between Mexico and the United States (U.S. Congress, 1968) affirms Mexico's rights to Colorado River water, and a subsequent 1973 international agreement established quality criteria for deliveries to Mexico. The Winters Doctrine, established by Federal authority in 1908, confirms the water rights of Indian reservations.

During the late 1940's and 1950's, California embarked on two major water programs. One program concentrated on collecting basic data and developing a statewide water plan—the California Water Plan (California Department of Water Resources, 1957; 1983). The other program considered specific projects, starting with Lake Oroville on the Feather River—the initial step in the State Water Project.

The California Water Plan, officially adopted in 1960, is updated as circumstances warrant—most recently in 1983 (California Department of Water Resources, 1983). Updating includes revised projection of future conditions and consideration of changes in the economic, legal, and social climate.

California has adopted a dual system of riparian and appropriative rights with respect to surface water. The laws continue to evolve as the State attempts to deal with the conflicts and complexities that arise.

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FOR ADDITIONAL INFORMATION

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COLORADO
Surface-Water Resources

Surface water is sustained largely by snowmelt in the mountainous western two-thirds of Colorado, and consequently, is not distributed uniformly areally or temporally. In the mountainous western part of the State where surface water is abundant, ground water is scarce; in the eastern part of the State where surface water is scarce, ground water is abundant. Ephemeral streams typify streamflow in most of the eastern one-third of Colorado—the exceptions generally are streams that head in the mountainous central part of the State and flow through the eastern part. About 2,210 ft³/s (cubic feet per second) or 1,430 Mgal/d (million gallons per day) of streamflow enters Colorado from Nebraska, New Mexico, Oklahoma, Utah, and Wyoming, and about 18,000 ft³/s or 11,600 Mgal/d leaves the State as streamflow to Kansas, Nebraska, New Mexico, Oklahoma, Utah, and Wyoming. In 1980, 84 percent of Colorado's population was served by surface water (table 1). Total surface-water withdrawals in Colorado in 1980 were 13,000 Mgal/d or 20,100 ft³/s; the largest withdrawals were for irrigation, 11,000 Mgal/d or 17,000 ft³/s. The water quality of 94 percent of Colorado's stream miles that have been fully assessed supports their classified uses (Colorado Department of Health, 1984). Waters that have not been assessed are little affected by human activities and are believed to have equal or better quality than those that have been assessed.

GENERAL SETTING

Colorado is located in five physiographic provinces (fig. 1). The Great Plains province in eastern Colorado is characterized by dissected plains, high plains, rolling hills, and sandhills. Average annual precipitation in this province ranges from about 12 to 16 inches. The Southern Rocky Mountains province, located to the west of the Great Plains province, is characterized by steep-sided valleys that drain very high mountain ranges with scattered high-elevation mountain parks (broad meadows). Average annual precipitation ranges from about 7 to 60 inches; maximum precipitation occurs in the mountains in local areas too small to delineate in figure 1. The Colorado Plateaus province is located along the western one-fourth of the State (except in the north) and is characterized by sharply incised valleys that contain numerous ephemeral streams which drain the lower mountain ranges. Average annual precipitation ranges from about 8 inches in the lower valleys to 40 inches locally along the mountain crests. The Wyoming Basin province, located in northwestern Colorado, is characterized by steep-sided valleys that drain mountain ranges along its eastern and southern boundaries and by numerous slightly incised ephemeral streams that originate in dissected plains. Average annual precipitation ranges from about 12 to 40 inches locally (fig. 1). The Middle Rocky Mountains province in extreme northwestern Colorado has characteristics of both the Southern Rocky Mountains and the Wyoming Basin provinces. Average annual precipitation ranges from about 12 to 20 inches locally.

Extreme variations in monthly precipitation across the State result from regional climatic variations and from the orographic effects of mountains. Monthly precipitation is relatively uniform in western Colorado but can be extremely variable locally. In contrast, monthly precipitation in eastern Colorado is highly variable but is distributed relatively uniformly areally.

Evaporation from water surfaces ranges from less than 35 in./yr (inches per year) to about 65 in./yr (Farnsworth and others, 1982). Less evaporation occurs along the higher mountain ranges, and more occurs in the valleys and along the eastern one-third of the State. The highest rates of evaporation occur in the extreme southeastern corner of the State.

Table 1. Surface-water facts for Colorado

[Data 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 SURFACE WATER, 1980	
Number (thousands)	2,440
Percentage of total population	84
From public water-supply systems:	
Number (thousands)	2,220
Percentage of total population	77
From rural self-supplied systems:	
Number (thousands)	220
Percentage of total population	8
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	16,000
Surface water only (Mgal/d)	13,000
Percentage of total	81
Percentage of total excluding withdrawals for thermoelectric power	81
Category of Use	
Public-supply withdrawals:	
Surface water (Mgal/d)	540
Percentage of total surface water	4
Percentage of total public supply	92
Per capita (gal/d)	243
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	62
Percentage of total surface water	0.5
Percentage of total rural domestic	63
Per capita (gal/d)	281
Livestock:	
Surface water (Mgal/d)	86
Percentage of total surface water	0.7
Percentage of total livestock	78
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	890
Percentage of total surface water	7
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	99
Irrigation withdrawals:	
Surface water (Mgal/d)	11,000
Percentage of total surface water	85
Percentage of total irrigation	79
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	5,500

Runoff in Colorado, like precipitation, is extremely variable seasonally, annually, and areally. Average annual runoff ranges from 0.1 inch or less over much of the eastern quarter of the State to 40 inches at the headwaters of the Conejos River (maximum not shown in fig. 1). A large percentage of runoff from the western mountains is a result of snowmelt in the spring and early summer; most runoff from eastern Colorado is from rainfall in spring and summer.

PRINCIPAL RIVER BASINS

Colorado occupies parts of four major regions (Seaber and others, 1984). These regions, and the principal river in each region, are the Missouri Region (the North and the South Platte Rivers); the Arkansas-White-Red Region (the Arkansas River); the Rio Grande Region (the Rio Grande); and the Upper Colorado

Region (the Colorado River main stem, the Green River, the Gunnison River, and the San Juan River). These river basins are described below; their locations, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Selected streamflow characteristics and other pertinent information are given in table 2.

MISSOURI REGION
North and South Platte Subregions

These subregions are the drainage basins of the North and the South Platte Rivers. The North Platte River basin occupies about 2 percent of the State's 104,247-mi^2 (square mile) area, and the South Platte River basin occupies about 18 percent. The North Platte River originates in the north-central mountains; it drains a high mountain park and flows about 45 miles north into Wyoming. There are no significant concerns about surface-water quality in the North Platte River basin. Principal use of surface water is for irrigation of hay meadows.

The South Platte River originates in the center of the State and flows generally northeastward about 270 miles into Nebraska. Water quality in this basin is suitable for most uses, except along the South Platte River (and the lower reaches of tributaries) from a few miles above Denver to a few miles below the mouth of the Cache la Poudre River, where the classified uses are impaired by fecal coliform bacteria, un-ionized ammonia (toxic to aquatic life), and metals (Colorado Department of Health, 1984). The classified uses along the upper reaches of Clear Creek are impaired by concentrations of trace metals. Principal use of water is for irrigation of croplands and for municipal supply. About 65 percent of the population of Colorado is concentrated in a 30-mile-wide area along the South Platte River from the point where it enters the plains (18 miles southeast of Denver) to a point about 80 miles northward along the eastern foothills (62 miles north of Denver). About 341 Mgal/d or 528 ft^3/s of water is imported annually from the Colorado River basin (Harold Petsch, U.S. Geological Survey, written commun., 1985), about 10 Mgal/d or 15.4 ft^3/s from the Arkansas River basin, and about 19 Mgal/d or 29.4 ft^3/s from the North Platte River basin, to supplement irrigation and municipal supplies. Because of water imports, an increasing streamflow trend is indicated by the curve of average discharge by water year in figure 2 for the South Platte River (site 3). About 77 percent of the imported water also is used to produce hydroelectric power. The South Platte River and its tributaries in the Great Plains province are a major cause of severe spring and summer flooding from thunderstorm activity in that part of the drainage basin. Three large flood-control structures in the drainage basin provide flood protection to much of the Denver metropolitan area: Chatfield Lake (completed in 1975 with 235,000 acre-ft (acre-feet) or 76,600 Mgal (million gallons) of storage capacity) on the South Platte River; Cherry Creek Lake (completed in 1950 with 92,800 acre- ft or 30,200 Mgal of storage capacity) on Cherry Creek; and Bear Creek Lake (completed in 1979 with 58,400 acre-ft or 19,000 Mgal of storage capacity) on Bear Creek. Recreational development has occurred at almost all storage and flood-control reservoirs in the basin.

Surface-water issues in the South Platte River basin relate to use of water rights granted in the South Platte River Compact of 1926; effects of increased urbanization and industrialization on water quality; effects of former mining and processing of metal ores, radium, and coal on water quality; effects of hazardous waste sites on ground-water quality (and probable resultant effects on surface-water quality); catastrophic flash floods on streams flowing through steep canyons in the eastern foothills; and flooding from thunderstorms in the eastern plains.

ARKANSAS-WHITE-RED REGION
Upper Arkansas Subregion

The Arkansas River drains about 27 percent of the State's area. The Arkansas River originates in the central part of the State; it flows to the south for about 75 miles, then flows generally eastward for about 160 miles into Kansas. Water quality is suitable for most uses, except for short reaches of the Arkansas River at the headwaters and below Fourmile Creek, where the classified uses are impaired by concentrations of trace metals; in short reaches near the center of Fountain Creek and the Huerfano River, where fecal coliform bacteria and metals impair classified uses; and along the Arkansas River from Pueblo to the Colorado-Kansas State line, where elevated fecal-coliform-bacteria counts have been found (Colorado Department of Health, 1984). Principal water use is for irrigation of croplands. About 114 Mgal/d or 176 ft^3/s of water is imported annually from the Colorado River Basin to supplement irrigation and municipal supplies. About 10 Mgal/d or 15 ft^3/s of the imported water is exported to the South Platte River basin for municipal use, and about 64 Mgal/d or 99 ft^3/s of the imported water is used to generate hydroelectric power. The Arkansas River and its tributaries in the Great Plains physiographic province are a major cause of severe spring and summer flooding from thunderstorm activity in that part of the basin. The unusually high periodic average discharge by water year shown in figure 2 for the Arkansas River (site 6) are the result of these severe thunderstorms. The basin contains three major flood-control structures: John Martin Reservoir (completed in 1943 with 616,000 acre-ft or 201,000 Mgal of storage capacity) on the Arkansas River, Pueblo Reservoir (completed in 1974 with 358,000 acre-ft or 117,000 Mgal of storage capacity) on the Arkansas River, and Trinidad Lake (completed in 1977 with 92,000 acre-ft or 30,000 Mgal of storage capacity) on the Purgatoire River. These reservoirs also are storage reservoirs for irrigation supply. Most storage-and flood-control structures in the basin are used for recreation.

Surface-water issues in the Arkansas River basin relate to whether Kansas is receiving the authorized amount of water under the Arkansas River Compact of 1948; the effects of increased urbanization and industrialization on water quality; the effects of mining and processing (former and current) of metal ores, uranium, and coal on surface-water and ground-water quality; and flooding from thunderstorms in the Great Plains province.

RIO GRANDE REGION
Rio Grande Headwaters Subregion

The Rio Grande drains about 7 percent of the State's area. The Rio Grande originates in the southern Colorado mountains and flows about 130 miles to the east and south into New Mexico. The State's smallest average annual precipitation (7 inches) occurs near the center of the Rio Grande drainage basin. Water quality is suitable for most uses, except for short reaches along the Rio Grande near the headwaters; in a short reach of the Conejos River near its mouth, where concentrations of trace metals impair the classified use; and in a short reach of the Rio Grande below Alamosa, where fecal-coliform bacteria are present (Colorado Department of Health, 1984). Principal uses of water are for irrigation of hay meadows and other croplands. About 3.2 Mgal/d or 5 ft^3/s is imported annually from the Colorado River Basin to supplement irrigation supplies. Most reservoirs in the basin were built to provide storage

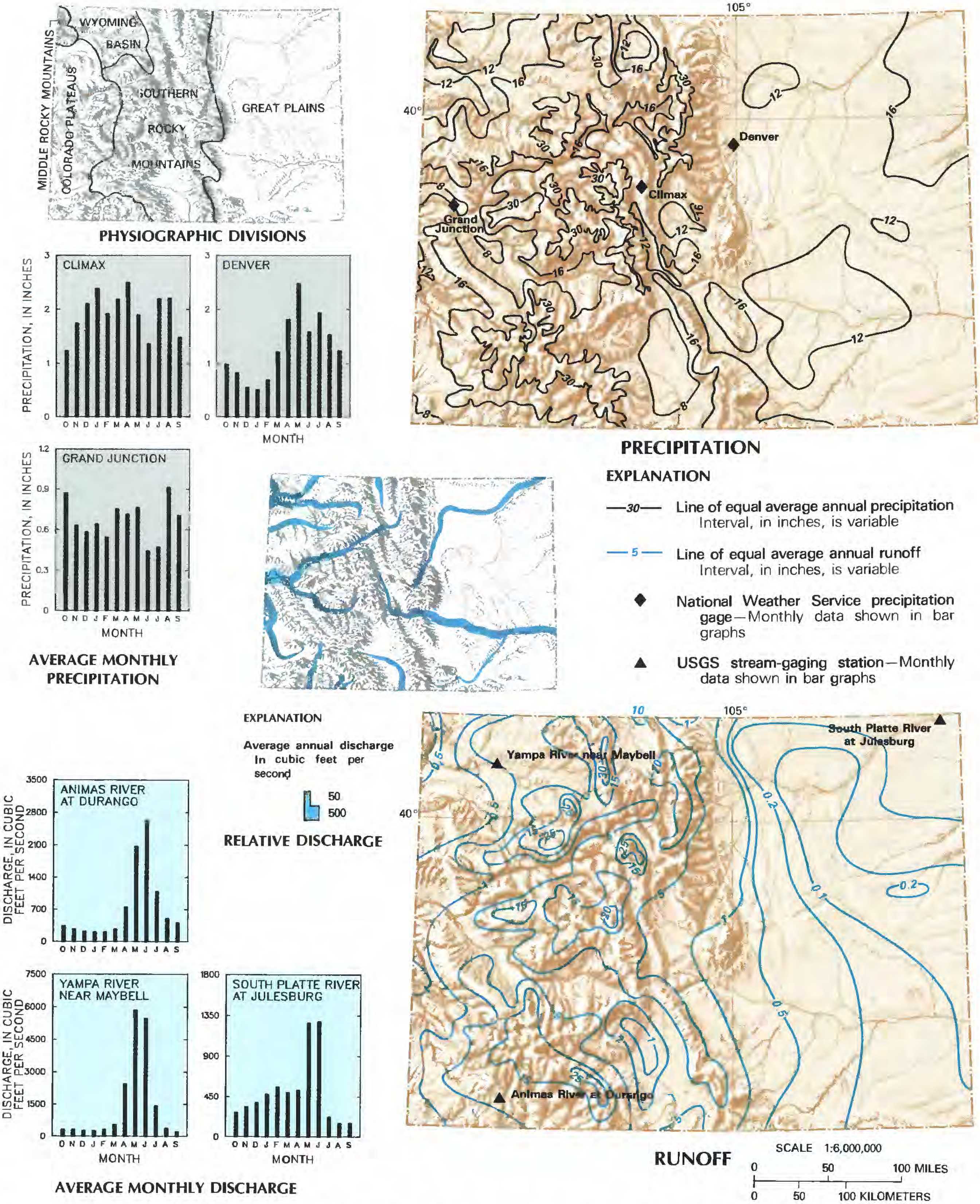

Figure 1. Average annual precipitation and runoff in Colorado and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from Colorado State University, 1984; monthly data from National Oceanic and Atmospheric Administration, 1982. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly-and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Colorado

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
	MISSOURI REGION **NORTH AND SOUTH PLATTE SUBREGIONS**							
1.	North Platte River near Northgate (06620000).	1,431	1915–84	35	440	7,870	Negligible	Irrigation development (hay meadows) upstream.
2.	South Platte River above Elevenmile Canyon Reservoir, near Hartsel (06695000).	880	1933–84	3.3	79.1	2,410	Moderate	Irrigation development (hay meadows) and storage upstream.
3.	South Platte River near Kersey (06754000).	9,598	1901–84	51	834	40,400	Appreciable	Affected by upstream regulation, irrigation diversion, bypass diversion, and imported water.The 7-day, 10-year low flow and 100-year flood analyses include effects of regulation in diversion period.
4.	South Platte River at Julesburg (06764000).	23,138	1902–84	7.6	524	62,300	. . . do . . .	Affected by upstream regulation, irrigation diversion, bypass diversion, and imported water. The 7-day, 10-year low flow and 100-year flood analyses include effects of regulation in diversion period.
	ARKANSAS—WHITE—RED REGION **UPPER ARKANSAS SUBREGION**							
5.	Arkansas River at Canon City (07096000).	3,117	1888–1981	129	715	14,300	Moderate	Affected by upstream regulation and imported water.
6.	Arkansas River at La Junta (07123000).	12,210	1912–73 1974–84	4.8 3.8	244 233	96,300 19,300	Appreciable . . . do . . .	Affected by upstream regulation, irrigation diversion, bypass diversion, and imported water. Flow further affected by Pueblo Reservoir 70 miles upstream, since January 1974. The 7-day, 10-year low flow and 100-year flood analyses include effects of regulation in diversion period.
7.	Purgatoire River at Trinidad (07124500).	795	1895–1976 1977–81	2.7	83.3 64.3	34,400	Negligible Appreciable	Virtually natural flow prior to regulation by Trinidad Lake, (August 1977).
8.	Purgatoire River near Las Animas (07128500).	3,503	1922–31, 1948–76 1977–84	0.34	116 81.0	94,000	Moderate . . . do . . .	Irrigation development upstream. For 1922-31, 1948-76, the 7-day, 10-year low flow and 100-year flood analyses include effects of regulation in diversion period.
9.	Arkansas River at Lamar (07133000).	19,780	1913–42 1948–84	1.1 0.63	301 93.6	131,000 35,500	Appreciable . . . do . . .	Sizable irrigation development upstream. For 1913–42, the 7-day, 10-year low flow and 100-year flood analyses include effects of regulation in diversion period. For 1948–84, analysis based on period since regulation began.
	RIO GRANDE REGION **RIO GRANDE HEADWATERS SUBREGION**							
10.	Rio Grande near Del Norte (08220000).	1,320	1889–1984	107	901	13,400	Moderate	Affected by irrigation-storage reservoirs upstream.
11.	Rio Grande near Lobatos (08251500).	7,700	1899–1984	7.1	575	19,900	Appreciable	Affected by irrigation diversion and storage upstream. Drainage area includes 2,940 mi^2 in closed basin in Colorado.

Table 2. Selected streamflow characteristics of principal river basins in Colorado—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi² = square miles; ft³/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				UPPER COLORADO REGION COLORADO HEADWATERS SUBREGION				
12.	Colorado River near near Dotsaro (09070500).	4,394	1940–84	536	2,136	23,800	Appreciable	Affected by storage reservoirs, exports of water, and hydropower generation.
13.	Colorado River near Camao (09095500).	8,050	1933–84	997	3,900	41,900	. . . do . . .	Affected by storage reservoirs, exports of water and hydropower generation.
				GUNNISON SUBREGION				
14.	Gunnison River near Gunnison (09114500).	1,012	1910–28 1944–84	148 115	888 709	11,500 9,000	Negligible Moderate	Virtually natural flow prior to regulation by Taylor Park Reservoir (1937). For 1944–84, the 7-day, 10-year low flow and 100-year flood analyses based on period since regulation began.
15.	Gunnison River near Grand Junction (09152500).	7,928	1896–1965 1968–84	265 495	2,611 2,659	38,100 30,500	Negligible Moderate	Virtually natural flow prior to 1966. For 1968–84, the 7-day, 10-year low flow and 100- year flood analyses based on period since regulation began.
				WHITE—YAMPA SUBREGION				
16.	Yampa River near Maybell (09251000).	3,410	1916–84	39	1,573	19,900	Negligible	Virtually natural flow.
17.	White River near Meeker (09304500).	755	1901–84	179	626	6,570	. . . do . . .	Do.
				SAN JUAN SUBREGION				
18.	Animas River at Durango (09361500).	692	1912–84	128	819	15,500	Negligible	Virtually natural flow.

for irrigation but now also are used for recreation. The decreasing trend in average discharge by water year streamflow shown in figure 2 for the Rio Grande (site 11) is probably caused by withdrawals of water for irrigation.

Deficiencies in delivery of water to New Mexico under the Rio Grande Compact of 1938, and ways to ameliorate these deficiencies, are the major surface-water issues in the basin.

UPPER COLORADO REGION

The Upper Colorado Region encompasses 37 percent of the State's area. About 448 Mgal/d or 693 ft³/s of water is exported annually to the Arkansas, the Platte, and the Rio Grande basins to the east, and about 95 Mgal/d or 147 ft³/s of water is exported annually to the Rio Grande basin in New Mexico. Severe flooding is rare. Even during the 1984 runoff season (April through July), which was much higher than normal (U.S. Geological Survey, 1985b), peak flows caused only minor flooding in Colorado. Most reservoirs in the basin were built to provide storage for irrigation, but they also provide recreation and flood control. Surface-water issues common to all of the Upper Colorado Region in Colorado are the use of water rights granted in the Colorado River Compact of 1922 and in the Upper Colorado River Basin Compact of 1948, the control of salinity in the Colorado River Basin (U.S. Geological Survey, 1984), and the transfer of water to the eastern side of the Continental Divide.

Colorado Headwaters Subregion

The Colorado River originates in the central mountains of the State and flows about 230 miles westward into Utah. Water quality in this subregion is suitable for most uses except for short reaches of tributaries in the Blue and the Roaring Fork River basins, in a short reach of the Colorado River above the Colorado-Utah State line, and along the Eagle River (except at its headwaters) where classified uses are impaired by concentrations of trace metals (Colorado Department of Health, 1984). Principal uses of water are for irrigation of hay meadows, croplands, and orchards. Surface-water issues are the same as those discussed for the Upper Colorado Region above, as well as potential hydrologic effects of oil-shale development.

Gunnison Subregion

The Gunnison Subregion encompasses about 8 percent of the State's area. The Gunnison River originates in the south-central mountains of Colorado; it flows generally westward for about 170 miles, then to the northwest for 30 miles to the city of Grand Junction, where it flows into the Colorado River. Water quality is suitable for most uses, except that classified uses are impaired by the occurrence of metals in short reaches in the Gunnison River headwaters and by the fecal- coliform bacteria in the Uncompahgre River below Montrose (Colorado Department of Health, 1984). Principal water use is irrigation of hay meadows, croplands, and orchards. Less than 3.2 Mgal/d or 5 ft^3/s is exported annually from the Gunnison River. The Curecanti unit of the U.S. Bureau of Reclamation Colorado River storage project is located on the Gunnison River. The Curecanti unit is comprised of Blue Mesa Reservoir (completed in 1965 with 830,000 acre-ft or 270,000 Mgal of storage capacity), Morrow Point Reservoir (completed in 1968 with 117,000 acre-ft or 38,100 Mgal of storage capacity), and Crystal Reservoir (completed in 1977 with 25,200 acre-ft or 8,200 Mgal of storage capacity).

White-Yampa Subregion

This subregion encompasses about 8 percent of the State's area. The Yampa and the White Rivers are the principal Colorado tributaries of the Green River. Water quality in this subregion is suitable for most uses except for a short reach of the Yampa River near its headwaters, where the classified use is impaired by trace metals (Colorado Department of Health, 1984).

The Yampa River originates in the northwestern central mountains of Colorado and flows generally westward for about 165 miles to its mouth at the Green River. Principal water use is irrigation of hay meadows. The major surface-water issues in the Yampa River basin are the effects of surface and underground coal mining on salinity, and trace-element concentrations.

The White River originates to the west of the Yampa River headwaters and flows westward for about 120 miles into Utah. Principal water use is irrigation of hay meadows. Major surface-water issues in the White River basin, other than those common to the Upper Colorado River Basin, are the potential hydrologic effects of oil-shale development.

San Juan Subregion

This subregion encompasses about 6 percent of the State's area. The rivers in this basin that originate in Colorado generally flow to the south into New Mexico or to the west into Utah (fig. 2). Streams in the western part of the basin are mostly perennial, have their origin in low mountains, and have tributaries that are mostly ephemeral. Streams in the eastern part of the basin are perennial, have their origin in the southwestern mountains (mostly along the Continental Divide), and have tributaries that are mostly perennial. Water quality in this subregion is suitable for most uses except for a short reach of the Animas River headwaters, where the classified uses are impaired by trace metals (Colorado Department of Health, 1984). In the western part of the basin, principal water use is irrigation of croplands; about 106 Mgal/d or 164 ft^3/s is imported annually from the Dolores River basin to supplement irrigation supplies. In the eastern part of the basin, principal water uses are irrigation of croplands and hay meadows, and limited hydroelectric-power generation (on the Animas River). A small amount of water (less than 2 Mgal/d or 3.1 ft^3/s) is exported annually from the eastern part of the basin to streams in the Rio Grande headwaters, but about 95 Mgal/d or 147 ft^3/s is exported annually to the Rio Grande basin in New Mexico. The Animas River—the largest San Juan River tributary in Colorado—originates in the State's southwestern mountains. The Animas River flows to the south for about 70 miles into New Mexico.

Principal uses of water in the Animas River are irrigation and hydroelectric-power generation. Major surface-water-related issues in the San Juan River basin are those common to the Upper Colorado Region, discussed earlier, as well as concerns of the Ute Indians regarding their water rights.

SURFACE-WATER MANAGEMENT

The water law of Colorado is solidly based on the doctrine of prior appropriation. According to sections 5 and 6 of Article XVI of the State Constitution, the water of every natural stream in the State of Colorado, not previously appropriated, is public property and is dedicated to the use of the people of Colorado. The right to divert unappropriated water for beneficial use cannot be denied. Water for domestic use has preference over all other uses, and water for agricultural use has preference over water for manufacturing use.

The State Engineer (Colorado Department of Natural Resources, Division of Water Resources) has general supervisory control over measurement, recordkeeping, and distribution of the public waters of the State. The State Engineer also is charged with the administration of the Interstate River Compacts and administers the decisions of the Supreme Court of the United States that affect Colorado's interstate water relations. Title 37, Article 90, Sections 101-141, of the 1973 Colorado Revised Statutes established the Colorado Ground Water Management Act and places the administration of ground water partly under the authority of the State Engineer and partly under the authority of the Colorado Ground Water Commission.

Many Federal, State, and local agencies are involved with the management of surface water in Colorado. Federal agencies with the largest management responsiblities are the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers. The Northern Colorado Water Conservation District and the Southeastern Water Conservancy District are the two largest recipients of water from U.S. Bureau of Reclamation projects in Colorado; these districts, in turn, are responsible for managing that water. The Board of Water Commissioners, City and County of Denver, are managers of the largest municipal supply in the State. Most Colorado cities and some counties also manage municipal supplies. Several irrigation districts, conservancy districts, and other State and Federal agencies play a role in managing water.

The U.S. Geological Survey, in cooperation with Federal, State, and local cooperators, maintains a network of 350 streamflow-gaging stations in Colorado, most of which provide data that support cooperator's water-management objectives. Hydrologic studies conducted by the U.S. Geological Survey also provide significant information needed by cooperators to manage Colorado water resources.

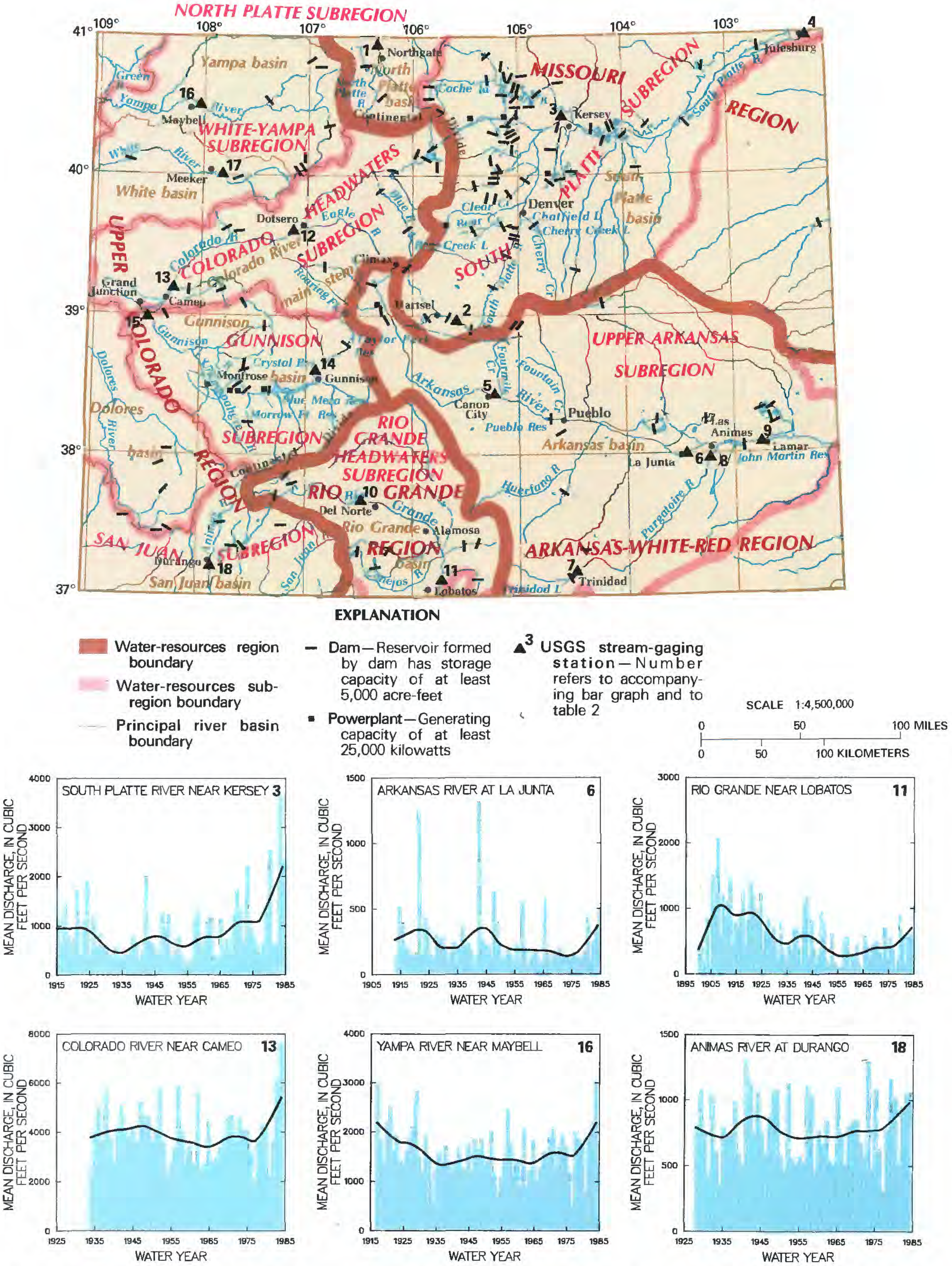

Figure 2. Principal river basins and related surface-water resources development in Colorado and average discharges for selected sites. Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development modified from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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CONNECTICUT
Surface-Water Resources

Surface water is a valuable natural resource that supplies 68 percent of Connecticut's 3.1 million people. More than 6,000 lakes and 8,400 miles of streams are visually prominent features of the Connecticut landscape. About 4,000 Mgal/d (million gallons per day) or 6,190 ft^3/s (cubic feet per second) of surface water is used to generate hydroelectric power (Connecticut Department of Environmental Protection, 1981). Surface water provides 1,200 Mgal or 1,860 ft^3/s or 92 percent of the total water withdrawn for offstream use. Industrial withdrawals of 860 Mgal/d or 1,330 ft^3/s and municipal withdrawals of 300 Mgal/d or 464 ft^3/s dominate offstream surface water use. Other surface-water withdrawal statistics for Connecticut in 1980 are given in table 1.

Streams in Connecticut generally are suitable for most uses because of an intensive program of water-pollution control that was instituted in 1967 (Connecticut General Assembly, 1967). The major water-related issues in the State today concern maintaining the quality of the State's streams in light of increasing demands on the resource and how the resource should be allocated. Legislative measures such as the passage of a comprehensive River Protection bill and a statewide surface- and ground-water-classification bill, and numerous local zoning ordinances are presently being used to protect the quality of streams (Connecticut Department of Environmental Protection, 1980).

GENERAL SETTING

Connecticut is located in the Taconic and New England Upland sections of the New England physiographic province (fig. 1). Average annual precipitation is about 47 inches statewide. Average annual precipitation generally is equally distributed throughout the year. Bar graphs of average monthly precipitation for Norfolk in the northwest, Hartford in central Connecticut, and Groton in the southeast, are shown in figure 1.

Streamflow in Connecticut varies significantly throughout the year. The variability of average monthly discharge for Burlington Brook in the west, Quinnipiac River in central Connecticut, and Yantic River in the east is shown in figure 1. Average annual runoff ranges from about 22 inches in north-central and southwestern Connecticut to about 29 inches in southeastern Connecticut. Evapotranspiration ranges from 27 inches in the northwest to 22 inches for central Connecticut, which is about 50 percent of the precipitation in those areas.

More detailed information on the relationship of rainfall, runoff, and evapotranspiration in Connecticut can be found in a series of reports titled "Water resources inventory of Connecticut," published by the Connecticut Department of Environmental Protection in Water Resources Bulletins 8, 11, 15, 17, 19, 21, 24, 27, 29, and 31.

Table 1. Surface-water facts for Connecticut

[Data 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 SURFACE WATER, 1980	
Number (thousands)	1,980
Percentage of total population	68
From public water-supply systems:	
Number (thousands)	1,980
Percentage of total population	68
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	1,300
Surface water only (Mgal/d)	1,200
Percentage of total	90
Percentage of total excluding withdrawals for thermoelectric power	80
Category of Use	
Public-supply withdrawals:	
Surface water (Mgal/d)	300
Percentage of total surface water	25
Percentage of total public supply	83
Per capita (gal/d)	152
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface-water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	1.8
Percentage of total surface-water	0.2
Percentage of total rural livestock	81
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	[1]860
Percentage of total surface-water	72
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	93
Irrigation withdrawals:	
Surface water (Mgal/d)	19
Percentage of total surface-water	1.6
Percentage of total irrigation	90
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	4,000

[1] 2,400 Mgal/d of saline surface water is used for cooling of condensors *and reactors.*

Major flooding can occur at any time during the year. During the winter and early spring, increased snowmelt resulting from warm weather can combine with rainfall to cause major flooding, such as the March 1936 flood on the Connecticut River (Grover, 1937). In the summer, locally severe thunderstorms often result in flash flooding, and, during the late summer and fall, hurricanes often produce severe flooding, such as the flood of September 1938 (Paulsen and others, 1940) and the flood of August and October 1955 (Bogart, 1960). Since the 1955 floods, 15 flood-detention reservoirs have been built by the U.S. Army Corps of Engineers (COE) to reduce peak runoff rates especially in the Quinebaug, Farmington, and Naugatuck River basins. In June 1982, major flooding occurred in many basins in southern Connecticut where there is no flood control and where the flood-recurrence intervals greatly exceeded 100 years. Evaluations of flood peaks and associated recurrence intervals for ungaged streams have been determined by regression analyses using data from 105 gaged sites in Connecticut (Weiss, 1983).

Drought conditions generally occur during the summer and early fall. The most notable drought of this century in Connecticut occurred in the middle 1960's (Barksdale and others, 1966), when 7-day, 10-year low flows of many streams declined to less than lowest long-term average annual low flows of record.

PRINCIPAL RIVER BASINS

Virtually all of Connecticut is in the New England Region (Seaber and others, 1984). Connecticut contains two subregions—Connecticut and Connecticut Coastal (fig. 2). The Connecticut Subregion contains the lower 1,450 mi^2 (square miles) of the Connecticut River basin. The largest rivers in the Connecticut Coastal Subregion are the Thames, Quinnipiac, Housatonic, and Saugatuck. The Thames and Housatonic originate outside of Connecticut. These rivers contribute about 94 percent of the average annual flow of 26,200 ft^3/s or 16,900 Mgal/d of freshwater inflow to Long Island

Sound. These river basins are described below; their locations and long-term variations in streamflow at representative gaging stations (Burlington Brook near Burlington, Salmon River near East Hampton, Mount Hope River near Warrenville, Yantic River at Yantic, Housatonic River at Falls Village, and Saugatuck River near Westport) are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

NEW ENGLAND REGION

Connecticut Subregion

Connecticut River Basin.—The Connecticut River, the longest stream in New England starts its 383-mile journey to Long Island Sound from the Connecticut Lakes in northern New Hampshire. Of the 66 miles of the Connecticut River in Connecticut, 55 miles are affected by the tides in Long Island Sound; 13 percent or 1,450 mi^2 of the drainage area is in Connecticut.

The major city in Connecticut located on the river is Hartford, about 47 miles from Long Island Sound. The downstream stretch of river below Hartford has been protected from flood-plain encroachment by the formation of a Connecticut River Gateway Commission since 1973 (Connecticut State, 1973).

The flow of the Connecticut River as it enters Connecticut is regulated by eight hydropower generation dams, by diversions for water supply, and by several lakes and reservoirs with a combined usable capacity of about 2.5 million acre-ft (acre-feet) or 815,000 Mgal (million gallons). In Connecticut, regulation is almost entirely restricted to the Farmington River basin, where flood control and water-supply reservoirs have a combined usable capacity of 270,000 acre-ft or 88,000 Mgal.

Public-water supply comprises 9 percent of total water use in the basins. The remaining 91 percent of the total water use is from streams, wells, and private reservoirs. These sources supply water for industrial use (3 percent); domestic use (5 percent); commercial use (2 percent); agricultural use (1 percent); and for cooling water for nuclear and steam-generating powerplants (89 percent), as described by Prisloe and Sternberg (1983) and Sternberg (1983). Figure 2 shows the 15-year moving average of average annual daily discharge at Burlington Brook (site 2) in western Connecticut and Salmon River (site 4) in eastern Connecticut. Readily apparent are the 20-year cyclic periods of high flow of the 1930's, 1950's, and 1970's as well as the drought periods of the mid-1940's and 1960's.

The Metropolitan District Commission (MDC) furnishes water to the greater Hartford area from the upstream part of the Farmington River basin (table 2, site 3). The scenic Farmington River provides class II and class III white-water kayaking areas, as well as extensive opportunities for boating, swimming, and fishing (Gabler, 1975).

The largest use of the Connecticut River in Connecticut is for cooling water and steam generation in the production of thermoelectric power. Two active power stations are on the river: An 820-MW (megawatt) thermoelectric plant at Middletown, and the 600 MW Connecticut Yankee Nuclear Powerplant that has been producing power since 1968. Flooding along the main stem of the Connecticut River has been greatly reduced by reservoirs that control runoff from 20 percent of the basin. Flood dikes were built in 1940 to protect Hartford and East Hartford from floods, such as the one that occurred in March 1936. As a result of the devastating floods of 1955, an intensive program of flood control was instituted in the Farmington River basin, and, today, about 25 percent of the basin is regulated by flood-control reservoirs. In spite of the flood control in the basin, flooding of small uncontrolled streams and the Connecticut and Farmington Rivers is expected to continue. One such flood occurred on May 31, 1984, when the flow at Thompsonville on the Connecticut River (table 2, site 1) reached 185,000 ft^3/s or 120,000 Mgal—the third largest flow ever recorded.

Connecticut Coastal Subregion

Thames River Basin.—Headwaters of the Thames River are located in Massachusetts about 93 miles upstream from its mouth at Long Island Sound. Of the 69 miles of the Thames River in Connecticut, 16 miles are affected by the tides in Long Island Sound. The Thames River and its tributaries in Connecticut drain 78 percent of the 1,480 mi^2 drainage basin; significant tributaries—the Quinebaug, Shetucket, and Yantic Rivers—drain undeveloped areas.

The flow of the Thames is controlled primarily for flood protection by eight reservoirs built by the COE. These reservoirs are located in the Quinebaug, Natchaug, and French River basins and have a combined usable capacity of almost 150,000 acre-ft or 48,900 Mgal. These reservoirs were built following the floods of August 1955. Many of the streams in the Thames were used during early settlement times to power grist mills and, later, knitting mills. Today, some of these sites are being considered for generation of hydroelectric power with small dams. One such site—Quinebaug River at Jewett City (table 2, site 7)—has recently been restored. The river system supplies water for many cities and towns and for industrial use. Long-term average discharges of Mount Hope River in northeastern Connecticut (table 2, site 5) and Yantic River (table 2, site 8) in the southeastern part of the State both show the same cyclic trends illustrated in figure 2, described earlier.

The Connecticut Department of Environmental Protection (DEP) has classified many Thames River basin tributaries in Connecticut excluding the French River, as having water that is suitable for drinking. The Quinebaug River downstream of the French River is suitable for fishing, whereas the French River is unsuitable for most uses between the Massachusetts-Connecticut State line to the confluence of the Quinebaug River (James Murphy, Connecticut Department of Environmental Protection, oral commun., 1985).

Quinnipiac River Basin.—The Quinnipiac River basin encompasses 166 mi^2 in south-central Connecticut. The river is 39 miles long, 9 miles of which are affected by tide in Long Island Sound. The river passes through a highly urbanized area that includes about 550,000 people and many industries. Large fluctuations in concentrations of dissolved solids in streams and the elevated bacterial content of the Quinnipiac River are evidence of human activities.

The Connecticut DEP has classified the headwaters of the Quinnipiac River and many of its tributaries as having water that is suitable for drinking. The Quinnipiac River from Southington to New Haven is acceptable only for fishing (James Murphy, Connecticut Department of Environmental Protection, oral commun., 1985).

The basin does not contain significant flood controls and in June 1982, 11 to 13 inches of rain fell on the Quinnipiac River basin in 48 hours, resulting in a discharge of 8,200 ft^3/s or 5,300 Mgal/d at Wallingford (table 2, site 9) that was greater than the 100-year flood (L. R. Johnston Associates, 1983). This storm caused the most severe flooding in the basin since the great floods of 1807 and 1854 (Thomson and others, 1964).

Housatonic River Basin.—The Housatonic River begins its 159-mile journey to Long Island Sound in western Massachusetts. Of the 94 miles of river in Connecticut, 13 miles are affected by tides in Long Island Sound. The Housatonic River basin drains 1,950 mi^2, of which 64 percent is in Connecticut. More than half of its population resides in major urban areas around Danbury, Waterbury, and Stratford in the south. The largest tributaries are the Naugatuck and Shepaug Rivers; the Shepaug is virtually undeveloped, whereas the Naugatuck supports the industrial towns of Torrington, Waterbury, and Beacon Falls.

The Housatonic River enters Connecticut at North Canaan. In Connecticut, low to medium main stream flows are completely regulated by hydroelectric powerplants at Falls Village, New Milford, and Stevenson. In the lower reaches of the river, the basin contains a series of lakes (Candlewood, Cairns, Shepaug, Lillinonah, and Zoar) that are operated primarily as hydroelectric storage reservoirs; they have a combined storage capacity of 165,000 acre-ft or 53,800 Mgal. Flood-control and water-supply reservoirs in the Naugatuck River have a combined storage capacity of 75,000 acre-ft or 24,400 Mgal.

The Housatonic River system provides 5 percent of all water used in the basin for public-water supplies, as well as 92 percent used for hydroelectric power and industrial use. Probably the most publicized use of the river is for recreation. The first 41 miles

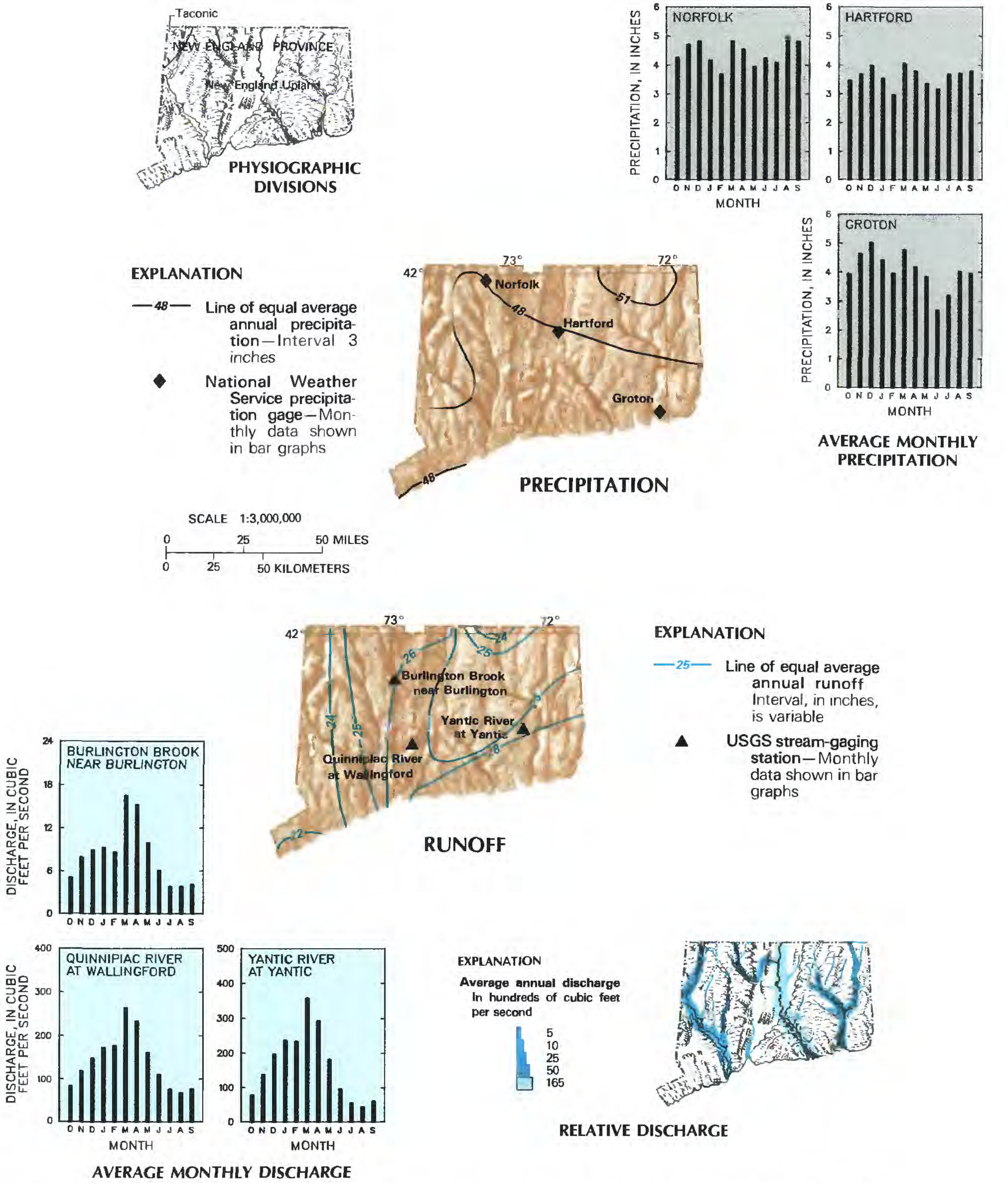

Figure 1. Average annual precipitation and runoff in Connecticut and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Connecticut

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and State of Connecticut Department of Environmental Protection]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				NEW ENGLAND REGION CONNECTICUT SUBREGION Connecticut River basin				
1.	Connecticut River at Thompsonville (01184000).	9,661	1928-83	2,200	16,400	209,000	Appreciable	Regulation by powerplants in Vermont and Mass. Diversion for water supply in Mass. Flood control for approximately 20 percent of basin. National stream-quality accounting station (NASQAN).
2.	Burlington Brook near Burlington (01188000).	4.10	1931-83	0.7	8.3	1,250	Negligible	Index station for long-term trends in natural streams.
3.	Farmington River at Rainbow (01190000).	590	1928-60 1961-83	144 101	1,030 1,040	44,000 24,000	Appreciable	Regulation by powerplant at Rainbow. Diversion for water supply of Metropolitan District Commission. Flood control since April 1960.
4.	Salmon River near East Hampton (01193500).	100	1928-83	5.2	184	16,600	Negligible	Index station for long-term trends in natural streams.
				CONNECTICUT COASTAL SUBREGION Thames River basin				
5.	Mount Hope River near Warrenville (01121000).	28.6	1940-83	0.9	51.2	5,620	Negligible	Index station for long-term trends in natural streams.
6.	Shetucket River near Willimantic (01122500).	404	1928-52 1953-83	46.5 44.2	667 734	25,000 22,500	Moderate	Flood control since March 1952. Diversion for water supply of city of Willimantic.
7.	Quinebaug River at Jewett City (01127000).	713	1918-58 1959-83	119 90.0	1,250 1,330	29,500 26,500	. . . do . . .	Flood control since Sept. 1958. NASQAN station.
8.	Yantic River at Yantic (01127500).	89.3	1930-83	5.2	165	10,800	Negligible	
				Quinnipiac River basin				
9.	Quinnipiac River at Wallingford (01196500).	115	1930-83	32.6	211	6,340	Moderate	Diversion for water supply of city of New Britain.
				Housatonic River basin				
10.	Housatonic River at Falls Village (01199000).	634	1912-83	119	1,090	24,000	Moderate	Regulation by Falls Village powerplant.
11.	Shepaug River near Roxbury (01203000).	132	1930-71	6.2	236	24,000	Appreciable	Diversion for water supply of city of Waterbury.
12.	Pomperaug River near Southbury (01204000).	75.1	1932-83	6.0	128	19,900	Negligible	Minor diversion for water supply of town of Woodbury. Index station for long-term trends in discharge in natural streams.
13.	Housatonic River at Stevenson (01205500).	1,544	1928-83	160	2,600	95,100	Appreciable	Regulation by powerplant at Stevenson. Diversion for water supply for city of Waterbury. Some flood control. NASQAN station.
14.	Naugatuck River at Beacon Falls (01208500).	260	1928-59 1960-83	61.2 59.4	484 557	46,000 23,000	. . . do . . .	Flood control since December 1960. Diversion for water supply of city of Waterbury.
				Saugatuck River basin				
15.	Saugatuck River near Westport (01209500).	79.8	1932-67	2.25	119	13,400	Appreciable	Diversion for water supply of Bridgeport Hydraulic Company.

of the Housatonic River in Connecticut (North Canaan to New Milford) has been classified as a protected river segment by the Connecticut DEP.

The quality of the Housatonic River main stem has been downgraded by polychlorinated biphenyls (PCB) that were introduced into the river system in Pittsfield, Mass. (Connecticut Department of Environmental Protection, 1980).

Recent notable floods in the Housatonic River basin have occurred in 1949, 1955, and 1984. The highest flood of record was 24.5 feet (75,800 ft³/s discharge or 49,000 Mgal/d) on October 16, 1955. Subsequent to the floods of 1955, extensive flood controls were installed at seven sites in the Naugatuck River basin, and about one-third of the main stem is controlled by three reservoirs.

The bar graph in figure 2 for the Housatonic River at Falls Village (table 2, site 10) shows the effects on streamflow of the severe drought of the mid 1960's and of the high flow periods of the mid 1950's and mid 1970's.

Saugatuck River Basin.—The Saugatuck River basin is located in southwestern Connecticut. This 26-mile-long river flows from Ridgefield to Westport and has a drainage area of 93.2 mi². Water-supply reservoirs that receive drainage from 51.4 mi² are used by a private company to supply 320,000 people in 8 towns—almost 50 percent of the population of southwestern Connecticut. A long-term declining trend in average annual daily discharge, shown in figure 2 (site 15), is caused by interbasin water demands; presently 60 percent of streamflow is used for water supply. Water shortages are frequent in southwestern Connecticut because of distribution problems and the relatively small size of its reservoirs, except in the Saugatuck River basin. Other companies, however, purchase water from the same water supplier during drought periods

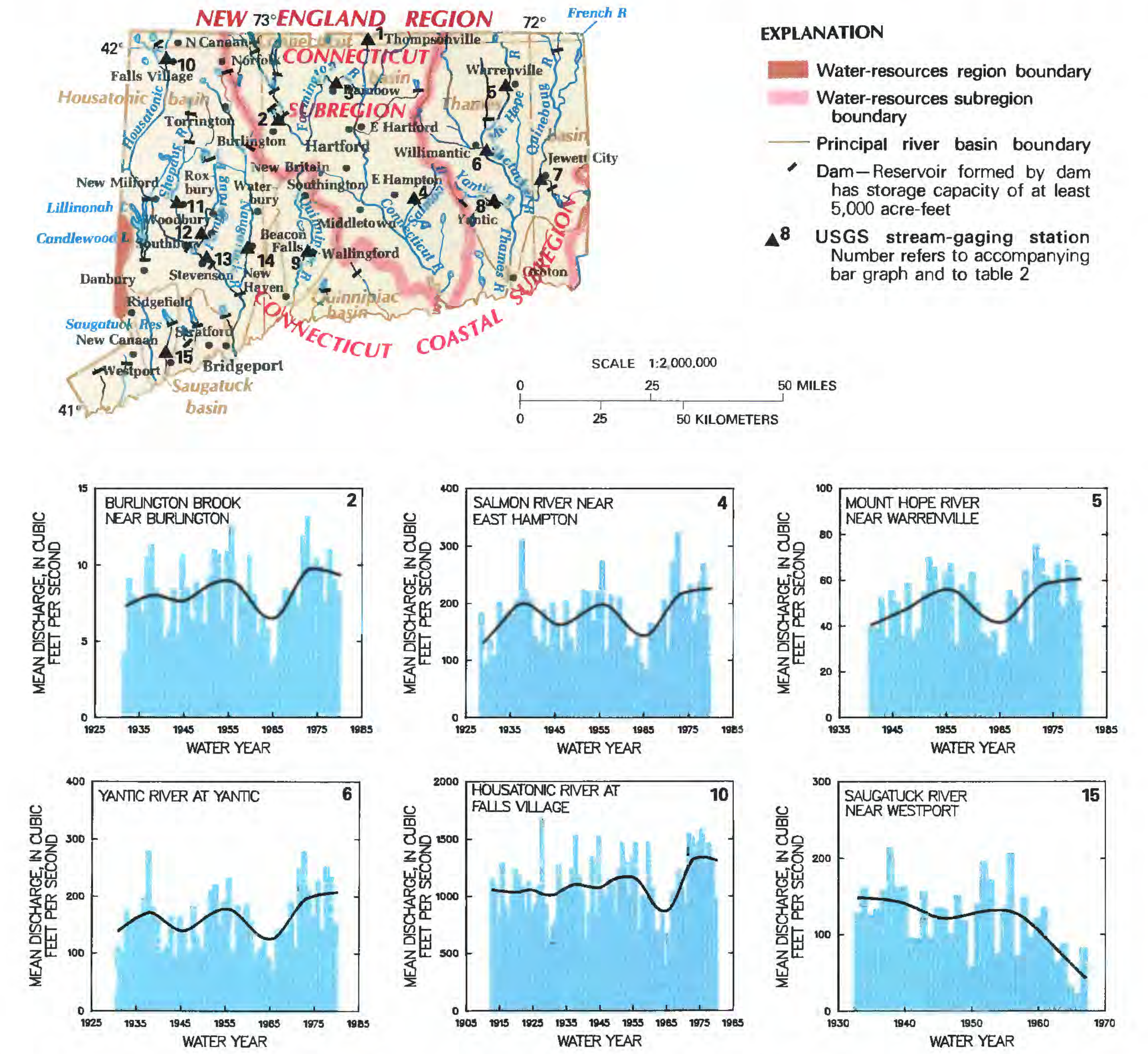

Figure 2. Principal river basins and related surface-water resources development in Connecticut and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

and impose additional demands on their supply by way of an interconnected pipe system such as the one to New Canaan.

There is no flood control in this basin and floods could still occur, such as the one on October 16, 1955, where the peak was 14,800 ft^3/s or 9,570 Mgal/d.

The quality of water upstream from the Saugatuck Reservoir is excellent and is presently used for public supply. The water quality of the Saugatuck River downstream from Saugatuck Reservoir is considered by the Connecticut DEP to be suitable for drinking water (James Murphy, Connecticut Department of Environmental Protection, oral commun., 1985).

SURFACE-WATER MANAGEMENT

The long-range plan for management of Connecticut's water resources, as set forth in Chapter 446i, Section 22a-352 of the Connecticut General Statutes (CGS), is the joint responsibility of the DEP, the Department of Health Services (DOHS), and the Office of Policy and Management (OPM). Specifically, these agencies are directed to (1) establish a continuing planning process and (2) periodically update a statewide long-range plan for the management of water resources. Section 22a-2 of the CGS created DEP and gave it jurisdiction over all matters relating to the preservation and protection of the air, water, and natural resources of the State.

Diversions and interbasin transfers of water are regulated under Sections 22a-365 through 22a-378 of the CGS. The administration of these statutes is the duty of the Commissioner of DEP. The Commissioner of DEP is directed by section 22a-424 to develop, administer, and enforce programs for the prevention, control, and abatement of new or existing pollution of the waters of the State in compliance with the Federal Water Pollution Control Act.

Sections 25-68b through 25-68h of the CGS (passed in 1984) requires the Commissioner of DEP to coordinate, monitor, and analyze the flood-plain management activities of State and local agencies. Among other specifics, this bill directs the Commissioner to designate the 100-year flood where this base flood is not designated by the National Flood Insurance Program.

The Commissioner of DEP is instructed to establish water-quality standards for streams involved in the fisheries-stocking programs under Sections 26-141a through 26-141L, inclusive, of the CGS. The DOHS has jurisdiction over purity of drinking-water supplies under Section 25-32 of the CGS. Surface-water sources supply 83 percent of the people served by public-water supplies in Connecticut. Under Section 22a-417 of the CGS, discharge of sewage into tributaries of water-supply impoundments or into proposed water-supply impoundments identified in the Long-Range Water-Resources Management Plan under "Protected Watersheds," Section 22a-352, is not permitted.

Section 22a-364 of the CGS directs the Commissioner of DEP to establish stream-gaging stations to supply data for water-resources investigations. To provide these data, the U.S. Geological Survey operates a network of 48 streamflow gaging stations, 44 of which are cooperatively funded by the DEP, the COE, various local governments, and a private utility. The U.S. Geological Survey also operates a network of 39 surface-water quality stations sampled on a monthly basis in cooperation with the Connecticut DEP and Federal agencies.

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DELAWARE
Surface-Water Resources

Surface water is one of Delaware's most important natural resources. About 40 percent of the State's population depends on surface water for various uses. The remaining 60 percent relies on ground-water withdrawals. Most streams flow perennially because of an abundance of ground water in most areas of the Coastal Plain region that supports streamflow during dry periods. Commercial navigation; recreation; numerous species of fish, water fowl, and upland wild game depend on fresh and saline surface water in Delaware. Freshwater withdrawals (offstream use) of surface water averaged 57 Mgal/d (million gallons per day) or 88.2 ft^3/s (cubic feet per second) in 1980. This is about 41 percent of all fresh surface water and ground water withdrawn each day. Instream freshwater use is negligible. Surface-water withdrawals in Delaware in 1980 for various purposes and related statistics are given in table 1.

Northern Delaware is heavily populated and industrialized. Some ground water is available but not in sufficient quantity to supply demand. Fresh surface water is used for public water supplies and industrial uses. Large quantities of saline water from the Delaware River and its tidal estuaries are used by industry and for thermoelectric-power generation.

Delaware normally does not have major water shortages except during periods of regional drought. Then, appropriations of streamflow in the Delaware River basin and conservation of water throughout the State become important issues. The only major storage reservoir in Delaware is Hoopes Reservoir (fig. 2) which is in the Red Clay Creek basin of northern Delaware. The reservoir, constructed in 1932, has a storage capacity of 6,140 acre-ft (acre-feet) or 2,000 Mgal (million gallons).

Brandywine Creek is the major source of water for the city of Wilmington, but the stream may not be able to provide enough water to supply the system during drought periods. The quality of water in Brandywine Creek during some low-flow periods may be unsuitable for most uses because of discharges or accidental chemical spills in upper reaches of the basin (Woodruff, 1984). During these conditions, the city of Wilmington withdraws water stored in Hoopes Reservoir.

Ground water is the main source of water supply south of the Piedmont area for public, domestic, and industrial uses; the quality in most areas is suitable for human consumption and most other uses.

Table 1. Surface-water facts for Delaware

[Data 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 SURFACE WATER, 1980	
Number (thousands)	240
Percentage of total population	40
From public water-supply systems:	
Number (thousands)	240
Percentage of total population	40
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	140
Surface water only (Mgal/d)	57
Percentage of total	41
Percentage of total excluding withdrawals for thermoelectric power	41
Category of Use	
Public-supply withdrawals:	
Surface water (Mgal/d)	48
Percentage of total surface water	84
Percentage of total public supply	62
Per capita (gal/d)	20
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total livestock	0
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	[1]6.2
Percentage of total surface water	11
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	23
Excluding withdrawals for thermoelectric power	29
Irrigation withdrawals:	
Surface water (Mgal/d)	2.4
Percentage of total surface water	4
Percentage of total irrigation	37
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	0

[1] Does not include withdrawal of 1,100 Mgal/d of saline water from the Delaware River, Delaware Bay, and estuaries.

GENERAL SETTING

Delaware is known as the Diamond State because of its small size and great value (Hoffecker, 1977, p. xiii). The land area of Delaware is about 1,978 mi^2 (square miles), in addition to 79 mi^2 of inland waters. This does not include the water-surface area of that part of the Delaware River and Bay within the boundaries of the State (Van Zandt, 1966). Two sea-level canals are part of the inland waters—the Chesapeake and Delaware Canal which is used primarily for commercial navigation, and the Lewes and Rehoboth Canal, which is part of the Intracoastal Waterway. About 60 freshwater ponds, originally mill sites, are also included in the inland waters.

Delaware is divided into two well-defined physiographic provinces by a boundary referred to as the Fall Line (fig. 1). The Piedmont province, which is north of the Fall Line, is underlain by crystalline bedrock, and comprises only 6 percent of the State. The Coastal Plain province, south of the Fall Line, includes the remaining 94 percent of Delaware and is underlain by alternating layers of unconsolidated sand and gravel. A ridge line extending from southern Delaware northward separates the Delaware River drainage basin and the Atlantic Ocean from the Chesapeake Bay drainage basin. Many small basins along the east coast drain directly into estuaries of the Delaware River and into Delaware Bay and the Atlantic Ocean.

Stream-channel slopes are very low and some areas of Delaware are poorly drained. The soils in the poorly drained areas are composed of silty clays and organic silts. The well-drained areas and prime farmland soils are underlain by loamy sands. One of Delaware's major industries is agriculture, and, during droughts, farmers rely heavily on irrigation to grow corn, soybeans, and other crops. The main source of water used for irrigation is ground water, but some surface water also is used (table 1).

Precipitation is fairly uniformly distributed both areally and temporally in Delaware (fig. 1). Average annual precipitation in Delaware is about 43 inches and ranges from about 45 inches in the southeast corner of the State to about 40 inches in a band across north-central Delaware. Average monthly precipitation generally ranges from 3 to 4 inches for most months (fig. 1). As a result of summer thunderstorms, most areas get the highest average monthly precipitation in August. Despite the uniform distribution of long-term average precipitation, Delaware has the normal short-term precipitation deficiencies and excesses.

Annual evapotranspiration losses in Delaware range from 26 inches in the south to 24 inches in the north (Mather, 1969) and average about 25 inches. Mather's data indicate that more than 90 percent of the evapotranspiration losses occur from April through October.

Average annual runoff for streams in the Coastal Plain of Delaware generally ranges from 17 to 20 inches (fig. 1). Annual runoff from streams in the Piedmont averages 18 to 20 inches, but most of the flow originates in Pennsylvania. Average monthly discharge, unlike precipitation, is not uniformly distributed throughout the year (fig. 1). Because of seasonal rates of evapotranspiration and seasonal changes in ground-water discharge to streams and wells, average monthly stream discharge generally declines from a high in March to a low in September or October. This pattern then reverses as evapotranspiration losses decrease after the growing season, resulting in an increasing contribution of ground-water discharge to streamflow.

Coastal flooding in Delaware is usually caused by extreme high tides and high northeast winds. One of the most destructive "northeasters" on the eastern coast was that of March 1962 (U.S. Army Corps of Engineers, 1963). Hurricanes and tropical storms usually cause coastal and inland flooding from heavy rainfall associated with these storms.

Runoff from heavy rains and severe thunderstorms may cause flooding of freshwater streams. This type of flooding is usually most destructive to highway bridges, culverts, roadways, and millpond spillways. Several of the most damaging floods of this type occurred during August 1967 (Carpenter and Simmons, 1969).

PRINCIPAL RIVER BASINS

Delaware lies entirely in the Mid-Atlantic Region and is about equally divided between the Delaware and Upper Chesapeake Subregions (fig. 2). In the Delaware Subregion, the Christina River basin contains the only major tributary to the Delaware River in northern Delaware. The Nanticoke River and the Indian River basins are the only significant drainages of the Upper Chesapeake Subregion in Delaware. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MID-ATLANTIC REGION

Delaware Subregion

The Delaware River (saline water in Delaware) is the largest river in Delaware, flowing from its headwaters in southern New York State to its mouth at the Delaware Bay. The length of the river is approximately 370 miles and the drainage area of the basin is about 12,765 mi^2. Flow from the Delaware River and Bay enters the Atlantic Ocean at Cape Henlopen.

The Delaware River is an important commercial waterway; many industries depend on this shipping route. The Chesapeake and Delaware Canal is an artery of this waterway and connects the Delaware River with the Chesapeake Bay. The Christina, the Smyrna, the Leipsic, the St. Jones, the Murderkill, the Mispillion, and the Broadkill are major tributaries that flow to the Delaware River and Bay.

Christina River Basin.—The Christina River (fig. 2 and table 2) and its tributaries drain the densely populated urban and suburban area of northwestern Delaware. Increased stormwater runoff from urbanization contributes to minor local flooding in the basin. Main tributaries to the Christina River include Brandywine Creek, White Clay Creek, and Red Clay Creek. All of these tributaries flow southward out of Pennsylvania and enter Delaware at its northern boundary.

Brandywine Creek (table 2), with a drainage area of 329 mi² at the mouth, is the largest tributary to the Christina River. Of this drainage area, 301 mi² are in Pennsylvania, and the remaining 28 mi² are in Delaware. The maximum discharge for Brandywine Creek at Wilmington for the period 1946–84 is 29,000 ft³/s or 18,700 Mgal/d. This peak occurred on June 23, 1972, and was caused by heavy rainfall associated with hurricane Agnes. Flows on the Brandywine are regulated in Pennsylvania, 27 miles upstream from the gaging station at Wilmington.

Upper Chesapeake Subregion

Indian River Basin.—The Indian River basin (fig. 2) drains almost all of southeastern Delaware. Cow Bridge Branch, which is the headwater reach, flows from forested areas and farmlands. Stockley Branch (table 2) is a major tributary to Cow Bridge Branch.

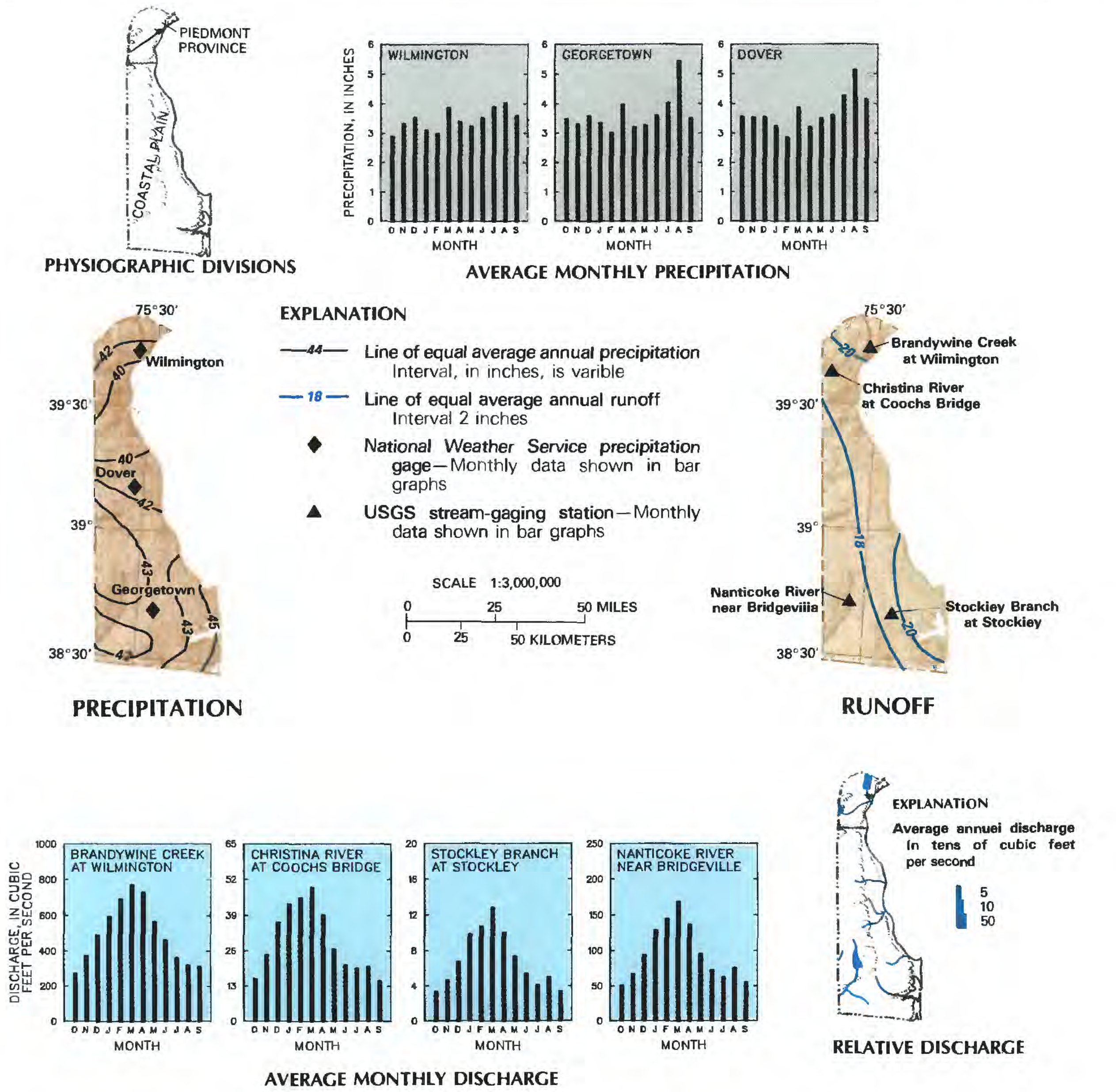

Figure 1. Average annual precipitation and runoff in Delaware and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from Mather, 1969, fig. 13; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Delaware

[Gaging station. Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Mi^2=square miles; ft^3/s=cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharga (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				MID-ATLANTIC REGION DELAWARE SUBREGION Christina River basin				
1.	Christina River at Coochs Bridge (01478000).	20.5	1943–84	1.5	28.8	4,840	Negligible	Major water uses are municipal supply, fish and wildlife, and recreation.
2.	Brandywine Creek at Wilmington (01481500).	314	1946–84	75	488	34,300	Moderate	Regulated 27 miles upstream since 1973. Water uses are municipal supply and recreation.
				UPPER CHESAPEAKE SUBREGION Indian River basin				
3.	Stockley Branch at Stockley (01484500).	5.24	1943–84	0.66	7.04	200	None	Water uses are fish and wildlife.
				Nanticoke River basin				
4.	Nanticoke River near Bridgeville (01487000).	75.4	1943–84	15	92.8	3,570	None	Water uses are irrigation, fish and wildlife

A millpond dam at the west end of Indian River Bay separates the tidal and nontidal reaches of the Indian River.

The mouth of the Indian River is at Indian River Bay. Indian River Bay and Rehoboth Bay are inland bays that are connected by a shallow channel. Both bays are protected by a narrow barrier island located between the bays and the Atlantic Ocean. A narrow passageway—the Indian River Inlet—is an artery between the bays and the ocean.

Land use in the headwaters of the basin is mainly agricultural; however, surrounding the bays and along the ocean the primary use of land is for recreation and summer resort purposes. Summer resort communities along the Atlantic Coast are sometimes damaged by flooding caused by coastal storms.

Nanticoke River Basin.—The Nanticoke River (fig. 2 and table 2) is the largest Coastal Plain stream in Delaware. Flowing south the river drains most of southwestern Delaware (490 mi²). The river then crosses the State boundary and flows through Maryland to the Chesapeake Bay. Land use in the basin is agricultural, and about 75 mi² of the headwaters of the basin have been drained by ditches constructed to improve farmland. Flooding in the unditched part of the basin during the growing season occasionally causes considerable crop damage. Downstream from the ditched area, the river is typical of other Coastal Plain rivers—low, swampy banks, and a meandering channel. The river is about 62 miles long and is affected by tides for a distance of about 45 miles upstream from its mouth. Total drainage area of the basin in Delaware and Maryland is about 815 mi². Deep Creek, Broad Creek, and Marshyhope Creek are major tributaries to the Nanticoke River.

SURFACE-WATER MANAGEMENT

The State of Delaware, through the Department of Natural Resources and Environmental Control (DNREC), acts as trustee of the State's water resources under terms of the Delaware Environmental Protection Act (7 Delaware Code, Chapter 60). DNREC has the responsibility for conserving and protecting all water resources within the State.

Diversions of surface water for any purpose require an allocation permit. Criteria used by DNREC in granting a permit are those of "equitable apportionment" which protect existing uses,

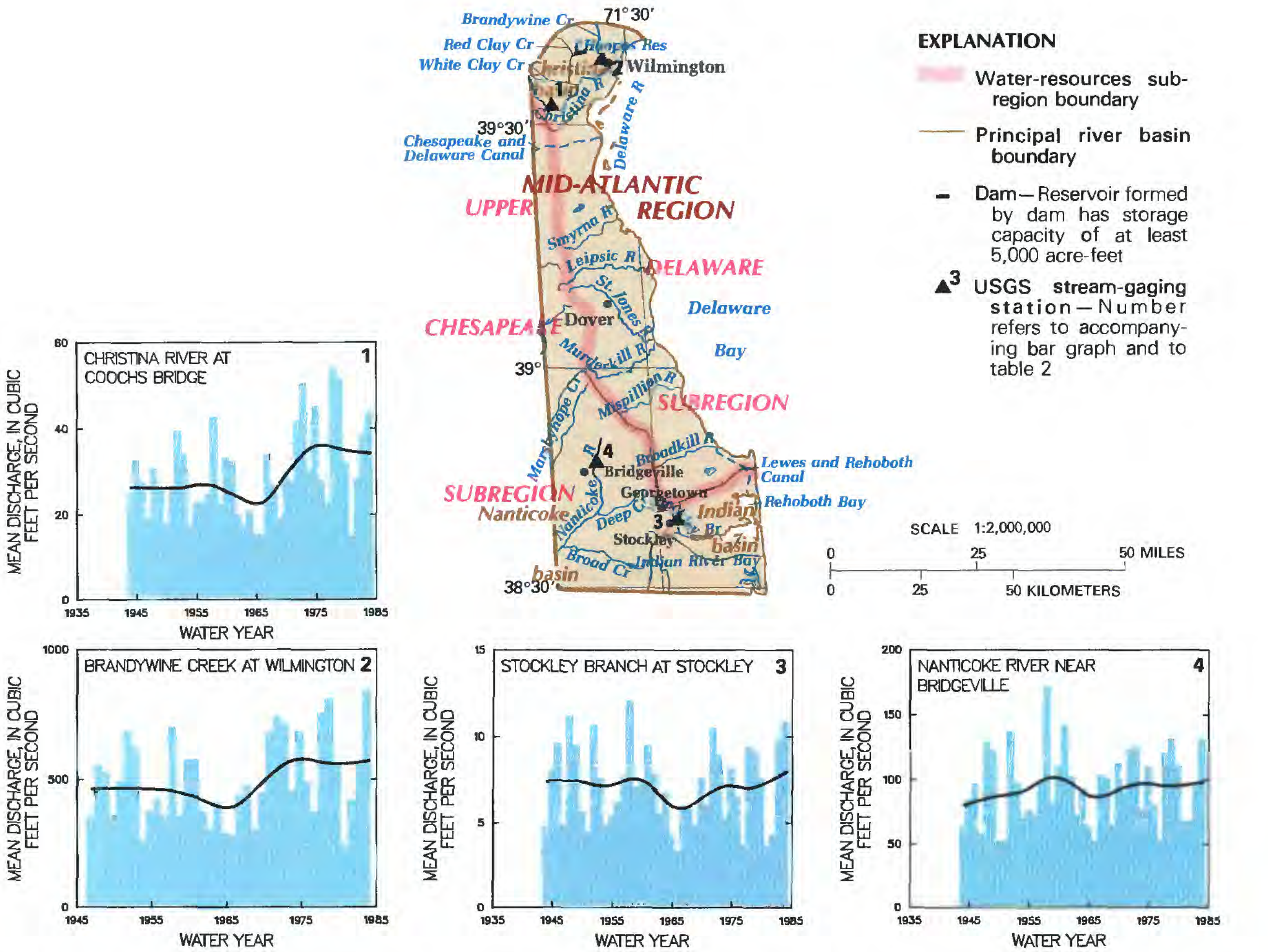

Figure 2. Principal river basins and related surface-water resources development in Delaware and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

and restrict interference with downstream flows (Vaughn, 1981, p. 6).

The Delaware River Basin Commission (DRBC) was created to provide appropriate planning, development, management, and use of water resources in the entire Delaware River basin. All withdrawals of water from the basin that would have a substantial impact on the water resources are subject to approval by DRBC. "In the event of drought or other conditions that may cause actual and immediate water shortage, DRBC may declare a water supply emergency in all or part of the Delaware River basin, thereby activating special regulatory systems that temporarily supersede State and regular basin water allocation programs" (Caron and others, 1979, p. 26).

Water withdrawals from navigable waterways must be approved by the U.S. Army Corps of Engineers in addition to DNREC. The Department of Health and Social Services, Division of Public Health; and the Public Service Commission are responsible for regulating public water-supply systems. The Water Resources Agency for New Castle County evaluates New Castle County's water systems, manages its water resources, and is striving to develop new sources and new water storage facilities.

The Delaware Geological Survey (DGS) is actively involved in preservation of Delaware's water resources. The U.S. Geological Survey, in cooperation with DGS, maintains a statewide surface water data-collection network.

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FLORIDA
Surface-Water Resources

The State of Florida has an abundance of surface-water resources, including more than 1,700 streams and 7,700 freshwater lakes and reservoirs (Heath and Conover, 1981). Extensive wetlands, a prominent feature in Florida, comprised an estimated 50 percent of the land area prior to development. It is estimated that, in 1974, the area of wetlands was 8.3 million acres—a loss of 3.4 million acres since 1955 (Hampson, 1984). Although many of Florida's wetlands have been destroyed by drainage for agricultural use, mosquito control, flood control, and urban development, they are now protected by State statute.

In 1980, freshwater withdrawals in Florida totaled about 7,300 Mgal/d (million gallons per day) or 11,300 ft³/s (cubic feet per second), of which 49 percent was from surface-water sources. Irrigation accounts for 39 percent of total surface-water withdrawals. Surface water is the principal source for 15 public-water supplies located mostly in central and south-coastal Florida. About 10 percent of Florida's population relies on surface water for its freshwater needs. Instream water use for hydroelectric-power generation was 15,000 Mgal/d or 23,200 ft³/s. Surface-water withdrawals in Florida in 1980 for various purposes and related statistics are given in table 1.

Florida's surface water generally is suitable for most uses with minimal treatment. Some streams originate in large swamps that contribute undesirable acidity and color to the water—notably the St. Marys, the St. Johns, the Withlacoochee, and the Suwannee Rivers (Florida Department of Environmental Regulation, 1980). Sources of pollution of streams in Florida are municipal sewage-treatment plants; pulp and paper mills; citrus-processing plants; chemical-processing and production plants; and runoff from croplands, dairies, and feedlots. Phosphate-mining activities have increased phosphorus concentrations in the Peace and the Alafia Rivers and in tributaries to the Suwannee River (Florida Department of Environmental Regulation, 1980).

Table 1. Surface-water facts for Florida

[Data 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 SURFACE WATER, 1980	
Number (thousands)	990
Percentage of total population	10
From public water-supply systems:	
Number (thousands)	990
Percentage of total population	10
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	7,300
Surface water only (Mgal/d)	3,600
Percentage of total	49
Percentage of total excluding withdrawals for thermoelectric power	33
Category of Use	
Public-supply withdrawals:	
Surface water (Mgal/d)	180
Percentage of total surface water	5
Percentage of total public supply	13
Per capita (gal/d)	175
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.1
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	128
Livestock:	
Surface water (Mgal/d)	20
Percentage of total surface water	1
Percentage of total livestock	34
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	2,000
Percentage of total surface water	56
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	77
Excluding withdrawals for thermoelectric power	33
Irrigation withdrawals:	
Surface water (Mgal/d)	1,400
Percentage of total surface water	39
Percentage of total irrigation	47
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	15,000

GENERAL SETTING

Florida is located in the Coastal Plain physiographic province (fig. 1). According to Snell and Kenner (1974), the variety of surface-water features in Florida is the result of the State's location in the subtropical zone between the Atlantic Ocean and the Gulf of Mexico, its average rainfall of 53 inches, its relatively flat terrain, and the permeable nature of its soils and underlying rocks. Surface-water features include extensive marshes and swamps; numerous streams, lakes, and ponds (except in the interior peninsula where streams are few); and an extensive network of ditches and canals, particularly in the southeastern part of the State.

Rainfall is plentiful in Florida and varies geographically as well as seasonally and annually. Average annual rainfall is about 53 inches but ranges from about 52 inches in central Florida to 60 inches in the southeastern part of the State and 64 inches in the northwestern part (fig. 1). Average annual rainfall in Key West is about 40 inches. The seasonal distribution differs from north to south (fig. 1). Climatic conditions in Florida range from a zone of transition between temperate and subtropical in the extreme northern interior to tropical in the Florida Keys. Northwestern Florida has two wet seasons—December through March and June through September. On the peninsula, more than half of the annual rainfall occurs during June through September. October and November are the driest months in the northwest, whereas October can be one of the wettest months in southeastern Florida and the Keys. A large percentage of the rainfall (60 to 88 percent) is lost to evapotranspiration. Annual evaporation from free-water surfaces ranges from 48 inches in the southeast to about 42 inches in the northwest (Farnsworth and others, 1982).

Tropical cyclones and hurricanes, which are capable of producing rainfall totals of several inches, usually occur from June through October, with September having the highest average number (three) annually.

Runoff, like rainfall and evaporation, varies geographically, as well as seasonally and annually. Statewide, average runoff is 14 inches and ranges from about 5 inches in the Florida Keys to 40 inches in northwestern Florida (fig. 1). In northwestern Florida, the average monthly discharge of the Yellow River is greatest from January through April (fig. 1) when the evapotranspiration rate is low. Discharge of the St. Johns River in east-central Florida is greatest from August through November. Discharge in the Peace River in southwestern Florida is greatest from July through October (fig. 1). Prolonged periods of deficient rainfall have caused less-than-normal runoff—notably in 1956 and 1982 (fig. 2).

PRINCIPAL RIVER BASINS

Florida is located entirely in the South Atlantic-Gulf Region (fig. 2). Two principal rivers—the St. Marys, which is a State boundary stream, and the Suwannee River—originate in the Okefenokee Swamp in Georgia. Two other principal rivers originate in Georgia—the Ochlockonee and the Apalachicola. Four other principal rivers in the Choctawhatchee-Escambia subregion of the Region—the Choctawhatchee, the Yellow, the Escambia, and the Perdido—originate in Alabama. These river basins are described below; their locations, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

SOUTH ATLANTIC-GULF REGION

Altamaha-St. Marys Subregion

The St. Marys River forms the State boundary between Georgia and Florida in the northeastern corner of the State. The headwaters of the St. Marys are in the Okefenokee Swamp. The river is about 175 miles long and has an average slope of 2.56 ft/mi (feet per mile). The river is affected by tides for about 60 miles upstream from the mouth. Principal uses of the river are boating and fishing. Quality in the upper part is degraded by acidity and color in drainage from headwater swamps. Quality in the lower part also is degraded by industrial discharges. Accordingly, water quality is better in the upper part than in the lower part (Florida Department of Environmental Regulation, 1980), but the water in both parts of the river still meets State drinking-water standards with minimal treatment. The principal surface-water related issue in the basins is the degradation of water quality by industrial point discharges.

St. Johns Subregion

The St. Johns River, one of the few north-flowing rivers in the United States, originates in a broad, marshy area south of Blue Cypress Lake. The river parallels the Atlantic coast and is never more than 30 miles inland. The St. Johns River is 273 miles long—the longest river entirely within Florida—and drains an area of 9,168 mi^2 (square miles). Because of the relatively flat stream gradient (about 0.1 ft/mi), the river is affected by tides about 160 miles upstream from the mouth that can reverse flows for several days each year (Snell and Kenner, 1974). During the last 50 years, more than 60 percent of the flood plain in the upper St. Johns River is believed to have been ditched, diked, and drained to provide fertile muck for rangeland and agriculture (Fernald and Patton, 1984, p. 158). Principal uses of the river are barge transport; commercial and sport fishing; and boating. Four thermoelectric powerplants use the river for cooling purposes. Surface-water-related issues in the basin include the contamination of the upper part of the St. Johns River by runoff from agricultural areas; and contamination of the lower part of the river by urban runoff, wastewater effluent, and industrial discharges, especially in the Jacksonville area (Florida Department of Environmental Regulation, 1980).

The Oklawaha River, the largest tributary to the St. Johns River, drains an area of 2,769 mi^2, or about one-third of the St. Johns basin. The Oklawaha basin has several large lakes in its headwaters that are regulated by canals and control structures constructed in 1956. Rodman Dam and Buckman Lock, which were constructed in 1968 as part of the Cross Florida Barge Canal, control a reservoir containing 82,000 acre-ft (acre-feet) or 26,700 Mgal (million gallons) of water in a lake covering about 10,800 acres. Evaporation from Lake Oklawaha and diversions through Buckman Lock have contributed to the downward trend in average discharge by water year for the Oklawaha River shown in figure 2. For example, the average discharge by water year of the Oklawaha River at Rodman Dam (table 2, site 4) from 1944 to 1968 was 2,020 ft^3/s or 1,310 Mgal/d. The average discharge from 1969 to 1983 was 1,550 ft^3/s or 1,000 Mgal/d, approximately half of which represents discharge from Silver Springs. Principal uses of the river are boating and fishing. Water quality in the Oklawaha River generally meets State standards for drinking water, with minimal treatment (Florida Department of Environmental Regulation, 1980). Surface-water-related issues include contamination of the chain of lakes in the upper part of the Oklawaha River by effluent from sewage-treatment plants, citrus-processing plants, and runoff from muck farms.

Southern Florida Subregion

The Kissimmee River is the main tributary to Lake Okeechobee and drains an area of about 2,900 mi^2. The upper Kissimmee River, above Lake Kissimmee, passes through a series of shallow lakes, most of which have outlet controls. During the 1960's, the river downstream from Lake Kissimmee was straightened and changed from a shallow, meandering river 90 miles long to a river 50 miles long with a 30-foot-deep channel; the flood plain also was altered by the addition of levees and water-control structures (Fernald and Patton, 1984, p. 154). The leveling effect that the levees and control structures have had on streamflow since 1964 is shown in figure 2 (site 6). Restoration of a 12-mile segment of the river is being undertaken as part of an overall plan to divert water back into historic oxbows and marshlands to protect and manage the natural resources of the Kissimmee River-Lake Okeechobee-Everglades ecosystems.

Lake Okeechobee, at an elevation of 14 feet above sea level, is the largest freshwater lake in the State. It has a surface area of 681 mi^2 and can store 2,700,000 acre-ft or 880,000 Mgal of water (Fernald and Patton, 1984). At the end of the wet season, the lake is regulated to a maximum stage of 17.5 feet above sea level to store water for later release during the dry season. Floodwaters are released to the east through the St. Lucie Canal and to the west through the Caloosahatchee River. A series of coastal canals, with controls, lead to the southeast and recharges the shallow aquifers that serve the populous southeastern coast.

The subregion contains the Big Cypress Swamp and The Everglades, extensive areas of marsh, sloughs, and tree islands that form the largest wetlands in Florida. During the wet season, water flows through these systems of marshes, broad sloughs, and tree islands.

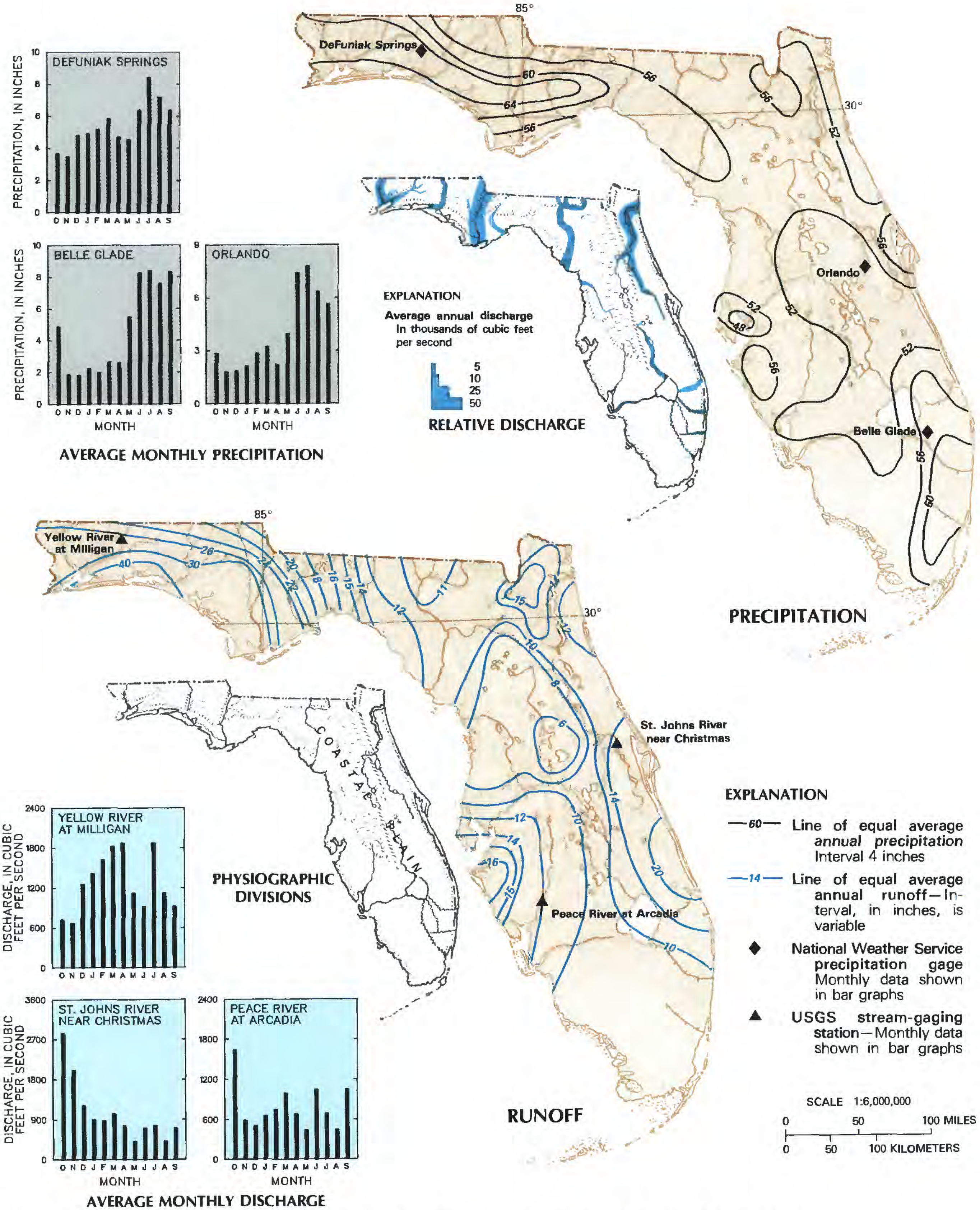

Figure 1. Average annual precipitation and runoff in Florida and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Florida

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				SOUTH ATLANTIC-GULF REGION ALTAMAHA-ST. MARYS SUBREGION				
1.	St. Marys River near Macclanny (02231000).	700	1927-83	18	672	40,500	None	Upstream effected by high acidity and color from swamp drainage.
				ST. JOHNS SUBREGION				
2.	St. Johns River near Christmas (02232500).	1,539	1934-83	24	1,310	18,500	None	
3.	St. Johns River near DeLand (02236000).	3,066	1934-83	0	3,120	21,900	. . . do . . .	
4.	Oklawaha River at Rodman Dam near Orange Springs (02243960).	2,747	1944-68 1969-83	788	2,020 1,550	12,900	Moderate	 Prior to 1969 at site 1 mile downstream.
				SOUTHERN FLORIDA SUBREGION				
5.	Fisheating Creek at Palmdale (02256500).	311	1932-83	0	257	21,400	None	Minimum monthly flow zero in most years.
6.	Kissimmee River at S-65E near Okeachobae (02273000).	2,886	1929-62 1964-83	809 36	2,190 1,390	29,800	Appreciable	High nutrient levels in headwaters.
				PEACE-TAMPA BAY SUBREGION				
7.	Peace River at Arcadia (02296750).	1,367	1932-83	57	1,150	34,400	None	Upstream quality affected by sewage-treatment plants and phosphate mines.
8.	Hillsborough River near Zephyrhills (02303000).	220	1940-83	53	259	10,300	. . . do . . .	Municipal water supply.
9.	Withlacoochee River near Holdar (02313000).	1,825	1932-83	158	1,090	9,750	. . . do . . .	High acidity and color from headwaters swamp drainage.
				SUWANNEE SUBREGION				
10.	Suwannee River at Branford (02320500).	7,880	1932-83	1,790	6,940	68,000	None	
11.	Santa Fe River near Fort White (02322500).	1,017	1928-29, 1933-83	730	1,610	16,400	. . . do . . .	
12.	Suwannee River near Wilcox (02323500).	9,640	1931, 1942-83	4,020	10,400	66,400	. . . do . . .	

Table 2. Selected streamflow characteristics of principal river basins in Florida—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Straamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				OCHLOCKONEE SUBREGION				
13.	Ochlockonee River near Havana (02329000).	1,140	1927–83	30	1,030	41,200	None	Hydroelectric-power generation.
				APALACHICOLA SUBREGION				
14.	Apalachicola Rivar at Chattahoochee (02358000).	17,200	1929–83	7,000	22,400	264,000	Moderate	Hydroelectric-power generation.
				CHOCTAWHATCHEE-ESCAMBIA SUBREGION				
15.	Choctawhatchee River near Bruce (02366500).	4,384	1931–83	1,630	7,140	128,000	None	
16.	Yellow River et Milligan (02368000).	624	1939–83	184	1,170	45,900	. . . do . . .	
17.	Shoal River near Crestview (02369000).	474	1939–83	291	1,100	33,600	. . . do . . .	
18.	Escambia River near Century (02375500).	3,817	1935–83	777	6,360	179,000	. . . do . . .	
19.	Perdido River et Barrineau Park (02376500).	394	1942–83	221	766	34,200	. . . do . . .	

Peace-Tampa Bay Subregion

This subregion is drained primarily by three major rivers—the Peace, the Hillsborough, and the Withlacoochee—and by many smaller streams that drain into the Gulf of Mexico and into coastal bays. These three rivers have headwaters in a broad, swampy area characterized by very low stream gradient and poorly defined basin divides. The Peace River has elevated nutrient and total chlorophyll concentrations, particularly in the upstream reaches where phosphate mines, fertilizer-manufacturing plants, sewage-treatment plants, agricultural operations, and runoff from urban areas adversely affect the quality of the river (Fernald and Patton, 1984, p. 76). The Hillsborough River is the primary water supply for the city of Tampa. The Withlacoochee River drains an area of 2,020 mi² and has a stream gradient of about 0.9 ft/mi. Along much of its course, it is in hydraulic contact with the Floridan aquifer system (Sinclair, 1978, p. 9). The variation in the average discharge by water year (fig. 2, site 9) of the Withlacoochee River is smaller than that of the Peace River (fig. 2, site 7) because of the contribution of ground water to base flow and the many lakes and swamps that provide temporary storage of flood runoff.

Suwannee Subregion

The Suwannee River, which drains an area of 9,950 mi², has its headwaters in the Okefenokee Swamp and flows southward to the Gulf of Mexico. Major tributaries are the Santa Fe, the Alapaha, and the Withlacoochee Rivers. The basin has a low stream density because porous limestone at or near the surface facilitates rapid infiltration of rainfall. Much of this water discharges through 7 springs with average flows of more than 100 ft³/s or 64.6 Mgal/d, and through 25 springs with average flows of 10 to 100 ft³/s (6.46 to 64.6 Mgal/d) (Rosenau and Faulkner, 1975). The Suwannee River has been declared an "Outstanding Florida Water" by the Florida Department of Environmental Regulation, which is responsible for restoring (to 1978–79 conditions) and protecting water quality (Fernald and Patton, 1984, p. 226). The principal uses of the river are canoeing, boating, and fishing. One thermoelectric powerplant uses the river for cooling. A tributary stream in the upper Suwannee receives drainage from a phosphate mine. With the exception of the area just downstream from this tributary, the water quality of the Suwannee River is considered to be suitable for most uses. A concern in the basin is a nonstructural flood-control plan, adopted by the Suwannee River Water Management District, to limit development on the flood plain.

Ochlockonee Subregion

The Ochlockonee River, with headwaters in southwestern Georgia, drains an area of 2,250 mi^2, of which 1,170 mi^2 are in Florida. Streamflow is variable and consists mainly of direct runoff with a small contribution from ground water that sustains low flow.

Jackson Bluff Dam (completed in 1929), 65 miles upstream from the mouth, forms a lake with a surface area of 6,850 acres and a usable capacity of 69,800 acre-ft or 22,700 Mgal. From 1930 through 1970, the lake was used for hydroelectric-power generation. Since 1970, the lake has been a State park and is regulated as a recreational area. New equipment has been installed, and power generation will be resumed in 1985.

The Ochlockonee River basin is primarily forested land that contains no significant point or nonpoint sources of pollution (Florida Department of Environmental Regulation, 1980). The water of the Ochlockonee River is suitable for most uses and requires only minimal treatment to meet State drinking-water standards. The adverse effects of drawdown in Lake Talquin during peak power on recreational use of the lake is a local issue of concern.

Apalachicola Subregion

The Apalachicola River is formed by the confluence of the Flint and the Chattahoochee Rivers at the Jim Woodruff Dam. It then flows 107 miles southward to Apalachicola Bay in the Gulf of Mexico. The lake behind Jim Woodruff Dam (completed in 1957 with 367,300 acre-ft or 119,700 Mgal of storage capacity) is used for hydroelectric-power generation. About 4 miles downstream from Jim Woodruff Dam, the river is used to cool a thermoelectric powerplant. In the upper reach of the Apalachicola, periodic dredging is required to maintain a 9-foot depth for navigation. Groups comprised of concerned citizens monitor proposals for development or other changes in the basin because the river empties into Apalachicola Bay—one of the most productive shellfish regions in the United States (Mattraw and Elder, 1984, p. 56). The Florida Department of Environmental Regulation has designated the Apalachicola River as an "Outstanding Florida Water" and protects its water quality.

Choctawhatchee-Escambia Subregion

The northwestern part of Florida contains the area of greatest runoff in the State (fig. 1)—from 20 inches to more than 40 inches annually. The northwestern part of Florida receives abundant rainfall (about 64 inches annually). Ground water discharges to tributary streams that are in hydraulic continuity with the sand-and-gravel aquifer. This combination of factors produces the large runoff. Principal rivers in this subregion include the Choctawhatchee, the Yellow, the Shoal, the Escambia, and the Perdido. These basins are mostly rural and largely undeveloped, and the rivers are used mainly for boating and fishing. The Escambia River is used to cool a thermoelectric powerplant 3 miles upstream from Escambia Bay. Florida's western border with Alabama is formed by the Perdido River. Water quality of the rivers in this subregion meets State drinking-water standards with minimal treatment.

SURFACE-WATER MANAGEMENT

Florida's water resources are managed by the Northwest Florida, St. Johns River, South Florida, Southwest Florida, and Suwannee River Water Management Districts. The Water Resources Act of 1972 (Chapter 373, Florida Statutes) created these districts and gave them authority to manage surface-water and ground-water use in the State. This act requires that permits be obtained for surface-water withdrawals and that the applicant show that the proposed use is a "reasonable-beneficial use"—that is, the water will be used for a purpose and in a manner that are reasonable and consistent with the public interest. The Florida Administrative Code, Rule 17-40, lists 10 factors that determine the "reasonable-beneficial use" of water.

The Water Resources Act also requires that the management districts adopt plans to deal with water shortages. Water-shortage plans provide a means for the equitable distribution of water resources among all water users during periods of water shortages.

The West Coast Regional Water-Supply Authority (WCRWSA) (for the counties of Hillsborough, Pinellas, Pasco, and the cities of Tampa and St. Petersburg) was formed in 1974 to deal with water shortages and to reduce prior conflicts over the interbasin transfer of ground water. The WCRWSA has examined the possibility of transferring surface water to the Tampa Bay area from the Suwannee River, 100 miles to the north (Fernald and Patton, 1984, p. 249).

The water management districts, under the 1972 Water Resources Act (Chapter 373, Sections 196, 223, Florida Statutes), are empowered to authorize the transfer of water across county boundaries and outside the basin areas if the transfer and use are determined to be consistent with the public interest.

The U.S. Geological Survey, through cooperative agreements with local, State, and Federal agencies, conducts hydrologic studies to define the quantity and quality of surface waters in the State. These studies provide cooperating agencies with the information needed to plan and manage the resource.

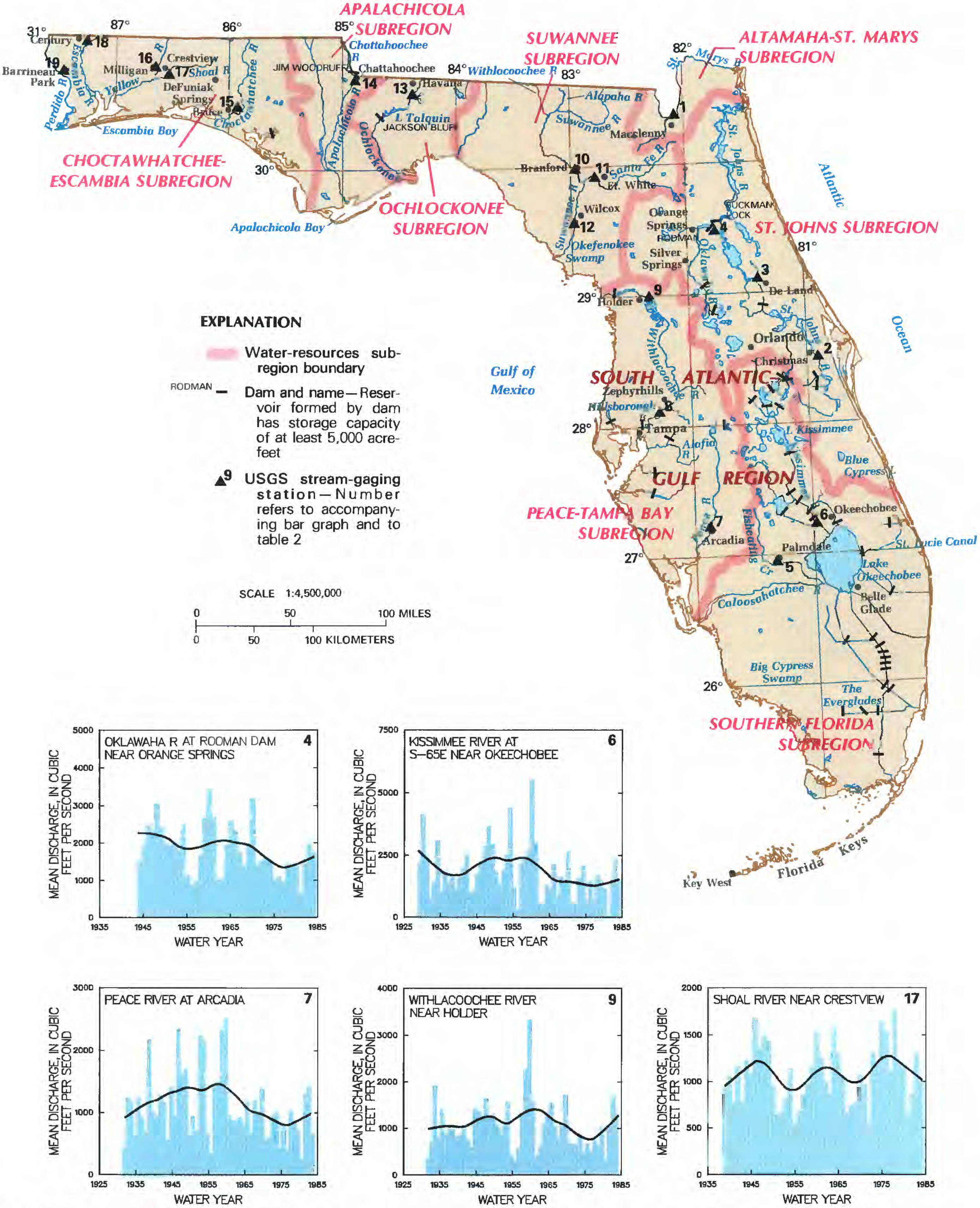

Figure 2. Principal river basins and related surface-water resources development in Florida and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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GEORGIA
Surface-Water Resources

Statewide, surface water provides more than two-thirds of the withdrawals for public supply, more than 40 percent of the water for self-supplied industry, and most of the water used for the generation of electricity. Fifty-two percent of the State's population depends on surface water for supply. The quality of surface water generally is suitable for most uses throughout most of the State. Surface water is used most extensively in the northern part of the State.

In southern Georgia, ground water is plentiful and is used for various large industrial and manufacturing needs as well as for most public supplies; surface water generally is not used for public supply, but is used for about one-third of irrigation needs. Surface-water withdrawals in Georgia in 1980 for various purposes, and related statistics, are given in table 1.

Periodic droughts cause competition for available surface-water supplies and require careful control and treatment of wastewater to maintain good stream-water quality. Flooding is a concern in many of the smaller stream basins, especially in urban areas.

GENERAL SETTING

Georgia is located in four physiographic provinces (fig. 1). Precipitation and runoff are highest in the Blue Ridge province in the northeast, and are moderately high in the Valley and Ridge province in the northwest (fig. 1). Precipitation and runoff are less in the Piedmont province than in the provinces to the north. The Coastal Plain in the south encompasses more than half of the State. Precipitation there is about the same as in the Piedmont province but runoff is considerably less (fig. 1). Statewide, average annual evaporation is less than average annual precipitation.

Average annual precipitation ranges from less than 44 inches in the Coastal Plain to more than 76 inches in the Blue Ridge province and is 50 inches statewide. Precipitation also varies greatly from year to year, but average monthly precipitation is distributed fairly uniformly throughout the year, as shown by the bar graphs in figure 1. Graphs for Covington and Waycross indicate that the least amount of monthly precipitation occurs in the fall. Annual evapotranspiration losses range from 30 inches in the north to 40 inches in the south; accordingly, runoff tends to be lowest in the south.

Average annual runoff for the State is approximately 15 inches (fig. 1), and ranges from less than 10 inches to more than 50 inches. Highest runoff rates occur in the mountainous Blue Ridge province in the northeast. Runoff rates generally diminish from north to south in the State; runoff rates are lowest in the Coastal Plain. Seasonally, highest monthly average runoff occurs during winter and spring months when evapotranspiration is low (fig. 1). Because of the high rates of evapotranspiration, runoff is lowest during the summer. Total runoff, like precipitation, varies greatly from year to year, as shown in the bar graphs in figure 2.

PRINCIPAL RIVER BASINS

Most of Georgia is in the South Atlantic-Gulf Region (Seaber and others, 1984). Several small areas in the north are in the Tennessee Region (fig. 2). Surface water in the Ogeechee-Savannah, the Altamaha-St Marys, and the Apalachicola Subregions originates in the Blue Ridge and the Piedmont provinces and flows in a southerly direction. The Suwannee and the Ochlockonee Subregions in the south are entirely in the Coastal Plain. Surface water in the Alabama Subregion originates in the Blue Ridge and flows southwesterly into Alabama. Streams originating in Georgia in the Upper Tennessee and the Middle Tennessee-Hiawassee Subregions of the Tennessee Region, flow in a northerly direction into North Carolina and Tennessee. With the exception of the Tennessee Region, which encompasses a relatively small area in the northernmost part of the State, the principal river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Georgia

[Data 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; instream use data from files of public-utility companies.]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	2,860
Percentage of total population	52
From public water-supply systems:	
Number (thousands)	2,860
Percentage of total population	52
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	6,700
Surface water only (Mgal/d)	5,500
Percentage of total	82
Percentage of total excluding withdrawals for thermoelectric power	48
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	540
Percentage of total surface water	9.8
Percentage of total public supply	70
Per capita (gal/d)	189
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	11
Percentage of total surface water	0.2
Percentage of total livestock	39
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	4,700
Percentage of total surface water	85
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	92
Excluding withdrawals for thermoelectric power	49
Irrigation withdrawals:	
Surface water (Mgal/d)	200
Percentage of total surface water	3.6
Percentage of total irrigation	34
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	52,000

SOUTH ATLANTIC-GULF REGION
Ogeechee-Savannah Subregion

Tributaries to the Savannah River and the main stem form the boundary between Georgia and South Carolina. The average outflow of the part of the basin in Georgia is about 7,500 ft^3/s (cubic feet per second) or 4,800 Mgal/d (million gallons per day), which is 11.5 percent of the surface-water outflow from the State. Considerable hydroelectric power is generated upstream from Augusta.

Hartwell Reservoir, completed in 1961 with 1,705,000 acre-ft (acre-feet) or 556,000 Mgal (million gallons) of usable storage, and Clarks Hill Reservoir, completed in 1951 with 1,730,000 acre-ft or 564,000 Mgal of usable storage, also contribute to flood control and navigation. Regulation is used to maintain minimum flows at and downstream from Augusta at about 5,500 ft^3/s or 3,600 Mgal/d, which is much greater than would occur under natural conditions. This augmented low flow has attracted industry to this reach of the Savannah River and has improved the navigability. The increase in low flows and attendant decrease in their variability following filling of Clarks Hill Reservoir are shown for the Savannah River at Augusta in bar graphs in figure 2 (site 2). Flood stages at Augusta and downstream are reduced by use of flood storage in the reservoirs.

Downstream from Augusta, the river provides cooling water for a thermoelectric powerplant among other uses. The river is an important source of municipal and industrial water supply at Augusta and at Savannah. There are few large tributaries to the Savannah River in the Coastal Plain. Surface-water quality in the Ogeechee-Savannah Subregion is suitable for most uses.

Altamaha-St Marys Subregion

The Altamaha River has two major tributaries—the Ocmulgee and the Oconee Rivers—that rise in the Piedmont and flow southward to the Coastal Plain where they join to form the Altamaha River. The Ocmulgee River supplies water for one hydroelectric and two thermoelectric powerplants as well as water for wastewater assimilation. Macon depends on the river for municipal and industrial water supplies. The average discharge of the Altamaha River at Doctortown (table 2, site 4) is 13,770 ft^3/s or 8,900 Mgal/d, or 21 percent of average annual runoff from the State.

The Oconee River supplies water for several cities in the Piedmont and for two hydroelectric installations: Lake Oconee (completed in 1979 with 336,000 acre-ft or 109,000 Mgal of usable storage) and Lake Sinclair (completed in 1952 with 215,000 acre-ft or 70,100 Mgal of usable storage). The Altamaha River provides cooling water for a nuclear thermoelectric powerplant. Surface-water quality in the Altamaha-St Marys Subregion is suitable for most uses. In the southeastern part of the subregion, the water is acidic and has a dark color caused by organic material.

Major streams that rise in the Piedmont province and flow into the Coastal Plain generally are deeply incised and most receive large contributions of water from underlying aquifers in the Coastal Plain during low-flow periods although shallow local streams may be dry or nearly so. Low-flow characteristics for Altamaha River at Doctortown (site 4), which has perennial flow, and Penholoway Creek near Jesup (site 5), which flows intermittently, are given in table 2.

Suwannee Subregion

Several tributaries to the Suwannee River rise in the Coastal Plain of Georgia and flow into Florida; they supply some water for irrigation, but generally are not deeply incised and do not have dependable low flows. Public and industrial supplies in this area depend on ground water. Surface-water quality is suitable for most uses, but the water is generally acidic and has a dark color. During low flow, wastewater may require high levels of treatment or temporary storage to prevent excessive stream pollution.

Apalachicola Subregion

The Apalachicola River basin in Georgia includes most of the Chattahoochee River and the Flint River. These rivers join in the southwestern corner of the State to form the Apalachicola River, which flows southward across Florida to the Gulf of Mexico. The Georgia part of the Chattahoochee River basin discharges an average of 8,000 ft^3/s or 5,200 Mgal/d, or 12.5 percent of the average annual runoff from the State. The Flint River basin discharges an average of 9,800 ft^3/s or 6,300 Mgal/d, or 15 percent of the average annual runoff. Surface-water quality in the Apalachicola Subregion is suitable for most uses. It is generally soft except in the extreme southwestern part, where it is moderately hard.

The Chattahoochee River is the most-used stream in the State for public supply. It provides more than half of the withdrawals from surface-water sources for public supply, as shown in table 1, in the Atlanta metropolitan area. Water stored in a large multipurpose reservoir—Lake Lanier, upstream from Atlanta—is essential to meeting the demands on this stream. The effect of the reservoir (completed in 1957 with 1,690,000 acre-ft or 550,000 Mgal of usable storage) in augmenting and reducing the variability of low flows is shown by the graph of the average annual daily discharge for the Chattahoochee River at Atlanta (fig. 2, site 7). In addition to its effect on Atlanta's water supply, Lake Lanier is a major recreational area and it has the greatest visitation rate of any U.S. Army Corps of Engineers reservoir.

Downstream from Atlanta, the river provides water for municipalities and industries, and for two thermoelectric and numerous hydroelectric powerplants including a hydroelectric powerplant at the multipurpose West Point Lake (completed in 1974 with 1,870,000 acre-ft or 609,000 Mgal of usable storage). Large municipal and industrial withdrawals occur at Columbus. From there the river is navigable to its mouth. Navigation depths are maintained by three dams equipped with locks. Two of these dams also produce hydroelectric power. The largest is Jim Woodruff Dam, completed in 1957, which impounds 36,200 acre-ft or 11,800 Mgal of usable storage.

The Flint River flows southward from the vicinity of Atlanta to join the Chattahoochee River. The river supplies municipal and industrial water to several cities in the Piedmont. Just downstream from the Fall Line near Montezuma, the river is joined by tributaries with exceptionally high annual flows and low flows. Contributions from these tributaries increase the flow of the Flint River severalfold during extreme droughts. Large withdrawals are made for industrial supply at Montezuma. Additional withdrawals for industrial water supply occur farther down in the Coastal Plain near Albany. Differences in flow in the Piedmont province at Flint River near Culloden (site 8) and in the Coastal Plain at Flint River near Albany (site 9) are given in table 2.

Irrigation has increased greatly in southwestern Georgia during recent years. The main source of water for irrigation is ground water, but withdrawals of ground water can have a significant effect on streamflow of the Flint and the Chattahoochee Rivers. In this part of the State, these streams are deeply incised into and receive much of their flow from the underlying limestone of the Floridan aquifer system—a source of much of the irrigation water. There is some concern that ground-water withdrawals and consumptive use in the Flint River basin may decrease streamflow and have a detrimental effect on navigation and other uses of the river downstream from the lake behind Jim Woodruff Dam (Hayes and others, 1983). Ground-water pumping capacity of irrigation equipment in the Flint River basin has been reported to be greater

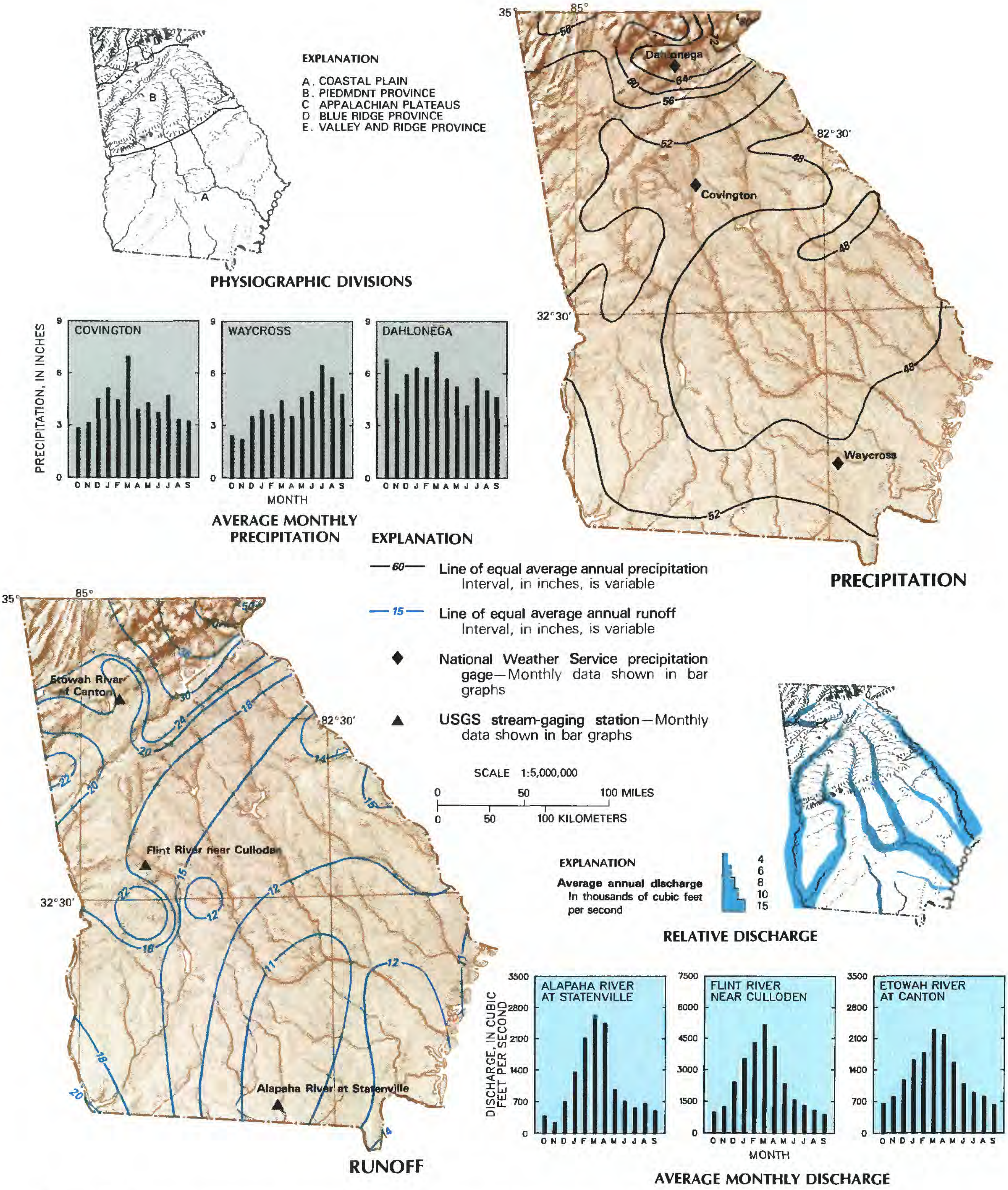

Figure 1. Average annual precipitation and runoff in Georgia and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA file. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Georgia

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				SOUTH ATLANTIC–GULF REGION **Ogeechee–Savannah Subregion**				
1.	Broad River near Bell (02192000).	1,430	1927–32 1937	200	1,809	60,400	None	
2.	Savannah River at Augusta (02197000).	7,508	1960–81	5,500	10,200	. . . .	Appreciable	
				Altamaha–St Marys Subregion				
3.	Oconee River near Greensboro (02218500).	1,090	1903–32, 1936–78	150	1,446	50,700	Negligible	
4.	Altamaha River at Doctortown (02226000).	13,600	1931–83	2,250	13,770	225,000	. . . do . . .	
5.	Penholoway Creek near Jesup (02226100).	210	1958–83	0	201	7,180	None	Minimum monthly flow zero in most years.
				Suwannee Subregion				
.6	Alapaha River at Statenville (02317500).	1,400	1931–83	25	1,044	24,200	None	
				Apalachicola Subregion				
7.	Chattahoochee River at Atlanta (02336000).	1,450	1959–81	860	2,840	. . . .	Appreciable	Large municipal withdrawals upstream and downstream.
8.	Flint River near Culloden (02347500).	1,850	1911–23, 1928–31, 1937–83	180	2,402	99,100	None	Receives some wastewater diverted from the Chattahoochee River.
9.	Flint River near Albany (02352500).	5,310	1901–21, 1929–83	1,000	6,303	94,600	Moderate	
				Alabama Subregion				
10.	Etowah River at Allatoona Dam above Cartersville (02394000).	1,120	1950–81	240	1,944	. . . .	Appreciable	Monitors outflow from multipurpose reservoir.
				TENNESSEE REGION **Middle Tennessee–Hiawassee Subregion**				
11.	Toccoa River near Dial (03558000).	177	1912–83	125	498	16,600	None	Mountain stream.

than the 30-day, 10-year low flow of the Flint River at Bainbridge (2,900 ft³/s or 1,900 Mgal/d).

Alabama Subregion

The Oostanaula, the Etowah, the Coosa, and the Tallapoosa Rivers are in the Alabama Subregion in Georgia. Total streamflow from the Georgia part of this subregion averages 8,400 ft³/s or 5,400 Mgal/d, or 12.7 percent of the average runoff from the State. Carters Lake (completed in 1974 with 135,000 acre-ft or 44,000 Mgal of usable storage) is a multipurpose reservoir on the Coosawattee River, that is formed by the highest earthen dam in the Eastern United States. Downstream, the Conasauga River joins the Coosawattee River to form the Oostanaula River. The Conasauga River supplies major withdrawals of municipal and industrial water near Dalton—the center for the Nation's largest concentration of carpet manufacturers. The Conasauga River has seasonally poor water quality due to the large volume of treated wastewater it receives from Dalton. However, this situation is being remedied by construction of a large land-disposal waste-treatment system that will eliminate discharges to the river.

The Etowah River supplies water for municipal and industrial supplies, including water needs of the mining industry, as well as cooling water for a thermoelectric powerplant. Regulation by Allatoona Dam (completed in 1950 with 587,000 acre-ft or 191,000 Mgal of usable storage) augments low flows on this river (fig. 2). At Rome, municipal withdrawals are made from the Oostanaula River and the Etowah Rivers and industrial withdrawals are from the Oostanaula, the Etowah, and the Coosa Rivers for the manufacture of textiles, machinery, and electrical equipment. Cooling water for a thermoelectric powerplant is withdrawn from the Coosa River downstream from Rome. Variable rates of flow caused by regulation of the Etowah River and by consumptive use of water from the Etowah River by a thermoelectric powerplant increase competition for water in the Coosa River.

Quality of surface water in the Alabama Subregion is suitable for most purposes. In the Valley and Ridge province in the western part, water in small streams is moderately hard to hard.

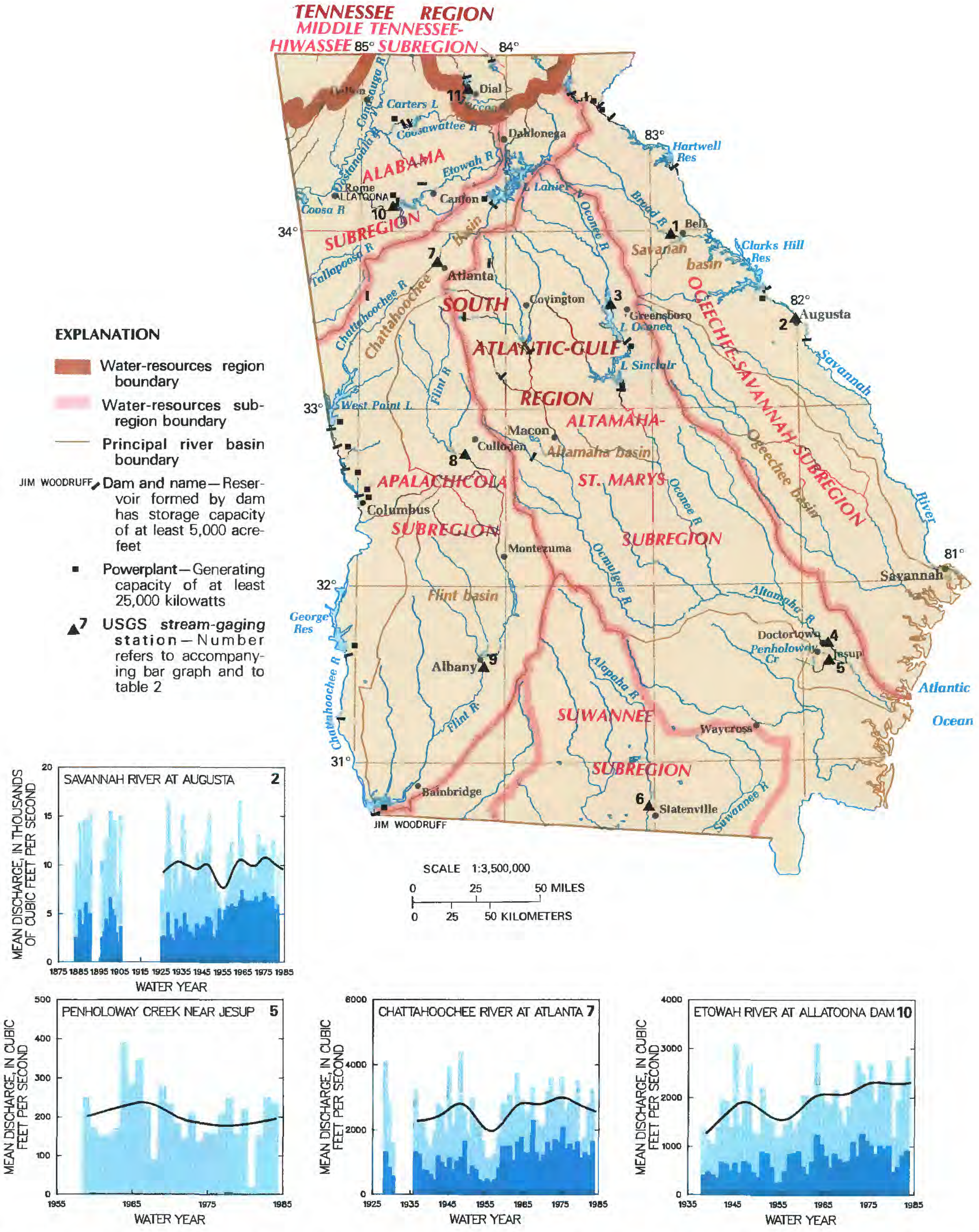

Figure 2. Principal river basins and related surface-water resources development in Georgia and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

SURFACE-WATER MANAGEMENT

The Georgia Environmental Protection Division (EPD) regulates the use of surface and ground water. Management policy is enforced by a permit system; permits are required for any discharges and for withdrawals of more than 100,000 gal/d (gallons per day). A permit is not required for agricultural use but the amount of withdrawal must be reported. This system was authorized by the Georgia Water Quality Control Act of 1964 as amended by the Surface Water Allocation Act of 1977. The EPD 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 surface water in the State. Various Area Planning and Development Commissions occasionally conduct water-resources studies.

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For Additional Information

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HAWAII
Surface-Water Resources

Hawaii has an abundant source of freshwater for its size. Both surface water and ground water are plentiful; however, ground water serves 90 percent of the State's public water supply. Although ground water is the most important source of water supply in Hawaii because it serves 95 percent of the population, surface water still plays a significant role in Hawaii's water use. In 1980, 450 Mgal/d (million gallons per day) or 696 ft^3/s (cubic feet per second) of surface water was used for irrigation. This amounted to 49 percent of the water used for irrigation and 88 percent of the total surface water withdrawals. The bulk of the irrigation use was for sugarcane. Only 15 Mgal/d or 23.2 ft^3/s of surface-water was used for public supply. This was 3 percent of the total surface-water use and 8 percent of the public supply. The remainder of the surface-water use was for industrial use and rural supply. Surface-water withdrawals in Hawaii in 1980 for various purposes and related statistics are given in table 1.

In general, the chemical quality of Hawaii's surface waters is excellent upstream from urbanized areas. The dissolved solids is less than 100 mg/L (milligrams per liter) and the pH ranges between 6.0 and 8.0 units. It is relatively soft water, or less than 60 mg/L hardness as calcium carbonate. The biological and physical quality of the water, however, requires treatment before it can be used for domestic supply.

One of the major issues for both surface-water and ground-water in Hawaii is the determination of ownership of the waters and water rights. In an attempt to overcome this problem, the Hawaii State Constitutional Convention of 1978 opted for a State Water Code. In 1982, the State legislature created the Advisory Study Commission on Water Resources to develop a State Water Code "to recognize, clarify, and systematize legal concepts relating to water resources." The code was developed and presented to the State legislature in January 1985. The State legislature, however, has not yet approved the proposed State Water Code.

GENERAL SETTING

Hawaii consists of 132 islands, shoals, and reefs. The State stretches more than 1,600 miles across the central Pacific Ocean in a northwest to southeast direction from approximately latitude 28° N. and longitude 179° W. to approximately latitude 19° N. and longitude 155° W. The State capital of Honolulu is on the Island of Oahu and is approximately 2,400 miles southwest of San Francisco. The total land area of the State is 6,450 mi^2 (square miles). The islands to the northwest contain about 0.1 percent of the land area. The other 99.9 percent of land area is comprised of the 8 major islands at the southeast end of the island chain.

The 8 major islands in order of decreasing size are: Hawaii (4,038 mi^2), Maui (729 mi^2), Oahu (608 mi^2), Kauai (553 mi^2), Molokai (261 mi^2), Lanai (139 mi^2), Niihau (73 mi^2), and Kahoolawe (45 mi^2) (Hawaii Water Resources Regional Study, 1979, p. 6). These islands are the summits of a range of volcanic mountains which, except for these islands, are submerged. Volcanic eruptions are still occurring on the youngest island, Hawaii.

Hawaii has abundant rainfall, which provides the large quantities of available freshwater on the five largest and most populated islands. The mountains and the trade winds are the principal causes for the abundant rainfall. Rainfall over the open ocean near Hawaii averages between 25 and 30 inches a year (Hawaii Division of Water and Land Development, 1982, p. 2). The orographic rains created when moist trade-wind air moves inland and overrides the steep and high terrain of the islands cause average annual rainfall to exceed 200 inches in many areas of the State. The average annual rainfall for the State is about 70 inches. The average annual rainfall ranges from less than 7 inches around Kawaihae Bay on the leeward side of the Island of Hawaii to 451 inches at the top of Mt. Waialeale on the Island of Kauai (Hawaii Division of Water and Land Development, 1982, p. 2). Figure 1 shows the variability of average annual rainfall in Hawaii, and graphs of average monthly rainfall and average monthly discharge at selected sites.

Table 1. Surface-water facts for Hawaii

[Data 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 SURFACE WATER, 1980	
Number (thousands)	53
Percentage of total population	5
From public water-supply systems:	
Number (thousands)	51
Percentage of total population	5
From rural self-supplied systems:	
Number (thousands)	2
Percentage of total population	0.2
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	1,300
Surface water only (Mgal/d)	510
Percentage of total	39
Percentage of total excluding withdrawals for thermoelectric power	41
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	15
Percentage of total surface water	3
Percentage of total public supply	8
Per capita (gal/d)	294
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.4
Percentage of total surface water	0.08
Percentage of total rural domestic	10
Per capita (gal/d)	200
Livestock:	
Surface water (Mgal/d)	0.2
Percentage of total surface water	0.04
Percentage of total livestock	4
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	45
Percentage of total surface water	9
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	24
Excluding withdrawals for thermoelectric power	80
Irrigation withdrawals:	
Surface water (Mgal/d)	450
Percentage of total surface water	88
Percentage of total irrigation	49
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	180

Though Hawaii has many areas of abundant rainfall, usually in the windward valleys, it also has arid areas, usually along the leeward coasts. Because of the size and topography of the islands, it is not uncommon for annual rainfall to vary more than 100 inches within a range of three miles. Extreme rainfall intensities also are not uncommon in Hawaii. Rainfall intensities in excess of 10 inches per day can be expected at least once a year somewhere in Hawaii. These high intensity rainfalls usually produce localized flooding. Drought periods occur somewhat frequently in lowland areas and on the leeward slopes of large mountains.

In general, Hawaii has two seasons—the wet season from October through April, and the dry season from May through September. June and September generally are the driest months (fig.

1). Summer, however, is the wet season in Kona on the leeward side of the Island of Hawaii.

Evapotranspiration, the loss of water from the soil by evaporation and by transpiration from growing plants, varies markedly in both time and space. In the wet areas and during the wet period, evapotranspiration may be about 20 inches per year, whereas, potential evapotranspiration exceeds 80 inches per year in the arid areas during the dry summer months (Hawaii Water Resources Regional Study, 1979, p. 33). Except for periods of high intensity rainfall, practically all of the rainfall in the dry areas is lost through evapotranspiration. The evapotranspiration loss in the State is estimated to be about 40 percent of rainfall (Takasaki, 1978, p. 12).

Runoff varies greatly between the islands. Estimates of runoff range from less than 4 inches for the Island of Kahoolawe to 65 inches for the Island of Kauai. Estimated average annual runoff for the State is 22 inches or about 31 percent of rainfall (Takasaki, 1978, p. 12). Streamflow characteristics and other pertinent information for a few streams are given in table 2.

PRINCIPAL BASINS

HAWAII REGION

The State of Hawaii is in the Hawaii Region and each of the major islands correspond to hydrologic subregions (fig. 2). Hawaii has no principal river basin and most of the rivers and streams flow to the Pacific Ocean. Thus, it is more practical to describe Hawaii's surface water with regard to its five largest island subregions rather than river basins. Lanai, Niihau, and Kahoolawe have no perennial streams.

Kauai Subregion

Kauai, the oldest and fourth largest island, also known as the "Garden Island," is the home of Mt. Waialeale, the wettest recorded area on Earth. The rainfall on Mt. Waialeale averages more than 450 inches per year. This wet area is located near the center of the island. Less than 20 miles west of Mt. Waialeale is the Kekaha-Mana coastal plain, where rainfall near the coast averages less than 20 inches per year. This is an extreme example of the large variation in rainfall throughout the State (fig. 1). With high rainfall in its central area and most rivers and streams radiating from the center of the island, Kauai has most of the largest rivers in the State, and the greatest runoff.

Nearly all of Kauai's surface-water uses in 1980, about 360 Mgal/d or 557 ft^3/s, were for agricultural and hydroelectric uses (Nakahara, 1984, p. 10). The island's 40,000 people rely on ground water for most of their domestic supply. Municipal water consumption from July 1, 1983 to June 30, 1984 was 3,600 Mgal (million gallons), or an average of 9.8 Mgal/d or 15.2 ft^3/s (Kauai County, 1984, p. 205).

Although Kauai has abundant surface water throughout most of the island, the Kekaha-Mana area has no significant amount of surface water available for development. In fact, 55 Mgal/d or 85 ft^3/s of surface water is imported to the area from the Waimea Basin just east of the Kekaha-Mana area (Hawaii Water Resources Regional Study, 1975, p. 83). This water supplements the 73 Mgal/d or 113 ft^3/s of ground water used for irrigation. The large pumpage of ground water from a small aquifer has created a problem of saltwater intrusion into the aquifer. More surface water may need to be imported to relieve the overpumpage and to provide water for recharging the aquifer.

Other areas of the island have ample supplies of surface water. Kauai's ground-water supply is not as plentiful as the three larger islands, and if the population and tourist industry of Kauai continue to grow, the island may need to add surface water to its municipal water system to adequately provide for its residents and visitors.

Oahu Subregion

Oahu is the third largest island with approximately 80 percent of Hawaii's population. In 1980, the domestic water use for Oahu totaled 63,200 Mgal or 173 Mgal/d or 268 ft^3/s. Practically all of the domestic supply came from ground water. During the same period, agriculture used 237 Mgal/d or 367 ft^3/s. Surface water contributed 44 Mgal/d or 68.1 ft^3/s to agricultural use (Nakahara, 1984, p. 10). This was the total surface water use on Oahu. The estimated average annual runoff for Oahu is 665 ft^3/s or 430 Mgal/d (Takasaki, 1978, p. 12).

Surface water has not been used for Oahu's domestic supply because of the ready availability of excellent quality ground water. In Hawaii, most domestic supplies from ground water do not need treatment. Stream waters of Oahu and the State are of excellent chemical quality upstream from urbanized areas, but their biological and physical qualities do not meet acceptable drinking-water standards without treatment. The continual cost to treat surface water for domestic use plus the development cost would probably be much higher than the cost to develop ground water for domestic use on Oahu. However, if the large agricultural use of ground water continues, and the population and tourism continue to grow, Oahu's residents may need to add surface water to supplement their domestic supply.

The windward side of Oahu is the only area in Hawaii that has an instream flow protection program. The purpose of this program is to establish streamflow standards and develop and implement a permit system for stream channel alterations in Windward Oahu. The program is administered by the State's Department of Land and Natural Resources, which manages all of the State's natural resources. The U.S. Geological Survey and the State are estimating median flows on ungaged streams in Windward Oahu.

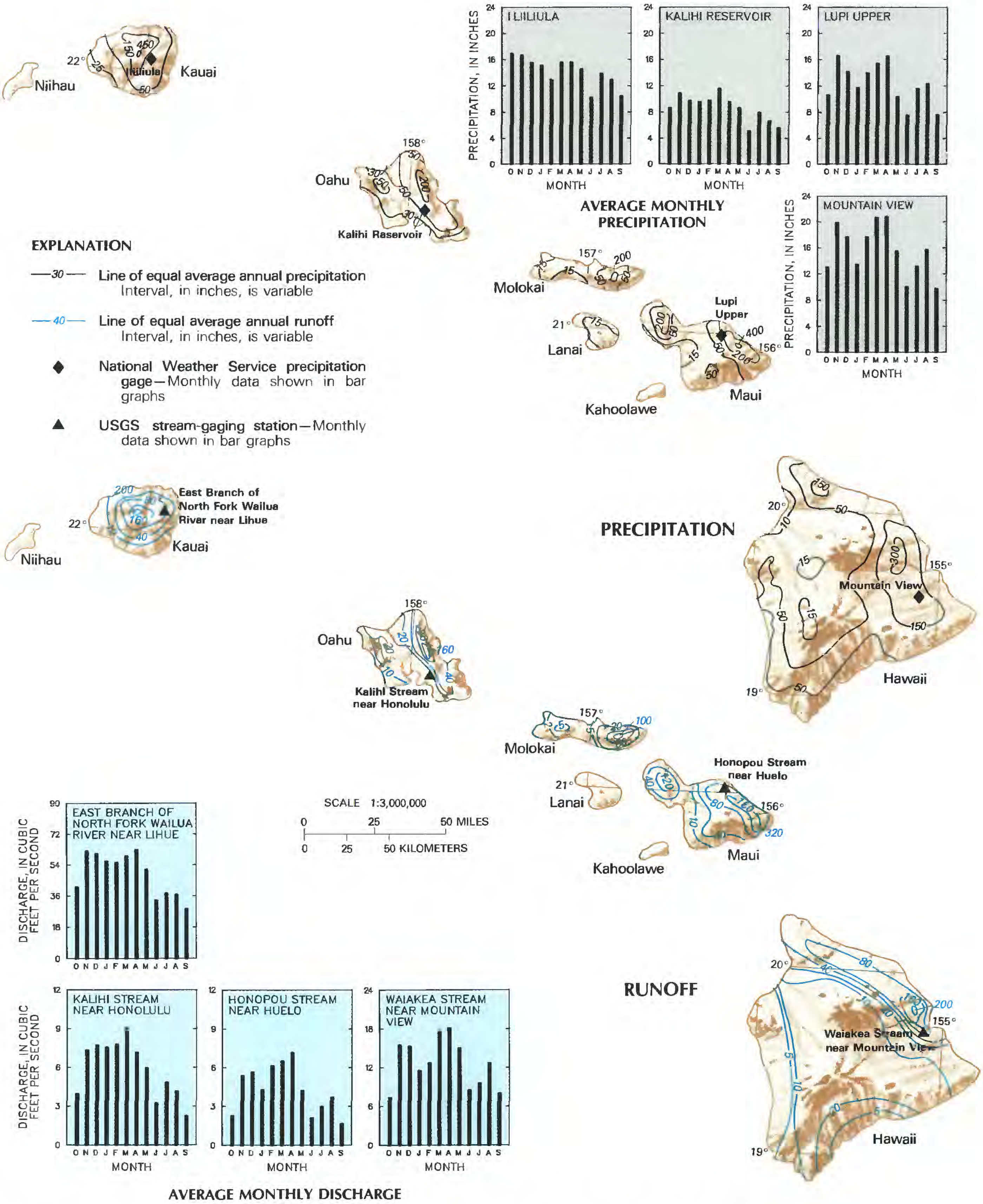
Molokai Subregion

Molokai, the Friendly Isle, is the fifth largest island. It is also the smallest island with perennial streamflow. Annual runoff is estimated to be 263 ft^3/s or 170 Mgal/d (Takasaki, 1978, p. 12). Agricultural use of surface water in 1980 was 2.7 Mgal/d or 4.2 ft^3/s, and domestic use was 0.2 Mgal/d or 0.3 ft^3/s (Nakahara, 1984, p. 10).

In the 1960's, when pineapple cultivation was still flourishing on Molokai, the State completed the construction of a 5-mile tunnel to transport water from windward Molokai to central Molokai. Since the demise of pineapple cultivation on the island, the system has not been fully utilized. However, if replacement crops are found, the system should satisfy the irrigation needs that develop.

Maui Subregion

Maui, the Valley Isle, is the second largest island in Hawaii. The estimated annual runoff for Maui is 2,010 ft^3/s or 1,300 Mgal/d (Takasaki, 1978, p. 12). The agricultural use of surface water on Maui amounted to 353 Mgal/d or 546 ft^3/s in 1980 (Nakahara, 1984, p. 10). This was greater than the total agricultural use of surface water of all the other islands. The second largest use of surface water on Maui was for hydroelectric power, 40 Mgal/d or 61.9 ft^3/s. The largest hydroelectric plant in Hawaii is on Maui. It has an installed capacity of 5,800 kilowatts.



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Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
HAWAII REGION KAUAI SUBREGION								
1.	East Branch of North fork Wailua River near Lihue (16068000).	6.27	1916-83	10.4	48.6	10,400	Nona	Index station for current national water conditions.
OAHU SUBREGION								
2.	Kalihi Stream, near Honolulu (16229000).	2.61	1917-83	0.29	6.74	10,400	None	Index station for current national water conditions. Periodic flooding in urbanized areas.
MAUI SUBREGION								
3.	Honopou Stream near Huolo (16587000).	0.64	1911-83	0.26	4.69	4,410	None	Index station for currant national water conditions. Major water use is for irrigation of sugarcane.
HAWAII SUBREGION								
4.	Waiakea Stream near Mountain View (16700000).	17.4	1931-83	0.10	11.8	1,140	None	Index station for current national water conditions.

The Island of Maui has the largest domestic use of surface water in Hawaii. In 1980, Maui used 9.6 Mgal/d or 14.9 ft^3/s of surface water for domestic use (Nakahara, 1984, p. 10). This was 91 percent of all the domestic use of surface water in the State, and 48 percent of the domestic use on the island. High costs of development and transport preclude replacing the existing domestic surface-water supply with ground water.

Hawaii Subregion

The Island of Hawaii, often referred to as the "Big Island," is the youngest and largest island in the State. It contains 63 percent of the total land area in the State, and with its active volcanoes, this island may continue to grow. The two largest mountains in the State, Mauna Kea (13,796 feet above sea level) and Mauna Loa (13,679 feet above sea level) are on the Big Island.

Estimated annual runoff for the Big Island is about 18 inches or 5,420 ft^3/s or 3,500 Mgal/d (Takasaki, 1978, p. 12). In 1980, only 84 Mgal/d or 130 ft^3/s of surface water was used (Nakahara, 1984, p. 10). About 75 percent was used to generate hydroelectric power; 12 percent was used for agriculture. Domestic use of surface water was only 4 percent of total domestic use and 0.3 percent of total surface water use on the Island of Hawaii.

SURFACE-WATER MANAGEMENT

The water resources of Hawaii are managed by the State Department of Land and Natural Resources, Division of Water and Land Development, the Departments or Boards of Water Supply for the counties, the large sugarcane plantations, who are the largest users of Hawaii's water resources, and the Federal Military. The State Department of Health is involved with the management of Hawaii's water resources only in regard to the quality of the water.

Ownership of water and water rights is probably the biggest water issue in Hawaii today. In 1973, the Hawaii Supreme Court, in the case of *McBryde Sugar Co.* v. *Robinson*, 54 Haw.174 (1973), declared that the ownership of water in natural watercourses, streams, and rivers, rests in the State for the common good of the people of Hawaii. This decision was set aside by the Federal District Court in Hawaii. The State has appealed the District Court's decision to the United States Court of Appeals for the Ninth Circuit.

The Hawaii State Constitutional Convention of 1978 proposed a number of significant changes to Hawaii's Constitution, which were approved. One of these was a new provision on water resources: "The State has an obligation to protect, control, and regulate the use of Hawaii's water resources for the benefit of its people."

In compliance with the State Constitution, the Hawaii Legislature created the Advisory Study Commission on Water Resources in 1982. This commission was charged with the task to review the issues relating to Hawaii's water resources and to formulate a water code for the State. The basic function of the code is "to recognize, clarify, and systematize legal concepts relating to water resources." The commission presented its report, including a recommended State Water Code, to the State legislature on January 14, 1985. The legislature has not yet passed legislation to accept the recommended State Water Code. If the recommended water code is accepted, the primary responsibility to implement and administer the code will rest with the Department of Land and Natural Resources.

The U.S. Geological Survey in cooperation with Federal, State, and local agencies, maintains a network of streamflow-gaging stations. They also conduct hydrologic investigations needed by various cooperators to manage Hawaii's water resources.

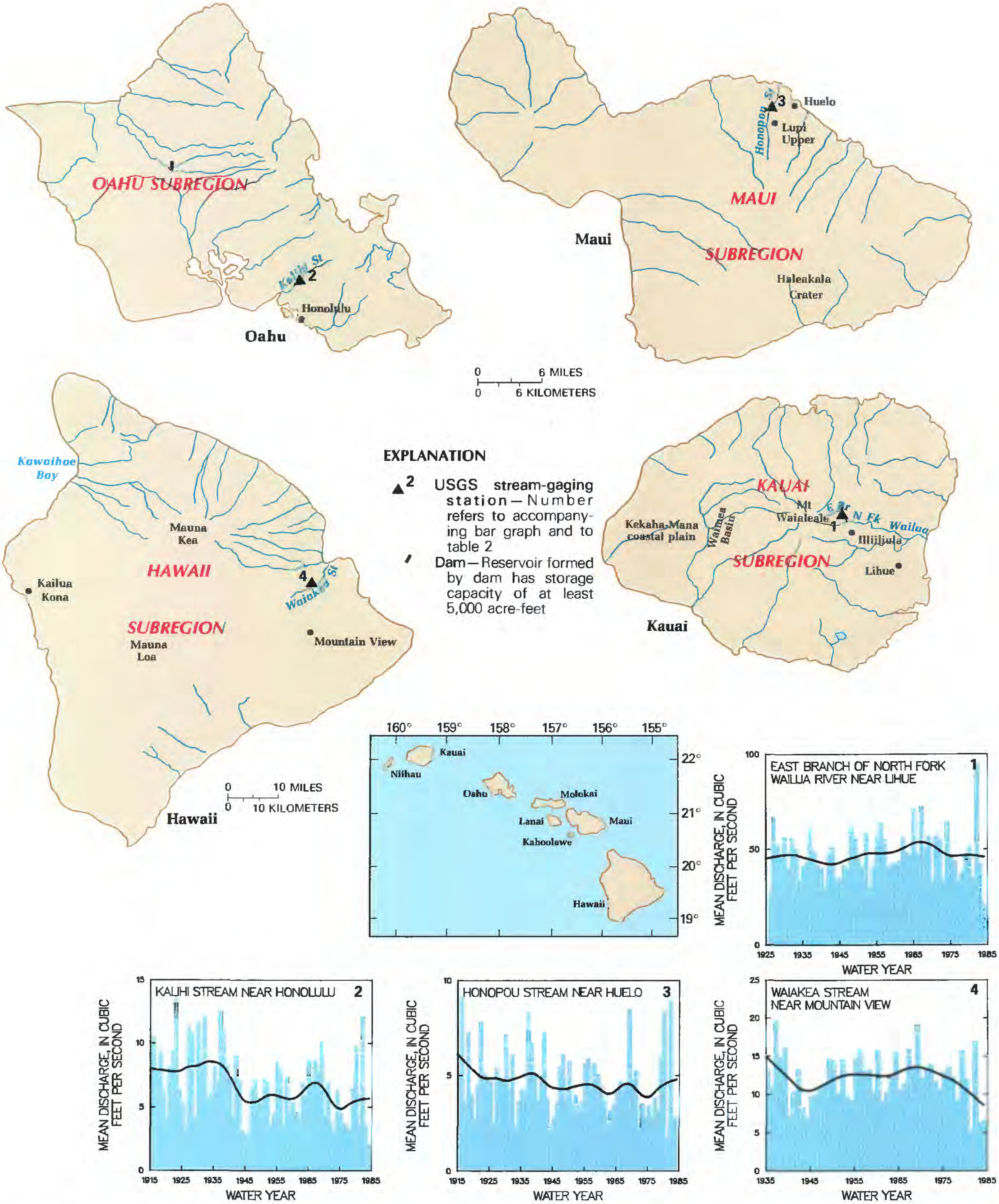

Figure 2. Principal river basins and related surface-water resources development in Hawaii and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber, Kapinos, and Knapp, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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IDAHO
Surface-Water Resources

Irrigated agriculture and hydroelectric power generation are major components of the State's economy. In 1980, surface water constituted 67 percent of Idaho's total offstream water use. About 13 percent of the population depends on surface water for supply. Flow in Idaho's rivers is used to produce more than 12.3 million MWh (megawatt-hours) of hydroelectric energy annually. In addition, hydroelectric projects are being developed on small streams, canals, and springs. Surface-water withdrawals in 1980 and related statistics are given in table 1.

Most surface water in Idaho originates from snow in the mountains and is stored in reservoirs to provide supplies for irrigation and power generation and to maintain flood control. Water quality is excellent in undeveloped reaches of streams but has been degraded in places by irrigation return flow, mine tailings, and municipal and industrial wastes. Water-management practices have been implemented to reduce pollution and to prevent further deterioration of Idaho's surface water. The availability of sufficient quantity during periods of low flow is the principal constraint on use.

Major surface-water issues include legal appropriation of water, interaction of surface-water and ground-water systems, and flooding. Droughts in the 1930's and in 1977 were disastrous to irrigated agriculture, especially where no stored water was available.

GENERAL SETTING

Mountains of central and northern Idaho are in the Northern Rocky Mountain physiographic province; those in the southeast are in the Middle Rocky Mountain province. Mountain ranges and plains of southern Idaho and the prairies and uplands in western Idaho are in the Columbia Plateaus province. The southeastern corner of Idaho is in the Basin and Range province. Physiographic provinces in Idaho are shown in figure 1.

Precipitation is affected by topography and varies widely throughout the State, ranging from less than 10 inches on the Snake River Plain in south-central Idaho to 40 to 50 inches in surrounding mountains (fig. 1). In the central mountains, precipitation may exceed 60 inches. In mountains surrounding the Snake River plain and in northern Idaho, most precipitation falls as snow in winter. Spring rains also are an important source of moisture on the Snake River plain.

About 1.4 million acre-ft (acre-feet) or 460,000 Mgal (million gallons) is evaporated from surface-water bodies annually; nearly 80 percent is from regulated reservoirs and lakes (Meyers, 1962, p. 93). Evaporation from surface water in Idaho ranges from 25 to 35 inches during the growing season and from 30 to 45 inches annually (National Oceanic and Atmospheric Administration, 1982).

Runoff varies geographically and seasonally. Snowpacks on some mountain ranges produce 40 to 50 inches of runoff annually. Average monthly discharges of the Salmon River at White Bird (fig. 1) represent the seasonal pattern of discharge that most streams in Idaho would have if unregulated. The bar graph of average monthly discharge for the Clearwater River shows the effect of partial upstream regulation, although a tendency for snow to melt earlier in this basin than in the Salmon River drainage basin also influences the flow distribution. Runoff in the Snake River basin is heavily regulated with a storage capacity exceeding 9 million acre-ft or 2,900,000 Mgal above Weiser. Storage has decreased spring floodflow below reservoirs, and diversions deplete flow in the summer. Bar graphs in figure 2 show that several years were dry in the 1930's and early 1940's and several years were wet from 1965 through 1976.

Table 1. Surface-water facts for Idaho

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	127
Percentage of total population	13
From public water-supply systems:	
Number (thousands)	117
Percentage of total population	12
From rural self-supplied systems:	
Number (thousands)	10
Percentage of total population	1
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	18,000
Surface water only (Mgal/d)	12,000
Percentage of total	67
Percentage of total excluding withdrawals for thermoelectric power	67
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	16
Percentage of total surface water	0.1
Percentage of total public supply	10
Per capita (gal/d)	137
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	2.0
Percentage of total surface water	<0.1
Percentage of total rural domestic	4
Per capita (gal/d)	200
Livestock:	
Surface water (Mgal/d)	13
Percentage of total surface water	<0.1
Percentage of total livestock	59
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	120
Percentage of total surface water	1
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	5
Excluding withdrawals for thermoelectric power	5
Irrigation withdrawals:	
Surface water (Mgal/d)	12,000
Percentage of total surface water	99
Percentage of total irrigation	74
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	76,000

PRINCIPAL RIVER BASINS

Four tributaries to the Columbia River (the Spokane, the Pend Oreille, the Kootenai, and the Snake Rivers) in the Pacific Northwest region (Seaber and others, 1984) drain all of Idaho except for the southeastern corner, which is drained by the Bear River of the Great Basin Region.

The Spokane, the Pend Oreille, and the Kootenai River basins are in the Northern Rocky Mountain province. The Bear River enters Idaho in the Middle Rocky Mountain province, makes a northern loop, turns south and enters the Basin and Range province, and flows into Utah.

The Snake River and Henrys Fork—its principal upstream tributary in Idaho—head in the Middle Rocky Mountain province. The Portneuf River basin in the northeastern corner of the Basin and Range province joins the Snake River at the southeastern edge of the Columbia Plateau province. The Bruneau River and several other southern tributaries to the Snake River drain mountains and uplands in the Columbia Plateau province. The Big Lost and the Big Wood Rivers and several other streams flow from the Northern Rocky Mountain province to the Columbia Plateau province (Snake River Plain section). Farther west, the Boise, the Payette, and the Weiser Rivers flow from the Northern Rocky Mountain province to the Payette section of the Columbia Plateau province. The Salmon and the Clearwater Rivers, which join the Snake River below Hells Canyon Dam, drain the remainder of the central mountains. About 87 percent of Idaho is in the Snake River drainage basin (Idaho Water Resources Research Institute, 1968, p. 11). The Snake River drainage is divided into upper, middle, and lower basins.

These river basins are described below; their geographic distribution, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

GREAT BASIN REGION

Bear Subregion

Bear River Basin.—The Bear River is the largest river, with respect to discharge, in the Western Hemisphere that does not flow to an ocean (Dion, 1969, p. 6). About 35 percent of the 7,100-mi^2 (square mile) Bear River basin is in Idaho; the remainder is in Wyoming and Utah. Annual flow to the Bear River in Idaho averages about 500,000 acre-ft or 160,000 Mgal.

Water from the Bear River is diverted through canals to Bear Lake for offstream storage of 1.4 million acre-ft or 460,000 Mgal. About 220 Mgal/d (million gallons per day) or 340 ft^3/s (cubic feet per second) is diverted to irrigate about 150,000 acres. Annual hydroelectric energy production is about 213,000 MWh (Heitz and others, 1980).

Streams in the Bear River basin are generally in direct hydraulic connection with ground water. Hundreds of springs throughout the basin are used for domestic water supplies. The Bear River is a gaining stream except where the channel cuts through fractured basalt.

Several phosphate mines are located in the northeastern part of the basin, but significant water-quality deterioration has not been detected. Siltation limits fisheries mainly to Bear Lake and the Cub River.

PACIFIC NORTHWEST REGION

Kootenai-Pend Oreille--Spokane Subregion

Pend Oreille and Kootenai River Basins.—Only about 8 percent of the Pend Oreille River basin is in Idaho; most of the drainage is in the mountains of western Montana. The Clark Fork River enters Idaho from Montana and flows to Pend Oreille Lake where it is dammed for power generation. Most of the inflow to the lake is from the Clark Fork River, which carries contaminants from pulp mills and mines in Montana. Excellent fishing and recreational activities at Lake Pend Oreille have created a sizable tourist industry. Lake depths of 1,100 feet provide an inland site for submarine experimentation and training. The Pend Oreille River drains the lake and has been regulated by Albeni Falls Dam at the Idaho-Washington border since 1952. The dam maintains the minimum lake level, but does not raise water above the natural lake level. Active storage in Pend Oreille Lake is 1.2 million acre-ft or 380,000 Mgal. Annual hydroelectric energy production at Cabinet Gorge and Albeni Falls Dams is about 1.3 million MWh.

Average annual net inflow to the Pend Oreille River in Idaho from 1953 to 1984 was 2.6 million acre-ft or 840,000 Mgal. The Priest River (table 2, site 2), which drains Priest Lake, is the largest tributary in the system and yields about 50 percent of the flow entering the Pend Oreille River in Idaho. Priest Lake is in a heavily wooded, mountainous setting and is largely pristine. The Priest River water is soft; hardness as calcium carbonate ranges from 15 to 43 mg/L (milligrams per liter). At issue is the degree of development to be permitted around Priest Lake.

About 1,400 mi^2, or 10 percent, of the Kootenai River basin above Porthill at the U.S.-Canadian border is in Idaho. Average flow of the Kootenai River at Porthill is nearly 16,000 ft^3/s or 10,300 Mgal/d, to which drainages in Idaho contribute about 1,300 ft^3/s or 840 Mgal/d. About 30,000 acres of the Kootenai River flood plain are used for agriculture. Water quality is good and the water is suitable for most uses.

Spokane River Basin.—Of the 6,680 mi^2 in the Spokane River basin, the upper 58 percent is in Idaho. Upper tributaries flow through narrow canyons that widen into a broad, rolling valley containing Coeur d'Alene Lake. Outflow from the lake—the Spokane River—is regulated by Post Falls Dam completed in 1908. Annual hydroelectric energy production is 79,000 MWh. Storage in Coeur d'Alene Lake is 225,000 acre-ft or 73,000 Mgal. An average of 10 ft^3/s or 6.5 Mgal/d is diverted to Rathdrum Prairie Canal for irrigation of about 3,000 acres.

Mining of silver, lead, zinc, and other metals began in 1885 in the South Fork Coeur d'Alene River basin. Until 1968, mine waste products were dumped into the river; subsequently, settling ponds were installed. Mill tailings containing heavy metals have been carried to the Coeur d'Alene River and Lake. Trace metals have, at times, exceeded U.S. Environmental Protection Agency drinking-water regulations (U.S. Environmental Protection Agency, 1982a and 1982b).

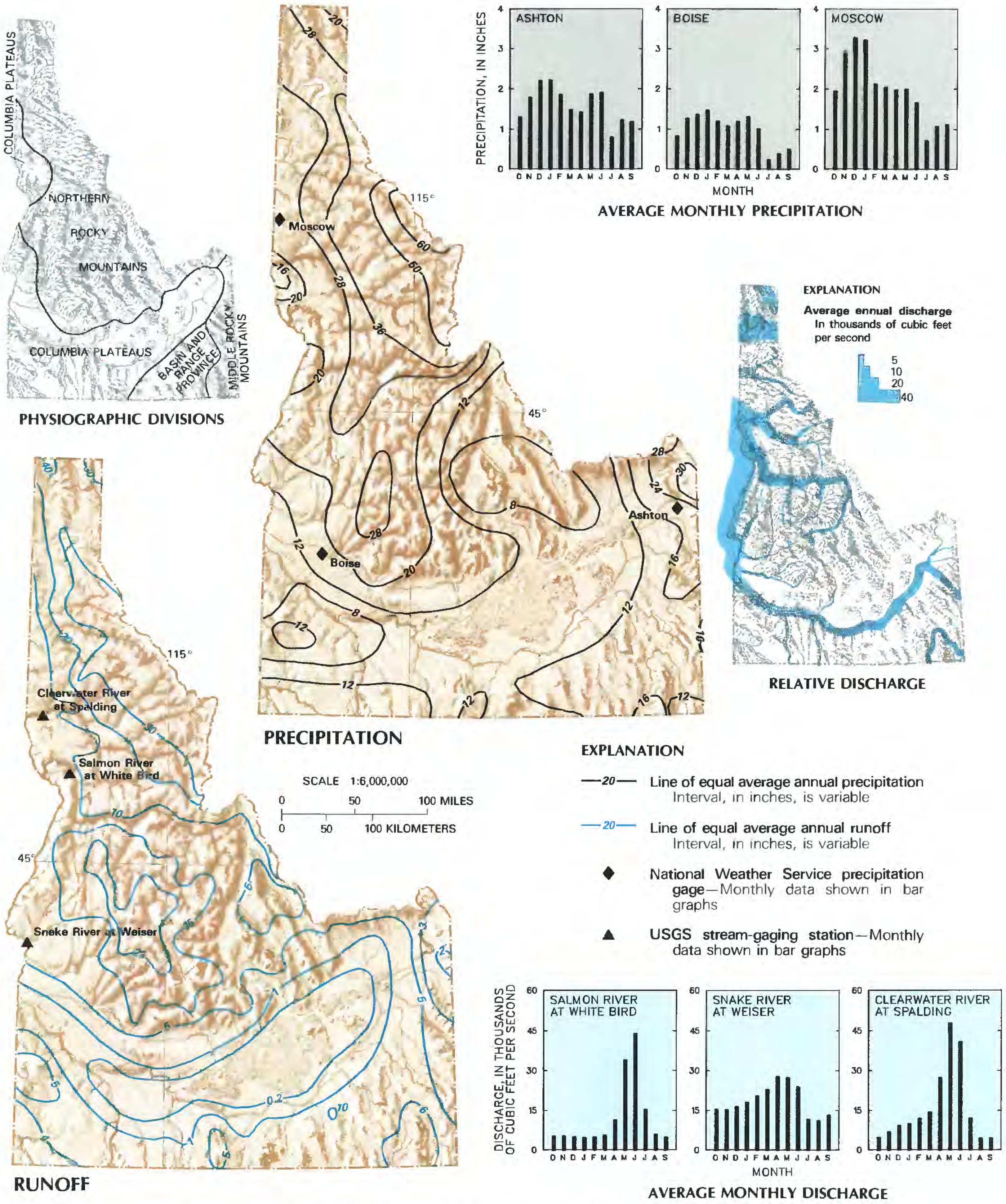

Figure 1. Average annual precipitation and runoff in Idaho and average monthly data for selected sites, 1951–80.

Sources: Precipitation—annual data modified from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA), based on U.S. Congress, 1969; monthly data from NOAA, 1984. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Idaho

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second;. . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Idaho State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
	GREAT BASIN REGION **BEAR SUBREGION** **Bear River basin**							
1.	Bear River near Preston (10090500).	4,545	1944–84	80	937	8,190	Appreciable	Regulation by three-State agreement.
	PACIFIC NORTHWEST REGION **KOOTENAI—POND OREILLE—SPOKANE SUBREGION** **Pend Oreille River basin**							
2.	Priest River near Priest River (12395000).	902	1904, 1930–84	200	1,686	11,500	Moderate	Probable expanding recreational area.
	Spokane River basin							
3.	Spokane River near Post Falls (12419000).	3,340	1913–84	180	6,297	46,000	Moderate	Heavily mined area along upstream tributary.
	UPPER SNAKE SUBREGION							
4.	Snake River near Irwin (13032500).	5,225	1950–84	560	6,691	31,700	Appreciable	Headwaters in Wyoming.
5.	Henrys Fork near Rexburg (13056500).	2,920	1910–84	400	2,088	12,100	Moderate	Unregulated tributaries.
6.	Portneuf River near Pocatello (13075500).	1,250	1913–16, 1918–84	14	280	2,650	Appreciable	Irrigated valleys upstream.
7.	Snake River at Milner (13088000).	17,180	1910–26, 1927–84	5	2,711	42,400 28,300	. . . do . . .	Downstream from Snake River gravity diversions.
8.	Big Lost River below Mackay Reservoir, near Mackay (13127000).	813	1905, 1913–14, 1920–84	36	314	3,280	. . . do . . .	Regulated for downstream irrigation.
9.	Big Wood River below Magic Dam, near Richfield, (13142500).	1,600	1913–84	2	480	10,400	. . . do . . .	Regulated for downstream irrigation.
	MIDDLE SNAKE SUBREGION							
10.	Snake River at King Hill (13154500).	35,800	1910–26 1927–84	6,000	10,910	54,600 39,100	Appreciable	Downstream from springs along canyon walls.
11.	Bruneau River near Hot Spring (13168500).	2,630	1909–14, 1943–84	47	409	7,500	Negligible	Irrigation diversions downstream.
12.	Boise River near Boise (13202000).	2,680	1953–84	1	2,951	10,000	Appreciable	Heavily irrigated area downstream.
13.	Payette River near Payette (13251000).	3,240	1936–84	400	3,183	10,000	. . . do . . .	Irrigated valley upstream.
14.	Weiser River near Weiser (13266000).	1,460	1953–84	54	1,132	26,000	Negligible	Downstream diversions for irrigation.
15.	Snake River at Weiser (13269000).	69,200	1911–84	6,600	18,490	10,000	Appreciable	Heavily irrigated area.
	LOWER SNAKE SUBREGION							
16.	Salmon River at White Bird (13317000).	13,550	1911–17, 1920–84	2,400	11,420	126,000	None	Wilderness areas upstream.
17.	Clearwater River at Spalding (13342500).	9,570	1910–13, 1925–84	1,500	15,550	188,000	Moderate	North Fork regulated since 1971.

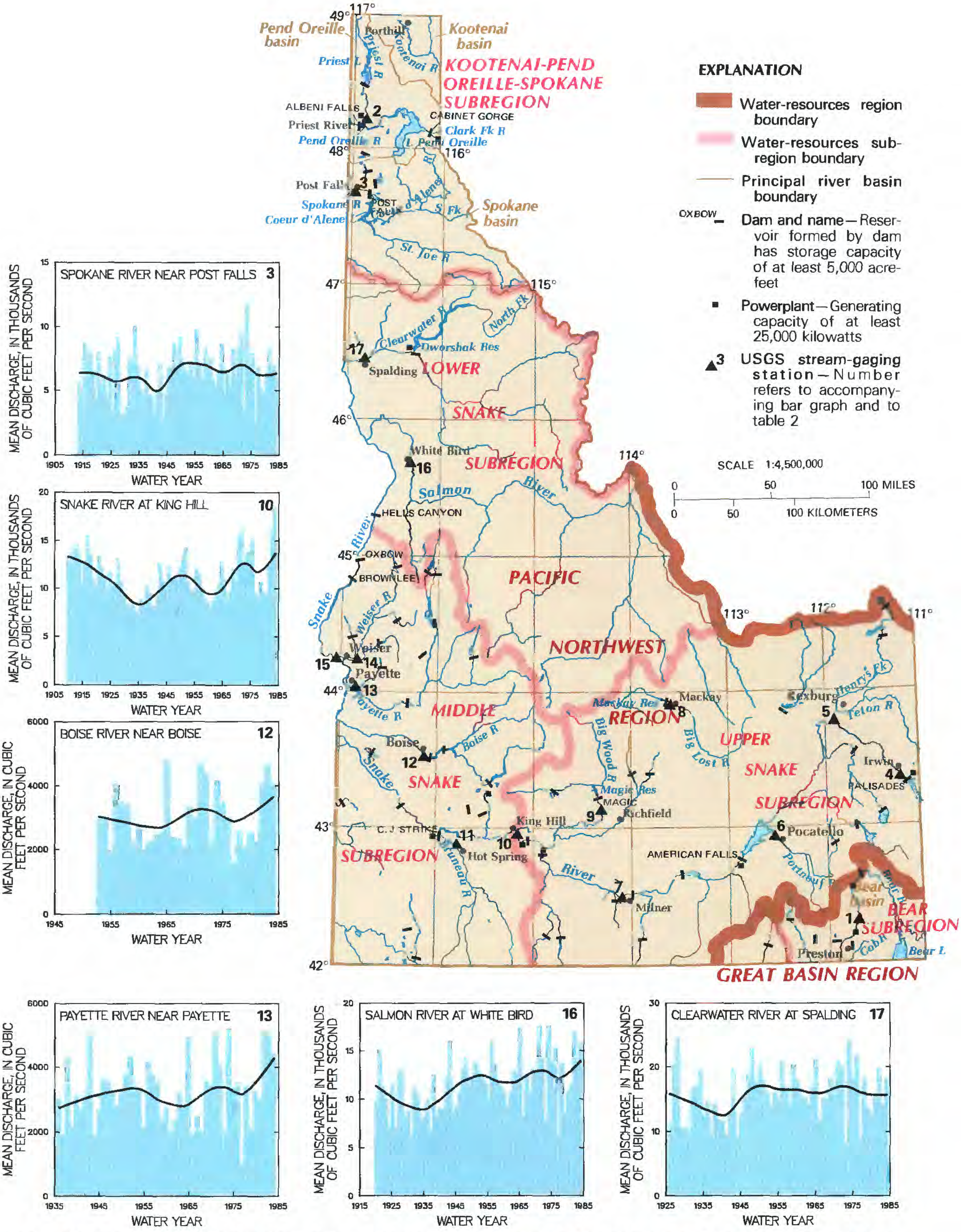

Figure 2. Principal river basins and related surface-water resources development in Idaho and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Logging is another important industry in much of the basin. Most of the upper St. Joe River basin is a wilderness area and water quality is suitable for most uses, but inadequate waste treatment has caused some deterioration of water quality in the lower St. Joe River.

Upper Snake Subregion

About 92 percent of the 30,050-mi² drainage area of the upper Snake River basin is in Idaho. The Snake River flows into a reservoir behind Palisades Dam (constructed in 1956 with 1.2 million acre-ft or 390,000 Mgal of storage) from its headwaters in Wyoming. The reservoir behind American Falls Dam (constructed in 1926), the other large storage facility in the upper basin, may store 1.7 million acre-ft or 550,000 Mgal and is used for irrigation supply, flood control, and power generation. Besides Palisades and American Falls Dams, 11 other dams in the Snake River and about 30 on its tributaries were built for one or more of these purposes. Storage capacity in the Snake River basin above King Hill is nearly 5.7 million acre-ft or 1,860,000 Mgal, about 85 percent of which is in Idaho. Annual hydroelectric energy production is about 2.64 million MWh. Diversions from the Snake River for irrigation averaged 6,200 Mgal/d or 9,600 ft³/s in 1980. About 65 percent of 2.5 million acres in the upper basin is irrigated with surface water. About 41 percent of the State's population of nearly 1 million live in the upper Snake River basin.

Ground-water discharge, mostly from springs, to American Falls Dam is about 2,500 ft³/s or 1,600 Mgal/d and to the Snake River from Milner to King Hill, about 6,500 ft³/s or 4,200 Mgal/d. Discharge from the 12 largest springs or groups of springs ranges from 100 to 1,400 ft³/s or 65 to 900 Mgal/d. Spring discharge is affected by recharge to the ground-water system from irrigation and stream seepage.

Surface-water diversions for irrigation from Henrys Fork in 1980 was 1,020 Mgal/d or 1,580 ft³/s. A disastrous flood occurred in the lower Henrys Fork basin when an earthen dam in the Teton River failed June 5, 1976, while the reservoir was being filled (Ray and Kjelstrom, 1978).

The Portneuf River drains about 1,380 mi² southeast of the Snake River Plain. About 2.6 ft³/s or 1.7 Mgal/d discharges to the Portneuf River below Pocatello from a phosphate ore-processing plant where leachate recovery systems and lined evaporation ponds are used (Jacobson, 1984, p. 25). Dissolved-solids concentrations in the Portneuf River near Pocatello range from 283 to 439 mg/L.

The Big Lost River is the largest of several streams north of the Snake River Plain that do not reach the Snake River. Streamflow entering the plain infiltrates to basalt aquifers. Mackay Reservoir, constructed in 1918, stores about 44,000 acre-ft or 14,300 Mgal for irrigation. About 80 percent of 58,000 acres in the Big Lost River basin is irrigated by surface water.

Springs discharge about 1,200 ft³/s or 780 Mgal/d in a deep gorge at the lower end of the Big Wood River. More than 223,000 acre-ft or 73,000 Mgal of water is stored behind Magic Dam (constructed in 1918 with 191,500 acre-ft or 62,400 Mgal of storage) and in several smaller reservoirs for irrigation of about 140,000 acres in the Big Wood River basin.

Middle Snake Subregion

Of the 36,700 mi² in the middle Snake River basin, 62 percent is in Idaho. About 36 percent of Idaho's population lives in the middle Snake River basin. Irrigated agriculture is the most important industry in the basin. About 87 percent of the 1.1 million irrigated acres is supplied by surface water. Surface water diverted in 1980 averaged 2,500 Mgal/d or 3,900 ft³/s. Annual hydroelectric energy production in the basin is about 4.2 million MWh, 80 percent of which is produced at Brownlee (1958) and Oxbow (1961) dams. Most of the 1.0 million acre-ft or 330,000 Mgal of storage behind these dams is in Brownlee Reservoir.

The Boise, the Payette, and the Weiser Rivers contribute about 79 percent of the tributary water yield to the basin (Kjelstrom, 1984). Nearly 75 percent of the middle Snake River basin's population live in the Boise River watershed. In 1980, surface-water diversions for irrigation in the Boise River watershed were 1,750 Mgal/d or 2,750 ft³/s. Return flow from irrigation and effluent from municipal and industrial treatment plants enter the Boise River, but the water is suitable for most uses.

Lower Snake Subregion

After leaving the irrigated plains in southern Idaho, the Snake River flows northward forming part of the Idaho-Oregon border.

Nearly 75 percent of the land in the Clearwater and the Salmon River basins (23,420 mi^2) is administered by public agencies. The region contains most of Idaho's wilderness resources and thousands of miles of free-flowing streams. More than 5 million acres of public land are of pristine quality. About 126,000 acres are irrigated, mainly in the valleys of the southeastern Salmon River basin. About 99 percent is supplied by surface water.

Logging, road building, mining, and grazing activities in some small basins have resulted in loss of aquatic habitat through siltation. Otherwise, water in the streams and lakes is of exceptionally good quality and suitable for most uses. Dissolved-solids concentrations in the Clearwater River at Spalding (table 2, site 17) range from 43 to 83 mg/L. The North Fork of the Clearwater River is regulated by Dworshak Reservoir (constructed in 1971 with storage of 2.0 million acre-ft or 650,000 Mgal). Annual hydroelectric energy production is about 1.9 million MWh.

SURFACE-WATER MANAGEMENT

Management of water resources and protection of those resources from waste and contamination are the responsibilities of the Idaho Department of Water Resources (IDWR), Idaho Water Resource Board, (IWRB) and Idaho Department of Health and Welfare (IDHW), Division of Environment. IDWR is the water-rights agency in Idaho. IWRB (1982) developed a State Water Plan to provide information to State and local planners and legislators for decisions concerning water management. Idaho operates under a prior appropriation doctrine; thus, the earliest users of water have priority-use rights. All water in Idaho belongs to the public and is subject to appropriation for beneficial purposes.

IDWR and IDHW 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 surface-water management decisions in Idaho are made.

Several other agencies, groups, or individuals have responsibilities for the administration and management of surface water. For adjudicated water rights, delivery to water users is the responsibility of watermasters under the supervision of IDWR. The Bear River Commission oversees the use of water as prescribed by the Bear River Compact of 1980. The U.S. Bureau of Reclamation is responsible for management of many dams and irrigation storage facilities. The U.S. Army Corps of Engineers is responsible for the flood-control management of several Federal projects, as well as Brownlee Dam and reservoir, under its Federal Energy Regulatory Commission license. The International Kootenai Board of Control coordinates the water policies of the U.S. and Canada for the Kootenai River.

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ILLINOIS
Surface-Water Resources

Illinois is almost completely bounded by surface water—the Mississippi River to the west, the Wabash and the Ohio Rivers to the southeast and south, and Lake Michigan to the northeast. Surface water serves 51 percent of Illinois' population. Municipal supplies generally are obtained from surface-water sources in the southern two-thirds of the State and from ground-water sources in the northern one-third of the State. Rural supplies are obtained almost entirely from ground-water sources. The two major offstream users in 1980 were self-supplied industry (14,000 Mgal/d (million gallons per day) or 21,700 ft³/s (cubic feet per second)) and municipalities (1,300 Mgal/d or 2,000 ft³/s). Surface-water withdrawals in Illinois in 1980 for various purposes and related statistics are given in table 1.

The Illinois Environmental Protection Agency (1984) recently completed an evaluation of the surface-water quality in the State. Based on results of the evaluation, degrees of severity (minimum or nonexistent, intermediate, moderate, severe) of water-quality problems in a stream were established. The above designations are used to describe water quality in the principal river basins in Illinois. The evaluation indicated that pollution from industrial and municipal point discharges decreased in the State since 1972, but nonpoint sources have a significant, deleterious effect on surface waters. Agriculture (row cropping) is the most significant nonpoint source of surface-water pollution in Illinois. Other sources include erosion at construction sites, coal mining, urban runoff, and oil field brines.

The three most critical surface-water issues in Illinois are erosion and sediment control, mitigation of flood-damage, and water conservation (Illinois State Water Plan Task Force, 1984). Excessive soil erosion, attributable to farming practices, affects 9.6 million acres of farmland in Illinois. Side effects of erosion include the degradation of stream quality and wildlife habitat, and accelerated eutrophication of reservoirs.

Development on flood plains continues to result in significant property damage from flooding. Millions of dollars are spent on programs to protect property from flooding and to ease the financial burdens caused by flooding.

Water-conservation efforts have generally been limited to the greater Chicago metropolitan area but were encouraged statewide during periods of drought in the 1920's, 1930's, and 1950's. Droughts have caused serious economic problems in Illinois. In many areas, reservoir storage is necessary to retain spring runoff and to augment low flows.

Table 1. Surface-water facts for Illinois

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: Kirk and others, 1982]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	5,827
Percentage of total population	51
From public water-supply systems:	
Number (thousands)	5,827
Percentage of total population	51
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	17,000
Surface water only (Mgal/d)	16,000
Percentage of total	94
Percentage of total excluding withdrawals for thermoelectric power	64
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	1,300
Percentage of total surface water	8
Percentage of total public supply	73
Per capita (gal/d)	220
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total livestock	0
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	14,000
Percentage of total surface water	92
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	99
Excluding withdrawals for thermoelectric power	71
Irrigation withdrawals:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total irrigation	0
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	26,000

GENERAL SETTING

Most of Illinois is in the Central Lowland physiographic province, except for a narrow band along the southwestern and southern margin of the State. This band includes parts of the Ozark Plateau, the Interior Low Plateau, and the Coastal Plain physiographic provinces (fig. 1).

Average annual precipitation for 1951-80 ranges from about 36 inches in the north to about 44 inches in the south (fig. 1). Seasonal patterns are generally pronounced in northern and central Illinois (fig. 1, bar graphs for Rockford and Springfield). In southern Illinois, precipitation is relatively evenly distributed throughout the year (bar graph for Cairo).

Average annual evaporation from lakes ranges from about 30 inches in the north and east to about 38 inches in the southeast. Evaporation from land and lake surfaces represents about 44 percent of the annual rainfall (Roberts and Stall, 1967, p. 3).

Runoff varies both seasonally and geographically (fig. 1). During the fall and early winter, runoff is relatively low, but warming trends can increase runoff from snowmelt and from precipitation that falls on the frozen ground. During the spring (March through May) runoff is highest because of snowmelt, thunderstorms, and the saturated condition of soils. Flooding is most common during this period but may occur during any month. During the growing season, evapotranspiration increases, soils have higher absorptive capacity, and runoff generally declines during the summer when evapotranspiration rates are high.

Average annual runoff ranges from 8 to 16 inches across the State. The highest runoff occurs in the hilly bedrock country of southeastern Illinois. Runoff decreases to the north and west across the relatively flat, poorly developed drainage in the unconsolidated drift deposits of the Central Lowland province. Relatively high runoff occurs in the heavily urbanized Chicago metropolitan area in the northeastern part of the State, even though that area receives the least amount of rain in the State.

PRINCIPAL RIVER BASINS

Illinois has an area of 56,400 mi² (square miles) and includes the Upper Mississippi, the Ohio, and the Great Lakes Regions

(Seaber and others, 1984). The Upper Mississippi Region is the largest and includes about 80 percent of the State; the principal river basins include the Illinois, the Rock, the Kaskaskia, and the Big Muddy. The Ohio Region includes about 20 percent of the State, and the principal river basins include the Embarras and the Little Wabash. The Great Lakes Region in Illinois includes only a narrow band along Lake Michigan. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

UPPER MISSISSIPPI REGION

Upper and Lower Illinois Subregions

Illinois River Basin.—The Illinois River basin—the largest drainage basin in Illinois—has an area of 28,906 mi^2 (Healy, 1979b, p. 8); 87 percent of which is in the State. The Illinois River originates at the confluence of the Kankakee and the Des Plaines Rivers southwest of Chicago. Its major tributaries include the following rivers: the Fox, the Vermilion, the Mackinaw, the Spoon, the Sangamon, and the La Moine. It flows from the densely urbanized and industrialized northeastern corner of Illinois through the agricultural heartland of the State. Several communities are located along its route, the largest of which is the city of Peoria. Development in the basin has been directed toward navigation, power generation, municipal and industrial water supplies, recreation, and flood control.

Major water users include hydroelectric-, thermoelectric-, and thermonuclear-power generation (9,900 Mgal/d or 15,300 ft^3/s, of which 1,900 Mgal/d or 2,940 ft^3/s is instream use); self-supplied industries (180 Mgal/d or 279 ft^3/s); public water supplies (90 Mgal/d or 139 ft^3/s); and mineral extraction (16 Mgal/d or 25 ft^3/s) (modified from Kirk and others, 1982).

The northern part of the basin contains several natural lakes, but the lakes elsewhere in the basin are manmade reservoirs. The largest reservoirs in the basin are near Decatur and Springfield and include Lake Decatur (completed in 1922; Bascule gates added in 1955 with 22,300 acre-ft (acre-feet) or 7,270 Mgal (million gallons) of storage) and Lake Springfield (completed in 1934 with 53,500 acre-ft or 17,400 Mgal of storage) (Illinois Environmental Protection Agency, 1978, p. 147, 149).

Natural flow in the Illinois River basin is augmented by diversions from the Great Lakes Region. An average annual diversion of 3,200 ft^3/s or 2,100 Mgal/d was decreed by the U.S. Supreme Court in 1967. The diversion is used to augment municipal supplies and navigational needs, and to dilute waste entering the Illinois River. Disposal of effluent from an increasing number of sewage treatment facilities in the Chicago metropolitan area has increased flows of the Des Plaines River (fig. 2, table 2, site 4).

Flooding along the river generally occurs in the spring, but may occur at any time during the year. The most recent floods on the Illinois River occurred in early March 1985. The historic peak discharge for the Illinois River at Marseilles (fig. 2, table 2, site 1) is 94,100 ft^3/s or 60,800 Mgal/d in December 1982 and at Meredosia (site 2) it is 123,000 ft^3/s or 79,500 Mgal/d in May 1943.

Water-quality problems in the basin are generally intermediate in severity (Illinois Environmental Protection Agency, 1984, p. 12). However, water-quality problems are moderate to severe in the Illinois River above Marseilles, in the Des Plaines River, and in the Sangamon River between Decatur and Springfield; water-quality problems are moderate in the Vermilion River.

Rock Subregion

Rock River Basin.—The Rock River originates in southern Wisconsin. About 59 percent of its 10,915 mi^2 drainage basin is in Illinois (Healy, 1979a, p. 266). The river has three major tributaries—the Pecatonica, the Kishwaukee, and the Green Rivers.

Development in the basin began in the early 1900's when two large swamps in the Green River basin were drained and the river was dredged and straightened. Eight low-head dams, which were 9 to 15 feet high, were constructed on the Rock River and served as a source of hydroelectric power. Only one dam is still used for that purpose; pools formed by the other seven dams are used for recreation. There are no reservoirs in the basin. A large part of the basin is used for agriculture. Instream water use for hydropower is 490 Mgal/d or 758 ft^3/s; withdrawals for thermoelectric use are 440 Mgal/d or 681 ft^3/s and for other self-supplied industries are 43 Mgal/d or 67 ft^3/s (modified from Kirk and others, 1982).

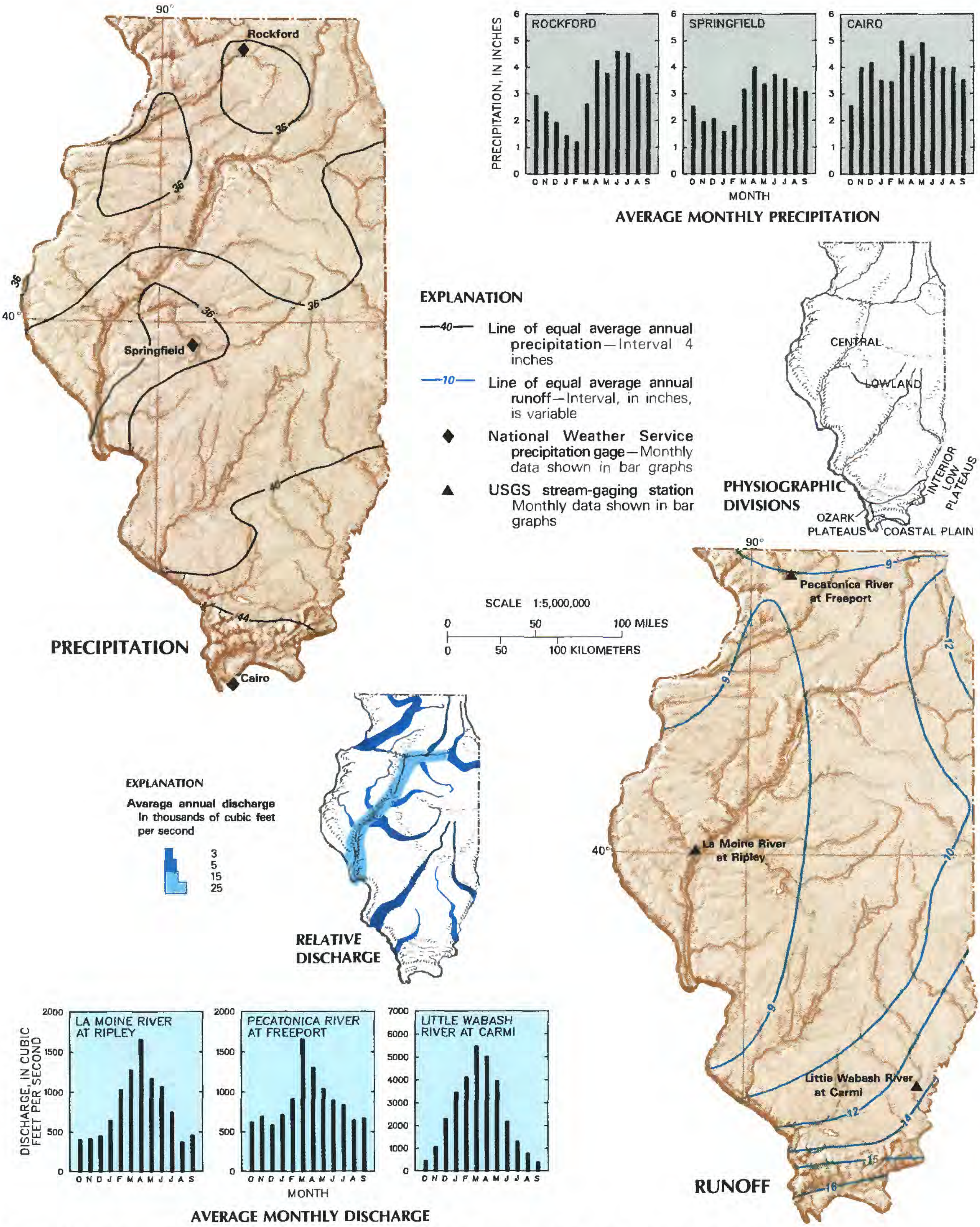

Figure 1. Average annual precipitation and runoff in Illinois and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA, file. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Tabla 2. Selected streamflow characteristics of principal river basins in Illinois

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Illinois State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
UPPER MISSISSIPPI REGION **Upper And Lower Illinois Subregions** **Illinois River main stem**								
1.	Illinois River at Marseilles (05543500).	8,259	1919-83 1940-83	 3,180	 9,791	91,100	Appreciable	Navigational lock and dam upstream.
2.	Illinois River at Meredosia (05585500).	26,028	1921-83 1940-83	 3,630	 21,976	132,300	. . . do . . .	Navigational locks and dams upstream.
Illinois River basin—tributaries								
3.	Kankakee River near Wilmington (05527500).	5,150	1915-83	463	4,233	68,100	Negligible	
4.	Des Plaines River at Riverside (05532500).	630	1914-83 1943-83 1974-83	. . . . 6.0 48	. . . . 471	7,830	None	Rapidly urbanizing area.
5.	Fox River at Dayton (05552500).	2,642	1915-83 1974-83	176 366	1,703	37,400	Appreciable	Regulated for hydropower and recraation.
6.	Vermilion River near Leonore (05555300).	1,251	1931-83 1973-83	. . . . 9.6	822	40,700	None	Rural basin.
7.	Mackinaw River near Congerville (05567500).	767	1945-83	1.3	511	43,900	Negligible	Do.
8.	Spoon River at Seville (05570000).	1,636	1914-83	20	1,054	37,600	None	Some surface coal mining.
9.	Sangamon River near Oakford (05583000).	5,093	1910-83 1974-83	147 263	3,335	82,800	Moderate	Water-supply reservoirs upstream.
10.	La Moine River at Ripley (05585000).	1,293	1921-83	10	802	27,500	None	
Rock Subregion **Rock River basin**								
11.	Pecatonica River at Freeport (05435500).	1,326	1914-83	191	900	21,300	None	Relatively unaffected basin.
12.	Kishwaukee River near Perryville (05440000).	1,099	1940-83	68	713	25,000	. . . do . . .	
13.	Rock River near Joslin (05446500).	9,549	1940-83	1,270	6,020	58,800	Moderate	
14.	Green River near Geneseo (05447500).	1,003	1936-83	40	610	13,000	None	
Upper Mississippi-Kaskaskia-Meramec Subregion **Kaskaskia and Big Muddy River basins**								
15.	Kaskaskia River at Vandalia (05592500).	1,940	1908-69 1970-83	14 34	1,412 1,769	33,000 30,400	None Appreciable	One of the largest reservoirs in Illinois in basin.
16.	Big Muddy River at Murphysboro (05599500).	2,169	1916-70 1931-70 1971-83	. . . . 2.3 47	. . . . 1,788 1,888	39,300 41,000	 None Appreciable	Habitat and wetlands preservation concerns; large reservoirs in basin.
OHIO REGION **Wabash And Lower Ohio Subregions** **Embarras and Little Wabash River basins**								
17.	Embarras River at Ste. Marie (03345500).	1,516	1910-83	14	1,224	53,700	None	Relatively unaffected basin.
18.	Little Wabash River at Carmi (03381500).	3,102	1940-83	6.2	2,529	45,300	. . . do . . .	

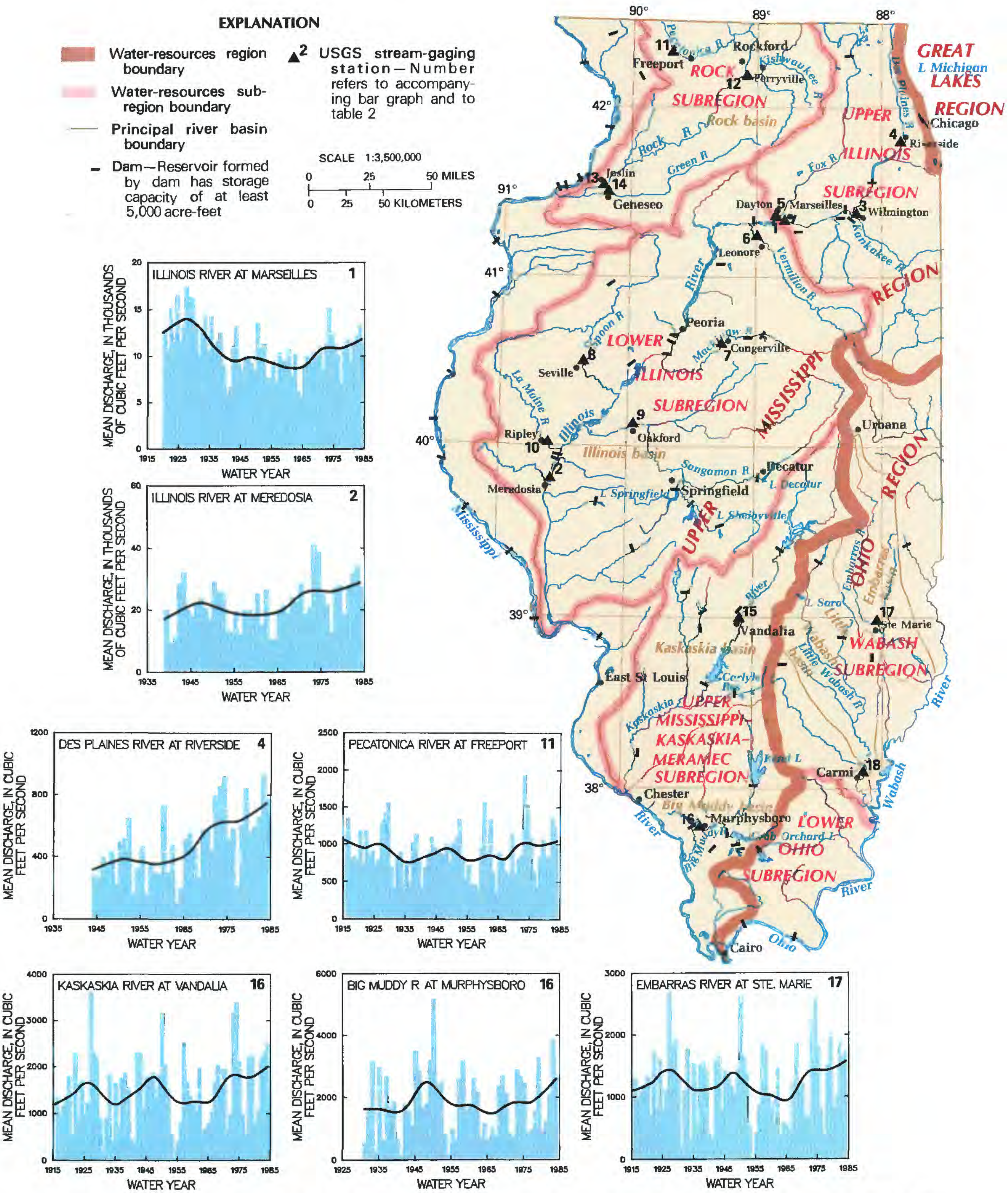

Figure 2. Principal river basins and related surface-water resources development in Illinois and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Flooding in the basin is usually the result of ice jams that occur during spring breakup. The historic peak discharge for the Rock River near Joslin is 46,200 ft³/s or 29,900 Mgal/d in March 1948 (fig. 2, table 2, site 13).

Water-quality problems in the basin generally are intermediate in severity (Illinois Environmental Protection Agency, 1984, p. 12).

Upper Mississippi-Kaskaskia-Meramec Subregion

Kaskaskia River Basin.—The Kaskaskia River originates just west of Urbana and empties into the Mississippi River upstream of Chester. The basin has an area of 5,801 mi² (Healy, 1979a, p. 166). Land use is primarily agricultural, but coal mining and oil and gas development are active in the basin. Offstream water use includes thermoelectric-power generation (320 Mgal/d or 495 ft³/s), public water supplies (14 Mgal/d or 22 ft³/s), self-supplied industries (7.4 Mgal/d or 11.4 ft³/s), and mineral extraction (1.8 Mgal/d or 2.8 ft³/s) (modified from Kirk and others, 1982).

Ten reservoirs have been constructed in the basin, including two of the largest in the State, Carlyle Lake (completed in 1967 with 283,000 acre-ft or 92,200 Mgal of storage) and Lake Shelbyville (completed in 1970 with 210,000 acre-ft or 68,400 Mgal of storage) (Illinois Environmental Protection Agency, 1978, p. 143, 150). The reservoirs were constructed for flood-control, water supply, recreation, and low-flow augmentation to enhance commercial navigation and water quality. As a result of regulation, low flows and average discharges of the Kaskaskia River have increased and flood magnitudes have decreased (fig. 2, table 2, site 15).

During periods of increased runoff, some flooding occurs in the lowlands. The historic peak discharge for the Kaskaskia River at Vandalia (fig. 2, table 2, site 15) is 62,700 ft³/s or 40,500 Mgal/d in June 1957.

Water-quality problems are generally minimal to intermediate in severity in the basin, but problems are moderate to severe in some areas (Illinois Environmental Protection Agency, 1984, p. 12).

Big Muddy River Basin.—The Big Muddy River has a total drainage area of 2,387 mi² (Healy, 1979a, p. 139). The basin is predominantly agricultural, but contains active coal mines.

The basin contains six reservoirs. The largest of these is Rend Lake (completed in 1970 with 185,000 acre-ft or 60,300 Mgal of storage) and the second largest is Crab Orchard Lake (completed in 1940 with 63,511 acre-ft or 20,700 Mgal of storage) (Illinois Environmental Protection Agency, 1978, p. 145, 150). Both are used as a water supply and for recreation and Rend Lake provides flood control in the Big Muddy River basin. Discharge characteristics of the river have changed since construction of the reservoirs. The magnitude of low flows and average discharges of the Big Muddy River (fig. 2, table 2, site 16) have increased. Flood magnitudes increased, but only because of above average precipitation during 1971–83.

Offstream water uses include public water supply (22 Mgal/d or 34 ft³/s), mineral extraction (7.7 Mgal/d or 11.9 ft³/s), and self-supplied industries (1.4 Mgal/d or 2.2 ft³/s) (modified from Kirk and others, 1982).

Flooding occurs in the lowland areas of the basin during periods of increased runoff. The historic peak discharge for the Big Muddy River at Murphysboro (fig. 2, table 2, site 16) is 33,300 ft³/s or 21,500 Mgal/d in May 1961.

Water-quality problems in the basin generally are minimal in severity, but some local areas have moderate to severe problems (Illinois Environmental Protection Agency, 1984, p. 12).

Mississippi River Main Stem.—That part of Illinois adjacent to the Mississippi River is not included in table 2, but it contains some of the larger industrial communities in the State. The major water users in these areas and their water withdrawals are thermoelectric (2,000 Mgal/d or 3,090 ft³/s), public water supplies (100 Mgal/d or 155 ft³/s), and self-supplied industries (35 Mgal/d or 54 ft³/s). Instream water use, which totals 22,000 Mgal/d or 34,000 ft³/s, represents half of the flow at hydroelectric plants along the Mississippi River between Illinois and Iowa (modified from Kirk and others, 1982).

Flooding along the Mississippi River is a serious problem and a major cause of floods along its tributaries. Water-quality problems are minimal to nonexistent in the river reach from the northern border of Illinois downstream to near Alton (Illinois Environmental Protection Agency, 1984, p. 12). From there to the mouth of the Ohio River, water-quality problems are moderate to intermediate.

OHIO REGION

Wabash and Lower Ohio Subregions

The Wabash River forms the boundary between Illinois and Indiana, and the Ohio River forms the boundary between Illinois and Kentucky. Offstream use of water from these two rivers is mainly for thermoelectric-power generation. In 1980, 20 Mgal/d or 30.9 ft^3/s were withdrawn from the Wabash River and 520 Mgal/d or 805 ft^3/s from the Ohio River (Kirk and others, 1982, p. 25). The severity of water-quality problems is intermediate to moderate in the Wabash River and minimal in the Ohio River (Illinois Environmental Protection Agency, 1984, p. 12). The major rivers that flow from Illinois into the subregions include the Embarras and the Little Wabash Rivers.

Embarras River Basin.—The Embarras River originates in east-central Illinois near Urbana and discharges into the Wabash River. Its drainage area is 2,440 mi^2 (Healy, 1979a, p. 71). One small reservoir (1,076 acre-ft or 350 Mgal of storage) is used as a public-supply source (Illinois Environmental Protection Agency, 1978, p. 143, 153). Land use in the basin is primarily agricultural. Water use in the area amounts to 1.6 Mgal/d or 2.5 ft^3/s for public supplies (modified from Kirk and others, 1982).

Some flooding occurs in the lowland areas during periods of heavy runoff. The historic peak discharge for the Embarras River at Ste. Marie (fig. 2, table 2, site 17) is 44,800 ft^3/s or 29,000 Mgal/d in January 1950. Water-quality problems are moderate in severity and increase to intermediate downstream from Ste. Marie (Illinois Environmental Protection Agency, 1984, p. 12).

Little Wabash River Basin.—The Little Wabash River drains an area of 3,203 mi^2 (Healy, 1979a, p. 31). Most of the basin is agricultural, but it also contains the largest concentration of oil- and gas-producing areas in the State.

Eleven water-supply reservoirs have been built in the basin. The largest of these is Lake Sara (completed in 1958 with 11,720 acre-ft or 3,820 Mgal of storage) (Illinois Environmental Protection Agency, 1978, p. 144). Public water-supply use totals 6.5 Mgal/d or 10.1 ft^3/s. The largest offstream use is for thermoelectric-power generation (300 Mgal/d or 464 ft^3/s) (modified from Kirk and others, 1982).

Flooding occurs in the lowland areas during periods of heavy runoff. The historic peak discharge for the Little Wabash River at Carmi (fig. 2, table 2, site 18) is 46,900 ft^3/s or 30,300 Mgal/d in May 1961. Water-quality problems are minimal in severity in the basin (Illinois Environmental Protection Agency, 1984, p. 12).

OTHER RIVER BASINS

GREAT LAKES REGION

Southwestern Lake Michigan Subregion

Offstream utilization of water from Lake Michigan amounted to 3,800 Mgal/d or 5,880 ft^3/s in 1980 (Kirk and others, 1982, p. 16). Over 70 percent (2,700 Mgal/d or 4,180 ft^3/s) of that was for thermoelectric-power generation. The water quality of the lake has been degraded by municipal discharges (Illinois Environmental Protection Agency, 1984, p. 2). However, concentrations of phosphate, ammonia nitrogen, coliforms, phenols, and phytoplankton have decreased since 1972 to the point where the total shoreline of Illinois partly or fully supported designated uses.

SURFACE-WATER MANAGEMENT

Several State and Federal agencies have responsibilities regarding various aspects of surface-water resources in Illinois, but none has the overall responsibility for managing the resource. The

U.S. Geological Survey works cooperatively with these agencies to maintain a statewide surface-water data network and to investigate the State's surface-water resources. In 1980, the Governor appointed State agency representatives to a Task Force to "develop a total water management system that is socially acceptable. . .with tentative goals to achieve more efficient resource utilization. . ." (Illinois State Water Plan Task Force, 1982, p. ii).

The allocation of surface-water resources in Illinois is governed by two sets of doctrines: The Judicial Doctrine (common law) and the Legislative Doctrine (statutory law) (Illinois State Water Plan Task Force, 1982, p. 183). At times, these doctrines conflict with one another and are affected by decisions of Federal and local governments, special-purpose (water, soil, levee) districts, interstate compacts, and local court decisions. The Judicial Doctrine is based on the common-law concept of riparian rights which grants water rights to owners of lands adjacent to water bodies. The Legislative Doctrine states that the State has full and complete jurisdiction over the public waters of the State and, therefore, has the authority to adjudicate water-rights issues regarding public waters. The greatest conflict and discrepancy between the two doctrines is in defining clearly the meaning of the term "public waters" in Illinois.

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FOR ADDITIONAL INFORMATION

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INDIANA
Surface-Water Resources

Surface water is abundant in Indiana and has been a significant factor in the State's development and growth. During the 175 years since statehood, the primary role of surface water has changed from a means of transportation to the major source of water supply. In 1980, self-supplied industries were the dominant users of freshwater in the State. Surface-water withdrawals in this use category were 12,000 Mgal/d (million gallons per day) or 18,600 ft³/s (cubic feet per second) and accounted for 86 percent of the total surface-water and ground-water withdrawals (14,000 Mgal/d or 21,700 ft³/s) in the State (table 1). More than 2.1 million people in Indiana (38 percent of the State's population) are served by surface water. Public-supply use accounted for 3 percent of total surface-water withdrawals in 1980. The quality of surface water throughout Indiana is suitable for most uses, except for areas just downstream from municipal and industrial discharge points. Surface-water withdrawals in Indiana in 1980 for various purposes and related statistics are given in table 1.

Table 1. Surface-water facts for Indiana

[Data 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 SURFACE WATER, 1980	
Number (thousands)	2,100
Percentage of total population	38
From public water-supply systems:	
Number (thousands)	2,000
Percentage of total population	36
From rural self-supplied systems:	
Number (thousands)	100
Percentage of total population	2
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	14,000
Surface water only (Mgal/d)	13,000
Percentage of total	93
Percentage of total excluding withdrawals for thermoelectric power	77
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	400
Percentage of total surface water	3
Percentage of total public supply	53
Per capita (gal/d)	200
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	6.3
Percentage of total surface water	0.1
Percentage of total rural domestic	6
Per capita (gal/d)	63
Livestock:	
Surface water (Mgal/d)	19
Percentage of total surface water	0.2
Percentage of total livestock	45
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	12,000
Percentage of total surface water	96
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	95
Excluding withdrawals for thermoelectric power	81
Irrigation withdrawals:	
Surface water (Mgal/d)	21
Percentage of total surface water	0.2
Percentage of total irrigation	9
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	9,500

GENERAL SETTING

The maximum extent of glaciation was used by Fenneman (1946) as the basis for determining the boundary between the two physiographic provinces in Indiana. The glaciated part is in the Central Lowland province and the unglaciated part is in the Interior Low Plateaus province (fig. 1). Schneider (1966) divided Indiana into three broad physiographic areas that closely reflect the surface-water characterictics of the State. The northern zone (north of 41 degrees latitude) is called the Northern Moraine and Lake Region. This region is characterized by landforms of glacial origin and includes end moraines, outwash plains and kettleholes, and closely related postglacial features such as lakes and sand dunes. The central one-third of the State is a depositional plain of low relief that has been modified only slightly by postglacial stream erosion. The third physiographic region is located south of the Wisconsin glacial boundary. It consists of a series of north- and south-trending uplands and lowlands. Landforms in this area are largely the result of normal degradational processes, such as weathering and stream erosion.

Precipitation patterns vary gradually both geographically and seasonally in Indiana (fig. 1). Precipitation is available in each month of the year but is highest from March through July. Average annual precipitation across Indiana ranges from about 36 inches in the northeast to about 44 inches in the south-central part of the State (National Oceanic and Atmospheric Administration, 1951–80). Losses from evaporation and transpiration are relatively uniform across the State. Potential evaporation for Indiana averages 28 in./yr (inches per year) (Geraghty and others, 1973, map 13).

Precipitation, evapotranspiration, and physiography affect stream runoff. The highest average monthly flows are in March or April (fig. 1) and are the result of high precipitation, low evapotranspiration, and, in some cases, snowmelt. Annual runoff is approximately one-third of precipitation (fig. 1). The effect of physiography on stream runoff is discussed for each of the three regions (as identified by Schneider, 1966) in the State. In southern Indiana, a thin soil layer over bedrock results in a highly variable average monthly discharge. Data from the Muscatatuck River near Deputy (fig. 1) show that the highest average monthly discharge in March is 15 times higher than the lowest average monthly discharge in October. The central third of the State has a thicker soil layer, which provides better sustained flow throughout the year. Data from the Wabash River at Mt. Carmel, Ill. (fig. 1), whose drainage basin is mostly in this region, show this runoff pattern. The highest average monthly discharge in March is less than six times the lowest average monthly discharge in October. In northern Indiana, the soils are thick and mostly sandy. Runoff is well sustained throughout the year as shown by the data from the Kankakee River at Shelby (fig. 1). The highest average monthly discharge in April is less than three times the lowest average monthly discharge in September.

PRINCIPAL RIVER BASINS

Indiana has an area of 36,291 mi² (square miles) in the Ohio, the Upper Mississippi, and the Great Lakes Regions (Seaber and others, 1984). These three regions are divided into nine subregions in Indiana, five of which drain 86 percent of the State. These five are the Great Miami and the Wabash Subregions of the Ohio Region, the Upper Illinois Subregion of the Upper Mississippi Region, and the Southeastern Lake Michigan and the Western Lake Erie Subregions of the Great Lakes Region. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

OHIO REGION

Great Miami Subregion

Whitewater River Basin.—The Whitewater River basin is in the east-central part of Indiana (fig. 2), and drains about 4 percent or 1,296 mi^2 of the State. This part of the State is gently rolling and agriculture is the predominant land use. Brookville Lake was formed in 1974 and has a capacity of 359,600 acre-ft (acre-feet) or 117,000 Mgal (million gallons), and regulates flow on the East Fork Whitewater River. Streamflow of the Whitewater River is not affected by urbanization.

Wabash Subregion

The Wabash is the largest river basin in the State (24,206 mi^2). Because of the importance of surface-water resources in the basin, the main stem Wabash River and two of its tributaries—the White and the Patoka Rivers—are discussed separately.

Wabash River Main Stem.—The shape of the Wabash River has the appearance of an inverted "J," the straight part of which forms the State border with Illinois. Major cities along the river are Lafayette and Terre Haute. Agriculture is the primary land use throughout the basin. Some coal mining is done south of Terre Haute. Much of the development along the main stem has been upstream of Lafayette and has been the result of dam construction. Three dams were constructed on the Salamonie, the Mississinewa, and the Wabash Rivers between 1967 and 1969 for flood control on the Wabash River. The three reservoirs formed by these dams are Salamonie Lake (completed in 1967 with 263,000 acre-ft or 85,700 Mgal of storage), Mississinewa Lake (completed in 1968 with 368,400 acre-ft or 120,000 Mgal of storage), and Huntington Lake (completed in 1969 with 153,100 acre-ft or 49,900 Mgal of storage). These lakes regulate the streamflow from 77 percent of the drainage basin upstream from Peru (fig. 2, site 6). Regulation has been effective at sustaining low flow and reducing the discharge of the 100-year flood at Peru by more than 50 percent (table 2, site 6). The effect of regulation is reduced at downstream locations as a greater percentage of the basin is not regulated. At Mount Carmel, Ill. (table 2, site 7), the 100-year flood has been reduced only 10 percent by upstream regulation. Reguluation does not have a large effect on the variability in annual flows for these two sites (fig. 2).

White River Basin.—The White River drains about 31 percent (11,349 mi^2) of Indiana in the central and southern parts of the State (fig. 2). The White River flows generally to the south-southwest as does its major tributary—the East Fork White River. Much of the development in the basin has been in its upper half, although many streams are relatively unaffected by this development (table 2, site 5). Major urban areas along the White River are Muncie, Anderson, and Indianapolis, which have a combined population of more than 1 million people. Industrial use, powerplant cooling, and public-water supply are the major uses of surface water from the White River. In 1983, Indianapolis installed an advanced wastewater-treatment facility that discharges to the White River. This plant has improved the water quality in the White River downstream of Indianapolis by decreasing the ammonia and carbonaceous biochemical oxygen demand concentrations, increasing the dissolved-oxygen concentration, and reducing or eliminating nitrification in the river. Streamflow on the White River and the lower part of the East Fork White River is affected by regulation. The basin contains 18 reservoirs with a capacity of 5,000 acre-ft or 1,630 Mgal or more that are used for flood control, water supply, and recreation. The largest of these are Monroe Lake (completed in 1966 with 446,000 acre-ft or 145,000 Mgal of storage) and Cagles Mill Lake (completed in 1953 with 228,000 acre-ft or 74,300 Mgal of storage).

Patoka River Basin.—The Patoka River drains about 862 mi^2 of southwestern Indiana and flows west to the Wabash River. The topography is primarily rolling plains. Several manmade factors have affected the quality and quantity of water in the basin. Since 1978, streamflow in the Patoka River has been regulated by Patoka Lake (completed in 1978 with 298,400 acre-ft or 97,200 Mgal of storage). The main stem and several of its tributaries also have been channelized. However, the greatest impact in the basin has been from surface coal mining (table 2, site 3). Crawford (1981) showed that the water in the Patoka River and its tributaries was generally acidic, and in several areas pH values were less than 6.0. Corbett (1965) stated that the areas with mine overburden are able to sustain streamflow during droughts when unmined watersheds have no flow. Similarly, water infiltrates quickly into the overburden areas and, therefore, peak flows are reduced.

UPPER MISSISSIPPI REGION

Upper Illinois Subregion

Kankakee River Basin.—The Kankakee River basin in northwestern Indiana (fig. 2) consists of the drainage basins of the Kankakee River and its major tributary, the Iroquois River. These rivers flow westerly into Illinois where the Iroquois River joins the Kankakee River. The Kankakee River basin encompasses 2,580 mi^2 (7 percent) of Indiana.

Since the 1850's, the character of the Kankakee River has been changed from a meandering stream in a marshy area to a largely channelized stream in an agricultural area. After more than a century, much of the main stem and many of the tributaries have been channelized. However, the river still receives a substantial amount of its streamflow from ground water. Levees have been built along the main stem and tributaries to reduce flooding. Discharge per square mile of drainage area for the 100-year flood at the Kankakee River at Shelby (table 2, site 8) is relatively low (4 cubic feet per second per square mile), but the peaks, which are sustained for a long time, cause breaks in the levees and flood large areas of farmland.

Even though the Iroquois River has been channelized, it does not receive a substantial part of its streamflow from ground water. The difference between high and low flows is greater in the Iroquois River (site 9) than in the Kankakee River (site 8). Streamflow characteristics of the Iroquois River are similar to those of streams in the Wabash River basin.

GREAT LAKES REGION

Southeastern Lake Michigan Subregion

St. Joseph River Basin.—The St. Joseph River has its source and its mouth in Michigan and only 42 miles of its more than 200 miles of stream length is in Indiana. However, approximately 1,780 mi^2 (4.9 percent of Indiana) of its 4,680-mi^2 drainage basin is in the northern part of the State (fig. 2). The dominant feature in the basin is the large number of lakes, most of which were formed as a result of glaciation. There are 150 lakes in the basin that have a surface area of 50 acres or more or with a storage capacity of 100 acre-ft or 32.6 Mgal or more (Clark, 1980). Recreation is the primary use of these lakes.

The lakes act as natural reservoirs that tend to moderate extremes of streamflow (table 2, site 11). Because the streamflows are well-sustained, numerous low-head power-generation plants have been constructed on the St. Joseph River and several of its tributaries (table 2, site 10).

Other River Basins.—The Grand Calumet and the Little Calumet River basins, in northwestern Indiana, are small and drain about 1 percent of the State. Because of the extremely large supply of freshwater from Lake Michigan, this area has developed into one of the most industrialized regions of the country. This development has affected both the quality and quantity of water in these basins. The effects on the water quality, of this dense concentration of people and industry and the resultant pollution from point and nonpoint sources, are being studied. The complex nature of

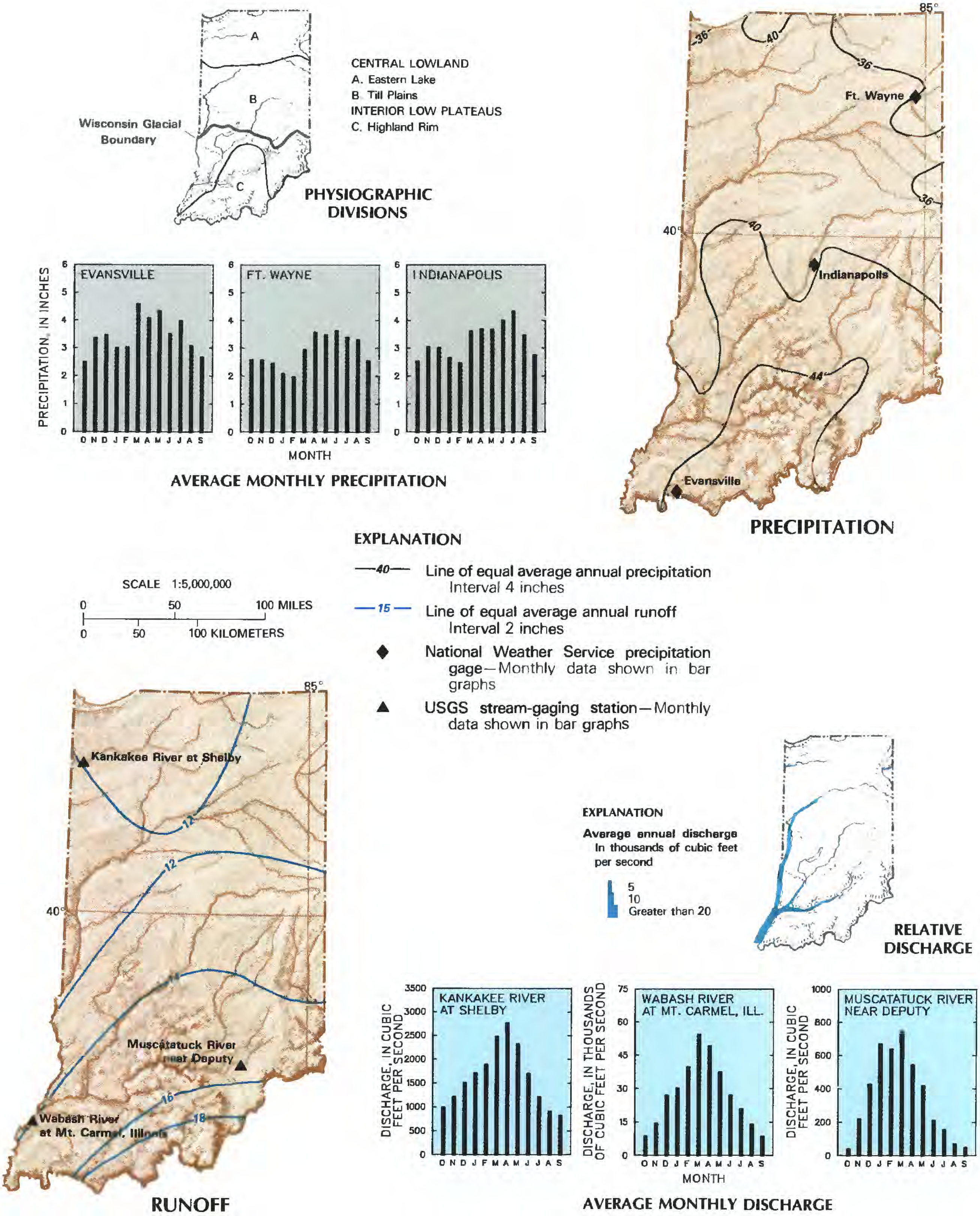

Figure 1. Average annual precipitation and runoff in Indiana and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

streamflow system, including flow reversals and streams which cross basin divides, makes this area difficult to quantify streamflow by traditional methods.

Western Lake Erie Subregion

Maumee River Basin.—The Maumee River basin is located in the northeastern part of Indiana (fig. 2) and drains slightly more than 3 percent of the State. The Maumee River is formed by the confluence of the St. Joseph and the St. Marys Rivers at Fort Wayne and flows northeasterly into Ohio. The St. Joseph River, which flows to the southwest, originates in Michigan and passes through Ohio before entering Indiana. Of the 1,086-mi² drainage area, 605 mi² is in Indiana. Streamflow is regulated by two reservoirs that have a combined storage capacity of 7,900 acre-ft or 2,580 Mgal. The St. Marys River, which flows north-northwesterly, orginates in Ohio. Of the 839-mi² drainage area, 381 mi² is in Indiana. Its flow is partially regulated in Ohio. Both basins drain primarily rural areas with predominantly agricultural land use. Fort Wayne is the largest Indiana city in the basin.

Flooding along the St. Joseph, the St. Marys, and the Maumee Rivers has caused considerable damage in and around Fort Wayne. Damage from the floods of March 1978 in the basin was estimated to be $44 million. About 15 percent of Fort Wayne was estimated to have been under water when the Maumee River rose to 9 feet above flood stage. The recurrence interval for the peak

Table 2. Selected streamflow characteristics of principal river basins in Indiana

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and Indiana agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				OHIO REGION GREAT MIAMI SUBREGION Whitewater River basin				
1.	Whitewater River near Alpine (03275000).	522	1928-83	48	551	49,000	None	
				WABASH SUBREGION Wabash River main stem-White River basin-Patoka River basin				
2.	Muscatatuck River near Deputy (03366500).	293	1947-83	0.0	348	41,200	None	Drainage basin is in unglaciated part of State.
3.	South Fork Patoka River near Spurgeon (03376350).	42 8	1964-83	2.2	51.9	5,990	Moderate	Regulation by coal-washing operation and strip mining.
4.	Eagle Creek at Indianapolis (03353500).	174	1938-68 1969-83	0.5 6.0	148 168	18,400 11,800	None Appreciable	Flow regulated since November 1969 by reservoir 4.7 miles upstream.
5.	Driftwood River near Edinburgh (03363000).	1,060	1940-83	91	1,144	49,500	None	
6.	Wabash River at Peru (03327500).	2,686	1943-67 1970-83	92 155	2,290 2,500	74,300 31,000	. . . do . . Appreciable	Flow reguleted by Huntington Lake, Salemonie Lake, and Mississinewa Lake.
7.	Wabash River at Mount Carmel, Ill. (03377500).	28,635	1927-83	2,280	27,440	315,000	Negligible	100-year peak prior to 1967 was 350,000 ft³/s. Regulation has not affected other flow characteristics.
				UPPER MISSISSIPPI REGION UPPER ILLINOIS SUBREGION Kankakee River basin				
8.	Kankakee River at Shelby (05518000).	1,779	1922-83	417	1,619	6,950	None	Marshland before 1900. Most channels heve been straightened.
9.	Iroquois River near Foresman (05524500).	449	1948-83	11	383	5,660	. . . do . . .	
				GREAT LAKES REGION SOUTHESTERN LAKE MICHIGAN SUBREGION St. Joseph River basin				
10.	St. Joseph River at Elkhart (04101000).	3,370	1947-83	818	3,177	21,500	Moderate	Regulated by hydroelectric plant at Elkhart.
11.	Pigeon Creek near Angola (04099510).	106	1947-83	5.8	78.5	843	None	Downstream of several lakes.
				WESTERN LAKE ERIE SUBREGION Maumee River basin				
12.	Maumee River at New Haven (04183000).	1,967	1956-83	72	1,645	25,600	Negligible	Regulated by hydro-powerplent on St. Joseph River 10.3 miles upstream.

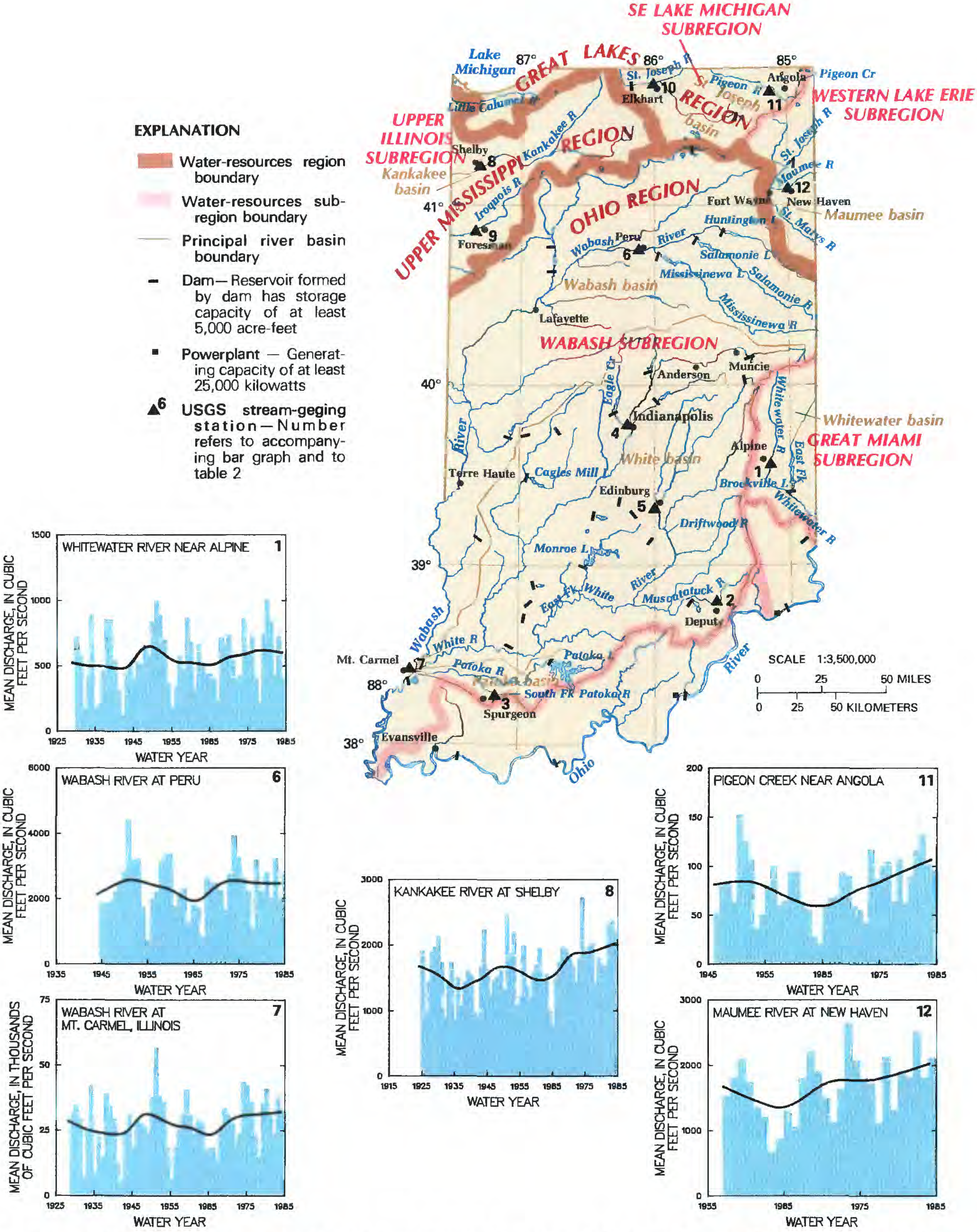

Figure 2. Principal river basins and related surface-water resources development in Indiana and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

(22,400 ft³/s or 14,500 Mgal/d) on the Maumee River at New Haven (site 12) was 75 years (Hoggatt, 1981).

In 1982, flooding in the basin caused more than $50 million in damage. This was the worst flooding since the historic flood of March 1913. Peak discharge recurrence intervals on the St. Joseph River ranged from 50 years to more than 100 years and on the St. Marys River, from 20 to 25 years. The recurrence interval for the peak (26,600 ft³/s or 17,200 Mgal/d) on the Maumee River at New Haven was 80 years (Glatfelter and others, 1984).

SURFACE-WATER MANAGEMENT

In 1983, the Indiana General Assembly enacted the Water Resource Management Act (Indiana Code 13-2-6.1), which is administered by the Natural Resources Commission. This commission established the Water Management Branch within the Indiana Department of Natural Resources to implement the objectives of this act. The three objectives are to (1) assess the availability of the State's water resource; (2) inventory significant users of surface and ground water; and (3) plan for the development, conservation, and use of the water resource for beneficial purposes. The Natural Resources Commission may establish the minimum flows of streams. This act considers Indiana's water resource to mean all water on or beneath the surface of the ground or in the atmosphere.

The Division of Water within the Indiana Department of Natural Resources has the responsibility to review all construction that takes place within the 100-year floodway at locations with more than a 1-mi² drainage area. The Division also is responsible for the protection of the natural lakes in Indiana and for ensuring that established legal lake levels are maintained.

The Indiana State Board of Health determines the waste-load allocations for industrial and sanitary facilities. These values are based on criteria established by the U.S. Environmental Protection Agency. The Board of Health also monitors instream water quality to ensure that the regulations are being met.

In November 1985, a decision by the U.S. Supreme Court settled a long-standing border dispute between Indiana and Kentucky along the Ohio River, which had shifted since Kentucky was granted statehood in 1792. The ruling, which gives to Indiana at least a 100-foot width of the Ohio River along the length of the river between the two States, is expected to stir waterfront development in Indiana.

In February 1985, Indiana, and the other seven States and two Canadian provinces that border the Great Lakes, signed the Great Lakes Charter. The Charter marks a move by each State and province toward self-discipline in agreeing to conserve and use the lakes' water more efficiently. This pact provides for increased cooperation and tighter controls over new and expanded uses of the lake reserves through a system of registration, permits, and joint consultation. In Indiana, 3,540 mi² of the State (10 percent) drains into the Great Lakes.

Of the various Federal agencies in the State, the U.S. Army Corps of Engineers (USCOE) is the most involved in water management. The responsibilities of the USCOE include flood control, shore and bank erosion, and ecological- and economic-based studies. Four USCOE Districts have responsibilties in Indiana: The Chicago District and the Detroit District in the Great Lakes Region, the Louisville District in the Ohio Region, and the Rock Island District in the Upper Mississippi Region.

The U.S. Geological Survey conducts investigations of the State's surface-water resource in cooperation with the Indiana Department of Natural Resources, the Indiana State Board of Health, the Indiana Department of Highways, the city of Indianapolis, the U.S. Army Corps of Engineers, and other local, State, and Federal agencies. These activities include data collection, data analyses, and interpretive studies that together form an information base for surface-water resource planning and management.

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IOWA
Surface-Water Resources

In addition to its border streams—the Mississippi River in the east and the Missouri and the Big Sioux Rivers in the west—Iowa is richly endowed with interior streams that normally have sustained flows. However, during periods of less-than-average precipitation, surface-water supplies become critically deficient, particularly in the western and south-central counties. Reservoir storage is an alternative by which more water can be made available for use. Four multipurpose reservoirs are in operation in the State. Their main functions are flood control, low-flow augmentation, water conservation, and recreation. As population and water use increase, additional surface-water storage for water supplies may be needed (Iowa Natural Resources Council, 1978).

In Iowa, surface water is withdrawn for public, industrial, and rural domestic supply; irrigation; livestock; and thermoelectric-power generation (table 1). Thermoelectric-power generation is by far the largest offstream use of surface water (Buchmiller and Karsten, 1983). Most of the major power-generating stations are located on the Missouri and the Mississippi Rivers. Nearly one out of five people in Iowa obtain their drinking water from surface-water reservoirs.

Instream use of water includes recreation, navigation, hydroelectric-power generation, wildlife conservation, and wastewater assimilation. Estimated water use for hydroelectric-power generation in Iowa in 1980 was nearly 9 times greater than the total amount withdrawn for all other ground-water and surface-water uses and more than 12 times greater than the amount withdrawn for all other surface-water uses. Demand for surface water in Iowa is relatively steady, although irrigation demands can vary significantly from year to year.

Except for short reaches of some streams, few of the streams and virtually none of the lakes of the State are being adversely impacted by point sources of pollution. Conversely, nonpoint sources of pollution are affecting most of Iowa's streams and lakes. Nonpoint sources are believed to have contributed significantly to the elevated nitrate concentrations detected at three stream sites and to the increasing concentrations of nitrates throughout central and eastern Iowa (Iowa Department of Water, Air, and Waste Management, 1984).

Table 1. Surface-water facts for Iowa

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Sources: Solley, Chase, and Mann, 1983; Buchmiller and Karsten, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	540
Percentage of total population	18
From public water-supply systems:	
Number (thousands)	530
Percentage of total population	18
From rural self-supplied systems:	
Number (thousands)	8
Percentage of total population	0.3
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	3,200
Surface water only (Mgal/d)	2,300
Percentage of total	72
Percentage of total excluding withdrawals for thermoelectric power	19
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	59
Percentage of total surface water	3
Percentage of total public supply	19
Per capita (gal/d)	110
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.4
Percentage of total surface water	<0.1
Per capita (gal/d)	50
Livestock:	
Surface water (Mgal/d)	1.3
Percentage of total surface water	0.1
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	2,200
Percentage of total surface water	97
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	87
Excluding withdrawals for thermoelectric power	29
Irrigation withdrawals:	
Surface water (Mgal/d)	16
Percentage of total surface water	0.7
Percentage of total irrigation	17
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	28,000

GENERAL SETTING

Iowa has an area of 56,239 mi^2 (square miles). The Mississippi River forms the eastern border with Illinois and Wisconsin; the Big Sioux and the Missouri Rivers form the western border with South Dakota and Nebraska, respectively. The rolling, largely agricultural landscape of Iowa is characterized by low elevations, moderate relief, gently inclined bedrock strata, numerous rivers, fertile soils, and a history of glaciation (Prior, 1976).

The major physiographic regions of Iowa, as defined by Prior (1976), are shown in figure 1. The Paleozoic Plateau in the northeast is a rugged region of deep valleys, high bluffs, caves, crevices, and sinkholes, while the Des Moines lobe is flat and poorly drained. The Western Loess Hills are a complex system of sharp ridges and ravines eroded from wind-deposited material along the Missouri River valley. Both the Missouri and Mississippi Alluvial Plains are broad valleys of level flood plains and terraces. The rest of the Iowa landscape consists of the gently rolling terrain of the Iowan Surface and Northwest Iowa Plains, and the stream-dissected rolling lands of the Southern Iowa Drift Plain.

The average annual precipitation in Iowa ranges from 25 inches in the northwest to 36 inches in the southeast (fig. 1); the statewide average annual is 32 inches. Data indicate that 92 percent of the precipitation occurs as rain, and the remainder as snow. Approximately 26 inches of the statewide average annual precipitation is lost to evapotranspiration, which varies from 24 to 29 inches from northwest to southeast (Iowa Natural Resources Council, 1978). The rate of loss varies seasonally with the greatest loss during the summer growing season. Fluctuations in streamflow in Iowa are a function of precipitation and snowmelt, as well as seasonal variations in land use, vegetation, and temperature. Although precipitation is the main source of streamflow, the precipitation-streamflow relationship varies seasonally because of changes in evapotranspiration. Compare, for example, the average monthly precipitation at Sioux City (fig. 1) to the the average monthly discharge of the Floyd River (fig. 1). Although precipitation is greater than average during the summer and early fall, more runoff occurs during March and April in response to lesser precipitation, primarily because the ground is often either frozen or saturated when snowmelt and spring rains occur, and evapotranspiration is high during the summer growing season. With minor differences, this rainfall-runoff pattern prevails throughout the State. Areal variations in average annual runoff parallel the areal variations in precipitation, ranging from about 2 inches in the extreme northwest to about 9 inches in the southeast (fig. 1).

The characteristic variability of streamflow in Iowa is a critical factor in the management, use, and development of water resources in the State. Streams in eastern Iowa are less variable than streams in western Iowa. The magnitude of stream variability can be illustrated by examining the data in table 2, which indicate a trend of increasing variability from east to west. Data for the Turkey River in eastern Iowa (site 3) show that the magnitude of the 100-year flood is about 35 times larger than the average discharge and about 400 times larger than the 7-day, 10-year low flow. Data for the Floyd River in western Iowa (site 22) show that the 100-year flood is about 170 times larger than the average discharge and about 13,000 times larger than the 7-day, 10-year low flow. The magnitude and pattern of annual streamflow variability is shown by the bar graphs for selected streams in figure 2. The 15-year moving average on the graphs indicate a statewide upward trend towards greater annual runoff that began in the late 1950's and continues to the present. Analysis of rainfall records for Iowa for the same period of time indicates a similar trend.

PRINCIPAL RIVER BASINS

Iowa is divided into the Upper Mississippi and the Missouri Regions (Seaber and others, 1984). These regions contain six principal river basins (fig. 2) as defined by the Iowa Natural Resources Council (1978): Northeast Iowa, Iowa-Cedar, Skunk, Des Moines, Western Iowa, and Southern Iowa (corresponding hydrologic units reported in Seaber and others (1984) are shown as footnotes in table 2. Note that the Southern Iowa River basin is portrayed as including parts of the Upper Mississippi and Missouri Regions.) The first four basins drain 69 percent or 38,860 mi² of Iowa, and are tributaries of the Mississippi River. The other two basins are tributaries to the Missouri River. These river basins, and the Mississippi and the Missouri main stems that border Iowa, are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

UPPER MISSISSIPPI REGION

Mississippi River Main Stem

The entire eastern border of Iowa is formed by the Mississippi River, which probably is Iowa's greatest asset for recreation, fish and wildlife, and transportation. The border reach includes 11 locks and dams extending from Lock and Dam 9 near Harper's Ferry to Lock and Dam 19 at Keokuk.

Northeast Iowa River Basin

This basin is one of the most scenic regions in Iowa; it is drained by small, picturesque rivers such as the Upper Iowa, the Turkey, the Maquoketa, the Wapsipinicon, and several smaller streams that drain directly to the Mississippi River. The total drainage area of these streams is 8,652 mi², 97 percent (8,400 mi²) of which is in Iowa; the remainder in Minnesota (Iowa Natural Resources Council, 1958b). These stream subbasins are predominantly agricultural except along the Mississippi River where a number of industrial centers have developed. Streams have low flows that are sustained by inflow of ground water from shallow aquifers. Valleys generally are narrow, which limit the areal extent of flooding. Routine water-quality monitoring in these basins indicates that surface water is of acceptable quality for most uses (Iowa Department of Water, Air, and Waste Management, 1984). Because of the topography, erosion control and water conservation are pressing issues (Iowa Natural Resources Council, 1958b).

Iowa-Cedar River Basin

The Iowa-Cedar River basin is the second largest in the State. The total drainage area of the basin is 12,637 mi² of which 92 percent (11,615 mi²) is in Iowa and the remainder in Minnesota (Iowa Natural Resources Council, 1955). The Iowa River begins at the junction of two tributaries in north-central Iowa and flows southeastward into the Mississippi River. About 30 miles upstream from its mouth, the Iowa River is joined by the Cedar River, which originates in the glacial-drift, lake region in southern Minnesota. Both the Iowa River and the Cedar River subbasins have elongated shapes, which are characteristic of most streams in eastern Iowa. Except for the English River, which drains 640 mi², most of the tributaries of the Iowa River are generally short and have relatively small drainage areas. The Shell Rock River, which is the largest tributary of the Cedar River, begins in Minnesota. The total drainage area of the Cedar River at the mouth is 7,819 mi², 13 percent (1,024 mi²) of which is in Minnesota. Eleven low-head dams have been constructed across the main stem of the Cedar River (Antosch and Joens, 1979). These were built primarily for power generation and recreation, but they are relatively small and do not affect the streamflow in the river. Coralville Lake, in operation since 1958, is a multipurpose impoundment located on the Iowa River, upstream from Iowa City; storage capacity is 475,000 acre-ft (acre-feet) or 155,000 Mgal (million gallons).

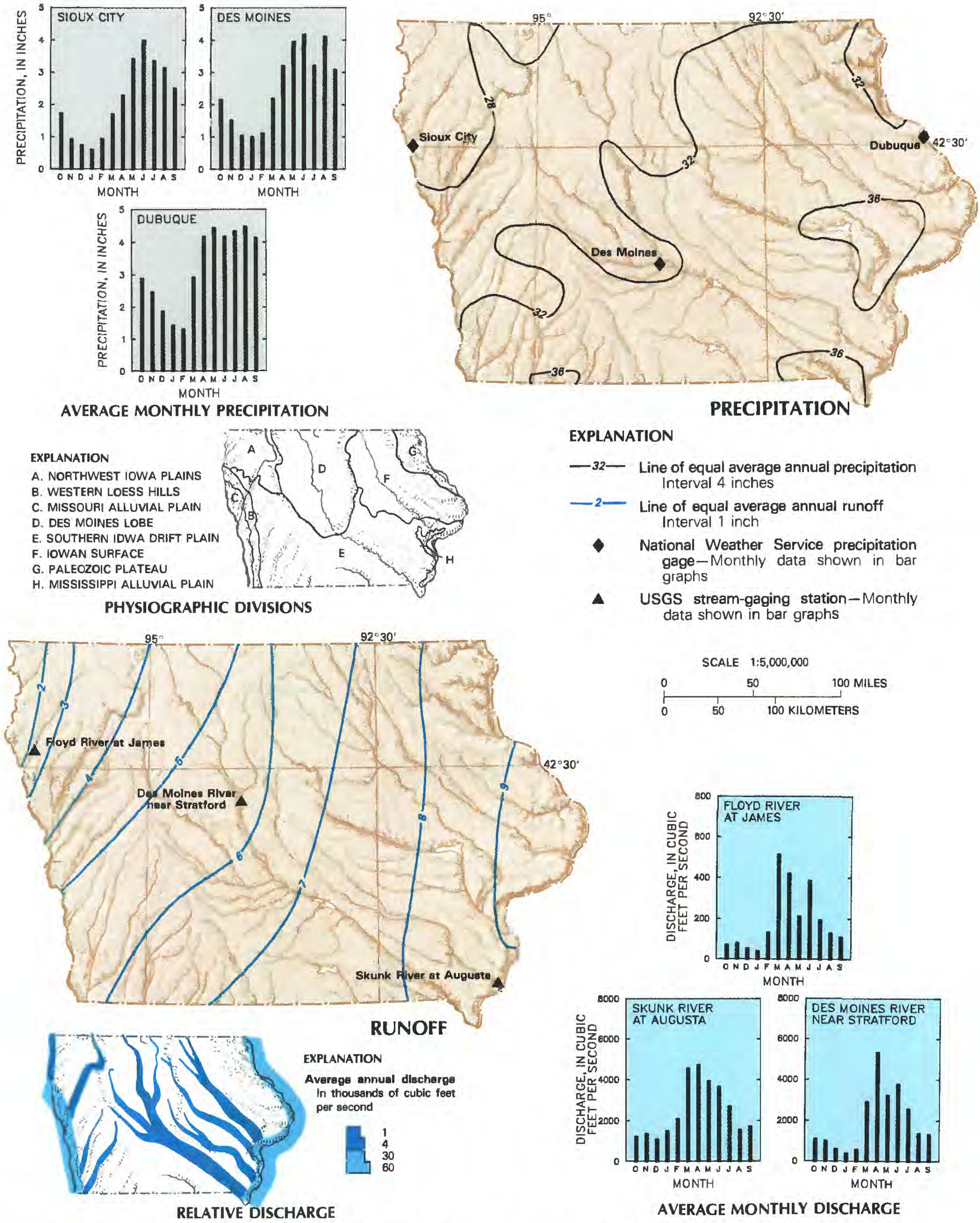
More than 93 percent of the land area in the Iowa-Cedar basin is suitable for cultivation (U.S. Department of Agriculture, 1976). However, there are some water- related problems that limit the full utilization of this land: erosion—3.8 million acres of crop, pasture, and forest lands are subject to surface-water erosion; flooding—46 cities in the basin have flood-prone areas and flooding is a problem on 774,000 acres of farmland; drainage—poor drainage affects 2.4 million acres of farmland.

Water quality has been monitored at 10 locations since 1980; these data indicate that biochemical oxygen demand (BOD) and ammonia concentrations have remained stable, but concentrations of nitrate have been increasing (Iowa Department of Water, Air, and Waste Management, 1984). Leaching of arsenic and organic chemicals from an industrial landfill adjacent to the Cedar River at Charles City has been an issue since the 1960's (Munter, 1981).

Skunk River Basin

The Skunk River originates in the central part of Iowa and flows in a southeasterly direction to its confluence with the Mississippi River 9 miles downstream from Burlington. The total drainage area of the basin is 4,377 mi² or 7.7 percent of the land area of the State. This basin is rural, and the primary use of surface water is for agriculture. Major floods that occurred in 1944, 1947, 1954, and 1975 (Heinitz and Wiitala, 1978) have caused extensive damage to crops and farm property. Erosion control and water conservation are pressing issues in the upland part of the basin (Iowa Natural Resources Council, 1957).

Water-quality information routinely collected at four sites on the main stem of the river indicate that the water is of suitable quality for most uses, except downstream from Ames where am-



EXPLANATION

A. NORTHWEST IOWA PLAINS
B. WESTERN LOESS HILLS
C. MISSOURI ALLUVIAL PLAIN
D. DES MOINES LOBE
E. SOUTHERN IOWA DRIFT PLAIN
F. IOWAN SURFACE
G. PALEOZOIC PLATEAU
H. MISSISSIPPI ALLUVIAL PLAIN

EXPLANATION

—32— Line of equal average annual precipitation Interval 4 inches

—2— Line of equal average annual runoff Interval 1 inch

◆ National Weather Service precipitation gage—Monthly data shown in bar graphs

▲ USGS stream-gaging station—Monthly data shown in bar graphs

SCALE 1:5,000,000

0 50 100 MILES

0 50 100 KILOMETERS

EXPLANATION

Average annual discharge
In thousands of cubic feet per second

1
4
30
60

Figure 1. Average annual precipitation and runoff in Iowa and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Prior, 1976.)

Table 2. Selected streamflow characteristics of principal river basins in Iowa

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				UPPER MISSISSIPPI REGION **Mississippi River Main Stem**				
1.	Mississippi River at Clinton (05420500).	85,600	1873–1983	10,050	47,390	[1]295,000	Negligible	Flow regulation is by navigation dams.
				Northeast Iowa River basin[2]				
2.	Upper Iowa River at Decorah (05387500).	511	1951–83	32	327	22,400	None	
3.	Turkey River at Garber (05412500).	1,545	1913–16, 1919–27, 1929–30, 1932–83	81	949	33,100	. . . do . . .	
4.	Maquoketa River near Maquoketa (05418500).	1,553	1913–83	160	1,027	47,700	Negligible	Diurnal fluctuations caused by powerplant 4 miles upstream.
5.	Wapsipinicon River near De Witt (05422000).	2,330	1934–83	98	1,537	31,600	None	
				Iowa—Cedar River basin[3]				
6.	Iowa River at Iowa City (05454500).	3,271	1903–58 1959–83	60 93	1,470 2,180	43,700 17,400	None Appreciable	Flow regulated by Coralville Lake, 9.1 miles upstream, since September 1958.
7.	English River at Kalona (05455500).	573	1939–83	2.3	370	25,300	None	
8.	Shell Rock River at Shell Rock (05462000).	1,746	1953–83	64	974	42,800	. . . do . . .	
9.	Cedar River at Waterloo (05464000).	5,146	1940–83	284	2,984	98,900	Negligible	Slight diurnal fluctuation during low water caused by upstream powerplant.
10.	Cedar River at Cedar Rapids (05464500).	6,510	1902–83	347	3,414	83,500	None	
11.	Iowa River at Wapello (05465500).	12,499	1914–58 1959–83	555 893	5,950 8,650	102,000 116,000	. . . do . . . Moderate	25 percent of basin regulated by Coralville Lake, 67.3 miles upstream, since September 1958.
				Skunk River basin[3]				
12.	South Skunk River near Oskaloosa (05471500).	1,635	1945–83	10	916	25,800	None	
13.	North Skunk River near Sigourney (05472500).	730	1945–83	2.3	436	27,400	. . . do . . .	
14.	Skunk River at Augusta (05474000).	4,303	1914–83	31	2,407	55,200	. . . do . . .	
				Des Moines River basin[4]				
15.	Des Moines River near Stratford (05481300).	5,452	1920–83	40	1,882	54,600	Negligible	Occasional regulation by dam at Fort Dodge.
16.	North Raccoon River near Jefferson (05482500).	1,619	1940–83	8.3	708	27,200	None	
17.	South Raccoon River at Redfield (05484000).	988	1940–83	26	449	32,200	. . . do . . .	

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[1] From Upper Mississippi River Basin Commission, 1978.

[2] Within the Upper Mississippi–Black–Root, Upper Mississippi–Maquoketa–Plum, and Upper Mississippi–Iowa–Skunk–Wapsipinicon Subregion (Seaber and others, 1984).

[3] Within the Upper Mississippi–Iowa–Skunk–Wapsipinicon Subregions (Seaber and others, 1984).

[4] Within the Minnesota and Des Moines Subregions (Seaber and others, 1984).

[5] Within the Missouri–Big Sioux, Missouri–Little Sioux, and Missouri–Nishnabotna Subregions (Seaber and others, 1984).

[6] Flow parameters based only on 1929–31 and 1939–56 water years.

[7] From U.S. Army Corps of Engineers, February 1978.

[8] Within the Missouri–Big Sioux, Missouri–Little Sioux, and Missouri–Nishnabotna Subregions (Seaber and others, 1984).

[9] Within the Missouri-Nishnabotna, Chariton-Grand, and Upper Mississippi-Salt Subregions (Seaber and others, 1984).

Table 2. Selected streamflow characteristics of principal river basins in Iowa—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi²=square miles; ft³/s=cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				Des Moines River basin[4]—Continued				
18.	Raccoon River at Van Meter (05484500).	3,441	1915–83	34	1,346	46,500	. . . do . . .	
19.	Des Moines River at Keosauqua (05490500).	14,038	1903–06, 1911–68, 1969–83	143 245	5,160 7,860	123,000 90,600	. . . do . . . Appreciable	Flow regulated by Lake Red Rock, 91.0 miles upstream, since March 1969.
				MISSOURI REGION MISSOURI RIVER MAIN STEM[5]				
20.	Missouri River at Sioux City (06486000).	314,600	[6]1897–1956, 1957–83	3,810 6,570	30,000 28,700	437,000 [7]144,500	Moderate Appreciable	Flow partly regulated by upstream reservoirs since November 1937; completely regulated since 1957.
				Western Iowa River basin[8]				
21.	Big Sioux River at Akron (06485500).	9,030	1928–83	19	901	71,000	None	
22.	Floyd River at James (06600500).	886	1934–83	2.7	197	34,300	. . . do . . .	
23.	Little Sioux River at Correctionville (06606600).	2,500	1918–25, 1928–32, 1936–83	14	766	32,600	. . . do . . .	
24.	Boyer River at Logan (06609500).	871	1918–25, 1937–83	6.5	315	31,800	. . . do . . .	
				Southern Iowa River basin[9]				
25.	Nishnabotna River above Hamburg (06810000).	2,806	1922–23, 1928–83	28	1,057	40,700	None	
26.	Nodaway River at Clarinda (06817000).	762	1918–25, 1936–83	5.8	338	37,900	. . . do . . .	Clarinda municipal water supply is withdrawn from river 500 feet upstream.
27.	Thompson River at Davis City (06898000).	701	1918–25, 1941–83	1.6	370	25,500	. . . do . . .	
28.	Chariton River near Rathbun (06903900).	549	1956–69, 1970–83	.25 4.0	303 382	40,327 2,130	. . . do . . . Appreciable	Flow regulated by Rathbun Lake since November 1969.

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[1] From Upper Mississippi River Basin Commission, 1978.
[2] Within the Upper Mississippi–Black–Root, Upper Mississippi–Maquoketa–Plum, and Upper Mississippi–Iowa–Skunk–Wapsipinicon Subregion (Seaber and others, 1984).
[3] Within the Upper Mississippi–Iowa–Skunk–Wapsipinicon Subregions (Seaber and others, 1984)
[4] Within the Minnesota and Des Moines Subregions (Seaber and others, 1984).
[5] Within the Missouri–Big Sioux, Missouri–Little Sioux, and Missouri–Nishnabotna Subregions (Seaber and others, 1984).
[6] Flow parameters based only on 1929–31 and 1939–58 water years.
[7] From U.S. Army Corps of Engineers, February 1978.
[8] Within the Missouri–Big Sioux, Missouri–Little Sioux, and Missouri–Nishnabotna Subregions (Seaber and others, 1984).
[9] Within the Missouri-Nishnabotna, Chariton-Grand, and Upper Mississippi-Salt Subregions (Seaber and others, 1984).

monia concentrations occasionally have exceeded Iowa water quality standards (Iowa Department of Water, Air, and Waste Management, 1984).

Des Moines River Basin

The Des Moines River is the largest and the most westerly of the major rivers in Iowa that are tributary to the Mississippi River. The Des Moines River originates in the glacial-moraine area in southern Minnesota. The river flows southeastward for 535 miles through the heart of Iowa's farmland and the urban areas of Fort Dodge, Des Moines, and Ottumwa to its confluence with the Mississippi River just downstream from Keokuk. The river drains all or part of 7 counties in Minnesota, 39 in Iowa, and 1 in Missouri. The total drainage area is 14,540 mi², of which 10 percent (1,525 mi²) is in Minnesota, 89 percent (12,925 mi²) is in Iowa, and 1 percent (90 mi²) is in Missouri (Iowa Natural Resources Council, 1953).

Two major multipurpose reservoirs have been built on the main stem: Saylorville Lake (completed in 1976 with a storage of 602,000 acre-ft or 196,000 Mgal) is located upstream from Des Moines; Lake Red Rock (completed in 1969 with a storage capacity of 1,740,000 acre-ft or 567,000 Mgal) is located southeast of Des Moines.

Water in most streams is of suitable quality for most uses, even in reaches downstream of Fort Dodge and Des Moines—the two largest cities in the basin (Iowa Department of Water, Air, and Waste Management, 1984).

MISSOURI REGION

Missouri River Main Stem

The Missouri River forms most, 179 miles, of the western border of Iowa. As a transportation route for barge traffic, this large river has a major effect on the economy of western Iowa. The U.S. Army Corps of Engineers provides a continous 735-mile-long, 9-foot-deep, 300-foot-wide navigation channel from Sioux City to the river's confluence with the Mississippi River (Iowa Natural Resources Council, 1959). Degradation of the riverbed, resulting in a lower water table and loss of wetlands in areas adjacent to the river, is a continuing problem.

Western Iowa River Basin

This basin extends from southwestern Minnesota across the western part of Iowa to the Missouri State line to the south. The total area is 7,495 mi^2; about 96 percent or 7,192 mi^2 is in Iowa (Iowa Natural Resources Council, 1959). Subbasins include the Little Sioux—largest with 4,507 mi^2 of drainage area, the Floyd, and the Boyer Rivers; and a number of smaller streams that are tributary to the Missouri River. The main economic activity in this area is agriculture; the only large industrial areas are at Council Bluffs and Sioux City. Water for recreation is well developed in the Iowa Great Lakes area of the upper Little Sioux River subbasin. The Boyer, like the other major rivers in this area, has been straightened throughout most of its length. Flooding is a major issue in this part of Iowa. In addition, gully and channel erosion are more serious problems here than in any part of the State, because of the thick, loess soils (Iowa Natural Resources Council, 1959).

Monitoring, during the past 5 years, has shown increasing nitrate concentrations in some streams, including the Floyd River. The Little Sioux and the Boyer Rivers did not show increases, but levels detected have approached and occasionally exceeded the Iowa Water Quality Standard for drinking water (Iowa Department of Water, Air, and Waste Management, 1984). Although these rivers are not used for this purpose, the data demonstrate that nonpoint sources are affecting their quality.

Southern Iowa River Basin

This area includes the Nishnabotna River subbasin (2,995 mi^2), and the Iowa parts of the Nodaway, the Thompson, and the Chariton River subbasins, as well as other, smaller subbasins. The area contains 8,393 mi^2 or about 15 percent of the area of Iowa. It is bounded on the north and east by the Des Moines River basin, on the west by the Western Iowa River basin, and on the south by the Iowa–Missouri State line. The basins in this area are predominantly rural. Since dependable ground-water supplies are difficult to find here, almost all municipalities and many farms are supplied by surface impoundments or by streamflow (Iowa Natural Resources Council, 1958a).

The Southern Iowa Basin is characterized by extremely variable streamflow, both daily and seasonally. Low flows usually occur during late summer and fall, followed by a gradual increase to higher flows during spring and early summer. Low flows in most streams in this area are not sustained by ground-water inflow because of the low hydraulic conductivity of deposits underlying stream channels. A multipurpose reservoir—Rathbun Lake (completed in 1969 with a storage capacity of 339,000 acre-ft or 110,000 Mgal)—has been built on the Chariton River, 6 miles north of Centerville.

Water-quality monitored at three stream sites in the Southern Iowa basin, shows that BOD and ammonia concentrations are remaining stable. Nitrate concentrations currently do not show the same increasing trend noted in the Northeast, the Iowa–Cedar, and the Des Moines River basins; less acreage in row crops and fewer drainage-tile systems here, than in other areas of the State, are believed to be responsible for this regional difference (Iowa Department of Water, Air, and Waste Management, 1984).

SURFACE-WATER MANAGEMENT

Although a number of State agencies have water resource-management programs, five agencies share most of the responsibility for collecting data and managing the water resources of Iowa. These are the Iowa Department of Water, Air and Waste Management; the Iowa Department of Soil Conservation; the Iowa Conservation Commission; the Iowa Geological Survey; and the University of Iowa Hygienic Laboratory.

The Department of Water, Air, and Waste Management's water resources programs address surface water, ground water, wastewater, flood-plain management, and regulation of water withdrawals and use. The Department of Soil Conservation, among other responsibilities, administers soil-erosion abatement programs and, in cooperation with the Department of Water, Air, and Waste Management, engages in nonpoint-source water-pollution-abatement programs. The Conservation Commission administers the State outdoor-recreation and fish-and-wildlife programs and regulates construction on streambeds. The Iowa Geological Survey, unlike the other State agencies, does not have water-related regulatory powers, but is authorized to engage in ground-water-resources research, data collection, and publication; and provides important technical-support services relating to water availability and quality to other State and Federal agencies. The University of Iowa Hygienic Laboratory is the primary source of water-quality data in the State and provides the necessary information for management of environmental resources.

Two basic legal doctrines are available to the State for governing the type and quantity of water use: the doctrine of riparian rights and the doctrine of prior appropriation. Central to the riparian doctrine is the concept that water-use rights are associated with the ownership of the land. In contrast, the prior-appropriation concept contends that water-use rights depend on the timing of the claim to use water. Iowa historically has used the riparian doctrine to allocate water. The Iowa Supreme Court, however, has not ruled on some aspects of that doctrine, and, in 1957, the Iowa Legislature passed a law (Iowa Code 455A) requiring the issuance of a permit for most uses of water in excess of 5,000 gal/d (gallons per day). This law was amended in 1983 to 25,000 gal/d (Iowa Code section 455B.261), with the stipulations that water must not be wasted and that the interests of prior users must not be jeopardized. As a result, Iowa now has a legal system that allocates water based primarily on riparian principles but also protects prior users. The riparian doctrine applies strictly to domestic and exempted uses not subject to the permit system.

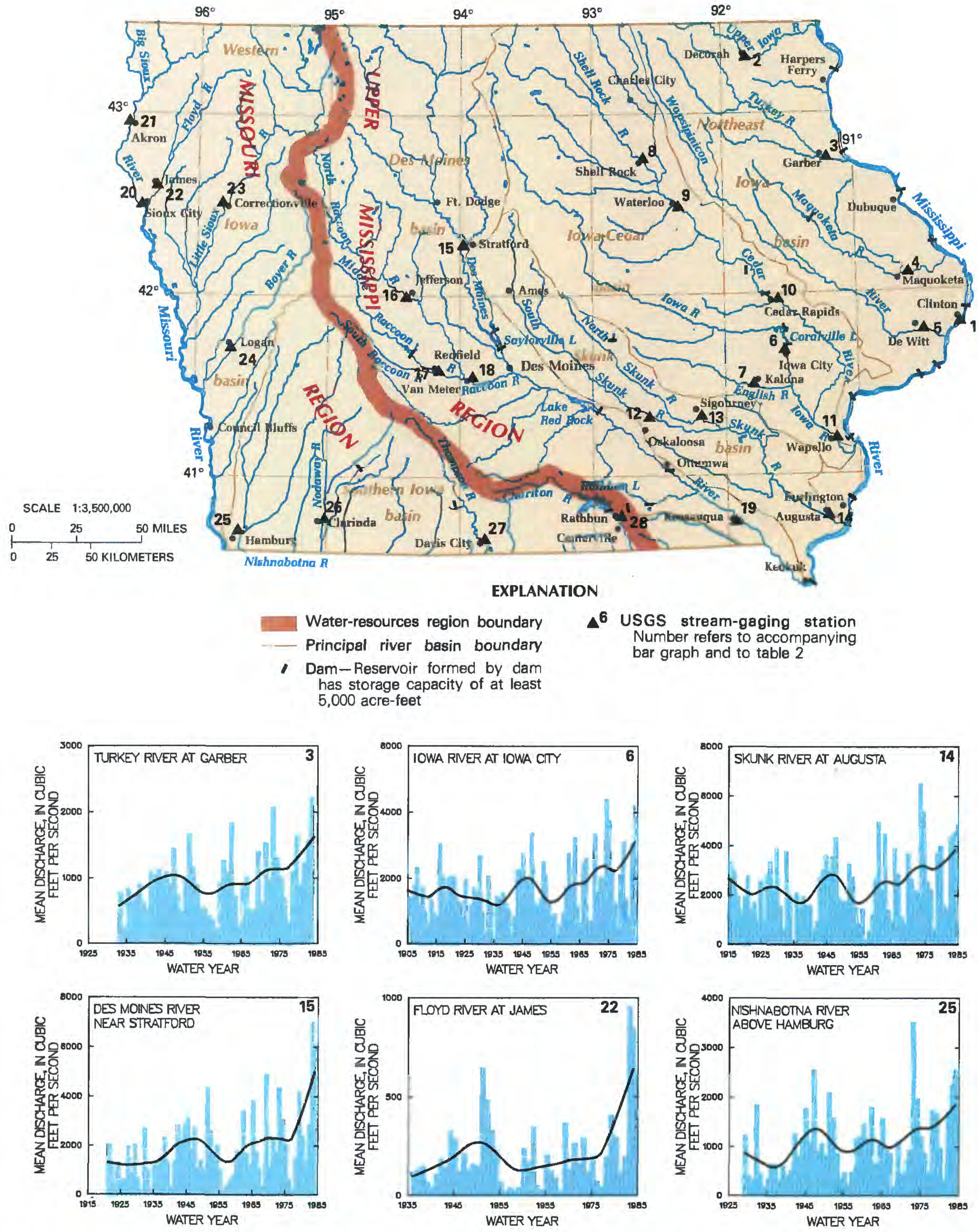

Figure 2. Principal river basins and related surface-water resources development in Iowa and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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KANSAS
Surface-Water Resources

Surface water is distributed unevenly across Kansas. With the exception of a few localities, western Kansas has little surface water most of the time; ground water is the principal source of freshwater in most of this area, although more ground water is being withdrawn than is being recharged. In contrast, ground water is not accessible in most of eastern Kansas, where surface water is the principal source of large supplies. About 37 percent of the population of Kansas is served by surface water. Surface-water withdrawals in Kansas in 1980 for various purposes and related statistics are given in table 1.

With few exceptions, the surface waters of Kansas are of suitable quality for instream uses and for irrigation. Standard treatment is adequate for offstream municipal and industrial uses. Twenty-four large reservoirs and scores of smaller ones are in use for water supply and flow regulation with a combined storage capacity of about 3.7 million acre-ft (acre-feet) or 1,210,000 Mgal (million gallons). Projected water-supply needs may require construction and operation of additional reservoirs. Flows of streams unregulated by reservoirs fluctuate between long periods of negligible flow and short periods when channels are full or flooding.

Major concerns related to surface water in Kansas are maintenance of streamflow during low-flow periods, development of drought-contingency regulations for equitable allocation during water shortages, water conservation, water quality, and the State's role in development of new reservoirs and control and management of water supplies in Federal reservoirs.

GENERAL SETTING

The major physiographic divisions in Kansas—the Great Plains and Central Lowlands physiographic provinces (fig. 1)—have diverse terrain including flat plains, rolling hills, sandhills, and steep slopes. Farmland, which generally consists of a mixture of cropland and pastureland, is the dominant land use in nearly all of the State. Precipitation increases fairly uniformly from an annual average of 16 inches in the western part of the State to 40 inches in the southeastern part (fig. 1). Precipitation usually is least in January and greatest in May or June, depending on location (fig. 1). Evaporation from lake surfaces ranges from 44 inches in the northeast to 68 inches in the southwest (Farnsworth and others, 1982). Average annual runoff ranges from 0.1 inch in the west to about 9 inches in the east (fig. 1). Average monthly runoff is closely related to average monthly precipitation. The period of least discharge usually occurs in December or January, and the period of greatest discharge usually occurs in May, June, or July (fig. 1).

PRINCIPAL RIVER BASINS

The northern half of Kansas is in the Missouri Region and has been divided, for the purpose of this report, into the Republican-Smoky Hill basins and Kansas-Osage-Missouri basins (fig. 2). The southern half of Kansas is in the Arkansas-Red-White Region and has been divided into the Arkansas basin and the Walnut-Verdigris-Neosho basins. These river basins are described below; their locations, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MISSOURI REGION
Republican and Smoky Hill Subregions

Republican and Smoky Hill River Basins.—Because the Republican and the Smoky Hill River basins span the western two-thirds of Kansas, the landscape is diverse, and the climate ranges from semiarid to subhumid. Less than one-third of the Republican River basin is in Kansas. The Republican River channel is sandy, wide, and shallow, and the surrounding uplands are flat to rolling. The Smoky Hill River basin is almost entirely in Kansas and comprises about one-fourth of the State's area. The Smoky Hill River is about 500 miles long and its major tributaries—the Solomon and the Saline Rivers—join it near Salina, which is the largest city (population 40,000) in the basin.

Tabla 1. Surface-water facts for Kansas

[Data 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 SURFACE WATER, 1980	
Number (thousands)	880
Percentage of total population	37
From public water-supply systems:	
Number (thousands)	830
Percentage of total population	35
From rural self-supplied systems:	
Number (thousands)	43
Percentage of total population	2
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	6,600
Surface water only (Mgal/d)	980
Percentage of total	15
Percentage of total excluding withdrawals for thermoelectric power	10
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	150
Percentage of total surface water	15
Percentage of total public supply	52
Per capita (gal/d)	180
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	4.3
Percentage of total surface water	0.4
Percentage of total rural domestic	7
Per capita (gal/d)	100
Livestock:	
Surface water (Mgal/d)	46
Percentage of total surface water	5
Percentage of total livestock	57
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	340
Percentage of total surface water	35
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	64
Excluding withdrawals for thermoelectric power	22
Irrigation withdrawals:	
Surface water (Mgal/d)	440
Percentage of total surface water	45
Percentage of total irrigation	8
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	570

Nine of the large reservoirs constructed in the Republican and Smoky Hill River basins are in Kansas; their predominant use has been for irrigation supply and flood control. Agriculture is the basis of the economy. Surface water for irrigation is supplied by five major reservoirs in Kansas (irrigation storage capacity 414,000 acre-ft or 135,000 Mgal) and one reservoir in Nebraska (capacity 343,000 acre-ft or 112,000 Mgal). Recent chronic shortages of surface water for irrigation have decreased agricultural use of surface water and have discouraged further development.

The western part of the Republican-Smoky Hill River basins is in an area that receives little precipitation and yields very little runoff (fig. 1); streams in these basins tend to be small, except during occasional floods (table 2, site 2). The eastern parts of both basins receive more precipitation and yield much greater runoff than the western parts. The eastern parts of the basins also contain more reservoirs, which are used to decrease flood peaks and sometimes augment low flows (table 2, sites 1, 3, and 4).

The bar graph for site 2 in figure 2 shows an example of a discharge trend typical of many streams in western Kansas. The clearly defined decline in average discharge by water year illustrates the chronic shortages of inflow to irrigation-supply reservoirs during recent years. The moving average of annual discharges for the Republican River (site 1, in figure 2) shows a decrease in discharge, probably because of an increase in consumptive use during the last two decades compared to the 1920's and 1930's.

Saline ground water contributes to flow in the Smoky Hill River basin near Wilson Lake and near the mouth of the Solomon River. Surface-water issues in these basins focus on methods of managing the available water supplies for most efficient use. The immediate concerns are non-point source pollution and inadequate supplies of surface water for irrigation at several locations and for municipal use in the Hays area.

Kansas, Gasconade-Osage, and Missouri-Nishnabotna Subregions

Kansas, Osage, and Missouri River Basins.—From the junction of the Republican and the Smoky Hill Rivers, the Kansas River flows about 170 miles eastward, where it joins the Missouri River at Kansas City. The Osage River basin in Kansas consists of the Marais des Cygnes River and smaller tributaries of the Osage River, which is formed downstream in Missouri. The Kansas and the Osage River basins have similar topography—rolling hills that are partly tilled and partly pastureland, interspersed with wooded and cleared valleys and some larger woodlands. The land along the Missouri River consists of flat flood plain as much as 2.9 miles wide on the Kansas side, and steep bluffs of silt and clay that are subject to the largest erosion rates in the State.

Flow of the Kansas River is affected by multipurpose reservoirs, completed from 1948 to 1977, in the Republican and the Smoky Hill River basins and on other major tributaries to the Kansas River. Three multipurpose reservoirs in the Osage River basin were completed during 1963, 1972, and 1981.

Major diversions from the Kansas, the Marais des Cygnes, and the Missouri Rivers are for the municipal supplies of Topeka, Lawrence, Leavenworth, Kansas City and its suburbs; for four fossil-fueled powerplants; and for a waterfowl refuge. Reservoirs on the Missouri River and its tributaries upstream from Kansas augment low flows, particularly during the late fall and early spring navigation seasons, and provide flood control. Low flows in the Kansas, the Big Blue (a tributary to the Kansas River), and the Missouri Rivers are sustained by ground-water inflow and by reservoir releases, but low flows of the Marais des Cygnes River are smaller and less dependable.

The Kansas River receives considerable flow from several large tributaries, including the Republican, the Smoky Hill, and the Big Blue Rivers. The Missouri River is so large that its low flow at St. Joseph (table 2, site 9) is more than three times the average discharge of the Marais des Cygnes River (table 2, site 8) and almost as large as the average discharge of the Kansas River at De Soto (table 2, site 7). Periodic high flows in channels and on flood plains of the Kansas and the Missouri Rivers recharge the underlying ground-water reservoirs.

Major concerns in the Kansas and the Missouri River basins are the possibility of transferring some of the relatively large average discharges of the Kansas and the Missouri Rivers to other river

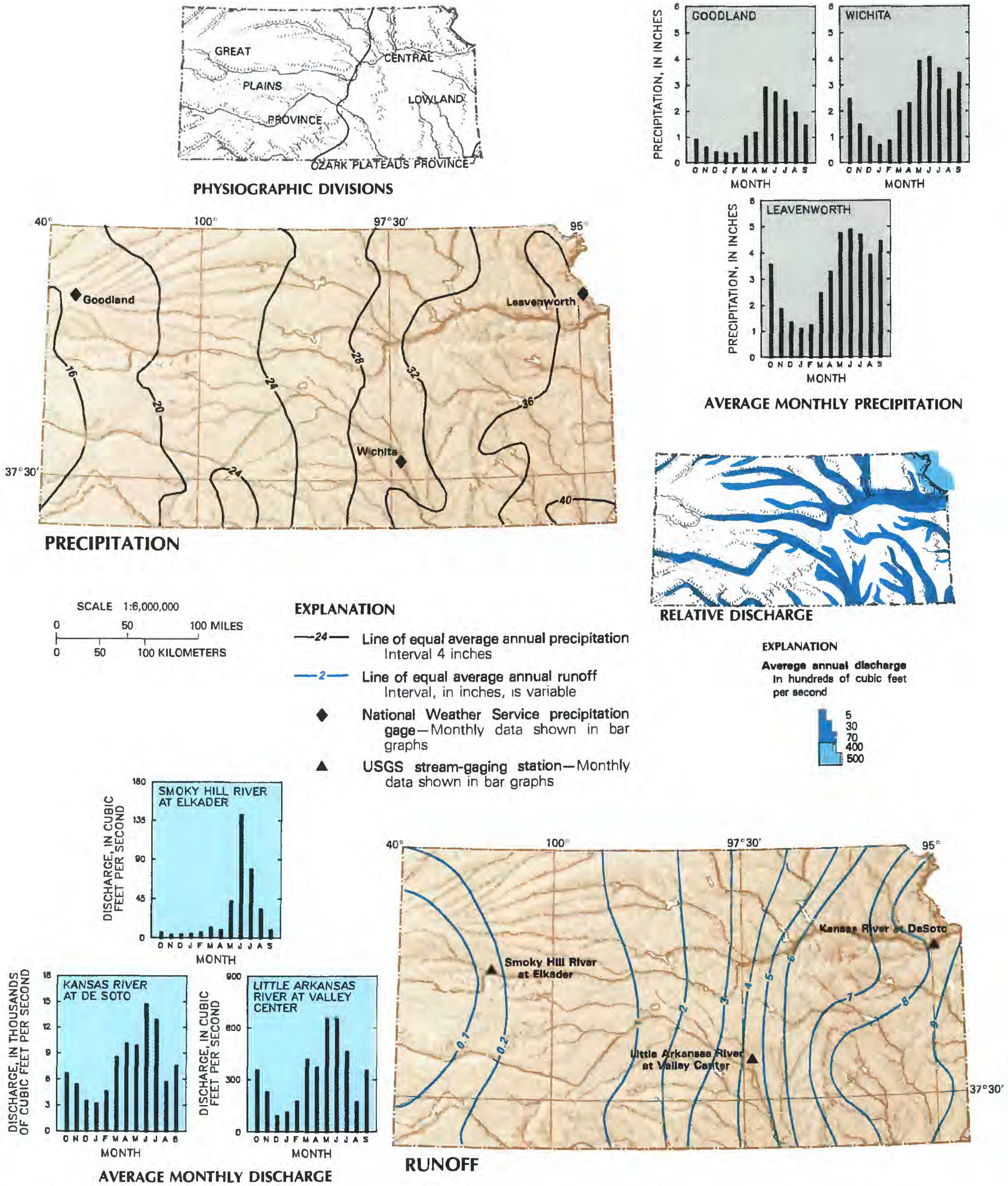

Figure 1. Average annual precipitation and runoff in Kansas and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Tabla 2. Selected streamflow characteristics of principal river basins in Kansas

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second;. . . .=insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Kansas State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-yeer flood (ft^3/s)	Degree of regulation	Remarks
MISSOURI REGION Repuslican And Smoky Hill Subregions Republican and Smoky Hill River basins								
1.	Republican Rivar at Clay Center (06856600).	24,542	1917-83	[1]75	990	[1]76,000	Appreciable	Major water uses are irrigation and power.
2.	Smoky Hill River at Elkader (06860000).	3,555	1940-83	0.0	30	70,000	Negligible	Water use is negligible; long periods of no flow are common.
3.	Solomon River at Niles (06876900).	6,770	1897-1903, 1917-83	[1]33	550	[2]51,000	Appreciable	Major water use is irrigation.
4.	Smoky Hill River at Enterprise (06877600).	19,260	1935-83	[1]120	1,600	[2]85,000	. . . do . . .	Mejor water use is irrigation.
Kansas, Gasconade-Osage, And Missouri-Nishnabotna Subregions Kansas, Osage, and Missouri River basins								
5.	Kansas River at Fort Riley (06879100).	44,870	1964-83	[1]240	2,600	[2]140,000	Appreciable	Major water use is irrigation.
6.	Big Blue River near Manhattan (06887000).	9,640	1955-83	[1]18	2,000	[2]50,000	. . . do . . .	Major water uses are irrigation and municipal supply.
7.	Kansas River at De Soto (06892350).	59,756	1917-83	[1]800	7,000	[2]230,000	. . . do . . .	Major water uses downstream from the Republican and the Smoky Hill Rivers are municipal and industrial supplies and transport of treated wastes.
8.	Marais des Cygnes River near Kansas-Missouri State line (06916600).	3,230	1959-83	[1]2.5	2,000	[1]67,000	. . . do . . .	Major water uses are municipal supply, fish and wildlife.
9.	Missouri River at St. Joseph, Mo. (06818000).	420,300	1929-83	[1]6,100	42,000	. . . .	. . . do . . .	Major water uses include irrigation, municipal and industrial supplies, barge traffic, hydroelectric power, fish and wildlife, waste transport, and recreation.
ARKANSAS-WHITE-RED REGIONS Middle Arkansas, Upper Cimarron, And Arkansas-Keystone Subregions Arkansas River basin								
10.	Arkansas Rivar at Syracuse (07138000).	25,763	1902-06, 1921-83	[1]0.3	310	[1]130,000	Appreciable	Major water use is irrigetion.
11.	Little Arkansas River at Valley Center (07144200).	1,327	1922-83	10	280	43,000	Negligible	Flow may be affected by pumpage from Wichita well field.
12.	Arkansas River at Arkansas City (07146500).	43,713	1902-06, 1922-83	[1]170	1,800	[2]99,000	Moderate	Major water uses are irrigation and transportation of treatad wastes.
Middle Arkansas And Neosho-Verdigris Subregions Walnut, Verdigris, and Neosho River basins								
13.	Verdigris River at Independence (07170500).	2,892	1895-1904, 1921-83	[1]9.0	1,700	[2]72,000	Appreciable	Major weter uses are municipal, fish and wildlife, and recreation.
14.	Neosho River near Parsons (07183500).	4,905	1922-83	[1]7.5	2,500	[1]56,000	. . . do . . .	Major water uses are industrial, municipal, fish and wildlife.

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[1] Based on period of analysis since regulation began. These values are not based on detailed analyses, are approximate estimates, and are for information purposes only.

[2] From flood-insurance hydrology study. Based on detailed analyses of regulated-flow conditions.

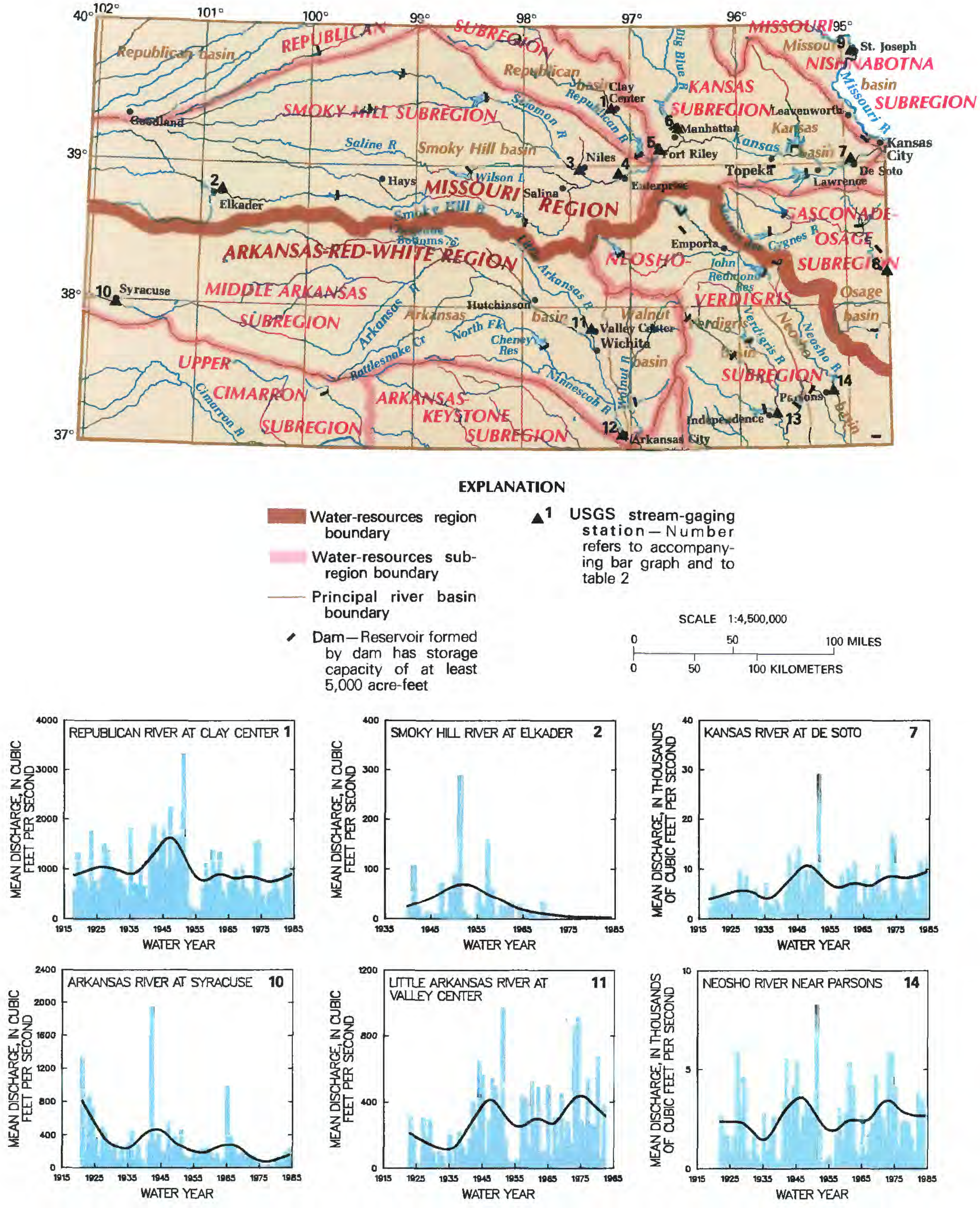

Figure 2. Principal river basins and related surface-water resources development in Kansas and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

basins, the need to develop and ensure water supplies from smaller streams in the basins during drought, sedimentation of reservoirs, and salinity in the Kansas River at Topeka. Salinity occasionally exceeds the Federal drinking-water standards for public supplies.

ARKANSAS-WHITE-RED REGION

Middle Arkansas, Upper Cimarron, and Arkansas-Keystone Subregions

Arkansas River Basin.—The Arkansas River originates in Colorado and a large part of its flow is derived from mountain snowmelt. Regulation of streamflow by storage and consumptive use of the water in Colorado has reduced the river to a small stream where it crosses the border into Kansas. Also, as a result of water use in Kansas, the river remains small for a considerable distance within the state. It then increases gradually to Wichita where it increases rapidly. Comparison of the low, average, and flood flows at Arkansas City (table 2, site 12) with those at Syracuse (table 2, site 10) shows the great change in the Arkansas River as it flows through the State. The low flow of the Little Arkansas River is enough to support some instream uses, particularly for recreation within Wichita where low dams increase the river's surface area.

Development of the Arkansas River basin in western Kansas began with diversions, with and without offstream storage, for irrigation of corn and sugar beets. Considerable development of the river has occurred in Colorado. The John Martin Reservoir on the Arkansas River in Colorado, completed in 1943 with 702,000 acre-ft or 227,000 Mgal of storage capacity, affects flows of the Arkansas River in western Kansas. Cheyenne Bottoms—a waterfowl and fishing area enlarged from a natural shallow lake—is maintained in part by diversions from the Arkansas River and a tributary. Other developments include diversions of floodwaters around Hutchinson and Wichita, and a pipeline from Cheney Reservoir to Wichita.

The downward trend of average discharge by water year at Syracuse (fig. 2, site 10) is the result of consumptive use of water for irrigation and evaporation from reservoirs. This trend has forced the decrease of irrigation by surface water in Kansas and also has decreased the quantity of water available for the Cheyenne Bottoms waterfowl area. In contrast, average discharge by water year of the Little Arkansas River (fig. 2, site 11) has not shown a downward trend despite large ground-water withdrawals at the Wichita well field.

Poor water quality constrains use of surface water during times of low flow in the Arkansas River from the mouth of Rattlesnake Creek to Wichita where saline ground water seeps into the river. The salinity downstream from Wichita is decreased by dilution from the city's treated effluent, most of which originates from low-salinity ground water north of the river. Much of the Ninnescah River has very saline low flow; however, the water in Cheney Reservoir on the North Fork is usable for part of the municipal supply of Wichita much of the time because of dilution by less saline high flow.

The major surface-water issue in the Arkansas River basin is the need for additional sources of water to supply the fast-growing economy of the Wichita-Hutchinson area.

Middle Arkansas and Neosho-Verdigris Subregions

Walnut, Verdigris, and Neosho River Basins.—The southeastern one-seventh of Kansas consists of the Walnut River basin and the Verdigris and the Neosho River basins (in the Neosho-Verdigris Subregion). This area has the largest average precipitation and runoff in the State, yet it has periodic water-supply shortages as severe as in any other part of Kansas. One large reservoir has been constructed in the Walnut basin (capacity 301,000 acre-ft or 98,000 Mgal), four in the Verdigris basin (total capacity 1,131,000 acre-ft or 369,000 Mgal), and three in the Neosho basin (total capacity 1,311,000 acre-ft or 427,000 Mgal), to moderate the extremes of high and low flows and to provide public-water supplies; the reservoirs also provide recreational opportunities and fish and wildlife habitats.

The largest water right in the basins will be used to cool by evaporation a nuclear powerplant near John Redmond Reservoir; the powerplant is undergoing tests in 1985 prior to full-time operation. The plant will use water transported by pipeline from John Redmond Reservoir to supplement the water in a smaller onsite impoundment. Surface water also is used by numerous small cities (the largest is Emporia, with a population of 26,000), by rural water districts, and by some farmers for supplemental irrigation. Water quality does not constrain surface-water use in most parts of these basins. Instream uses in the basins are for fish and wildlife habitats, and recreation, although the flow periodically is less than the desired minimum. The major rivers have substantial average discharges, but the 7-day low flows are very small (table 2, sites 13 and 14). The average discharge by water year at site 14 in figure 2 shows no apparent long-term trend, primarily because consumptive use of water has changed little in the basin over the years.

The major water issue in these basins is the need to assure adequate streamflow for municipal and industrial supplies during drought conditions. A related issue is substantial conveyance losses of water for public supply in river channels downstream from reservoirs.

SURFACE-WATER MANAGEMENT

Kansas has five State agencies with major responsibilities for managing surface water. In addition, Federal water projects are managed by the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation. Data used in the management include hydrologic data collected by the U.S. Geological Survey in cooperation with several Federal, State, and local agencies.

The Kansas Water Office is the water-planning, policy, and coordination agency for the State and the marketing agent for water from State-owned storage in Federal reservoirs (Kansas Statutes Annotated (KSA) 74-2605 et seq.). A new process of water planning was developed and implemented during 1983 and 1984, culminating in a new Kansas Water Plan (Kansas Water Office, 1985) that was approved by the legislature during the 1985 session. Because the planning process is continuous, the Kansas Water Plan is expected to be modified and updated frequently.

The Kansas Water Authority (KSA 74-2605 et seq.) is responsible for advising the Governor, legislature, and Director of the Kansas Water Office on water-policy issues. Twelve local River Basin Advisory Committees, created in 1985, are responsible for advising the Kansas Water Authority on needs and courses of action within the river basins.

The Kansas State Board of Agriculture, Division of Water Resources, administers laws related to water rights, conservation, and use of water resources, including appropriation of surface water and ground water. Enacted during 1945, the Kansas Water Appropriation Act (KSA 82a-701 et seq.) operates on the principle of prior appropriation. The date of application for a permit establishes the priority to continue the use of water during periods of shortage. Allocation, storage, and diversion of water in the Republican, the Big Blue, and the Arkansas River basins are affected by Interstate Compacts with Colorado, Nebraska, and Oklahoma.

The Kansas Department of Health and Environment, Division of Environment, has regulatory authority over matters dealing with pollution of surface water.

The State Conservation Commission administers the following assistance programs that affect surface water: State aid to Conservation Districts, Water Resources Cost-Share Program, State assistance in construction of watershed dams, and beginning in 1985, administration of a new Small Lakes Program.

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KENTUCKY
Surface-Water Resources

Kentucky has abundant surface water during most of the year. However, seasonal and areal variations in precipitation can limit surface-water supplies in certain areas during the summer, and releases from reservoir storage are necessary to augment low flows. Water quality generally is suitable for most uses during periods of high to average flows, but locally may be unsuitable for some uses during periods of low flow.

Surface water provides 4,409 Mgal/d (million gallons per day) or 6,820 ft³/s (cubic feet per second) which is 96 percent of the total water withdrawn for offstream use in Kentucky (table 1); ground water provides the remainder (182 Mgal/d or 282 ft³/s). Surface water withdrawn for thermoelectric power dominates the offstream water use with 3,836 Mgal/d or 5,940 ft³/s being used. Approximately 98,000 Mgal/d or 152,000 ft³/s of surface water is used for hydroelectric-power generation. Fifty-six percent of Kentucky's population relies on surface water from public suppliers and 2 percent relies on surface water from rural self-supplied systems.

The surface-water issues of great concern to State and local officials pertain to both water quantity and quality. Recent droughts have focused attention on critical water shortages that can occur. Coal mining, oil and gas operations, agriculture, and domestic-waste discharges have adversely affected surface-water quality in Kentucky. The State also is concerned about the effects of acid precipitation on reservoirs, lakes, and streams. Flooding is a recurring problem along many streams throughout the State, especially from November through May.

GENERAL SETTING

Kentucky is located in the Appalachian Plateaus, the Interior Low Plateaus, and the Coastal Plain physiographic provinces (fig. 1). The topography is rugged in the Appalachian Plateaus province and streams flow in steep narrow valleys. The topography of the Interior Low Plateaus province generally is gently rolling, but some stream valleys in areas underlain by limestone are several hundred feet deep. The topography of the Coastal Plain province is gently rolling and relief is low. Elevations in Kentucky range from 4,145 feet above sea level at Black Mountain in the southeast to 256 feet above sea level in the western part of the State near the Mississippi River.

The distribution of precipitation varies areally and seasonally (fig. 1). Precipitation varies with latitude and ranges from about 40 inches per year in the northernmost part of the State to about 52 inches in the southern part. Precipitation generally is least during August, September, and October.

Potential evaporation is about 30 inches per year, about 75 percent of which occurs from April through October (Krieger and others, 1969). Evaporation exceeds precipitation in the summer.

Average annual runoff ranges from about 15 inches in the extreme northern part of the State to about 26 inches in the southeastern part (fig. 1). The statewide average is about 18 inches, which is more than twice that of the continental United States (Bell, 1963). Runoff is least during June through October and is highest during March (fig. 1).

PRINCIPAL RIVER BASINS

Most of Kentucky is in the Ohio Region (Seaber and others, 1984); the region in Kentucky includes the Ohio River main stem and six subregions. These subregions are the Middle Ohio, the Lower Ohio, the Big Sandy-Guyandotte, the Kentucky-Licking, the Green, and the Cumberland. A small part of the southwestern corner of the State is in the Tennessee Region, and a few small streams in the extreme southwestern corner of the State drain into the Mississippi River and are part of the Lower Mississippi Region (this region is not discussed).

The Ohio River main stem and the major subregions in Kentucky are discussed below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Kentucky

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Mull and Lee, 1984; Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	2,167
Percentage of total population	58
From public water-supply systems:	
Number (thousands)	2,080
Percentage of total population	56
From rural self-supplied systems:	
Number (thousands)	87
Percentage of total population	2
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	4,600
Surface water only (Mgal/d)	4,400
Percentage of total	96
Percentage of total excluding withdrawals for thermoelectric power	78
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	320
Percentage of total surface water	7
Percentage of total public supply	87
Per capita (gal/d)	156
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	4.3
Percentage of total surface water	0.1
Percentage of total rural domestic	10
Per capita (gal/d)	50
Livestock:	
Surface water (Mgal/d)	38
Percentage of total surface water	0.9
Percentage of total livestock	95
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	4,000
Percentage of total surface water	92
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	75
Irrigation withdrawals:	
Surface water (Mgal/d)	4.7
Percentage of total surface water	0.1
Percentage of total irrigation	94
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	98,000

OHIO REGION

Middle and Lower Ohio Subregions

Ohio River Main Stem.—The Ohio River forms the northern boundary of Kentucky for a distance of 664 miles, extending from West Virginia to the junction of the Ohio and the Mississippi Rivers at the western tip of Kentucky. The river drains an area of 204,000 mi² (square miles) in 14 States; 33,300 mi² (about 82 percent of the State) are in Kentucky.

The Ohio River has a 7-day, 10-year low flow at the western end of the State of 46,000 ft³/s or 29,700 Mgal/d (table 2, site 3). The maximum discharge for the period 1928-83 for the Ohio River at this site was 1,780,000 ft³/s or 1,150,000 Mgal/d.

Several water-quality problems have been detected in the Ohio River (Kentucky Natural Resources and Environmental Protection Cabinet, Division of Water, 1975). Elevated coliform-bacteria counts, probably due to discharge of raw sewage, have been found along the entire reach of the river. Elevated iron and manganese concentrations, attributed to large areas of surface mining, commonly exceed 300 $\mu g/L$ (micrograms per liter) near the mouth.

Flooding also is a problem in the basin. Flooding on the Ohio River in December 1978 caused damages of about $20 million.

Salt River Basin.—The Salt River flows directly into the Ohio River; its principal tributary is Rolling Fork. Rolling Fork flows westward from its headwaters for many miles before turning north to join the Salt River. There are no major improvments for navigation in the basin, except for a short section near the mouth. Taylorsville Lake, completed in 1983, provides flood control, low-flow augmentation, water supply, and recreation; it has a storage capacity of 291,000 acre-ft (acre-feet) or 94,800 Mgal (million gallons).

The maximum discharge for Rolling Fork near Boston (table 2, site 5) for the period 1938-83 was 65,000 ft^3/s or 42,000 Mgal/d on December 10, 1978. Damages during the December 1978 flood exceeded $2 million.

Big Sandy-Guyandotte Subregion

The Big Sandy River, formed by the confluence of Levisa Fork and Tug Fork at Louisa, Ky., flows 27 miles northward to the Ohio River. The Tug Fork and the Big Sandy Rivers form the boundary between Kentucky and West Virginia. Coal mining is the main industry in the area. The lower 5 miles of the river is improved for navigation.

Fishtrap Lake, constructed in 1968 on the Levisa Fork for flood control, has a usable storage capacity of 164,000 acre-ft or 53,400 Mgal. Erosion at surface coal mines has substantially increased sedimentation in the lake. The maximum discharge for Levisa Fork at Pikeville (table 2, site 6) for the period 1937-83 was 85,500 ft^3/s or 55,300 Mgal/d and the minimum was 1.5 ft^3/s or 0.97 Mgal/d.

Kentucky-Licking Subregion

Kentucky River Basin.—The Kentucky River is formed by the confluence of the North Fork, the Middle Fork, and the South Fork. The Kentucky River flows in a northwesterly direction from its headwaters in the North Fork for a distance of about 250 miles to the Ohio River. The 6,870-mi^2 drainage area lies entirely within the State. Other principal tributary streams are the Red and the Dix Rivers in the central part of the basin and Elkhorn and Eagle Creeks in the lower part of the basin.

Licking River Basin.—The Licking River is 320 river miles long and drains 3,660 mi^2. Because the tributary streams are relatively short and have steep gradients, runoff rates tend to be high, and low flows are poorly sustained during dry periods. The area is predominantly rural; farming is the chief industry, but some mining occurs in the upper part of the basin.

The Licking River lacks locks and dams and has only limited potential for hydropower development. Cave Run Lake, completed in 1973 with a storage capacity of 614,000 acre-ft or 200,000 Mgal, is the only major impoundment on the river. The lake is designed for flood control and low-flow augmentation. The maximum discharge at Licking River at Catawba (table 2, site 7) for the period 1914-83 was 95,000 ft^3/s or 61,300 Mgal/d and the minimum was 2.5 ft^3/s or 1.6 Mgal/d.

Green Subregion

Green River Basin.—The Green River flows about 330 miles from its headwaters to its confluence with the Ohio River. The Green River basin comprises about one-fourth of the State's area and is the largest drainage basin in Kentucky; it drains approximately 8,896 mi^2 in west-central Kentucky and 377 mi^2 in northern Tennessee.

Streams draining into the Green River include the Rough, the Barren, the Nolin, and the Pond Rivers. Major multipurpose reservoirs in the Green River basin include Rough River Lake (completed in 1959 with 305,000 acre-ft or 99,400 Mgal of storage), Nolin Lake (completed in 1963 with 609,000 acre-ft or 198,534 Mgal of storage), Barren River Lake (completed in 1964 with 815,000 acre-ft or 266,000 Mgal of storage), and Green River Lake (completed in 1969 with 723,200 acre-ft or 236,000 Mgal of storage).

The maximum discharge for the period 1921-83 of the Green River at Munfordville (table 2, site 10) was 76,800 ft^3/s or 49,600 Mgal/d, and the minimum was 39 ft^3/s or 25 Mgal/d. The recurrence intervals of peak discharges on streams in the basin during the December 1978 flood exceeded 50 years, and damages totaled about $7 million.

The Green River and its tributaries provide water for numerous municipal, private, and industrial water supplies; agriculture; wastewater dilution; and recreation. The river has been improved for navigation for a distance of 198 miles on the main stem, 30 miles on the Barren River, and about 30 miles on the Rough River.

Cumberland Subregion

Cumberland River Basin.—The Cumberland River basin has a total drainage area of 17,700 mi^2, but less than half of the basin is in Kentucky. The Cumberland River originates in Kentucky, flows southward into Tennessee where it follows a circular course for more than 130 miles, and then reenters Kentucky. It then flows northward to join the Ohio River. Farming is the main occupation in the basin, but coal mining is important in the headwaters area.

Major tributaries to the Cumberland River in the upper part of the basin in Kentucky include the South Fork and the Rockcastle Rivers. Tributaries in the lower part of the basin in Kentucky are the Little, the West Fork Red, and the Red Rivers.

The most important reservoir in the Cumberland River basin is Lake Barkley (completed in 1966) in the lower part of the basin. Lake Barkley is more than 118 miles long, has an area of 93,400 acres, and has a storage capacity of 2,082,000 acre-ft or 678,000 Mgal at the maximum regulated level. A hydroelectric dam can generate 582 million kilowatt hours annually.

The maximum discharge for the period 1959-83 at Cumberland River at Williamsburg (table 2, site 12) was 49,700 ft^3/s or 32,100 Mgal/d and the minimum was 6.1 ft^3/s or 3.9 Mgal/d. The peak discharge at Little River near Cadiz (table 2, site 13) exceeded a recurrence interval of 100 years during the December 1978 flood.

TENNESSEE REGION

Lower Tennessee Subregion

The Tennessee River drains the largest area (40,910 mi^2) of any tributary to the Ohio River. However, only about 1,000 mi^2 of the basin is in Kentucky. Kentucky Lake and Dam are located 22 miles above the mouth. Kentucky Lake has a total length of 185 miles, 40 miles of which is in Kentucky. The storage capacity of the lake is 4,000,000 acre-ft or 1,300,000 Mgal. This is the largest reservoir used for flood control on the Ohio and the Lower Mississippi Rivers. During the flood season, this reservoir regulates discharge from the Tennessee River into the Ohio. Kentucky Lake and Dam also is used for navigation, recreation, and power generation. The flow of the Tennessee River is now completely regulated by Kentucky Dam. The Barkley-Kentucky Canal diverts water to and from Barkley Lake on the Cumberland River.

SURFACE-WATER MANAGEMENT

A number of State agencies under the jurisdiction of Kentucky Cabinets of Energy, Human Resources and Natural Resources and Environmental Protection are responsible for comprehensive surface-water management.

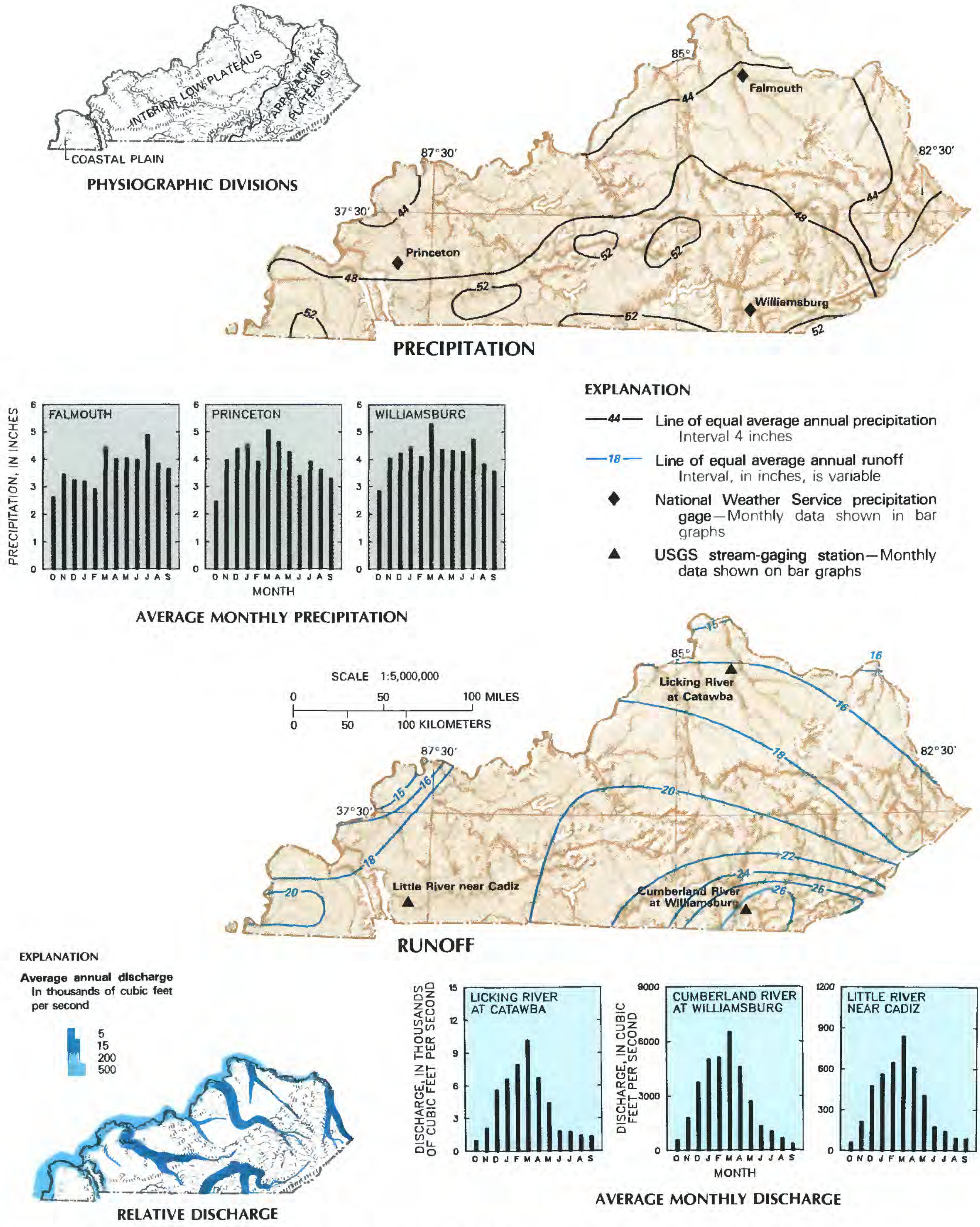

Figure 1. Average annual precipitation and runoff in Kentucky and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Kentucky

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi²=square miles; ft³/s=cubic feet per second; . . . .=insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Kentucky agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				OHIO REGION **Middle And Lower Ohio Subregions** **Ohio River main stem**				
1.	Ohio River at Greenup Dam (03216600).	62,000	1968-83	7,400	92,530	699,000	Moderate	Quality of the Ohio River is generally suitable for most uses. Raw sewage and spills of toxic materials cause problems at times.
2.	Ohio River at Louisville (03294500).	91,170	1928-83	8,200	115,700	862,000	. . . do . . .	
3.	Ohio River at Metropolis, Ill. (03611500).	203,000	1928-83	46,000	271,000	1,580,000	. . . do . . .	
				Salt River basin				
4.	Selt River at Shepherdsville (03298500).	1,197	1938-83	0.22	1,572	61,900	Appreciable	Subregion experiences periodic flooding.
5.	Rolling Fork near Boston (03301500).	1,299	1938-83	2.3	1,801	65,600	None	
				Big Sandy-Guyandotte Subregion				
6.	Levisa Fork at Pikeville (03209500).	1,232	1937-83	5.8	1,474	76,400	Moderate	Subregion experiences problems with siltation, heavy metals, and chlorides.
				Kentucky-Licking Subregion **Licking River basin**				
7.	Licking River at Catawba (03253500).	3,300	1914-83	13	4,143	84,900	Moderate	Subregion experiences water-supply shortages during low flows, especially in the Cynthiana area. Period of analysis not continuous
				Kentucky River basin				
8.	Middle Fork Kentucky River at Tallega (03281000).	537	1930-83	0.64	730	51,400	Appreciable	Periodic flooding in the area of Frankfort is a problem during high flows. Period of analysis not continuous for site 8.
9.	Kentucky River at Lock 6 near Selvisa (03287000).	5,102	1925-83	136	6,737	125,000	Moderate at low flows	
				Green Subregion **Green River basin**				
10.	Green River at Munfordville (03308500).	1,673	1915-83	73	2,722	70,300	Moderate	Streams in the subregion are degraded by siltation and acid-mine drainage from strip-mined areas. Period of analy- not continuous for site 10.
11.	Pond River near Apex (03320500).	194	1940-83	0	267	25,800	None	
				Cumberland Subregion **Cumberland River basin**				
12.	Cumberland River at Williamsburg (03404000).	1,607	1959-83	22	2,736	54,000	Negligible	Degradation of water quality in some streams is associated with coal mining, oil and gas drilling, and municipal discharges.
13.	Little River near Cediz (03438000).	244	1940-83	11	349	18,200	None	
				TENNESSEE REGION **Lower Tennessee Subregion**				
14.	Tennessee River near Paducah (03609500).	40,200	1889-1983	8,190	[1]64,060 [2]65,450	. . . .	Appreciable	

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[1] Prior to opening of Barkley-Kentucky Canal (1889-1965).

[2] Since the opening of Barkley-Kentucky Canal(1965-93).

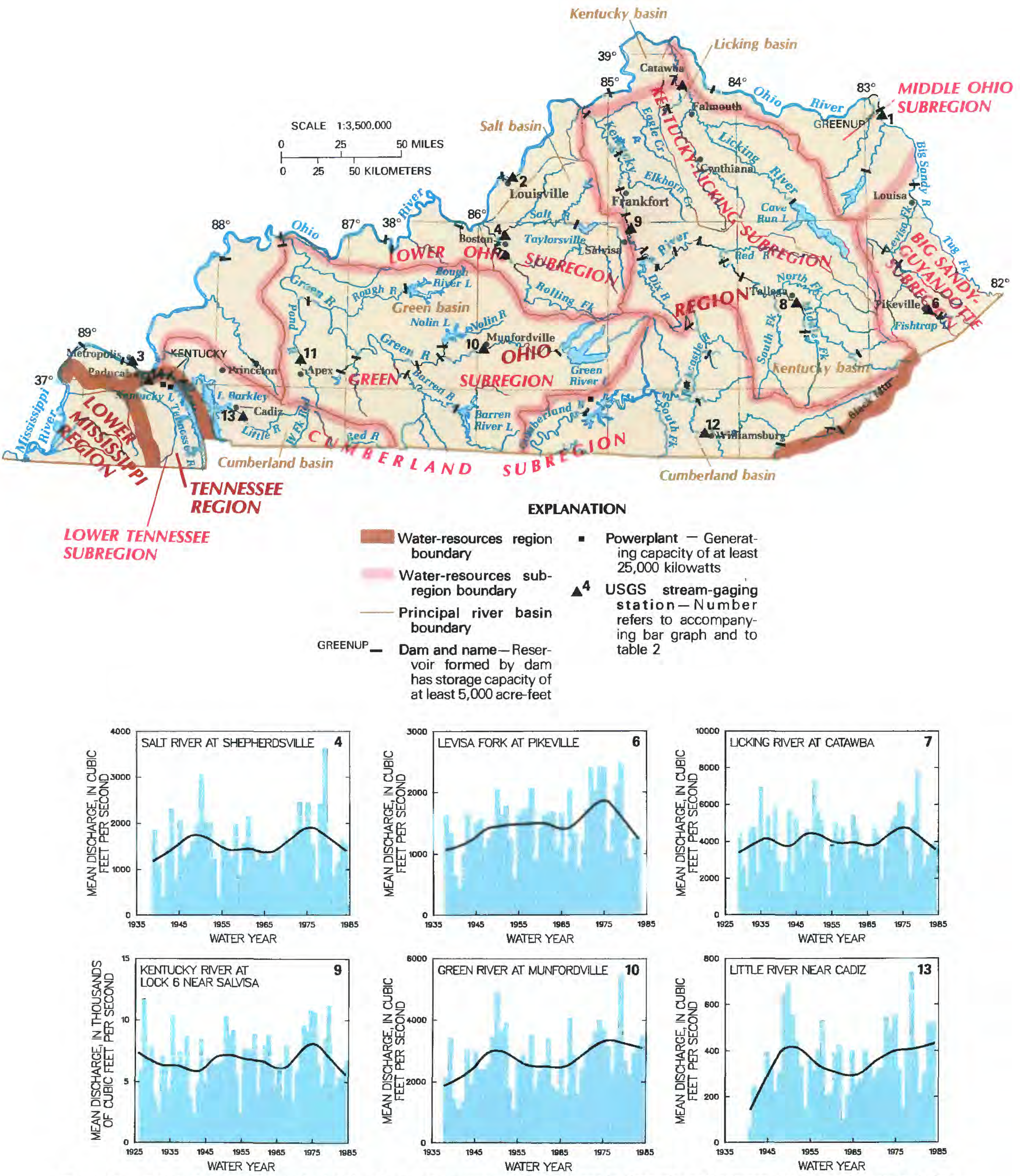

Figure 2. Principal river basins and related surface-water resources development in Kentucky and average discharges for selected sites. Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Specific water-quality standards are established for aquatic life, domestic water-supply use, recreation use, and outstanding resource waters (wild and scenic areas, nature preserves, and so on) (401 Kentucky Administrative Regulation No. 5:031). Under provisions of Kentucky Revised Statutes, Chapter 151, a user of public water is required to obtain a permit from the Natural Resources and Environmental Protection Cabinet to withdraw 10,000 gal/d (gallons per day) or more (use of water for agriculture, steam-generating plants, and domestic use is exempted). The protection of surface-water resources from contamination by brine waters resulting from oil and gas exploration is addressed under provisions of 401 Kentucky Administrative Regulation 5:090. Solid- and hazardous-waste management regulations are administered by the Division of Waste Management (401 Kentucky Administrative Regulations Chapter 30). Performance standards for waste-disposal sites and protection of surface-water resources also are the Division's responsibility.

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 surface-water-management decisions are made by appropriate State agencies. The U.S. Geological Survey also cooperates with other State, local, and Federal agencies in studies of selected areas.

The Ohio River Valley Water Sanitation Compact, composed of States in the Ohio River Basin, promotes, coordinates, and maintains pollution-control and water- quality standards in the Ohio River Basin. The Tennessee River Basin Water Pollution Compact, composed of States in the Tennessee and Cumberland River Basins, promotes, coordinates, and maintains pollution-control and water-quality standards in the Tennessee River Valley area.

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FOR ADDITIONAL INFORMATION

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LOUISIANA
Surface-Water Resources

Louisiana has several large rivers that either flow through or border the State. Of these, the Mississippi River is the largest; it drains more than 40 percent of the continental United States and has an average annual discharge of 514,200 ft³/s (cubic feet per second) or 332,300 Mgal/d (million gallons per day) at Tarbert Landing, Miss. Although the Mississippi River has a dominant role in the economy of the State, the Pearl, the Red, the Ouachita, the Mermentau, the Atchafalaya, the Calcasieu, and the Sabine Rivers are important to the State. In addition to these rivers, there are more than 154 lakes in Louisiana (Shampine, 1970).

Surface water in Louisiana is used for public and industrial supplies, agriculture, navigation, and recreation. The Mississippi River corridor from Baton Rouge to New Orleans, the Calcasieu River basin near Lake Charles, and the Ouachita River basin at Monroe are heavily industrialized areas that rely heavily on surface water. Approximately 31 percent of the population uses fresh surface water as a source of supply. Offstream use of surface water amounts to 11,000 Mgal/d or 17,000 ft³/s, which represents 86 percent of the estimated total freshwater withdrawals in Louisiana in 1980. The largest offstream withdrawals were for self-supplied industries (8,900 Mgal/d or 13,800 ft³/s) and the largest instream use was for hydroelectric power (1,400 Mgal/d or 2,170 ft³/s). Surface-water withdrawals and related statistics for Louisiana in 1980 are given in table 1.

The quality of surface water is a major issue in Louisiana. Many streams contain elevated counts of fecal-coliform bacteria and low concentrations of dissolved oxygen. Flooding is a recurrent problem in the State; the floods of 1953 and 1983 were especially disastrous. Coastal erosion, loss of marsh, and subsidence are other concerns of the State. An estimated 39 mi² (square miles) or 25,000 acres of coastline is being lost each year (Gagliano and others, 1981).

Tabla 1. Surface-water facts for Louisiana

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	1,310
Percentage of total population	31
From public water-supply systems:	
Number (thousands)	1,310
Percentage of total population	31
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	12,000
Surface water only (Mgal/d)	11,000
Percentage of total	86
Percentage of total excluding withdrawals for thermoelectric power	73
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	340
Percentage of total surface water	3
Percentage of total public supply	56
Per capita (gal/d)	81
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	5.2
Percentage of total surface water	<0.1
Percentage of total livestock	29
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	8,900
Percentage of total surface water	85
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	95
Excluding withdrawals for thermoelectric power	88
Irrigation withdrawals:	
Surface water (Mgal/d)	1,300
Percentage of total surface water	12
Percentage of total irrigation	59
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	1,4000

GENERAL SETTING

Louisiana is located in the Coastal Plain physiographic province (fig. 1). Coastal marshes extend 25 to 30 miles inland from the Gulf of Mexico. Elevations range from below sea level in southern Louisiana to more than 400 feet above sea level near the Arkansas-Louisiana State line.

Average annual precipitation varies from 48 inches in northwestern Louisiana to about 64 inches in southern Louisiana, (fig. 1). A high degree of variability exists areally during the summer months when precipitation is due to convective thunderstorms instead of frontal storms (fig. 1, bar graphs). Monthly evaporation ranges from 7 inches in southern Louisiana to 9 inches in northern Louisiana during July through September.

Runoff varies seasonally and areally depending on precipitation patterns. Average-annual runoff ranges from 10 inches in northwestern Louisiana to 26 inches in southeastern Louisiana (Gebert and others, 1985). The greatest runoff typically occurs from January through May (fig. 1). Runoff has been increasing since the late 1960's, and this trend, which is largely attributable to long-term climatic changes (Lee and Arcement, 1981), is observed at most streamflow-gaging stations in Louisiana—for example, those at Big Creek at Pollock (fig. 2, site 5), a gaging station in a watershed with few land-use changes, and at the Amite River near Denham Springs (fig. 2, site 6), a watershed with increasing urban development.

PRINCIPAL RIVER BASINS

Louisiana is in the South Atlantic-Gulf, Lower Mississippi, Arkansas-White-Red, and Texas-Gulf Regions (Seaber and others, 1984). The Pearl River basin is the principal basin in the South Atlantic-Gulf Region in Louisiana. The Lower Mississippi Region includes most of the State; the major river basins in this region are the Mississippi, the lower Red, the Ouachita, the Atchafalaya, the Teche, the Vermilion, the Calcasieu, and the Mermentau. In the Arkansas-White-Red Region, the Red River basin predominates. The Texas-Gulf Region includes the Sabine River at the Texas-Louisiana State line. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow statistics and other pertinent information are given in table 2.

SOUTH ATLANTIC-GULF REGION
Pearl Subregion

Pearl River Basin.—Approximately 10 percent of the 8,669-mi² drainage area of the Pearl River basin is in Louisiana. Other principal streams in this basin in Louisiana are the Bogue Chitto and Bogue Lusa Creek.

Surface-water withdrawals from this basin in Louisiana in 1980 amounted to 17.0 Mgal/d or 26 ft^3/s; all of this water was withdrawn from Bogue Lusa Creek and was used by paper-product industries (Louisiana Department of Transportation and Development, 1982).

Water quality in this basin is improving concurrent with improvement in treatment of municipal and industrial waste discharges. Fecal-coliform bacteria counts exceeded 1,000 cols/100 mL (colonies per 100 milliliters) in July 1978, but have since declined. The bacterial criteria applicable to a particular stream segment in Louisiana depends upon the use designation of that individual stream segment (Louisiana Department of Environmental Quality, 1984).

In addition to concerns about water quality, a major issue in the Pearl River basin is the severe flooding that has occurred during the past 10 years, especially in 1979, 1980, and 1983. The 1979 annual peak discharge for the Pearl River near Bogalusa (table 2, site 1) was 129,000 ft^3/s or 83,400 Mgal/d on April 24. The 1983 annual peak discharge for Bogue Chitto near Bush (table 2, site 2) was 131,700 ft^3/s or 85,100 Mgal/d on April 8 (the greatest flood for the period of record). The 1983 peak discharge for the Pearl River at Pearl River was 230,000 ft^3/s or 148,700 Mgal/d on April 9 (also the greatest flood for the period of record).

LOWER MISSISSIPPI REGION

Mississippi River Main Stem

The Mississippi River forms the northeastern border of the State. Following the flood of 1927, the elevations of the levees were raised to protect the Mississippi River Valley from major flooding. An extreme flood occurred on the Mississippi River in May 1973. The discharge on May 16 was 1,500,000 ft^3/s or 969,000 Mgal/d at Tarbert Landing (table 2, site 4). The Old River outflow channel (fig. 2) provides a major diversion from the Mississippi River. Approximately 30 percent (but not greater than 620,000 ft^3/s or 400,700 Mgal/d) of all streamflow in the Mississippi River is diverted to the Atchafalaya River through the Old River control structure. Two other structures—the Morganza spillway near Morganza (used only in 1973) and the Bonnet Carre spillway near New Orleans—are used to divert water from the Mississippi River during floods thereby reducing river stages at New Orleans.

The major instream use of the Mississippi River is for navigation. Baton Rouge and New Orleans have major deep-draft port facilities. The main offstream uses are for public and industrial supplies and for cooling in thermoelectric plants. Total surface-water withdrawal from the Mississippi River in 1980 was approximately 7,000 Mgal/d or 10,800 ft^3/s.

Water quality of the Mississippi River is affected by the heavily urbanized and industrialized corridor from Baton Rouge to New Orleans. There is continual concern over the possibility of major spills of toxic or hazardous materials from industries, barges, and ships. Phenols and DDT have been identified in the lower Mississippi River (Wells, 1980). Elevated fecal-coliform bacteria counts downstream from New Orleans are a problem; for instance, 2,000 cols/100 mL were detected in January 1983 at Belle Chase.

Lower Red-Ouachita Subregion

Ouachita River Basin.—The Ouachita River originates in Arkansas and has three locks and dams in Louisiana. Major tributaries to the Ouachita River in Louisiana are Bayou Bartholomew and Bayou D'Arbonne.

The major instream uses of the Ouachita River are for navigation and waste assimilation. The main offstream uses are for industrial supplies, irrigation, and for cooling in thermoelectric plants. The Ouachita River provides 490 Mgal/d or 758 ft^3/s and Bayou Bartholomew provides about 23 Mgal/d or 36 ft^3/s of surface water for these uses.

The locks and dams on the Ouachita River create large pools of water, which typically contain low concentrations of dissolved oxygen, especially during periods of very low streamflow.

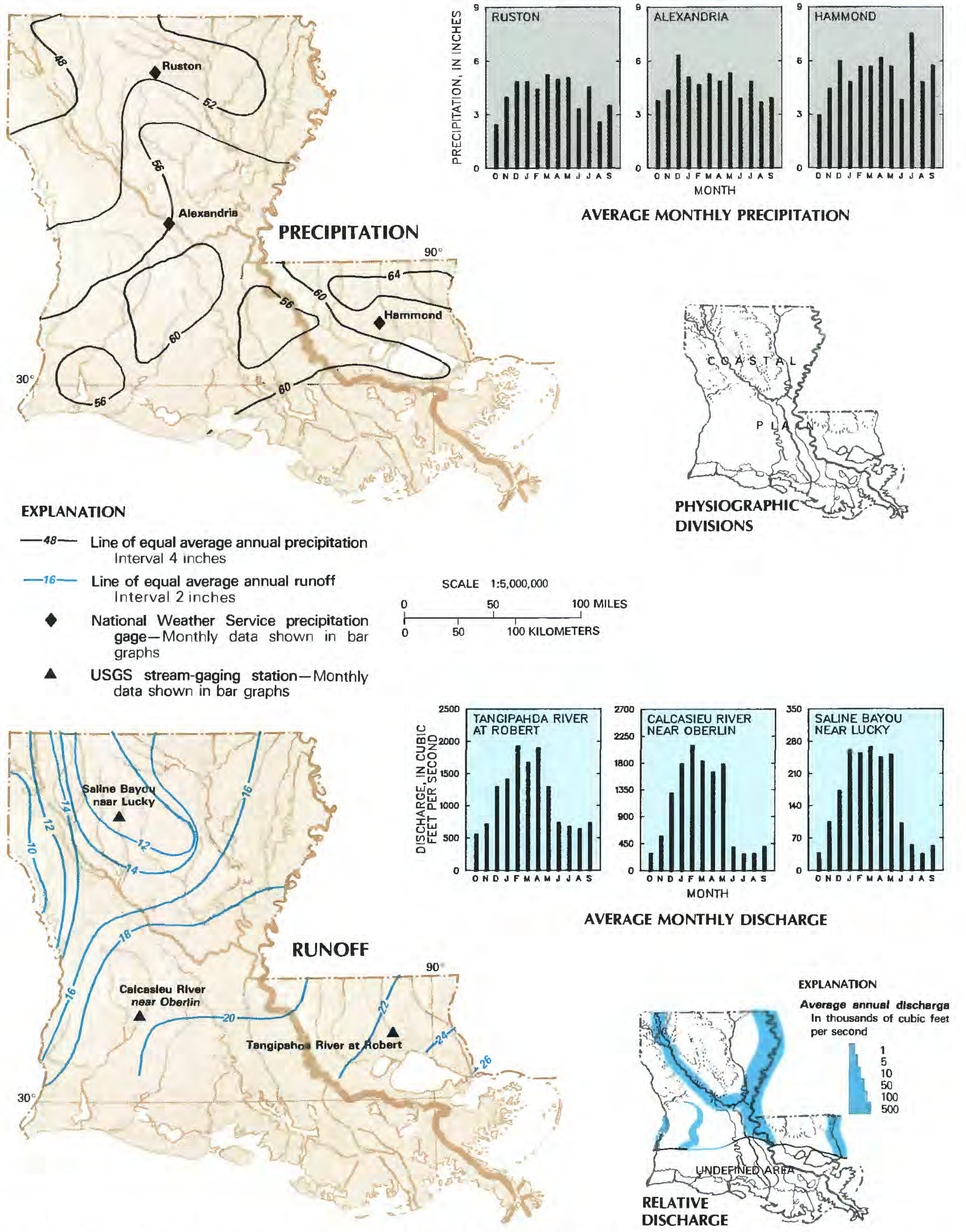

Figure 1. Average annual precipitation and runoff in Louisiana and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Louisiana

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				SOUTH ATLANTIC—GULF REGION PEARL SUBREGION Pearl River basin				
1.	Pearl River near Bogalusa (02489500).	6,573	1939–83	1,320	9,887	129,000	Negligible	Regulation due to Ross Barnett Reservior.
2.	Bogue Chitto near Bush (02492000).	1,213	1938–83	460	1,915	93,200	None	
				LOWER MISSISSIPPI REGION Mississippi River main stem[1]				
3.	Mississippi River at Vicksburg, Miss. (07289000).	1,118,160	1929–83	127,000	578,800	2,203,000	Appreciable	Drainage area is contributing.
4.	Mississippi River at Tarbert Landing, Miss. (07295100).	1,124,900	1939–83	142,000	514,200	. . . .	. . . do . . .	Drainage area is contributing.
				LOWER RED—OUACHITA SUBREGION Ouachita River basin				
5.	Big Creek at Pollock (07373000).	51	1943–83	7.4	61.4	37,200	None	Benchmark station.
				LOWER MISSISSIPPI—LAKE MAUREPAS SUBREGION				
6.	Amite River near Denham Springs (07378500).	1,280	1939–83	304	2,021	136,000	Negligible	
7.	Tangipahoa River at Robert (07375500).	646	1939–83	284	1,154	81,900	. . . do . . .	
				LOUISIANA COASTAL SUBREGION Atchafalaya—Teche—Vermilion and Calcasieu—Mermentau River basin				
8.	Atchafalaya River at Simmesport (07381490).	87,570	1939–83	26,000	196,700	. . . .	Appreciable	Drainage area is approximate.
9.	Calcasieu River near Oberlin (08013500).	753	1923–24, 1939–83	37	1,147	58,900	None	
10.	Calcasieu River near Kinder (08015500).	1,700	1923–24, 1939–57, 1962–83	202	2,568	121,000	Negligible	Regulation due to Bundick Lake.
				ARKANSAS-WHITE-RED REGION RED—SULPHUR SUBREGION Red River basin				
11.	Red River at Shreveport (07348500).	60,613	1929–83	1,150	24,030	297,000	Appreciable	100-year flood computed for period 1929–80.
12.	Red River at Alexandria (07355500).	67,500	1929–83	1,650	30,870	251,000	. . . do . . .	100-year flood computed for period 1929–80.
13.	Saline Bayou near Lucky (07352000).	154	1941–83	4.5	162	17,200	None	
				TEXAS—GULF REGION SABINE SUBREGION Sabine River basin				
14.	Sabine River near Ruliff, Tex., (08030500).	9,329	1925–83	432	7,491	90,700	Appreciable	Regulation due to Toledo Bend Reservoir began October 1966.

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[1] Includes all or parts of the Lower Mississippi–Yazoo, Lower Mississippi–Big Black, Lower Mississippi–Lake Maurepas, and the Lower Mississippi Subregions (Seaber, Kapinos, and Knapp, 1984).

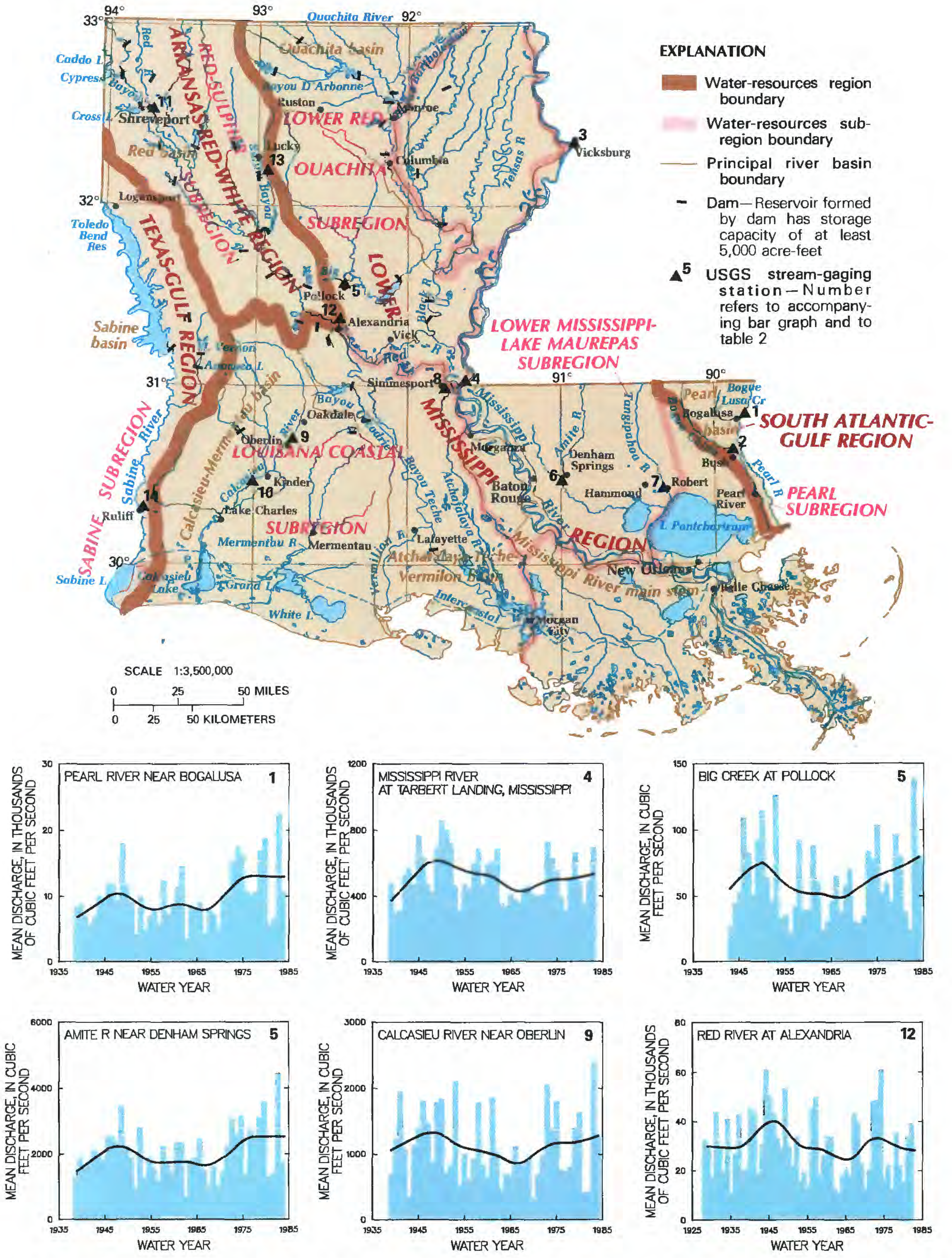

Figure 2. Principal river basins and related surface-water resources development in Louisiana and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

For example, a concentration of 3.3 mg/L (milligrams per liter) was measured in June 1983 at Columbia. The State water-quality standards specify that dissolved oxygen concentrations for freshwater shall be at or above 5.0 mg/L except for very short periods of time.

Major concerns relate to water quality and flooding in the lower part of the basin. Flooding caused by backwater from the Black and the Red Rivers is of special concern.

Louisiana Coastal Subregion

Atchafalaya-Teche-Vermilion River Basin.—The Atchafalaya River receives all of the discharge from the Red River and 30 percent of all streamflow from the Mississippi River (not to exceed 620,000 ft^3/s or 400,700 Mgal/d) through the Old River control structure into the Old River outflow channel. The Atchafalaya River flows through the Atchafalaya basin, which is part of a flood-control project designed to provide a diversion for extreme flooding on the Mississippi River.

The major instream uses for the Atchafalaya and the Vermilion Rivers and Bayou Teche are navigation and waste assimilation. The major use of the Atchafalaya basin is for recreation and the crawfishing industry. A total of 820 Mgal/d or 1,270 ft^3/s was withdrawn in this basin in 1980, 54 percent was for rice irrigation and 48 percent was for cooling in thermoelectric plants. Of the total offstream use, 37 percent was from the Vermilion River, 34 percent was from Bayou Cocodrie, and 22 percent from Charenton Canal.

The water quality in the Atchafalaya River is generally suitable for most uses except in the lower reach, which is affected by saltwater encroachment and fecal-coliform bacteria from municipal wastes. The Vermilion River is affected by municipal and industrial discharges, agricultural nonpoint-source discharges, and saltwater encroachment in the lower reach. Elevated counts of fecal-coliform bacteria (12,000 cols/100 mL in July 1983) and low concentrations of dissolved oxygen (0.8 mg/L in October 1982) have been measured in the Vermilion River near Lafayette. Most water-quality problems in Bayou Teche are related to agricultural nonpoint sources, but some problems are caused by discharges from sugar and food-processing plants.

Serious concerns for the Atchafalaya River include the deposition of large amounts of sediment in the Atchafalaya basin because of diversions from the Mississippi River, flooding near Morgan City, and the possible failure of the Old River control structure. The major concern in the Vermilion River and Bayou Teche basins is the degradation of water quality from inadequately treated municipal and industrial wastes.

Calcasieu-Mermentau River Basin.—The Calcasieu and the Mermentau Rivers are the principal sources of surface water in southwestern Louisiana. The lower Calcasieu River basin is dominated by broad coastal lakes such as Calcasieu Lake with a storage capacity of 210,000 acre-ft (acre-feet) or 68,400 Mgal (million gallons), in which the average depth is less than 5 feet and the water is moderately saline (8,900 mg/L of chloride in June 1976). The lower Mermentau River basin also is dominated by broad coastal lakes, such as Grand Lake and White Lake with storage capacities of 147,000 acre-ft or 47,900 Mgal and 234,000 acre-ft or 76,200 Mgal, respectively. These lakes are slightly to moderately saline. The channels of the Calcasieu and the Mermentau Rivers have been improved to allow navigation.

The Sabine River diversion has provided water to the Lake Charles area since 1982 for agricultural and chemical-industrial use. The major instream uses for the Calcasieu and the Mermentau Rivers are navigation and waste assimilation. In 1980, offstream withdrawals from the Mermentau River were 590 Mgal/d or 913 ft^3/s, most of which was for rice irrigation. The Calcasieu River provided 440 Mgal/d or 681 ft^3/s of surface water, most of which was for cooling in thermoelectric plants and for rice irrigation.

Substantial amounts of freshwater are available in the Calcasieu River; average discharge near Kinder (table 2, site 10) is 2,568 ft^3/s or 1,660 Mgal/d. The Calcasieu River from Oakdale to the Gulf of Mexico is considered to have the most severe surface-water quality problem in the State. For example, in April 1983, the Calcasieu River near Kinder had a fecal-coliform bacteria count of 6,300 cols/100 mL.

The principal water-quality problem in the Mermentau River is turbidity resulting from nonpoint agricultural sources. A dissolved-oxygen concentration of 0.7 mg/L was observed in October 1982 and elevated fecal-coliform bacteria counts of 3,700 cols/100 mL in April 1983 were present in water samples taken at Mermentau.

The major concerns in this subregion are severe flooding, coastal erosion, loss of marsh, and degradation of water quality by municipal and industrial effluents and by saltwater encroachment.

ARKANSAS-WHITE-RED REGION

Red-Sulphur Subregion

Red River Basin.—The Red River is highly regulated by numerous reservoirs in several States, including Louisiana. The largest lake in the Red River basin in Louisiana is Caddo Lake, which is located in Texas and Louisiana on Cypress Bayou, near Shreveport; it has a storage capacity of 188,000 acre-ft or 61,300 Mgal. Flood protection from the Red River is provided by levees throughout the river valley. A navigation route from the Mississippi and the Atchafalaya Rivers to Shreveport will be provided by a system of five locks and dams on the Red River. Lock and Dam No. 1 is completed near Vick, and Lock and Dam No. 2 below Alexandria is under construction; three others are planned.

The total surface water used in the basin is 260 Mgal/d or 420 ft^3/s of which 77 percent is used for cooling in thermoelectric plants and 19 percent is used for public supply. Of that used for public supply, most of the water is withdrawn from Cross Lake.

Water from the Red River in the Shreveport area occasionally contains elevated fecal-coliform counts (1,000 cols/100 mL in August 1982). Many of the water-quality problems in the Red River are directly related to municipal and industrial wastes, agricultural activities, oil and gas operations, and urban stormwater runoff.

Other concerns in the basin include the adequacy of water supplies, and the possible effects of the Red River waterway and of future strip mining. Although the average flow of the Red River at Shreveport is 24,030 ft^3/s or 15,500 Mgal/d (table 2, site 11), at times the flow is less than 3,000 ft^3/s or 1,940 Mgal/d, which causes concern about the future use of the Red River for water supply.

TEXAS-GULF REGION

Sabine Subregion

Sabine River Basin.—The Sabine River originates in Texas and forms the Louisiana-Texas border downstream from Logansport. Only about 12 percent of its 20,944-mi^2 drainage area is in Louisiana.

Toledo Bend Reservoir (completed in 1966 with 5,102,000 acre-ft or 1,662,000 Mgal of storage capacity) is the largest reservoir in the basin. It is used for conservation, recreation, water supply, and hydropower generation. Other reservoirs in the basin in Louisiana are Lake Vernon (completed in 1963) and Anacoco Lake (completed in 1961) with storage capacities of 57,000 acre-ft or 18,600 Mgal and 24,000 acre-ft or 7,820 Mgal, respectively.

Total surface-water withdrawals from Toledo Bend Reservoir for use in Louisiana is 1.3 Mgal/d or 2.0 ft^3/s, 90 percent of which is used for public supply. Toledo Bend Reservior also provides 1,400 Mgal/d or 2,170 ft^3/s of surface water for hydropower generation.

Surface-water quality in the basin is suitable for most uses. However, elevated coliform-bacteria counts in the reservoir caused by discharges of inadequately treated domestic wastewater occasionally have restricted use.

One of the major concerns in the basin is flooding. Effects of lignite mining in Desoto Parish on quality of water in streams tributary to the Toledo Bend Reservoir is also a major concern.

SURFACE-WATER MANAGEMENT

Louisiana's surface waters are managed by a number of agencies that are responsible for various aspects of this resource. No single agency has sole jurisdiction over the management of water quantity and quality in the State. Different State agencies, cities, and parishes participate with the U.S. Geological Survey in cooperative programs such as data collection, areal studies, and research.

The Louisiana Water-Resources Study Commission was established in 1964 to investigate the State's water policy and the roles of the different agencies that have water-resources responsibilities. The commission published a report on the water situation in the State (Louisiana Department of Transportation and Development, 1984) and made recommendations on water policy to the 1984 Louisiana Legislature.

Surface-water rights in Louisiana are determined under the riparian doctrine. Louisiana's statutes define rights of landowners, nonriparians, and the State with respect to withdrawal and use of surface waters.

The Sabine River Compact between Texas and Louisiana was ratified in 1954, and the Red River Compact between Oklahoma, Texas, Arkansas, and Louisiana was ratified in 1978. These compacts provide for an equitable apportionment of streamflow between the participating States.

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FOR ADDITIONAL INFORMATION

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MAINE
Surface-Water Resources

Maine has an abundance of surface-water resources, including more than 2,900 lakes and 32,000 miles of rivers and streams. Plentiful surface-water resources suitable for most uses have attracted industrial, municipal, and recreational development. Approximately 75,000 Mgal/d (million gallons per day) or 116,000 ft³/s (cubic feet per second) of surface water generates about 20 percent of the electric power used in the State at about 100 hydropower dams (table 1). Surface water also provides 770 Mgal/d or 1,190 ft³/s, which is 91 percent of the total water withdrawn for offstream use including water supply for 43 percent of the State's population. Ground water, which is a less abundant resource in Maine, provides the remaining 80 Mgal/d or 124 ft³/s, which is 9 percent of the total. Two major uses—industrial supplies (670 Mgal/d or 1,040 ft³/s) and municipal supplies (85 Mgal/d or 132 ft³/s)—dominate offstream surface-water use.

The surface-water issues of greatest concern to State and local officials and to the citizens of Maine are protection of the State's water resources, that are now generally in excellent condition, and identification and improvement of those resources that have been adversely affected by development. These concerns have to be weighed against demands for industrial and municipal supplies and recreational use, and proposals for hydroelectric development. Flooding during spring snowmelt along the flood plains of larger rivers also is a major concern.

GENERAL SETTING

Maine is located in the New England physiographic province of the Applachian Highlands (fig. 1). The topography is diverse, ranging from the Seaboard Lowlands in southwestern Maine to the mountainous White Mountain section in the northwestern part of the State (fig. 1). This diversity of terrain is reflected in the geographic distribution of annual precipitation in the State. Annual precipitation ranges from about 34 inches in the northeast to 55 inches in the northwest and north-central mountains and averages about 42 inches statewide (Knox and Nordenson, 1955). Precipitation does not exhibit a strong seasonal pattern and is distributed uniformly throughout the year (fig. 1).

Runoff varies both geographically and seasonally as a result of precipitation patterns. During the winter months of December through March, precipitation falls primarily as snow and runoff rates are low. During April and May, snowmelt, concurrent rainfall, the saturated condition of the soils, and reduced evapotranspiration combine to cause high rates of runoff. Flooding is common during this period. Runoff rates during the summer months of June through August tend to be low because of increased evapotranspiration and absorbtive capacity of the soils. During the fall months of September through November, runoff typically increases slightly in response to a reduction in evapotranspiration that occurs after the growing season. Examples of the seasonal runoff pattern for relatively unregulated rivers are the St. John River below Fish River at Fort Kent and the Little Androscoggin River near South Paris (fig. 1, bar graphs).

Regulation of streamflow reduces peak runoff rates in the spring as reservoirs are filled. Runoff captured during the spring months is used to maintain summer base flow—primarily for industrial supply and hydroelectric power generation. The Kennebec River at Bingham (fig. 1) illustrates the seasonal pattern of runoff for a regulated river.

PRINCIPAL RIVER BASINS

Maine is located in the New England Region and can be subdivided into six major subregions (fig. 2). Four of the subregions—the St. John, the Penobscot, the Kennebec, and the Androscoggin—are dominated by the river basins for which they are named. The remaining two subregions—the Maine Coastal and Saco Subregions—consist of several smaller drainage systems that drain the coastal sections of Maine. These subregions are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Maine

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Adapted from: Solley, Chase, and Mann, 1983; Maine Ground Water Quality Subcommittee]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	483
Percentage of total population	43
From public water-supply systems:	
Number (thousands)	473
Percentage of total population	42
From rural self-supplied systems:	
Number (thousands)	10
Percentage of total population	1
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	850
Surface water only (Mgal/d)	770
Percentage of total	91
Percentage of total excluding withdrawals for thermoelectric power	90
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	85
Percentage of total surface water	11
Percentage of total public supply	81
Per capita (gal/d)	180
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.5
Percentage of total surface water	0.1
Percentage of total rural domestic	2
Per capita (gal/d)	50
Livestock:	
Surface water (Mgal/d)	0.7
Percentage of total surface water	0.1
Percentage of total livestock	41
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	670
Percentage of total surface water	87
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	94
Excluding withdrawals for thermoelectric power	95
Irrigation withdrawals:	
Surface water (Mgal/d)	5.9
Percentage of total surface water	1
Percentage of total irrigation	97
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	75,000

NEW ENGLAND REGION
St. John Subregion

From its headwaters in northwestern Maine, the St. John flows northwestward to the Canadian border near St. Francis. From St. Francis to Hamlin, the St. John forms approximately 100 miles of the boundary between the United States and Canada. The St. John River has a drainage area of 21,360 mi² (square miles) at its mouth, 7,360 mi² of which are located in Maine. Major tributaries to the St. John in Maine include the Big Black, the Allagash, the Fish, and the Aroostook Rivers.

The runoff characteristics of the St. John River basin in Maine remain relatively unaffected by human activities (table 2), except for the diversion of runoff from the 249-mi² drainage area of Chamberlain Lake through Telos Canal into the East Branch of the Penobscot River.

Recreational water use is of prime importance in the St. John River basin. Allagash Wilderness Waterway is the only wild and scenic river in New England. Most rivers and lakes in the basin are noted for their fisheries and canoeing. Flooding in the St. John River basin is an annual occurrence and a major concern. Water quality is suitable for most uses in the subregion.

Maine Coastal Subregion

The Maine Coastal Subregion is comprised of several lesser rivers that drain the coastal plain of Maine. The subregion extends from Merrymeeting Bay to the Canadian border. Principal rivers in the basin include the St. Croix (an international river), the Machias, the Dennys, the Narraguagus, the Pleasant, the Union, the St. George, and the Sheepscot Rivers. The total drainage area of the basin in Maine is 2,486 mi^2.

Although several rivers in the Maine Coastal basin are regulated, the St. Croix is the most extensively regulated. Major storage reservoirs in the St. Croix include East and West Grand Lakes, Spednik Lake, and Grand Falls Flowage. These reservoirs have a combined usable storage capacity of about 540,000 acre-ft (acre-feet) or 176,000 Mgal (million gallons) and are operated primarily for hydropower and industrial supply.

The Maine Coastal basin is recognized primarily for its recreational value. Rivers in the basin support the only self-sustaining Atlantic salmon runs in the United States. Cold-water fisheries opportunities are outstanding, especially in the pristine West Grand Lakes region. The Machias, the Narraguagus, and the Pleasant are all major recreational rivers and are heavily used for canoeing. Water quality is suitable for most uses in the subregion.

Penobscot Subregion

The Penobscot River Subregion—the largest river basin located totally in Maine—occupies 8,592 mi^2 or about one-fourth of the State's area. The Penobscot River originates at the junction of the East and West Branches at Medway. The West Branch flows eastward from the mountains of northwestern Maine through several regulated lakes to Medway. Storage capacity of these lakes in the West Branch is 1.3 million acre-ft or 424,000 Mgal. Headwaters of the East Branch are in north- central Maine. Storage capacity of reservoirs in the smaller East Branch is 157,000 acre-ft or 51,200 Mgal. The East Branch drainage includes runoff from the 249-mi^2 basin of Chamberlain Lake that is diverted from the St. John River Basin into the East Branch through the Telos Canal. From Medway, the Penobscot River flows in a southerly direction to the Atlantic Ocean. Major tributaries to the Penobscot River are the Mattawamkeag and the Piscataquis Rivers.

Recreational significance of the Penobscot River basin continues to grow. Fishing and whitewater rafting on the West Branch are being enjoyed by an increasing number of people annually. New municipal and industrial wastewater treatment facilities have reduced waste discharges to the river and improved water quality, thereby fostering the return of Atlantic salmon runs in the basin. Atlantic-salmon fishing in the Penobscot is internationally famous and is now an important activity in the basin.

Principal water users in the Penobscot River basin are hydropower plants and industries such as paper mills and textiles. The East and West Branches are regulated primarily to meet the needs of these users.

Kennebec Subregion

Headwaters of the Kennebec River Basin are in the Moose River drainage basin in northwestern Maine. The Moose River and several lesser tributaries flow into the 74,900-acre Moosehead Lake, the outlet of which is the origin of the Kennebec River. From Moosehead Lake, the river flows southward to Merrymeeting Bay and the Atlantic Ocean. At the inlet to Merrymeeting Bay, the Kennebec River drains a total area of 5,893 mi^2. The principal tributaries to the Kennebec River below Moosehead Lake are the Dead, the Carrabassett, the Sandy, and the Sebasticook Rivers.

Storage capacity is concentrated in the upper parts of the basin. Upstream from Bingham, principal reservoirs have a combined usable capacity of about 1.3 million acre-ft or 424,000 Mgal. Moosehead Lake alone accounts for about 42 percent of this total.

Recreational use of surface waters in the Kennebec River basin has become increasingly important in recent years. Canoeing and whitewater rafting are extremely popular on reaches of the Dead River and the Kennebec River below Indian Pond. Moosehead Lake is one of the most popular fishing and boating lakes in the State. Although recreational uses are important in the basin, principal water users are hydropower plants and industries located along the main stem of the Kennebec River. Water quality is adequate to meet the needs of the hydropower and industrial users.

Regulation in the basin tends to reduce magnitudes of flood peaks along the main stem of the Kennebec River. For example, the flow that is equaled or exceeded an average of once every 100 years (100-year flood) on the unregulated Carrabassett River near North Anson (table 2, site 10) is 39,500 ft^3/s or 25,500 Mgal/d or a runoff rate of 112 (ft^3/s)/mi^2 (cubic feet per second per square mile of drainage area). The 100-year flood for the Kennebec River at Bingham (table 2, site 9) is 59,200 ft^3/s or 38,300 Mgal/d or a runoff rate of only 22 (ft^3/s)/mi^2. Although flood peaks are reduced by regulatory capacity in the basin, flooding remains a problem. Flood damage that occurs in several communities in the lower Kennebec River—principally from Waterville to Gardiner—have prompted recent studies by State and Federal agencies.

Androscoggin Subregion

Headwaters of the Androscoggin River drain mountainous areas in northwestern Maine near the New Hampshire border. The upper part of the basin is dominated by a series of lakes (Kennebago, Rangley, Mooselookmeguntic, Upper and Lower Richardson, Azischos, and Umbagog) that are operated primarily as storage reservoirs. These lakes have a combined storage capacity of about 644,000 acre-ft or 210,000 Mgal and account for most of the regulated storage in the basin.

The river enters Maine from New Hampshire and flows to Merrymeeting Bay and the Atlantic Ocean. Major tributaries to the Androscoggin River in Maine include the Ellis, the Swift, the Nezinscot, and the Little Androscoggin Rivers. Drainage area of the Androscoggin River at its mouth is 3,524 mi^2.

Principal surface-water users in the Androscoggin River basin in Maine are industrial and hydropower facilities along the main stem of the Androscoggin River in the towns of Rumford, Livermore Falls, Jay, Lewiston, Topsham, and Brunswick.

As a result of intensive industrial development along the main stem of the Androscoggin River, water quality is a problem. Historically, the Androscoggin has been considered the most polluted river in Maine. However, construction of modern industrial and municipal wastewater-treatment facilities has improved conditions in recent years. Depletion of dissolved-oxygen concentrations in reaches of the Androscoggin between Livermore Falls and Lewiston and in the Little Androscoggin near South Paris remains a problem.

Runoff peaks along the Androscoggin River are reduced but not eliminated by regulatory storage in the basin. Flood damage has been and continues to be a concern in communities along the river. Maximum discharge of record (1928–84) on the Androscoggin River near Auburn (table 2, site 13) was 135,000 ft^3/s or 87,200 Mgal/d on March 20, 1936.

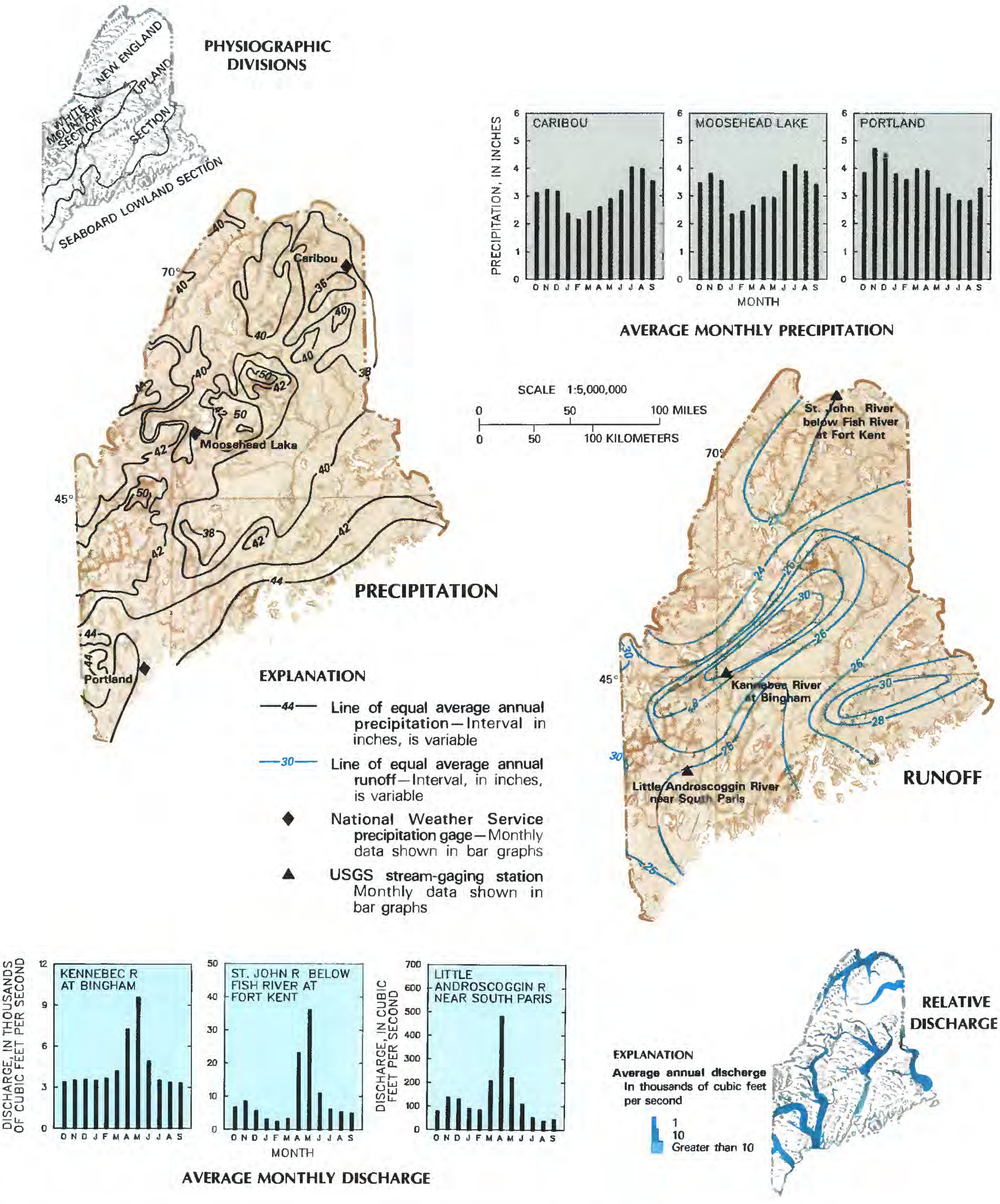

Figure 1. Average annual precipitation and runoff in Maine and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA), based on U.S. Congress, 1969, and Knox and Nordenson, 1955; monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Maine

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
	NEW ENGLAND REGION ST. JOHN SUBREGION							
1.	St John River at Ninemile Bridge (01010000).	1,341	1950-85	96	2,330	47,900	None	Recreational area.
2.	St. John River below Fish River at Fort Kent (01014000).	5,665	1926-85	747	9,730	167,000	. . . do . . .	Recreational area. International river.
3.	Aroostook River at Washburn (01017000).	1,654	1930-85	143	2,670	51,500	Moderate	Industrial supply.
	MAINE COASTAL SUBREGION							
4.	St Croix River at Bering (01021000).	1,374	1958-85	484	2,760	31,000	Appreciable	Industrial supply and power generation. International river.
5.	Narraguagus River at Cherryfield (01022500).	227	1948-85	29	503	11,300	Negligible	Recreational area and important Atlantic salmon fishery.
6.	Sheepscot River at North Whitefield (01038000).	148	1938-85	8.8	249	7,080	. . . do . . .	Recreational area.
	PENOBSCOT SUBREGION							
7.	Penobscot River at Dover-Foxcroft (01031500).	298	1902-85	19	603	25,400	Negligible	Industrial supply and power generation.
8.	Penobscot River at West Enfield (01034500).	6,671	1901-85	2,970	11,960	150,000	Appreciable	Industrial supply and power generation.
	KENNEBEC SUBREGION							
9.	Kennebec River at Bingham (01046500).	2,715	1907-10, 1930-85	1,310	4,450	59,200	Appreciable	Power generation, recreational area, water supply.
10.	Carrabassett River near North Anson (01047000).	353	1902-07, 1925-85	45	717	39,500	None	Recreational area.
	ANDROSCOGGIN SUBREGION							
11.	Swift River near Roxbury (01055000).	96.9	1929-85	6.9	199	21,100	None	Recreational area.
12.	Little Androscoggin River near South Peris (01057000).	75.8	1913-24, 1931-85	2.6	139	6,700	Negligible	Industrial supply.
13.	Androscoggin River near Auburn (01059000).	3,263	1928-85	1,690	6,140	99,700	Appreciable	Industrial supply and power generation.
	SACO SUBREGION							
14.	Royal River at Yarmouth (01060000).	141	1949-85	24	275	11,000	Moderate	Power generation.
15.	Saco River at Cornish (01066000).	1,293	1916-85	386	2,710	36,800	Appreciable	Recreational area, power generation, and water supply.

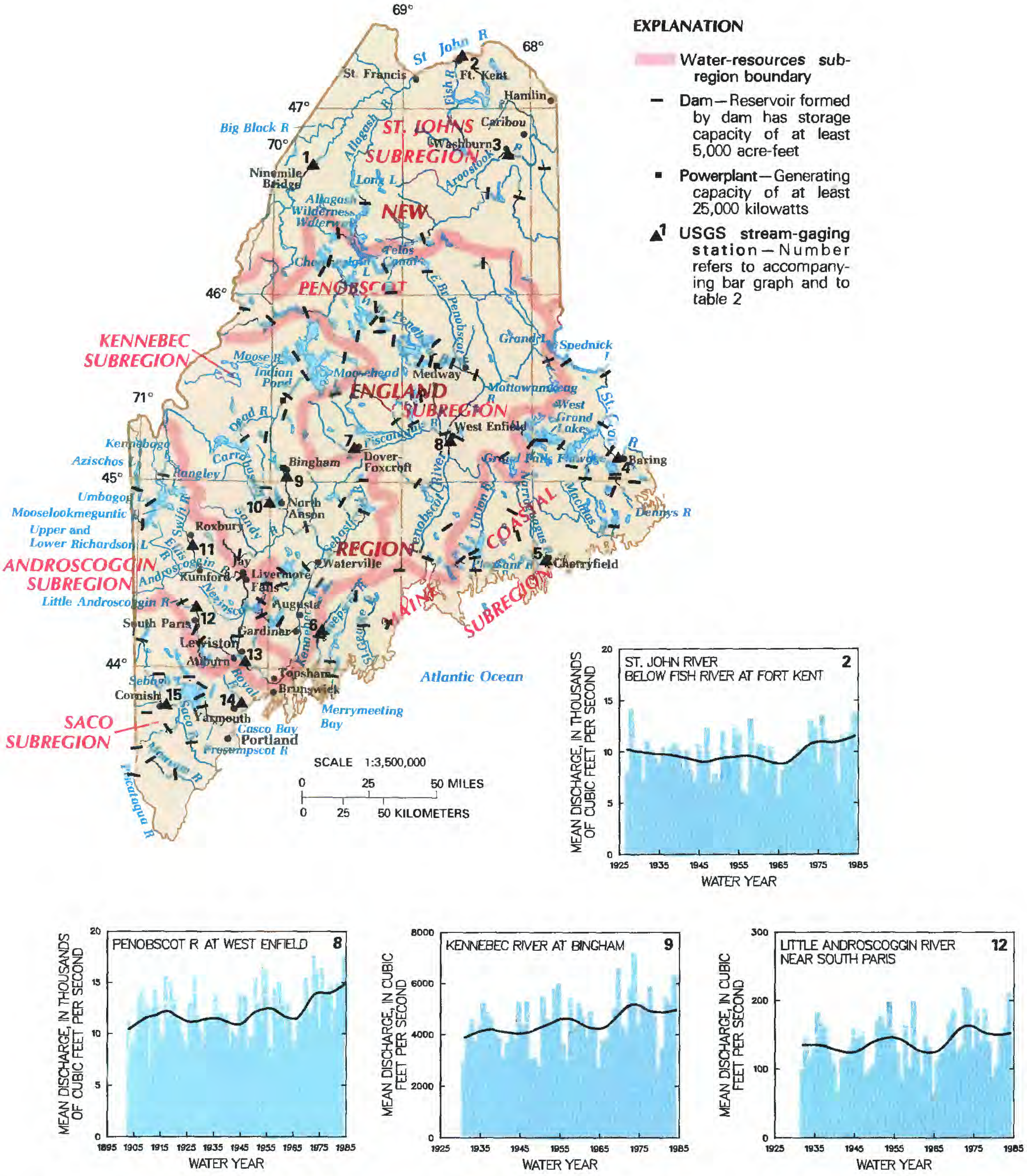

Figure 2. Principal river basins and related surface-water resources development in Maine and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Saco Subregion

The Saco Subregion in Maine extends from Merrymeeting Bay to the New Hampshire border. Major rivers in the basin include the Presumpscot, the Saco, the Mousam, and the Piscataqua.

The Presumpscot River, which originates at the outlet of Sebago Lake, flows eastward to its mouth in Casco Bay. Drainage area of the Presumpscot is 647 mi^2, all of which is located in Maine. Long and Sebago Lakes which have a combined usable capacity of approximately 223,000 acre-ft or 72,700 Mgal, are operated primarily to provide uniform streamflow for the several hydropower and industrial users located downstream. Sebago Lake, known for its excellent quality, is the major supply for Portland Water District, which serves about 140,000 people. Sebago Lake also is used extensively for recreational purposes, such as boating and fishing.

The Saco River originates in eastern New Hampshire and flows southeastward from New Hampshire across Maine to the Atlantic Ocean. The drainage area of the Saco River at its mouth is 1,700 mi^2. There is no significant manmade storage capacity in the basin. Combined usable capacity of several minor reservoirs in the basin totals only 78,000 acre-ft or 25,400 Mgal. Broad, overbank flood plains provide natural storage that significantly flattens flood peaks.

Principal water users in the Saco basin are several hydropower facilities on the main stem of the river. Use of the river for municipal and industrial supply is of increasing importance, especially as development in the basin increases. The Saco River is a valued recreational asset to Maine. The Saco River has been called the most heavily canoed river in New England. Its use has been estimated at 90,000 canoer-days per season (Land and Water Resources Center, 1984).

SURFACE-WATER MANAGEMENT

The surface-water resources of Maine are managed by public and private agencies. Flows in most major rivers are regulated by private companies that use the river for hydropower generation or for process water. Streamflow requirements for the private river managers are usually established by the Federal Energy Regulatory Commission or State regulatory agencies through licensing procedures.

The water-quality classification of the State's rivers and lakes and their protection are the responsibility of the Maine Department of Environmental Protection (MDEP). The MDEP licenses waste discharges to surface-water bodies and monitors the licensees and receiving waters to ensure that water-quality standards are being met.

The Maine Department of Inland Fisheries and Wildlife (MDIFW) and the Department of Marine Resources (DMR) manage and protect the aquatic life in streams. The MDIFW reviews all applications that involve alteration of streambeds and streamflows in streams above head of tide. The DMR reviews all developments in tidal streams and upland streams with anadromous fish populations.

Use of surface waters for public-supply purposes is regulated by the Maine Department of Human Services (MDHS). The MDHS reviews water-supply development plans, establishes water-supply quality standards, and monitors the quality of water delivered to consumers to ensure that it meets standards.

Overall, Maine's surface-water-management program is better developed than the State's ground-water program, which is now being formulated by the MDEP and other State agencies. The great importance of surface-water resources to the economy of Maine ensures that the surface-water-management program will continue to be a top priority of Federal, State, regional, and local officials. The U.S. Geological Survey and organizations of the State of Maine have had cooperative agreements for the systematic collection of streamflow records since 1909, and for water-quality and ground-water records since 1957.

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MARYLAND AND THE DISTRICT OF COLUMBIA
Surface-Water Resources

Maryland and the District of Columbia both have abundant surface-water resources. In 1980, 72 percent of the population of Maryland and 100 percent of the population of the District of Columbia (table 1) depended on surface water to meet municipal water-supply needs. In 1980, 15,000 Mgal/d (million gallons per day) or 23,200 ft^3/s (cubic feet per second) were used to generate hydroelectric power—the primary instream use of surface water. Offstream use primarily is for municipal and industrial supply; in 1980 this water use accounted for 98 percent of offstream surface-water usage in Maryland and 100 percent of offstream usage in the District of Columbia. In Maryland, where ground-water and surface-water resources are used extensively, surface-water withdrawals amounted to 70 percent of the total water withdrawn in 1980. Ground water, which provides the remaining 30 percent of water withdrawals, is used primarily in the Coastal Plain of Maryland where fresh surface-water supplies are less dependable.

The quantity and quality of surface waters and the mitigation of damages caused by floods are important issues in Maryland and the District of Columbia. State and local governments are being challenged to balance increasing demands by industry and municipalities for additional water supplies to sustain economic growth with the need for recreational areas for an expanding population.

Table 1. Surface-water facts for Maryland and the District of Columbia

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Maryland—Herring (1983), Solley, Chase, and Mann, (1983); District of Columbia—Solley, Chase, and Mann (1983)]

	Md	D.C.
POPULATION SERVED BY SURFACE WATER, 1980		
Number (thousands)	3,040	638
Percentage of total population	72	100
From public water-supply systems:		
Number (thousands)	3,040	638
Percentage of total population	72	100
From rural self-supplied systems:		
Number (thousands)	0	0
Percentage of total population	0	0
OFFSTREAM USE, 1980		
FRESHWATER WITHDRAWALS		
Surface water and ground water, total (Mgal/d)	1,400	340
Surface water only (Mgal/d)	970	340
Percentage of total	70	100
Percentage of total excluding withdrawals for thermoelectric power	58	100
Category of use		
Public-supply withdrawals:		
Surface water (Mgal/d)	440	210
Percentage of total surface water	45	62
Percentage of total public supply	90	100
Per capita (gal/d)	145	329
Rural-supply withdrawals:		
Domestic:		
Surface water (Mgal/d)	0	0
Percentage of total surface water	0	0
Percentage of total rural domestic	0	0
Per capita (gal/d)	0	0
Livestock:		
Surface water (Mgal/d)	0.5	0
Percentage of total surface water	<0.1	0
Percentage of total livestock	5	0
Industrial self-supplied withdrawals:		
Surface water (Mgal/d)	520	130
Percentage of total surface water	53	38
Percentage of total industrial self-supplied:		
Including withdrawals for thermoelectric power	93	100
Excluding withdrawals for thermoelectric power	80	43
Irrigation withdrawals:		
Surface water (Mgal/d)	9.4	0
Percentage of total surface water	1	0
Percentage of total irrigation	47	0
INSTREAM USE, 1980		
Hydroelectric power (Mgal/d)	15,000	8.0

GENERAL SETTING

Maryland is located in the Coastal Plain, the Piedmont, the Blue Ridge, the Valley and Ridge, and the Appalachian Plateaus physiographic provinces (fig. 1). The District of Columbia is located in the Piedmont and the Coastal Plain provinces. The Coastal Plain province, which is underlain by gently dipping unconsolidated strata, rises from sea level to slightly less than 100 feet above sea level east of Chesapeake Bay and to a little more than 200 feet above sea level in southern Maryland. The Piedmont and the Blue Ridge provinces are underlain by crystalline rock and consolidated sedimentary units. The gently rolling hills of the Piedmont have elevations of generally less than 800 feet above sea level. In the Blue Ridge province, elevations rise to more than 1,600 feet above sea level. Sharply folded and faulted consolidated sedimentary strata form the Valley and Ridge province where elevations generally range from about 400 feet in the valleys to about 1,500 feet on ridges. The Appalachian Plateaus are underlain by flat-lying to gently folded sedimentary strata; elevations generally range from 1,500 to 3,000 feet above sea level. The Appalachian Plateaus province contains the highest point in Maryland—3,360 feet above sea level—near the southwestern corner of the State.

Average annual precipitation in Maryland, based on a 30-year period of record (1951-80), is about 42 inches. In general, precipitation is higher in the eastern and far western parts of the State and lower in the rest of the State (fig. 1). The greatest precipitation (more than 50 inches per year) occurs in the extreme southwestern corner of the Appalachian Plateaus province in western Maryland. The least precipitation occurs just east of the Appalachian Plateaus province where less than 36 inches per year fall because of orographic effects. Average annual precipitation in the District of Columbia is about 43 inches.

Precipitation is fairly well distributed throughout the year. The variability of average monthly precipitation at selected rainfall stations in Maryland is shown in figure 1. In general, slightly more precipitation occurs in the spring and summer than in the fall and winter. Throughout the State, average precipitation during all months in the year generally exceeds 2.5 inches.

The percentage of precipitation that becomes runoff varies considerably over the State. As much as two-thirds of the precipitation that falls on the far western part of Maryland ultimately becomes streamflow. In contrast, only about one-third of the total precipitation in the southeastern part of the State becomes streamflow. In other parts of the State and in the District of Columbia, generally from one-third to one-half becomes runoff. The difference between amounts of precipitation and runoff is made up almost entirely of evapotranspiration losses.

Runoff varies geographically and seasonally, depending on the geology and the seasonal precipitation patterns (fig. 1). During the winter months of December through February, precipitation falls primarily as snow, and runoff rates are relatively low. During the spring months of March through April, snowmelt, rain, the saturated condition of the soils, and reduced evapotranspiration combine to increase runoff. Runoff during the summer months of June through September is low because of large evapotranspiration losses. During the months of October and November, runoff increases as evapotranspiration declines at the end of the growing season. Examples of the seasonal runoff pattern are shown in figure 1 for the Youghiogheny River near Oakland, the Monocacy River at Jug Bridge near Frederick, and the Choptank River near Greensboro.

PRINCIPAL RIVER BASINS

The District of Columbia and almost all of Maryland are within the Mid-Atlantic Region (fig. 2). The Mid-Atlantic Region in Maryland includes the Potomac Subregion (which includes the District of Columbia), the Upper Chesapeake Subregion, and the Susquehanna Subregion. The extreme northwestern corner of Maryland is in the Monongahela Subregion of the Ohio Region. The Potomac, the Susquehanna, and the Monongahela Subregions are dominated by the river basins for which they are named. Large parts of all three basins lie outside of the State; only the Upper Chesapeake Subregion, which includes streams that primarily drain the Coastal Plain province, lies almost entirely in Maryland. These river basins are described below; their location, and long-term average streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MID-ATLANTIC REGION

Potomac Subregion

The headwaters of the Potomac River drain the mountainous areas of western Maryland, beginning at the State's southwestern corner, and become the North Branch Potomac River—the border between Maryland and West Virginia. The North Branch combines with the South Branch Potomac River, about 20 miles below Cumberland, to form the Potomac River. From there, the river continues for 285 miles as the border between Maryland and West Virginia and, as the border between Maryland and Virginia before it empties into the Chesapeake Bay. The drainage area of the basin at the mouth of the Potomac River is 14,670 mi^2 (square miles); 26 percent of the basin is located in Maryland and the District of Columbia. Selected streamflow characteristics are given in table 2 for Conococheague Creek (site 1), Antietam Creek (site 2), and the Monocacy River (site 3)—the major Maryland tributaries to the Potomac River.

Principal surface-water uses in the Potomac River basin include run-of-the-river hydroelectric facilities; industrial facilities, and public water-supply systems. Bloomington Dam in western Maryland (fig. 2) helps to ensure adequate water supplies for Washington, D.C., during times of drought by making controlled releases to augment natural flows. Construction of the dam was prompted by a severe drought during the summer of 1966, during which flow of the Potomac River at Washington, D.C., dropped to a daily low of 121 ft^3/s or 78 Mgal/d after diversions of 480 ft^3/s or 310 Mgal/d for municipal use. Projections of population growth for the D.C. area at that time suggested that municipal water needs during another drought of similar magnitude might reduce the flow to levels insufficient to sustain aquatic life.

Surface-water quality in the basin is related primarily to the type of consumptive use. Extensive agriculture (especially the cultivation of tobacco), coal mining, and increasing industrial activity have resulted in significant erosion, severe siltation, and chemical degradation of the Potomac River. Major sources of the chemical degradation are acid-mine drainage in western Maryland and the discharge of raw sewage from municipal and industrial areas. Many of these problems have been mitigated by upgrading municipal and industrial wastewater-treatment facilities, use of improved land-management practices, and reclamation of mined lands.

Because of the predominantly rural nature of the Potomac River basin, its runoff characteristics are relatively unaffected by human activities (table 2). Bloomington Dam, the largest manmade structure on the Potomac River, regulates drainage from only 266 mi^2 of the basin at a point 41 miles upstream from Cumberland. The lake, in addition to small run-of-the-river hydroelectric plants on the main stem, affects low flows in the basin, but has no major effect on flood peaks along the main stem below the confluence of the North and South branches of the Potomac. Major flooding in the Potomac basin occurred in 1889, 1924, 1936, 1937, 1942, and 1972. In the Washington, D.C. area, the flood of March 1936 had a peak flow of 484,000 ft^3/s or 313,000 Mgal/d.

The bar graph for the Monocacy River at Jug Bridge near Frederick (fig. 2, site 3) shows the variability of annual average discharge at the site with time. During the late 1930's and 1940's, average flows were increasing because of periodic flooding. From the late 1940's to the early 1970's, average flows generally declined because of periodic droughts. From about 1972 to 1981, average flows increased because of above-average rainfall. Trends for the Monocacy River are representative of those for the remainder of the Potomac River basin in Maryland and the District of Columbia.

Upper Chespeake Subregion

The Upper Chesapeake Subregion has a drainage area of approximately 7,400 mi^2 in Maryland. This area comprises the major part of the Coastal Plain in Maryland and one-third of the Piedmont province. Principal rivers in the subregion include the Patuxent, the Patapsco, the Gunpowder, the Chester, the Choptank, the Nanticoke, and the Pocomoke. Selected streamflow characteristics for the Pocomoke (site 4), the Choptank (site 5), and the Patuxent (site 6) Rivers are given in table 2.

The Gunpowder and Patapsco Rivers both have appreciable regulation. Major storage is provided by Liberty Reservoir on the Patapsco River [completed in 1954 with 129,000 acre-ft (acre-feet)) or 42,100 Mgal (million gallons) of storage]; and Prettyboy (completed in 1933) and Loch Raven (completed in 1914) Reservoirs on Gunpowder Falls, with a combined storage capacity of 133,000 acre-ft or 43,300 Mgal. These reservoirs are operated to help meet the municipal water-supply needs of the city of Baltimore and its suburbs. The Patuxent River also has major storage available in the Triadelphia (completed in 1943) and T. Howard Duckett (completed in 1954) Reservoirs, with a combined storage capacity of 36,200 acre-ft or 11,800 Mgal. These reservoirs are used to regulate flood peaks, provide recreational areas, and help meet the water-supply needs of Washington, D.C., and its suburbs.

The bar graph for the Choptank River near Greensboro (fig. 2, site 5), which shows the long-term variability of annual average discharge for this site, is representative of other unregulated streams in the subregion. Droughts in 1966 and 1977 clearly show the effect of deficient rainfall for extended periods on average discharge. During the drought of 1966, the average monthly flow for August was 5.3 ft^3/s or 3.4 Mgal/d compared to the long-term August average of 30 ft^3/s or 19 Mgal/d. The high annual average discharges of 1952, 1958, and 1972 occurred in response to above-average rainfall during those years. A maximum discharge of 6,970 ft^3/s or 4,500 Mgal/d occurred during August 1967.

The Upper Chesapeake Subregion is well known for its agriculture (especially the tobacco industry in southern Maryland) and, more importantly, for the maritime industries supported by the Chesapeake Bay. These industries include shipping, commercial fishing, oystering and clamming, and harvesting and marketing the world-famous Maryland blue crab. The importance of preserving these industries has led to ongoing programs by Federal, State, and local governments to minimize water pollution caused by rapid urban growth, disposal of industrial and municipal wastes, and agricultural runoff.

Susquehanna Subregion

Only 282 mi^2 of the Susquehanna Subregion is located in Maryland; the remaining 27,187 mi^2 of the subregion is in Pennsylvania and New York. The principal river in the subregion is the Susquehanna, which is regulated extensively in Pennsylvania and also in Maryland by Conowingo Dam (fig. 2) (completed in 1928)

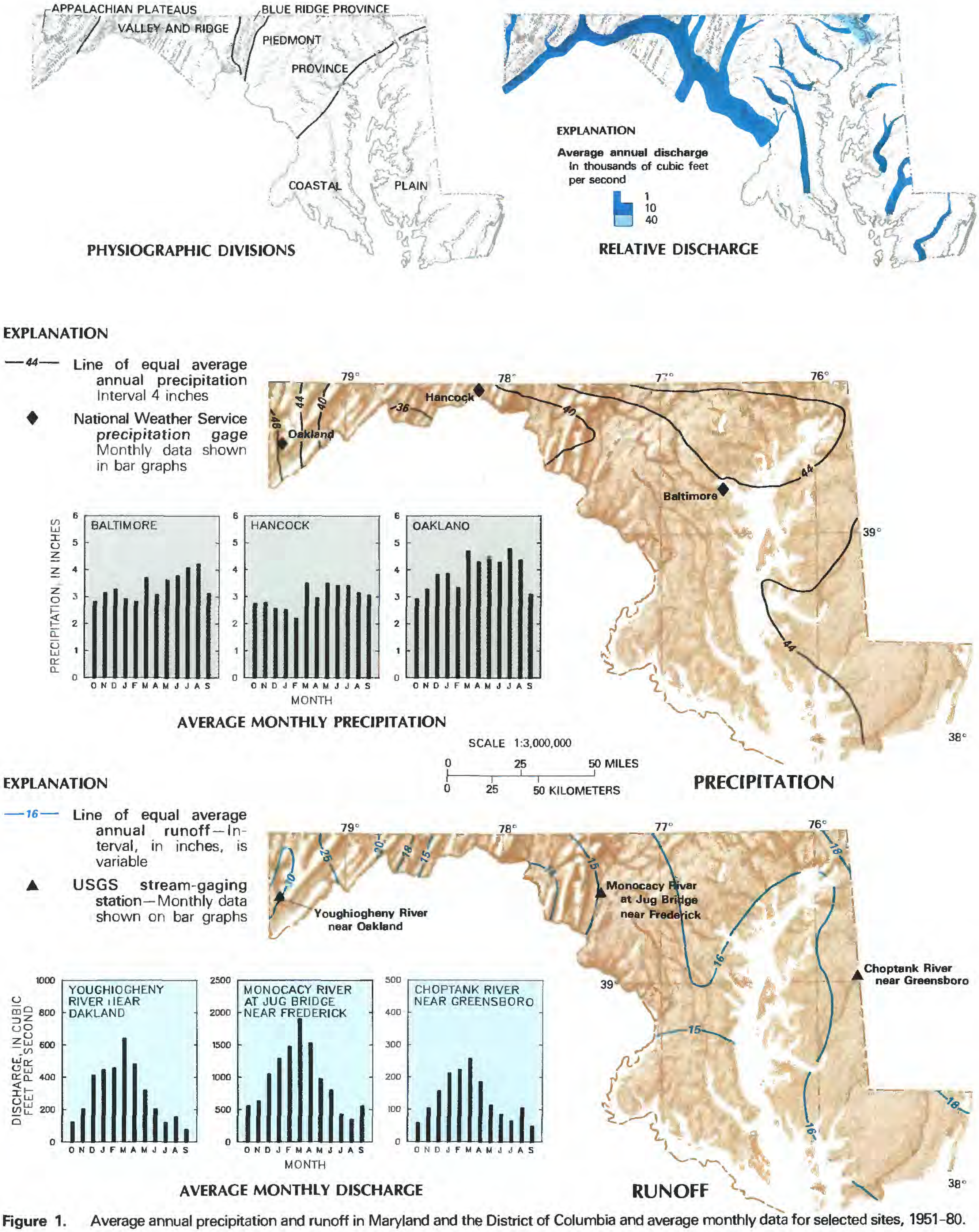

Figure 1. Average annual precipitation and runoff in Maryland and the District of Columbia and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

with a usable storage capacity of 169,000 acre-ft or 55,100 Mgal. Conowingo Dam is operated primarily for hydroelectric power, but it also provides flood control and recreational benefits. The only gaging station in Maryland on the main stem of the Susquehanna River is located at Conowingo Dam. During Hurricane Agnes in June 1972, peak flow at the dam reached 1,130,000 ft³/s or 730,000 Mgal/d. Other information on the Conowingo Dam station (site 7) can be found in table 2.

Ohio Region

Monongahela Subregion

The Monongahela Subregion drains 419 mi² of western Maryland; however, the major part of the subregion is located outside the State. The Youghiogheny is the principal river in the Maryland part of the subregion.

The Youghiogheny River begins in West Virginia and flows northward into Maryland where it continues northward until it enters Pennsylvania. The largest manmade reservoir in Maryland in the Youghiogheny River basin is Deep Creek Lake (completed in 1925) with a usable storage capacity of 93,000 acre-ft or 30,300 Mgal. The dam that forms the reservoir is on Deep Creek—a tributary to the Youghiogheny River about 7 miles north of Oakland—and provides hydroelectric power to the nearby area. The lake created by the dam is a major recreational attraction for the entire State and is a significant source of revenue during the summer.

Development of the Monongahela Subregion in Maryland has focused primarily on recreational opportunities and the promotion of tourism; and on industrial exploration, development, and production of natural gas and coal. Agriculture is present throughout the Youghiogheny River basin, but is limited to relatively flat land.

Runoff characteristics of the Youghiogheny River below the confluence of Deep Creek and Youghiogheny River are affected by the hydroelectric-power generation at Deep Creek Lake. Flow from the lake is totally regulated.

The bar graph for the Youghiogheny River near Oakland (fig. 2, site 8) is representative of the long-term variability in annual average discharge in the unregulated part of the basin. The general increase in discharge over the period of record may be related to development of recreational areas by the clearing of forested lands and construction of numerous vacation homes and condominiums.

SURFACE-WATER MANAGEMENT

Two State organizations are responsible for implementing most of the regulatory, planning, and research programs in Maryland. The Maryland Department of Natural Resources through its agencies—the Water Resources Adminstration (WRA) and the Maryland Geological Survey (MGS)—has a major role in surface-water resource planning and management. The WRA provides

Table 2. Selected streamflow characteristics of principal river basins in Maryland and the District of Columbia

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi²=square miles; ft³/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Maryland State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				MID-ATLANTIC REGION Potomac Subregion				
1.	Conococheague Creek at Fairview (01614500).	494	1928-83	53	590	26,800	Negligible	Major water use is irrigation.
2.	Antietam Creek near Sharpsburg (01619500).	281	1899-1983	66	275	14,400	. . . do . . .	Adjusted for inflow since Jan. 1930. Major water use is irrigation.
3.	Monocacy River at Jug Bridge near Frederick (01643000).	817	1929-83	50	926	65,900	. . . do . . .	Major water uses include irrigation and municipal supply.
				Upper Chesapeake Subregion				
4.	Pocomoke River near Willards (01485000).	60.5	1949-83	3.4	71	1,830	Negligible	Major water use is for recreation.
5.	Choptank River near Greensboro (01491000).	113	1948-83	5.4	132	9,360	. . . do . . .	Diversions for irrigation above station. Major water use is for recreation.
6.	Patuxent River near Unity (01591000).	34.8	1944-83	2.8	39	26,900	. . . do . . .	Major water uses include municipal and industrial supplies and recreation.
				Susquehanna Subregion				
7.	Susquehanna River at Conowingo (01578310).	27,100	1968-83	. . . .	42,180	. . . .	Appreciable	Regulated since Oct. 1928. Major water uses include hydroelectric and recreation.
				OHIO REGION Monongahela Subregion				
8.	Youghiogheny River near Oakland (03075500).	134	1941-83	5.9	297	12,800	Negligible	Major water use is for recreation.

direction in the development, management, and conservation of water in the State. Its various divisions are responsible for regulation—through permits and management practices related to flood control, erosion and sediment control, watershed development control, dam safety, stormwater control for municipalities, water appropriation for municipal and industrial needs, and mining control. The MGS is responsible for maintaining a statewide water-data network and evaluating 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 surface-water management decisions are made by the WRA.

The Maryland Department of Health and Mental Hygiene, through its Office of Environmental Programs, is responsible for regulatory and operational programs with regard to the water-quality aspects of surface-water management. As part of these responsibilities, the Office of Environmental Programs issues waste-discharge permits and monitors surface-water quality throughout the State.

In the District of Columbia, one Federal and two local agencies are responsible for managing the surface-water resources. The U.S. Army Corps of Engineers is responsible for developing and maintaining the water-supply source for the District. The District of Columbia Department of Public Works, through its Water and Sewer Utility Administration, is responsible for delivering and metering supplies to users and for repairing the distribution system. The District of Columbia Department of Consumer and Regulatory Affairs regulates permits for withdrawals and disposal of wastewaters, monitors water quality, and handles chemical spills that might adversely affect water supplies.

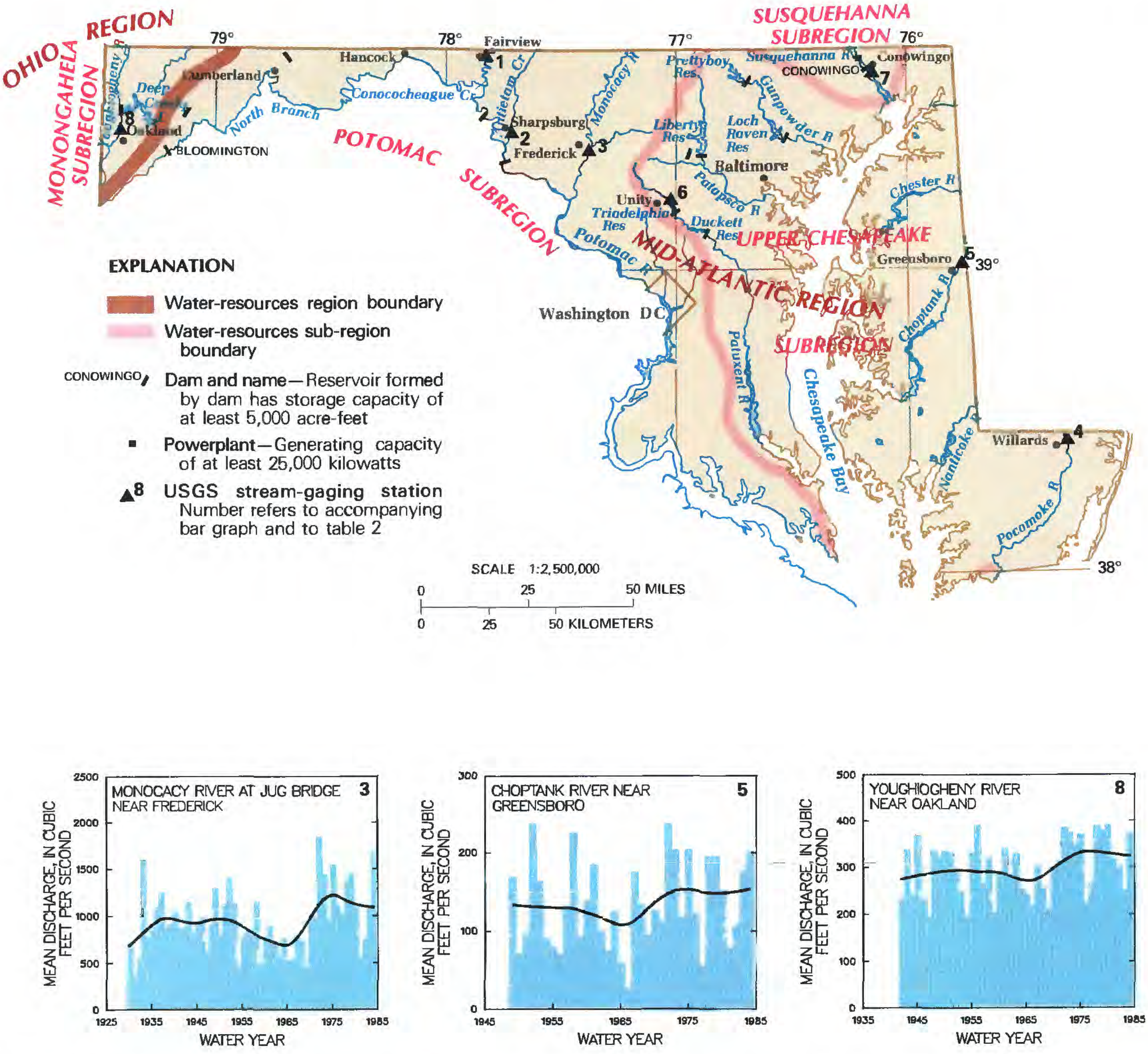

Figure 2. Principal river basins and related surface-water resources development in Maryland and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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MASSACHUSETTS
Surface-Water Resources

Two-thirds of the 5.7 million people in Massachusetts depend upon urface water for their water needs. Approximately 610 Mgal/d (million gallons per day) or 944 ft^3/s (cubic feet per second) of surface water is drawn from lakes, rivers, and reservoirs for public supply (table 1). An additional 1,500 Mgal/d or 2,320 ft^3/s is withdrawn from streams for industrial purposes (about 220 Mgal/d or 340 ft^3/s for manufacturing, 1,300 Mgal/d or 2,010 ft^3/s for thermoelectric power). About 25,000 Mgal/d or 38,700 ft^3/s is used instream for hydroelectric-power generation. Ground water is used for water supply in small communities and almost exclusively on Cape Cod and the islands of Nantucket and Martha's Vineyard. Surface water is the major source of supply of all the major urban areas of the State, because no other source is capable of meeting the large demands of these areas. Most reservoirs contain water of high quality, suitable for human consumption and most other uses with little, if any, treatment.

The largest water-supply reservoirs in the State are Quabbin Reservoir and Wachusett Reservoir in central Massachusetts and Borden Brook and Cobble Mountain Reservoirs in southwestern Massachusetts. The U.S. Army Corps of Engineers operates 11 flood-control reservoirs in Massachusetts, with storage capacities ranging from 3,700 to 50,000 acre-ft (acre-feet) or 1,200 to 16,300 Mgal (million gallons). Twenty-nine flood-control reservoirs, totaling 29,000 acre-ft or 9,450 Mgal, have been constructed under the U.S. Soil Conservation Service–Massachusetts Water Resources Commission Public Law 566 program.

Surface water in the State is relatively plentiful, but is not distributed in proportion to the distribution of population. More than 75 percent of the population resides in the eastern one-third of the State, but most sites suitable for additional reservoirs are in the western two-thirds of the State. The Metropolitan District Commission (MDC) supplies communities in the Greater Boston area with 320 Mgal/d or 495 ft^3/s—about half the State usage of surface water—from reservoirs in the Connecticut and the Merrimack River basins. The MDC estimates that an additional 60 Mgal/d or 93 ft^3/s would be needed by 1990 for the area currently serviced. The addition of other communities to the system would further increase demand. In protracted dry periods, even the reserves of the MDC system can be seriously depleted. Communities with small reservoir storage are more susceptible to shortages during dry periods. Urbanization of the Lake Cochituate watershed between 1846 and 1947 led to the deterioration of water quality and eventual abandonment of that lake for public supply in 1947. The water-supply reservoirs for the city of Cambridge are similarly threatened, because sodium levels have reached 50 mg/L (milligrams per liter) in recent years.

GENERAL SETTING

Massachusetts is included in the Coastal Plain and the New England physiographic provinces (fig. 1). The Coastal Plain province includes Cape Cod, Martha's Vineyard, and Nantucket (fig. 1) and 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. Ground water is the principal source of public water supplies in this province. The New England 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 eastern one-third of the State, where few suitable reservoir sites are available, to the New England Upland Section, and to the Green Mountain and Taconic sections in the west where many suitable potential reservoir sites are available.

Precipitation in Massachusetts averages about 45 inches per year and is fairly evenly distributed throughout the State (D. A. Olson, National Oceanic and Atmospheric Administration, written commun., 1985). Monthly precipitation throughout Massachusetts is also fairly evenly distributed (fig. 1). Average annual evaporation of free water surfaces ranges from about 26 inches in western Massachusetts to about 28 inches in the eastern half of the State (National Oceanic and Atmospheric Administration, 1982).

Table 1. Surface-water facts for Massachusetts

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	3,900
Percentage of total population	68
From public water-supply systems:	
Number (thousands)	3,900
Percentage of total population	68
From rural self-supplied systems.	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	2,500
Surface water only (Mgal/d)	2,100
Percentage of total	84
Percentage of total excluding withdrawals for thermoelectric power	67
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	610
Percentage of total surface water	29
Percentage of total public supply	76
Per capita (gal/d)	160
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	0.5
Percentage of total surface water	<0.1
Percentage of total livestock	42
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	1,500
Percentage of total surface water	71
Percentage of total industrial self-supplied.	
Including withdrawals for thermoelectric power	94
Excluding withdrawals for thermoelectric power	71
Irrigation withdrawals:	
Surface water (Mgal/d)	14
Percentage of total surface water	0.7
Percentage of total irrigation	74
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	25,000

Yearly runoff ranges from about 20 inches in Cape Cod in the southeastern corner of the state to about 32 inches in the northwestern corner of Massachusetts (fig. 1). Monthly runoff varies more than the corresponding monthly precipitation (fig. 1). The lowest runoff generally occurs during July, August, and September because of increased evaporation, transpiration, and depletion of soil moisture. Runoff then increases from October to December as evaporation and transpiration gradually decrease and soil moisture increases (Barksdale and others, 1966). In the western two-thirds of the State, winter runoff is lower in January and February than in December and March because precipitation usually remains on the ground as snow. In coastal areas the snow usually melts soon after falling, and runoff more closely follows precipitation patterns. Runoff is highest in March in the eastern sections of the State and highest in April in the western sections and at the higher elevations (fig. 1). Annual peak discharge is most likely to occur in March or April when snowmelt is supplemented by storms. Peaks that occur at other times of the year can be caused by intense thunderstorms, storms of unusual duration, or hurricanes.

PRINCIPAL RIVER BASINS

Massachusetts lies within the New England and the Mid-Atlantic Regions (Seaber and others, 1984). Three percent of the State's surface drainage is in the Mid-Atlantic Region. Massachusetts streams are in four subregions of the New England Region—Connecticut, Merrimack, Massachusetts-Rhode Island Coastal, and Connecticut Coastal (fig. 2). The Connecticut Subregion contains the Connecticut River basin, which comprises 37 percent of the surface drainage of the State. The Merrimack Subregion contains the Merrimack River basin, which is the second largest basin in the State, comprising 16 percent of the surface drainage. The Massachusetts-Rhode Island Coastal Subregion contains several small river basins that account for 34 percent of the State's surface drainage and includes rivers that flow to the Atlantic Ocean, Buzzards Bay, and Narragansett Bay. The Connecticut Coastal Subregion contains the headwaters of the Housatonic and the Thames River basins and accounts for 10 percent of the State's surface drainage.

These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

NEW ENGLAND REGION

Connecticut Subregion

The Connecticut River flows along the New Hampshire-Vermont border, and passes through central Massachusetts and Connecticut. Twenty-four percent of the river's 11,269-mi^2 (square mile) drainage area is in Massachusetts and 60 percent is north of Massachusetts. The Connecticut River has been a significant New England resource since its discovery by the Dutch in 1614 and its initial development near the mouth in 1631 by Pilgrims (Bartlett, 1984). Settlements in Springfield and Deerfield had been established by the 1670's. Commerce and agriculture were early developments, and the river was an important shipping link. In the course of the region's development, the river's waters became polluted by wastewater discharges. In the past 20 years, Federal, State, and local efforts have improved the river's quality, and today much of the river is of satisfactory quality for swimming.

The average annual flow at the main stem gaging station at Montague City (table 2, site 4) is 13,760 ft^3/s or 8,890 Mgal/d or 22.05 inches of runoff and has ranged from a high of 20,680 ft^3/s or 13,400 Mgal/d in 1928 to a low of 6,788 ft^3/s or 4,390 Mgal/d in 1965. Monthly average flows vary from 39,300 ft^3/s or 25,400 Mgal/d in April to 5,230 ft^3/s or 3,380 Mgal/d in August. Floods have played an important role in the history of the river. The first recorded flood occurred in 1635. Floods of record occurred in the spring of 1936 and during the hurricanes of 1938 and 1955. The peak discharge (236,000 ft^3/s or 153,000 Mgal/d) for period of record at Montague City occurred in March 1936. Three U.S. Army Corps of Engineers flood-control reservoirs were constructed following the 1938 flood and three more were constructed after the 1955 flood.

The principal tributaries in Massachusetts are the Millers, the Deerfield, the Chicopee, and the Westfield Rivers. The Deerfield and the Westfield Rivers flow into the Connecticut River from the mountainous western side of the basin. The Deerfield River is used for power because of its steep gradient and abundance of water (average annual runoff is 31 inches). Six hydroelectric powerplants, one nuclear powerplant, and one pump-storage powerplant have been constructed along the 42 miles of river that flow through Massachusetts. The terrain of the Westfield River and its tributaries is steep; runoff averages 25 inches, and rainfall runs off quickly with little natural storage. For example, the peak discharge of 26,100 ft^3/s or 16,900 Mgal/d recorded at the West Branch Westfield River at Huntington (table 2, site 8) on August 19, 1955, represented a discharge of 378 (ft^3/s)/mi^2 (cubic feet per second per square mile). Borden Brook and Cobble Mountain Reservoirs (total capacity, 78,000 acre-ft or 25,400 Mgal), completed in 1909 and 1931, respectively, and operated as a unit, serve as the principal supply of the city of Springfield. One of the two flood-control reservoirs in this basin is designed to serve as an as-yet-unused water supply for Springfield.

The Millers and the Chicopee Rivers are the principal tributaries flowing from the east. The terrain of these basins is not as steep nor is runoff intensity as great as in the western tributaries. The Millers River flow is moderated by numerous lakes and ponds. Runoff averages 23 inches. Tourism, paper goods, machine tools, furniture, and dairy products are the basin's principal industries. A significant feature in the Chicopee River basin is Quabbin Reservoir (capacity, 1.2 million acre-ft or 391,000 Mgal) in the headwaters of the Swift River. The reservoir was completed in 1939 by MDC to serve as the major source to its water-supply system; during the 10-year period 1973–82 an average of 192 Mgal/d or 273 ft^3/s was diverted to the system. Average runoff at the Chicopee River at Indian Orchard (table 2, site 7) since diversions began in 1941 is 16.5 inches, about 5.5 inches less than runoff in uncontrolled parts of the basin. However, base flow is augmented by minimum releases from Quabbin Reservoir to the Swift River of 20 Mgal/d or 31 ft^3/s year-round and an additional 51 Mgal/d or 79 ft^3/s between June 1 and November 1, whenever average flow of the Connecticut River at Montague City is less than 4,900 ft^3/s or 3,170 Mgal/d. Because of increasing population and increasing demand for water, there are proposals to supplement Quabbin Reservoir water by diverting water during periods of high flow from the main stem of the Connecticut River or from the Millers River.

Merrimack Subregion

The lower 24 percent of the Merrimack River basin's 5,014 mi^2 drainage area is in Massachusetts. The river flows easterly through northeastern Massachusetts. Major tributaries in the State are the Concord River (table 2, site 11), which joins the Merrimack at Lowell, and the Nashua River (table 2, site 10), which flows northward into New Hampshire before joining the Merrimack River. The average annual flow of the Merrimack River at Lowell (table 2, site 12) is 7,530 ft^3/s or 4,870 Mgal/d, or 23 inches of runoff. Monthly average flows vary from 19,470 ft^3/s or 12,600 Mgal/d in April to 2,648 ft^3/s or 1,710 Mgal/d in August. The greatest discharge, (173,000 ft^3/s or 112,000 Mgal/d), occurred in March 1936. Floods of record on tributary streams in Massachusetts have occurred in October 1955 and January 1979. During 1965, yearly runoff of the Merrimack River was only 9.42 inches. Wachusett Reservoir (capacity, 200,000 acre-ft or 65,200 Mgal) at the headwaters of the Nashua River has been a part of the MDC water-supply system since its completion in 1906 and has served as a connector for Quabbin Reservoir since 1939; it provided an average of about 102 Mgal/d or 158 ft^3/s during 1973–82. Water from Quabbin Reservoir flows first to Wachusett Reservoir by aqueduct and then to the Greater Boston area by other aqueducts. By law, 12 Mgal or 36.8 acre-ft per week must be released to the Nashua River. The remaining water is diverted from the Merrimack River basin.

Massachusetts-Rhode Island Coastal Subregion

The Massachusetts-Rhode Island Coastal Subregion contains 34 percent of the State's drainage area. The principal coastal basins north of Boston are the Parker, the Ipswich, and the Mystic Rivers. The eastward flowing Charles River forms a scenic urban basin along the Boston-Cambridge city line, where its shores are flanked by many recreational greenbelt parks and major transportation arteries. South of Boston, the Neponset, the Weymouth, the

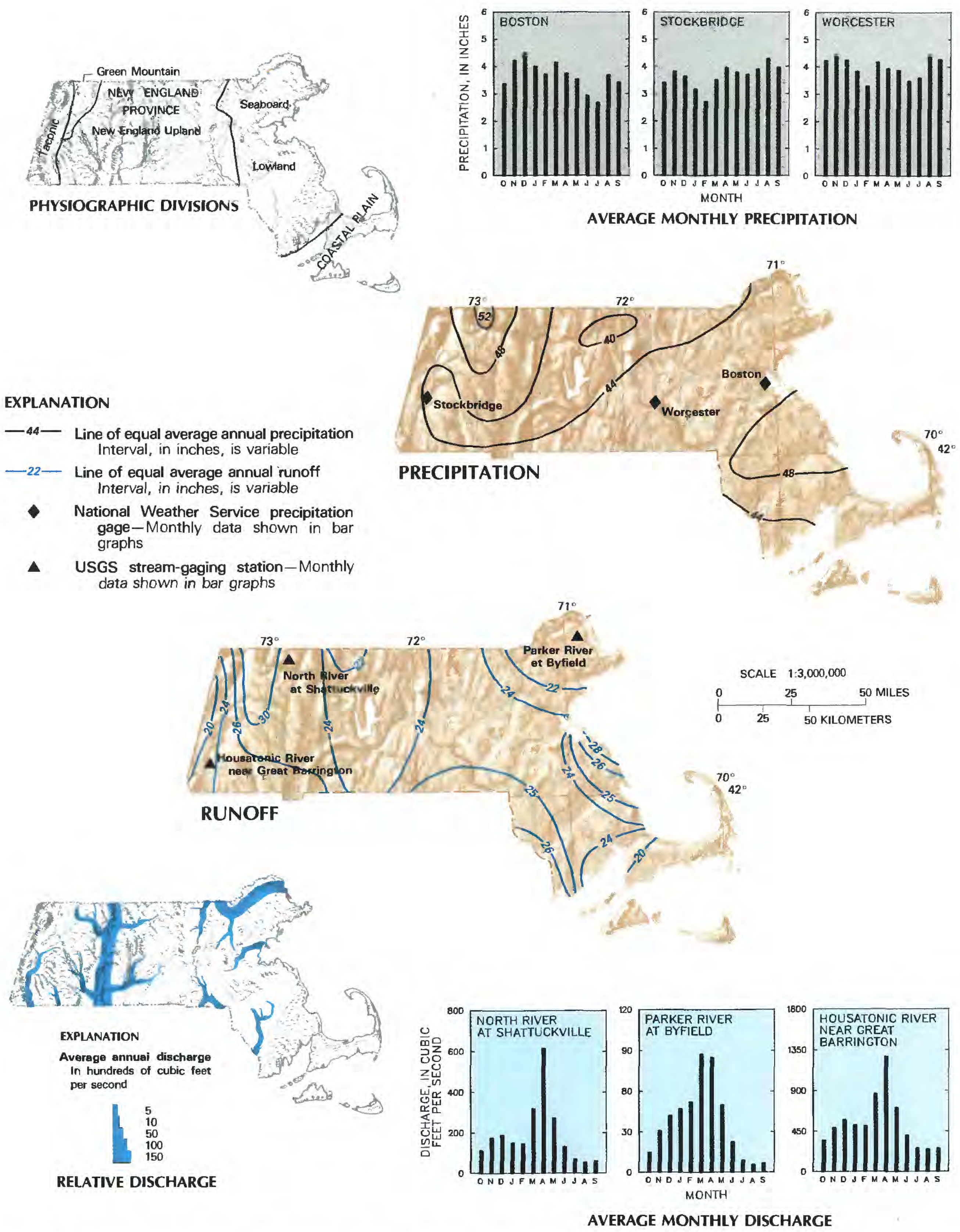

Figure 1. Average annual precipitation and runoff in Massachusetts and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data modified from Knox and Nordenson, 1955; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

North, the South, and the Jones Rivers also flow east to the Atlantic Ocean. Several small streams drain to Buzzards Bay. The Taunton, the Ten Mile, and the Blackstone Rivers flow south into Narragansett Bay. These coastal rivers drain gently rolling terrain and generally have considerable channel storage. The flood of record at gaging stations on most of these rivers occurred in March 1968. During that flood, the peak discharges for the Parker River, the Charles River, and the Wading River gages (table 2, sites 13, 15, and 17) were only 23, 18, and 34 (ft^3/s)/mi^2, respectively. Flood damage most often occurs where there has been development in

Table 2. Selected streamflow characteristics of principal river basins in Massachusetts

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				NEW ENGLAND REGION CONNECTICUT SUBREGION				
1.	Millers River at Erving (01166500).	372	1915-83	47	630	. . . .	Appreciable	
2.	North River at Shattuckville (01169000).	89.0	1940-83	8.1	183	17,000	Negligible	
3.	Deerfield River near West Deerfield (01173000).	557	1941-83	97	1,285	56,000	Appreciable	Power generation.
4.	Connecticut River at Montague City (01170500).	7,860	1905-83	1,700	13,760	. . . .	. . . do . . .	Do.
5.	Ware River at intake works near Barre (01173000).	96.3	1929-83	6.4	167	. . . .	. . . do . . .	High flow regulated since 1958. Diversion to Washusett or Quabbin Reservoir since 1931.
6.	East Branch Swift River near Hardwick (01174500).	43.7	1938-83	0.2	69.5	3,100	None	Flows into Quabbin Reservoir.
7.	Chicopee River at Indian Orchard (01177000).	689	1929-83	130	903	. . . .	Appreciable	Power generation Diversion from basin. Average discharge since 1940, 839 ft^3/s.
8.	West Branch Westfield River at Huntington (01181000).	94.0	1936-83	5.7	190	29,000	None	
9.	Westfield River near Westfield (01183500).	497	1915-83	84	921	. . . .	Appreciable	Water supply.
				MERRIMACK SUBREGION				
10.	Nashua River at East Pepperell (01096500).	316	1936-83	46	568	16,000	Appreciable	Area excludes 119 mi^2 for water supply.
11.	Concord River below River Meadow Brook at Lowell (01099500).	307	1937-83	33	630	6,000	. . . do . . .	Area excludes 93 mi^2 for water supply.
12.	Merrimack River below Concord River at Lowell (01100000).	4,423	1924-83	937	7,530	. . . .	. . . do . . .	Area excludes 212 mi^2 for water supply.
				MASSACHUSETTS-RHODE ISLAND COASTAL SUBREGION				
13.	Parker River at Byfield (01101000).	21.3	1946-83	0.2	36.7	610	Negligible	Occasional regulation.
14.	Ipswich River near Ipswich (01102000).	125	1931-83	2.0	187	3,120	Moderate	Diversions for municipal supply.
15.	Charles River at Dover (01103500).	183	1938-83	13	302	3,800	. . . do . . .	Do.
16.	Indian Head River at Hanover (01105730).	30.2	1967-83	1.4	62.4	1,800	Negligible	
17.	Wading River near Norton (01109000).	43.3	1926-83	2.3	73.3	1,500	Moderate	Diversions for municipal supply.
				CONNECTICUT COASTAL SUBREGION				
18.	Housatonic River near Great Barrington (01197500).	280	1914-83	69	526	11,000	Moderate	

the flood plain. The Charles River basin's natural valley storage, in the form of riverine wetlands, contributed to a remarkable coincidence at Dover; the peak discharges of both the 1955 and 1968 floods were 3,220 ft^{3}s or 2,080 Mgal/d, and the March 1936 flood produced a nearly identical peak of 3,170 ft^3/s or 2,050 Mgal/d. Annual runoff in the subregion averages 20 to 24 inches.

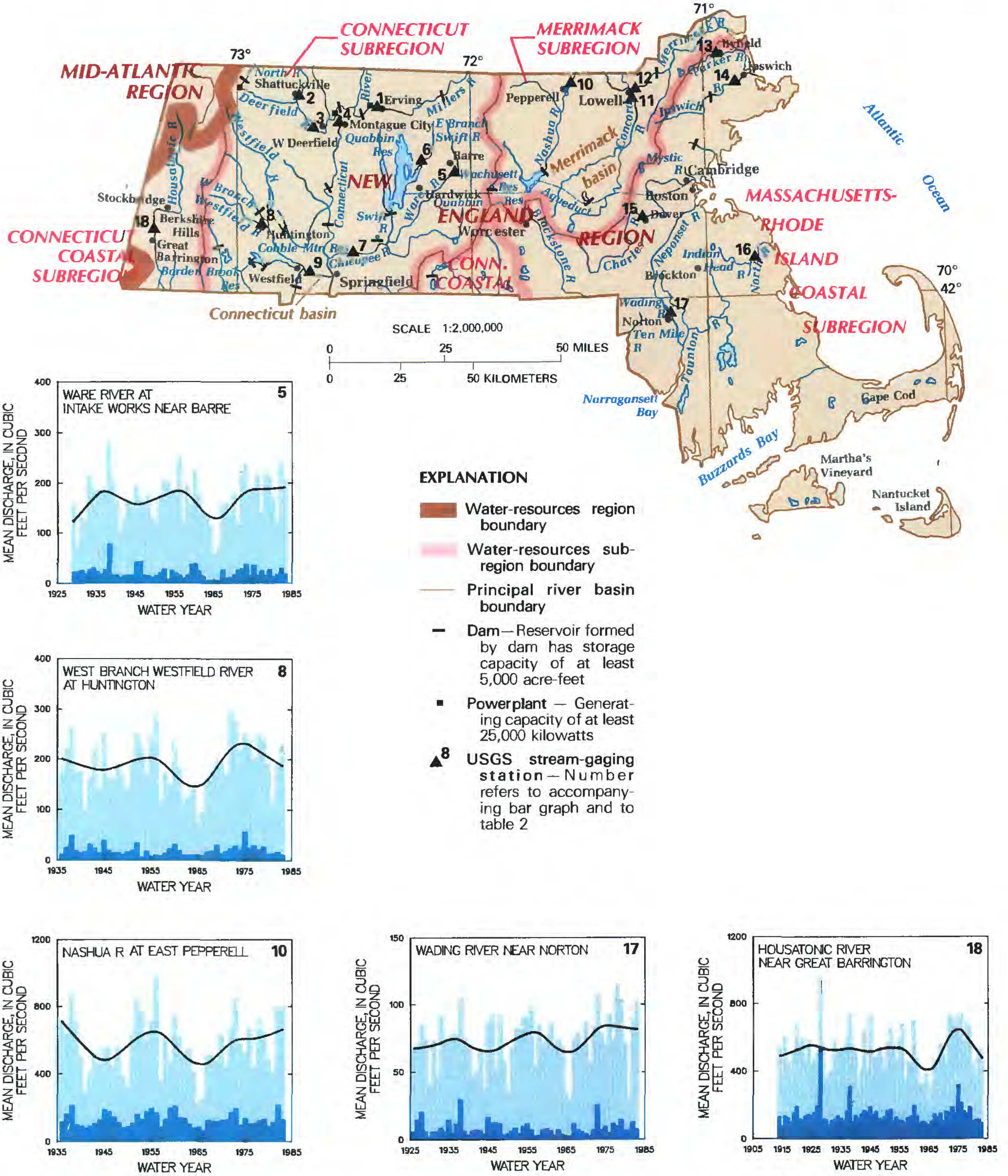

Figure 2. Principal river basins and related surface-water resources development in Massachusetts and average discharges for selected sites. Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

More than 55 percent of the population of this subregion is served by surface water from the MDC system. About half of the remaining population, principally in the southern half of the subregion where lakes, ponds, and reservoirs are numerous, is served by local surface-water sources. However, reserves in most of these reservoirs are not great, and protracted dry periods have caused supplies to drop to dangerously low levels. By the end of the 1980–81 drought, Brockton's principal water supply reservoir had declined to its lowest level ever with only a few day's reserve. This fact is illustrative of the increases in water use by communities in the subregion since the more severe and protracted drought of the 1960's.

SURFACE-WATER MANAGEMENT

Water-resources planning and management policies are determined by the Executive Office of Environmental Affairs (EOEA) and the Massachusetts Water Resources Commission. The Commission is chaired by the Secretary of Environmental Affairs. Other members of the Water Resources Commission are the Executive Office of Communities and Development; Department of Environmental Quality Engineering; Department of Environmental Management; Department of Fisheries, Wildlife and Recreational Vehicles; Department of Food and Agriculture; Metropolitan District Commission; and six public members. The planning, management, and development of policy by these State agencies are coordinated and guided by the EOEA as outlined in the Massachusetts Water Supply Policy (Massachusetts Executive Office of Environmental Affairs, 1978), as updated by the Massachusetts Water Resources Commission (1984).

Riparian doctrine applies in Massachusetts (Massachusetts Water Resources Commission, 1971). Therefore, intertown allocation of surface water or ground water is determined by acts of the State legislature. Interbasin transfer of water or wastewater is approved or denied by the Water Resources Commission (chapter 21, sections 8B through 8D). The Division of Water Resources is responsible for developing water-resources plans for 27 planning basins pursuant to the Water Resources Commission's Water Resources Planning Regulations (313 CMR 2.00) and U.S. Geological Survey studies pursuant to chapter 21, section 9B.

The Division of Water Pollution Control regulates discharges to surface and ground water to meet and maintain State water-quality standards. The Division of Water Supply regulates surface-water and ground-water withdrawals to ensure the reliability of water quality in the interest of public health. To provide fundamental hydrologic measurements in support of these responsibilities, the U.S. Geological Survey operates a network of 47 continuous streamgaging stations in cooperation with the Divisions of Water Resources and Water Pollution Control, and 15 stations in cooperation with the Metropolitan District Commission. In addition, 13 stations are supported by the U.S. Army Corps of Engineers for flood-control management, 2 are supported by the Federal Energy Regulatory Commission, and 2 are supported by the U.S. Geological Survey as part of a Federal water-resources network.

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MICHIGAN
Surface-Water Resources

Michigan has an abundance of surface-water resources. The State has more than 3,000 miles of shoreline along the Great Lakes and 11,000 inland lakes with a total area of 1,150 mi^2 (square miles). Much of the State is bounded by the Great Lakes (Superior, Michigan, Huron, and Erie) (fig. 1).

There are 242 streams with a total length of 36,350 miles that flow to the Great Lakes. Because of the State's peninsular configuration, Michigan's streams are relatively short and have small drainage basins. Most of the basins (93 percent) are entirely within State boundaries. About 65,000 Mgal/d (million gallons per day) or 101,000 ft^3/s (cubic feet per second) of surface water are used instream to generate hydroelectric power at 82 dams. These facilities produce about 3 percent of the electric power used in the State. Surface water provides 14,000 Mgal/d or 21,700 ft^3/s or 96 percent of freshwater withdrawals for offstream use. Industrial supplies of about 13,000 Mgal/d or 20,100 ft^3/s and municipal supplies of 1,000 Mgal/d or 1,500 ft^3/s account for most offstream surface-water use. Most of Michigan's population (57 percent) depends on surface-water supply. Surface-water withdrawals in Michigan in 1980 and related statistics are given in table 1.

Control of toxics in surface water and ground water, protection of the Great Lakes with respect to diversions and water quality, and flood-hazard management are major priorities of State and local officials and of the citizens of Michigan. Overall, the quality of surface water in Michigan is suitable for all uses.

GENERAL SETTING

Michigan is divided into two principal physiographic provinces—the Central Lowland and the Superior Upland (fig. 1). Topography ranges from level to gently rolling in the eastern part of the Upper Peninsula and southern part of the Lower Peninsula, to hilly and rugged country in the western part of the Upper Peninsula and the north-central part of the Lower Peninsula.

The climate of Michigan is affected by the surrounding Great Lakes. The lakes have a stabilizing effect on temperature and, because of prevailing westerly winds, winters are milder and summers cooler than at identical latitudes farther west.

Precipitation, which averages about 31 inches annually, is fairly well distributed throughout the year; precipitation increases slightly during the growing season (fig. 1, bar graphs). Snowfall varies widely over the State, ranging from 160 inches in the western part of the Upper Peninsula to 30 inches in the southeastern part of the Lower Peninsula. In the northwestern part of the Lower Peninsula, snowfall exceeds 100 inches annually.

Runoff varies both geographically and seasonally (fig. 1); it is greatest (as much as 20 inches per year) in areas of heavy snowfall accumulation. Highest monthly runoff generally is during March, April, and May, when snowmelt, rainfall, saturated soils, and reduced evapotranspiration combine to increase runoff. Although precipitation is abundant during summer, runoff declines because of increased evapotranspiration and absorptive capacity of the soils. Evaporation (class A pan) during May through October ranges from 20 inches in parts of the Upper Peninsula to 34 inches near the State's southern boundary (National Oceanic and Atmospheric Administration, 1982, 1970–83). Average discharge of streams at 18 gaging stations ranges from 205 to 3,570 ft^3/s or 132 to 2,310 Mgal/d (table 2).

Table 1. Surface-water facts for Michigan

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than . Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	5,280
Percentage of total population	57
From public water-supply systems:	
Number (thousands)	5,280
Percentage of total population	57
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	15,000
Surface water only (Mgal/d)	14,000
Percentage of total	96
Percentage of total excluding withdrawals for thermoelectric power	75
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	1,000
Percentage of total surface water	7
Percentage of total public supply	83
Per capita (gal/d)	189
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	5
Percentage of total surface water	<0.1
Percentage of total livestock	23
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	13,000
Percentage of total surface water	93
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	99
Excluding withdrawals for thermoelectric power	96
Irrigation withdrawals:	
Surface water (Mgal/d)	110
Percentage of total surface water	0.8
Percentage of total irrigation	52
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	65,000

PRINCIPAL RIVER BASINS

Michigan is entirely in the Great Lakes Region (fig. 1). River basins in Michigan are comparatively small, and river gradients are usually gentle. Four of the principal basins are the Escanaba in the Northwestern Lake Michigan Subregion, the Grand in the Southeastern Lake Michigan Subregion, the Tittabawassee in the Southwestern Lake Huron–Lake Huron Subregion, and the Manistee in the Northeastern Lake Michigan–Lake Michigan Subregion. Rivers in the first three basins vary strongly in response to climatic conditions. The Manistee River, however, shows only minor response to climate reflecting the effects of large groundwater inflow. The four principal basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics for these and other river basins are given in table 2.

GREAT LAKES REGION

Northwestern Lake Michigan Subregion

Escanaba River Basin.—The Escanaba River basin, in the center of Michigan's Upper Peninsula (fig. 2), covers an area of 925 mi^2 of level, swampy land and rolling, hilly terrain. The Escanaba River rises as the Middle Branch from a group of 15 to 20 small lakes. The highest point of perennial flow is from Wolf Lake at an elevation of 1,719 feet above sea level. The Middle Branch flows southeastward for 53 miles until it joins with the East Branch Escanaba River at Gwinn where it forms the Escanaba River. The Escanaba River flows south for 10 miles to its junction with the West Branch Escanaba River, then southeastward for 35 miles to Lake Michigan at an elevation of 580 feet. The basin contains more than 275 lakes that range in size from a few acres to 454 acres (Little Lake). Two impoundments—the Gribben and Empire basins near Palmer with a combined area of 3,700 acres—are settling basins for iron-mining slurry. The Escanaba River basin is underlain by Precambrian igneous and metamorphic rocks in the northern part; by glacial deposits and alluvium through its central part; and by glacial deposits, alluvium, and Paleozoic rocks in its southern part.

Most of the Escanaba River basin is forested—primarily with aspen, birch, maple, and swamp conifers. Nearly all of the southern part of the basin—possibly as much as 400 mi^2—is swampy. Iron ore has been, and still is, mined from metamorphic rocks at places along the boundary of the basin and in the basin. Farms are sparse and small. Estimated population of the basin is 16,000, based on the 1980 census (U.S. Department of Commerce, 1982). The most populated area is in the east-central part of the basin, where 1,500 people reside in Gwinn and 5,000 reside at K. I. Sawyer Air Force Base.

The Escanaba River basin has considerable recreational potential, although present use for this purpose is moderate. The Escanaba River and its tributaries are noted for trout fishing, and reservoirs in the basin provide fishing for many other species. Canoeing on the main stem is increasing in popularity. Principal surface-water users in the Escanaba River basin are iron-ore-processing facilities in the upper reaches and hydroelectric facilities on the Middle Branch and near the mouth. Large quantities of water also are used by papermaking facilities near the mouth. Reservoirs that store water for iron-ore processing were constructed on Schweitzer Creek near Palmer in 1962 (5,300 acre-ft (acre-feet) or 1,730 Mgal (million gallons) capacity) and on the Middle Branch near Greenwood in 1972 (23,300 acre-ft or 7,600 Mgal capacity). Diversions are discharged through tailings ponds and returned to the system downstream. Regulation affects monthly and annual runoff on the Middle and East Branches, but not on the main stem downstream from the West Branch.

Average slope of the Escanaba River is 11.6 ft/mi (feet per mile). Minimum discharge observed on the Escanaba River at Cornell gaging station (table 2, site 6) was 90 ft^3/s or 58 Mgal/d in 1910. Maximum discharge of record on the river was 10,700 ft^3/s or 6,900 Mgal/d in April 1979. Historically, flood damage has not been a major concern along the Escanaba River. Floods with less than a 100-year recurrence interval generally do not cause appreciable damage. Extreme flood events typically are the result of runoff from sudden melting of a heavy snow cover coupled with heavy precipitation. Such was the condition during the flood of April 1985, when flooding occurred with recurrence intervals that ranged from 25 years on the Escanaba River main stem to more than 100 years on the Middle Branch.

The chemical quality of water in the Escanaba River basin is suitable for most uses. A sample collected in September 1983 from the Escanaba River about 16 miles upstream from the mouth contained the following major constituents: Calcium, 22 mg/L (milligrams per liter); magnesium, 9 mg/L; sodium, 17 mg/L; sulfate, 20 mg/L; chloride, 6 mg/L; hardness (as calcium carbonate), 92 mg/L; and dissolved solids, 147 mg/L. Suspended sediment was 1 mg/L at a discharge of 495 ft^3/s or 320 Mgal/d.

Southeastern Lake Michigan Subregion

Grand River Basin.—The Grand River basin is the second largest river basin in the State. It covers an area of 5,572 mi^2 of relatively level to hilly land. The main stem of the Grand River rises near the State's southern boundary at an elevation of 1,040 feet above sea level, flows northward for about 70 miles and then westward for another 190 miles until it flows to Lake Michigan at an elevation of 580 feet. Tributary rivers are the Portage, the Red Cedar, the Lookingglass, the Maple, the Flat, the Thornapple, and the Rogue. The basin contains more than 300 lakes; the largest is Center Lake with an area of 1,000 acres. The basin is underlain by glacial deposits except for a few small areas in the headwaters of the Grand River and a short stretch along the river at Grand Ledge where sedimentary rocks are exposed. The glacial deposits are underlain by Mississippian and Pennsylvanian-aged bedrock composed of sandstone, siltstone, shale, limestone, and some coal.

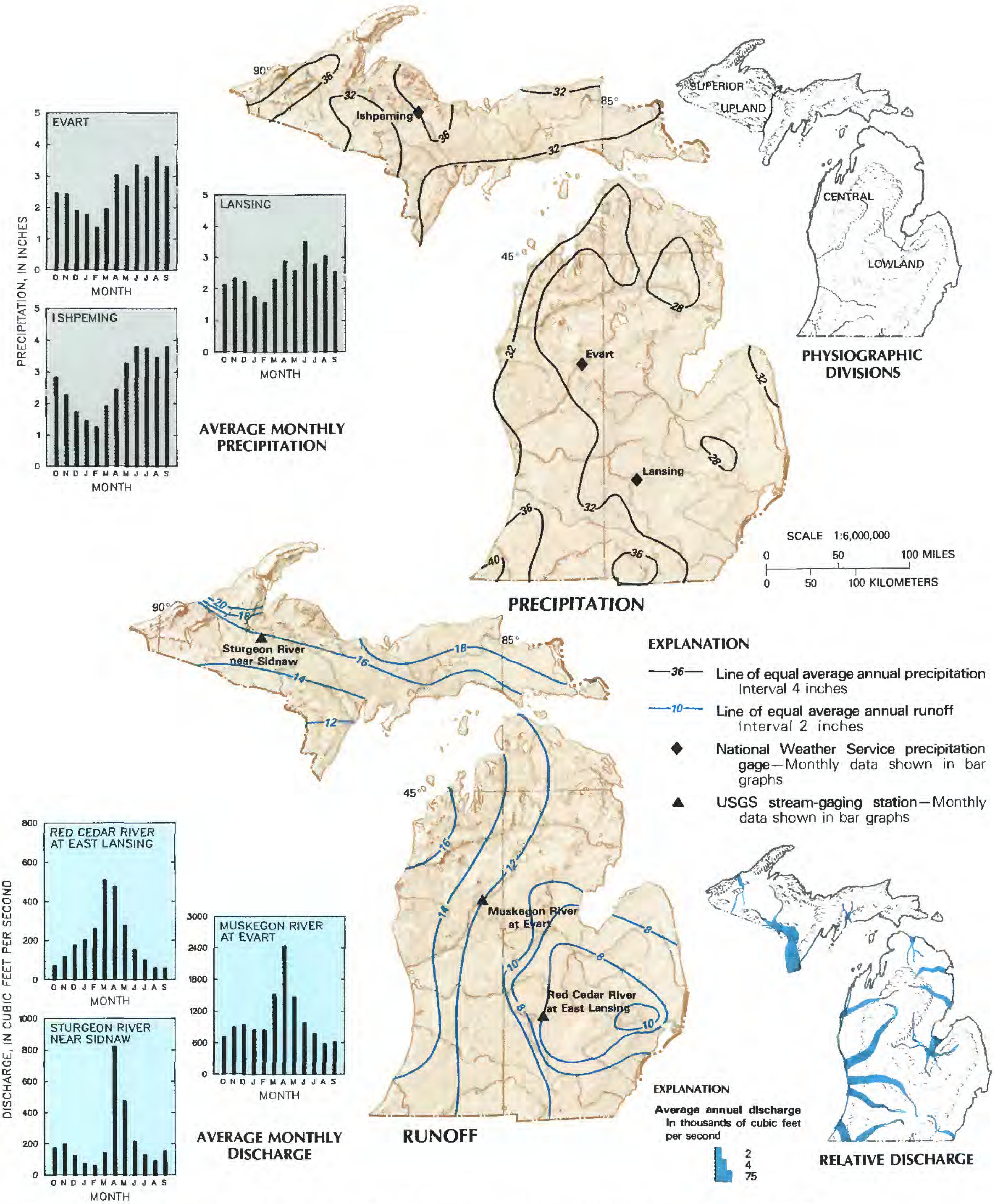

Figure 1. Average annual precipitation and runoff in Michigan and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Michigan

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and Michigan agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	GREAT LAKES REGION **NORTHWESTERN LAKE MICHIGAN AND SOUTHEASTERN LAKE MICHIGAN SUBREGIONS**							
1.	St. Joseph River at Niles (04101500).	3,666	1931–84	945	3,260	20,400	Moderate	Regulation by powerplants upstream.
2.	Kalamazoo River near Fennville (04108500).	1,600	1930–36, 1938–84	335	1,420	12,300	Appreciable	Regulation by powerplants upstream
3.	Red Cedar River at East Lansing (04112500).	355	1903, 1932–84	9.79	205	6,890	None	Index station used to define current hydrologic conditions.
4.	Grand River at Lansing (04113000).	1,230	1902–06, 1935–84	80.2	833	8,800	Moderate	Diurnal fluctuation caused by powerplants upstream.
5.	Grand River at Grand Rapids (04119000).	4,900	1902–05, 1931–84	721	3,570	53,000	Negligible	Diurnal fluctuation caused by powerplants upstream.
6.	Escanaba River at Cornell (04059000).	870	1904–12, 1951–84	168	892	13,000	Moderate	Industrial supply and diversions.
	NORTHEASTERN LAKE MICHIGAN-LAKE MICHIGAN SUBREGION							
7.	Muskegon River at Evart (04121500).	1,450	1931, 1934–84	314	998	9,060	Negligible	Index station used to define current hydrologic conditions.
8.	Muskegon River at Newaygo (04122000).	2,350	1910–14, 1917–19, 1931–84	672	1,970	14,100	Moderate	Regulation by powerplants upstream.
9.	Manistee River near Manistee (04126000).	1,780	1952–84	1,210	2,000	8,240	Appreciable	Regulation by powerplant upstream.
	SOUTHWESTERN LAKE HURON-LAKE HURON SUBREGION							
10.	Shiawassee River near Fergus (04145000).	637	1940–84	42.1	420	9,330	Negligible	
11.	Flint River near Fosters (04149000).	1,188	1940–84	66.4	743	16,700	. . . do . . .	
12.	Cass River at Frankenmuth (04151500).	841	1936, 1940–84	20.4	490	20,800	. . . do . . .	
13.	Tittabawassee River at Midland (04156000).	2,400	1937–84	187	1,680	44,600	. . . do . . .	Diversion for industrial use.
	SOUTHERN LAKE SUPERIOR—LAKE SUPERIOR AND ST. CLAIR—DETROIT SUBREGIONS							
14.	Ontonagon River near Rockland (04040000).	1,340	1943–84	308	1,430	32,400	Moderate	Flow regulated by powerplant, reservoir, and lakes upstream.
15.	Sturgeon River near Sidnaw (04040500).	171	1913–15, 1944–84	8.19	216	4,830	None	Index station used to define current hydrologic conditions.
16.	Tahquamenon River near Paradise (04045500).	790	1954–84	196	936	7,660	. . . do . . .	Recreational area.
17.	Clinton River at Mt. Clemens (04165500).	734	1935–84	61.4	531	23,200	. . . do . . .	
18.	Huron River at Ann Arbor (04174500).	729	1905–84	43.6	456	5,940	Appreciable	Diversion for Ann Arbor municipal supply. Regulation by dams upstream.

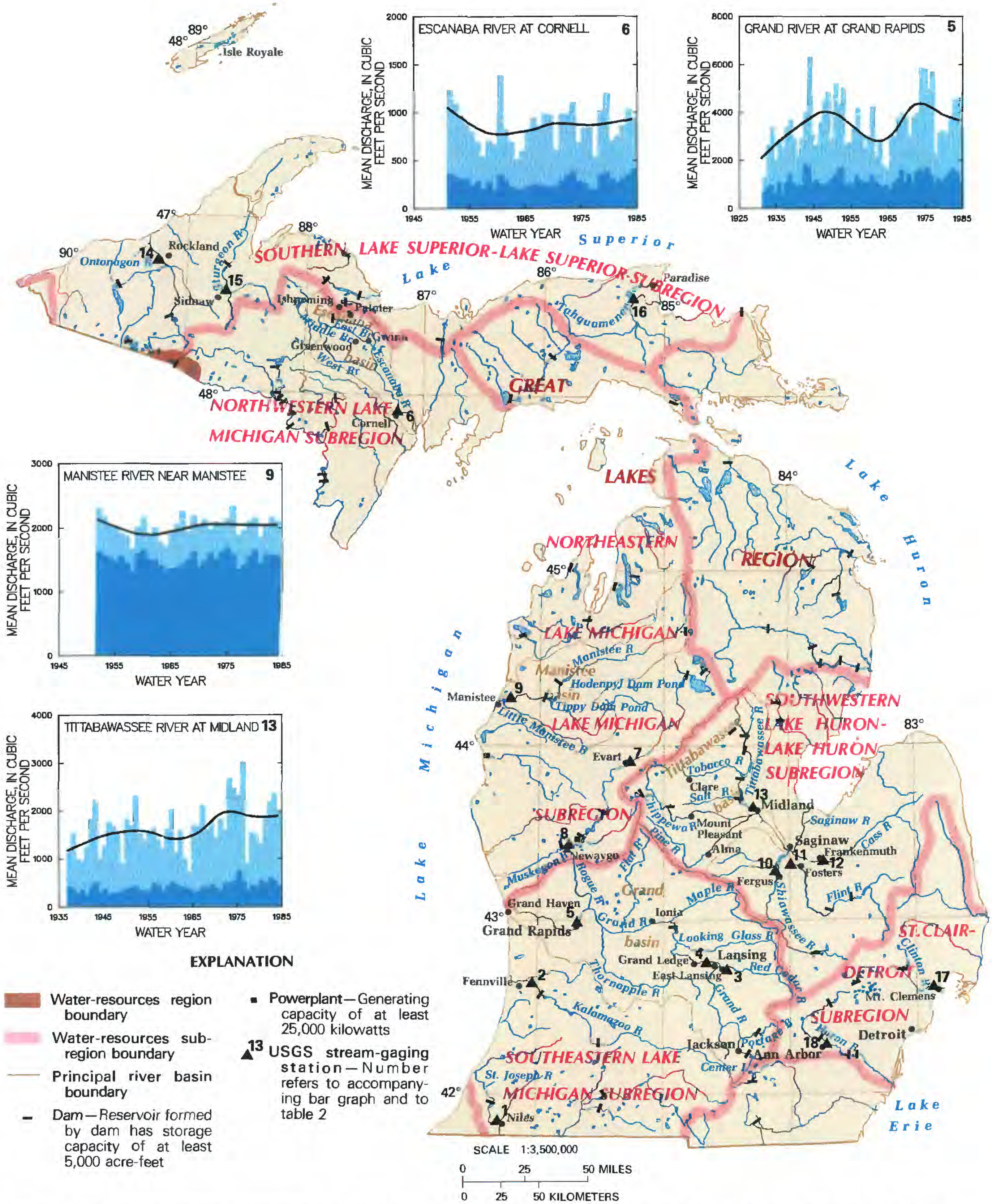

Figure 2. Principal river basins and related surface-water resources development in Michigan and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

In the early 1800's, most of the basin was covered with a forest of mixed hardwoods. Today, only 15 percent of the basin is wooded, mostly along water-courses and in hilly lands; the rest of the basin consists of farmland and urbanized areas. Estimated population of the basin, based on the 1980 census (U.S. Department of Commerce, 1982), is 1,300,000. The largest urbanized areas and their approximate populations are: Grand Rapids, 320,000; Lansing, 195,000; Jackson, 50,000; and Grand Haven, 12,000. Nearly 50 percent of the population is employed in manufacturing and service industries. Salmon were introduced into the Grand River some years ago and, by the early 1980's, had progressed upstream to the Lansing area.

Average slope of the Grand River is 1.8 ft/mi. From its source to Ionia (90 miles above mouth), the slope is 2.4 ft/mi. From Ionia to the mouth, the slope is 0.6 ft/mi. Average discharge by water year of the Grand River at Grand Rapids (table 2, site 5) during the past 50 years has ranged between 1,500 ft^3/s or 968 Mgal/d and 6,300 ft^3/s or 4,060 Mgal/d (fig. 2). Minimum daily discharge recorded at Grand Rapids, was 381 ft^3/s or 246 Mgal/d in 1936. The major flood of record on the Grand River was in 1904; discharges were 24,500 ft^3/s or 15,800 Mgal/d at Lansing and 54,000 ft^3/s or 34,800 Mgal/d at Grand Rapids. The major uses of surface water in the basin are for recreational purposes and power generation. Most communities near the mouth of the basin use water from Lake Michigan for municipal supplies. Although Grand Rapids withdraws about 2 Mgal/d or 3.0 ft^3/s (Bedell, 1982) from the Grand River, its principal withdrawal of 38 Mgal/d or 59 ft^3/s is from Lake Michigan. Upstream from the river mouth, most water for community, industrial, and rural-domestic supplies is from ground-water sources. Another important use of streams is for the disposal of treated water from community wastewater-treatment plants. Water from these plants, which was originally derived from ground water in most communities in the Grand River basin, increases streamflow when added to streams. For example, in the Lansing area, wastewater added to the Grand and the Red Cedar Rivers averaged 38 Mgal/d or 59 ft^3/s—a significant amount during low-flow periods.

The chemical quality of water in the Grand River basin is suitable for most uses. For example, a sample collected in September 1983 from the Grand River about 20 miles upstream from the mouth contained the following major constituents; calcium, 59 mg/L; magnesium, 23 mg/L; sodium, 29 mg/L; sulfate, 60 mg/L; chloride, 47 mg/L; hardness (as calcium carbonate), 242 mg/L; and dissolved solids (sum), 329 mg/L. Suspended sediment was 38 mg/L at a discharge of 1,590 ft^3/s or 1,030 Mgal/d.

Northeastern Lake Michigan-Lake Michigan Subregion

Manistee River Basin.—The Manistee River rises in the northwestern part of the lower peninsula at an elevation of 1,235 feet above sea level, flows southwestward for 125 miles to Hodenpyl Dam, then southward for 15 miles to Tippy Dam Pond. It covers an area of 1,930 mi^2 of flat to rolling land. From this pond, the river flows westward for 35 miles until it enters Lake Michigan at an elevation of 580 feet. Tributary to the Manistee are a number of small creeks and the Pine and the Little Manistee Rivers. The Little Manistee River enters the main stem in an embayment at the community of Manistee. The basin contains nearly 350 lakes that range in size from a few acres to 1,869 acres (Bear Lake). The Manistee River basin is underlain by thick glacial deposits that consist mostly of sand and gravel.

The northwestern part of Michigan's Lower Peninsula was settled in the latter part of the 1800's. The extensive logging that followed wiped out extensive forests of white and red pine. Although the Manistee River basin is presently about 70 percent forested, much of the forest covers areas where original stands were removed. About 7 percent of the basin is used for agriculture. Christmas-tree production is an important part of the economy. Estimated population of the basin, based on the 1980 census (U.S. Department of Commerce, 1982), is 42,000. The most populous area is the community of Manistee (population 7,500). Fishing, hunting, and other forms of recreation are of prime importance to the basin and account for the major use of surface-water resources. The Manistee River is rated among the best streams in Michigan for fish production and trout fishing. Areas along the river are used extensively by waterfowl. A study by the U.S. Forest Service (1979, p. 151) indicated that about 188 miles of the Manistee River qualify for inclusion in the National Wild and Scenic Rivers System. Much of the basin already is in the National and State Forest system. Another major use of surface water in the basin is by hydroelectric plants at Hodenpyl and Tippy Dams (fig. 2).

Average slope of the Manistee River is 3.7 ft/mi. Minimum daily discharge of the river at the gaging station about 11 miles upstream from the mouth (table 2, site 9) was 570 ft^3/s or 368 Mgal/d in June 1980. Maximum discharge of record was 7,120 ft^3/s or 4,590 Mgal/d in March 1976. Average discharge by water year varies only slightly from 2,000 ft^3/s or 1,290 Mgal/d (fig. 2). Ground-water inflow from highly permeable glacial deposits maintains streamflow during drought periods.

The chemical quality of water in the Manistee River basin is suitable for most uses. A sample collected in September 1983 at Manistee contained the following major constituents; calcium, 58 mg/L; magnesium, 13 mg/L; sodium, 14 mg/L; sulfate, 15 mg/L; chloride, 48 mg/L; hardness (as calcium carbonate), 199 mg/L; and dissolved solids (sum), 246 mg/L. Suspended sediment, was 4 mg/L at a discharge of 1,320 ft^3/s or 852 Mgal/d. Except in dam ponds and open-marsh country, water temperatures during the summer are kept sufficiently low by a large inflow of ground water.

Southwestern Lake Huron-Lake Huron Subregion

Tittabawassee River Basin.—The Tittabawassee River basin, in the east-central part of Michigan's Lower Peninsula, covers an area of 2,620 mi^2 of land that ranges from hilly to flat and swampy. The main stem of the Tittabawassee River rises as the East, the West, and the Middle Branches at elevations ranging from 820 to 1,000 feet above sea level. From the headwaters, the river flows southeastward for 86 miles until it joins with the Shiawassee River at an elevation of 580 feet to form the Saginaw River. Four tributary rivers join the river at and upstream from Midland. These rivers and their drainages areas are: the Pine, 395 mi^2; the Chippewa, 598 mi^2; the Salt, 196 mi^2; and the Tobacco, 543 mi^2. The basin contains nearly 350 lakes that range in size from a few acres to 770 acres (Chippewa Lake). Ponds of four power dams are on the Tittabawassee River above Midland. The water level of each pond nearly reaches the base of the dam next upstream. The basin is underlain by glacial deposits. Deposits in the eastern part of the basin are lakebeds that consist of clay, silt, and fine sand; deposits in the western part are moraines that consist of an intermixture of gravel, sand, and clay, and outwash that consists of sand and gravel.

Until the early 1800's, the Tittabawassee basin was completely forested, containing many giant white pines up to 150 feet tall. By the mid-1800's, however, lumbering had become a major industry and, by the end of the century, more than 30 billion feet of lumber had been harvested. Today, 50 percent of the land is forested but mostly by secondary growth. Much of the remaining land is artifically drained and is used for agriculture and industry.

Estimated population of the basin, based on the 1980 census (U.S. Department of Commerce, 1982), is 210,000. The largest urbanized areas and their approximate populations are: Midland, 40,000; Mount Pleasant, 24,000; and Alma, 10,000. The Saginaw urbanized area (population 120,000) is located at the mouth of the Tittabawassee River. Midland is a major chemical manufacturing center. The area from Midland to Mount Pleasant and Clare is a rapidly developing oil-production area. The principal uses of surface water in the basin are for operation of hydroelectric plants and for recreation.

Average slope of the Tittabawassee River from the headwaters of Middle Branch is 4.5 ft/mi. Downstream from Midland the slope is less than 1 ft/mi. Minimum discharge of the river at Midland (table 2, site 13) was 39 ft^3/s or 25.2 Mgal/d in 1942. The maximum recorded discharge was 34,000 ft^3/s or 22,000 Mgal/d in March 1948. From 10 to 25 ft^3/s or 6.45 to 16.1 Mgal/d are diverted at Midland for industrial use. During the past 50 years, average annual daily discharge has shown an increasing trend (fig. 2). The possible factors causing this increase have not been fully investigated.

Few data are available to establish the chemical quality of surface water in the Tittabawassee River basin. In March 1967, a sample collected from the Tittabawassee River at Midland contained the following major constituents: chloride, 110 mg/L; sulfate, 42 mg/L; hardness (as calcium carbonate), 260 mg/L; and dissolved solids (at 180°Celsius), 418 mg/L. Discharge at that time was 14,300 ft^3/s or 9,230 Mgal/d. In June 1984, suspended sediment in the Tittabawassee River near Saginaw was 14 mg/L at a discharge of 1,090 ft^3/s or 703 Mgal/d.

SURFACE-WATER MANAGEMENT

Surface-water resources of Michigan are managed by public and private agencies. Many river flows are regulated by private firms for processing water, hydropower generation, flood control, recreation, low-flow augmentation, irrigation, and water supply. Streamflow requirements for dam operations commonly are established by the Federal Energy Regulatory Commission or State regulatory agencies through licensing permits.

The Michigan Department of Natural Resources (MDNR) administers a flood-hazard management program, collects and analyzes water-use data in conjunction with the U.S. Geological Survey, and administers dam-safety and lake-level control programs.

The MDNR also licenses facilities for waste discharge to surface-water bodies and monitors the licensees and receiving waters to ensure that water-quality standards are met. Increasing emphasis is being directed toward integration of water-quality and quantity concerns. A comprehensive planning process has been proposed to address water-management issues in the State. The Michigan Department of Public Health (MDPH) oversees the use of surface waters for public supply. MDPH reviews water-supply development plans, sets drinking-water quality standards, and monitors the water delivered to consumers to ensure that standards are met.

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MINNESOTA
Surface-Water Resources

Minnesota, "The Land of 10,000 Lakes" (actually, 15,291 lakes have been inventoried) and more than 90,000 miles of rivers, streams, and ditches, has an abundance of surface-water resources. Minnesota (loosely translated from the Sioux word for "sky-tinted water") lives up to its name; 5.7 percent of its area is covered by lakes and streams. Water quality is suitable for most uses, except during low flows of some streams that have been polluted locally by human activities. The abundance and quality of Minnesota's surface-water resources have been instrumental in determining types and locations of industry, location and growth of municipalities, expansion of tourism, and growth of recreational activities and facilities in the State.

In 1980, 77 percent, 2,400 Mgal/d (million gallons per day) or 3,710 ft^3/s (cubic feet per second), of the total offstream water supply came from surface-water sources (table 1). Ground-water sources supplied the remaining 23 percent or 700 Mgal/d (1,080 ft^3/s). Industry and municipalities use almost the entire offstream surface-water supply. Municipal domestic surface-water withdrawals supply 25 percent of the population of Minnesota, mostly in the twin cities of Minneapolis and St. Paul; rural domestic withdrawals are entirely from ground-water sources. Irrigation uses less than 1 percent of the total offstream surface-water supply; however, the demand for irrigation water is increasing rapidly and soon will become an important issue. Presently, Minnesota's hydroelectric-power facilities use 20,000 Mgal/d or 30,900 ft^3/s to generate 4 percent of the State's electricity.

Flooding of larger rivers and streams during spring snowmelt is a major concern in most years and has led to numerous studies of flood-prone urban and rural areas for insurance purposes. Floods at most of the streamflow sites listed in table 2 have approached or exceeded the 100-year flood. The greatest drought in this century occurred in the 1930's. The drought of 1976–77 reduced streamflow to rates similar to those of the 1930's in several areas of the State, but the drought was not as prolonged.

The quality of water in Minnesota streams is good except in the headwaters of the Minnesota River and in a few small tributaries near the South Dakota border. Water in these streams is slightly saline at lower flows, with dissolved solids exceeding 1,000 mg/L (milligrams per liter). Minnesota's surface waters tend to be hard (see table 2, remarks column) with the degree of hardness decreasing in the northeastern part of the State.

Conservation and preservation of the State's water resources and their improvement in areas where adversely affected by human activities are major objectives of water managers. The ever-increasing demands and competition for irrigation water, industrial and municipal water supplies, and hydroelectric power and recreational facilities must be weighed and regulated with regard to these objectives.

Table 1. Surface-water facts for Minnesota

[Data 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 SURFACE WATER, 1980	
Number (thousands)	1,010
Percentage of total population	25
From public water-supply systems:	
Number (thousands)	1,010
Percentage of total population	25
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	3,100
Surface water only (Mgal/d)	2,400
Percentage of total	77
Percentage of total excluding withdrawals for thermoelectric power	50
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	210
Percentage of total surface water	9
Percentage of total public supply	48
Per capita (gal/d)	208
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Service water (Mgal/d)	10
Percentage of total surface water	0.4
Percentage of total livestock	15
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	2,200
Percentage of total surface water	92
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	96
Excluding withdrawals for thermoelectric power	80
Irrigation withdrawals:	
Surface water (Mgal/d)	18
Percentage of total surface water	0.8
Percentage of total irrigation	11
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	20,000

GENERAL SETTING

Minnesota lies in the Superior Upland and the Central Lowland physiographic provinces (fig. 1). Only the northeastern or "Arrowhead" area of Minnesota is in the Superior Upland province; the rest of the State is in the Central Lowland province.

Minnesota contains four regional drainage divides. Runoff is carried by rivers and streams northward to Hudson Bay, eastward to the Atlantic Ocean, or southward to the Gulf of Mexico.

Almost two-thirds of central and southern Minnesota is drained by the Mississippi River and its tributaries. The Mississippi River begins in Lake Itasca in north-central Minnesota and meanders for 514 miles through the central lakes region on its way to Minneapolis and St. Paul (Twin Cities). The Mississippi continues southeastward for 35 miles to the Wisconsin border and forms the boundary between Wisconsin and Minnesota for another 137 miles southeastward to Iowa. The two largest tributaries are the Minnesota River, which drains most of west-central and southern Minnesota and joins the Mississippi River at the southern side of the Twin Cities, and the St. Croix River, which originates in northwestern Wisconsin and forms the border for 125 miles between Wisconsin and Minnesota, joining the Mississippi where the Mississippi first reaches the Wisconsin border. A small area at the southwestern corner of the State drains southwestward.

The Red River of the North and its tributaries drain the northwestern and western parts of the State, which are flat, largely treeless prairies. The Rainy River and its tributaries drain north-central and part of northeastern Minnesota, which is a relatively flat but irregular region of swamps, forests, and lakes. The Red and the Rainy Rivers carry runoff into Canada that eventually discharges to Hudson Bay.

To the east of the Rainy River is the Arrowhead area with the greatest topographic relief in the State. This area is characterized by wooded hills and valleys, thin soil, and rock outcrops. The well-defined drainage pattern of many small streams and rivers carries runoff directly to Lake Superior. The larger streams of the area are the Pigeon River, along the border with Canada, and the St. Louis River, which empties into the southwestern tip of Lake Superior at Duluth. The St. Louis River carries 4.5 times the volume of runoff carried by the Pigeon River and drains more than one-half of the Arrowhead area.

Average annual precipitation in Minnesota ranges from about 20 inches in the northwest to 32 inches in the southeast (fig. 1). Fortunately, 65 to 75 percent of the annual precipitation occurs during the growing season of May through September, and only 15 percent occurs during December through March, usually as snow (Baker and others, 1979, p. 5). The bar graphs in figure 1 illustrate this seasonal variation. Average annual evaporation (from a free water surface) ranges from about 40 inches in the southwestern part of the State to 28 inches in the northeastern part; about 75 percent of the evaporation occurs during the growing season (National Oceanic and Atmospheric Administration, 1982, map 3).

Annual runoff ranges from 1 inch in the west to more than 14 inches in the northeast (fig. 1) and exhibits strong seasonal variation. As much as 50 percent of total annual runoff can occur during the spring rain and snowmelt periods (see graphs of average monthly discharge in fig. 1). The amount of runoff is closely related to precipitation, which increases from west to east, and to evaporation potential, which decreases from west to east. In addition, other factors influence the Arrowhead area of the State where runoff increases significantly in an easterly direction. A lower proportion of the annual precipitation occurs during the growing season, which, along with lower temperatures and greater cloud cover reduces evapotranspiration. Greater amounts and accumulation of snowfall during the winter, coupled with shallow soils that have greatly reduced capacity to retain moisture, produce larger runoff volumes with faster response times. As a result, the average annual runoff of a typical basin in western Minnesota is 8 percent of the precipitation, whereas it is 44 percent in a typical basin in the Arrowhead area (Baker and others, 1979, p. 6–7).

PRINCIPAL RIVER BASINS

The rivers of Minnesota are headwaters of three subcontinental divides and flow through four major water-resources regions. The largest of these is the Upper Mississippi Region (fig. 2), which drains the southern two-thirds of Minnesota. The Souris–Red–Rainy Region drains all of northern Minnesota except the extreme northeastern part. The northeastern Arrowhead section of Minnesota is drained by the Great Lakes Region. A few small streams in the southwestern corner of the State are in the Missouri Region; these streams are not discussed in the text, although water-use data for this area are included in table 1. The major river basins, with the exception of the Missouri, are described below; their location and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

UPPER MISSISSIPPI REGION

Mississippi River Basin

The Mississippi River is the most significant river in the State, based on extent of area drained, economic importance, intensity of use, and value as a natural resource. It originates in Lake Itasca in north-central Minnesota and flows through many northern lakes on its journey southward. Principal tributaries above the Twin Cities are the Crow Wing, the Sauk, the Crow, and the Rum Rivers (Mississippi Headwaters Subregion). The Minnesota River—largest tributary in the State—enters the Mississippi River near the southern boundary of Minneapolis–St. Paul at Fort Snelling (Minnesota Subregion). Below the Twin Cities, 35 miles farther downstream, the second largest tributary—the St. Croix River—joins the Mississippi at Prescott, Wisc., (a border town) (St. Croix Subregion). At this point, the Mississippi River has flowed 550 miles from its source and drained approximately 38,000 mi^2 (square miles) in Minnesota. The Minnesota River drains the Central Lowland physiographic province, and the St. Croix River drains both the Central Lowland province and the Superior Upland province (fig. 1). From Prescott to the southern border of Minnesota, the Mississippi River forms the boundary between Minnesota and Wisconsin. Major tributaries that drain Minnesota in this reach of the Mississippi are the Cannon, the Zumbro, and the Root Rivers (Upper Mississippi–Black–Root Subregion). At the southern boundary of Minnesota, the Mississippi River is 686 miles from its source and has drained about 65,000 mi^2, approximately 47,500 mi^2 of which are in Minnesota. The Mississippi River, in its upper reaches, drains the Superior Upland and Central Lowland provinces; it drains only the Central Lowland province below the junction of the St. Croix River.

The Mississippi River above St. Paul is slightly regulated by six headwater reservoirs that have a combined storage capacity of 1,640,000 acre-ft (acre- feet) or 534,000 Mgal (million gallons); the reservoirs are Lake Winnibigoshish and Leech, Pokegama, Pine, Big Sandy, and Gull Lakes. The primary purpose of these reservoirs is to augment discharge through the Twin Cities during periods of low flow to dilute sewage effluent, preserve fisheries, and maintain flow for navigation below the Twin Cities; a secondary function is to reduce flood peaks.

In 1936, the U.S. Army Corps of Engineers began constructing locks and dams on the upper Mississippi River to extend navigation to the Twin Cities. Nine locks and dams are located within Minnesota or along its border with Wisconsin, and a 9-foot-deep channel is maintained in this reach, which was opened for navigation in 1939. In the 1960's, the head of navigation was extended 4.6 miles farther upstream into Minneapolis with the construction of Upper and Lower St. Anthony Falls Lock and Dam.

The Mississippi River has played an important role in the development and history of the State. From its use as a fur-trade route for two centuries, to its use for transporting millions of feet of pine logs to sawmills at St. Anthony Falls, to its present use

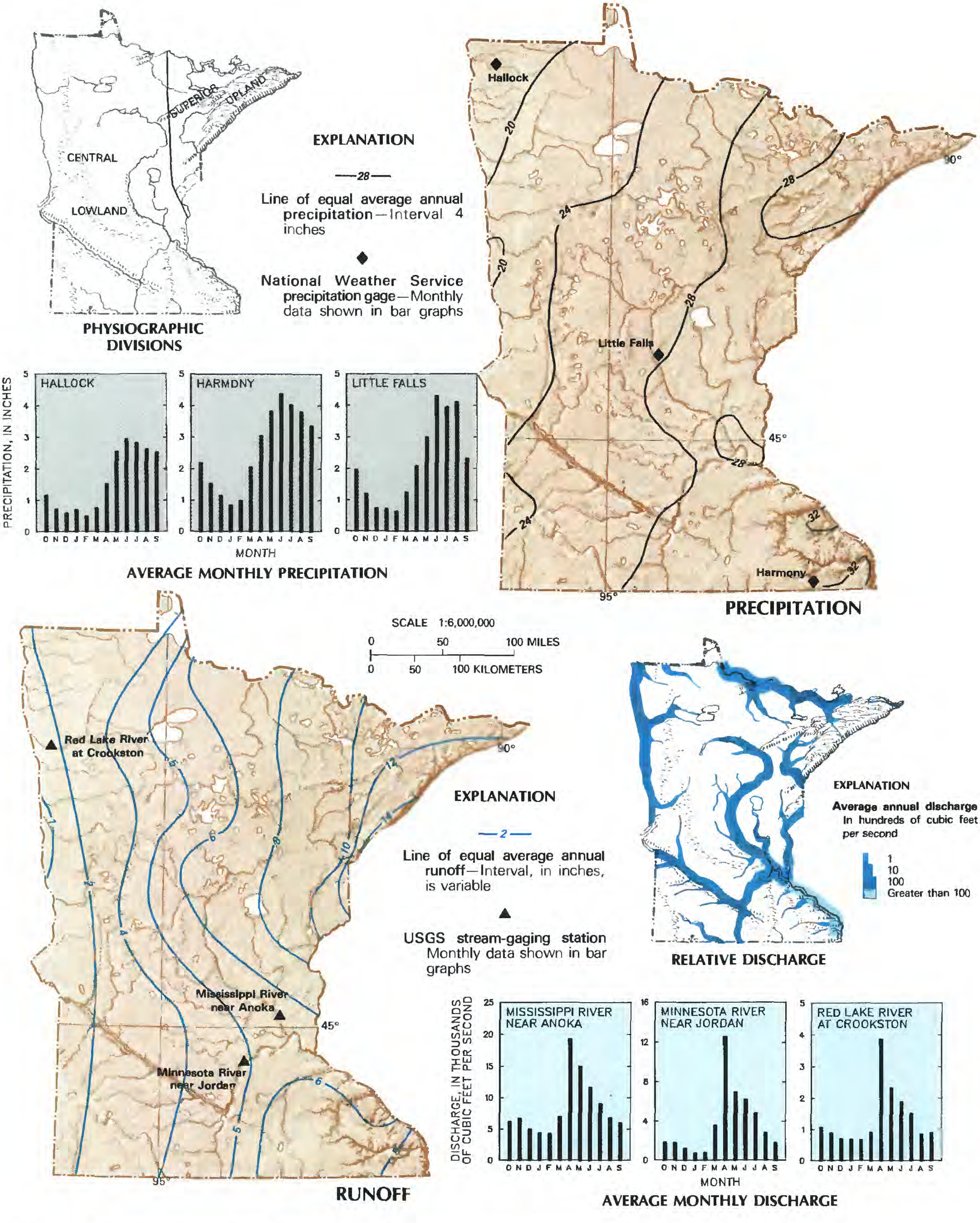

Figure 1. Average annual precipitation and runoff in Minnesota and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Minnesota

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainege area (mi²)	Period of analysis	7-dey, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				UPPER MISSISSIPPI REGION MISSISSIPPI RIVER BASIN[1]				
1.	Mississippi River near Anoka (05288500).	19,000	1932-83	1,194	7,655	98,000	Moderate	Six headwater reservoirs have small regulatory effect, diurnal regulation by powerplant upstreem. Dissolved solids between 120 and 300 mg/L. Hardness range 65 to 250 mg/L as calcium carbonate.
2.	Crow Wing River near Pillager (05247500).	3,300	1968-83	173	1,264	15,300	Appreciable	Power generetion at two dams upstream.
3.	Sauk River near St. Cloud (05270500).	925	1910-12 1931 1935-81	13.1	276	10,000	Moderate	Regulation by powerplants and reservoirs upstream. Dissolved solids between 160 and 320 mg/L. Hardness range 100 to 350 mg/L as calcium carbonate.
4.	Crow River at Rockford (05280000).	2,520	1910-17 1931 1935-83	14.7	664	19,000	None	Dissolved solids between 200 and 650 mg/L. Hardness range 100 to 450 mg/L as calcium carbonate.
5.	Rum River near St. Francis (05286000).	1,360	1931 1934-83	64.4	602	14,000	Negligible	Occasional regulation by upstream lakes. Dissolved solids between 100 and 250 mg/L. Hardness range 50 to 220 mg/L as calcium carbonate.
6.	Cannon River at Welch (05355200).	1,320	1911-13 1931-71	61.6	501	34,000	Appreciable	Diurnal fluctuation by powerplents upstream.
7.	Zumbro River at Zumbro Fells (05374000).	1,130	1910-17 1931-80	77.7	517	40,200	. . . do . . .	Diurnal fluctuation by powerplants upstream.
8.	Root River near Houston (05385000).	1,270	1910-17 1931-83	178	696	51,500	Negligible	Powerplants upstream affect low flows (diurnal fluctuation).
				MINNESOTA SUBREGION				
9.	Minnesota River near Jordan (05330000).	16,200	1935-83	171	3,520	115,000	None	Dissolved solids between 250 and 950 mg/L. Hardness range 150 to 750 mg/L as calcium carbonate.
10.	Lac qui Perle River near Lac qui Perle (05300000).	983	1913,1932 1934-83	0.20	120	19,300	. . . do . . .	
11.	Chippewa River near Milan (05304500).	1,870	1938-83	2.90	269	12,400	Negligible	Several small lakes upstream.
12.	Cottonwood River at New Ulm (05317000).	1,280	1912-13 1936-37 1939-83	2.77	289	33,000	. . do . . .	Regulation by lakes upstreem.
13.	Blue Earth River near Repidan (05320000).	2,430	1940-45 1950-83	14.9	895	34,600	Appreciable	Power generation.
				ST. CROIX SUBREGION				
14.	St. Croix River at St. Croix Falls (05340500).	6,240	1903-83	1,099	4,235	61,000	Appreciable	Power generation. Dissolved solids between 50 and 160 mg/L. Hardness range 25 to 150 mg/L as calcium cerbonate.

[1] Includes the Mississippi Headwaters and the Upper Mississippi Black-Root Subregions

Table 2. Selected streamflow characteristics of principal river basins in Minnesota—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
SOURIS-RED-RAINY REGION **Red Subregion** **Red Lake River basin**								
15.	Otter Tail River below Orwell Dam near Fergus Falls (05046000).	1,830	1931-83	12.3	304	4,800	Appreciable	Regulated by Orwell Lake beginning March 1953, also by powerplants upstream.
16.	Red River of the North at Grand Forks (05082500).	30,100	1883-1983	71.4	2,558	89,000	Negligible	Small dam upstream can affect low flows. Dissolved solids between 160 and 550 mg/L. Hardness range 100 to 380 mg/L as calcium carbonate.
17.	Red Lake River at Crookston (05079000).	5,280	1902-83	31.6	1,130	31,000	Appreciable	Diurnal fluctuation by powerplant upstream until 1975, also regulated by several headwater lakes. Dissolved solids between 140 and 400 mg/L. Hardness range 90 to 310 mg/L as calcium carbonate.
Rainy Subregion **Little Fork and Big Fork River basins**								
18.	Rainy River at Manitou Rapids (05133500).	19,400	1929-83	3,597	12,830	80,000	Moderate	Diurnal fluctuation by powerplant at International Falls, low and medium flows affected by headwater lakes. Dissolved solids between 40 and 150 mg/L. Hardness range 25 to 75 mg/L as calcium carbonate.
19.	Little Fork River at Littlefork (05131500).	1,730	1912-16 1929-83	40.3	1,053	27,400	None	Dissolved solids between 80 and 250 mg/L. Hardness range 40 to 200 mg/L as calcium carbonate.
20.	Big Fork River at Big Falls (05132000).	1,460	1929-79 1983	33.7	715	21,800	Moderate	Diurnal fluctuation by powerplant upstream. Dissolved solids between 90 and 300 mg/L. Hardness range 50 to 250 mg/L as calcium carbonate.
GREAT LAKES REGION **Western Lake Superior Subregion**								
21.	Pigeon River above Middle Falls near Grand Portage (04010500).	600	1924-83	44.5	506	13,600	Negligible	Small regulatory effect by headwater lakes.
22.	Baptism River near Beaver Bay (04014500).	140	1928-83	3.45	169	8,820	None	Dissolved solids between 0 and 150 mg/L. Hardness range 20 to 80 mg/L as calcium carbonate.
23.	St. Louis River at Scanlon (04024000).	3,430	1909-83	316	2,313	38,000	Appreciable	Regulated by several headwater reservoirs, diurnal fluctuation by powerplants upstream. Dissolved solids between 50 and 260 mg/L. Hardness range 30 to 190 mg/L as calcium carbonate.

for transporting millions of tons of grain and other bulk commodities to and from Minnesota to world markets, the "Father of Waters" has been and continues to be a reliable and inexpensive "highway." In addition, the river has provided hydroelectric power from several small dams above the Twin Cities, eight of which are still in operation. The river provides many miles of recreational facilities for boating, fishing, sailing, water skiing, and camping. Minneapolis, the largest city in Minnesota (population 370,950), as well as several smaller cities upstream, draw almost their entire municipal water supply from the Mississippi River. During the drought in the summer of 1976, the water level at the Minneapolis municipal pumping station dropped to within 1 foot of top of intakes, indicating the possibility of future shortages as this is the only present supply source for the city of Minneapolis. Minimum discharge of the Mississippi River near Anoka (table 2, site 1) since 1932 was 529 ft^3/s or 342 Mgal/d occurring in 1976; the flood of record was 91,000 ft^3/s or 58,800 Mgal/d in 1965.

A nuclear powerplant at Monticello, 39 miles upstream from the Minneapolis water-supply intakes, poses a potential problem when or if accidental spills of radioactive water occur. Overflow of combined storm and sanitary sewage and inflow of sediment- and nutrient- laden water from the Minnesota River caused water-quality problems downstream from the Twin Cities, which affect our neighbors in Wisconsin. Farther downstream, several tributaries to the Mississippi River in southeastern Minnesota drain an area of karst topography. This is a predominantly rural area where agricultural practices allow pollutants from fertilizers, herbicides, and insecticides to seep rapidly into the ground-water system and reappear as polluted surface water downgradient.

Minnesota Subregion

The Minnesota River flows southeasterly and then northeasterly from the west-central boundary of Minnesota to join the Mississippi River at Fort Snelling; it drains a large part of west-central and southern Minnesota (16,200 mi^2). This basin contains some of the richest agricultural land in the State. Major tributaries of the Minnesota River are the Lac qui Parle, the Chippewa, the Cottonwood, and the Blue Earth Rivers. Several small hydropower and hydroelectric facilities were operated in the basin during early development of the State. Two of these facilities are still in operation, one of which was recently reactivated because of the current trend toward using renewable natural resources for power generation. Several small headwater reservoirs have been built by the U.S. Army Corps of Engineers since the 1930's for flood control and for fish and wildlife management and preservation. These dams control 25 percent of the basin or 4,050 mi^2. Minimum discharge of the Minnesota River near Jordan (table 2, site 9) since 1935 was 75 ft^3/s or 51 Mgal/d in 1955. The maximum flood during the same period was 117,000 ft^3/s or 75,600 Mgal/d in 1965.

As irrigation is expanded along the Minnesota River and its tributaries, there is greater need for evaluating flow rates at various locations, controlling and metering withdrawals, and policing unauthorized withdrawals.

St. Croix Subregion

The St. Croix River has its source in northwestern Wisconsin and flows southward, forming the boundary between Minnesota and Wisconsin for 125 miles to its junction with the Mississippi River. This basin has considerable relief and many natural, virtually undisturbed areas along the river's course. As a result, part of the St. Croix has been designated a "Wild and Scenic River." As Minnesota was settled and developed, the St. Croix provided an invaluable highway for homesteaders to the new lands. However, the St. Croix is best remembered for its contribution to the lumber industry, both as an avenue for transportation of millions of board feet of logs as well as furnishing hydropower for several sawmills along its course. Presently, only one small hydroelectric plant remains on the St. Croix main stem, but, with the increasing cost of energy and depletion of fossil fuels, several old dam sites on tributaries to the St. Croix are again being considered for generation of hydroelectric power. Because of its pristine state and proximity to the Twin Cities, the St. Croix River and surrounding shores are highly-prized recreational areas; several State parks are located along its course. Minimum discharge in the St. Croix River at St. Croix Falls (table 2, site 14) since 1903 was 75 ft^3/s or 48 Mgal/d in 1910. The flood of record occurred in 1950 and was 54,900 ft^3/s or 35,500 Mgal/d. Because of its pristine quality, local residents are sensitive to even minor changes in water quality.

SOURIS-RED-RAINY REGION

Red Subregion

The Otter Tail River (head of the Red River of the North) flows in a southwesterly direction toward the North Dakota border and drains 2,040 mi^2 of west- central Minnesota above its confluence with the Bois de Sioux River at Breckenridge. At this point, the Red River of the North is formed and is the boundary between Minnesota and North Dakota for 394 river miles to the Canadian border. Many tributaries enter the Red River as it winds its way northward through a flat treeless prairie that was once part of a large glacial lake. The largest of these tributaries on the Minnesota side is the Red Lake River. The Red River of the North and all its tributaries drain the Central Lowland province. At the international boundary, the Red River has drained 40,200 mi^2. About 16,000 mi^2 (40 percent) of this area is in Minnesota; the remainder (60 percent) is in North Dakota and Canada. The Red River Valley is noted for its rich soil and bountiful crops. Therefore, much of the industry and commerce in western and northwestern Minnesota is related to support of agriculture. Because of the extremely flat slope of the Red River, which averages about 0.5 ft/mi (foot per mile), drainage of surrounding agricultural areas can be a problem during the growing season with abundant or excessive precipitation. The problem is compounded in spring when thawing and runoff begin in the southern extremity of the Red River basin in Minnesota and North Dakota while the northern outlet in Canada is still frozen. It is not uncommon for large areas to be inundated by shallow flood waters during this period in the spring. Fortunately, most of these floods recede in time to allow agricultural lands to be worked and seeded at the beginning of the growing season. Major floods oc-

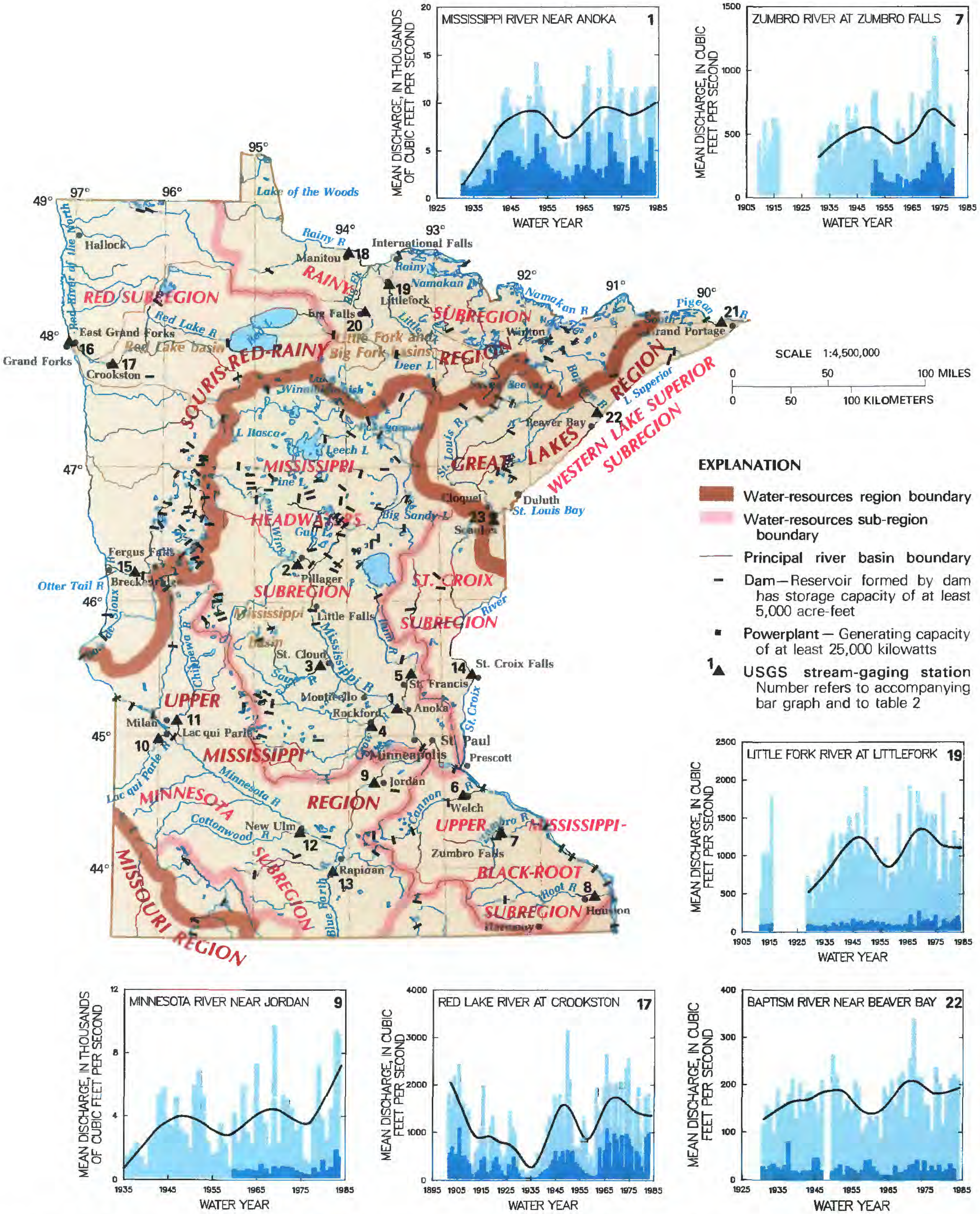

Figure 2. Principal river basins and related surface-water resources development in Minnesota and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

curred in 1950, 1965, 1966, 1969, 1975, 1978, and 1979. The greatest flood in the upper reaches of the Red River of the North occurred in 1969; farther downstream the greatest flood occurred in 1979; near the international boundary the greatest flood was in 1950. Based on available records, all these floods were exceeded in the previous century. The minimum discharge in the Red River of the North at Grand Forks (table 2, site 16) since 1883 was 1.8 ft^3/s or 1.2 Mgal/d in 1977. The flood of record was 85,000 ft^3/s or 54,900 Mgal/d in 1897. In response to the regular flooding in the Red River Valley, Minnesota farmers in recent years have built unauthorized levees on their property along the river. This reduces overbank conveyance on the Minnesota side of the river, raising the elevation of the flood peak, and further inundating land in North Dakota.

Red Lake River Basin.—The Red Lake River begins in Red Lake—the largest body of water (451 mi^2) entirely within the State (Minnesota Department of Conservation, 1968, p. 44)—and flows westerly 196 miles to join the Red River of the North at East Grand Forks. It drains approximately 5,500 mi^2, beginning with extensive swamp and marshlands near Red Lake to relatively flat agricultural land farther west in the Red River Valley. In the past, hydroelectric power was generated at four small plants along the river's course, but none of these remain in operation today.

Wild rice growers on at least one tributary of the Red Lake River divert a large part of the flow to flood rice paddies at crucial times during each year. Accurate flow figures are needed to regulate and manage this practice adequately.

Rainy Subregion

The Namakan River, which originates in Canada and drains several lakes on each side of the international boundary as well as along the boundary, is actually the headwaters of the Rainy River. After passing through Namakan and Rainy Lakes, which are part of Voyageurs National Park on the international boundary, the Namakan River becomes the Rainy River at the outlet of Rainy Lake. From the outlet of Rainy Lake at International Falls, the Rainy River flows 87 miles to its mouth on Lake of the Woods, forming the boundary between Minnesota and Canada and draining a considerable part of north-central Minnesota as well as parts of southern Canada. The Rainy River basin in Minnesota drains approximately equal areas of the Central Lowland and Superior Upland provinces. With the exception of the Rainy River headwater-lakes area, two of the largest tributaries are the Little Fork River, which primarily drains the Superior Upland, and the Big Fork River, which drains the Central Lowland. Lake of the Woods contains the Northwest Angle of Minnesota, which is the northernmost point in the conterminous United States (49°23′04′ north latitude). Water leaving Lake of the Woods flows northward into Canada. At Lake of the Woods, the Rainy River drains about 20,000 mi^2 of Minnesota and Canadian territory; slightly more than one-half of this area is in Minnesota.

Many small timber and rock dams were built in the headwater lakes and tributary channels of the Rainy River during early development of the area to facilitate logging and transportation of logs to sawmills. A few of these still remain today but are used only to stabilize and maintain lake levels. Two small hydroelectric plants at Winton and International Falls were built early in the 20th century and continue to operate today. Minimum discharge in the Rainy River at Manitou Rapids (table 2, site 18) for the period of record (1929–83) was 928 ft^3/s or 600 Mgal/d in 1929; maximum discharge during the same period was 71,600 ft^3/s or 46,300 Mgal/d in 1950.

There is very little industry in the Rainy River basin to cause pollution of its high-quality water. However, a paper-pulp mill has been a source of considerable pollution in the past, but screens have been installed in the effluent channel to substantially reduce suspended solids. Regulation of international border lakes in the Rainy River basin in accordance with terms of the International Waterways Treaty is a local and international concern.

Little Fork and Big Fork River Basins.—The headwaters of the Little Fork River lie in north-central Minnesota, an area with numerous lakes. The Little Fork River flows generally northward for approximately 150 river miles to its junction with the Rainy River about 11 miles downstream from International Falls; it drains 1,800 mi^2 of remote swamp and woodland interspersed with small agricultural areas.

The Big Fork River originates in a recreational-lake area similar to the headwaters of the Little Fork River. It flows northward from Dora Lake 173 river miles to join the Rainy River 7 miles downstream from the mouth of the Little Fork River. The Big Fork River drains approximately 1,900 mi^2 of predominantly wilderness area.

Pulpwood and lumbering are the principal industries in both the Big Fork and Little Fork basins; tourism is next in importance. Agriculture is very limited in each basin. One hydroelectric-powerplant remained in operation on the Big Fork River at Big Falls until 1971; none are presently operating in either basin.

GREAT LAKES REGION

Western Lake Superior Subregion

In this subregion, many small tributaries flow directly into Lake Superior; three of the largest are the Pigeon, the Baptism, and the St. Louis Rivers, all of which drain the Superior Upland province. The Pigeon River is located at the extreme northern tip of the Minnesota Arrowhead and forms the international boundary between Minnesota and Canada for 60 river miles from South Lake to Lake Superior. It drains approximately 630 mi^2 of wilderness in a virtually roadless area where tourism is the chief industry and logging and trapping become important during the long winter season. In the early history of Minnesota, the Pigeon River was a well-traveled fur-trade route.

The Baptism River flows generally southeasterly to its mouth in Lake Superior, draining 140 mi^2 of the central Arrowhead territory. This river has the greatest annual runoff per square mile in the State's stream-gaging network because of thin soils and large expanses of bedrock outcrop in the basin. The area drained is predominantly forested and principal industries are tourism and logging.

The largest river in the Arrowhead—the St. Louis—drains fully one-half of Minnesota's area in the Great Lakes Region. It begins in Seven Beaver Lake and flows in a "horseshoe" configuration—first westward, then southward, and finally eastward to Lake Superior at Duluth, 205 miles from its beginning. The source of the St. Louis River is only 50 miles north and 20 miles east of its mouth, but, because of its long, roundabout course, the St. Louis River drains about 3,500 mi^2—the entire lower Arrowhead area.

The St. Louis River also was prominent in the development of Minnesota—first as a route traveled by explorers, fur traders, and voyageurs in the 1700's, and later in the 1800's as a means of transporting logs to sawmills and furnishing hydropower for these mills. Some of the richest timberland in America was found in the St. Louis basin where the most treasured of all trees for lumber, the White Pine, grew in abundance. So plentiful were the timber stands that in 1880–83, 11 sawmills operated along St. Louis Bay below Fond du Lac. Cloquet, located 16 miles upstream, was called the "White Pine Capital" of the United States (Bartlett, 1984, p. 168). The steep gradient of the river in its lower reaches (38 ft/mi from Cloquet to Fond du Lac) and its relatively dependable volume of flow at lower stages encouraged early development of hydroelectric power, and some plants still are in operation today. The sawmills have since disappeared, but some of the companies survive following conversion from lumber to pulp and paper products (Bartlett, 1984, p. 169). Minimum flow in the St. Louis River at Scanlon (table 2, site 23) since 1909 was 54 ft^3/s or 35 Mgal/d, which occurred in 1980; maximum flow during the same period was 37,900 ft^3/s or 24,500 Mgal/d in 1950.

In the recent past, the lower St. Louis River was polluted by several industries involved in the manufacture of wood products. Presently, all effluent from these industries passes through sewage-treatment facilities; consequently, water quality in the lower reaches of the St. Louis River is now suitable for most uses.

SURFACE-WATER MANAGEMENT

Minnesota, unlike states to the west that manage surface water under the doctrine of prior rights, embraces the doctrine of riparian rights. This means "riverbank" landowners have equal rights to "reasonable use" of waters that border their land. The doctrine can be contrary to public interest at times because it restricts water use to landowners and makes no distinction between relative values of different uses. Present thinking on water allocation is that water is a public resource held in trust by the State, and that rights to this resource should be apportioned according to the best interests of society and to the economy.

The Division of Waters within the Minnesota Department of Natural Resources (MDNR) is vested with the authority to issue or discontinue permits for water use and to limit withdrawals of surface and ground water in accordance with public goals. Minnesota law states that, where a conflict exists over water from a particular source, permits will be granted in the following order:

First—Domestic use
Second—Any consumptive use less than 10,000 gallons per day
Third—Agricultural irrigation and processing
Fourth—Power generation
Fifth—Any other use in excess of 10,000 gallons per day

However, certain "basic needs" and "environmental" requirements take precedence over the priorities listed above. Appropriation permits must be denied, according to MDNR rules, if public safety, safe yields, or minimum flows are threatened. Water-resources-management programs are administered by 16 State agencies and by numerous regional, county, city, township, watershed districts, soil and water conservation districts, rural water systems, sanitary districts, and lake basin or drainage districts. Three agencies—the Department of Natural Resources (allocation and use), the Pollution Control Agency (quality), and the Department of Health (safe drinking water and well construction)—administer three-fourths of these programs.

Under a 1909 treaty, the International Joint Commission (IJC) has power to prohibit water use that would affect levels or flows of international waters (Canadian–United States). However, in actuality, many diversions and consumptive uses are not closely monitored. For example, all of Minnesota's North Shore communities that draw water from Lake Superior for their municipal systems need apply only to the MDNR for water-supply permits and not to the IJC.

An application to export water outside Minnesota was approved by the legislature for the first time on March 22, 1984. This involved extension of a rural water system in northwestern Minnesota northward to the city of Emerson, Manitoba, Canada. Recent legislation attempts to limit water exports and requires approval of the legislature as well as the MDNR. Considerable additional data and long-range planning will be needed to enact effective state, interstate, or Federal legislation governing water export.

Minnesota has long realized the need for an organization to coordinate and integrate State water policy through one governing body. This was first attempted by the Water Planning Board, which was merged with the Environmental Quality Board (EQB) in 1983. Currently, the EQB and the Governor's subcabinet committee on Energy-Environment-Resources plan and coordinate water policy.

Research, data collection, and management of vital water-resources information by the U.S. Geological Survey in programs financed cooperatively with State agencies, municipalities, watershed districts, and other public entities provide much needed data for effective, intelligent planning, coordination, and management of the State's surface-water resources.

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MISSISSIPPI
Surface-Water Resources

Mississippi, with an average annual runoff of about 20 inches has an abundance of surface water. The Mississippi River forms the State's western boundary, and 5 interior streams have average discharges in excess of 4,000 ft³/s (cubic feet per second) or 2,590 Mgal/d (million gallons per day). The State has 6 major reservoirs, each with more than 25,000 acre-ft (acre-feet) or 8,150 Mgal (million gallons) of storage, that are used primarily for flood control and recreation. These reservoirs are potential sites for future hydroelectric-power generation. Currently, no hydroelectric power is generated in the State.

Offstream use of surface water in 1980, mostly for cooling at thermoelectric plants, averaged 1,400 Mgal/d or 2,170 ft³/s accounting for 48 percent of the total water use in the State. Thermoelectric-power generation and industrial use accounted for 86 percent of surface-water withdrawals. Withdrawals for irrigation accounted for about 9 percent and withdrawals for public-water supplies accounted for about 3 percent of the total surface-water use in 1980. Surface water served the water-supply needs of 7 percent of the population. Additional information on surface-water withdrawals in Mississippi during 1980 is given in table 1.

Historically, Mississippi has had an agricultural economy. Concerns about water resources generally have related to flooding and droughts, which are harmful to agriculture. However, there is a growing awareness of the need for better water management in the State, and two comprehensive water laws designed to improve the regulation and management of water-resources development in the State were enacted in 1985.

Table 1. Surface-water facts for Mississippi

[Data 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 SURFACE WATER, 1980	
Number (thousands)	182
Percentage of total population	7
From public water-supply systems:	
Number (thousands)	182
Percentage of total population	7
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	2,900
Surface water only (Mgal/d)	1,400
Percentage of total	48
Percentage of total excluding withdrawals for thermoelectric power	17
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	42
Percentage of total surface water	3
Percentage of total public supply	14
Per capita (gal/d)	231
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita	0
Livestock:	
Surface water (Mgal/d)	12
Percentage of total surface water	1
Percentage of total livestock	57
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	1,200
Percentage of total surface water	86
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	77
Excluding withdrawals for thermoelectric power	22
Irrigation withdrawals:	
Surface water (Mgal/d)	130
Percentage of total surface water	9
Percentage of total irrigation	13
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	0

GENERAL SETTING

Mississippi lies almost entirely in the East Gulf Coastal Plain section of the Coastal Plain physiographic province (fig. 1). The land surface is generally rolling to hilly with low to moderate topographic relief, except in the Mississippi Alluvial Plain in northwestern Mississippi and the Pine Meadows district along the Gulf Coast where there is very little topographic relief. Elevations reach a maximum of 806 feet above sea level in extreme northeastern Mississippi, and the land surface generally slopes to the south and southwest toward the Gulf of Mexico and the Mississippi River.

Average annual precipitation in Mississippi ranges from about 50 inches in the northwest to about 68 inches in the southeast (fig. 1). In the southern part of the State, July, August, and September are often the wettest months (fig. 1). Elsewhere, the highest monthly precipitation usually occurs in March or April. October is usually the driest month of the year throughout the State. About 50 percent of the precipitation evaporates or is transpired by vegetation, about 10 percent infiltrates to the water table, and about 40 percent runs off as streamflow.

The average annual runoff in Mississippi ranges from about 18 inches in the northwestern and central parts of the State to about 26 inches in the coastal area (Gebert and others, 1985). Average monthly streamflows are generally highest in March or April (fig. 1).

PRINCIPAL RIVER BASINS

Except for a few small basins in the northeastern part of the State, Mississippi is located in the Lower Mississippi and the South Atlantic-Gulf Regions (Seaber and others, 1984) (fig. 2). The Mississippi River forms much of the State's western border. The Yazoo and the Big Black Rivers in the Lower Mississippi Region originate in the hilly north-central part of the State and flow in a southwesterly direction to the Mississippi River. The Tombigbee, the Pascagoula, and the Pearl River basins in eastern and south central Mississippi flow southward to the Gulf of Mexico and are in the South Atlantic-Gulf Region.

These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

LOWER MISSISSIPPI REGION

The Mississippi River is a major artery for waterborne commerce. At Vicksburg, the river has an average discharge of more than eight times the combined average flow of all other streams that drain the State. The quality of water in the Mississippi River is suitable for most uses but, presently, the only offstream use of water from the Mississippi River is for cooling at thermoelectric plants. Although most of the low-lying areas along the river are protected by levees, backwater flooding along the tributaries to the Mississippi River is a major concern of agricultural interests in the area.

Lower Mississippi-Yazoo Subregion

Yazoo River Basin.—The Yazoo River basin, largest of the major river basins completely within the State, drains about 14,000 mi^2 (square miles) in northwestern Mississippi. The basin includes a hilly upland in north-central Mississippi where four headwater tributaries originate, and extensive flat lowlands in the Mississippi Alluvial Plain, commonly referred to as the delta. The delta—part of the flood plain of the Mississippi River—constitutes an area of almost 7,000 mi^2 of some of the most fertile and productive farmland in the world.

The upland part of the basin consists largely of forests, pastures, and small farms and is sparsely populated. Recreational use of Arkabutla, Sardis, Enid, and Grenada Lakes—large flood-control reservoirs constructed on the four headwater tributaries in the 1940's and 1950's—is the principal use of surface water in the area. Small amounts of surface water also are used for livestock watering and irrigation.

Most of the delta consists of relatively large farms that produce cotton, soybeans, and rice; catfish farming is common in some parts of the area. Principal uses of surface water in the delta include transportation of agricultural products (on the Yazoo and the Mississippi Rivers), cooling at thermoelectric powerplants, and irrigation. Surface-water withdrawals for thermoelectric-power generation at sites along the Mississippi River and the Sunflower River, principal tributary to the Yazoo River in the delta, averaged about 370 Mgal/d or 572 ft^3/s in 1983. Surface-water withdrawals for irrigation, which accounted for less than 15 percent of total irrigation withdrawals, averaged about 100 Mgal/d or 155 ft^3/s in 1983.

Despite the many levees, drainage ditches, channel improvements, and other flood control measures, flooding in the delta, either from excessive rainfall in the area or backwater flooding from the Mississippi River at Vicksburg, continues to be a principal concern of farmers.

The 15-year moving average of average discharge by water year on the Yazoo (site 1) and the Big Sunflower (site 2) Rivers (fig. 2) increased in the late 1960's and early 1970's and has since remained relatively high. This apparently long-term increase in average discharge may be caused by a series of unusually wet years and, in part, to discharge of surplus and waste ground water used for irrigation and fish farming. Ground-water withdrawals for these purposes averaged more than 1,000 Mgal/d or 1,550 ft^3/s in 1980.

Surface waters in the Yazoo River basin generally are low in dissolved mineral content and are suitable for most uses, however, in the heavily farmed areas, particularly in the lower part of the basin, streams receive large amounts of sediment and agricultural chemicals.

Lower Mississippi-Big Black Subregion

Big Black River Basin.—The Big Black River basin originates in north-central Mississippi and flows southwesterly to the Mississippi River. The Big Black River drains a 3,500 mi^2 area about 160 miles long and 20 to 25 miles wide. It has no major tributaries; many of the small tributaries in the upper part of the basin are perennial.

Elevations in the Big Black River basin and in the basins of several smaller tributaries to the Mississippi River in the subregion (fig. 2) range from about 50 feet to a little more than 500 feet above sea level. The subregion is sparsely populated and is hilly to gently rolling and largely forested, with significant amounts of cattle ranching and farming (principally soybeans and cotton). Oil and gas production is a major industry in the area, particularly in southwestern Mississippi where more than 2,600 wells produce oil and gas.

Use of surface water in the Big Black River basin is relatively small and is limited primarily to recreational use and livestock watering. Streams in the basin are unregulated and there are no large lakes or reservoirs. Flooding along the larger streams is frequent and a major concern of agricultural interests in the basin, but relatively few homes are flooded. In southwestern Mississippi, some stream channels are unstable and several highway bridges have been destroyed by large floods.

The flow of the Big Black River near Bovina (table 2, site 3) averages about 3,800 ft^3/s or 2,460 Mgal/d but is occasionally less than 100 ft^3/s or 64.6 Mgal/d. The 15-year moving average of average discharge by water year for the Big Black River near Bovina has increased steadily since 1968 (fig. 2) due to a large number of unusually wet years and above-average streamflow.

Surface waters in the Big Black River basin generally are low in dissolved mineral content and are suitable for most uses. However, some tributaries receive municipal waste treatment effluent and oil field wastes. The Big Black River receives significant amounts of sediment and agricultural chemicals.

SOUTH ATLANTIC-GULF REGION

Pearl Subregion

Pearl River Basin.—The Pearl River rises in east-central Mississippi, flows southwesterly to Jackson, then continues southeasterly to the Gulf of Mexico. The river is about 490 miles long and drains an area of about 8,000 mi^2. Fifty miles above the mouth, the river divides into the Pearl River and the West Pearl River. The Pearl River forms the boundary line between Mississippi and Louisiana.

Much of the upper two-thirds of the Pearl River basin consists of gently rolling to hilly terrain. In the southern part of the basin, the land is much flatter. More than 60 percent of the basin is forested, and about 30 percent of the basin is farmed. Soybeans and poultry are the major components of the economy in the upper basin, whereas lumber and manufacture of wood products dominate the ecomony of the lower basin.

Jackson, the State capital, withdraws most of its municipal water supply from the Pearl River. Jackson and several smaller cities discharge treated sewage and some industrial wastes into the river.

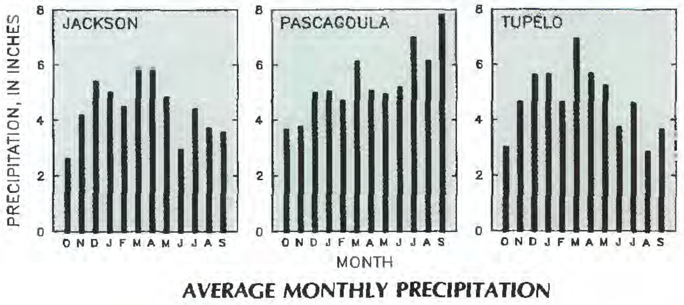
Ross Barnett Reservoir (completed in 1961 with a 310,000 acre-ft or 101,000 Mgal storage capacity) just upstream from Jackson, is the most commonly used recreational lake in the State. The reservoir also is used to augment low flows in the river in order to dilute municipal waste treatment effluent entering the river downstream of Jackson. Under a strict management plan, the reservoir also can be used to make minor but beneficial reductions in major floods.

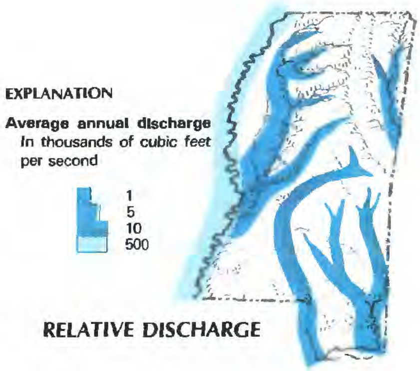
The flow of the Pearl River near Monticello (table 2, site 4) averages about 7,500 ft^3/s or 4,850 Mgal/d and has been as much as 122,000 ft^3/s or 78,900 Mgal/d during the extreme flood of April 1979. Since the late 1960's, there have been a number of years when the average annual discharge of the Pearl River near Monticello was above average and several years when large floods occurred (fig. 2). The 15-year moving average discharge by water year near Monticello has increased steadily since about 1968 due to a large number of unusually wet years and above-average streamflow.

The Pearl River and some of its tributaries receive municipal waste treatment effluent and industrial wastes. However, surface waters in the Pearl River basin generally are low in dissolved mineral content and are suitable for most uses.

Mobile-Tombigbee Subregion

Tombigbee River Basin.—The Tombigbee River drains about 6,100 mi^2 in northeastern Mississippi and about 7,600 mi^2 in northwestern Alabama. The topography in the basin is mostly hilly and elevations in the headwaters are about 700 to 800 feet





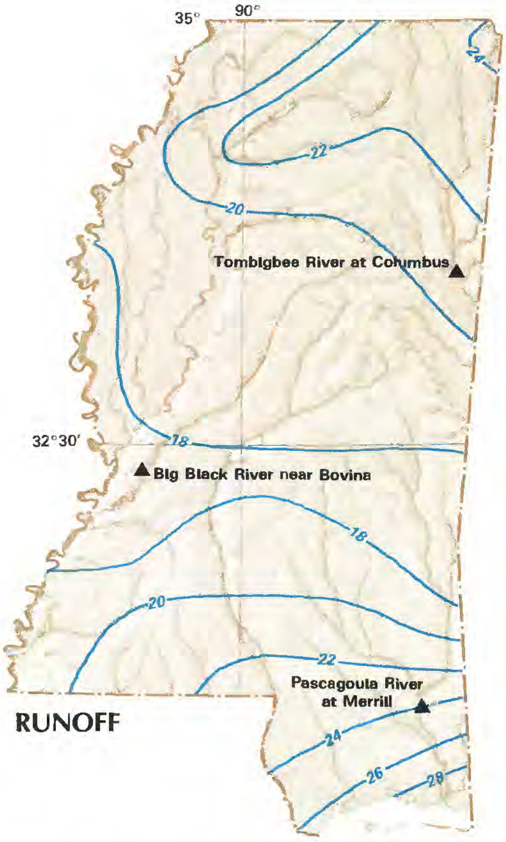
EXPLANATION

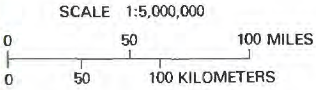
—56— Line of equal average annual precipitation Interval 2 inches

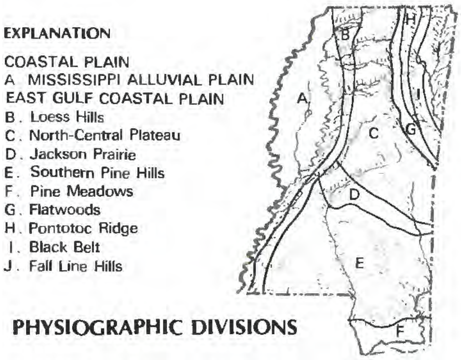
—26— Line of equal average annual runoff—Interval 2 inches

◆ National Weather Service *precipitation* gage Monthly data shown in bar graphs

▲ USGS stream-gaging *station*—Monthly data shown in bar graphs







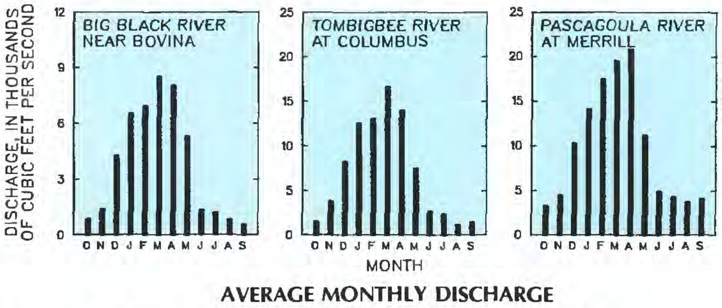


Figure 1. Average annual precipitation and runoff in Mississippi and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by H. Landers, National Weather Service Forecast Office, Jackson, Mississippi; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions modified from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Mississippi

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				LOWER MISSISSIPPI REGION Lower Mississippi—Yazoo Subregion Yazoo River basin				
1.	Yazoo River at Greenwood (07287000).[1]	7,450	1907–12, 1927–39	831	9,330	. . . .	None	Regulated by four reservoirs completed in the 1940's and early 1950's. Extensive agriculture.
			1940–84	741	10,900	45,000	Appreciable	
2.	Big Sunflower River at Sunflower (07288500).[1]	767	1935–84	87	1,070	14,100	Negligible	Heavily farmed (rice, soybeans, cotton production, and fish farming). Flow affected by irrigation.
				Lower Mississippi—Big Black Subregion Big Black River basin				
3.	Big Black River near Bovine (07290000).	2,810	1936–84	84	3,800	73,400	None	Forested, with some cattle, cotton, and soybean production, and oil and gas development.
				SOUTH ATLANTIC—GULF REGION Pearl Subregion Pearl River basin				
4.	Pearl River near Monticello (02488500).	4,993	1938–60	324	6,110	. . . .	None	Predominantly agricultural, with some light industry and oil and gas development. 100-year flood based on records for 1938–83.
			1961–84	365	7,530	97,100	Negligible	
				Mobile—Tombigbee Subregion Tombigbee River basin				
5.	Tombigbee River at Columbus (02441500).	4,463	1899–1912, 1928–82	233	6,520	223,000	None	Forested, with some cattle, soybeans, cotton, and light industry.
				Pascagoula Subregion Pascagoula River basin				
6.	Pascagoula River at Merrill (02479000).	6,590	1930–68	865	9,350	. . . .	None	Area is heavily forested, with wood and paper industries, shipbuilding, and oil and gas development.
			1969–84	1,080	11,800	221,000	Negligible	

[1] Data furnished by U.S. Army Corps of Engineers.

above sea level—among the highest in the State. Livestock production and row crops, principally soybeans and cotton, are major components in the local economy.

The river rises in extreme northeastern Mississippi and then flows southerly for about 130 miles before entering Alabama. Streamflow at Columbus (table 2, site 5) generally exceeds 230 ft³/s or 149 Mgal/d, even during periods of unusually low flow, and averages about 6,500 ft³/s or 4,200 Mgal/d. The 15-year moving average of average discharge by water year has declined since about 1975—a trend opposite that observed at many sites in other basins (fig. 2). The decline may be related to rainfall patterns in the State but also may reflect the filling of several reservoirs on the recently completed Tennessee-Tombigbee Waterway. Although these impoundments provide some storage for flood control, flooding is expected to remain a concern of residents along the waterway.

The Tennessee-Tombigbee Waterway, completed in 1985, connects the north-flowing Tennessee River with the south-flowing Tombigbee River and provides a shorter route for waterborne commerce between the Gulf of Mexico and areas farther north. Before completion of the waterway, use of surface water in the basin was primarily for the disposal of municipal and industrial wastes. Some surface water also was used to water livestock and irrigate row crops. With the completion of the waterway, the principal use will be for recreation and waterborne commerce. Tupelo, the largest city in the basin, proposes to withdraw water from the waterway for its municipal water supply in the near future.

Several of the western tributaries to the Tombigbee River receive significant amounts of municipal waste treatment effluent and industrial wastes but the dissolved mineral content of most streams is very low and the waters are suitable for most uses.

Pascagoula Subregion

Pascagoula River Basin.—The Pascagoula River, which drains an area of about 8,900 mi² in southeastern Mississippi, is formed by the confluence of the Chickasawhay and the Leaf Rivers. From this confluence, the river flows southward for about 80 miles before emptying into the gulf. The Escatawpa River, located mostly in Alabama, flows into the Pascagoula River very near the Gulf Coast. Much of the Pascagoula River drainage basin and the coastal area that drains directly into the gulf is forested. Near the coast, these areas are low-lying flatlands and marshlands. Farther inland, the landforms consist primarily of low rolling hills and broad, flat flood plains.

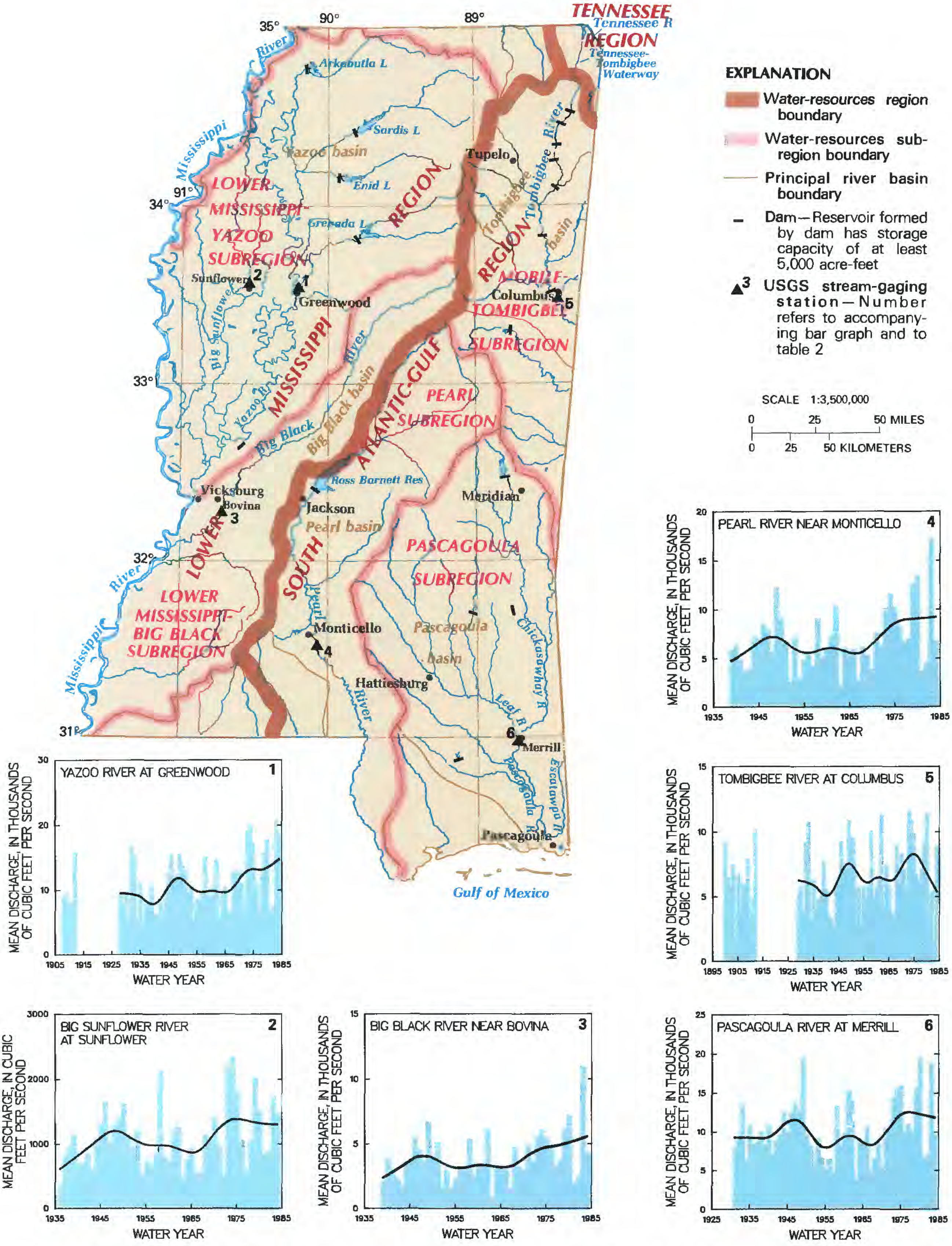


Figure 2. Principal river basins and related surface-water resources development in Mississippi and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

The economy of the area has relied heavily on lumber, the manufacture of wood products, and shipbuilding since before the Civil War. The city of Pascagoula on the densely populated Mississippi Gulf Coast is one of the great shipbuilding centers of the world. Tourism, commercial fishing, and oil and gas production also are significant components of the economy in the basin.

Water from the Pascagoula and the Escatawpa Rivers is distributed for industrial use in the Pascagoula area. Water from a major tributary to the Pascagoula River is withdrawn for thermoelectric-power generation. Industries located in Meridian, Hattiesburg, and other cities in the basin withdraw surface water and discharge treated wastes to the streams in the area. Several small recreational impoundments or "water parks" have been developed in the basin in recent years but most streams in the basin are unregulated. Flooding in the basin remains a principal concern of residents in the area.

Flow of the Pascagoula River at Merrill (table 2, site 6) averages 11,800 ft^3/s or 7,630 Mgal/d and exceeds 1,000 ft^3/s or 646 Mgal/d even during very dry periods. The lower reaches of the Pascagoula and the Escatawpa Rivers, as well as the smaller coastal streams, are estuaries.

Average annual flow of the Pascagoula River for the period of record is quite variable, ranging from about 4,000 ft^3/s or 2,580 Mgal/d to almost 20,000 ft^3/s or 12,900 Mgal/d (fig. 2). The increase in the 15-year moving average and variability of average discharge by water year at Merrill in recent years is similar to that observed at sites on the Pearl and the Big Black Rivers and, to a lesser extent, on the Yazoo River (fig. 2). The upward trend in 15-year moving average is due to a large number of unusually wet years.

Surface waters in the Pascagoula River basin receive some treated municipal effluent, industrial wastes, and oil-field brines, but dissolved mineral content of most streams is relatively low and the water is suitable for most uses.

SURFACE-WATER MANAGEMENT

Until mid-1985, Mississippi's surface-water resources were managed by the Mississippi Department of Natural Resources under a permitting system based on the prior-appropriation doctrine. The Department of Natural Resources Bureau of Land and Water Resources administered and enforced the statutes of the 1956 omnibus water law, which provided for the permitting and regulation of surface-water withdrawals. The Department of Natural Resources, Bureau of Pollution Control is charged with the permitting of all waste discharges into the State's surface waters.

In 1985, the Mississippi Legislature passed two comprehensive water laws that restructured the basic water law for the State. The first of these laws amended existing laws that regulated and controlled the use of surface water by providing for the permitting and regulation of ground and surface waters and eliminating several exemptions and exclusions from the regulatory authority granted to the Department of Natural Resources. This law also provided for the creation of a Central Water Management Data Base and a State Water Management Plan. The second law authorized the creation of local governmental water-management districts.

Several basinwide water-management districts were established in Mississippi before the passage of the 1985 water laws. Some of these districts were active in developing small impoundments and other recreational facilities on surface waters in their respective areas. The 1985 legislation, which authorized the creation of water-management districts at the city or county level of government is expected to result in the further development and management of surface-water and ground-water resources in the State.

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 5 Federal agencies.

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MISSOURI
Surface-Water Resources

Missouri is drained directly or indirectly by two of the Nation's largest rivers—the Mississippi and the Missouri. The State has about 20,000 miles of streams, has one of the greatest concentrations of springs in the Nation to sustain streamflow, and ranks among the top 10 States in the number of large manmade lakes. Although more towns in the State use ground water than surface water, the major population centers are located on the Mississippi and the Missouri Rivers and use them as the principal source for municipal supplies. Surface-water quality generally is suitable for most uses, although some treatment, such as softening and chlorination, is needed for municipal and some industrial uses. Variation in seasonal flow is the major constraint on use.

The largest use of surface water during 1980 was 13,000 Mgal/d (million gallons per day) or 20,100 ft³/s (cubic feet per second) for hydroelectric-power generation. The offstream use of surface water during 1980 represented 93 percent of the State's total ground-water and surface-water withdrawals; however, about 30 percent of that total was used for cooling purposes in thermoelectric-power generation. About 66 percent of the State's population depends on surface water for domestic use. Information about surface-water withdrawals in Missouri during 1980 is shown in table 1.

Table 1. Surface-water facts for Missouri

[Data 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; Johnson, 1984; per capita withdrawals for rural-domestic supply from L. F. Emmett, U.S. Geological Survey, written commun., 1985]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	3,241
Percentage of total population	66
From public water-supply systems:	
Number (thousands)	3,160
Percentage of total population	64
From rural self-supplied systems:	
Number (thousands)	81
Percentage of total population	2
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	6,900
Surface water only (Mgal/d)	6,400
Percentage of total	93
Percentage of total excluding withdrawals for thermoelectric power	64
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	570
Percentage of total surface water	9
Percentage of total public supply	78
Per capita (gal/d)	180
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	24
Percentage of total surface water	0.4
Percentage of total rural domestic	26
Per capita (gal/d)	90
Livestock:	
Surface water (Mgal/d)	48
Percentage of total surface water	0.8
Percentage of total livestock	74
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	5,700
Percentage of total surface water	89
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	67
Irrigation withdrawals:	
Surface water (Mgal/d)	30
Percentage of total surface water	0.5
Percentage of total irrigation	23
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	13,000

GENERAL SETTING

The Mississippi River forms the 500-mile eastern boundary of the State. The Missouri River forms the western boundary from the Iowa State line to Kansas City—a distance of about 200 miles—then flows eastward across the State, generally defining the boundary between the glaciated region to the north and unglaciated region to the south (fig. 1). Both rivers are partially controlled by lock and dam structures, reservoirs, and diversions along their main stems and tributaries.

Missouri is located in three physiographic provinces (fig. 1): in the north and west, plains or prairie of the Central Lowland province; in the extreme southeast, an alluvial plain of the Mississippi Alluvial Plain of the Coastal Province; and between them, the Missouri part of the Ozark Plateaus province (fig. 1). The Central Lowland province includes the glaciated area north of the Missouri River and a large area south of the river in the western part of the State. The extensively farmed lowland has numerous, wide, flat valleys eroded by meandering streams, which are not well-sustained during droughts and require storage reservoirs for effective use. The Ozark Plateaus is a wooded, hilly region that comprises about half of the State and consists of the Salem-Springfield plateaus. The Salem plateau includes the remnants of a maturely dissected, rolling upland surface—a rugged area of narrow valleys as much as 500 feet deep. The Springfield Plateau is an area of relatively low relief, and its gentler slopes and wider valleys allow more diversified agricultural activity than in the Salem Plateau area. Major Ozark Plateaus streams are sustained by outflow from the thousands of springs in the region. The Mississippi Alluvial Plain is a relatively flat region of about 3,000 mi² (square miles) that consists largely of alluvial deposits. The region is well-drained for the most part, contains excellent farmland, and its streams are sustained by ground-water outflow from the alluvial aquifer.

The average annual precipitation in Missouri increases from about 36 inches in the northwest to about 48 inches in the extreme southeast (fig. 1). Snowfall varies from 24 inches in the north to 8 inches in the southeast. Most precipitation in the late fall and winter is associated with the passage of frontal weather systems that move from west to east across the State. In late spring, summer, and fall, much of the precipitation occurs during brief, but intense local thunderstorms. The bar graphs in figure 1 illustrate seasonal variations in average monthly precipitation in different parts of the State. The maximum average monthly precipitation occurs in spring or early summer in most areas. Minimum average precipitation occurs in October in the southeast and in late fall and winter in other areas of the State.

Average annual runoff ranges from about 6 inches in the northwest to 20 inches in the extreme southeast (fig. 1). The percentage of precipitation that appears as runoff varies from about 20 percent in northern Missouri, to 25 to 30 percent in central and southern Missouri, to 35 to 40 percent in extreme southeastern Missouri. The remaining 60 to 80 percent of the precipitation primarily is lost to evapotranspiration (Gann and others, 1976). The bar graphs (fig. 1) illustrate the seasonal variation in runoff patterns. Because of the incidence of hot, dry weather in late summer and early fall and excessive evapotranspiration rates, runoff usually is at a minimum in August and September in southern Missouri. In northern Missouri, minimum runoff often occurs in early winter. The most significant droughts recorded in Missouri occurred in the mid-1930's and mid-1950's.

PRINCIPAL RIVER BASINS

The surface drainage in Missouri is included in parts of four water-resources regions: The Upper Mississippi, Lower Mississippi, Missouri, and the Arkansas-White-Red (Seaber and others, 1984). The principal river basins in each region are described in the following paragraphs preceded by a short discussion of the characteristics of the main stems of the Mississippi and the Missouri Rivers. The location of the basins, and long-term variations in streamflow at representative streamflow-gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MISSISSIPPI AND MISSOURI RIVER MAIN STEMS

The Mississippi and the Missouri Rivers are the most significant surface-water sources in Missouri; the average flow of the Mississippi River at Thebes, Ill. (table 2, site 4), is 198,000 ft^3/s or 128,000 Mgal/d. More than 50 percent of Missouri's population is located in urban centers along these rivers, and these centers depend on the rivers for their water supply and for disposal of treated wastes. Five public water-supply intakes are located along the Mississippi River and 11 along the Missouri River (Schroeder, 1982, p. 85).

The Mississippi and the Missouri Rivers are regulated by locks and dams, reservoirs, and diversions; channels and flow conditions are maintained on both rivers to accommodate barge traffic. The rivers also are used to generate hydroelectric power and for industrial supplies and recreation.

Flooding is a major concern along the main stems. Flooding of tributary areas by backwater also is a concern, and a Mississippi River flood-plain identification- and-use agreement is being negotiated between Missouri and Illinois (Barnett and others, 1985). Chlordane contamination of fish throughout the Missouri River and contamination of fish by polychlorinated biphenyls (PCB) in the Missouri River near Kansas City and in the Mississippi River downstream from St. Louis also are issues (John R. Howland, Missouri Department of Natural Resources, written commun., 1985).

UPPER MISSISSIPPI REGION

Upper Mississippi-Kaskaskia-Meramec Subregion

Meramec River Basin.—The Meramec River, which drains about 3,980 mi^2 of the Salem Plateau in east-central Missouri, flows about 110 miles to its confluence with the Mississippi River. Forests cover about 62 percent of the basin, cropland and pasture about 35 percent, and other land uses about 3 percent (Barnett and others, 1985). Numerous sinkholes and some losing stream reaches in the basin divert surface flow through underground solution channels in the carbonate bedrock to downstream springs or to adjacent basins.

Streams are used for municipal-industrial supply, fish and wildlife propagation, recreation, waste disposal, and irrigation. Local water-supply shortages and degradation of stream quality, and an outdoor recreation demand that generally exceeds available resources (Barnett and others, 1985), are the principal concerns in the basin. Dioxin contamination has been confirmed in the soil and in whole-fish samples in reaches of the Meramec River (U.S. Geological Survey, 1984; Barnett and others, 1985). Lead has been found in the tissue of fish caught from the Big River (John R. Howland, Missouri Department of Natural Resources, written commun., 1985).

LOWER MISSISSIPPI REGION

Lower Mississippi-St. Francis Subregion

St. Francis River Basin.—From its headwaters, the St. Francis River flows south for about 140 miles to the Arkansas State line, draining about 1,500 mi^2 in Missouri. There is considerable topographic relief in the basin except in the Mississippi Alluvial Plain, where the land surface is relatively flat and locally swampy. The lowland drainage from the Mississippi Alluvial Plain, which enters the St. Francis River in Arkansas, is contained in a network of lateral ditches constructed in the early 1900's to drain the productive farmland. No significant surface diversions are made from the ditches, but significant ground-water withdrawals from shallow alluvial wells for irrigation decrease surface flow of the ditches during the irrigation season.

Wappapello Dam, constructed in 1941 with 613,000 acre-ft (acre-feet) or 199,700 Mgal (million gallons) of storage, is the major water-resource development in the basin. It provides flood protection to the lowland areas and is a major recreation area. Upstream from Wappapello Dam, surface-water quality is suitable for most uses, but there are isolated areas where active and inactive lead mining has generated large quantities of heavy-metal-laden sediment (Barnett and others, 1985). Downstream from the dam, extensive row-crop agriculture has produced some nitrate contamination and small dissolved-oxygen concentrations in some streams.

MISSOURI REGION

Chariton-Grand Subregion

Grand River basin.—From the junction of East and West Forks, the Grand River flows southeast through the Central Lowland for about 135 miles into the Missouri River, draining about 7,500 mi^2 in Missouri (96 percent of its total drainage area). About 80 to 85 percent of the basin is cropland or pasture and 15 to 20 percent is forest. At least half of the basin streams are channelized.

Clayey till and underlying shale restrict infiltration of precipitation to the subsurface. As a result, base flows are small during dry weather; this is characteristic of most streams in the Central Lowland physiographic province.

Streams in the basin are used for municipal supply, fishing, livestock watering, recreation, and irrigation. Fifteen public water supplies depend on surface sources in the basin because ground water is excessively mineralized and unsuitable for municipal use (Missouri Department of Natural Resources, 1985).

Major issues in the basin are erosion control, water supply, and the presence of chlordane in fish tissue. Soil erosion, which can cause surface waters to exceed Federal secondary drinking-water regulations for iron, manganese, and turbidity, as well as cause undesirable sediment deposition, is a basinwide concern. Runoff containing animal wastes has caused violations of State dissolved-oxygen standards in the Grand River and some tributaries (Missouri

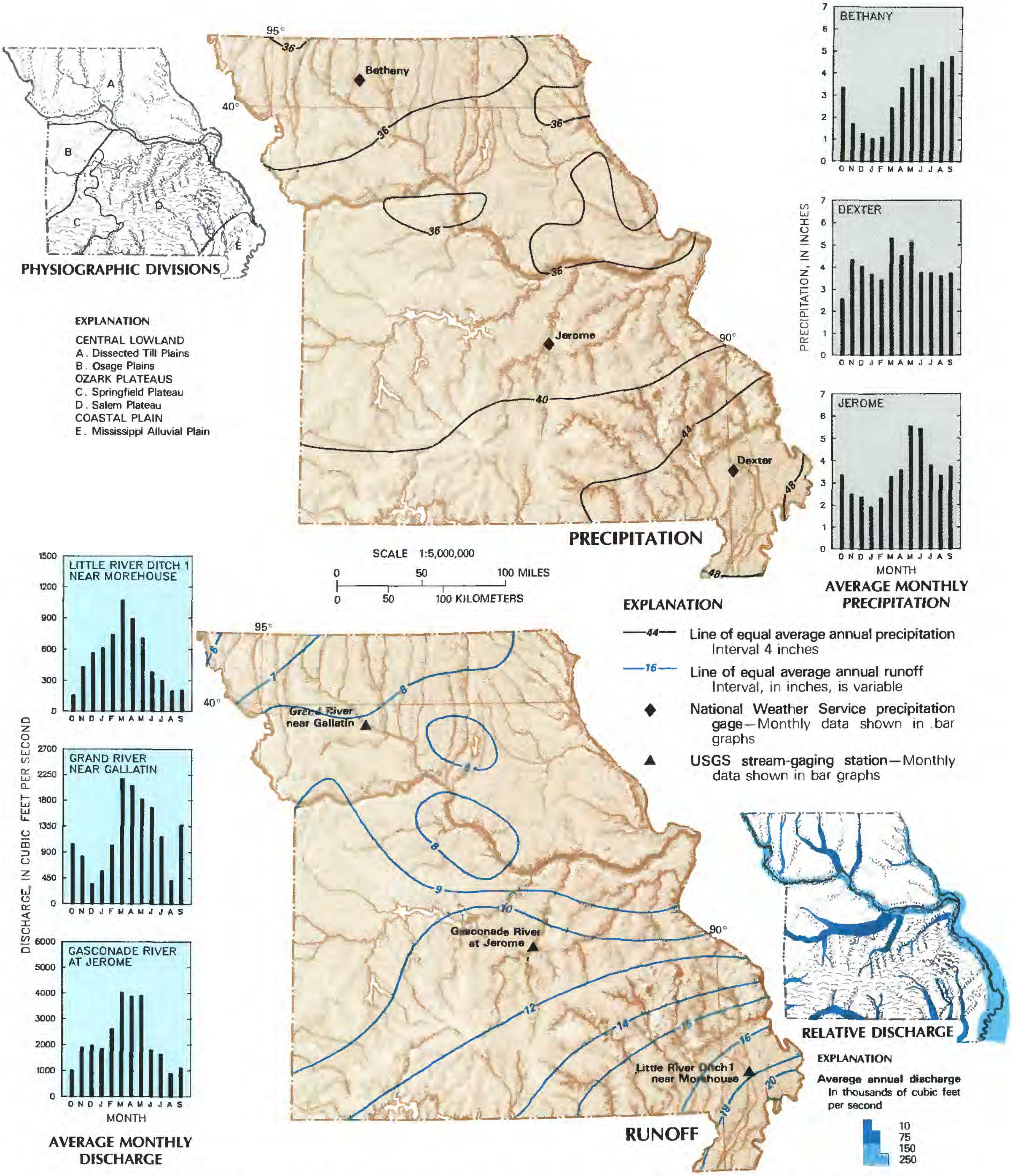

Figure 1. Average annual precipitation and runoff in Missouri and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions modified from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Missouri

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Missouri agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
UPPER MISSISSIPPI REGION UPPER MISSISSIPPI-KASKASKIA-MERAMEC SUBREGION								
1.	Salt River near New New London (05508000).	2,480	1922-83	1.7	1,700	87,000	Appreciable	
2.	Mississippi River at St. Louis (07010000).	697,000	1951-83	43,000	183,000	1,000,000	. . . do . . .	Streamflow data available since 1861.
3.	Meramec River near Eureka (07019000).	3,788	1921-83	280	3,100	144,000	Negligible	
4.	Mississippi River at Thebes, Ill. (07022000).	713,200	1951-83	47,100	198,000	1,100,000	Appreciable	Streamflow data available since 1933.
LOWER MISSISSIPPI REGION LOWER MISSISSIPPI-ST. FRANCIS SUBREGION St. Francis River basin								
5.	St. Francis River near Patterson (07037500).	956	1920-83	15	1,100	89,000	Negligible	
6.	Little River Ditch 1 near Morehouse (07043500).	450	1945-83	33	530	11,000	. . . do . . .	
MISSOURI REGION GASCONADE-OSAGE AND CHARITON-GRAND SUBREGIONS Osage and Grand River basins								
7.	Missouri River at Kansas City (06893000).	485,200	1955-83	6,400	51,000	. . . .	Appreciable	Streamflow data available since 1898.
8.	Grand River near near Gallatin (06897500).	2,250	1921-83	4.0	1,200	72,000	Negligible	Major water uses are municipal supply, fish and wildlife propagation, livestock watering, recreation, and irrigation. Chlordane found in fish tissue.
9.	Osage River near St. Thomas (06926500).	14,500	1931-83	480	9,900	. . . .	Appreciable	Major water uses are hydroelectric power, fish and wildlife propagation, livestock watering, recreation, and irrigation. Flow regulated by Lake of the Ozarks.
10.	Gasconade River at Jerome (06933500).	2,840	1923-83	320	2,500	106,000	Negligible	Major water uses are municipal supply, fish and wildlife propagation, livestock watering, and recreation.
11.	Missouri River at Hermann (06934500).	524,200	1955-83	11,000	72,000	. . . .	Appreciable	Streamflow data available since 1898.

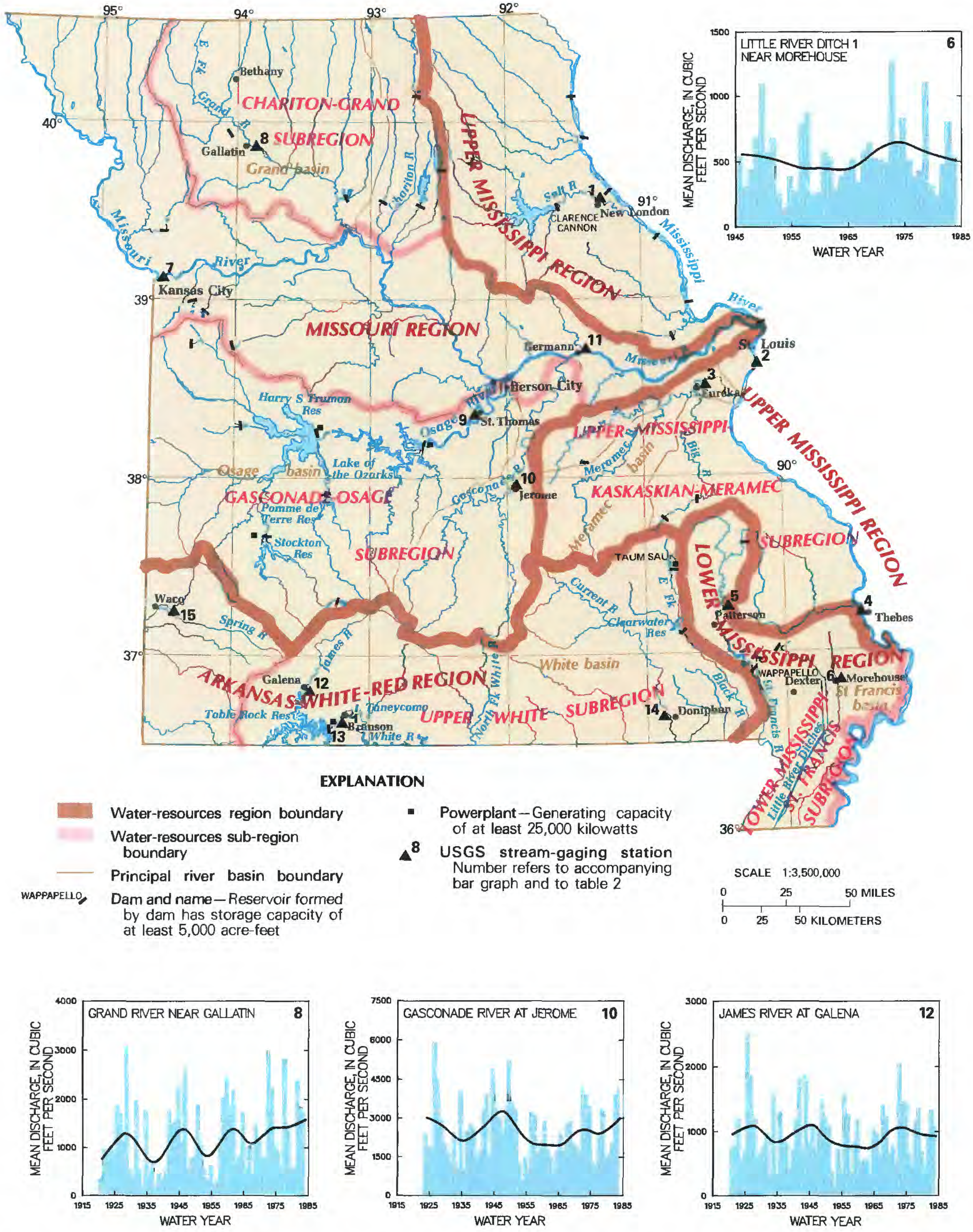

Figure 2. Principal river basins and related surface-water resources development in Missouri and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Department of Natural Resources, 1985; John R. Howland, Missouri Department of Natural Resources, written commun., 1985).

Gasconade-Osage Subregion

Osage River Basin.—The Osage River (Marais des Cygnes) flows in an easterly direction from the Missouri-Kansas State line for about 250 miles through the Central Lowland and Ozark Plateaus to its confluence with the Missouri River, draining about 10,700 mi^2 in Missouri (70 percent of its drainage area). About 50 percent of the basin is forest, 45 percent is row crops and pasture, 4 percent is mined land, and 1 percent is urban or other use. In the Central Lowland area, the low-flow yield of the streams is minimal. In the Ozark Plateaus region, the streams generally have well-sustained low flows, although there are some losing stream reaches and sinkhole areas where ground water is susceptible to surface pollution (Homyk and Jeffery, 1967).

Several large multipurpose reservoirs are located in the basin (fig. 2). Lake of the Ozarks, completed in 1931 with 1,218,000 acre-ft or 396,700 Mgal storage capacity, is the most extensive water-recreation area in the State, and is an important source of hydroelectric power. Pomme de Terre Reservoir, completed in 1960

Table 2. Selected streamflow characteristics of principal river basins in Missouri—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Missouri agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-yeer flood (ft^3/s)	Degree of regulation	
				ARKANSAS-WHITE-RED REGION UPPER WHITE SUBREGION White River basin				
12.	Jamas River at Galena (07052500).	987	1921-83	38	940	69,000	Negligible	Major water uses are municipal-industrial supply, waste transport, fish and wildlife propagation, livestock watering, recreation, and irrigation. Affected by industrial and municipal effluent.
13.	White River near Branson (07053500).	4,020	1956-83	78	3,500	. . . .	Appreciable	Major water uses are municipal-industrial water supply, hydroelectric power, recreation, and fish and wildlife propagation. Intensive recreational use is an issue. Streamflow data available since 1952.
14.	Current River at Doniphan (07068000).	2,038	1918-83	940	2,700	104,000	Negligible	
15.	Spring River near Waco (07186000).	1,164	1924-83	18	840	80,000	. . . do . . .	

with a 648,700 acre-ft or 211,300 Mgal storage capacity, is used for flood control and recreation. The largest reservoirs, Stockton and Harry S. Truman, were completed in 1969 and 1977, respectively, have a total storage capacity of about 6,880,000 acre-ft or 2,242,000 Mgal, and provide flood control, recreation, water supply, and hydroelectric power.

Surface-water quality generally is suitable for most uses. There are 16 public surface-water supply withdrawals in the basin (Missouri Department of Natural Resources, 1985). Nonpoint sources of water-quality pollution include coal mining and agricultural activities. Acid coal-mine drainage affects some small streams, and erosion is a concern. Wastewater treatment is an issue in some areas, especially around recreational developments and in karst areas.

Another major issue in this basin is out-of-State use of the Osage basin headwaters. A potential exists for decreased streamflow into Missouri, which can adversely affect Missouri towns that use water from these rivers (Barnett and others, 1985, p. 11).

ARKANSAS-WHITE-RED REGION

Upper White Subregion

White River Basin.—The White River originates in northwestern Arkansas, enters Missouri, flows northeast for about 75 miles, and then southeast for about 35 miles into Arkansas. The White River and its major tributaries drain the Ozark Plateaus; their drainage area in Missouri is about 8,700 mi^2 (31 percent of the basin area). Major White River tributaries in Missouri are the James, the North Fork, the Current, and the Black Rivers.

The basin is a hilly, scenic area of forest and pastureland. It is underlain by carbonate bedrock containing solution cavities that form a conduit system that permits rapid recharge of ground water from the surface. Significant developments in the basin in Missouri are Lake Taneycomo, completed in 1913 with a 28,000 acre-ft or 9,120 Mgal storage capacity, created for hydroelectric power generation; Table Rock Reservoir, completed in 1956 with a 3,568,000 acre-ft or 1,162,000 Mgal storage capacity, provides electric power, flood control, and recreation; Clearwater Reservoir, completed in 1948 with a 413,700 acre-ft or 134,800 Mgal storage capacity, provides flood control and recreation; and Taum Sauk hydroelectric powerplant on the East Fork Black River, which was completed in 1969 with a storage capacity of 33,000 acre-ft or 10,750 Mgal.

Surface water generally is moderately mineralized and fairly uniform in chemical characteristics. Except for some reaches of the James River, which are affected by industrial and municipal effluent, surface water is suitable for most uses.

Extensive recreational use is the most significant basin issue and includes excessive litter and inadequately treated sewage effluent discharged into lakes and streams. Extensive karst geology makes it difficult to develop economical, environmentally safe landfills (Barnett and others, 1985).

SURFACE-WATER MANAGEMENT

The water doctrine under which Missouri's surface-water resources are managed is the riparian-rights doctrine; there is no State water law and no State water plan. State permits are not required for surface-water withdrawals; however, under the provisions of the Major Water Users Registration Law of 1983 (Revised Statute 256), all users of 100,000 gal/d (gallons per day) or more are required to report water use to the Missouri Department of Natural Resources (DNR). The U.S. Geological Survey contributes to surface-water management by cooperating with DNR and other State agencies in collecting hydrologic data and investigating the State's water resources.

Missouri has no water compacts or treaties with other States at present (1985). However, preliminary negotiations between Missouri officials and their counterparts in Kansas and Arkansas have been held. The objective is to develop interstate water compacts relating to the flow of the streams that cross State boundaries (Jerry D. Vineyard, Missouri Department of Natural Resources, written commun., 1985).

Water allocation for the Missouri River is an issue because of differences in water law and allocation from State to State. At present, there is no agreement as to allocation of the Missouri River waters between prior appropriation States of the West and the riparian States of Missouri and Iowa (Barnett and others, 1985).

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FOR ADDITIONAL INFORMATION

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MONTANA
Surface-Water Resources

Most of the larger rivers in Montana provide abundant, dependable supplies of water. Smaller streams, particularly in the eastern half of the State, do not provide dependable supplies except during spring runoff. Water quality generally is suitable for most uses except when flows are low. The seasonal variation in quantity, rather than quality, is the primary constraint on use.

Surface water provided 98 percent of the total offstream water use in 1980, and 98 percent of the surface-water withdrawals was for irrigated agriculture. The next largest use of surface water was for public supplies, where 0.8 percent of the withdrawal served a population of 331,000 or about 43 percent of the total State population. The instream use of surface water also is important, especially for hydroelectric-power generation, recreation, and aquatic life. Surface-water withdrawals in Montana in 1980 for various purposes and related statistics are given in table 1.

The major surface-water issues in Montana include the periodic shortages that occur in some basins and the potential degradation of water quality in some areas as a result of mining, agriculture, forest practices, and other activities. Water-rights issues also are significant as competing users, including upstream and downstream States, make increased demands on the finite surface-water resource.

Table 1. Surface-water facts for Montana

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: K. Guehlstorff, Montana Department of Natural Resources and Conservation, written commun., 1985; Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	335
Percentage of total population	43
From public water-supply systems:	
Number (thousands)	331
Percentage of total population	43
From rural self-supplied systems:	
Number (thousands)	4
Percentage of total population	0.5
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	11,000
Surface water only (Mgal/d)	11,000
Percentage of total	98
Percentage of total excluding withdrawals for thermoelectric power	98
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	83
Percentage of total surface water	0.8
Percentage of total public supply	59
Per capita (gal/d)	251
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.3
Percentage of total surface water	0
Percentage of total rural domestic	2
Per capita (gal/d)	75
Livestock:	
Surface water (Mgal/d)	17
Percentage of total surface water	0.2
Percentage of total livestock	68
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	27
Percentage of total surface water	0.3
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	81
Excluding withdrawals for thermoelectric power	48
Irrigation withdrawals:	
Surface water (Mgal/d)	10,000
Percentage of total surface water	98
Percentage of total irrigation	99
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	66,000

GENERAL SETTING

Montana includes three geographic and physiographic settings (fig. 1). The western and south-central parts of the State are in the Northern and Middle Rocky Mountains physiographic provinces, and are characterized by a series of mountain ranges separated by intermontane valleys. Most of the larger streams have their headwaters in the Northern and Middle Rocky Mountains provinces, including the Missouri, the Yellowstone, and the Kootenai Rivers and the Clark Fork. Annual precipitation varies considerably across the rugged topography of the Rocky Mountains, ranging from about 6 inches in the driest valleys to more than 100 inches along the mountain peaks near the northern State boundary (fig. 1). In the mountain valleys, about 60 percent of the annual precipitation occurs during the April through September growing season. Annual snowfall averages about 50 inches in the valleys and may exceed 300 inches in some mountain areas.

Eastern Montana is in the Great Plains physiographic province and is characterized by rolling prairie land interspersed with low mountains. The area is drained by the Missouri River, which is formed by the confluence of the Jefferson, the Madison, and the Gallatin Rivers, and by the Yellowstone River. Annual precipitation in the Great Plains province is much less variable than in the Northern Rocky Mountains province, ranging from about 12 inches along the northern border to about 16 inches in the southeastern corner of the State (fig. 1). Almost 70 percent of the annual precipitation in the Great Plains province occurs during the April through September growing season. The monthly variation in precipitation is shown by bar graphs (fig. 1). Snowfall also is generally less than in the Northern Rocky Mountains province, with most areas of the plains receiving 20 to 50 inches annually.

Annual evaporation varies from about 25 inches in the northwestern part of the State to about 45 inches in the southeastern part. Almost 80 percent of the evaporation statewide occurs during the April through September growing season (Farnsworth and others, 1982).

The annual-runoff pattern generally is similar to the annual-precipitation pattern, with the greatest and most variable runoff occurring in the Rocky Mountains. Annual runoff ranges from 5 inches in the lower valleys to more than 80 inches in the rugged northern mountains (fig. 1). In the Great Plains province, annual runoff ranges from 0.5 to about 5 inches, with the greatest runoff occurring in the west from foothill streams draining the adjacent Rocky Mountains. The least annual runoff occurs in the east-central part of the State. Most of the annual runoff occurs during spring and early summer as a result of snowmelt and rainfall. Snowmelt runoff in the Great Plains (the Milk River and the Yellowstone River) occurs 1 to 2 months earlier than snowmelt runoff in the Rocky Mountains (Clark Fork, as shown by the bar graph in figure 1).

PRINCIPAL RIVER BASINS

All streams in Montana are in two water-resources regions (fig. 2). The Missouri Region includes the area of Montana within the Great Plains and Middle Rocky Mountains provinces as well as the eastern part of the Northern Rocky Mountains province. The principal river basins in the region are those of the Missouri and the Yellowstone Rivers; the Yellowstone is a major tributary that joins the Missouri just inside North Dakota. The Pacific Northwest Region consists of the western one-third of Montana in the Northern Rocky Mountains province. The major river basins within the Pacific Northwest Region are those of the Clark Fork and the Kootenai River. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MISSOURI REGION

Missouri River Basin

The Missouri River originates in the mountains of southwestern Montana at the confluence of three tributary streams. From this point, the river flows north through mountainous terrain for about 100 miles before turning eastward near the city of Great Falls. From Great Falls to where it flows from the State, the Missouri River traverses almost 400 miles of sparsely populated, rolling prairie land. Important tributaries that join the Missouri include the Sun, the Marias, the Musselshell, and the Milk Rivers. More than one-half the land area of Montana, about 82,000 mi^2 (square miles), is drained by the Missouri River.

The earliest water development in the Missouri River basin occurred in response to mining activities in the headwaters area, as small streams were dammed and diverted to supply water for sluicing gold. In the early 1900's the first large-scale dams were constructed to provide hydroelectric power for mining and ore-processing operations in Butte and Great Falls. Irrigation development followed soon after the initial mining activities, and dams to provide storage water for irrigation were constructed on several of the Missouri River tributaries. The largest reservoirs in the basin are multiple-purpose projects constructed on the main stem, Fort Peck Lake (completed in 1939) and Canyon Ferry Lake (completed in 1953). The storage capacity of Fort Peck Lake is more than 19 million acre-ft (acre-feet) or 6,190,000 Mgal (million gallons), and the storage capacity of Canyon Ferry Lake is greater than 2 million acre-ft or 650,000 Mgal. Lake Elwell (completed in 1956) is an irrigation project on the Marias River with a storage capacity of more than 1 million acre-ft or 325,000 Mgal. The combined capacity of all other reservoirs in the basin is about 2 million acre-ft or 650,000 Mgal.

Agriculture is the dominant economic activity in the Missouri River basin, and irrigation is by far the largest offstream water use. Most of the irrigation occurs along the tributary streams, notably the Big Hole, the Jefferson, the Madison, the Gallatin, the Sun, the Teton, and the Milk Rivers. More than 1.4 million acres are irrigated, primarily for the production of alfalfa, pasture, wheat, and barley.

The basin has been subjected to both prolonged droughts and severe floods. The dust-bowl drought of the 1930's was the most damaging drought of recent times. (See graphs of streamflow in fig. 2.) Flooding was significant in the basin in 1908, 1948, 1952, 1953, 1964, and 1975. The greatest urban damages occurred in 1964, particularly in Great Falls from the Sun River. Because of the periodic droughts and intensive use of surface water for irrigation, water shortages commonly occur in such tributary streams as the Big Hole, the Musselshell, and the Milk Rivers. The shortages have intensified the disagreements between competing water users—principally other irrigators and recreational users—and the quantification of unresolved water rights has become a significant issue in the basin. Downstream States also have increasing demands on the water of the Missouri River, and a negotiated allocation among the various States or an equitable apportionment by the U.S. Congress or U.S. Supreme Court may be required to prevent interstate disagreements. The surface-water quality is generally good for most uses in the Missouri River basin, except for smaller streams when flows become low.

Yellowstone River Basin

The Yellowstone River originates in the rugged mountains of Wyoming and winds its way north through a steep and narrow canyon before reaching a gradually broadening valley near Livingston. From Livingston, the river turns east into the flatter prairie country of the Great Plains. About 100 miles east of Livingston, the Yellowstone River flows through Billings, the largest city in Montana. From Billings, the Yellowstone River flows northeast for almost 300 miles through rolling prairies before joining the Missouri River just inside North Dakota. The major tributaries of the Yellowstone River are the Clarks Fork Yellowstone, the Bighorn, the Tongue, and the Powder Rivers. All enter the Yellowstone River from the south, and all except the Clarks Fork Yellowstone River have their headwaters in Wyoming. The Clarks Fork Yellowstone River originates in the mountains of Montana and flows southward into Wyoming before reentering Montana. The Yellowstone River drains about 25 percent of Montana (36,000 mi^2).

Irrigation is the major offstream water use in the basin, and most of the early water development in the basin was for irrigation. The largest reservoir is Bighorn Lake (completed in 1965) a multiple-purpose structure on the Bighorn River with a storage capacity of about 1.4 million acre-ft or 460,000 Mgal. Six other major reservoirs are located in the Yellowstone River basin in Montana, all on tributary streams; their combined storage capacity is 163,000 acre-ft or 53,000 Mgal. The Yellowstone River is one of the longest free-flowing streams in the United States; it has no reservoirs along its 800-mile course. Significant irrigation occurs along Rock Creek (a tributary of the Clarks Fork), and the Clarks Fork, the Bighorn, and the Tongue Rivers, and the Yellowstone River main stem. More than 730,000 acres are irrigated, mostly for the production of alfalfa, pasture, and sugar beets.

The widely variable seasonal and annual streamflows have created issues and disagreements within the Yellowstone River basin just as they have in the Missouri River basin. Droughts have been damaging to agricultural interests, most notably during the dust-bowl era of the 1930's, when streamflow was very low (fig. 2, site 7). Flooding was significant in 1918, 1944, 1974, and 1978. The community with the most serious flood problem is Miles City, which is located at the confluence of the Tongue and the Yellowstone Rivers.

Because of the enormous deposits of coal in the Yellowstone River basin, concerns have been expressed about the possible depletion and degradation of surface water due to large-scale mining and other potential energy-related development. The quantification of Indian and non-Indian Federal reserved water rights and the resolution of water claims by other States are also issues in the Yellowstone River basin.

PACIFIC NORTHWEST REGION

Clark Fork Basin

The Clark Fork originates in the Rocky Mountains near the mining community of Butte and follows a winding, generally northwesterly 250-mile route through forested, generally narrow mountain valleys before entering Idaho. The Clark Fork drains about 22,000 mi^2, or about 15 percent of the total area of Montana. Although the Clark Fork drains a smaller part of the State than either the Missouri River or the Yellowstone River, it transports substantially more water on an annual basis (fig. 2). The major tributaries of the Clark Fork are the Bitterroot and the Flathead Rivers, both of which originate in scenic, rugged mountains before flowing through wider valleys that are important agricultural areas.

The earliest storage projects were irrigation reservoirs constructed in the Flathead River basin. The largest storage projects are Hungry Horse Reservoir (completed in 1952)—a multiple-purpose project on the South Fork Flathead River with a capacity of about 3.5 million acre-ft or 1,140,000 Mgal, and Flathead Lake—a large natural lake (surface area 195 mi^2) whose capacity was increased by about 1.7 million acre-ft or 550,000 Mgal with the construction of a hydroelectric project in 1937.

Irrigation is the largest offstream use of surface water in the Clark Fork basin, where about 440,000 acres of mostly alfalfa, pasture, and wheat presently are under irrigation. Most of the irrigation is along the Bitterroot River and in the Flathead River valley south of Flathead Lake. Recreational use of surface water in the Clark Fork basin is significant and increasing, especially in the Flathead River and its tributaries near Glacier National Park.

Droughts have caused problems for agriculture and hydroelectric-power generation, but droughts generally are not as serious

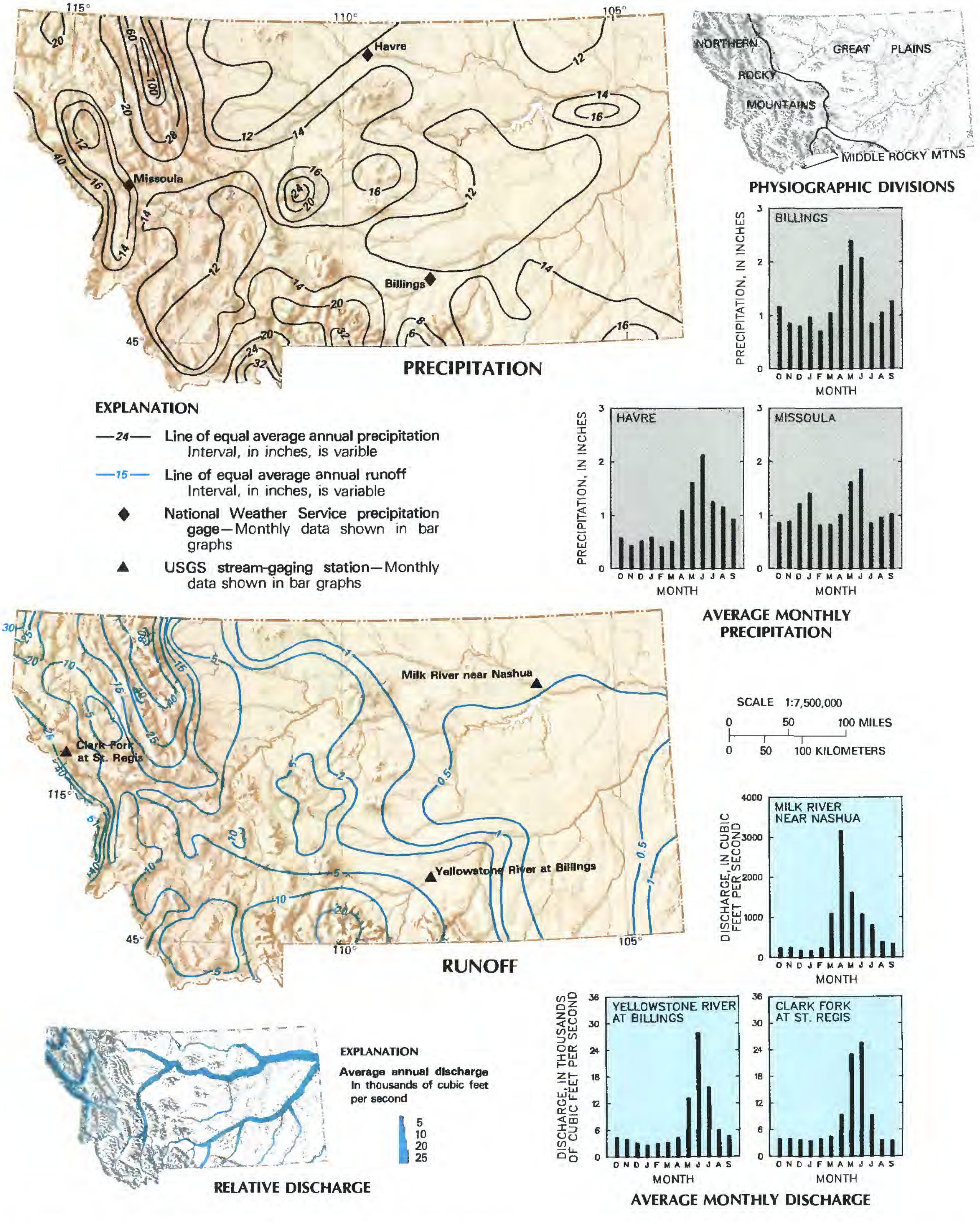

Figure 1. Average annual precipitation and runoff in Montana and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); U.S. Department of Agriculture, 1981 and average annual precipitation, Montana, based on 1941–1970 base period; monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

or prolonged as in the river basins in eastern Montana. Flooding was serious in 1894, 1908, 1948, and 1964. The area most affected by flooding is the unincorporated area near Kalispell on the Flathead River.

Because of its origins near the mining community of Butte, the upstream reaches of the Clark Fork are extensively polluted from mine and mill waste. Settling ponds constructed near Anaconda eliminated most of the mine waste, but periodic overflows have caused fishkills far downstream from the ponds. In addition, significant concentrations of heavy metals have been found in stream and reservoir-bottom sediments near Missoula, and concern has been expressed about contamination of ground water used for domestic

Table 2. Selected streamflow characteristics of principal river basins in Montana

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	MISSOURI REGION **Missouri River basin[1]**							
1.	Beaverhead River at Barretts (06016000).	2,737	1907–83	122	430	3,040	Appreciable	Major source for irrigation.
2.	Missouri River at Fort Benton (06090800).	24,749	1890–1983	2,230	7,827	96,000	Moderate	Major source for irrigation and hydroelectric-power generation. Recreation use important in headwaters.
3.	Marias River near Shelby (06099500).	3,242	1902–04, 1905–06, 1907–08, 1911–83	65	940	. . . .	. . . do . . .	Some irrigation use.
4.	Musselshell River at Mosby (06130500).	7,846	1929, 1930–32, 1934–83	0.00	301	34,600	. . . do . . .	Major source for irrigation; undependable during low flow.
5.	Milk River at Nashua (06174500).	22,332	1939–83	13	710	36,600	. . . do . . .	Major source for irrigation; undependable during low flow.
6.	Missouri River near Culbertson (06185500).	91,557	1941–51, 1958–83	1,520	11,000	54,900	Appreciable	Little offstream use in Montana downstream from Fort Peck Lake; major source for hydroelectric-power generation.
	Yellowstone River basin[2]							
7.	Yellowstone River at Billings (06214500).	11,795	1928–83	1,090	7,074	80,000	Negligible	Major source for irrigation. Recreation use important in headwaters.
8.	Bighorn River at Bighorn (06294700).	22,885	1945–83	767	3,939	41,700	Appreciable	Major source for irrigation.
9.	Tongue River at Miles City (06308500).	5,379	1938–42, 1946–83	3.3	440	17,800	Moderate	Some irrigation use.
10.	Powder River near Locate (06326500).	13,194	1938–83	1.6	612	48,100	. . . do . . .	Some irrigation use.
11.	Yellowstone River at Sidney (06329500).	69,103	1910–31, 1933–83	1,410	13,080	156,000	Negligible	Major source for irrigation.
	PACIFIC NORTHWEST REGION **Clark Fork basin[3]**							
12.	Clark Fork at St. Regis (12354500).	10,709	1910–83	1,440	7,583	79,800	Negligible	Some irrigation use. Potential water-quality issues in headwaters.
13.	Bitterroot River near Darby (12344000).	1,049	1937–83	123	931	13,200	Moderate	Major source for irrigation. Recreation use important.
14.	Flathead River at Columbia Falls (12363000).	4,464	1928–83	1,090	9,737	84,000	. . . do . . .	Major source for irrigation and hydroelectric-power generation. Recreation use important.
15.	Clark Fork near Plains (12389000).	19,958	1910–83	4,440	20,010	145,000	. . . do . . .	Some irrigation use. Potential water-quality issues in headwaters. Major source for hydroelectric-power generation.
	Kootenai River basin[3]							
16.	Kootenai River at Libby (12303000).	10,240	1911–70, 1973–83	1,610 2,560	12,100 11,740	116,000 76,300	Negligible Appreciable	Regulated since 1973. Little offstream use in Montana. Recreation use important. Major source for hydroelectric-power generation.

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[1] Includes the Saskatchewan, the Missouri Headwaters, the Missouri-Marias, the Missouri-Musselshell, the Milk, and the Missouri-Poplar Subregions.

[2] Includes the upper Yellowstone, the Big Horn, the Powder-Tongue, the lower Yellowstone, and the Missouri-Little Missouri Subregions.

[3] Contained within the Kootenai-Pend Oreille-Spokane Subregion.

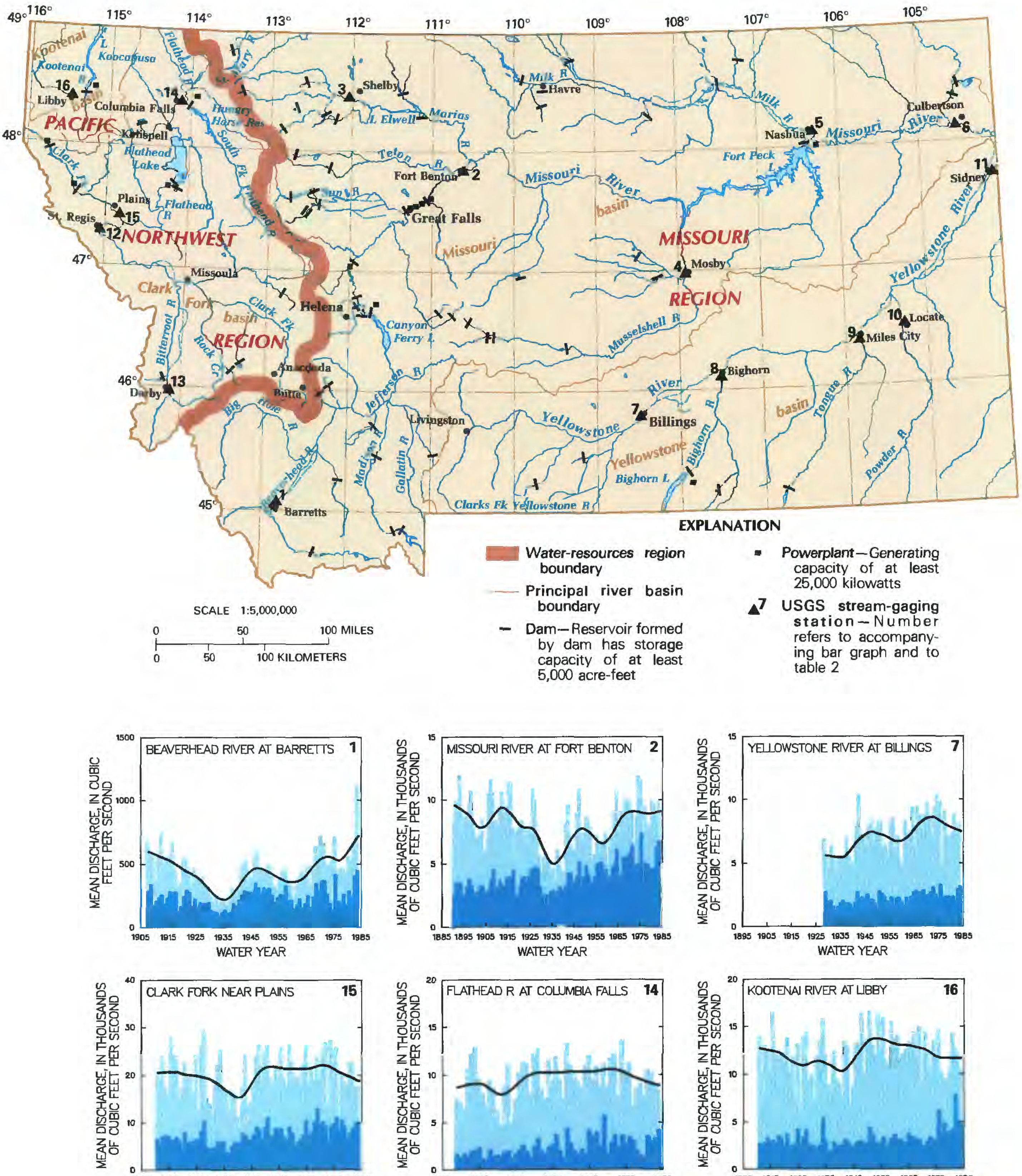

Figure 2. Principal river basins and related surface-water resources development in Montana and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

purposes. Other significant water-quality issues in the Clark Fork basin include the potential water-quality degradation from the city of Missoula and from a wood-pulp plant downstream from Missoula, the potential effects from coal mining in Canada, and accelerated eutrophication of Flathead Lake.

Kootenai River Basin

The Kootenai River originates in Canada mountains. The river flows south into the rugged and densely forested northwestern corner of Montana for about 50 miles before turning west near the logging community of Libby. From Libby, the Kootenai River traverses only about 50 miles more through forested mountains before entering Idaho. The total drainage area of the Kootenai River within Montana is about 4,000 mi^2, which is only about 3 percent of the total land area of the State. Nevertheless, the average annual discharge of the Kootenai River is second only to that of the Clark Fork (fig. 1).

Offstream use of surface water in the Kootenai River basin in Montana is limited because of the sparse population and absence of irrigated agriculture. Lake Koocanusa (completed in 1973) is a large reservoir near Libby that is used primarily for power generation. The storage capacity of Lake Koocanusa is more than 5.7 million acre-ft or 1,860,000 Mgal. Recreation also is an important instream use of the waters of the Kootenai River, and issues have arisen between recreational users and proponents of increased power-generation facilities. Water quality in the Kootenai River basin is generally good for most uses.

SURFACE-WATER MANAGEMENT

Several agencies in Montana are responsible for managing the surface-water resource. The Montana Department of Natural Resources and Conservation has overall responsibility for developing and implementing a State water plan. This department also administers the Montana Water Use Act—a water-rights permitting program based on the doctrine of prior appropriation. A statewide water-rights adjudication program under the auspices of several State district water courts also is underway. Because of the uncertainty about the quantification of Indian water rights under State law, a Reserved Water Rights Compact Commission was established by the legislature to negotiate water-rights compacts with the various Indian tribes in Montana. To date, one compact allocating the surface waters of the Fort Peck Indian Reservation in the Missouri River basin has been approved by the tribe and the Montana Legislature.

In addition, the Boundary Waters Treaty of 1909 and the Columbia River Treaty of 1964 provide for the division of the waters of the St. Mary, the Milk, and the Kootenai Rivers between the United States and Canada. One interstate compact governing the Yellowstone River basin also is presently in effect.

The Montana Department of Health and Environmental Sciences establishes and enforces water-quality standards for all State waters and administers a permit program regulating the discharge of any treated water into any surface-water drainage. This department also has general supervision over all State waters used for public supplies.

The Montana Department of Fish, Wildlife, and Parks administers land and water conservation funds provided for outdoor recreation purposes. The department also reviews proposed stream-alteration projects to ensure that fish and wildlife resources are not damaged.

All the foregoing State agencies have cooperative programs with the U.S. Geological Survey to collect surface-water data and to conduct local and regional hydrologic investigations throughout the State. The data collection, research, and analyses provided through the cooperative program form an information base that helps the State regulating agencies make sound surface-water management decisions.

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NEBRASKA
Surface-Water Resources

Nebraska has an abundant supply of surface water, although the quantity varies areally, as well as seasonally and annually. Excluding the Missouri River, an average of about 2,800 ft³/s (cubic feet per second) or 1,800 Mgal/d (million gallons per day) of streamflow enter the State from South Dakota, Wyoming, Colorado, and Kansas, and an average of 11,000 ft³/s or 7,100 Mgal/d flows from the State into South Dakota and Kansas and directly into the Missouri River (Nebraska Natural Resources Commission, 1984). Sixty-one multiple-purpose lakes and reservoirs, controlled by manmade structures and used for irrigation supply, flood control, hydroelectric-power generation, recreation, and wildlife propagation, have capacities greater than 1,000 acre-ft (acre-feet) or 326 Mgal (million gallons) (Nebraska Natural Resources Commission, 1984). Also, about 200 natural lakes in the sandhills region of the State have surface areas greater than 100 acres (McCarraher, 1977). Surface-water quality generally is suitable for most uses in most basins. Major surface-water issues in Nebraska concern rights to unallocated flows for offstream and instream uses, flooding, and stream depletion.

Surface-water use during 1980 was 5,200 Mgal/d or 8,040 ft³/s, which was 42 percent of the total water use in Nebraska (table 1). Public water-supply systems furnished surface water to 18 percent of the State's population in 1980. Agriculture is the major industry in Nebraska, and 2,600 Mgal/d or 4,020 ft³/s for irrigation constituted the major use of surface water in the State during 1980; the water was obtained from reservoirs and canal systems, as well as directly from stream channels.

GENERAL SETTING

Nebraska is entirely within the Missouri River basin, and the Missouri River forms the eastern boundary of the State (fig. 1). Land-surface elevations decrease from west to east and surface drainage generally is in an eastward or southeastward direction. The eastern one-fourth of Nebraska, part of the Central Lowland physiographic province, is a glaciated region that is characterized by rolling hills. The remainder of the State is part of the Great Plains physiographic province, the majority of which is composed of dissected plains, high plains, and sandhills. The sandhills, which are sand dunes stabilized by native grasses, are a major physiographic feature of Nebraska and cover about one-fifth of the State (fig. 1).

Average annual precipitation in Nebraska ranged from about 14 inches in the west to about 35 inches in the southeast during 1951–80 (fig. 1). Although 75 percent of the precipitation occurs during the growing season (April through September), rainfall is extremely variable (fig. 1, bar graphs) and two consecutive, dry summer months can result in dryland crop failures. Average annual lake evaporation varies from about 40 inches in the northeast to 54 inches in the southwest (Nebraska Soil and Water Conservation Commission, 1971).

Runoff is extremely variable across the State. The average annual runoff varies from about 0.5 inch in the west and southwest to about 6 inches in the southeast (fig. 1). A large percentage of the annual runoff from most areas of the State occurs from snowmelt in the spring or from thunderstorms in the spring and early summer, as indicated by graphs of average monthly discharge for Medicine Creek and the Big Nemaha River (fig. 1). Substantial annual runoff from the sandhills area is the result of a very uniform flow produced by a nearly constant ground-water inflow to the streams and not from overland runoff as indicated by the Middle Loup River (fig. 1).

Table 1. Surface-water facts for Nebraska

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Lawton, Veys, and Goodenkauf, 1983; Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	279
Percentage of total population	18
From public water-supply systems:	
Number (thousands)	279
Percentage of total population	18
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	12,000
Surface water only (Mgal/d)	5,200
Percentage of total	42
Percentage of total excluding withdrawals for thermoelectric power	27
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	67
Percentage of total surface water	1
Percentage of total public supply	22
Per capita (gal/d)	241
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	23
Percentage of total surface water	0.4
Percentage of total livestock	20
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	2,500
Percentage of total surface water	48
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	97
Excluding withdrawals for thermoelectric power	15
Irrigation withdrawals:	
Surface water (Mgal/d)	2,600
Percentage of total surface-water withdrawals	50
Percentage of total irrigation	28
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	5,900

PRINCIPAL RIVER BASINS
MISSOURI REGION
Missouri River Main Stem

All of Nebraska is in the Missouri Region (Seaber and others, 1984). The Missouri River forms the boundary between Nebraska and Iowa and Missouri, and part of the boundary between Nebraska and South Dakota. Upstream from Gavins Point Dam at the Nebraska–South Dakota border, the Missouri River is regulated by a series of reservoirs to control floods, generate power, store irrigation water, and regulate the flow downstream for navigation.

Major uses of water from the main stem along Nebraska's border are hydroelectric-power generation, navigation, municipal-industrial supply, fish and wildlife habitat, and recreation. The Gavins Point hydroelectric powerplant generated about 793,000 megawatt hours of power during 1980, using about 6,500,000 Mgal or 20 million acre-ft of water, which was more than 3 times the quantity used by all other hydroelectric powerplants in Nebraska combined (Lawton and others, 1983). About 2,200 Mgal/d or 3,400 ft^3/s of water were withdrawn from the Missouri River during 1980 for cooling purposes at thermoelectric generating plants in Nebraska (Solley and others, 1983). The Missouri River is navigable for barge traffic downstream from Sioux City, Iowa. About 98 percent of the surface water used for public supply in Nebraska is withdrawn from the Missouri River for the city of Omaha (Lawton and others, 1983).

Niobrara Subregion

The Niobrara River originates in Wyoming about 35 river miles west of the Nebraska border and meanders across northern Nebraska for about 400 river miles. It enters the Missouri River near the upstream end of Lewis and Clark Lake. The river flows through dissected plains in the western and eastern third of its length, but flows through rolling sandhills in north-central Nebraska. About 86 percent of the basin's 13,180-mi^2 (square mile) area is in Nebraska; the remainder is in Wyoming and South Dakota. The flow of the Niobrara River throughout most of its length is derived mainly from ground-water inflow, although overland runoff provides a significant percentage of the flow in the lower reaches in some years.

The major use of water in the Niobrara River basin is for irrigation. The earliest surface-water diversion for irrigation was in 1883 (Shaffer, 1975). Two U.S. Bureau of Reclamation irrigation projects—the Mirage Flats project and the Ainsworth Irrigation project—are located in the basin. During 1980, 169,000 acres in the basin were irrigated with 247,200 acre-ft or 80,600 Mgal of surface water (includes conveyance losses and return flows).

A current water issue is a proposal for a U.S. Bureau of Reclamation project to divert water from the Niobrara River downstream from the gaging station near Norden (fig. 2, site 3) for irrigation, and ground-water recharge.

North Platte Subregion

The North Platte River originates in the northern Colorado Rocky Mountains, flows north into Wyoming, then east and southeast through Wyoming, entering Nebraska west of Scottsbluff. It joins the South Platte River about 200 river miles downstream from the Wyoming–Nebraska State line to form the Platte River. About 7,200 mi^2 of the total drainage area of 30,900 mi^2 is in Nebraska. The area in Nebraska is characterized by high plains dissected by stream valleys.

The major surface-water use in the North Platte River basin is for irrigation. Streamflow is regulated by reservoirs in Wyoming that store snowmelt runoff for later release. The North Platte decree by the Supreme Court in 1945 allocates water between Colorado, Wyoming, and Nebraska.

Irrigation in the North Platte Subregion also is provided by surface-water withdrawals from tributary streams and from ground water. The flow of some small streams in the Subregion increases from irrigation return flow; whereas, flow of others, such as Pumpkin Creek (fig. 2, site 4), is depleted as a result of declining ground-water levels and direct pumpage from the stream.

Lake McConaughy (completed in 1941) on the North Platte River, is the largest lake in Nebraska (32,200 acres) and has a storage capacity of 1.9 million acre-ft or 619,000 Mgal. The water is used for irrigation, recreation, and hydroelectric-power generation. During 1980, diversions in the North Platte Subregion of 1,361,000 acre-ft or 443,000 Mgal of surface water, which includes conveyance losses and return flows, was used to irrigate 335,300 acres; this is the largest quantity of surface-water use for irrigation of any basin in the State.

South Platte Subregion

The South Platte River originates in central Colorado and flows generally northeastward through Colorado. After entering Nebraska, it flows about 80 miles east to its junction with the North Platte River. About 15 percent of the 24,300-mi^2 drainage area is in Nebraska. Lodgepole Creek, which originates and drains about 1,500 mi^2 in Wyoming before entering Nebraska, contributes more than half of the South Platte River drainage in Nebraska.

Surface water is diverted for irrigation from Lodgepole Creek and the South Platte River in Nebraska. About 22,600 acres were irrigated with 25,800 acre-ft or 8,400 Mgal of surface water in the South Platte River basin in Nebraska during 1980. Water diverted for hydroelectric-power generation bypasses the gaging station on the South Platte River at North Platte (table 2, site 6).

South Platte River water becomes highly mineralized from irrigation use and reuse in Colorado. Sulfate concentrations exceed secondary drinking-water standards, averaging about 650 mg/L (milligrams per liter) near the Colorado–Nebraska State line (Engberg, 1983).

Platte Subregion

The Platte River is formed by the confluence of the North Platte and the South Platte Rivers near North Platte. The Platte flows 310 miles across Nebraska to join the Missouri River downstream from Omaha. Its drainage area, including the Loup and the Elkhorn River basins, is about 30,000 mi^2. Including the North Platte and the South Platte Rivers, the Platte River system drains about 86,000 mi^2, of which about 41,000 mi^2 are in Nebraska; this represents about 53 percent of the area of the State. The Loup and the Elkhorn Rivers contribute more than half of the total flow of the Platte River near the mouth (table 2).

Salt Creek, which enters the Platte River 26 miles upstream from the mouth, is comprised, at low-flow conditions, of highly mineralized ground-water seepage and of treated sewage effluent from the city of Lincoln. During low flow in the Platte River, water from Salt Creek degrades the quality of the water in the downstream reach of the Platte (Engberg, 1983).

Reservoirs on the North Platte River, particularly Lake McConaughy, and return flows from irrigation projects and powerplants have decreased the variability of the Platte River flows in central Nebraska. Flood flows and periods of no flow have decreased in the reach upstream from the confluence with the Loup River. Surface-water use has decreased the average flow. (Note the Platte River near Overton, table 2 and fig. 2, site 7.) However, recent flooding, derived from mountain snowmelt in the North Platte and the South Platte River basins, occurred on the Platte River in 1971, 1973, and 1983.

Water is diverted at the confluence of the North Platte and the South Platte Rivers for hydroelectric-power generation and for irrigation of more than 100,000 acres south of the Platte River, and smaller diversions are made for irrigation north of the river.

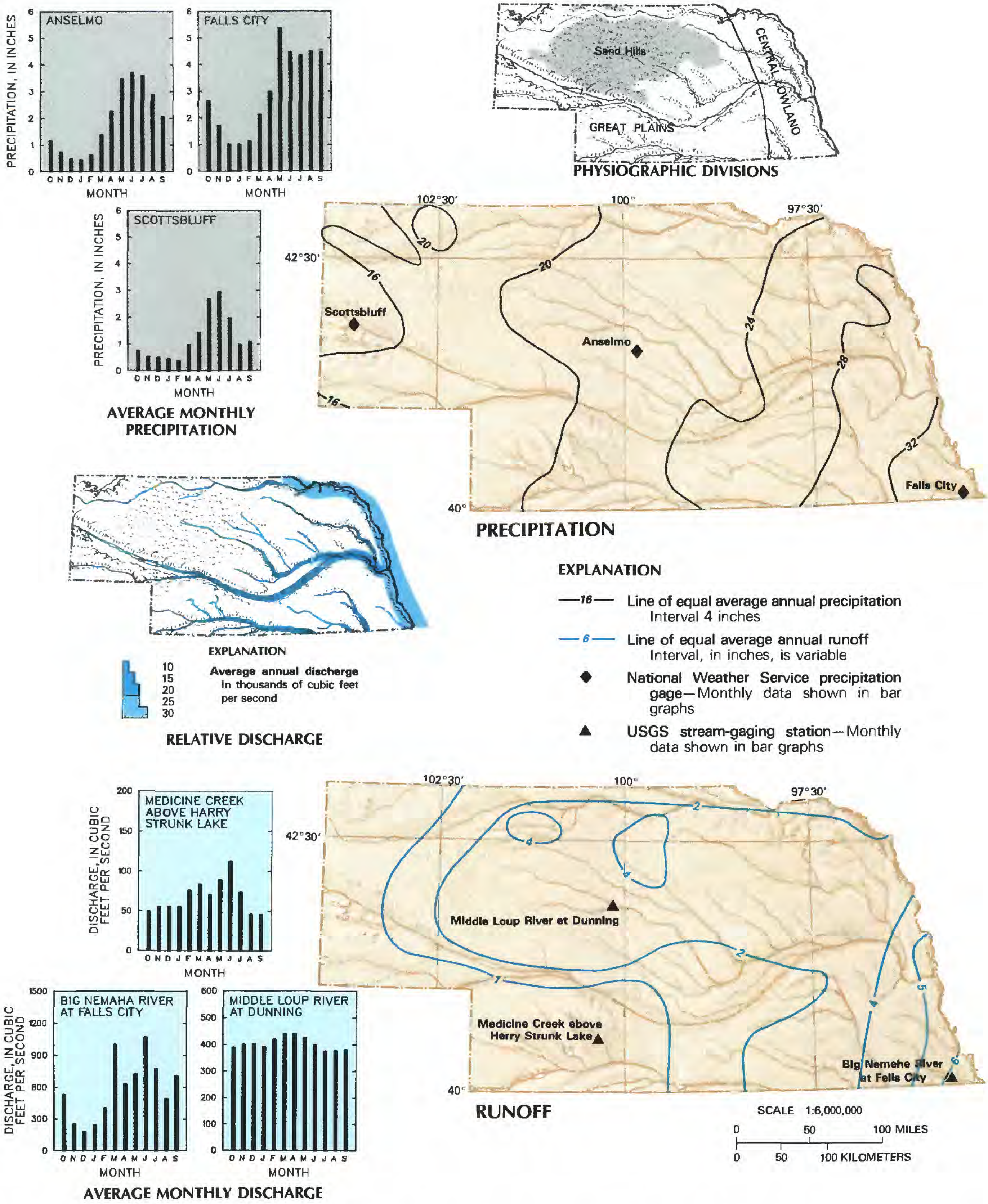

Figure 1. Average annual precipitation and runoff in Nebraska and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

About 213,000 acres were irrigated in the Platte River basin, excluding the Loup and the Elkhorn River basins, with about 618,000 acre-ft or 201,000 Mgal of surface water during 1980.

The central Platte River valley is a major stopover for migratory waterfowl on the Central flyway. A major instream water use is maintenance of critical habitat for wildlife in the reach between Lexington and Grand Island.

Loup Subregion

The Loup River in central Nebraska drains 15,200 mi^2 or nearly one-fifth the area of the State. The South Loup River is a tributary to the Middle Loup River which in turn joins the North Loup River to form the Loup River, which enters the Platte River near Columbus.

The sandhills area, which constitutes about 60 percent of the basin, produces very little overland runoff, except immediately along the stream valleys. Large deposits of saturated sands underlying the sandhills area contribute nearly uniform ground-water inflow to the streams, resulting in some of the least variable stream discharges in the Nation. (See the Middle Loup River at Dunning, figs. 1 and 2, site 9). In the downstream part of the basin, overland runoff from loess hills contributes to streamflow. The many natural lakes in the sandhills area are an important surface-water resource to local ranchers and for fish and wildlife propagation. Approximately 1,300 lakes in 13 counties have a combined surface area of about 78,500 acres (McCarraher, 1977).

Projects of the Middle and North Loup Public Power and Irrigation Districts and the U.S. Bureau of Reclamation's Sargent and Farwell units, are responsible for the major surface-water diversions in the basin. The North Loup Division, a U.S. Bureau of Reclamation project, is under construction and is scheduled to supply surface water from the Calamus and the North Loup Rivers to irrigate about 53,000 acres. Additionally, many private irrigators pump directly from the streams. About 142,000 acres in the basin were irrigated with 322,000 acre-ft or 105,000 Mgal of surface water during 1980.

The Loup River Public Power District diverts Loup River water for hydroelectric-power generation into its canal just upstream from the Loup River near Genoa gaging station (table 2, site 10). This diversion passes through two powerplants before being returned to the Platte River downstream from Columbus.

Elkhorn Subregion

The Elkhorn River begins in the northeastern part of the sandhills area; about one-third of its 7,000-mi^2 area consists of sandhills. The rest of the basin is in the hilly glaciated area of eastern Nebraska. The Elkhorn River flows 330 miles through northeastern Nebraska where it enters the Platte River about 20 miles west of Omaha. In the western part of the basin, the streamflow is sustained from ground-water inflow. Streamflow in the eastern part of the basin varies greatly monthly and annually (table 2 and fig. 2). Flooding occurs as a result of overland runoff from thunderstorms and from ice jams during breakup of ice in the spring. The Elkhorn River contributes about 20 percent of the Platte River's flow to the Missouri River.

Pumpage for irrigation is the principal use of the surface water. During 1980, 30,000 acres were irrigated with an estimated 45,500 acre-ft or 14,800 Mgal of surface water.

Missouri-Nishnabotna Subregion

The Missouri-Nishnabotna Subregion consists of three principal streams that flow into the Missouri River: Weeping Water Creek, the Little Nemaha River, and the Big Nemaha River. Also, a number of smaller streams drain directly to the Missouri. The Subregion is in the extreme southeastern corner of the State and has an area of about 2,700 mi^2. The Subregion is in the glaciated region of the State and consists of rolling hills and stream valleys.

Most of the streamflow in the Subregion occurs from direct runoff from rainfall. Flooding frequently occurs after intense rainfall.

Uses of surface water in the Subregion are for irrigation, waste-water disposal, fish and wildlife propagation, and stock watering from farm ponds; adequate ground-water supplies generally are limited. The Subregion receives the most rainfall in the State, and irrigation is used only to supplement rainfall. About 7,800 acre-ft or 2,540 Mgal of surface water was used for irrigation during 1980.

Republican Subregion

The Republican River is formed by the North Fork Republican River and the Arikaree River (considered the main stem) about 6 miles east of the Colorado-Nebraska border in southwestern Nebraska. The Republican River flows through southern Nebraska until entering Kansas near Superior. Upstream from this point on the Nebraska-Kansas border, the river drains 22,400 mi^2, of which 9,650 mi^2 are in Nebraska.

The Republican River in Nebraska is regulated to a great extent. Four major reservoirs constructed by the U.S. Bureau of Reclamation on the main stem and tributaries and the years when their storage first began are: Harry Strunk Lake (1949) on Medicine Creek, Enders Reservoir (1950) on Frenchman Creek, Swanson Lake (1953) on the main stem, and Hugh Butler Lake (1961) on Red Willow Creek. These reservoirs have a total irrigation-pool capacity of about 216,000 acre-ft or 70,400 Mgal, with an additional 265,000 acre-ft or 86,400 Mgal of storage for flood control. Downstream, Harlan County Reservoir (1952), constructed by the U.S. Army Corps of Engineers on the main stem of the Republican River, has a conservation-pool capacity of 328,000 acre-ft or 107,000 Mgal and an additional flood-control storage of about 500,000 acre-ft or 163,000 Mgal.

Surface water in the basin is used primarily for irrigation. During 1980, 92,100 acres were irrigated with about 180,000 acre-ft or 58,700 Mgal of surface water.

Kansas Subregion

Blue River Basin.—The Blue River basin in Nebraska includes the Big Blue River and the Little Blue River basins in the southeastern part of the State. The basin has an area of about 7,200 mi^2 and consists of very flat plains in the headwaters and gently rolling hills along the downstream reaches.

The streamflow in the basin mainly is the result of direct surface runoff. Flooding occurs on the Big Blue and the Little Blue Rivers and their tributaries as a result of intense rainfall.

The major use of surface water in the basin is for crop irrigation. During 1980, about 54,000 acre-ft or 17,600 Mgal of surface

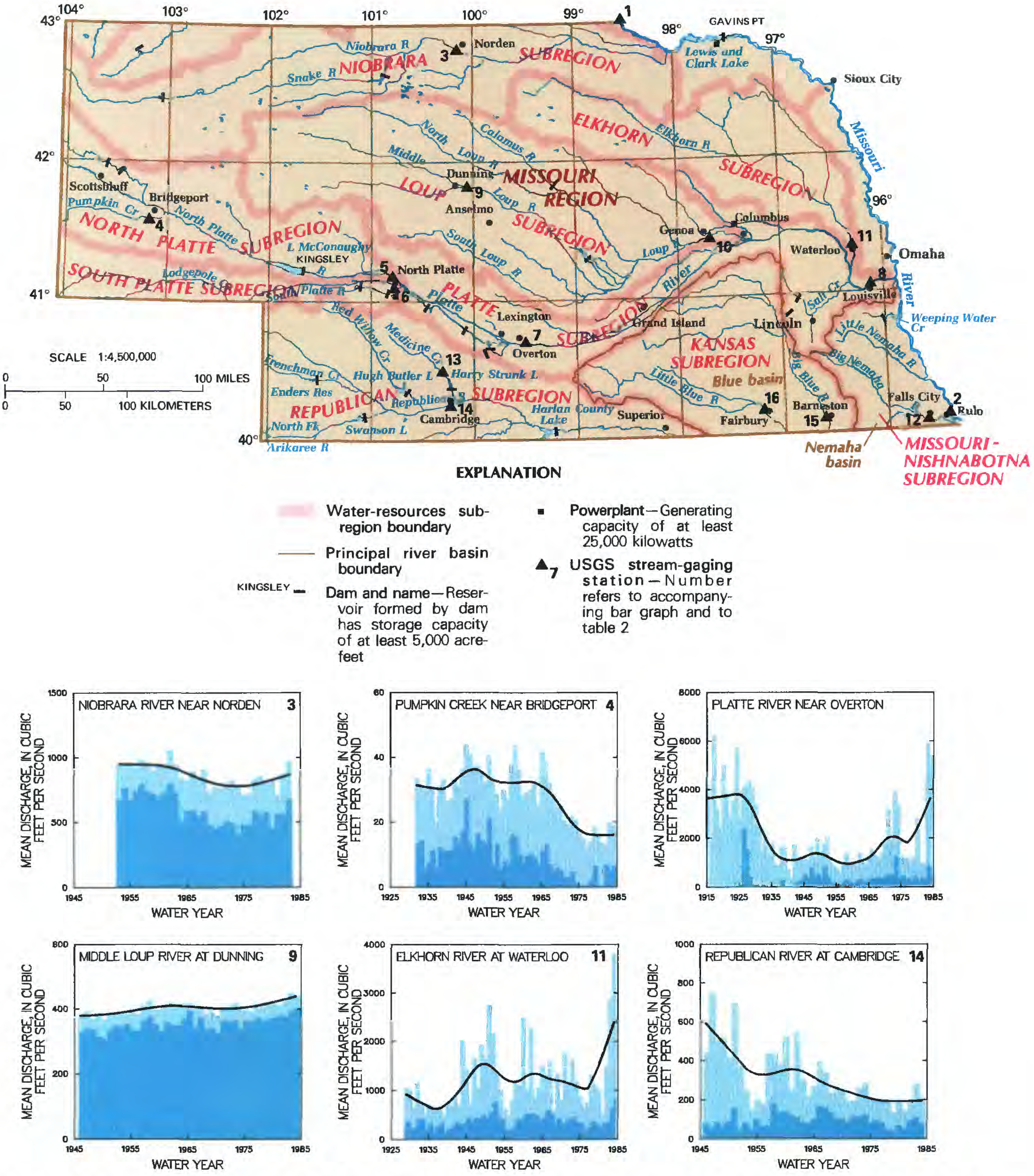

Figure 2. Principal river basins and related surface-water resources development in Nebraska and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Table 2. Selected streamflow characteristics of principal river basins in Nebraska

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
	MISSOURI REGION **Missouri River main stem[1]**							
1.	Missouri River at Fort Randall Dam, S.D. (06453000).	263,500	1947-83	[2]1,450	[2]25,230	[2]99,000	Appreciable	Major water uses include hydroelectric-power generation, irrigation, rural domestic water and municipal-industrial supply, fish and wildlife propagation, and recreation.
2.	Missouri River at Rulo (06813500).	414,900	1950-83	[2]6,210	[2]40,190	[2]241,000	. . . do . . .	Major water uses include navigation, municipal-industrial supply, fish and wildlife propagation, and recreation.
	NIOBRARA SUBREGION							
3.	Niobrara River near Norden (06462000).	8,390	1953-63 1964-83	516 398	952 810	 10,900	Negligible Moderate	Flow affected by diversions from Snake River.
	NORTH PLATTE SUBREGION							
4.	Pumpkin Creek near Bridgeport (06685000).	1,020	1932-83	0.35	28.3	3,320	None	Surface-water and ground-water withdrawals.
5.	North Platte River at North Platte (06693000).	30,900	1896-40 1941-83	 135	2,720 713	36,700 10,700	Appreciable . . . do . . .	Flow regulated by Kingsley Dam since 1941.
	SOUTH PLATTE SUBREGION							
6.	South Platte River at North Platte (06765500).	24,300	1918-46 1947-83	 78	435 402	77,300 57,300	Moderate Appreciable	Affected by diversions, particularly since 1947.
	PLATTE SUBREGION							
7.	Platte River near Overton (06768000).	57,700	1915-40 1941-83	 46	2,860 1,470	60,700 32,800	Moderate Appreciable	Affected by upstream regulation and diversions.
8.	Platte River at Louisville (06805500).	85,800	1954-83	430	5,980	169,000	Moderate	Large natural reach downstream from regulation.
	LOUP SUBREGION							
9.	Middle Loup River at Dunning (06775500).	1,850	1946-83	260	401	1,100	None	Natural flow. Typical sandhills stream.
10.	Loup River near Genoa (06793000).	14,400	1943-83	0.96	574	130,000	Appreciable	Average annual flow of 1,570 ft^3/s bypasses station.
	ELKHORN SUBREGION							
11.	Elkhorn River at Waterloo (06800500).	6,900	1929-83	119	1,120	83,500	Negligible	Near natural conditions.

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[1] Within the Missouri-Big Sioux, Missouri-Little Sioux, and Missouri-Nishnabotna Subregions (Seaber and others, 1984).

[2] Analyses based on period of record since regulation began.

Tabla 2. Selected streamflow characteristics of principal river basins in Nebraska—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
Missouri-Nishnabotna Subregion								
12.	Big Nemaha River et Falls City (06815000).	1,340	1945-83	11.4	587	80,700	None	Low flow affected by pumping from streams.
Republican Subregion								
13.	Medicine Creek above Harry Strunk Leke (06841000).	770	1951-83	16.0	65.9	23,700	None	Some irrigation development upstreem from station.
14.	Republican River at Cembridge (06843500).	14,520	1950-83	[2]18.0	[2]279	[2]16,800	Appreciable	Affected by upstream regulation.
Kansas Subregion Blue River bbsin								
15.	Big Blue River at Barneston (06882000).	4,447	1933-83	35.1	787	50,100	Moderate	Low flows affected by powerplent and withdrawals.
16.	Little Blue River et Feirbury (06884000).	2,350	1911-15, 1930-83	48.3	369	48,500	Negligible	Low flows effected by withdrewels.

[1] Within the Missouri-Big Sioux, Missouri-Little Sioux, and Missouri-Nishnabotna Subregions (Seaber and others, 1984).

[2] Analyses based on period of record since regulation began.

water was used to irrigate about 54,000 acres. A compact between the States of Kansas and Nebraska provides specific procedures to meet minimum daily flow requirements of the Big Blue and the Little Blue Rivers at the State line during the months of May through September.

SURFACE-WATER MANAGEMENT

The surface water in Nebraska is dedicated for use by the general public of the State by the State Constitution and Statutes. Two distinct rights to use surface water (riparian and prior appropriation) have been recognized in Nebraska. A riparian water right is the right of the owner of land that abuts a natural stream to make beneficial use of the water. Acquisition of new rights under the riparian doctrine has been prohibited since 1895. At that time, the system of prior appropriation was adopted by the State (Nebraska Soil and Water Conservation Commission, 1971). Under the doctrine of prior appropriation, the earliest permit to divert water has priority. Within this priority system, there is an order of preference for the use of surface water: Domestic use has the highest preference, then agricultural use, followed by manufacturing (including hydroelectric-power generation).

The Nebraska Department of Water Resources has responsibility for administering the system of water rights in Nebraska. The Department rules on applications for permits to divert or store water and must settle conflicts that arise between users. The Department also is responsible for approving plans for drainage projects and for allowing construction within flood plains.

The Nebraska Natural Resources Commission is responsible for planning the management of Nebraska's natural resources, including surface water. The Commission works closely with the 24 Natural Resources Districts (political subdivisions that manage the State's natural resources at the local level).

Operation of reservoirs is controlled by the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers. Projects are operated by individual irrigation and power districts.

A network of stream gages is maintained in Nebraska to provide hydrologic information. This network consists of gages maintained by the Department of Water Resources in order to perform its management role, gages maintained through a cooperative program between the U.S. Geological Survey and the Department, and gages maintained through cooperative programs of the U.S. Geological Survey with other Federal agencies and local agencies.

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NEVADA
Surface-Water Resources

In most of Nevada, surface water is a precious resource, and all of it is appropriated. In 1980, about 81 percent of all freshwater withdrawals were from surface sources. Ninety percent of the surface-water withdrawals were for irrigation, 5 percent for public supply, and 5 percent for self-supplied industries (table 1). About 400,000 people, or 50 percent of the State's population, rely on surface water for their freshwater needs.

The surface-water issues of greatest importance relate to appropriations of water, maintenance of water quality, flash flooding, interaction of surface water and ground water, and Lake Tahoe. Surface-water quality in Nevada generally is suitable for most uses.

GENERAL SETTING

Nevada is surface-water poor. Perennial rivers, except for the Colorado River, are small by nationwide standards. Almost all of Nevada is in the Basin and Range physiographic province (fig. 1), which is characterized by isolated, long and narrow, roughly north-south trending, parallel mountain ranges and broad, intervening relatively flat valleys. Extreme northeastern Nevada is in the Columbia Plateaus province and a small area near Lake Tahoe is in the Cascade-Sierra Mountains province (fig. 1). Internal drainage is the significant feature of the surface-water hydrology of Nevada. Flow in the larger rivers generally decreases in the downstream reaches as water is lost through evaporation, diversion, or infiltration.

Statewide annual precipitation averages about 9 inches—the lowest of any State in the Nation. Areally, average annual precipitation ranges from 4 inches in some low-altitude valleys to about 16 inches in higher areas (fig. 1); locally in the higher mountains, precipitation may exceed 30 inches. The orographic effect of the mountains, typically 3,000 to 5,000 feet higher than the intervening valleys, induces precipitation from storm systems, generally in the form of snow. In the nonmountainous parts of Nevada, virtually all the precipitation evaporates. In open bodies of water, annual evaporation exceeds annual precipitation in all parts of the State (Houghton and others, 1975, p. 62) and ranges from about 40 inches in the relatively wet areas of the north to about 80 inches in the lowlands near the Colorado River. Spring and summer snowmelt supplies most of Nevada's streamflow (fig. 1). Isolated summer convective storms can cause damaging flash floods. Although such storms do not contribute significantly to streamflow in major rivers, they probably cause most of the streamflow in low-altitude basins in southern Nevada. Most ground-water recharge occurs in the mountains and adjacent upper areas of alluvial fans. Some of this ground water eventually reappears as springflow.

Runoff patterns in the State vary greatly both seasonally and geographically (fig. 1). Average annual runoff varies from about 0.1 inch on some valley floors to about 10 inches from small areas in the highest mountains. Although runoff patterns are mainly determined by precipitation patterns, the surface geology, seasonal distribution of precipitation, and precipitation amounts and intensities modify that general relation.

PRINCIPAL RIVER BASINS

Almost all of Nevada is located in the Great Basin Region. Small parts of the State also are in the Pacific Northwest Region (in the north), the California Region (in the west and southwest), and the Lower Colorado Region (in the southeast) (Seaber and others, 1984). The major rivers in Nevada are the Colorado, the Walker, the Carson, the Truckee, and the Humboldt. All are in the Great Basin Region except the Colorado River, which forms a small part of the border with Arizona in the southeast (fig. 2). The Truckee, the Carson, and the Walker Rivers originate in the Sierra Nevada in California and terminate in sinks or playas in Nevada. The Humboldt River—the longest river entirely in Nevada—also terminates in a playa. A few small rivers drain northward from the State. The major river basins in the Lower Colorado and Great Basin Regions are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Nevada

[Data may not add to totals because of independent rounding Mgal/d = million gallons per day; gal/d = gallons per day. Population using spring water counted as served by ground water. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980[1]	
Number (thousands)	397
Percentage of total population	50
From public water-supply systems:	
Number (thousands)	392
Percentage of total population	49
From rural self-supplied systems:	
Number (thousands)	5
Percentage of total population	1
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	3,600
Surface water only (Mgal/d)	2,900
Percentage of total	81
Percentage of total excluding withdrawals for thermoelectric power	80
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	140
Percentage of total surface water	5
Percentage of total public supply	61
Per capita (gal/d)	357
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.7
Percentage of total surface water	0
Percentage of total rural domestic	6
Per capita (gal/d)	140
Livestock:	
Surface water (Mgal/d)	8.5
Percentage of total surface water	0.3
Percentage of total livestock	71
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	160
Percentage of total surface water	5
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	68
Excluding withdrawals for thermoelectric power	53
Irrigation withdrawals:	
Surface water (Mgal/d)	2,600
Percentage of total surface water	90
Percentage of total irrigation	84
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	1,200

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[1] Does not include populations served by water from springs. Population using spring water counted as service by ground water.

LOWER COLORADO REGION

The Colorado River is fully regulated in the reach bordering Nevada—except for a short river reach between Hoover Dam and Lake Mohave where the river is impounded. Its waters apparently meet all water-quality standards. Streamflow characteristics of the Colorado River below Hoover Dam are presented in the Arizona section of this report. Nevada's annual allotment from the Colorado River is 300,000 acre-ft (acre-feet) or 97,800 Mgal (million gallons). The Las Vegas area currently uses about half of that. Without some reuse of river water or water from other sources, the allotment may limit development after the year 2000.

Lower Colorado-Lake Mead Subregion

The outflow from Las Vegas Valley before development was probably relatively insignificant. The flow to Lake Mead from the Las Vegas Wash (Las Vegas Valley outflow), as measured near Henderson (fig. 2, site 4), is mostly treated sewage; the long-term increase in flow reflects increased urbanization.

Although Las Vegas Valley receives annual precipitation of about 4 inches, flash floods are a severe problem. In July 1975, flooding from rainfall of as much as 3 inches in several hours killed two people and caused extensive property damage (Katzer and others, 1976). An even more severe flash flood occurred in Eldorado Canyon in September 1974. Eldorado Canyon is tributary to Lake Mohave about 50 miles southeast of Las Vegas. The peak discharge of 76,000 ft^3/s or 49,100 Mgal/d from a drainage area of about 23 mi^2 (square miles) is extraordinary, regardless of location in the Nation (Glancy and Harmsen, 1975).

GREAT BASIN REGION

Black Rock Desert-Humboldt Subregion

Humboldt River Basin.—The Humboldt River is more than 300 miles long and drains more than 16,000 mi^2 of the Great Basin before it terminates in the Humboldt Sink about 70 miles northeast of Reno. Because of the river's general east-west course, it served as a lifeline for explorers and trappers in the 1820's and 1830's and pioneers in the 1840's and 1850's. Historical figures who left their imprint on the Humboldt are trappers Peter Ogden and Joe Walker, explorer John C. Fremont, and humorist Mark Twain.

The Humboldt River is not heavily developed; irrigation in the Lovelock area near its terminus is by far the greatest use. Most other withdrawals are for mining and ranching. Development in the basin is limited, probably because water is so scarce. Competition between upstream and downstream users is a prominent issue. As measured near Imlay (table 2, site 6), the long-term average annual flow of the river is 235 ft^3/s or 152 Mgal/d—the equivalent of about 0.2 inch of runoff from the basin.

Although the runoff is relatively small, damaging floods do occur. Floods in February 1910 and February 1962, caused by light rainfall during midwinter thaws, damaged transportation facilities and livestock. Another significant cause of flooding is rapid snowmelt throughout the basin. Flows in 1983 and 1984 that resulted from the melting of record snowpacks were the greatest since about 1900. In the upper reaches of the river, peak flows in 1910 exceeded peak flows in 1983 and 1984; however, in the lower reaches of the river, the peak flows of 1983 and 1984 were unprecedented. The excess water could not be stored or used. Extensive inflow to the Humboldt Sink and eventually to the Carson Sink began in 1983 and continued to 1985. The total flow to the Carson Sink from the Humboldt River in the period 1983-85 has exceeded 1,000,000 acre-ft or 326,000 Mgal.

Central Lahontan Subregion

Walker Lake Basin.—The East and the West forks of the Walker River drain the eastern side of the Sierra Nevada. Almost all of the flow used in Nevada for agriculture, livestock watering, mining, and public supply originates in California.

Early exploration (1820's to 1850's) centered around beaver trapping and the search for routes to California. Mining and ranching development followed. Irrigation development was limited by frequent droughts and the lack of storage. In 1919, the privately owned and financed Walker River Irrigation District was formed. The construction of reservoirs on the West Walker and the East Walker in California in the 1920's with a combined capacity of 102,000 acre-ft or 33,200 Mgal provided storage which was sufficient to irrigate 80,000 acres. The Federal Government constructed Weber Reservoir (completed in 1937, storage capacity of 10,700 acre-ft or 3,500 Mgal) for the Paiute Indians on the Walker River Indian Reservation.

The terminus of the Walker River is Walker Lake. Due mainly to upstream irrigation demands, the lake level has declined at a rate of about 2 ft/yr (feet per year) for most of this century, although the water level rose 12 feet in the 1983 water year. The waters of the lake have become increasingly saline because of evaporation, which concentrates minerals in the lake, and decreasing streamflow in the Walker River, which limits dilution of mineral concentrations. If the general water-level decline continues, the lake level may stabilize as a small remnant with a maximum depth of about 40 feet (Rush, 1970).

The main stem of the Walker River has been relatively free of damaging floods, but prolonged high water, such as occurred in 1983, causes erosion, siltation, and bank instability.

Irrigation is by far the major use of the Walker River; mines and ranches are relatively minor uses. Because irrigated acreage in the basin has not changed appreciably in more than 50 years, use of the Walker River for this purpose has remained relatively constant. The effect of ground-water pumping on streamflow quantity may become a significant issue.

Carson River Basin.—The Carson River is one of several streams that flow from the eastern side of the Sierra Nevada into the lake bed of an ancient glacial lake, which covered much of Nevada during the close of the last Ice Age. The maximum extent of the lake was as large as that of present-day Lake Ontario, and it received inflows from the Walker, the Truckee, the Humboldt, and the Carson Rivers. Today, only small remnants remain.

From the 1840's to the 1860's, the pioneer trails to California and the rush to the Comstock Mines followed the Carson River and its east and west forks. The Carson River became Nevada's first industrial river. Its power operated the great crushers used to extract gold and silver from its ores. Irrigation use, which began before large-scale use for mining, became a major use after mining declined following the 1890's. The Newlands Act (1902) authorized the construction of Lahontan Reservoir by the Bureau of Reclamation. The dam, which was completed in 1915, had a capacity of 295,000 acre-ft or 96,100 Mgal of water for irrigation in the Fallon area and enabled power generation. At present, irrigation in the Fallon area and in Carson Valley upstream of Carson City is the largest use of river water. The competition between upstream and downstream water users is a major water issue and the possible reduction of streamflow by ground-water pumping may become a major issue. In most years, very little, if any, surplus water reaches the Carson Sink, and the lake is nearly dry. Record-setting flows in 1983 and spills from the Humboldt Sink in 1983-85 increased the size of the lake in the Carson Sink to a surface area of more than 300 mi^2—the largest lake entirely in Nevada. Historical information on Carson Sink is sketchy, but available evidence indicates that present lake levels approach those of the 1860's or 1870's.

Although large volumes of spring runoff in 1983 caused some flood damage in the basin, historical floods in the winter months, caused by heavy precipitation in the Sierra Nevada in the form of rain have been greater and caused more damage.

Truckee River Basin.—The clear waters of the Truckee River were a boon to California-bound pioneers in the 1840's and 1850's. Later, these trails became railway and highway routes.

The Truckee River of western Nevada and northern California flows about 100 miles from Lake Tahoe in the Sierra Nevada to Pyramid Lake. The river and its tributaries, lakes, and impoundments are presently used for a variety of purposes. Lake Tahoe, one of the purest large bodies of water in the world, has been a focus of debate between proponents of conservation and proponents of development. In the Reno area, the river water is used for irrigation and water supply uses. At Derby Dam, a major part of the river flow is diverted to Lahontan Reservoir in the Carson River basin. The remaining flow enters Pyramid Lake. Legal conflicts

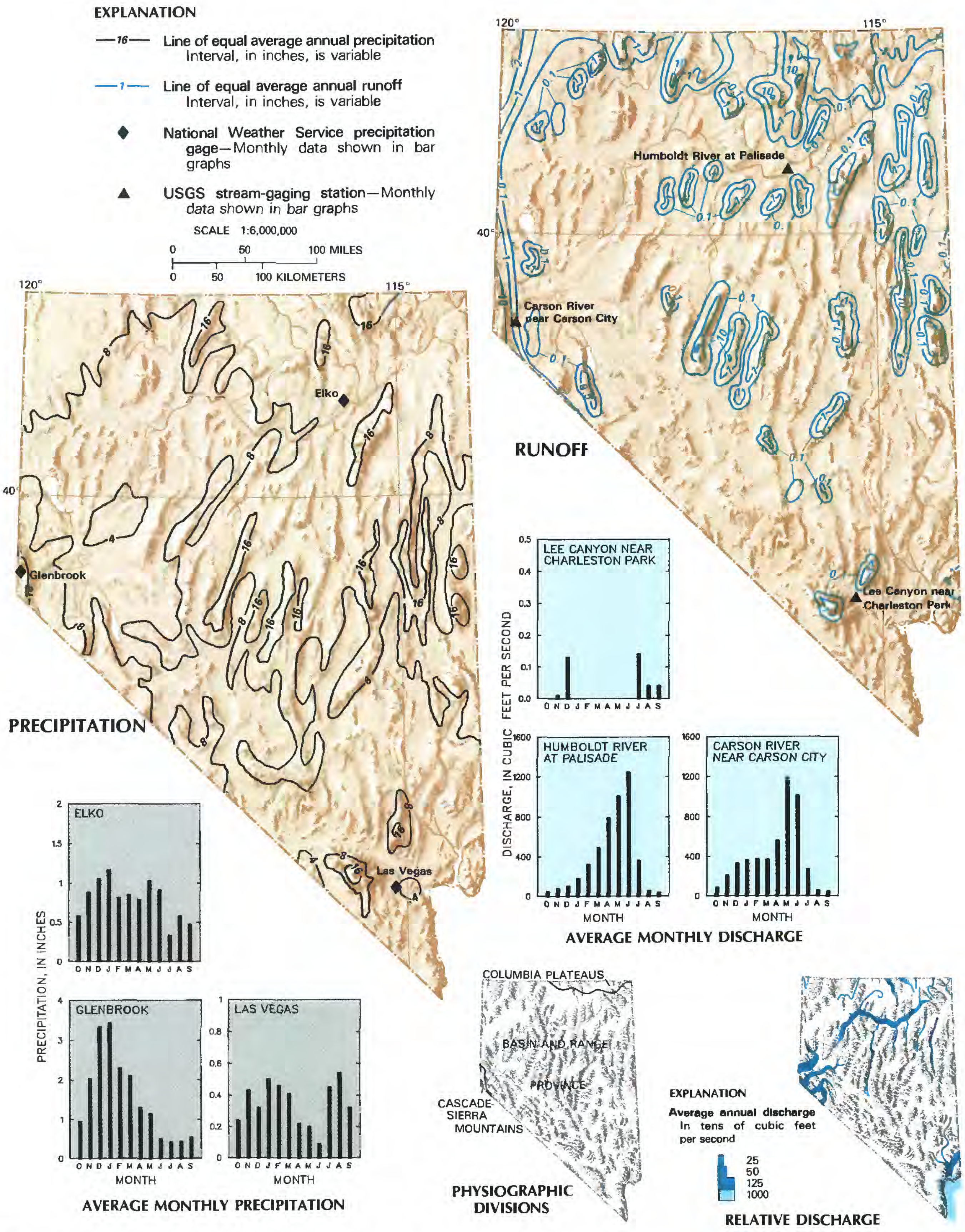

Figure 1. Average annual precipitation and runoff in Nevada and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—data from Houghton and others, 1975. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Nevada

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
	LOWER COLORADO REGION **LOWER COLORADO-LAKE MEAD SUBREGION**							
1.	Virgin River at Littlefield, Ariz. (09415000).	5,090	1929-83	48	243	35,300	Negligible	Most flow originates in Utah.
2.	Muddy River near Moapa (09416000).	3,820	1913-15, 1916-18, 1928-31, 1944-83	31	41.5	5,000	. . . do . . .	Spring discharge is main source.
3.	Lee Canyon near Charleston Park (09419601).	9.20	1963-83	0	0.025	4,300	None	Ephemeral stream.
4.	Las Vegas Wash near Henderson (09419700).	2,125	1957-83	. . . .	46.6	6,500	. . . do . . .	Treated sewage flow is main source. Average annual discharge has increased from 20 ft^3/s in 1957 to about 100 ft^3/s in 1983.
	GREAT BASIN REGION **BLACK ROCK DESERT-HUMBOLDT SUBREGION** **Humboldt River basin**							
5.	Humboldt River at Palisade (10322500).	5,010	1902-06, 1911-83	8.9	385	7,700	Negligible	
6.	Humboldt River near Imlay (10333000).	15,700	1911-83	0.3	235	5,700	. . . do . . .	River water occasionally exceeds dissolved oxygen, turbidity, and nutrient standards throughout the length of the river.
	CENTRAL LAHONTAN SUBREGION **Walker Lake basin**							
7.	Walker River near Wabuska (10301500).	2,600	1902-04, 1920-24, 1925-35, 1939-41, 1942-43, 1944-83	3.8	170	6,700	Moderate	Flow is the approximate inflow to Walker Lake. The quality of water in the basin is generally good and meets most standards and is suitable for most uses.
	Carson River basin							
8.	Carson River near Carson City (10311000).	886	1939-83	4.8	418	28,300	Moderate	The quality of Carson Basin waters is generally good, however taste and odor problems from algal blooms in Lahontan Reservoir occur occasionally. Mercury-contaminated sediments in the Carson River and Lahontan Reservoir are a concern.
	Truckee River basin							
9.	Truckee River near Nixon (10351700).	1,827	1957-83	14	538	28,300	Appreciable	Flow is inflow to Pyramid Lake. Domestic and agricultural return flows, especially in low-flow periods, increase in nitrogen, phosphorus, and water temperature in the lower river.
	CENTRAL NEVADA DESERT BASINS SUBREGION							
10.	Newark Valley tributary near Hamilton (10245800).	157	1962-83	0	0.325	1,100	None	Ephemeral stream.
11.	South Twin River near Round Mountain (10249300).	20	1965-83	0.78	7.06	260	. . . do . . .	

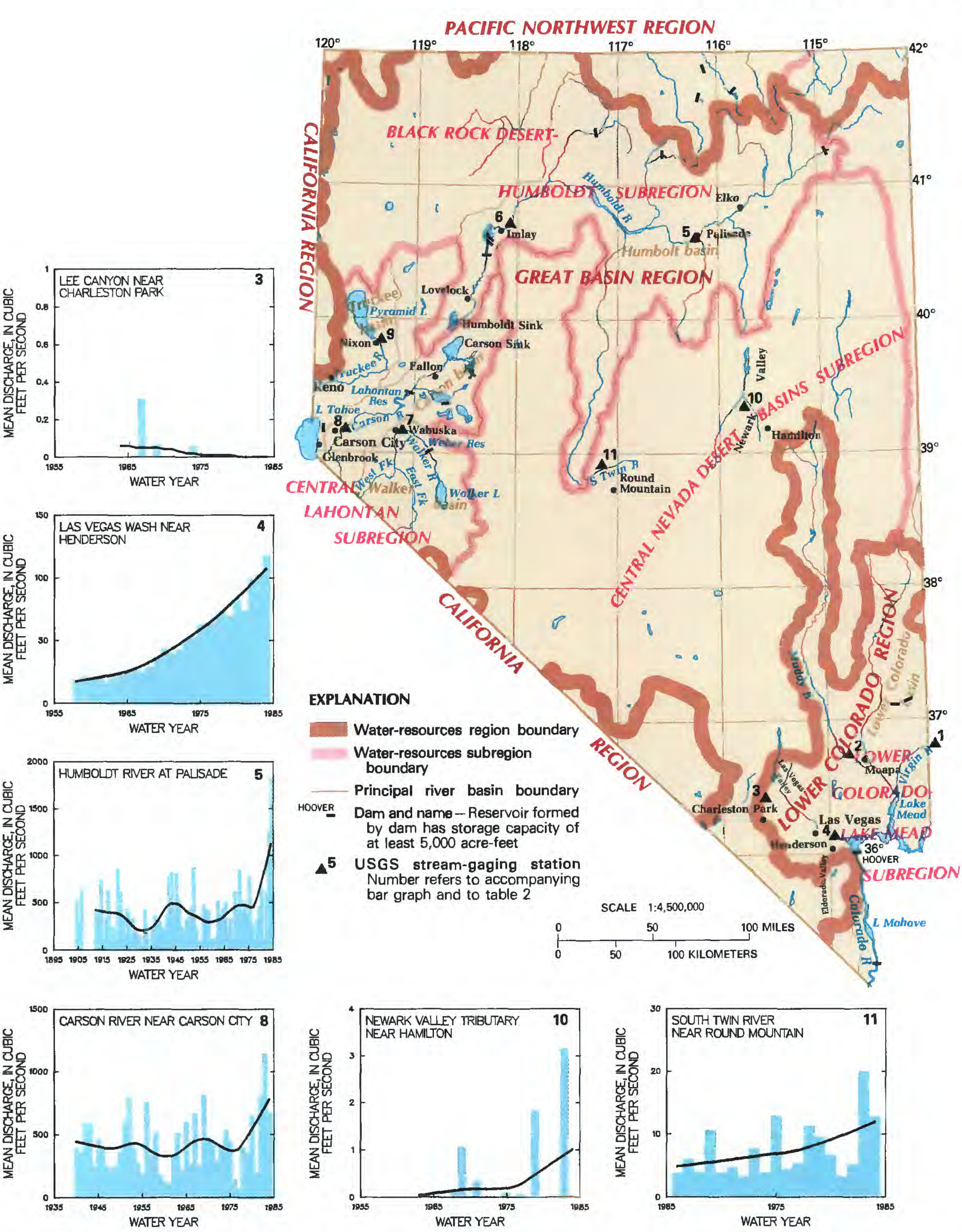

Figure 2. Principal river basins and related surface-water resources development in Nevada and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

over the apportionment of river flow and its quality, among Federal, State, and private interests have been intense and show no signs of being resolved soon.

Flows on the Truckee River, although modified by impoundments, basically result from snowmelt. Prolonged high flow in 1983 caused some damage, but severe floods generally result from heavy rains in the Sierra Nevada during warm periods in the winter. The river has overflowed its banks many times at Reno. At the present level of development, future floods of the magnitude experienced in the 1950's and 1960's will cause multimillion dollar damage.

For most of this century, the level of Pyramid Lake has declined an average of about 1 ft/yr (Harris, 1970). In the 3-year period, 1982–84, Pyramid Lake rose about 26 feet to the highest level since the 1940's. Based on historical data, a drier period will probably occur and cause another decline in lake level.

Central Nevada Desert Basins Subregion

Except for the major river basins, small, topographically closed basins typify the Great Basin Region in Central Nevada. Commonly, the small streams that issue from the mountains are appropriated for ranching, farming, or mining. Little or no flow occurs in these streams in most years. In "wet" years or after intense storms, excess water may occupy playas for days or months until it evaporates. The average annual daily flow of Newark Valley tributary near Hamilton (fig. 2, site 10), is probably typical of a stream that is a considerable distance from the mountain front. The South Twin River near Round Mountain (fig. 2, site 11), is measured where the stream issues from the mountains and also drains a basin with greater precipitation than Newark Valley tributary. Although the graphs indicate a trend toward increasing streamflow, the extremely wet year of 1983 probably unduly affects the statistics (fig. 2) of both streams. The water quality is generally suitable for most uses except for high-flow periods when sediment concentrations are excessive.

SURFACE-WATER MANAGEMENT

Surface-water and ground-water resources are managed by the State Engineer, Division of Water Resources, under the Nevada Department of Conservation and Natural Resources. The U.S. Geological Survey, in cooperation with the State Engineer, collects data and conducts hydrologic investigations. Water laws in Nevada are based on the concept of "first in time—first in right." The concept has proved to be effective and in the State's interest (Nevada State Engineer, 1974, p. 8).

Generally, Nevada's surface-water sources have been fully appropriated for many years. Most priority rights for water in the major river basins were established before the turn of the century. For example, rights to use water for irrigation date back to the 1850's in streams draining the Sierra Nevada and to the 1870's and 1880's in the Humboldt River basin. Although the amount of interstate streamflow between Nevada and the adjacent States of Oregon, Idaho, and Utah is significant, no compacts with the States have been enacted. The California–Nevada Compact of 1968 allocates the waters of Lake Tahoe and the Truckee, the Carson, and the Walker River basins but has not yet been ratified by the U.S. Congress. Nevada's use of the Colorado River is governed by the Rio Grande, Colorado, and Tijuana Treaty of 1944 with Mexico, and by the Colorado River Compact of 1922 (Nevada, Arizona, California, Colorado, New Mexico, Utah, and Wyoming). The Colorado River Commission of Nevada allocates the Colorado River water with the concurrence of the Nevada State Engineer and the Secretary of the Interior (Nevada State Engineer, 1971, p. 27).

Protection of surface-water quality and the prevention, control, and abatement of surface-water pollution are the responsibilities of the Nevada Department of Environmental Protection also under the Department of Conservation and Natural Resources.

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FOR ADDITIONAL INFORMATION

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NEW HAMPSHIRE
Surface-Water Resources

Surface water is an important natural resource in New Hampshire. It serves as a source of water supply for about 40 percent of the State's population and is a major source of water for industrial purposes. Of the 320 Mgal/d (million gallons per day) or 500 ft^3/s (cubic feet per second) of fresh surface water withdrawn, 270 Mgal/d or 420 ft^3/s are used for industrial purposes and 46 Mgal/d or 71 ft^3/s are used for public-water supplies (table 1). Of the 27 municipalities that have a population of more than 7,000, 11 are served by systems that use surface water, 9 by water systems that use ground water, and 7 by systems that use combined sources (New Hampshire Water Supply and Pollution Control Commission, 1982). Instream use of 26,000 Mgal/d or 40,000 ft^3/s of surface water for hydroelectric-power generation represented 99 percent of the estimated total water use in New Hampshire during 1980.

The quality of surface water is generally suitable for recreational purposes; however, some water treatment is typically required prior to human consumption. The quality of surface water continues to improve as a result of an increase in the number of waste-treatment facilities. In 1982, 506 miles of streams failed to meet Federal and State water-quality standards, particularly the bacteriological and the dissolved-oxygen standards (New Hampshire Water Supply and Pollution Control Commission, 1982). Presently, lakes and ponds meet most recreational standards, but there is much concern about the effects of acid precipitation and the potentially adverse effects of increasing recreational use of lakes, ponds, and streams.

GENERAL SETTING

New Hampshire is known for its many lakes, ponds, streams, and rivers in a setting of highlands and rolling lowlands. The State is located in the Seaboard Lowland, New England Upland, and White Mountain sections of the New England physiographic province (fig. 1). Average annual rainfall is about 42 inches, ranging from about 34 inches in the Connecticut River Valley to more than 89 inches in the White Mountains (National Oceanic and Atmospheric Administration, 1982). Average annual runoff ranges from 18 inches in parts of the Connecticut River Valley and seacoast area to about 42 inches in the White Mountains.

Precipitation is evenly distributed throughout the year as shown by graphs of average monthly precipitation at Errol, Lakeport, and Nashua (fig. 1). Monthly precipitation generally ranges between 3 and 4 inches, but is a little less than 3 inches at Errol and Lakeport in January and February. Commonly, the driest months at Nashua are February, June, and July.

Runoff varies both seasonally and geographically. The high "spring" flows occur during March, April, and May and are caused by the melting snowpack and concurrent precipitation (fig. 1). Generally, flows are greater in March and April for the southern streams and are greater in April and May in central and northern streams (fig. 1). In the White Mountains, the melting snowpack contributes to streamflow as late as June in some years. With the start of the growing season, water requirements for transpiration increase dramatically and warm temperatures increase evaporation from free-water surfaces. Much of the precipitation during the summer recharges soil moisture and replaces water evaporated from surfaces of ponds and lakes. Streamflows decrease progressively from June through August (fig. 1). As transpiration decreases during September, streamflow increases. Following the first killing frost, growth of vegetation stops, greatly reducing the demands on soil moisture. Thus, more water can be available for runoff or ground-water recharge. Commonly, streamflow increases from September through November or December, depending on when the snowpack starts to accumulate. From that time, flows generally decrease until melting begins in March.

The greatest known floods in New Hampshire occurred during 1927, 1936, 1938, 1955, 1973, and 1984 (Thomson and others, 1964; reports of the U.S. Geological Survey). These floods resulted from rainstorms that accelerated snowmelt (1936), from hurricanes (1938 and 1955), or from major storms (1927, 1973, and 1984).

Table 1. Surface-water facts for New Hampshire

[Data 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 SURFACE WATER, 1980	
Number (thousands)	370
Percentage of total population	40
From public water-supply systems:	
Number (thousands)	365
Percentage of total population	40
From rural self-supplied systems:	
Number (thousands)	5
Percentage of total population	0.5
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	380
Surface-water only (Mgal/d)	320
Percentage of total	84
Percentage of total excluding withdrawals for thermoelectric power	80
Category of use	
Public supply withdrawals:	
Surface water (Mgal/d)	46
Percentage of total surface water	14
Percentage of total public supply	52
Per capita (gal/d)	130
Rural supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.2
Percentage of total surface water	0.1
Percentage of total rural domestic	2
Per capita (gal/d)	40
Livestock:	
Surface water (Mgal/d)	0.5
Percentage of total surface water	0.2
Percentage of total livestock	65
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	270
Percentage of total surface water	85
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	95
Excluding withdrawals for thermoelectric power	94
Irrigation withdrawals:	
Surface water (Mgal/d)	1.6
Percentage of total surface water	0.5
Percentage of total irrigation	100
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	26,000

Agricultural droughts of varying lengths and severity are common and occur when soil moisture is deficient, resulting in economic losses from reduced yields of crops, pasture, and forests. Droughts that cause water-supply deficiencies tend to persist from one year to the next as a consequence of longer periods of below-normal precipitation. The most recent protracted drought, which occurred in the early to mid 1960's, was more severe in the southern parts (fig. 2) of the State (Barksdale, and others, 1966).

PRINCIPAL RIVER BASINS

The U.S. Water Resources Council has cataloged New Hampshire streams and rivers into the Merrimack, the Connecticut, the Androscoggin, and the Saco Subregions, all within the New England Region (Seaber and others, 1984) (fig. 1). The Merrimack Subregion contains the Merrimack River basin, which drains central and south-central parts of the State, about 42 percent of the surface drainage of the State. The Connecticut Subregion within New Hampshire contains the upper part of the Connecticut River basin, which drains western New Hampshire, about 33 percent of the State's drainage. The Androscoggin Subregion contains the Androscoggin River basin, part of which drains northeastern New Hampshire. The Saco Subregion contains parts of the Saco, the Ossipee, and the Piscataqua River basins, which drain the southeastern part of the State. The Androscoggin and the Saco Subregions contain 8 percent and 17 percent, respectively, of the State's surface drainage. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and pertinent information are given in table 2.

NEW ENGLAND REGION

Merrimack Subregion

The Merrimack River is formed by the confluence of the Pemigewasset and the Winnipesaukee Rivers in central New Hampshire and flows southward into Massachusetts. Indians once gathered for fishing at the falls and rapids, which are common throughout the length of the river. Settlers located at the falls, which, as barriers to navigation, were logical places for trading and commerce. Later, the water power available at these falls was developed by the textile industry. As the textile industry waned, many of these sites were developed to generate hydroelectric power. Presently, many of these sites are still used or are being rehabilitated for hydroelectric-power generation.

Flow in the Merrimack River is regulated by powerplants, by five U.S. Army Corps of Engineers flood-control reservoirs on tributary streams, and by numerous lakes. Water in these lakes and reservoirs is stored during spring runoff and is then gradually released through the summer and fall to maintain base flow in streams and levels in lakes and ponds. In the winter, the level of many ponds and lakes is lowered to reduce the possibility of ice damage to dams and shoreline structures and to provide storage for the spring runoff; there is little net change in storage from year to year. Therefore, average annual daily discharges for the Merrimack River below Manchester (fig. 2, site 7) are representative of the basin. The 7-day, 10-year low-flow statistic is greatly affected by regulation but is a usable statistic for planning and design purposes because the present patterns of regulation are not expected to change significantly in the near future.

Major tributaries to the Merrimack in New Hampshire are the Pemigewasset, the Winnipesaukee, and the Contoocook Rivers. The Pemigewasset River drains the southwestern part of the White Mountains, and the Winnipesaukee and the Contoocook Rivers drain the New England Upland section.

The Pemigewasset River basin provides year-around recreation in a mountainous setting. Streamflow tends to be flashy—a characteristic of mountain streams. The Winnipesaukee River basin includes many lakes. Storage available in Lake Winnipesaukee, and in other lakes in the Winnipesaukee drainage, greatly reduces streamflow fluctuations. The Contoocook River basin contains a mixture of recreational, forested, and agricultural areas spotted with small communities, and light industry. Flow patterns of streams in the basin tend to be intermediate between the flashiness of the Pemigewasset and the dampened fluctuations of the Winnipesaukee. The Soucook, the Suncook, the Piscataquog, the Souhegan, and the Nashua Rivers, and many smaller tributaries contribute water to the Merrimack before it leaves New Hampshire. Types of water use in the Merrimack basin change from those related to the rural-forest setting of the Contoocook River to the west, to those related to the industrialization and urbanization of the Nashua River to the south.

Connecticut Subregion

The Connecticut River is the longest river in New England (Bartlett, 1984) and forms the border between Vermont and New Hampshire for more than half of its length. From its headwaters at Third Connecticut Lake in northern New Hampshire, it drains western New Hampshire from the Canadian border to the Massachusetts border. Its drainage area in New Hampshire ranges from about 8 to about 30 miles in width and includes about one-third of the State's area. The Connecticut River, like the Merrimack, was a natural path for travel, trading, and commerce. Settlements were established at or near falls and at the mouths of major tributaries. Where water power was available, small industries developed and then evolved into major manufacturing complexes. Many of the waterpower sites were converted to hydroelectric-power sites in the early 1900's and more are presently being considered.

Tree farming, forestry products, and wilderness recreation are important to the economy and water use of the area. Principal tributaries of the Connecticut River south of Indian Stream are the Upper Ammonoosuc and the Israel Rivers, which drain the central White Mountains section. Streamflow statistics for the Upper Ammonoosuc River near Groveton (table 2, site 9) is typical of other streams in this area. Flow at the Connecticut River below Indian Stream, near Pittsburg (table 2, site 8) is representative of discharge from the northern White Mountains section. The 7-day, 10-year low-flow statistic is not representative of natural conditions because the river is regulated.

New Hampshire tributaries to the Connecticut River south of the Israel River include the Ammonoosuc, the Mascoma, the Sugar, the Cold, and the Ashuelot Rivers. These tributaries traverse the New England Upland section.

Flow of the Connecticut River in New Hampshire is regulated by powerplants and by several lakes and reservoirs with a total capacity of about 390,000 acre-ft (acre-feet) or 127,000 Mgal (million gallons). Regulation has an appreciable effect on flow statistics, and the low flow given in table 2 for the Connecticut River at North Walpole (site 13) is useful only for planning purposes. However, because regulation by lakes and reservoirs is seasonal and the net annual changes in storage are small, the annual and long-term average discharges are representative of the streamflow in the basin.

Androscoggin Subregion

This basin, most of which is in Maine, drains the eastern half of northernmost New Hampshire. Its economic importance and water uses lie with production of forestry products and provision of recreational opportunities. In the past, this river was the scene of massive log drives; traces of the facilities used to guide and store the logs can still be seen along the reach north of Berlin. Waterpower was developed first, followed by conversion to hydroelectric-power generation. Other potential hydroelectric powerplant sites are being considered for development, but recreational interests contest the need to convert the remaining falls and steep reaches of the river for hydroelectric-power generation.

Saco Subregion

The Saco and the Ossipee Rivers drain the east-central part of New Hampshire. The Saco River drains part of the southeastern White Mountains section, and the Ossipee River drains part of the New England Upland section (fig. 1). Recreational interest in these basins is strong because of the opportunities offered by the wilderness of the White Mountains and by the many lakes in the Ossipee basin. Agriculture, forestry products, and light industry also are important to the economy of these basins. The Salmon Falls, the Cocheco, the Lamprey, and the Exeter Rivers in New Hamp-

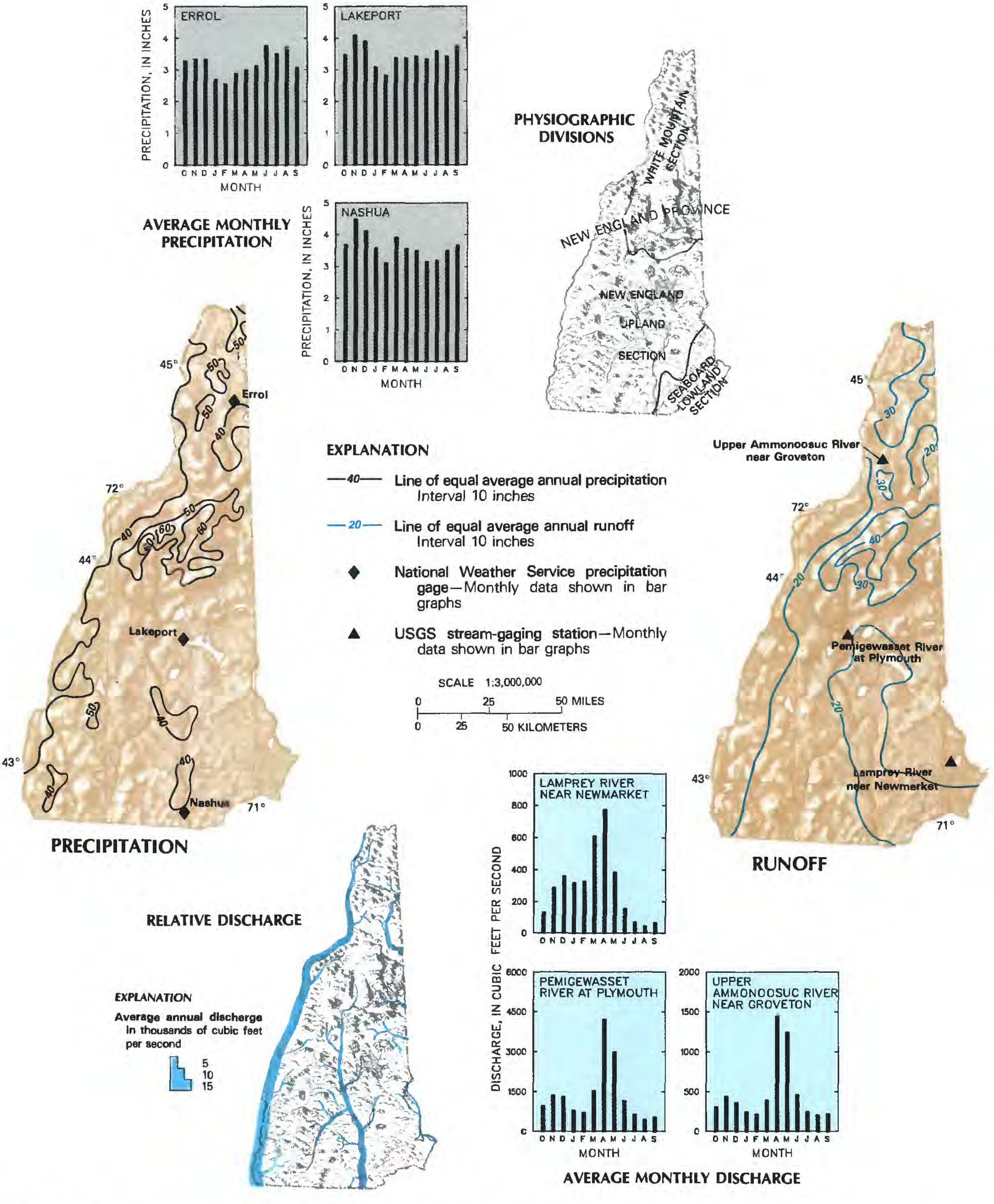

Figure 1. Average annual precipitation and runoff in New Hampshire and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data adapted from Knox and Nordenson, 1955; monthly data from National Oceanic and Atmospheric Administration files, 1984. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenmneman, 1946.)

shire are tributaries to the Piscataqua River, which drains the southeastern and coastal areas of the State. This area has a mixture of recreation, agriculture, and light and heavy industry. The northern area is predominantly rural; toward the southern and coastal areas, urbanization gradually increases and predominates along the coast and the borders of Massachusetts and Maine. Portsmouth, which was the first area to be settled in New Hampshire, was, and continues to be, the State's major shipping port and shipbuilding center.

The average annual daily streamflow in the Saco River varies considerably from year to year (fig. 2). Streamflow records for the

Table 2. Selected streamflow characteristics of principal river basins in New Hampshire

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow[1] (ft³/s)	Average discharge (ft³/s)	100-year flood[1] (ft³/s)	Degree of regulation	
				NEW ENGLAND REGION ANDROSCOGGIN SUBREGION				
1.	Androscoggin River near Gorham (01054000).	1,361	1913–83	1,280	2,465	20,900	Appreciable	Recreational, forestry products, light industrial areas.
				SACO SUBREGION				
2.	Saco River near Conway (01064500).	385	1903–09, 1929–83	93	933	53,800	None	Recreational area.
3.	Lamprey River near Newmarket (01073500).	183	1934–83	4.9	282	6,310	Moderate	Recreational, agricultural, urban, light and heavy industrial, and commerce areas.
				MERRIMACK SUBREGION				
4.	Pemigewasset River at Plymouth (01076500).	622	1903–83	115	1,358	60,800	None	Recreational area.
5.	Blackwater River near Webster (01087000).	129	1918–20, 1927–83	13	213	. . . .	Moderate	Recreational, agricultural, forestry products areas. High flows regulated.
6.	Soucook River near Concord (01089000).	76.8	1951–83	3.7	112	4,080	None	Recreational, agricultural, forestry products, light industrial areas.
7.	Merrimack River near Goffs Falls below Manchester (01092000).	3,092	1936–83	663	5,280	. . . .	Appreciable	Recreational, agricultural, light and heavy industrial, urban areas. Hydroelectric powerplants.
				CONNECTICUT SUBREGION				
8.	Connecticut River below Indian Stream, near Pittsburg (01129200).	254	1956–83	35	571	. . . .	Appreciable	Recreational, forestry products areas.
9.	Upper Ammonoosuc River near Groveton (01130000).	232	1940–80, 1982–83	49	473	10,800	None	Recreational, forestry products areas. Small diversion for Berlin's water supply.
10.	Ammonoosuc River at Bethlehem Junction (01137500).	87.6	1939–83	27	208	13,600	. . . do . . .	Recreational, forestry products areas.
11.	Connecticut River at Wells River, Vt. (01138500).	2,644	1949–83	632	4,731	. . . .	Appreciable	Recreational, forestry products, agricultural, light industrial areas. Hydroelectric powerplants.
12.	Sugar River at West Claremont (01152500).	269	1928–83	40	404	13,800	Moderate	Recreational, forestry products, agricultural, light industrial, scattered urban areas.
13.	Connecticut River at North Walpole (01154500).	5,493	1942–83	993	9,380	. . . .	Appreciable	Recreational, agricultural, forestry products, small industrial areas. Hydroelectric powerplants.
14.	Ashuelot River at Hinsdale (01161000).	420	1907–11 1914–83	46	671	. . . .	. . . do . . .	Recreational, forestry products, agricultural, light industrial, scattered urban areas.

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[1] Based on record to 1981.

Lamprey River near Newmarket (fig. 1), a river that is representative of a drainage in the middle of the Seaboard Lowlands section, show that runoff during the fall-winter period is proportionally much greater than during the summer, compared to other rivers in the State.

SURFACE-WATER MANAGEMENT

The two State agencies that have the greatest involvement with surface water for supply purposes are the Water Resources Board and the Water Supply and Pollution Control Commission.

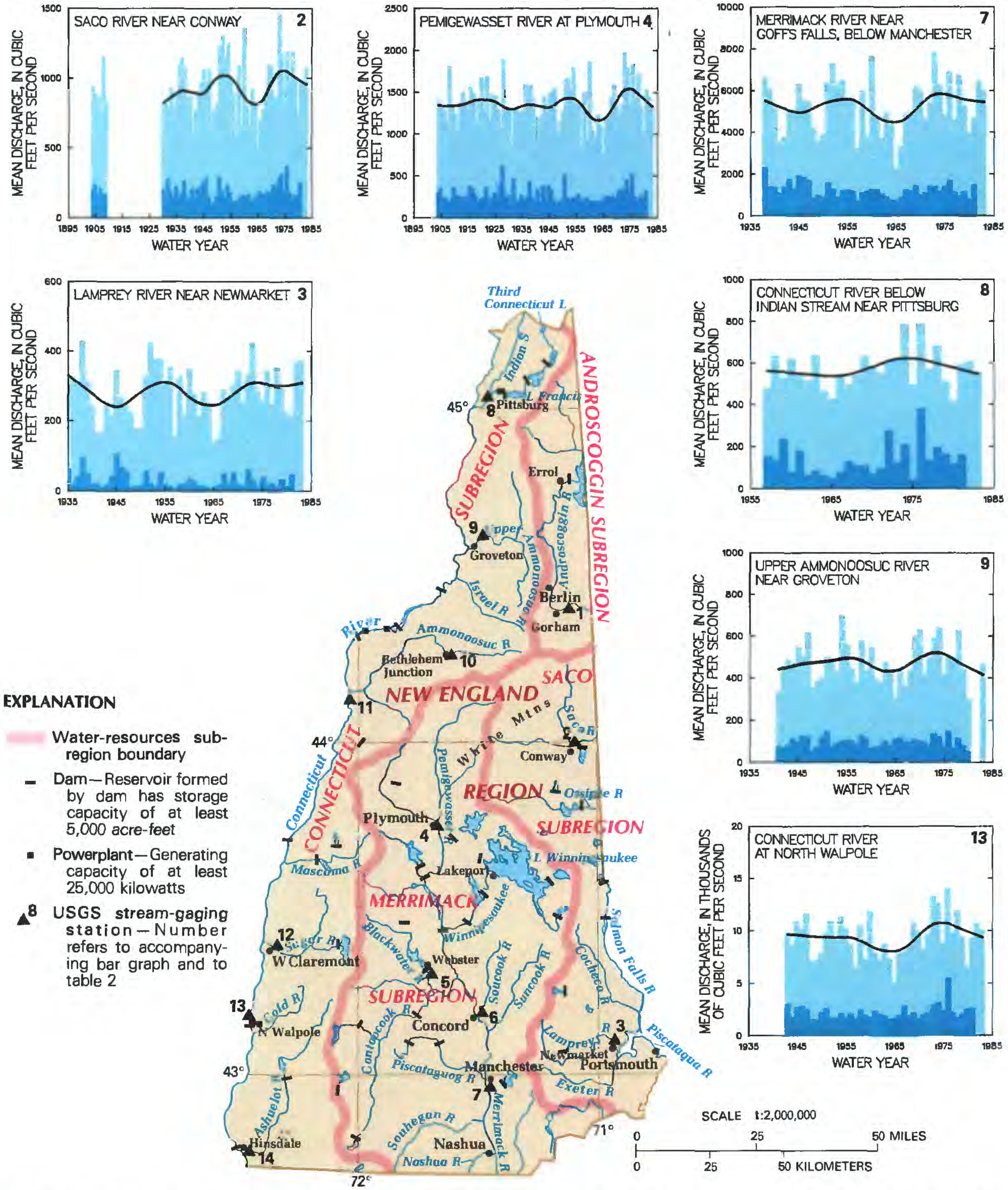

Figure 2. Principal river basins and related surface-water resources development in New Hampshire and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Several other agencies have a small but important role in surface-water management.

The Water Resources Board has legislative authorization to collect and evaluate data on water use, to implement a water allocation program, and to regulate hydroelectric-power development. Responsibility for determining water availability (through resource investigations, including cooperative programs with the U.S. Geological Survey) and water consumption (through registration of and reporting by water users) also lies with the Board. Empowered by State law, the Board manages surface-water flows, owns, operates, and maintains many dams statewide, and regulates surface-water flows to lessen flood damage and to promote the State's welfare. Another major responsibility of the Board is the regulation of Lake Winnipesaukee in the Merrimack basin, and Lake Francis in the Connecticut basin, to manage instream water use and augment low flows.

The Water Supply and Pollution Control Commission is authorized to regulate the construction and operation of public water-supply systems and other legislated water uses, to study regional water-supply requirements, to regulate discharges into the surface waters of the State as they affect water quality, and to perform all necessary planning for the protection of water quality. Also, the Commission is authorized to regulate specific types of development, including the approval of septic systems, where the quality of the State's waters may be affected.

Other State agencies involved with health, recreational, and environmental aspects of surface water are the Public Health Services, Wetlands Board, Fish and Game Department, Office of State Planning, and Council on Resources and Development. The Division of Public Health Services (Department of Health and Welfare) is authorized to protect public health and the environment through the permitting of facilities for the treatment, storage, and disposal of solid and hazardous wastes. Health assessments relative to environmental pollution also are provided by the Division. Regulation of development in the wetlands and construction of docks and wharves in lakes and ponds is done by the Wetlands Board. The Fish and Game Department protects, preserves, and propagates the fish and wildlife resources of the State. Provision of a State development plan which reflects resource management and fosters responsible planning and development of land and water by towns is required of the Office of State Planning. Created by statute, the Council on Resources and Development is composed of members of key State resource agencies and is chaired by the Director of the Office of State Planning. The primary function of the Council is to coordinate participation among member agencies, and it is empowered to resolve conflicts concerning water management and supply.

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NEW JERSEY
Surface-Water Resources

Surface water is used extensively throughout New Jersey for public, industrial, domestic, and agricultural supply. Nearly 4 million people or 54 percent of New Jersey's population depends on surface water. In 1980, about 2,100 Mgal/d (million gallons per day) or 3,200 ft^3/s (cubic feet per second) of freshwater was withdrawn from the numerous lakes, reservoirs, and streams in the State (Solley and others, 1983). An additional 7,500 Mgal/d or 11,600 ft^3/s of saline water was used by industry, largely for cooling of thermoelectric powerplants. Surface-water withdrawals for various uses in 1980 and other statistics are given in table 1. Areal and seasonal variations in surface-water withdrawals are significant.

In northern New Jersey, for example, water-supply development has not kept pace with increases in demand, which has led to water-supply shortages during periods of average or less-than-average precipitation. Major droughts occurred during 1930-32 and 1961-66. Flooding is a significant problem in many urbanized parts of the State. The water quality of the downstream reaches of the Hackensack, the Passaic, the Raritan, and the Delaware Rivers is degraded to varying degrees by municipal and industrial discharges and by runoff from agricultural areas.

Table 1. Surface-water facts for New Jersey

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	3,940
Percentage of total population	54
From public water-supply systems:	
Number (thousands)	3,940
Percentage of total population	54
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	2,900
Surface water only (Mgal/d)	2,100
Percentage of total	72
Percentage of total excluding withdrawals for thermoelectric power	60
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	620
Percentage of total surface water	30
Percentage of total public supply	56
Per capita (gal/d)	157
Rural supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	1.0
Percentage of total surface water	<0.1
Percentage of total livestock	33
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	[1]1,500
Percentage of total surface water	71
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	90
Excluding withdrawals for thermoelectric power	79
Irrigation withdrawals:	
Surface water (Mgal/d)	15
Percentage of total surface water	0.7
Percentage of total irrigation	27
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	140

[1] An additional 7,500 Mgal/d of saline water is used industrially; of this, 6,500 Mgal/D is used for thermoelectric power.

GENERAL SETTING

New Jersey is divided into four major physiographic provinces—Valley and Ridge, New England, Piedmont, and Coastal Plain (fig. 1). The Valley and Ridge, New England, and Piedmont provinces can be further subdivided into glaciated and unglaciated, inasmuch as the last glacial advance covered about half of northern New Jersey. The Coastal Plain has topographic, geologic, and hydrologic characteristics that are markedly different from the northern three provinces. The Piedmont and the Coastal Plain provinces are separated by the Fall Line. The diversity of terrain is reflected in its effect on the geographic distribution of precipitation throughout the State (fig. 1). Annual precipitation ranges from 40 inches in the southeast to 52 inches in the northern mountains and averages about 44 inches statewide. Precipitation does not exhibit a significant seasonal pattern and is distributed fairly uniformly throughout the year (fig. 1).

Runoff varies seasonally in New Jersey. During December through February, precipitation can either be rain or snow, and runoff rates differ accordingly. During March and April, abundant rainfall, the saturated condition of the soil, greatly reduced evapotranspiration, and snowmelt may cause high rates of runoff. Flooding in the spring is common. May through October are usually marked by low rates of runoff because of increased evapotranspiration and absorptive capacity of the soils. Although flooding is more common in the spring, recordbreaking floods generally result from thunderstorms and hurricanes during summer and early fall. During the fall, runoff typically increases in response to the decrease in evapotranspiration after the first killing frost. The seasonal runoff pattern for relatively unregulated rivers is exemplified by bar graphs of average monthly discharges for the Passaic River (site 2), the South Branch Raritan River (site 5), and the Great Egg Harbor River (site 12) (fig. 1).

Runoff also varies geographically in the State. In northern New Jersey, the greatest rates of runoff occur in the north-central mountains in the area of greatest rainfall (fig. 1). In southern New Jersey, rates of runoff vary greatly in response to rainfall and to the contribution of ground water to streamflow.

PRINCIPAL RIVER BASINS

All the rivers of New Jersey are in the Mid-Atlantic Region (fig. 2). For purposes of this State summary, the State has been divided into four major hydrologic areas: the Hackensack and the Passaic River basins, the Raritan River basin, Atlantic coastal basins, and the Delaware River basin and streams tributary to Delaware Bay. The water-resources subregions to which these areas correspond are indicated in footnotes in table 2. These basins are described below; their locations, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2. Additional low-flow, flow-duration, flood-magnitude, and flood-frequency data and gaging-station descriptions are given in Thomas (1964), Stankowski (1974), Gillespie and Schopp (1982), and Bauersfeld and others (1985).

MID-ATLANTIC REGION

Lower Hudson-Long Island Subregion

Hackensack and Passaic River Basins.—The drainage area of the Hackensack River basin is 202 mi^2 (square miles), of which 139 mi^2 are in New Jersey; the remaining area is in New York.

The basin has 23 mi^2 of tidal marshes that extend 10 miles upstream from the mouth at Newark Bay. The basin is 4 to 7 miles wide and 34 miles long. The basin is rapidly being urbanized and is intensively developed for water supply; the effect of water-supply withdrawals on streamflows is shown by the bar graph of discharge of the Hackensack River at New Milford in figure 2 (site 1). Three major water-supply reservoirs are in the New Jersey part of the basin: Oradell Reservoir (completed in 1922 with 8,740 acre-ft (acre-feet) or 2,850 Mgal (million gallons) of storage capacity), Lake Tappan (completed in 1966 with 10,360 acre-ft or 3,378 Mgal of storage capacity), and Woodcliff Lake (completed in 1905 with 2,560 acre-ft or 835 Mgal of storage capacity); all are owned by the Hackensack Water Company. Water is brought into the basin for supply from Sparkill Creek in the Hudson River basin and the Saddle and the Ramapo Rivers in the Passaic River basin.

The Passaic River basin is the third-largest drainage system in New Jersey. About 800 mi^2 of the 950-mi^2 drainage area is in New Jersey; the remaining area is in southeastern New York. The Passaic River is almost 100 miles long. Its major tributaries and their drainage areas are the Pompton River (381 mi^2), the Rockaway River (205 mi^2), and the Saddle River (60.5 mi^2). The Passaic River is tidal as far upstream as Dundee Dam, about 14 miles from its mouth. The New England Province in the basin is mostly forested, whereas the Piedmont is densely populated and highly industrialized. The Passaic River basin is one of the most urbanized basins in the State, and its waters are withdrawn for use by numerous water-supply companies. The major water-supply reservoirs in the Passaic River basin are Wanaque (completed in 1928 with 83,450 acre-ft or 27,210 Mgal of storage capacity), Boonton (completed in 1904 with 23,380 acre-ft or 7,620 Mgal of storage capacity), and the five reservoirs of the city of Newark system (completed between 1880 and 1961, with a total storage capacity of 44,100 acre-ft or 14,367 Mgal). Many municipal and industrial waste-treatment plants discharge treated effluents into the river. Flooding has been a problem in the Passaic River basin since colonial times. The flood of record for most of the basin occurred in 1903 when a peak discharge of 31,700 ft^3/s or 20,500 Mgal/d was recorded at the Passaic River at Little Falls gaging station (fig. 2, site 3).

The downstream reaches of the Hackensack and the Passaic Rivers are polluted to varying degrees by municipal and in dustrial point discharges. The Passaic River has a large biochemical-oxygen demand and elevated concentrations of fecal-coliform bacteria.

Raritan River Basin.—The Raritan River basin is the largest basin entirely within the State (fig. 2). It has a drainage area of 1,105 mi^2. Major tributaries and their drainage areas are the North Branch Raritan River (190 mi^2), the South Branch Raritan River (279 mi^2), the Millstone River (287 mi^2), and the South River (133 mi^2). The Raritan River is tidal for 14 miles upstream from its mouth at Raritan Bay to a point about 1 mile downstream of Fieldville Dam.

The topography of the basin ranges from a low hilly area in the northwest (maximum elevation, 1,200 feet above sea level) to the gently rolling coastal plain in the southeast. The basin extends across the New England, Piedmont, and Coastal Plain physiographic provinces.

The basin contains two major water-supply reservoirs—Spruce Run and Round Valley. Spruce Run (completed in 1963 with 33,750 acre-ft or 11,000 Mgal of storage capacity) is an onstream reservoir, whereas Round Valley (completed in 1966 with 168,700 acre-ft or 55,000 Mgal of storage capacity) is an offstream pumped-storage reservoir. Round Valley is perched on the drainage divide between the North and South Branches of the Raritan River and releases water into both streams. In 1980, the public-water use in the basin from surface-water supplies amounted to 75 percent.

In the upstream reaches of the basin, suburbanization is proceeding at a moderate rate, but dairy and grain farming are still prevalent. The downstream reaches of the basin are intensively urbanized.

Flooding has been a problem, especially in the downstream part of the Raritan River basin, since the early days of its settlement. The flood of record on the Raritan River below Calco Dam at Bound Brook (fig. 2, site 7) occurred in 1971 and had a peak discharge of 46,100 ft^3/s or 29,800 Mgal/d.

Downstream reaches of the Raritan River are polluted to varying degrees by municipal and industrial point-discharges. The downstream reaches are polluted by runoff from agricultural areas (U.S. Geological Survey, 1984).

Delaware and Lower Hudson-Long Island Subregions

Atlantic Coastal Basins.—The streams that flow into the Atlantic Ocean and Raritan Bay between Perth Amboy and Cape May drain much of the eastern part of the Coastal Plain physiographic province in New Jersey. More than half of this area is less than 50 feet above sea level. Major river basins and their drainage areas are the Toms (192 mi^2), the Mullica (569 mi^2), and the Great Egg Harbor (347 mi^2) Rivers. Much of the inland parts of these river basins are in the Pinelands National Preserve. The Pinelands, which covers 1.1 million acres, are sandy lowlands covered by scrub pine and oak; this area has large ground-water resources of almost pristine quality. The ecology of the Pinelands, however is fragile.

As much as 90 percent of the surface water in the Coastal Plain is derived from ground water. Because the ground-water reservoir can temporarily store precipitation from storms for later release to streams, streamflow in the Coastal Plain varies less than in other areas of the State. (See bar graph for fig. 2, site 12.) Development of the abundant ground-water and surface-water resources in these basins for water supply has been proposed. Most streams on the Coastal Plain have low gradients, and tidewater extends far inland at many places. The quality of water in the Coastal Plain generally is suitable for most uses. Swimming River Reservoir (completed in 1962 with 8,000 acre-ft or 2,600 Mgal of storage capacity) is the largest reservoir in the Atlantic coastal basins. Increasing diversions from Swimming River Reservoir contribute to the downward trend exhibited in the long-term average annual discharge for the Swimming River, as shown in the bar graph in figure 2 (site 9). A new reservoir is planned for the Manasquan River basin (New Jersey Department of Environmental Protection, 1980).

Riverine flooding is not ordinarily a significant concern in the Atlantic Coastal basins. Tidal flooding and beach erosion resulting from "northeasters," hurricanes, and other tropical storms are a problem along the coast. The worst tidal flood of this century was caused by the March 1962 "northeaster" storm. Most of the seashore resorts in southern New Jersey, such as Atlantic City, Ocean City, and Wildwood, are on barrier islands that are vulnerable to inundation during hurricanes and other coastal storms.

Delaware River Basin and Streams Tributary to Delaware Bay.—The Delaware River forms the western boundary of New Jersey. The basin has a drainage area of 12,765 mi^2 (excluding the surface area of Delaware Bay), of which 2,969 mi^2 (23 percent of the basin) is in New Jersey; this is the largest river basin in the State. The river forms the boundary between New Jersey and Pennsylvania and, farther south, the boundary between New Jersey and Delaware. The New Jersey part of the river is about 254 miles long. The major tributaries of the Delaware River and Bay in New Jersey and their drainage areas are Paulins Kill (177 mi^2), the Pequest River (157 mi^2), the Musconetcong River (156 mi^2), Crosswicks Creek (144 mi^2), Rancocas Creek (347 mi^2), the Salem River (117 mi^2), the Cohansey River (107 mi^2), and the Maurice River (382 mi^2).

The Delaware River flows through all four physiographic provinces in the State. Upstream from the Fall Line, the basin con-

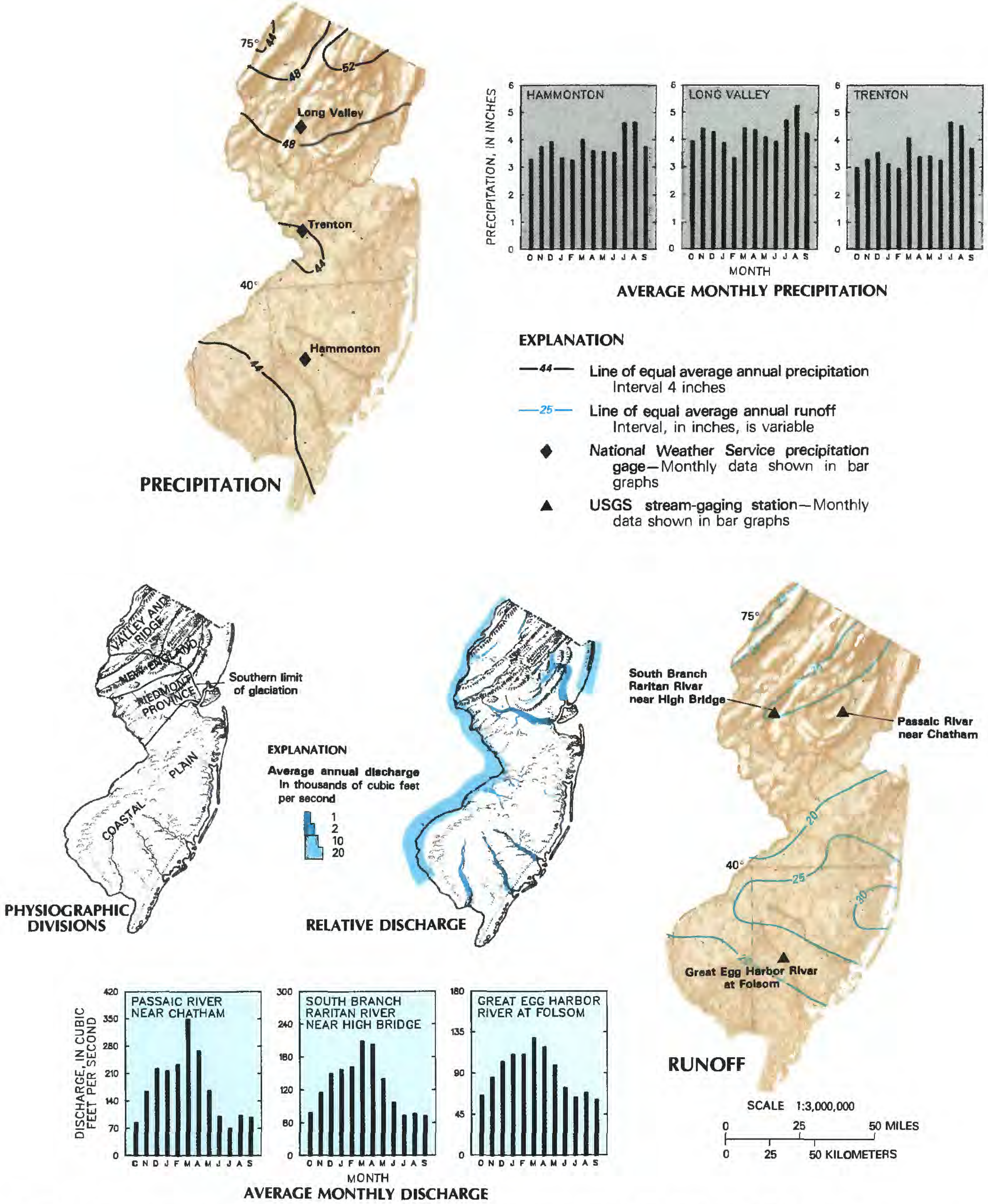

Figure 1. Average annual precipitation and runoff in New Jersey and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in New Jersey

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				MID-ATLANTIC REGION LOWER HUDSON-LONG ISLAND SUBREGION Hackensack and Passaic River basins				
1.	Hackensack River at New Milford (01378500).	113	1922-84	0	103	5,570	Appreciable	Large diversions for municipal supply.
2.	Passaic River near Chatham (01379500).	100	[1]1904-84	3.7	172	3,730	Negligible	High nitrogen and phosphorus levels during low flow.
3.	Passaic River at Little Falls (01389500).	762	1898-84	32	1,168	22,500	Appreciable	Many reservoirs and diversions for municipal supply.
4.	Saddle River at at Lodi (01391500).	54.8	1924-84	13	102	5,750	Moderate	Urbanized basin, diversions for municipal supply, high nitrogen and phosphorus levels.
				Raritan River basin				
5.	South Branch Raritan River near High Bridge (01398500).	65.3	1919-84	22	123	8,600	Negligible	Farmland, forest, and light development.
6.	Stony Brook at Princeton (01401000).	44.5	1954-84	0.1	65.1	8,390	. . . Do . . .	Do.
7.	Raritan River below Calco Dam at Bound Brook (01403060).	785	[1]1904-84	72	1,293	40,800	Appreciable	Large diversions for municipal supply.
8.	Green Brook at Plainfield (01403500).	9.75	1939-84	0	12.9	3,280	Moderate	Urbanized basin, heavy ground-water development affects streamflow.
				DELAWARE AND LOWER HUDSON-LONG ISLAND SUBREGIONS Atlantic coastal basins				
9.	Swimming River near Red Bank (01407500).	49.2	1923-84	0	[2]80.8	11,000	Appreciable	Farmland, forest, and light development.
10.	Manasquan River at Squankum (01408000).	44.0	1932-84	18	75.9	2,870	Negligible	Do.
11.	Oyster Creek near Brookville (01409095).	7.43	1966-84	13	28.7	514	. . . Do . . .	Considerable ground-water inflow, low-pH may limit water use.
12.	Great Egg Harbor River at Folsom (01411000).	57.1	1926-84	22	88.8	1,230	. . . Do . . .	Farmland, forest, and light development.
				DELAWARE SUBREGION Delaware River basin and streams tributary to Delaware Bay				
13.	Maurice River at Norma (01411500).	112	1933-84	37	188	2,880	Negligible	Farmland, forest, and light development.
14.	Flat Brook near Flatbrookville (01440000).	64.0	1924-84	7.8	110	7,070	. . . Do . . .	Do.
15.	Delaware River at Trenton (01463500).	6,780	1914-84	[3]1,800	11,740	[3]217,000	Moderate	Regulated by many reservoirs, diversions, and powerplants.
16.	Crosswicks Creek at Extonville (01464500).	81.5	[1]1941-84	24	138	5,800	Negligible	Farmland, forest, and light development.
17.	McDonalds Branch in Lebanon State Forest (01466500).	2.35	1954-84	0.9	2.32	49	None	State forest, low-pH may limit water use.
18.	Cooper River at Haddonfield (01467150).	17.0	1964-84	8.6	36.3	3,840	Moderate	Urbanized basin.

[1] Period of record not continuous. [2] Adjusted for diversion and change in reservoir contents. [3] Analysis based on regulated period 1955-84.

sists primarily of plateaus and ridges and valleys, most of which are densely wooded. The Coastal Plain is an area with little topographic relief and contains industrialized areas, including several petrochemical refineries. New York City is permitted to divert as much as 800 Mgal/d or 1,240 ft³/s from the headwaters of the basin into reservoirs in the Hudson River basin for municipal supply. The effect of the New York City reservoirs on the flow at Trenton is to increase low flows significantly and to decrease moderate and high flows slightly (Schopp and Gillespie, 1979). New Jersey also can divert as much as 100 Mgal/d or 155 ft³/s for municipal supply through the Delaware and Raritan Canal to the Raritan River basin. The U.S. Supreme Court decreed these diversion quantities in 1954 and established the position of Delaware River Master to ensure that these diversions were observed.

Flooding has been a problem along the Delaware River since colonial times. The flood of record on the main stem occurred

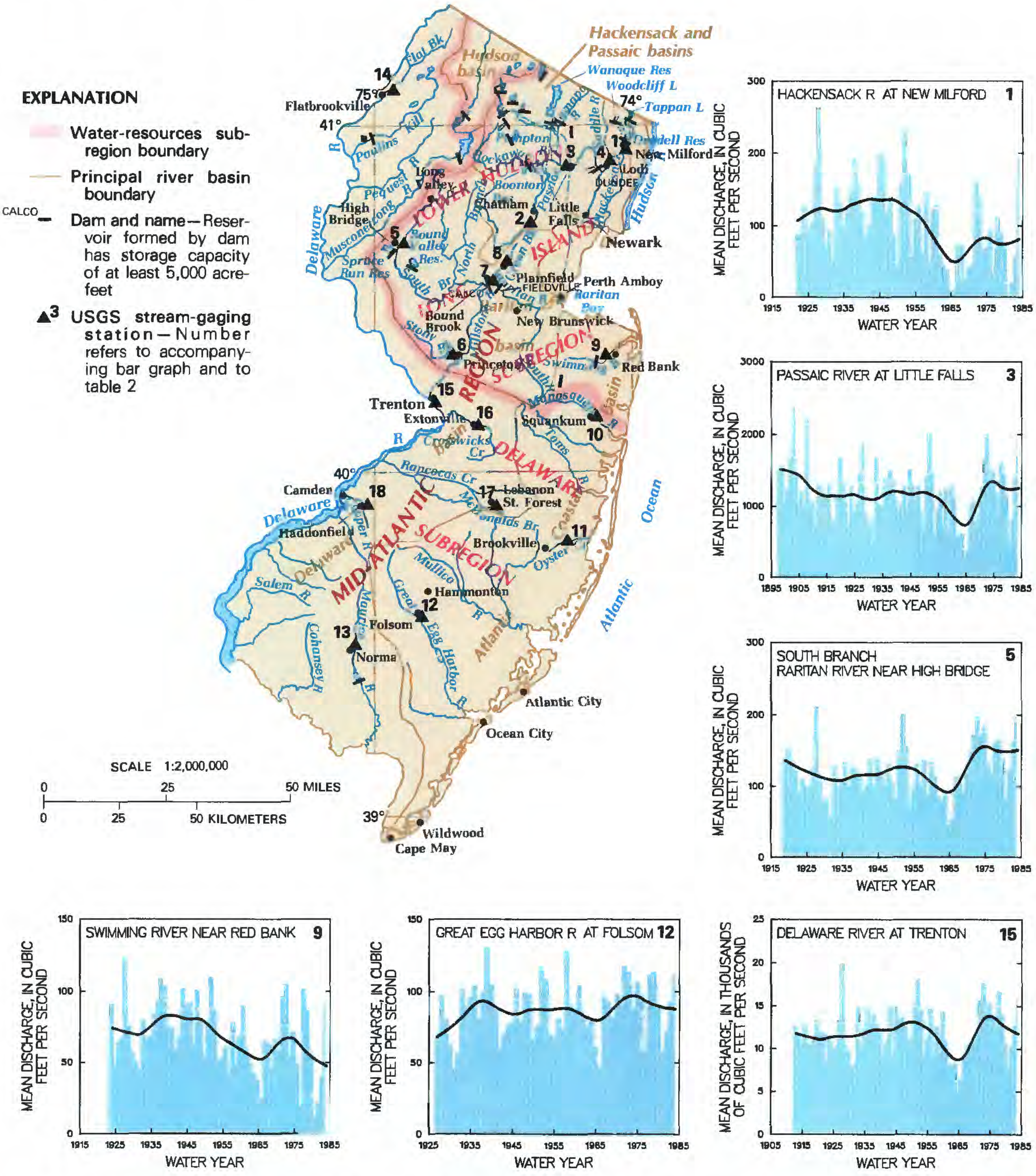

Figure 2. Principal river basins and related surface-water resources development in New Jersey and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

in 1955 (Bogart, 1960). At Trenton, the 1955 flood produced the greatest flood discharge (329,000 ft³/s or 213,000 Mgal/d) since 1692 (Bogart, 1960; Thomas, 1964).

The quality of water in the basin north of Trenton is suitable for most uses. Downstream from Trenton, however, the quality of the river is degraded by large quantities of inadequately treated industrial and municipal wastewater. Maintenance of adequate freshwater inflow to the Delaware Estuary to prevent the movement of saline water into the underlying ground water in the Camden area is a major concern (U.S. Geological Survey, 1984).

SURFACE-WATER MANAGEMENT

The New Jersey Department of Environmental Protection, Division of Water Resources (NJDEP/DWR), is the primary agency responsible for managing and regulating the water resources of the State. All diversions of 100,000 gal/d (gallons per day) or 0.155 ft³/s or more require a permit and reports of monthly withdrawals to the NJDEP/DWR. The NJDEP/DWR licenses waste discharges to surface waters and monitors licensees and receiving waters to ensure that State water-quality standards are met (U.S. Geological Survey, 1985).

In addition to NJDEP/DWR, other State agencies have responsibility with respect to water supply. The NJDEP Division of Fish, Game, and Shellfisheries manages and protects aquatic life in the streams of the State. The New Jersey Water Supply Authority, which was established in 1981, controls specific State water supplies and can issue bonds to finance water-supply projects. The North Jersey District Water Supply Commission, which was established in 1916 to provide water to northern counties in New Jersey, is one of the largest purveyors of potable water in the State. The Delaware River Basin Commission, formed in 1961, has broad powers over the planning, development, and control of water and related natural resources of the Delaware River basin. The U.S. Geological Survey, in cooperation with NJDEP/DWR and other agencies, collects streamflow, water-quality, and ground-water data to help assess and manage the water resources of the State.

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New Mexico
Surface-Water Resources

Residents of the State of New Mexico take pride in the warm, sunny weather that prevails most of the year. Because the long periods of sunshine are interrupted only occasionally by clouds, little precipitation falls. Albuquerque, the home of one-third of the State's residents, receives only about 8 inches of precipitation annually. As a result, the climate is arid to semiarid and surface water is scarce. Only 7 percent of the population depends on surface water for its freshwater needs.

Except in the mountainous areas of the State, most smaller streams are ephemeral. The larger perennial rivers, such as the Rio Grande and the Pecos and the San Juan Rivers, have become water-transmission systems through construction of reservoirs. These reservoirs were constructed to reduce streamflow variability and the severity of floods, to control sediment, and to assure delivery of water allocated by various water-rights laws and legal compacts. The major water issues in the State relate to the scarcity and variability of streamflow.

Diversion structures in streams provide irrigation water that allows the desert to bloom with crops of various kinds. Irrigation is the largest user of surface water and ground water. Total withdrawals during 1980 for irrigation were 2,000 Mgal/d (million gallons per day) or 3,090 ft^3/s (cubic feet per second) of surface water and 1,340 Mgal/d or 2,070 ft^3/s of ground water (Sorensen, 1982). Withdrawals of surface water for all purposes totaled 2,100 Mgal/d or 3,250 ft^3/s; total ground-water withdrawals were 1,800 Mgal/d or 2,790 ft^3/s. Surface-water withdrawals in New Mexico in 1980 for various purposes and related statistics are given in table 1.

Electrical power is produced in New Mexico by gas-fired or coal-fired powerplants that are cooled by water-tower evaporation. The Four Corners and San Juan powerplants in northwestern New Mexico (fig. 1) are two such powerplants. Offstream withdrawals of surface water for power production increased by 24 Mgal/d or 37 ft^3/s from 1970 to 1980 to a total of 38 Mgal/d or 59 ft^3/s (Sorensen, 1982). Hydroelectric-power production was negligible during that period. However, currently planned hydroelectric projects at Cochiti, El Vado, Navajo, and Abiquiu Dams should significantly increase the instream water use for electric-power production in New Mexico.

Water-quality concerns in the State stem from three sources. The first is the high concentration of suspended sediment that results in decreases in reservoir storage capacity. The second is discharge of wastewaters from industrial sites and urban areas. The third is increases in stream salinity caused by inflow of subsurface brines or salts leached from irrigated fields.

Most water needs, excluding irrigation, are met by ground-water withdrawals, in part because of the limited surface-water resources in the State. For example, Albuquerque, the largest city in the State, derives its municipal water supply from wells. Most irrigable land is located in the Rio Grande, the Pecos, and the San Juan River basins. Reservoirs provide surface water for irrigation.

GENERAL SETTING

New Mexico, with an area of 121,666 mi^2 (square miles), is the fifth largest State. It is characterized by great variations in topography and climate. The State is located in four physiographic provinces—the Great Plains, the Southern Rocky Mountains, the Colorado Plateaus, and the Basin and Range (fig. 1). Mountain ranges are present in all except the Great Plains province.

The mountainous areas of New Mexico receive the most precipitation (20 inches or more annually) and produce the most runoff (about 15 inches maximum annually) (fig. 1). In contrast to the mountains, precipitation and runoff in the desert areas are as little as 8 inches and less than 0.1 inch, respectively (fig. 1). Much of the runoff from the mountains occurs during concurrent snowmelt and rainfall in the spring and summer. In the remainder of the State, runoff results from short duration, intense rainstorms that produce locally severe floods. The patterns of precipitation and runoff at representative gaging stations are shown in figures 1 and 2, respectively. Much of the State's rainfall falls during May through September; many months have little or no precipitation. Evaporation from the State's reservoirs and lakes ranges from 40 to 80 inches per year; most evaporation occurs from March through September.

Table 1. Surface-water facts for New Mexico

[Data 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 SURFACE WATER, 1980	
Number (thousands)	96
Percentage of total population	7
From public water-supply systems:	
Number (thousands)	82
Percentage of total population	6
From rural self-supplied systems:	
Number (thousands)	14
Percentage of total population	1
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	3,900
Surface water only (Mgal/d)	2,100
Percentage of total	53
Percentage of total excluding withdrawals for thermoelectric power	52
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	21
Percentage of total surface water	1
Percentage of total public supply	10
Per capita (gal/d)	240
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	1.1
Percentage of total surface water	0.1
Percentage of total rural domestic	3
Per capita (gal/d)	78
Livestock:	
Surface water (Mgal/d)	9.6
Percentage of total surface water	0.5
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	54
Percentage of total surface water	3
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	75
Excluding withdrawals for thermoelectric power	2
Irrigation withdrawals:	
Surface water (Mgal/d)	2,000
Percentage of total surface water	95
Percentage of total irrigation	56
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	430

PRINCIPAL RIVER BASINS

New Mexico is in the Arkansas-White-Red, Texas-Gulf, Rio Grande, Upper Colorado, and Lower Colorado Regions (fig. 2). The Arkansas-White-Red Region in New Mexico consists of the Upper Canadian Subregion (the principal river basin) and part of five other subregions (not discussed). The Upper Canadian Subregion and the other four regions are discussed below. Their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information (excluding the Texas-Gulf Region) are given in table 2.

ARKANSAS-WHITE-RED REGION

Upper Canadian Subregion

Canadian River Basin.—The Canadian River basin is an area of 12,616 mi^2 in the northeastern part of the State. The basin contains little manufacturing and no heavy industry. Most of the consumptive use of surface water is for irrigation. The three major reservoirs in the area—Conchas, Ute, and Eagle Nest—have a combined storage capacity of 499,700 acre-ft (acre-feet) or 162,800 Mgal (million gallons). The effect of the Ute Reservoir on streamflow can be seen in the hydrograph of average discharge by water year for the Canadian River at Logan (fig. 2, site 1). Streamflow dramatically decreased downstream after the reservoir's completion. In 1980, withdrawals of 165 Mgal/d or 255 ft³/s of water were made for irrigation (Sorensen, 1982).

The quality of water in the Canadian River basin is generally suitable for its present use as irrigation water. Some salinity problems have occurred near the New Mexico–Texas State line, probably as a result of inflow from salt springs. Large suspended sediment concentrations result from storm runoff in ephemeral channels.

RIO GRAND REGION

Upper and Lower Pecos Subregions

Pecos River Basin.—The Pecos River basin has an area of 25,962 mi² in New Mexico; the basin extends from its headwaters in the Sangre de Cristo Mountains in the north-central part of the State to the Texas State line. Major tributaries to the Pecos are the Gallinas River, the Arroyo del Macho, the Rio Hondo, the Rio Felix, the Rio Penasco, and the Black River.

Many stories of the "wild west" have included the Pecos and the surrounding countryside. Judge Roy Bean practiced his brand of law on its banks, and the Pecos was the scene for stories told of Pecos Bill, the mythical "Greatest Cowboy of All Times." The major issue in this basin today is the lack of enough water for all the needs of the area's residents.

Principal water uses in the Pecos River basin are for agriculture, oil and gas development, potash mining, ranching, and tourism. In order to meet these needs, reservoirs were constructed to capture the irregular streamflow of the basin. Lake Avalon (completed in 1891), Lake McMillan (1893), Lake Sumner (1937), Two Rivers Reservoir (1963), and Santa Rosa Lake (1980) provide a combined storage of 746,500 acre-ft or 243,000 Mgal for flood control, recreation, and water supply. A major concern is the rapid accumulation of sediment in several of these reservoirs that has decreased their storage capacity. Brantley Dam is being constructed to replace the nearly silted Lake McMillan.

Surface-water discharges are, in part, regulated by terms of the 1948 Pecos River Compact between New Mexico and Texas. Average discharge by water year illustrates the large year-to-year variations in natural discharge in the basin. The result of such variations is competition among various water users for a resource that, at times, is severely limited.

Water quality along the Pecos River varies greatly. Inflow from highly mineralized springs causes dissolved-solids concentrations to range from about 100 mg/L (milligrams per liter) to 10,000 mg/L. Salinity also increases as the river flows across deposits of gypsum, halite, and other soluble salts.

Rio Grande River basin (main stem)

Rio Grande River Basin.—The Rio Grande and its tributaries drain 26,295 mi² in central New Mexico. An additional 23,460 mi² are contained in various closed basins that under normal circumstances do not contribute surface flow to the Rio Grande and its tributaries. The Rio Grande basin has a rich and colorful history. European exploration of the area was begun by the Spanish in the 1500's. Their colonization resulted in the founding of Santa Fe in 1609 and Albuquerque in 1706. The Rio Grande Valley became a Mexican territory in 1821 when Mexico established independence, and became an American territory in 1848 as a result of the Treaty of Guadalupe Hidalgo.

The Rio Grande flows southward through New Mexico and is joined along its course by numerous tributaries including the Red River, the Rio Chama, Galisteo Creek, the Jemez River, the Rio Puerco, and the Rio Salado before it enters Texas.

Reservoirs have been used on this river system to control sedimentation, prevent downstream flooding, and provide storage for various downstream users. The Abiquiu, Bluewater, Caballo, Cochiti, Elephant Butte, El Vado, Heron, and Jemez Canyon Reservoirs, which were completed between 1915 and 1970, have a total storage capacity of 4.5 million acre-ft or 1.5 Mgal.

Development of this extensive system of reservoirs is a direct result of demands placed on the basin's limited surface-water resources. Because of the variability of streamflow, reservoirs are necessary to store water for future downstream use. The greatest use of surface water is for irrigation (980 Mgal/d or 1,520 ft³/s in 1980) (Sorensen, 1982). To help meet these needs, a major transmountain diversion of water was made from the San Juan River basin in Colorado through the Azotea Tunnel into the Rio Chama, a tributary to the Rio Grande.

A substantial part of the basin's surface waters are required to meet legal obligations to Texas and Mexico. Water deliveries to Texas are specified by the Rio Grande Compact that was signed in 1938 by the States of Colorado, New Mexico, and Texas. Deliveries of 53.6 Mgal/d or 82.9 ft³/s of water to Mexico are specified in a 1906 treaty between the United States and Mexico.

The quality of surface water in the basin is suitable for most uses. The Red River and several other northern tributaries are excellent cold-water fisheries. Problems in parts of the basin are associated with municipal wastewater and urban runoff that contain potentially toxic chemicals such as lead, mercury, molybdenum, radium, pesticides, and organic compounds.

Water-related concerns in the basin relate to the scarcity and variability of streamflow. The year-to-year variation in average daily discharge at the Rio Grande at Albuquerque gaging station is shown in figure 2 (site 4). The need for water by expanding urban areas is conflicting with the traditional use of water for agriculture. Even though flood magnitudes have decreased through the efforts of the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, and other governmental agencies, increased streamflow in the Rio Grande caused by greater-than-normal precipitation in recent years has renewed fears of flooding; localized flooding on unregulated tributaries continues to be a problem. In spring 1985, the water level in Elephant Butte Reservoir was the highest in 43 years. Sediment accumulation in reservoirs also is a concern, and recreational uses of the streams are receiving more attention. The need to meet legal obligations for water allocations is a continuing problem.

UPPER COLORADO REGION

San Juan Subregion

San Juan River basin.—The Upper Colorado River basin in New Mexico is drained by the San Juan River and its tributaries, which include the Los Pinos, the Animas, the La Plata, the Mancos, and the Chaco Rivers, and Canon Largo. This river system drains 9,530 mi² within New Mexico. Most water used in the basin is obtained from surface sources. Discharge of the San Juan River downstream from Navajo Dam (fig. 2) has been largely regulated since completion of the dam (with a storage capacity of 1,700,000 acre-ft or 554,000 Mgal) in June 1962. However, average discharge by water year for the San Juan River at Shiprock displays considerable variation from year to year (fig. 2, site 5). In the basin, 330 Mgal/d or 510 ft³/s of surface water was used to irrigate 98,800 acres in 1980 (Sorensen, 1982). All surface waters in the basin are appropriated, creating competition for available supplies.

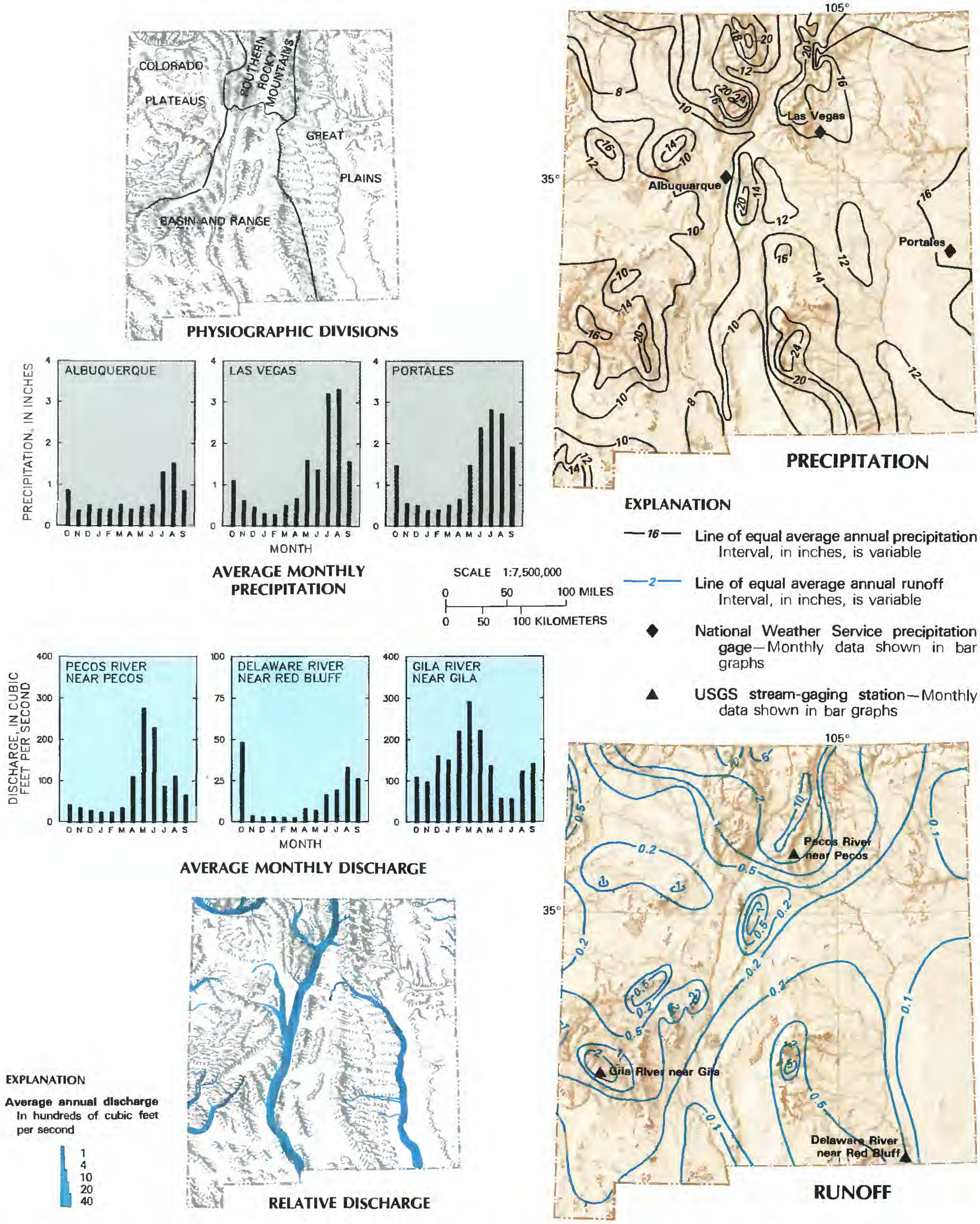

Figure 1. Average annual 1931-52 precipitation and runoff in New Mexico and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from New Mexico State Engineer Office, 1967; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in New Mexico

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Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				ARKANSAS-WHITE-RED REGION[1] **Upper Canadian Subregion** **Canadian River basin**				
1.	Canadian River at Logan (07227000).	11,141	1904-83	0.0	[2]392 [3]257 [4]39.7	333,000	Appreciable	Regulation due to Conchas Dam started 1938 Regulation due to Ute Dam started 1962.
				RIO GRANDE REGION **Upper And Lower Pecos Subregions** **Pecos River basin**				
2.	Pecos River near Pecos (08378500).	189	1919-83	12.0	98.1	3,070	None	
3.	Delaware River near Red Bluff, Texas (08408500).	689	1912-83	0.0	13.0	82,500	. . . do . . .	
				Rio Grande River basin (main stem)[5]				
4.	Rio Grande at Albuquerque (08330000).	117,440	1941-83	0.3 [7]1,232	[6]1,068	22,000	Appreciable	
				UPPER COLORADO REGION **San Juan Subregion**				
5.	San Juan River at Shiprock (09368000).	12,900	1927-83	53.6	2,181	67,200	Moderate	Partially regulated by Navajo Reservoir. Unadjusted for storage.
				LOWER COLORADO REGION[8]				
6.	Gila River near Gila (09430500).	1,864	1927-83	19.7	141	24,900	None	

[1] Also includes parts of the Upper Arkansas, Upper Cimarron, Lower Canadian, North Canadian, and Red Headwaters Subregions.
[2] Fifteen years, prior to completion of Conchas Dam.
[3] Twenty-four years, prior to completion of Ute Dam.
[4] Twenty-one years (1963-63), subsequent to completion of Ute Dam.
[5] Includes all or parts of Rio Grande Headwaters, Rio Grande-Elephant-Butte, Rio Grande-Mimbres, and Rio Grande Closed Basins Subregions
[6] Thirty-two years, prior to closure of Cochiti Dam.
[7] Ten years (1974-83), subsequent to closure of Cochiti Dam.
[8] Includes parts of the Little Colorado, Upper Gila, and Sonora Subregions.

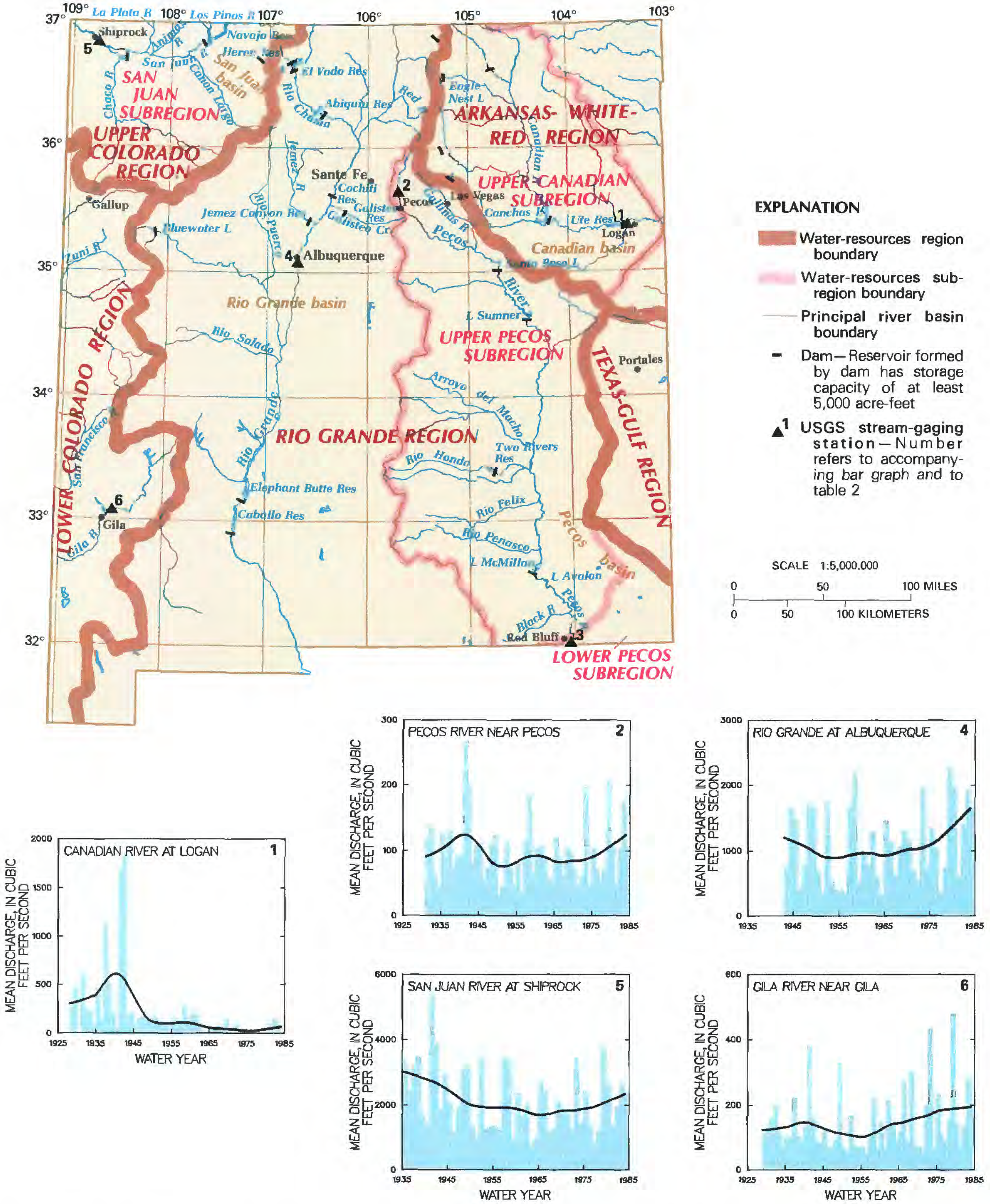

Figure 2. Principal river basins and related surface-water resources development in New Mexico and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Water quality in the San Juan River, its northern perennial tributaries, and the Navajo Reservoir are considered to be adequate for high-quality uses such as cold-water fisheries, municipal supplies, and industrial uses. Problems arise from the inflow of saline water and suspended sediment from southern ephemeral tributaries.

LOWER COLORADO REGION

The Lower Colorado River basin in New Mexico consists of 10,950 mi^2 along the western border of New Mexico. An additional 2,388 mi^2 are contained within a closed basin (Animas) that under normal circumstances does not contribute to streamflow. It is an area of marked contrasts in environment, resources, and development.

The economy of the area is largely based on agriculture, mining, and ore milling and smelting. Gallup is a trading center for the Navajo and Zuni Indians. Withdrawals of surface water for irrigation were 29 Mgal/d or 45 ft^3/s in 1980 (Sorensen, 1982).

Major rivers that drain the area include the Gila, the San Francisco, the Puerco, and the Zuni. A hydrograph of average discharge by water year of the Gila River near Gila is shown in figure 2 (site 6). The water quality in these rivers is suitable for its major use as irrigation water; however, storm runoff results in large suspended-sediment concentrations. The surface water supply is not adequate for all users. The States of New Mexico and Arizona and the various Indian tribes have all been litigants to water rights in the Lower Colorado Region, an issue that has not been settled completely.

OTHER RIVER BASINS

The Texas-Gulf Region in New Mexico includes the Brazos headwaters and Upper Colorado (New Mexico–Texas) Subregions. The region is in the eastern part of the State and has an area of 6,087 mi^2; it does not contain any major streams. Water supply for the area generally is obtained from wells, many of which are completed in the Ogallala Formation. Runoff from precipitation is stored in shallow natural depressions and is used by wildlife and domestic stock. Brines pumped from oil wells are separated from the petroleum and collected in small waste ponds throughout the region. If accidentally spilled, the brines will increase the salinity of local runoff.

SURFACE-WATER MANAGEMENT

Under the terms of the State constitution, surface water in New Mexico belongs to the public but may be appropriated privately for benefical use. The State Engineer has been charged with the general supervision of surface waters and of the measurement, appropriation, and distribution of those waters.

A permit must be obtained from the State Engineer to obtain new rights of appropriation of surface water. The State operates under the doctrine of prior appropriation. Thus, any new applications for surface-water appropriations must not be detrimental to any existing rights. Because most of the State's surface waters have been appropriated, the State Engineer receives relatively few applications for new appropriations.

Surface waters are apportioned to the State by three treaties, eight interstate compacts, a decree of the U.S. Supreme Court, and three decrees by Federal District Courts. The State's Interstate Stream Commission is directed by statute to develop, protect, and conserve the waters and stream systems of the State, interstate or otherwise. The U.S. Geological Survey collects surface-water data and conducts investigations of surface-water resources in cooperation with various Federal, State, and local governmental agencies.

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FOR ADDITIONAL INFORMATION

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NEW YORK
Surface-Water Resources

New York's abundant surface-water resources have been a major factor in the State's economic, agricultural, and commercial growth since the 17th century. New York has attracted and retained settlers and industry with more than 70,000 miles of streams, 13.5 million acres of lakes, and 3,000 miles of bordering ocean and lakeshore that are used for navigation, waterpower, and water supply. Today, this resource provides 7,200 Mgal/d (million gallons per day) or 11,100 ft³/s (cubic feet per second) for a variety of offstream uses (table 1), the largest of which are for cooling thermoelectric plants (4,300 Mgal/d or 6,700 ft³/s) and for other industrial uses. Public-water supplies withdraw 1,900 Mgal/d or 2,900 ft³/s, upon which 66 percent of the State's population is dependent. Only on Long Island is surface water less abundant than ground water.

New York ranks third among the States in use of its rivers for hydropower. Led by the facilities on the Niagara and the St. Lawrence Rivers, the State's total instream use of 310,000 Mgal/d or 480,000 ft³/s for hydropower generates 3 percent of the State's electric power (P. Mathusa, New York State Energy Research and Development Agency, oral commun., 1985). Recreation accounts for another important surface-water use. The lakes and streams of the Adirondack, Catskill, and Finger Lakes regions are especially prized by outdoor enthusiasts. In the State's more populated regions, surface waters carry away municipal and industrial wastes.

The protection and improvement of water quality is a major issue in the State. In 1984, New York became the first State in the Nation to enact legislation to regulate acid precipitation, which has an adverse impact on the aquatic environment of many lakes and streams in the Adirondack Mountain region. Sewage-treatment plants are successfully responding to the "conventional" water quality problems, but degradation of streams by toxic levels of heavy metals and organic compounds is becoming a serious issue in some areas. These harmful constituents enter surface and ground waters in stormwater runoff and landfill leachate near urban and industrial areas. In some rivers, sediments that were contaminated by past activities continue to restrict use of water for many purposes. Eutrophication limits the recreational use of several ponds and lakes that receive drainage from population centers and from agricultural lands.

Water availability also is an important issue in some parts of the State. Competition for water stored in reservoirs is the major concern.

Table 1. Surface-water facts for New York

[Data 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 SURFACE WATER, 1980	
Number (thousands)	12,100
Percentage of total population	66
From public water-supply systems:	
Number (thousands)	12,100
Percentage of total population	66
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	8,000
Surace water only (Mgal/d)	7,200
Percentage of total	90
Percentage of total excluding withdrawals for thermoelectric power	81
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	1,900
Percentage of total surface water	26
Percentage of total public supply	86
Per capita (gal/d)	157
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock	
Surface water (Mgal/d)	20
Percentage of total surface water	0.3
Percentage of total livestock	34
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	5,300
Percentage of total surface water	74
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	96
Excluding withdrawals for thermoelectric power	89
Irrigation withdrawals:	
Surface water (Mgal/d)	25
Percentage of total surface water	0.3
Percentage of total irrigation	54
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	310,000

GENERAL SETTING

New York encompasses parts or all of eight physiographic provinces (fig. 1). Extensive areas of level and rolling plains border Lakes Erie, Ontario, and Champlain, and flank the St. Lawrence and the Mohawk River Valleys. Most of Long Island consists of relatively flat glacial outwash. The principal mountain ranges are the Adirondacks in the north, where some of the peaks are higher than 5,000 feet above sea level, and the Catskill Mountains in the south, which range up to 4,200 feet above sea level. Fairly rugged terrain also characterizes New York's Southern Tier.

Annual precipitation ranges from almost 30 inches along the western Lake Ontario shore and the Champlain Valley to about 52 inches in the southern Catskill and southwestern Adirondack Mountains (fig. 1). Areal distribution of rainfall conforms to relief patterns across the State and to the general eastward to northeastward direction of storm tracks. As illustrated in the bar graphs in figure 1, the State has no distinct rainy or dry season. Rather, the fate of precipitation after it reaches the ground varies seasonally. On the average, some of the winter snowpack is still unmelted by mid-March over all but the extreme southeastern part of the State. At this time, more than 10 inches of water can still remain stored in the snowpack in the Adirondack Mountains and in the highlands to the east of Lake Ontario. In contrast, most rain that falls during the summer is lost through evapotranspiration, which accounts for approximately half the State's annual precipitation; however, the amount varies areally and ranges from about two-thirds in the western Finger Lakes and extreme northern areas to about one-third in the mountainous regions.

Annual runoff ranges from about 10 to 40 inches per year and reflects the areal distribution pattern of precipitation (fig. 1). Almost half of the annual runoff occurs during the 3-month period of mid-February through mid-May, as shown in the bar graphs in figure 1. Reservoir systems depend on spring runoff to sustain withdrawals during the summer and fall, and water levels in the flood-control reservoirs are at their annual lows at the beginning of the 3-month period. Most of the time from July to the end of the growing season in October, streamflow in natural systems is derived from ground water although the natural streamflow in some regulated rivers is augmented by releases from reservoirs.

PRINCIPAL RIVER BASINS

Most of New York (53 percent) is in the Mid-Atlantic Region, which is divided into five subregions: Richelieu (Lake Champlain), Upper Hudson, Lower Hudson-Long Island, Delaware, and Susquehanna (Seaber and others, 1984). An additional 43 percent of the State drains the Great Lakes Region, which is subdivided into four subregions—Eastern Lake Erie-Lake Erie, Southeastern Lake Ontario, Southwestern Lake Ontario, and Northeastern Lake Ontario-Lake Ontario-St. Lawrence. The Allegheny River basin, in the Ohio Region, includes about 4 percent of the State. Less than 1 percent of the State drains into the New England Region on New York's southeastern border.

Several of the above subregions and basins (fig. 1) are not discussed, but their water-use statistics are included in table 1. The other basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MID-ATLANTIC REGION

Upper Hudson Subregion

The Upper Hudson Subregion in New York has an area of 12,650 mi^2 (square miles), the largest single subregion in the State. The principal stream—the Hudson River—flows almost entirely within the State and flows 315 miles from its source in the Adirondack Mountains to its mouth at New York Harbor. The lower 161 miles is an estuary. The Hudson's largest tributary is the Mohawk River (3,456-mi^2 drainage basin). Other major tributaries to the Hudson River include the Sacandaga River, the Batten Kill, the Schroon River, the Hoosic River, Catskill Creek, Esopus Creek, Rondout Creek, and Wappinger Creek. The Mohawk's major tributaries include West Canada Creek, East Canada Creek, and Schoharie Creek.

Surface-water resources in the Upper Hudson basin are extensively developed; among the oldest developments are the Erie and Champlain Canals. These navigation links to the Great Lakes and to Lake Champlain were once vital to the State's economy but have since been replaced in importance by other transportation systems.

Reservoir storage in the basin totals almost 1,700,000 acre-ft (acre-feet) or 554,000 Mgal (million gallons). The largest reservoir—Great Sacandaga Lake—was completed in 1930 and contains more than 760,000 acre-ft or 248,000 Mgal of usable storage and is operated for flood control, power generation, low-flow augmentation, and water supply for the Champlain (Barge) Canal. The decline of lake levels during the summer, in response to releases to meet these needs, has come into conflict with recreational interests in recent years. The Catskill reservoirs—Ashokan (1913), Rondout (1951), and Schoharie (1926)—have a combined usable storage of about 583,000 acre-ft or 190,000 Mgal, and are used to supply water to New York City (Tom Connell, New York City Department of Environmental Protection, oral commun., 1986). The Rondout Reservoir holds water diverted from reservoirs in the Delaware basin. The major reservoirs in the Mohawk basin—Hinckley (1914) and Delta (1912)—have a combined storage of more than 140,000 acre-ft or 45,600 Mgal and supply water to municipalities and to the Erie Canal.

Regulation of the Sacandaga River has profoundly affected the river's high- and low-flow characteristics (table 2, site 1). Most other reservoirs in the basin also afford some attenuation of flooding during winter and spring when water levels are normally low. Not all the reservoirs supplement low flows, however; for example, water impounded by the Catskill reservoirs is eventually diverted from their drainage basins (except during floods, when the reservoirs may overflow).

A graph of average annual discharge of the Mohawk River (fig. 2, site 2) relects streamflow trends of most streams in the upper Hudson basin. Most noteworthy are the recent decades in which the droughts of the mid-1960's and early 1980's bracket a period of unusually high flows in the 1970's. The flood of record in the basin occurred in March 1913. More recently, flooding in March 1977 and March 1980 were notable in the northern part of the Hudson River basin and in the Catskill Mountains, respectively.

Among the most serious water quality problems are some that have come to light only within the last decade. PCB (polychlorinated biphenols) contamination of sediments in the Hudson River below Fort Edward prompted a ban on commercial fishing in the estuary and on sport fishing between Fort Edward and Troy.

Acidic precipitation is disrupting the aquatic systems of poorly buffered lakes and streams in the Adirondack Mountains. The acidity can dissolve soil minerals and release metals such as aluminum, iron, and mercury to water supplies. The Catskill Mountains receive precipitation of similar acidity, but the effects may be less extensive because the watersheds have greater buffering capacities.

The leaching of toxic substances into surface waters from nearby landfills is still being evaluated. Sites under study in the upper Hudson River basin include landfills along the Mohawk River in the Utica-Rome area and along Wappinger Creek.

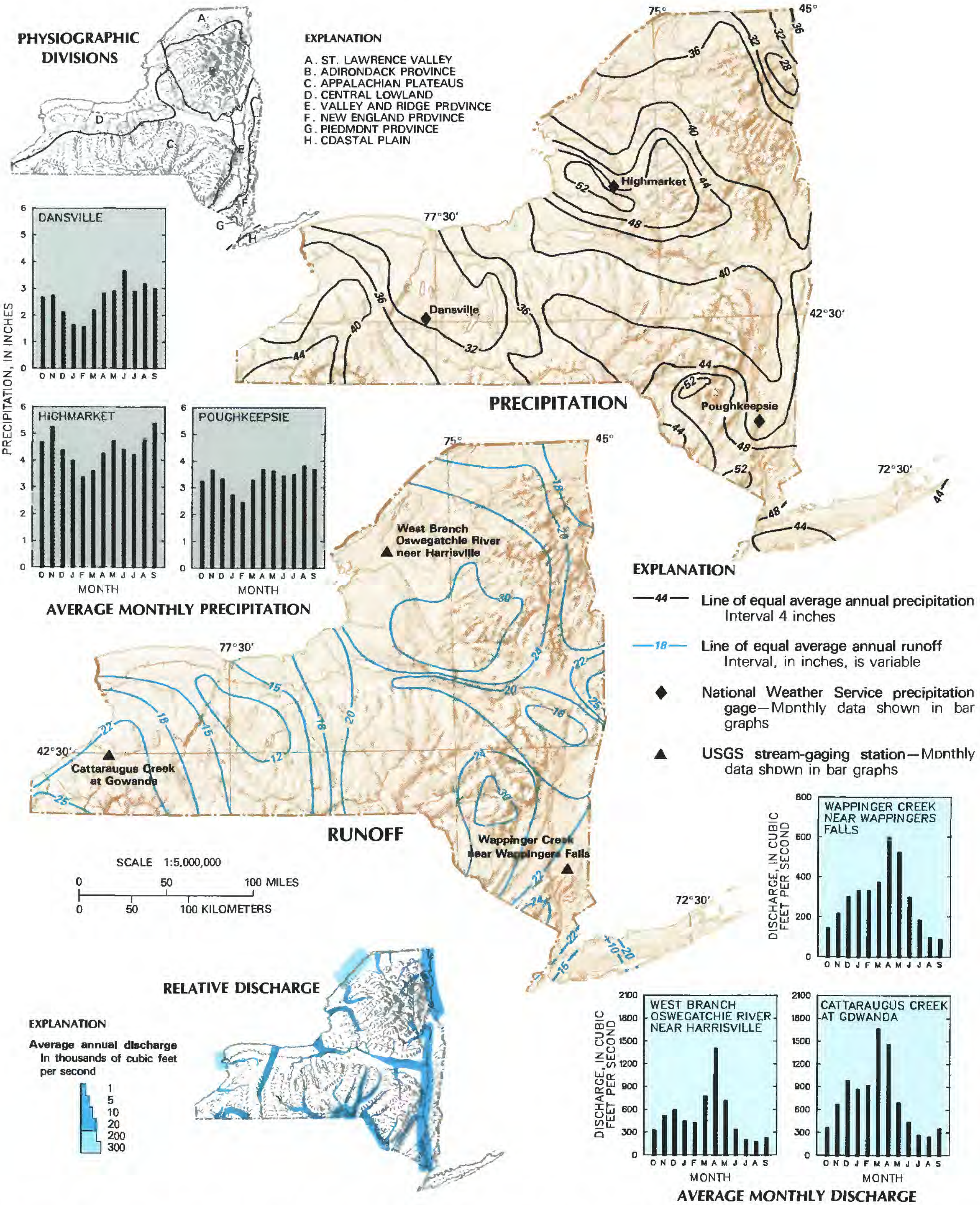

Figure 1. Average annual precipitation and runoff in New York and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in New York

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
MID-ATLANTIC REGION Upper Hudson Subregion								
1.	Sacandaga River at Stewarts Bridge (01325000).	1,055	1907–29 1931–84	106 757	2,230 2,090	30,400 14,800	None Appreciable	Recreational area. Regulated since 1930 for flood control and flow augmentation. Low flow (757) is for growing season.
2.	Mohawk River at Cohoes (01357500).	3,456	1917–84	772	5,750	128,000	Moderate	Hydropower, water supply, navigation.
3.	Hudson River at Green Island (01358000).	8,090	1946–84	2,810	13,700	191,000	Appreciable	Head of Hudson River estuary, regulated since 1930.
4.	Wappinger Creek near Wappingers Falls (01372500).	181	1928–84	6.5	253	18,500	None	Growing industrial and residential area.
Delaware Subregion								
5.	East Branch Delaware River at Fishs Eddy (01421000).	784	1912–54 1955–84	89 111	1,670 1,100	73,700 40,100	None Appreciable	Regulated since 1954 by Pepacton Reservoir for New York City water supply.
6.	Delaware River at Port Jervis (01434000).	3,070	1904–54 1963–84	416 832	5,570 4,750	184,000 170,000	None Appreciable	Regulated for water supply and hydropower.
Susquehanna Subregion								
7.	Susquehanna River near Waverly (01515000).	4,773	1937–84	385	7,580	139,000	Negligible	Reservoirs control high flows of 360 mi².
8.	Chemung River at Chemung (01531000).	2,506	1903–84	104	2,530	143,000	Moderate	Reservoirs control high flows of 786 mi².
GREAT LAKES REGION Southwestern And Southeastern Lake Ontario Subregions								
9.	Genesee River at Rochester (04232000).	2,467	1919–51 1952–84	511 311	2,780 2,880	44,100 30,600	Moderate Appreciable	Hydropower, water supply. Flood control since 1952 by Mount Morris Reservoir.
10.	Oswego River at Oswego (04249000).	5,100	1933–84	980	6,690	38,600	. . . do . . .	Water supply, barge canal, hydropower, numerous lakes.
Northeastern Lake Ontario—Lake Ontario—St. Lawrence Subregion								
11.	Black River at Watertown (04260500).	1,874	1920–84	825	4,020	41,000	Moderate	Hydropower.
12.	West Branch Oswegatchie River near Harrisville (04252600).	244	1916–84	43	515	7,290	None	Recreational area.
13.	St. Lawrence River near Massena (04264331).	298,000	1860–1984	179,000	243,000	358,000	Appreciable	Navigation, hydropower.

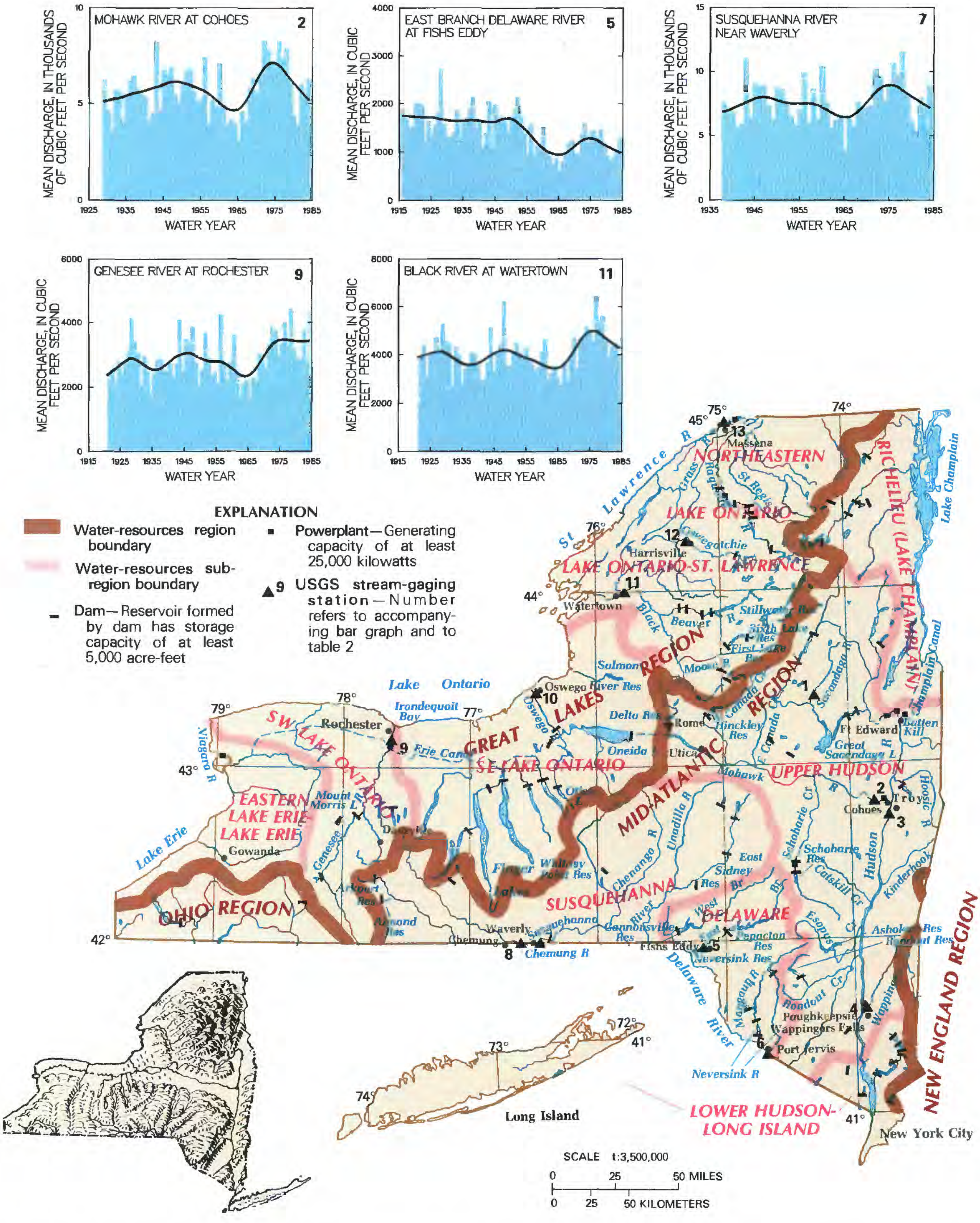

Figure 2. Principal river basins and related surface-water resources development in New York and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Delaware Subregion

The New York part of the Delaware River basin has a drainage area of 2,362 mi² (18 percent of the basin's total area). The main stem of the Delaware River forms at the confluence of its East and West Branches and flows southeastward along the New York–Pennsylvania border. The principal tributaries are the Neversink and the Mongaup Rivers.

Three reservoirs—Pepacton (1954), Cannonsville (1963), and Neversink (1953)—have combined usable storage of 831,000 acre-ft or 271,000 Mgal. Their effects on downstream flow characteristics are exemplified by data in table 2 for sites 5 and 6. Diversions of up to 800 Mgal/d or 1,240 ft³/s for New York City water supply and for downstream requirements are made in accordance with a 1954 Supreme Court decree. The bar graph in figure 2 for the East Branch Delaware River (site 5) clearly shows the effect of diversions from Pepacton Reservoir, which began in 1954.

Reservoir managers depend on the high spring runoff to replenish supplies. Large floods can occur any time, however, as evidenced by the flood of record in August 1955. Drought is the more persistent problem in the Delaware basin, however. Because of the substantial diversions, the basin is especially vulnerable to the effects of prolonged dry spells, such as those of the mid-1960's and early 1980's. Competition among downstream users and the New York City water-supply system is a recurring issue.

Surface waters of the upper Delaware River basin generally are of excellent quality and suitable for most uses. Present major uses of water resources include municipal and industrial water supply, hydropower, and recreation.

Susquehanna Subregion

The Susquehanna River rises in the rolling uplands of the Appalachian Plateau Province. Twenty percent (about 5,450 mi²) of the basin's total area is in New York. The major tributaries are the Unadilla, the Chenango, and the Chemung Rivers.

The Susquehanna basin contains few natural lakes of appreciable size. The four major reservoirs—Whitney Point (1942), East Sidney (1950), Almond (1949), and Arkport (1940)—are operated by the U.S. Army Corps of Engineers, primarily for flood control, and since 1964, for recreation. Their combined storage totals about 143,000 acre-ft or 46,600 Mgal.

Although streamflow tends to be greatest in the spring, the most devastating floods in recent times have occurred during the summer and fall, as a result of the tropical depressions left in the wakes of Hurricanes Agnes (June 1972) and Eloise (September 1975). These floods compounded damages to structures by destroying crops on the extensively cultivated flood plains. Flooding and flood warning are among the most critical issues in the basin today, and several communities along the Chemung River have organized their own flood-warning systems.

Periodic droughts also stress water supplies and the ability of the basin's rivers to assimilate wastes. The effect of the mid-1960's drought on streamflow of the Susquehanna River near Waverly is shown in figure 2 (site 7).

The basin's major water-quality problems are related to acidic drainage from coal mines originating in Pennsylvania and the exceedance of some streams' capacity to assimilate waste discharges during low flows.

GREAT LAKES REGION

Southwestern and Southeastern Lake Ontario Subregions

Almost three-fourths of these subregions is drained by two rivers—the Genesee in western New York (Southwestern Lake Ontario Subregion) and the Oswego (Southeastern Lake Ontario Subregion) in central New York. The Oswego basin (5,122 mi²) is about twice the size of the Genesee basin and has an extensive, dendritic network of tributaries. This basin includes the famous Finger Lakes and is traversed by the Erie Canal. In contrast, the Genesee basin is long and narrow, extends southward into Pennsylvania, and has fairly short tributaries to the main stem. The other small streams directly tributary to Lake Ontario have a wide range of annual runoff characteristics.

These subregions contain two significant manmade reservoirs. Mount Morris Lake (completed in 1951 with 336,000 acre-ft or 109,800 Mgal of storage) on the Genesee River, is operated by the U.S. Army Corps of Engineers for flood control. Its effect on reducing flood peaks is shown in table 2 (site 9). The Salmon River Reservoir (completed in 1913 with 61,000 acre-ft or 20,000 Mgal of storage) north of the Oswego basin is operated by the Niagara Mohawk Power Corporation to regulate flows for hydropower. The levels of all the Finger Lakes have been artificially raised to provide storage for a variety of purposes such as municipal water supply, hydropower, low-flow augmentation, Erie Canal supply, and recreation.

Serious flooding can occur any time of the year in some parts of these subregions. The large floods of June 1972 in the western part and of December 1984 in the northeast are the most recent examples. The considerable storage afforded by the Finger Lakes controls main-stem flooding in the Oswego basin, however.

Both subregions were affected by the regional drought of the mid-1960's, as attested by the streamflow record of the Genesee River at Rochester (fig. 2, site 9).

The two most important water issues in these subregions are management of the Finger Lakes system and water quality. Eutrophication limits the use of many lakes and bays—notably Irondequoit Bay and Oneida and Otisco Lakes. Industrial pollution of Onondaga Lake has precluded all uses except noncontact recreation.

Northeastern Lake Ontario-Lake Ontario-St. Lawrence River Subregion

The major river basins in this subregion are the Black and the St. Lawrence. The Black River drains 1,914 mi^2, all of which is in New York. The river flows 115 miles from its source in the southwestern Adirondack Mountains to its mouth in northeastern Lake Ontario. Its largest tributaries are the Moose and the Beaver Rivers. The St. Lawrence River is 533 miles long, 115 miles of which form the international boundary between the United States and Canada. About 5,539 mi^2 in northern New York drains into the St. Lawrence; this represents less than 2 percent of the entire Great Lakes drainage. The major New York tributaries of the St. Lawrence River include the Oswegatchie, the Grass, the Raquette, and the St. Regis Rivers.

Steep relief and high runoff have led to extensive development of the Black River and its major tributaries for hydropower. Reservoir storage exeeds 172,000 acre-ft or 56,000 Mgal, 70 percent of which is principally for regulation of flows for hydropower. These reservoirs are on the Beaver River (Stillwater, completed in 1885) and the Moose River (First and Sixth Lakes, both completed in 1881). The remaining storage is in several smaller reservoirs in the headwaters of the Black River and is used for diversion to the Erie Canal.

The large number of lakes and wetlands in the tributaries to the St. Lawrence River affords a degree of natural regulation. Manmade storage in several reservoirs accounts for about 235,000 acre-ft or 76,600 Mgal and is used primarily to regulate flows for hydropower.

The flood season in this subregion is in mid-spring. Large floods also can accompany rainy thaws during the winter, but flooding during other seasons is rare. The reservoirs, drawn down each winter, provide some attenuation of peak flows on the major rivers as they fill with the spring runoff. Flows are then augmented through the growing season by releases for hydropower.

The most recent major floods were in March 1977, April 1982, and December 1984. In some communities, these floods were accompanied by ice jams. As noted from the bar graph for the Black River at Watertown (fig. 2, site 11), the impact of the statewide drought in the 1960's was less severe in northern New York than in most other areas.

The flow of the St. Lawrence River is moderated by the Great Lakes (table 2, site 13). The St. Lawrence Seaway, completed in 1956, provides the navigation link between the Atlantic Ocean and the Great Lakes for oceangoing vessels.

Water quality is generally excellent and suitable for most uses. Some of the major issues in the subregion include effects of acidic precipitation on streams and lakes, especially in the Adirondack area, and a proposal to keep the St. Lawrence Seaway open to navigation year-round.

SURFACE-WATER MANAGEMENT

The three State agencies with responsibilities most directly related to surface-water management are the New York State Departments of Health (DOH), Environmental Conservation (DEC), and Transportation (DOT).

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 provide safe and adequate supplies. The program involves 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 natural-resource programs, including those relating to the control of water pollution and management of water resources. Major elements of the water program that are integral to surface-water management include water resources planning, establishment of water-quality standards, water-quality monitoring, issuance of water-discharge permits, and administration of municipal wastewater-treatment programs. Also, the New York State Pollutant Discharge Elimination System Program, which regulates point-source wastewater discharges, is administered by DEC.

DOT's surface-water-related responsibilities entail the operation and maintenance of the Barge Canal system.

In addition to the above agencies, the Delaware River Basin and the Susquehanna River Basin Commissions were formed to promote interstate comity, remove causes of present and future controversy, and encourage and provide for the management of water resource of the basins.

The Hudson River–Black River Regulating District is a public-benefit corporation that operates and maintains reservoir facilities in the Hudson and the Black River basins for flood control, low-flow augmentation, and hydropower.

The International Joint Commission is a permanent unitary body established under the Boundary Waters Treaty of 1909. This treaty was designed to help prevent and settle disputes regarding the use of boundary waters.

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

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NORTH CAROLINA
Surface-Water Resources

North Carolina has an abundance of surface water. Streams and lakes are the principal source of public water supplies in the Piedmont and Blue Ridge and for several of the larger cities in the Coastal Plain. Surface water is used for public and industrial supplies, for hydroelectric power generation, for cooling of thermoelectric powerplants, and for recreation. Surface water supplies more than 2.6 million people or about 45 percent of the State's total population. Self-supplied industries use 6,700 Mgal/d (million gallons per day) or 10,400 ft^3/s (cubic feet per second) or 92 percent of all surface-water withdrawn for offstream use, and about 40,000 Mgal/d or 61,900 ft^3/s are used instream for hydroelectric power generation. Surface water withdrawals for various uses and other related statistics are given in table 1.

In most areas of North Carolina, the quality of surface water is a more immediate concern than the quantity. Pollution of streams, lakes, sounds, and estuaries by toxins, nutrients, and sediment are the most pressing water issues. In some areas, however, water use is approaching the limit of available supply and interbasin transfer of water is an unresolved and sensitive issue. Occasionally, water use has been curtailed during very dry years.

GENERAL SETTING

North Carolina is located in the Coastal Plain, Piedmont, and Blue Ridge physiographic provinces (fig. 1). The Blue Ridge, Piedmont, and western part of the Coastal Plain are well drained by a dense network of streams. The eastern part of the Coastal Plain, most of which is less than 30 feet above sea level, has a relatively poorly developed drainage system. Major sounds and estuaries, separated from the Atlantic Ocean by barrier islands, occupy several thousand mi^2 (square miles) along the coast. These sounds and estuaries comprise the largest inland waters of any State in the Union (Stuckey, 1965).

Precipitation is distributed fairly uniformly throughout most of the year, but areal variations are extreme (D. A. Olson, National Oceanic and Atmospheric Administration, written commun., 1985) (fig. 1). The highest annual precipitation found in the eastern United States, 82 inches, occurs in the Blue Ridge province as does the State's lowest precipitation of 40 inches, only 50 miles away (Eder and others, 1983). This extreme difference is caused by the orographic effect of the mountains on precipitation in western North Carolina. The monthly average precipitation recorded for 1951–80 at Brevard, Greensboro, and Kinston is shown in bar graphs in figure 1.

Evaporation varies seasonally and areally across the State. Annual evaporation ranges from 32 inches in the Blue Ridge to 42 inches in the Coastal Plain (Heath and others, 1975). In dry years, lake evaporation exceeds precipitation in the Coastal Plain and Piedmont. Because of high precipitation, the probability that lake evaporation could exceed rainfall in the Blue Ridge is slight.

Runoff in North Carolina is affected by differences in precipitation, evapotranspiration, and geology. Variation is the most important aspect of runoff; it varies not only from year to year, and day to day, but from place to place. Annual runoff is highest in the Blue Ridge and western Piedmont and lowest in the eastern Piedmont and northwestern Coastal Plain (Gebert and others, 1985) (fig. 1). Runoff is generally highest in February and March and lowest in September and October. This seasonal pattern is caused by the increased evapotranspiration that occurs during the summer. Floods occur at any time during the year, but major floods are usually associated with tropical storms and hurricanes. Frequent flooding of low-lying urban areas is common in most basins.

Table 1. Surface-water facts for North Carolina

[Data 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 SURFACE WATER, 1980	
Number (thousands)	2,640
Percentage of total population	45
From public water-supply systems:	
Number (thousands)	2,640
Percentage of total population	45
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	8,100
Surface water only (Mgal/d)	7,300
Percentage of total	90
Percentage of total excluding withdrawals for thermoelectric power	79
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	500
Percentage of total surface water	7
Percentage of total public supply	88
Per capita (gal/d)	189
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)0	
Livestock:	
Surface water (Mgal/d)	5.6
Percentage of total surface water	0.1
Percentage of total livestock	14
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	6,700
Percentage of total surface water	92
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	93
Excluding withdrawals for thermoelectric power	83
Irrigation withdrawals:	
Surface water (Mgal/d)	93
Percentage of total surface water	1
Percentage of total irrigation	70
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	40,000

PRINCIPAL RIVER BASINS

North Carolina occupies parts of the South Atlantic–Gulf, Tennessee, and Ohio Regions (Seaber and others, 1984) (fig. 2). Most of the State, including all the Coastal Plain and Piedmont provinces, (87 percent of the State's land surface) and a small part of the Blue Ridge province, is in the South Atlantic–Gulf Region. The Tennessee and Ohio Regions are confined to the Blue Ridge province. The principal river basins in these regions are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Selected streamflow characteristics and other pertinent information for the South Atlantic–Gulf and Tennessee Regions are given in table 2.

SOUTH ATLANTIC–GULF REGION

Chowan–Roanoke River Subregion

The Chowan–Roanoke River basin consists chiefly of two major subbasins that drain southeastern Virginia and northeastern North Carolina and flow into Albemarle Sound. The basin encompasses 17,500 mi^2, one-third of which is in North Carolina.

The Chowan River is an estuary extending southward from the confluence of the Blackwater and the Nottaway Rivers near the North Carolina–Virginia State line to Albemarle Sound. The estuary is about 50 miles long and has a surface area of about 45 mi². Extensive swamps border much of the estuary. Approximately 25 percent of the 4,943 mi² drainage basin is in North Carolina.

Flow in the estuary varies in amount and direction as a result of changes in inflow, tides, and direction and velocity of winds (the predominant factor). Tides are generally less than 1 foot, but wind-caused tides can exceed 4 feet. Except during periods of high runoff, the volume of inflow is small compared to the volume of water in the estuary. As a result, flows are often sluggish for long periods, and pollutants are not flushed from the estuary. A serious water-quality problem in the Chowan River is the occasional occurrence of surface blooms of blue-green algae. In 1979, the State Environmental Management Commission designated the basin "nutrient sensitive" and began a major effort to reduce nutrient loading.

The Roanoke River basin encompasses an area of 9,666 mi², one-third of which is in North Carolina, and comprises 6 percent of the State's land surface. Major tributaries in North Carolina include the Dan, the Mayo, the Smith, and the Hyco Rivers.

The Roanoke River is intensively developed. Flow is regulated by six major dams on the main stem or its major tributaries (fig. 2). These dams reduce the variability of daily streamflow, reduce flood peaks, and augment minimum streamflows (table 2). The total volume of water impounded by the major dams is 4,372,000 acre-ft (acre-feet), or 1,420,000 Mgal (million gallons).

Perhaps the most sensitive surface-water issue in North Carolina is a proposed interbasin transfer of 60 Mgal/d or 93 ft³/s from Lake Gaston to Virginia to augment municipal supplies. Opponents of the proposed diversion fear magnification of water-quality problems along the lower Roanoke River and Albemarle Sound, and reduction of upstream lake levels below minimum levels desired for recreational uses.

Neuse-Pamlico Subregion

Two major river basins comprise the Neuse–Pamlico Subregion—the Tar–Pamlico River basin and the Neuse River basin. Both are entirely in the State.

The Tar–Pamlico River originates in the northeastern part of the Piedmont and flows southeasterly through the Coastal Plain to Pamlico Sound. The stream is known as the Tar River above Tranters Creek, near the town of Washington, and as the Pamlico River below. The Tar–Pamlico River is 190 miles long and drains an area of 4,302 mi² or 9 percent of the State's land area. At its headwaters, the Tar is a swift, rocky river but slows and broadens as it nears the Pamlico River and Sound. The town of Rocky Mount completed a water-supply reservoir on the Tar River in 1972 (capacity 8,000 acre-ft or 2,610 Mgal). Greenville and Tarboro also obtain water for public supply from the Tar River. Water quality in the river and its major tributaries is suitable for most uses.

The Neuse River begins at the confluence of the Eno and the Flat Rivers in Durham County and flows 222 miles to the Pamlico Sound. The basin has an area of 5,710 mi², 12 percent of the State's land surface, and contains 14 percent of its population. In addition to the Eno and the Flat Rivers, major tributaries to the Neuse include Crabtree, Middle, and Contentnea Creeks, and the Little and the Trent Rivers. Flooding in newly developed urban and suburban areas is a recurring problem, especially in areas near Raleigh along Crabtree Creek.

Approximately 48 manmade lakes and large ponds are scattered throughout the Neuse River basin. Of these, the Falls Lake is by far the largest, representing more than two-thirds of the total surface area of the lakes and ponds in the basin. The lake was filled in 1983 and serves flood control, water supply, low-flow augmentation, and recreational purposes. Water quality in the Neuse–Pamlico subregion is generally suitable for most uses, but eutrophication in Falls Lake and the lower Neuse River is a major concern.

Cape Fear Subregion

The Cape Fear River is the largest river entirely within North Carolina and is the only major stream in the State directly tributary to the Atlantic Ocean. The basin contains an area of 9,010 mi², 18 percent of the State's land surface, and 27 percent of the State's population. The Cape Fear's major tributaries are the Haw, the Deep, and the Northeast Cape Fear Rivers. The Haw and the Deep Rivers drain areas of 1,666 and 1,436 mi², respectively. Both are characterized by numerous falls and rapids, steep, high banks, and narrow flood plains. The Haw River is popular among canoeing enthusiasts.

Most of the population and industry in the Cape Fear River basin is concentrated near the headwaters of the Haw and the Deep Rivers. As the basin population grows, demand for additional water will strain current surface-water supplies. Hence, several cities of the region are supporting construction of a new multipurpose, U.S. Army Corps of Engineers reservoir on the Deep River to augment existing supplies. Interbasin transfer of water from the Yadkin River or the Dan River has been considered.

B. Everett Jordan Lake (completed in 1981) is a multipurpose reservoir on the Haw River that is used for flood control, water-supply, and recreational purposes (fig. 2); the lake contains 215,130 acre-ft or 70,110 Mgal of storage at normal pool elevation. High nutrient loadings and upstream municipal and industrial wastewater discharge are major water-quality concerns. The state has classified the lake "nutrient sensitive" and is working with local governments within the lake's watershed on a point and nonpoint source pollution-control program.

Pee Dee Subregion

The Pee Dee River drains parts of Virginia, North Carolina, and South Carolina. The drainage area of the Pee Dee River basin in North Carolina is 9,300 mi² (19 percent of the State's land surface). The river rises on the eastern slope of the Blue Ridge and flows approximately 100 miles in a northeasterly direction toward Winston–Salem, and then turns southeast through South Carolina to enter the Atlantic Ocean. The stream is known as the Yadkin River above the Uwharrie River and as the Pee Dee, or Great Pee Dee River, below. The Lumber River, which drains southeast North Carolina, also is a major tributary to the Pee Dee River.

The Yadkin River drains an area of 4,164 mi². It is one of the most developed rivers in North Carolina. Seven major dams originally built for hydropower now serve as multipurpose impoundments providing limited flood control, hydroelectric power generation and water for cooling, recreation, and municipal supply. Surface-water concerns in the basin relate mainly to lake eutrophication and sedimentation.

The Lumber River is located in the lower part of the basin; it is a typical Coastal Plain stream with a very low gradient. The river is bordered throughout its length by swamp and marshland. Many of the communities along the river are frequently flooded.

Edisto-Santee Subregion

The Catawba and Broad River basins in west-central North Carolina form the upper part of the Edisto–Santee River basin of South Carolina. The drainage area of the Catawba River basin in North Carolina is 3,250 mi², whereas that of the Broad River is 1,450 mi². Together they encompass 10 percent of the State's land surface.

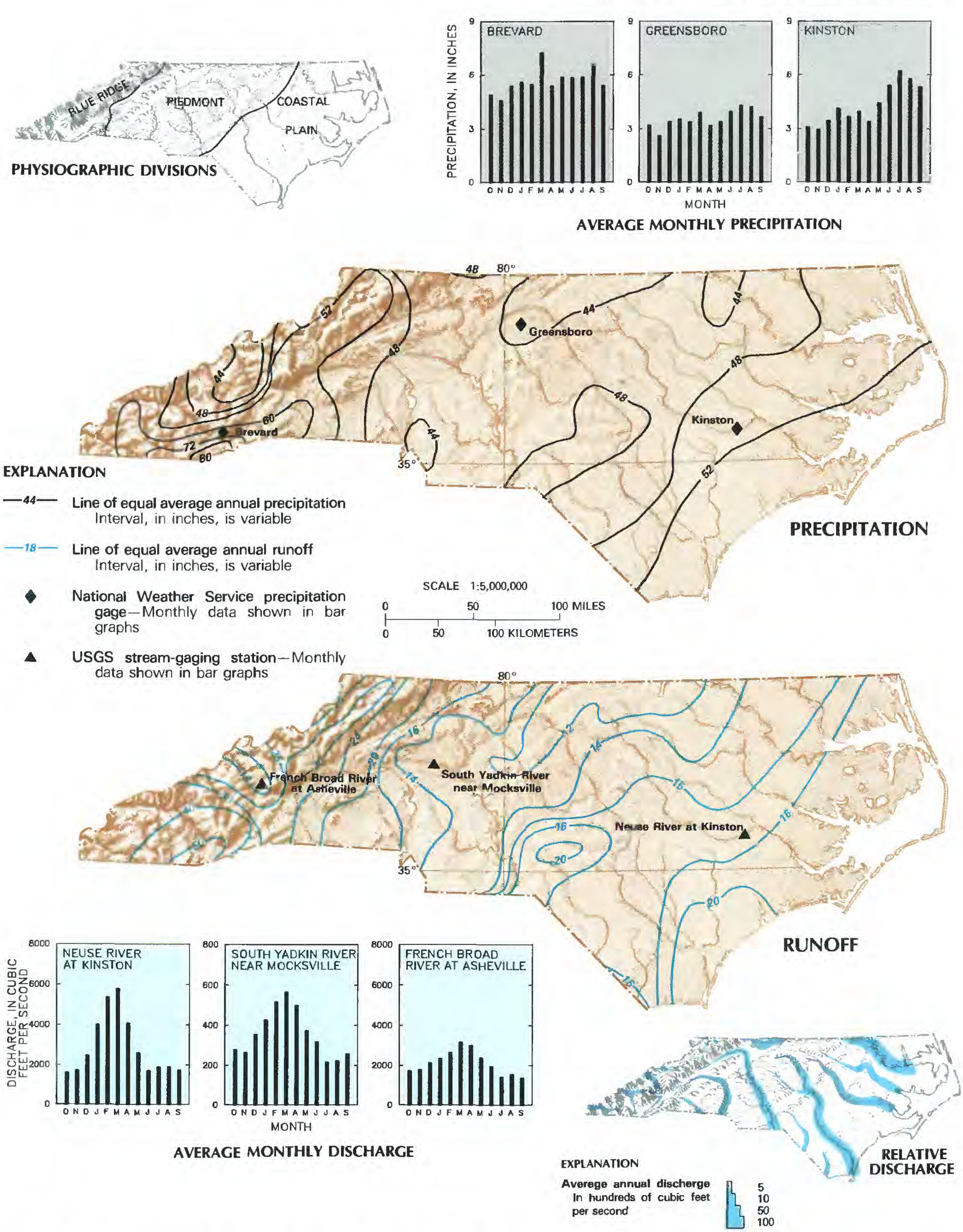

Figure 1. Average annual precipitation and runoff in North Carolina and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

The Catawba River is the State's most developed stream. Eight major dams regulate more than 85 percent of the river's fall, primarily for hydroelectric power generation. These dams provide more than 510,000 kilowatts of generating capacity in the North Carolina section of the river alone, earning the Catawba the title of "the most electrified river in the United States."

The Catawba River also supplies water for many of the largest cities in North Carolina, including Charlotte—the State's most populous. For this reason, possible pollution by toxic substances in waste discharge from cities and industries is a major concern.

TENNESSEE AND OHIO REGIONS

Many of the streams of western North Carolina are in the Tennessee or Ohio Regions. Among these are the Little Tennessee, the Hiwassee, the French Broad, the Watauga (Tennessee Region), and the New Rivers (Ohio Region). The streams in these regions drain an area of approximately 6,346 mi^2 (13 percent of the State's land surface). Swift, rocky, wild and scenic, they provide a valuable recreational resource. State and Federal Governments have created several parks and forest preserves to accommodate such popular activities as canoeing and whitewater rafting. These attractions spur commercial and residential development. Because flat land along the mountain slopes is not available, some developments are beginning to encroach on flood plains which may create flood hazards, especially in the more mountainous areas where stream slopes are steep and flash flooding is common.

In addition to recreation, manufacturing and hydroelectric power generation are important uses of water. Several textile, wood, and paper mills use large amounts of water. Occasionally, these industries discharge wastewater containing high concentrations of cellulose and dyes which degrade water quality. However, water quality in the North Carolina parts of the basins is generally excellent.

SURFACE-WATER MANAGEMENT

Responsibility for managing the surface waters of North Carolina falls under the jurisdiction of a number of State and Federal agencies. Laws that have been enacted generally follow the Riparian Doctrine.

The North Carolina Department of Natural Resources and Community Development is responsible for many State water-management programs. The Division of Environmental Management manages an integrated program to protect water quality, including water-quality monitoring, establishment of stream water-quality standards, control of waste discharges by permitting, and water-quality planning. The Division of Water Resources is responsible for regional and river-basin water-resources planning; technical assistance to local governments regarding water-supply problems; special water-management studies to deal with water shortages or multiple demands for limited supplies; and civil works projects for navigation, flood control, drainage, beach protection, recreation, and aquatic-weed control. The Division of Land Resources is responsible for controlling sedimentation through a program of permits and enforcement and for issuing dam-safety permits. The Environmental Management Commission has policy- and decision-making authority over a number of statutory programs administered by the Department.

Table 2. Selected streamflow characteristics of principal river basins in North Carolina

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and North Carolina agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				SOUTH ATLANTIC-GULF REGION CHOWAN-ROANOKE SUBREGION				
1.	Roanoke River at Roanoke Rapids (02080500).	8,386	1911–49 1950–84	1,010 1,310	8,085 7,700	215,000 66,800	Negligible Appreciable	Flow regulated by John H. Kerr Reservoir since 1950.
				NEUSE-PAMLICO SUBREGION				
2.	Tar River at Tarboro (02083500).	2,183	1896–1900 1931–84	90	2,234	45,500	Negligible	
3.	Neuse River at Kinston (02083500).	2,692	1930–81 1981–84	210	2,892	43,100 33,000	. . . do . . . Moderate	Falls Lake partly filled in 1981. Effects not yet known.
				CAPE FEAR SUBREGION				
4.	*Cape Fear River* at Lillington (02102500).	3,464	*1923–75* 1975–81	75 600	*3,300* 3,300	*117,000* 80,000	*Negligible* Appreciable	*B. Everett Jordan Dam, a* multipurpose reservoir on Haw River, completed in 1981. Data for 1975–81 estimated.
				PEE DEE SUBREGION				
5.	South Yadkin River near Mocksville (0211800).	306	1939–84	61	340	15,700	Negligible	
				TENNESSEE REGION TENNESSEE SUBREGION				
6.	French Broad River at Asheville (03451500).	945	1896–1984	455	2,093	49,100	Negligible	

The Division of Coastal Management manages a development program in 20 coastal counties and provides technical assistance to these counties for a mandated program of land-use planning. Protection of coastal-water resources has a high priority in this program. The Division of Soil and Water Conservation provides technical assistance to Soil and Water Conservation Districts and also plans small watershed projects in cooperation with the U.S. Soil Conservation Service. The Division of Parks and Recreation manages water-based recreation sites at reservoirs and on streams and rivers, and the State program for designation of "wild and scenic rivers."

The Department of Human Resources, Environmental Health Section, has jurisdiction over the public-health aspects of water supplies, including review of plans for water-treatment plants and approval of sources of raw water for public systems.

Local governments are the primary providers of water and sewer services and are important in water-quality protection through operation of wastewater treatment plants and control of nonpoint sources of pollution related to urban activities.

Federal agencies have a major role in both the protection and development of water resources in North Carolina. The U.S. Environmental Protection Agency provides financial assistance and

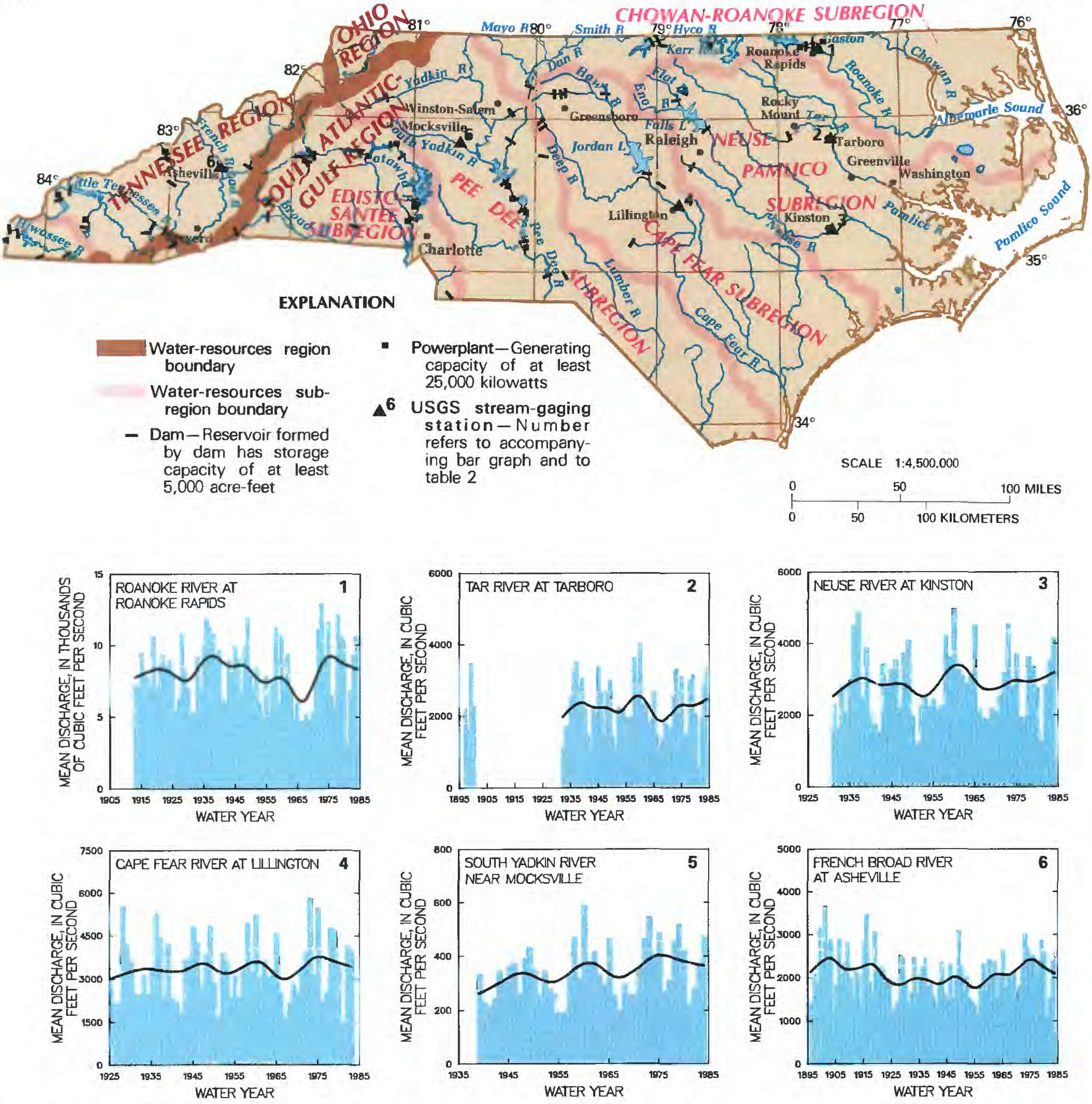

Figure 2. Principal river basins and related surface-water resources development in North Carolina and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Federal standards on water-quality protection. The U.S. Army Corps of Engineers, the U.S. Soil Conservation Service, and the Tennessee Valley Authority are active in the plannning, development, and management of the State's water-resources. The U.S. Geological Survey provides the essential water-resources data that are used by all management agencies within the State.

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FOR ADDITIONAL INFORMATION

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NORTH DAKOTA
Surface-Water Resources

Surface water is an important resource to North Dakota. Cities, industry, irrigators, and power generation facilities all depend upon it. Water use in the State during 1982 totaled 1,000 Mgal/d (million gallons per day) or 1,550 ft^3/s (cubic feet per second) of which 89 percent was obtained from surface-water sources (Patch and Haffield, no date). Six of the 10 largest cities in the State, including the 3 largest cities, obtain their municipal water supplies from surface-water sources. Thirty-eight percent of the State's population depended on surface water for supply in 1980.

Surface-water sources supply 63 percent of the water used for irrigation, 75 percent of the water used by industry, 99.9 percent of the water used for thermoelectric-power generation, and 41 percent of the water used for municipal and rural supplies (Patch and Haffield, no date). Surface-water withdrawals in North Dakota for various purposes and related statistics are given in table 1.

North Dakota's surface-water resources are abundant in Lakes Sakakawea and Oahe in the west-central part of the State, but can be in short supply in other parts of the State. In addition to Lakes Sakakawea and Oahe, numerous smaller reservoirs have been constructed. These help ensure adequate water supplies during low flow. These reservoirs vary from impoundments behind low-head dams constructed in river channels, to impoundments behind dams built across flood plains. However, because of the lack of facilities to transport water, even areas a short distance from the large reservoirs do not make extensive use of the available surface water. Use also is limited by the quality of the water. The water in many natural lakes and even some empoundments is too saline for general use.

Current issues related to surface water in North Dakota include flooding, surface drainage of wetlands, wastewater return flows, and the Garrison Diversion project. The Garrison Diversion project, as originally authorized, was to have provided water from the Missouri River for irrigation of 250,000 acres, municipal and industrial delivery systems, fish and wildlife enhancement, recreation, and flood control.

Table 1. Surface-water facts for North Dakota

[Data 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; Patch and Haffield, no date]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	247
Percentage of total population	38
From public water-supply systems:	
Number (thousands)	247
Percentage of total population	38
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1982	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	1,000
Surface water only (Mgal/d)	910
Percentage of total	91
Percentage of total excluding withdrawals for thermoelectric power	13
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	33
Percentage of total surface water	3.6
Percentage of total public supply	46
Per capita (gal/d)	134
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	8.2
Percentage of total surface water	0.9
Percentage of total livestock	39
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	790
Percentage of total surface water	87
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	100
Excluding withdrawals for thermoelectric power	75
Irrigation withdrawals:	
Surface water (Mgal/d)	84
Percentage of total surface water	9
Percentage of total irrigation	63
INSTREAM USE, 1982	
Hydroelectric power (Mgal/d)	14,000

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 Great Plains province consists mainly of rolling to hilly plains with gentle slopes. Local relief generally ranges from 300 to 500 feet (Bluemle, 1977). However, the Badlands along the Little Missouri River in the southwestern corner of the State are rugged, with deeply eroded hilly areas along the river. Gentle slopes characterize only 20 to 50 percent of the Badlands area, and local relief commonly is more than 500 feet. The Missouri River drains most of the Great Plains province in North Dakota. Its southeasterly route generally parallels the limit of former glaciation.

The Central Lowland province consists mainly of rolling, glaciated plains. Large areas have poorly defined drainage patterns and do not contribute to surface runoff received by streams and rivers. More than 80 percent of the area is gently sloping, and local relief is less than 100 feet. The eastern boundary of the State is defined by the channel of the Red River of the North, which lies in the flat plain of a glacial lakebed. Local relief in most places within the plain is less than 25 feet. Most of the Central Lowland province is drained by the Red River, which flows north into Canada. The Souris River, which drains the northwestern corner of the province in the State, also flows north and eventually enters the Red River in Manitoba. The James River, which drains the southern extent of the State's glaciated plains, flows south and joins the Missouri River in South Dakota.

The average annual precipitation ranges from about 14 inches in the western part of the State to about 20 inches along the eastern border (fig. 1). Precipitation is seasonal; 75 percent of the annual precipitation falls during the crop-growing season of April through September.

Moisture stored during the winter as snow generally begins to melt and run off in the western part of the State in March. Peak spring runoff for most of the rest of the State generally occurs during April. However, the downstream part of the Devils Lake basin does not receive the majority of its spring runoff until May because of the long interconnecting system of lakes and streams in the basin. Typical of these seasonal runoff patterns are the Little Missouri River at Marmarth, the Wild Rice River near Abercrombie, and the Big Coulee near Churchs Ferry (fig. 1). Potential average annual evaporation ranges from about 32 inches in the northeastern part of the State to about 40 inches in the southwestern (Winter and others, 1984). Potential average annual evaporation exceeds average annual precipitation across the State with the greatest difference in western North Dakota.

PRINCIPAL RIVER BASINS

Hydrologically, North Dakota is divided into the Souris–Red–Rainy Region and the Missouri Region (fig. 2). The Souris–Red–Rainy Region can be further divided into the Red River of the North basin and the Souris River basin. The Missouri Region in North Dakota consists mainly of the Missouri River main stem, the Little Missouri, the Knife, the Heart, and the Cannonball River basins, and the James River basin. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Selected streamflow characteristics and other pertinent information are given in table 2.

SOURIS-RED-RAINY REGION

Souris Subregion

Souris River Basin.—The Souris River has its headwaters in southern Saskatchewan and flows southward, crossing the northern boundary of North Dakota west of Sherwood. It then forms a loop and flows back north, entering Manitoba near Westhope. Large areas in the Souris River basin have poorly defined drainage patterns and do not contribute to streamflow. By the time the Souris River crosses the North Dakota border at Westhope, it drains about 16,900 mi^2 (square miles), but only about 6,600 mi^2 contributes to streamflow.

Because the Souris River flows through Saskatchewan, North Dakota, and Manitoba, the apportionment of flow has been placed under the jurisdiction of an International Joint Commission (Winter and others, 1984). Two of the interim measures from the Commission's Docket No. 41, adopted March 19, 1958, are: (1) Saskatchewan will not decrease the annual streamflow to North Dakota at the western crossing by more than one-half that which would have occurred in a state of nature, and (2) North Dakota has the right to use this streamflow plus that which originates in North Dakota provided that, except during a severe drought, a regulated flow of not less than 20 ft^3/s or 13 Mgal/d be permitted to flow into Manitoba from June 1 through October 31. Saskatchewan exercises some regulation on flows through several onstream and tributary reservoirs for municipal, thermoelectric-power generation, and irrigation supplies. Flood control is not a design function of these reservoirs (Winter and others, 1984).

Water from the Souris River in North Dakota is used for municipal supply, stock watering, irrigation, recreation, and fish and wildlife propagation. Lake Darling [built in 1936 with a capacity of 114,000 acre-ft (acre-feet) or 37,100 Mgal (million gallons)], located upstream of Minot, and the refuge pools of the J. Clark Salyer National Wildlife Refuge (built between 1935 and 1940 with combined capacities of 43,700 acre-ft or 14,200 Mgal), located upstream of Westhope, are maintained for propagation of fish and wildlife. Both of these reservoirs and several smaller reservoirs partly control floodflows, although flood control was not an original design function.

Based on chemical composition, water in the Souris River appears to be marginally suitable for domestic use. Average concentrations of dissolved solids are slightly higher than Federal secondary drinking-water standards (Winter and others, 1984).

Red Subregion

Red River of the North Basin.—The Red River of the North begins at Wahpeton, at the confluence of the Otter Tail River, which originates in east-central Minnesota, and the Bois de Sioux River, which originates in northeastern South Dakota. From Wahpeton, the Red River of the North flows northward. It forms the border between North Dakota and Minnesota and drains about equal areas in both states. About 28 percent of North Dakota is drained by the Red River of the North. The Sheyenne River enters the Red River of the North just downstream from Fargo. The Sheyenne River is regulated by Lake Ashtabula (built in 1949 with a capacity of 116,500 acre-ft or 38,000 Mgal), which provides flood control and can be used to supplement downstream discharge during low flow. The Devils Lake basin is a 3,900 mi^2 closed basin in the Red River of the North basin. Recent rising water levels of Devils Lake are causing concern about potential flooding. Only a few years ago,

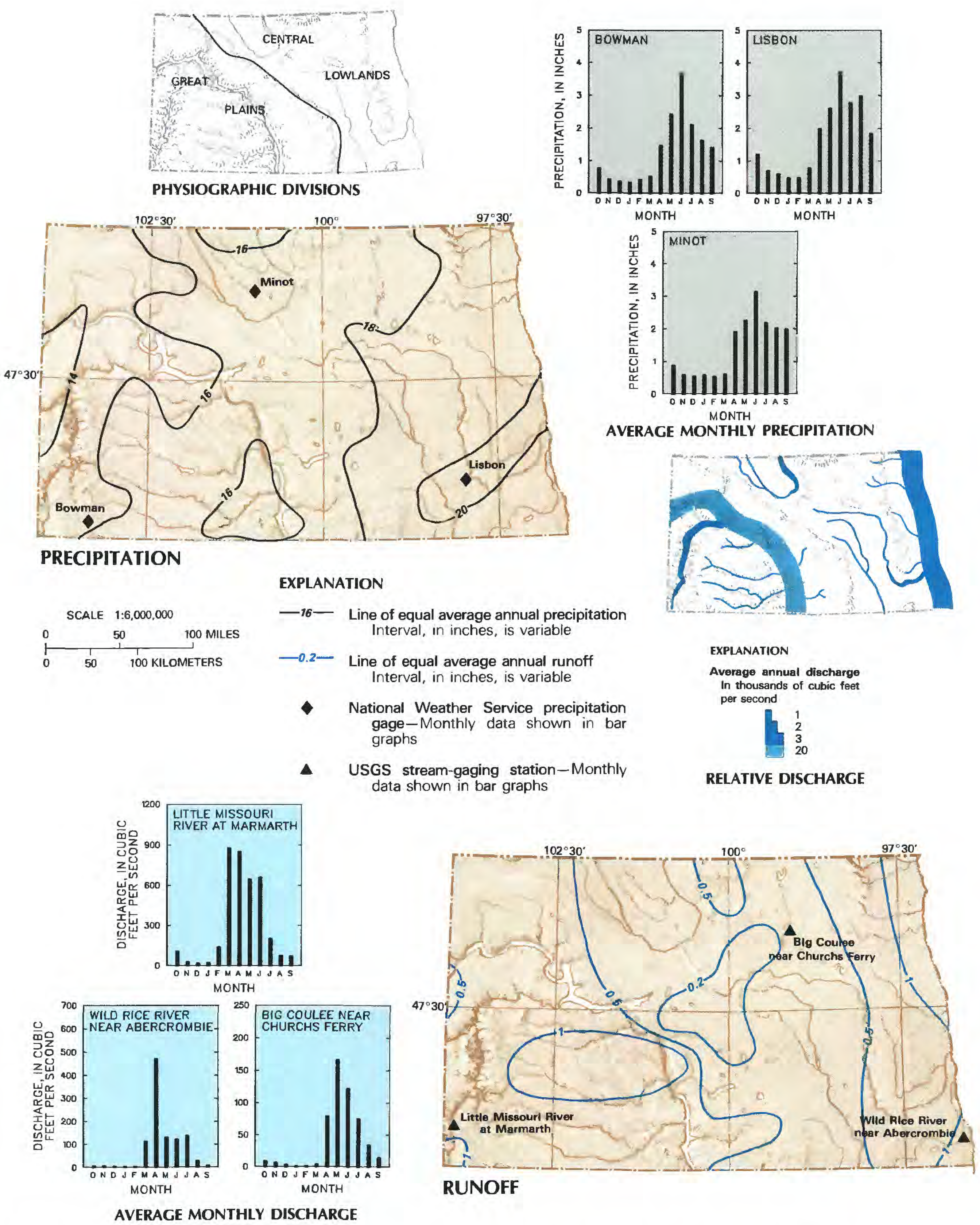

Figure 1. Average annual precipitation and runoff in North Dakota and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in North Dakota

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; < = less than. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage erea (mi^2)	Period of analysis	7-day, 10-yeer low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				SOURIS-RED-RAINY REGION Souris Ano Reo Subregions Souris River and Red River of the North basins				
1.	Souris River above Minot (05117500).	[1]10,600 [2]6,700	1904–83	< 0.1	171	11,500	Appreciable	Flow almost completely regulated by Lake Darling.
2.	Red River of the North et Wahpeton (05051500).	[1]4,010	1943–83	12.3	519	11,000	. . . do . . .	Both tributaries ara regulated.
3.	Big Coulee near Churchs Ferry (05056400).	[1]2,510 [2]690	1951–79	0	44.1	3,370	. . . do . . .	In 1979, Channel A near Penn was constructed upstream, effectively decreasing tha drainage area of Big Coulee by about one third and shunting those flows directly into Oevils Lake.
4.	Sheyenne River at West Fargo (05059500).	[1]8,870 [2]5,780	1904–05 1930–83	12.9	176	5,280	. . . do . . .	Regulated by Lake Ashtabula.
5.	Red River of the North at Grand Forks (05082500).	[1]30,100 [2]3,800	1883–1983	69.1	2,558	89,000	Moderate	Regulation on many of the major tributaries.
				MISSOURI REGION Missouri–Little Missouri Ano Missouri–Oahe Suaregions Missouri River main stem and tributary river basins				
6.	Little Missouri River near Watford City (06337000).	[1]8,310	1935–83	< 0.1	593	78,700	None	Stock ponds are about the only form of regulation in the basin.
7.	Knife River at Hezen (06340500).	[1]2,240	1930–33, 1938–83	2.7	181	36,200	Negligible	Lake Ilo, located in the upper end of the basin, is the only major reservoir in the basin.
8.	Missouri River at Bismarck (06342500).	[1]186,400	1921–83	6,570	22,740	63,700	Appreciable	Flow statistics based on reguletion patterns of Lake Sakakawea.
9.	Heart River near Mendan (06349000).	[1]3,310	1929–32 1938–83	< 0.3	268	49,500	Moderate	Lake Tschida and Edward Arthur Patterson Lake are in the basin.
10.	Cannonball River at Breien (06354000).	[1]4,100	1935–83	< 0.1	256	60,000	Negligible	Stock ponds are about the only form of regulation in the basin.
11.	James River at Jamestown (06470000).	[1]2,820 [2]1,650	1929–34	1.1	62.2	4,800	Appreciable	Arrowwood Lake, Mud Lake, Jim Lake, Pipestem Lake and Jamestown Reservoir located upstream.

[1] Approximate.

[2] Noncontributing.

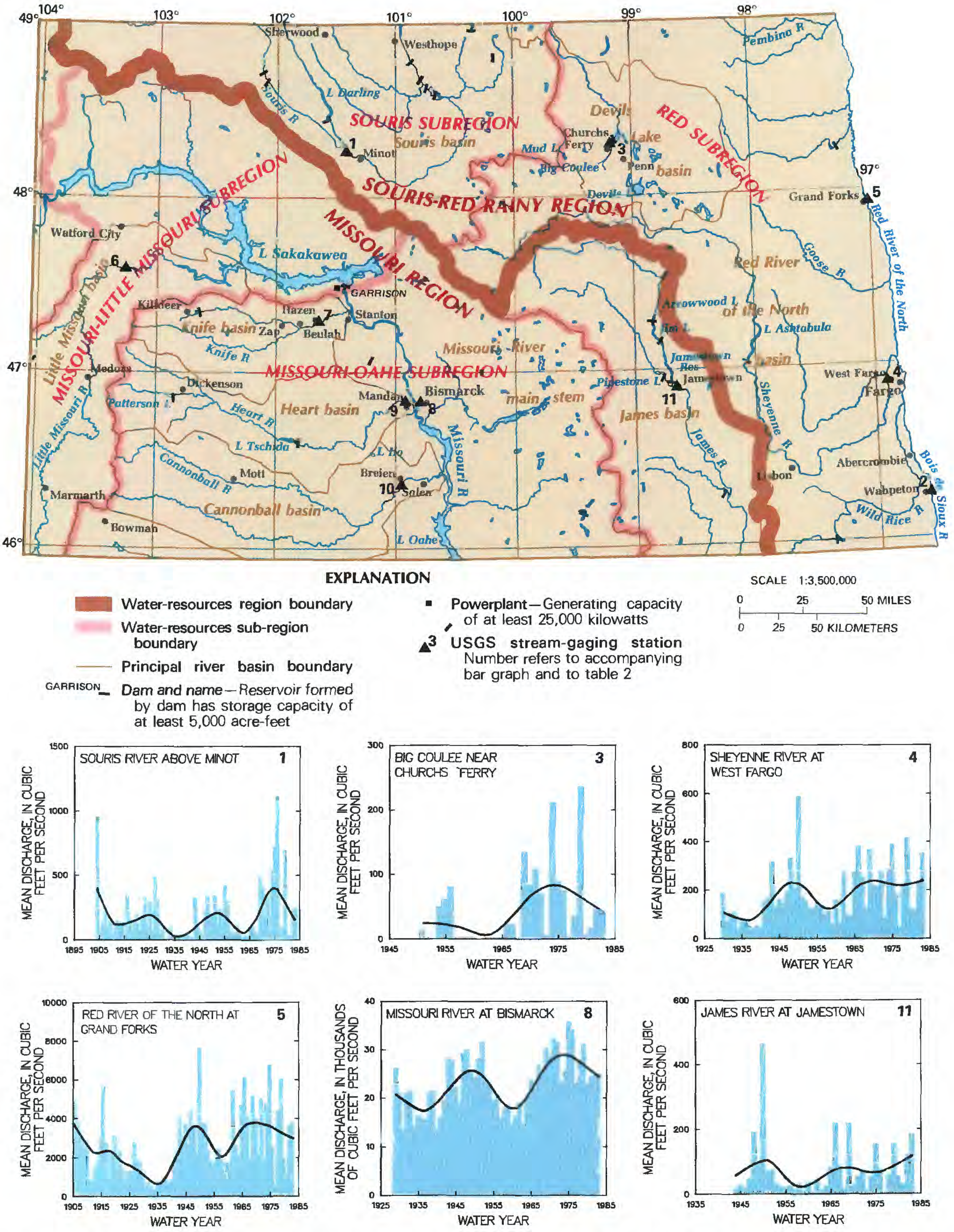

Figure 2. Principal river basins and related surface-water resources development in North Dakota and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

planners were looking for supplemental flows from outside of the basin to help freshen, restore, and stabilize Devils Lake (U.S. Bureau of Reclamation, 1975).

The valley of the Red River of the North is the most populated area of the State, as well as the most intensely farmed. Historically, floods in the Red River of the North basin have had a major effect on North Dakota. The 1979 flood was exceeded only by the flood of 1897, but many other major floods occurred during the interim. In 1979, the Red River of the North, which normally floods to 200 to 500 feet wide, was more than 10 miles wide. Flood damages exceeded $114 million (North Dakota and Minnesota combined), including more than $84 million in damages in rural areas (Ericson and others, 1980).

The Red River of the North has several basin characteristics that make it susceptible to destructive flooding. It has an undersized main channel in relation to its flood plain, and the gradient of its main channel is very small; consequently, flows do not move down the channel quickly. Also, the Red River of the North flows northward, which tends to synchronize flooding in the whole basin with the northward progression of the spring thaw (Ericson and others, 1980). Most notable floods have occurred during late spring ice breakups that often are accompanied by quickly rising temperatures, spring rains, melting of heavy snow cover, and substantial soil-moisture content retained from the previous fall. In addition to flooding, other important surface-water issues in the Red River of the North basin include availability and quality of water for domestic, industrial, and irrigation supplies, and wastewater return flows.

Water in the Red River and its tributaries—the Sheyenne and the Pembina Rivers—is generally suitable for drinking-water supply and domestic use. Water from the Wild Rice and the Goose Rivers probably is not suitable for drinking-water supply, because average sulfate concentrations exceed Federal secondary drinking-water standards (Winter and others, 1984).

MISSOURI REGION

Missouri-Little Missouri and Missouri-Oahe Subregions

Missouri River Main Stem.—The Missouri River is almost entirely regulated in its course through North Dakota (Winter and others, 1984). Of the 390 miles of river in the State, only the 90-mile reach between Lake Sakakawea (capacity, 19,000,000 acre-ft or 6,200,000 Mgal) and Lake Oahe (capacity, 16,800,000 acre-ft or 5,500,000 Mgal) has not been inundated. The cities of Bismarck (second largest city in the State) and Mandan (seventh largest), as well as several other small communities, are located along that 90-mile reach. Water supplies for Bismarck and Mandan are withdrawn from the Missouri River. Water in the reservoirs and the Missouri River main stem is generally suitable for drinking-water supply and domestic use.

Lake Sakakawea was completed in 1955 when work was finished on Garrison Dam. The dam provides flood protection for the cities of Bismarck and Mandan, as well as for rural areas and other cities downstream of the dam. Discharge from Garrison Dam provides an average of 2,719,000 megawatt hours per year of hydroelectric power (Searles Hornstein, Western Area Power Administration, oral commun., 1985). Lake Sakakawea also is a large source of supply for irrigation water, as well as a source of cooling water for thermoelectric powerplants. The lake is becoming an important recreational area.

Lake Oahe is formed by Oahe Dam (completed in 1958 with a storage capacity of 16,800,000 acre-ft or 5,500,000 Mgal) in central South Dakota and inundates the last 80 miles of the Missouri in southern North Dakota. The major use of water from Lake Oahe in North Dakota is irrigation.

Little Missouri River Basin.—The Little Missouri River originates in northeastern Wyoming. The river enters the southwestern corner of North Dakota and flows in a northerly and then easterly direction to its confluence with Lake Sakakawea near Killdeer. The Little Missouri River has a drainage area of about 4,750 mi^2 in North Dakota. The treeless and barren slopes of the Little Missouri River basin produce rapid and excessive overland runoff, and tributary streams flood frequently. Two communities, Marmarth and Medora, are subject to occasional damage by floods; although property damage within the basin generally is minor because of the paucity of development along the river. Because the river channels of the basin are in the easily eroded shale and sandstone of the Badlands, large quantities of sediment are transported downstream. The basin does not contain any major flood-control works. The principal uses of water from the river are stock watering and irrigation. Water in the river appears to be, at best, marginally suitable for domestic supplies because average sulfate concentrations exceed Federal secondary drinking-water standards (Winter and others, 1984).

Knife River Basin.—The Knife River originates in the Badlands area in west-central North Dakota and flows easterly for about 200 miles to its confluence with the Missouri River near Stanton. The Knife River has a drainage area of about 2,510 mi^2. The communities of Beulah, Zap, Hazen, and Stanton are periodically subject to damage by floods from the Knife River or its tributaries.

The principal uses of water from the river are stock watering, recreation, and irrigation. Average sulfate concentrations in the Knife River exceed Federal secondary drinking-water standards, making the water, at best, marginally suitable for domestic use (Winter and others, 1984).

Heart River Basin.—The Heart River originates in the same part of North Dakota as the Knife River. The Heart River is about 270 miles long and has a drainage area of about 3,340 mi^2. Edward Arthur Patterson Lake (completed in 1950 with a capacity of 10,200 acre-ft or 3,320 Mgal) and Lake Tschida (completed in 1949 with a capacity of 224,000 acre-ft or 73,000 Mgal) are located on the main stem of the Heart River and provide flood control, irrigation, municipal supply, and recreation. These two reservoirs generally provide adequate flood protection along the main stem, although parts of Dickinson and Mandan have occasionally been flooded. The principal uses of water from the river are stock watering, recreation, and irrigation. Water in the Heart River is, at best, marginally suitable for domestic supplies because average sulfate concentrations exceed Federal secondary drinking-water standards (Winter and others, 1984).

Cannonball River Basin.—The Cannonball River, which is 320 miles long, generally parallels the Heart River from southwestern North Dakota to the Missouri River in south-central North Dakota. The total drainage area is about 4,310 mi^2. Severe floods resulting from thunderstorms can occur along the tributaries of the Cannonball, and the main stem can flood occasionally during spring runoff. The communities of Mott, Breien, and Solen are subject to flood damage. Erosion has produced a series of local badlands along the Cannonball. Surface water in the basin is used primarily for stock watering and irrigation. Average sulfate concentrations in the Cannonball River exceed Federal secondary drinking-water standards, making the water marginally suitable for domestic supplies (Winter and others, 1984).

James River Basin.—The James River originates in central North Dakota and meanders east and south 260 miles before it enters South Dakota. The topography of the James River basin is characterized by low hills, scattered lakes, and low bluffs along the river. The basin includes 5,480 mi^2 in North Dakota, but about 3,300 mi^2 of the total is noncontributing. Because the average slope of the river is 1.2 ft/mi (feet per mile), spring and summer floods can cause prolonged inundation (Winter and others, 1984). Jamestown Reservoir (completed in 1953 with a capacity of 229,500 acre-ft or 74,800 Mgal) and Pipestem Lake (completed in 1973 with a capacity of 147,000 acre-ft or 47,900 Mgal), which are located upstream of Jamestown, are the major reservoirs in the basin. Two national wildlife refuges on the main stem store an additional 32,000 acre-ft or 10,400 Mgal (Missouri River Basin Commission, 1980). Water in the James River, based on chemical composition, appears to be generally suitable for domestic use; although, data confirming this are somewhat limited (Winter and others, 1984).

SURFACE-WATER MANAGEMENT

The North Dakota State Water Commission has broad powers and primary responsibility for managing the State's water resources. The State Water Commission's direction is guided by the State Water Plan (North Dakota State Water Commission, 1983). The State Department of Health also has responsibilities: ". . .for the development of comprehensive programs for the prevention and control of contamination of all waters of the State. . ." (North Dakota State Department of Health, 1984). Other State agencies involved in certain aspects of water management include the Game and Fish Department, the Parks and Recreation Department, the Soil Conservation Committee, the Geological Survey, the Weather Modification Board, and the Public Service Commission (North Dakota State Water Commission, 1983; North Dakota State Department of Health, 1984).

In 1963, the North Dakota Legislature adopted "the prior appropriation doctrine," which embraces the concept of "first in time is first in right." For nearly 60 years prior to 1963 the State followed a duel water-rights doctrine involving both prior appropriation and riparian ownership (North Dakota State Water Commission, 1983).

Compacts for the Yellowstone and the Souris Rivers establish the rights and constraints of the various compact members to the surface waters of the respective basins. Members of the Yellowstone River Compact include Montana, Wyoming, and North Dakota. The Souris River Compact includes North Dakota and the Canadian Provinces of Saskatchewan and Manitoba (North Dakota State Water Commission, 1983). Specific information concerning State water laws is provided in a document entitled "North Dakota Water Laws, 1981" published by North Dakota State Water Commission (1981).

The U.S. Geological Survey, in cooperation with several State and Federal agencies, maintains a network of stream-gaging stations across North Dakota. Information gathered from these stations is used to help manage and monitor the State's surface-water resources.

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OHIO
Surface-Water Resources

Surface water is the source of 93 percent of all offstream withdrawals in Ohio (table 1). Although nearly two-thirds of the State's annual precipitation is lost through evapotranspiration, the remaining runoff and ground-water discharge to streams provide ample surface-water supplies. Surface water provides 71 percent of withdrawals by public-water supplies and 86 percent of the industrial withdrawals in Ohio. Much of this surface-water withdrawal comes from Lake Erie and the main stem Ohio River.

Ohio's principal river basins have played a major role in the State's history. The development of water power at favorable stream sites and the canal system that operated from the 1820's until the turn of the century largely determined the locations of early centers of settlement, commerce, and industry. Of the 22 largest cities in Ohio, 14 are on canal routes, 4 are on Lake Erie, and 4 are on the Ohio River. Each of the principal basins discussed herein was traversed by a canal.

The quality of Ohio's surface-water resources is a major concern in the State. Of particular concern are the need for continued improvement in the quality of point-source discharges, the effects of agricultural nonpoint discharges, sedimentation, mining, and hazardous-waste disposal sites on surface-water quality.

GENERAL SETTING

Ohio is located in three physiographic provinces (fig. 1), each with its own distinctive surface-water characteristics. The topography of the Till Plains section of the Central Lowlands province consists of gently rolling ground moraine with bands of terminal moraine and outwash-filled valleys. Glaciation altered the courses of numerous streams in this area. The Eastern Lake Plains section consists of wide expanses of level or nearly level land interrupted only by the sporadic sandy ridges that are the last visible remnants of glacial-lake beaches. Much of the area was swamp prior to development, and marshes are still present along Lake Erie near Toledo.

The Lexington Plains section of the Interior Low Plateau province (fig. 1) is characterized by rolling terrain with isolated large hills and ridges. The "barbed" drainage pattern formed when small streams were captured as their headwaters cut back into the hills over time (Elfner, 1979, p. 253-256).

Streams have carved the Kanawha section of the Appalachian Plateau province (fig. 1) into an intricate series of hollows and steep-sided ridges. Only the large streams in the section have any appreciable flood plain. In the southern New York section, successive waves of glaciation have subdued the relief, buried many preglacial valleys, and rerouted many streams.

The average annual precipitation in Ohio is about 39 inches. The rainfall decreases from around 42 inches on the southern border to about 32 to 34 inches along most of the northern border. An area of greater precipitation (up to 44 inches) in northeastern Ohio results from air masses that absorb moisture and heat from Lake Erie and subsequently release precipitation over a range of hills stretching northeastward from Cleveland (fig. 1). Monthly precipitation typically is greatest from June through August and least in September and October.

Table 1. Surface-water facts for Ohio

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	6,269
Percentage of total population	58
From public water-supply systems:	
Number (thousands)	6,068
Percentage of total population	56
From rural self-supplied systems:	
Number (thousands)	201
Percentage of total population	2
OFFSTREAM USE, 1980	
Freshwater Withdrawals	
Surface water and ground water, total (Mgal/d)	14,000
Surface water only (Mgal/d)	13,000
Percentage of total	93
Percentage of total excluding withdrawals for thermoelectric power	75
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	1,000
Percentage of total surface water	8
Percentage of total public supply	71
Per capita (gal/d)	165
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	8.8
Percentage of total surface water	0.1
Percentage of total rural domestic	10
Per capita (gal/d)	44
Livestock:	
Surface water (Mgal/d)	16
Percentage of total surface water	0.1
Percentage of total livestock	40
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	12,000
Percentage of total surface water	92
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	86
Irrigation withdrawals:	
Surface water (Mgal/d)	3.4
Percentage of total surface water	<0.1
Percentage of total irrigation	64
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	380

Of the approximate 39 inches of average annual precipitation, about 11 inches runs off immediately, 2 inches is retained at or near the surface and evaporates or transpires, and 26 inches enters the ground. Of the 26 inches that enters the ground, 20 inches is retained in the unsaturated zone and is later lost by evapotranspiration. The remaining 6 inches reaches the water table. Of this 6 inches, 2 inches is eventually discharged to streams, and the rest is lost by evapotranspiration or consumptive use (Norris, 1969). Average runoff ranges from about 15 to 18 inches along the southern border to about 8 to 12 inches along most of the northern border, except in the northeast where runoff reaches 20 inches. The pattern of streamflow differs from the pattern of precipitation (fig. 1) because of the contribution of snowmelt to streamflow in the early spring and the reduction of flows by evapotranspiration from June through September. The graphs of discharge for the three sites in figure 1 show a similar runoff pattern even though the sites represent different physiographic regions.

There also is regional similarity in long-term discharge. The bar graphs in figure 2, which represent average annual discharges for the past 25 years (at selected sites), all show an increase in flow following a dry period in the mid-1960's, and very little change after that.

PRINCIPAL RIVER BASINS

Ohio is located in the Ohio and Great Lakes Regions (fig. 2). The State contains the Muskingum, the Scioto, and the Great Miami Subregions in the Ohio Region and the Western Lake Erie and the Southern Lake Erie Subregions in the Great Lakes Region. These river basins are described below. Their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

OHIO REGION

Muskingum Subregion

The Muskingum River has the largest drainage area of any river lying completely within Ohio. The Muskingum drains 8,051 mi² (square miles) or about 20 percent of the State. The Walhonding and the Tuscarawas Rivers join at Coshocton to form the Muskingum. From there, the Muskingum flows south, joins with the major tributaries Wills Creek and the Licking River, and empties into the Ohio River at Marietta.

The Muskingum is regulated throughout its entire length by reservoirs that are mainly on its tributaries. Usable capacity of all the reservoirs in the basin exceeds 1,800,000 acre-ft (acre-feet) or 587,000 Mgal (million gallons). Flow on the main stem also is affected somewhat by a series of locks and dams. There is a diversion from the Tuscarawas River to the Cuyahoga River basin by way of the Portage Lakes near Akron.

Agriculture and urban land uses predominate in the glaciated part of the basin. In the unglaciated part, land use is characterized by small farms, light industry, coal mining, and water-based recreation. Nearly 100 miles of the main stem Muskingum River is navigable to pleasure boats up to 30 feet long and 4 feet in draft.

The Muskingum River and some of its major tributaries have extensive unconsolidated aquifers within their valleys. Major well fields tap aquifers adjacent to streams in the Canton and Zanesville areas.

Water quality in the Muskingum basin is suitable for most uses, although urbanization, agricultural nonpoint pollution, industry, and acid-mine drainage have degraded water quality in a few places. The most significant water issues concern maintenance of acceptable water quality while permitting a variety of land uses, many of which have the potential for environmental degradation.

Scioto Subregion

The Scioto River system drains 6,510 mi², all of which is in Ohio. The Scioto River originates approximately 50 miles northwest of Columbus and continues generally southward to its mouth at the Ohio River at Portsmouth. Major tributaries to the Scioto (from north to south) are the Olentangy River, Alum Creek, Big Walnut Creek, Big Darby Creek, Deer Creek, Paint Creek, and Salt Creek.

Eight main reservoirs are in the basin—two on the main stem north of Columbus and the remaining six on tributaries. Usable capacity of the basin's reservoirs exceeds 200,000 acre-ft or 65,200 Mgal. The southern part of the main stem is considered to be only moderately regulated. Lowland flooding has occurred south of Columbus for many years during the late winter or early spring.

Glacial outwash deposits along the main stem Scioto River south of Columbus are productive aquifers in places. Ground-water supplies developed in these deposits are used in the vicinity of Columbus, Chillicothe, and Piketon.

Water quality of the Scioto and its tributaries is suitable for most uses in the headwaters, except for seasonally high concentrations of nutrients in the upper Scioto basin. A significant water issue in the basin is the problem of low concentrations of dissolved oxygen and elevated biochemical-oxygen demand near and downstream of cities in the lower basin, especially during periods of low flow.

Great Miami Subregion

The Great Miami River drains a total area of 5,371 mi², of which 3,946 mi² (73 percent) is in Ohio and 1,425 mi² (27 percent) is in Indiana. The river originates at Indian Lake in west-central Ohio, flows generally to the southwest, and empties into the Ohio River at the Ohio–Indiana State line. Major tributaries include Loramie Creek and the Stillwater, the Mad, and the Whitewater Rivers. The most significant diversion of water from the Great Miami basin is to the Mill Creek basin near Cincinnati.

Water-resources development has been significant in the basin. Following the disastrous flooding of 1913, the Miami Conservancy District was established and began an ambitious program for flood control. Starting in 1918, the District constructed five flood-retarding structures that have significantly reduced flood peaks. Usable capacity of the basin's reservoirs in Ohio exceeds 840,000 acre-ft or 274,000 Mgal.

The extensive unconsolidated aquifer system in the Mad River and the lower Great Miami River valleys is one of the most heavily developed ground-water supplies in the State. Cities served by major well fields adjacent to streams include Springfield, Dayton, Hamilton, and Middletown.

Water quality in the basin generally is suitable for most uses. The primary water issues in the basin concern the effect of hazardous-waste sites on surface- water resources, erosion and sedimentation, and continued improvement of discharges from waste-treatment facilities.

GREAT LAKES SUBREGION

Western Lake Erie Subregion

Maumee River Basin.—The Maumee River is formed in Indiana and flows to the east-northeast across Ohio into Lake Erie at Toledo. The Maumee drains a total of 6,608 mi², of which 1,283 mi² (19 percent) is in Indiana, 463 mi² (7 percent) is in Michigan, and 4,862 mi² (74 percent) is in Ohio. Major tributaries are the Auglaize and the Tiffin Rivers.

Surface-water regulation in the basin is minimal, primarily because the relatively flat topography makes reservoirs impractical. A few inactive powerplants have minor effects on flow, and some streams have low-flow augmentation. There are no significant river-valley aquifers in use in northwestern Ohio, and interaction of ground water and surface water is minimal.

Although there is heavy industry and a major port in Toledo, the basin is primarily agricultural. Water quality is suitable for most uses throughout most of the basin with the possible exception of Toledo. Major surface-water issues in the basin are how to reduce agricultural nonpoint pollution, how to reduce sedimentation, and how to improve water quality near cities.

Southern Lake Erie Subregion

Cuyahoga River Basin.—The Cuyahoga River basin is entirely within Ohio. The Cuyahoga River originates from two small springs, flows southwest to Akron, curves northward, and flows north to Lake Erie at Cleveland. The stream is about 100 miles long, but because of its U-shaped configuration, its drainage area is only 809 mi². Some water is imported into the Cuyahoga basin from the Tuscarawas River in the Muskingum basin.

There is some regulation of the Cuyahoga by headwater reservoirs. At Hiram Rapids, the peak of the 100-year flood has been reduced by 16 percent as a result of regulation (table 2). Usable capacity of the basin's reservoirs exceeds 22,000 acre-ft or 7,170 Mgal. Many of the impoundments in the basin are primarily used for water supply.

Land use within the Cuyahoga basin is varied. Rural areas, which contain few farms, are interspersed between extensive urban and industrial areas. Much of the reach of the Cuyahoga River between Akron and Cleveland has become part of the Cuyahoga Valley National Recreation Area administered by the National Park Service.

Some ground water is used within the basin by industry, small towns, and suburban residents, but interactions of ground

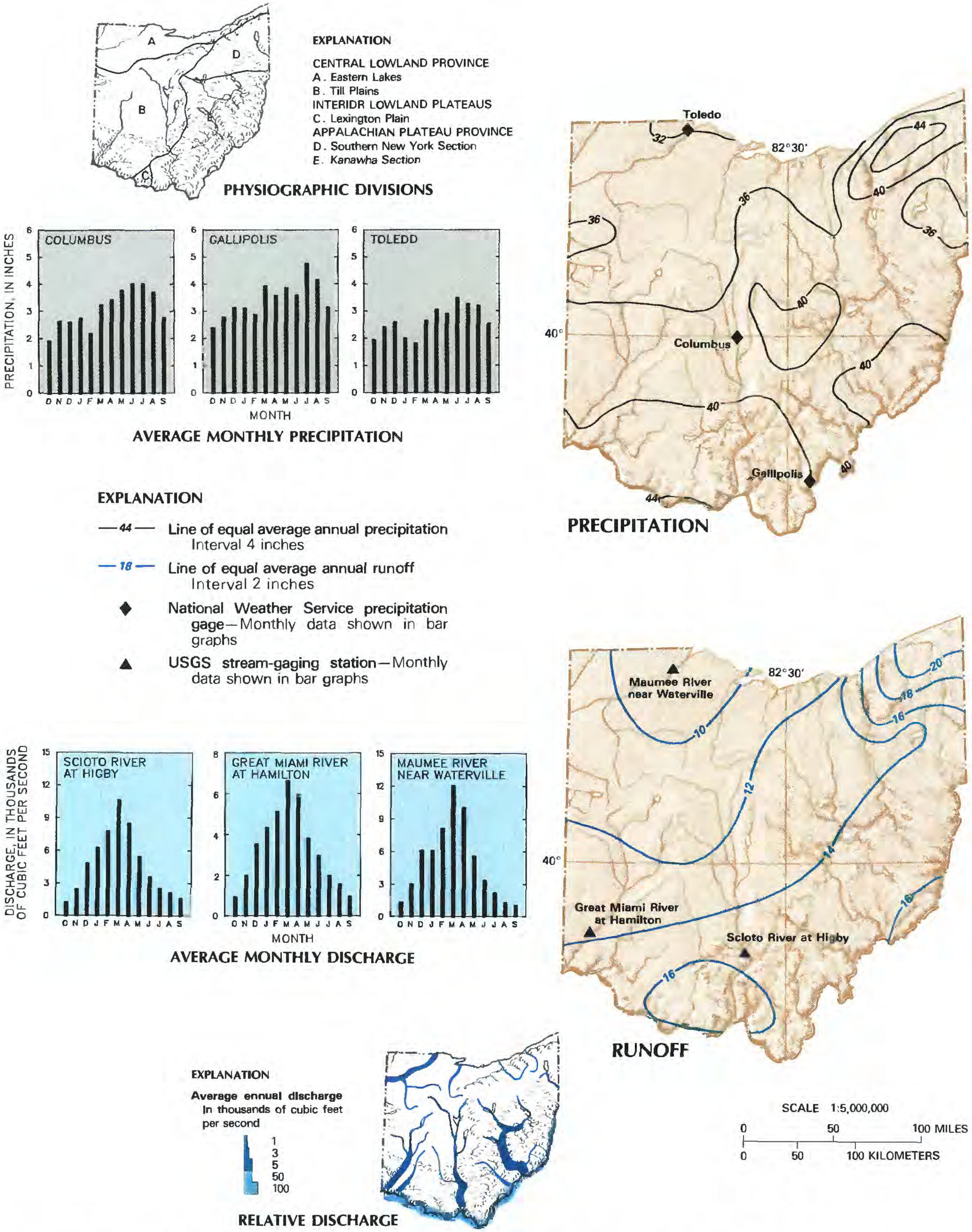

Figure 1. Average annual precipitation and runoff in Ohio and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

water and surface water are negligible. River-valley deposits are not especially productive and not heavily used as water supplies.

Despite major water-quality improvements in recent years, there are still problems in the lower reaches of the river, where industrial and municipal discharges amount to as much as 75 percent of the total flow during low-flow periods. In contrast, water quality in the headwaters is suitable for most uses, and one reach has been designated a "scenic river." Improvement of water quality in the lower reaches, including abatement of sedimentation at the mouth, is the major water issue in the basin.

SURFACE-WATER MANAGEMENT

Agencies at all levels of government are involved in the management of Ohio's water resources. On the Federal level, these include the U.S. Army Corps of Engineers, U.S. Soil Conservation Service, U.S. Forest Service, U.S. Environmental Protection

Table 2. Selected streamflow characteristics of principal river basins in Ohio

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and Ohio State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
	OHIO REGION **Muskingum Subregion**							
1.	Tuscarawas River at Massillon (03117000).	518	1937-84	71	441	8,670	Moderate	Diversion from basin through Ohio Canal. Industrial plants upstream.
2.	Tuscarawas River at Newcomerstown (03129000).	2,443	1921-37, 1938-84	253	2,541	66,900 23,000	None Appreciable	Eight flood control reservoirs plus diversions.
3.	Muskingum River at McConnelsville (03150000).	7,422	1921-37 1938-84	641	7,596	183,000 97,100	None Appreciable	Seventeen flood control reservoirs. Powerplants.
	Scioto Subregion							
4.	Scioto River near Prospect (03219500).	567	1925-32, 1939-84	9.3	454	13,900	None	
5.	Olentangy River near Delaware (03225500).	393	1923-34, 1938-51, 1951-84	5.2	351	22,000 6,280	. . . do . . . Appreciable	Completely regulated since 1951.
6.	Scioto River at Higby (03234500).	5,131	1930-84	296	4,579	184,000	Moderate	Problems with water quality at low flows.
	Great Miami Subregion							
7.	Great Miami River at Sidney (03261500).	541	1914-84	21	477	27,300	Negligible	Minor regulation and diversion.
8.	Stillwater River at Englewood (03266000).	650	1925-84	15	579	10,500	Moderate	Flood flow regulation by retarding basin.
9.	Mad River near Dayton (03270000)	635	1914-84	131	629	21,100	. . . do . . .	Retarding dam. Reservoir on tributary.
10.	Great Miami River at Hamilton (03274000).	3,630	1907-18, 1927-84	284	3,279	140,000 95,900	None Appreciable	Low flow regulated by industrial plants, flood flows by five retarding basins. Minor diversions.
	GREAT LAKES REGION **Western Lake Erie Subregion** **Maumee River basin**							
11.	Blanchard River near Findlay (04189000).	346	1923-35, 1940-84	2.3	251	14,300	Appreciable	Diversions and low-flow augmentation.
12.	Auglaize River near Defiance (04191500).	2,318	1915-84	11	1,718	62,700	. . . do . . .	Flow affected by dam at former powerplant.
13.	Maumee River at Waterville (04193500).	6,330	1898-1901, 1921-35, 1939-84	95	4,926	97,800	. . . do . . .	Low flow affected by upstream powerplants. Minor diversions.
	Southern Lake Erie Subregion **Cuyahoga River basin**							
14.	Cuyahoga River at Hiram Rapids (04202000).	151	1927-35, 1944-84	16	207	4,410 3,690	None Moderate	Two reservoirs upstream.
15.	Cuyahoga River at Independence (04208000).	707	1921-23, 1927-35, 1940-84	63	817	18,000	. . . do . . .	Flow affected by reservoirs, powerplants, and diversions.

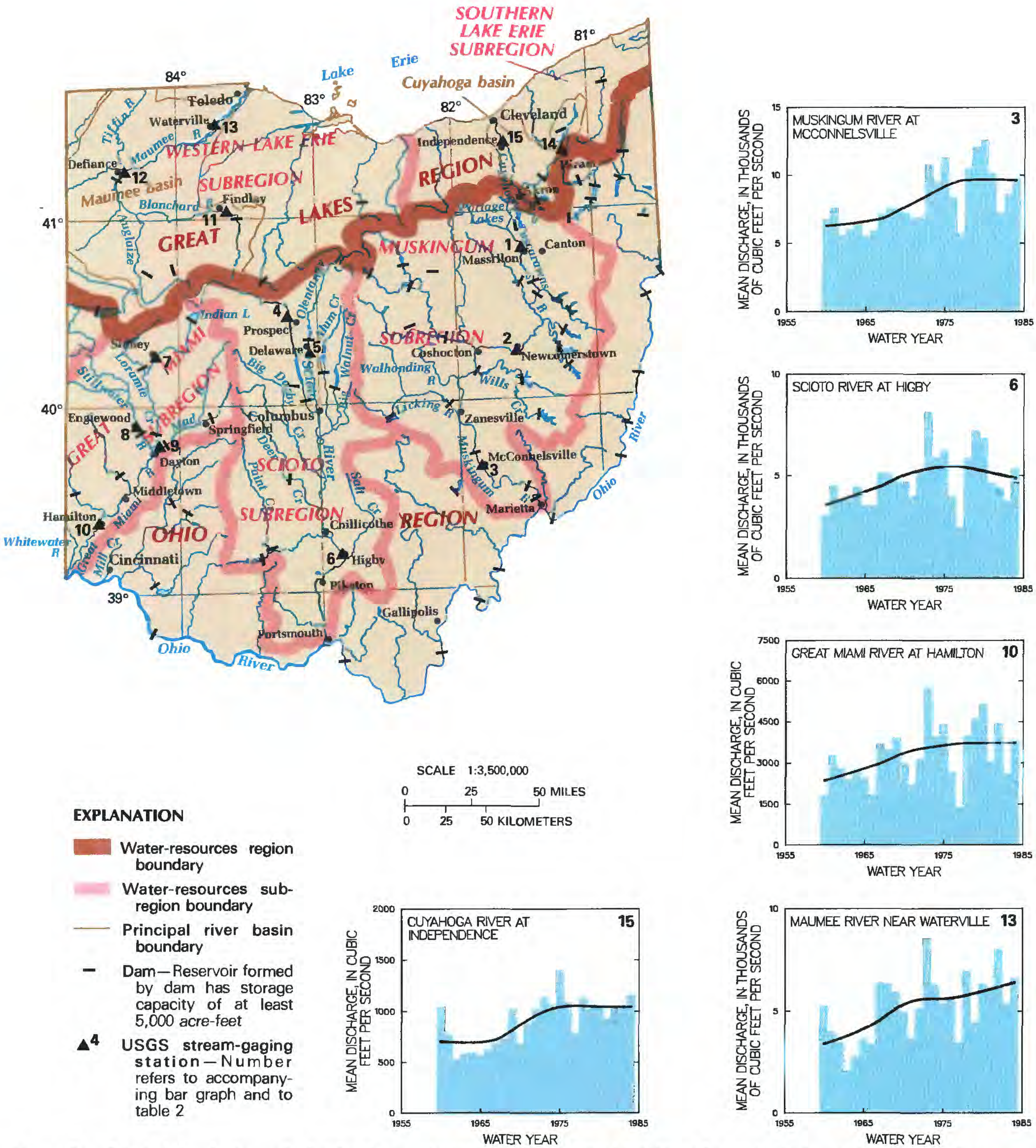

Figure 2. Principal river basins and related surface-water resources development in Ohio and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Agency, National Weather Service, and the International Joint Commission (with Canada). The most visible of these in Ohio is the U.S. Army Corps of Engineers, whose responsibilities include flood control, navigation, shore and bank protection, and ecologic-and economic-base studies. A statewide surface-water quantity and quality measurement program is conducted by the U.S. Geological Survey in cooperation with other Federal, State, and local agencies.

The Ohio Environmental Protection Agency and the Ohio Departments of Natural Resources, Health, Transportation, and Administrative Services are active at the State level. For example, the Department of Natural Resources helps communities develop surface-water and ground-water resources and is responsible for non-Federal dams, erosion problems, Lake Erie coastal resources, water-based recreational facilities, and general water-resources planning. The Ohio Environmental Protection Agency manages statewide programs to guarantee safety of drinking water, and issues permits to control wastewater discharges from private and public facilities. The Ohio Department of Health, in cooperation with county health departments, issues permits to install and operate private water-supply and sewage-disposal systems.

Conservancy districts also are important to Ohio's surface water. The districts have authority to control flooding, regulate streamflow, reclaim wetlands, act in cases of sewage-disposal problems, reduce erosion, and provide water-based recreational facilities. Currently, there are 18 districts with active programs.

The largest regional water organization operating in Ohio is the Ohio River Valley Sanitation Commission (ORSANCO), which was established in 1948 through an agreement with eight of the States that contribute drainage to the Ohio River. ORSANCO was established to protect the quality of the Ohio River by reducing the amount of insufficiently treated waste discharges through voluntary compliance by municipalities and industries.

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FOR ADDITIONAL INFORMATION

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OKLAHOMA
Surface-Water Resources

Oklahoma has an abundance of surface water; over half of the State's population use about 220 Mgal/d (million gallons per day) or 340 ft^3/s (cubic feet per second) for public supply. The availability of surface water, however, is not equally distributed across the State. There is a surplus of surface water in eastern Oklahoma, but not in western Oklahoma where water users must rely on ground water because of the undependable surface-water supplies. Major statewide issues regarding surface water include: water-rights allocation, natural and manmade water-quality degradation, rules for reservoir operation, and recurrent flooding.

Oklahoma has 79 reservoirs that have storage capacities of more than 5,000 acre-ft (acre-feet) or 1,630 Mgal (million gallons); 31 of these are considered major reservoirs with a combined storage of 12.9 million acre-ft or 4,200,000 Mgal available for beneficial use (Oklahoma Water Resources Board, 1984a). Ninety-three percent of this storage is in eastern Oklahoma. Hydroelectric power generation at nine of these dams uses 34,000 Mgal/d or 52,600 ft^3/s.

These 79 reservoirs were constructed, in part, to help alleviate adverse effects of spring flooding and summer droughts. As dependable water supplies became available, industrial use of surface water increased. During 1980, 46 percent, 350 Mgal/d or 542 ft^3/s, of all surface water withdrawn was used for industrial purposes.

The completion of the McClellan-Kerr Arkansas River Navigation System in 1971 marked the beginning of a new era and the culmination of a series of reservoir construction projects in eastern Oklahoma. Although the system's primary purpose is navigation, secondary benefits are flood control, hydroelectric-power generation, recreation, and fish and wildlife propagation.

After the dust bowl of the 1930's, irrigation of crops increased substantially in western Oklahoma. Statewide, irrigated acreage using surface-water and ground-water sources peaked at 1 million acres during 1978, but decreased to 750,000 acres during 1983 for economic reasons (Oklahoma Water Resources Board, 1984a). During 1980, about 16 percent of irrigation withdrawals were from surface-water sources (140 Mgal/d or 217 ft^3/s). Surface-water withdrawals in Oklahoma during 1980 for various purposes and related statistics are given in table 1.

Tabla 1. Surface-water facts for Oklahoma

[Data 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 SURFACE WATER, 1980	
Number (thousands)	1,671
Percentage of total population	58
From public water-supply systems:	
Number (thousands)	1,670
Percentage of total population	58
From rural self-supplied systems:	
Number (thousands)	1
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	1,700
Surface water only (Mgal/d)	760
Percentage of total	44
Percentage of total excluding withdrawals for thermoelectric power	39
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	220
Percentage of total surface water	29
Percentage of total public supply	73
Per capita (gal/d)	130
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	5.2
Percentage of total surface water	0.7
Percentage of total rural domestic	15
Per capita (gal/d)	56
Livestock:	
Surface water (Mgal/d)	50
Percentage of total surface water	6
Percentage of total livestock	86
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	350
Percentage of total surface water	46
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	75
Excluding withdrawals for thermoelectric power	63
Irrigation withdrawals:	
Surface water (Mgal/d)	140
Percentage of total surface water	18
Percentage of total irrigation	16
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	34,000

GENERAL SETTING

Oklahoma is in an area of diverse climatic zones and hydrologic characteristics. The climate is mostly continental but with milder winters than the remainder of the central United States. Precipitation ranges from about 16 in./yr (inches per year) in the western panhandle to about 52 inches in southeastern Oklahoma (fig. 1). Because maximum precipitation occurs in May, spring is the wettest season. Summers generally are hot and dry; droughts of varying duration are common. Evapotranspiration ranges from 16 in./yr in the western panhandle to 36 in./yr in the southeast (Pettyjohn and others, 1983). The combination of climatic factors, physiography, and geology contributes to stream runoff that ranges from about 0.1 in./yr in the west, increasing to more than 20 in./yr in a southeasterly direction.

PRINCIPAL RIVER BASINS

Oklahoma lies entirely within the Arkansas-White-Red Region (Seaber and others, 1984). Streams in the northern two-thirds of the State flow to the Arkansas River, whereas streams in the southern one-third of the State flow to the Red River. The hydrologic subregions corresponding to the Arkansas and the Red River basins are footnoted in table 2. Many of the State's rivers flow in a southeasterly direction; most principal rivers have their headwaters in adjoining States.

Eight principal rivers in Oklahoma are tributary to the Arkansas River: The Salt Fork Arkansas, the Cimarron, the Verdigris, the Grand (Neosho), the Illinois, the Poteau, and the Canadian and its principal tributary, the North Canadian. The Grand and the Illinois Rivers primarily drain the Ozark Plateaus physiographic province and the Poteau River drains the Ouachita physiographic province, whereas the other streams primarily drain the Central Lowland physiographic province (fig. 1). The Red River has five principal tributaries in Oklahoma: the North Fork Red and the Washita Rivers that drain the Central Lowland physiographic province, Muddy Boggy Creek, and the Kiamichi and the Little Rivers that primarily drain the Coastal Plain province. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

ARKANSAS-WHITE-RED REGION

Arkansas River Basin

The Arkansas River enters Oklahoma just north of Newkirk and traverses 328 miles across Oklahoma in a southeasterly direction before leaving the State east of Sallisaw. About 30 percent or 44,815 mi^2 (square miles) of the total Arkansas River basin is located in Oklahoma. Upstream from Oklahoma the flow of the Arkansas River is decreased by irrigation diversion; however, in the relatively short distance in Oklahoma, stream discharge is increased.

The Arkansas River is completely regulated by the McClellan-Kerr Arkansas River Navigation System, completed in 1971. The System's 17 locks permit barge traffic up the Arkansas and the Verdigris Rivers as far inland as Tulsa in the landlocked plains. Seven multipurpose reservoirs that have a major role in the operation of the system are Keystone (completed in 1965), Oologah (1963), Eufaula (1964), Tenkiller Ferry (1953), Lake O' the Cherokees (1940), Hudson (1964), and Fort Gibson (1953). Five additional major multipurpose reservoirs that contribute to the system are Kaw (completed in 1976), Heyburn (1950), Robert S. Kerr (1970), Webbers Falls (1970) and Wister (1949). The total reservoir storage in the Arkansas River main stem is about 2,450,000 acre-ft or 798,000 Mgal.

These reservoirs affect the flow regime by decreasing maximum peak discharges to varying degrees. The low flows may increase and average annual flows may remain about the same after regulation, depending on the purpose of each individual reservoir. The 100-year flood of the Arkansas River at Tulsa (table 2, site 3) has been decreased 49 percent by regulation from Keystone Lake. The 7-day, 10-year low flow increased from 155 ft^3/s or 100 Mgal/d to 346 ft^3/s or 224 Mgal/d, whereas the average annual discharge remained about the same.

Development along the unregulated part of the Illinois River, designated a scenic river, has caused pollution because of increased septic-system discharge and recreational use (U.S. Geological Survey, 1984). Sustained low flows have made this river popular with canoeists and sportsmen. The 7-day, 10-year low flow near Tahlequah (table 2, site 5) is 16.8 ft^3/s or 10.8 Mgal/d.

Flooding is a major issue in urban areas and areas along tributary streams. In Tulsa, damages were estimated to be $150 million and 14 lives were lost during flooding caused by prolonged intense rains in May 1984 (U.S. Geological Survey, 1985). The 100-year flood of the rural Fourche Maline (table 2, site 8), a tributary to the Poteau River, has been substantially decreased with 64 percent of the basin controlled by 14 floodwater-retarding structures.

Salt Fork Arkansas River and Cimarron River Basins.— The Salt Fork Arkansas River enters Oklahoma from Kansas and flows easterly to the Great Salt Plains Lake. The river continues southeasterly, meandering 160 miles through rolling prairie hills, draining a total of 6,764 mi^2 where it joins the Arkansas River. The Cimarron River enters the State from New Mexico in the extreme western panhandle. After leaving and reentering twice, the river flows southeasterly to the Arkansas River, transversing 410 miles in Oklahoma. One-third of the total drainage areas of the basins are in Oklahoma, including most of the north-central part of the State. The total major reservoir storage in the Salt Fork Arkansas and Cimarron basins is 30,000 acre-ft or 9,780 Mgal.

Great Salt Plains Lake (completed in 1941) provides flood protection for the lower Salt Fork Arkansas basin; the regulated 100-year flood peak at Tonkawa (table 2, site 1) is 69,400 ft^3/s or 44,900 Mgal/d. No major impoundment restricts the flow of the Cimarron River. The 100-year flood discharge at Perkins (table 2, site 2) is 174,000 ft^3/s or 112,000 Mgal/d. Several tributaries of the Cimarron are known for their recurrent flooding. Major floods of 1959, 1974, and 1983 (Oklahoma Water Resources Board, 1984b; U.S. Geological Survey, 1985) have sent Guthrie residents to higher ground.

Lake Hefner (completed in 1943), on the southern edge of the Cimarron basin, provides municipal water supply to Oklahoma City as well as a recreation area near the State's largest population center. Water for Lake Hefner is imported from the North Canadian River through an Oklahoma City water permit.

Many current uses and most future development in these two basins is limited by natural brine seeps and springs (U.S. Geological Survey, 1984), although some development is possible along freshwater tributaries. Large chloride concentrations render the water unsuitable for irrigation, industrial, and commercial uses. Combined, these two basins contribute 34 percent of the total, average annual dissolved-solids load while contributing only 4 percent of the average annual water discharge of the Arkansas River (U.S. Geological Survey, 1985). Because many of the streams in these basins are saline, 95 percent of the water withdrawn for use is from ground-water sources.

Verdigris River and Grand (Neosho) River Basins.—The Verdigris and Grand River basins cover only one sixth of the land area, but have more surface water per square mile than any other part of the State. The Verdigris River flows southerly from its source in Kansas through Oologah Reservoir and is joined from the west, a short distance downstream, by the Caney River and Bird Creek before entering the Arkansas River near Muskogee. The drainage

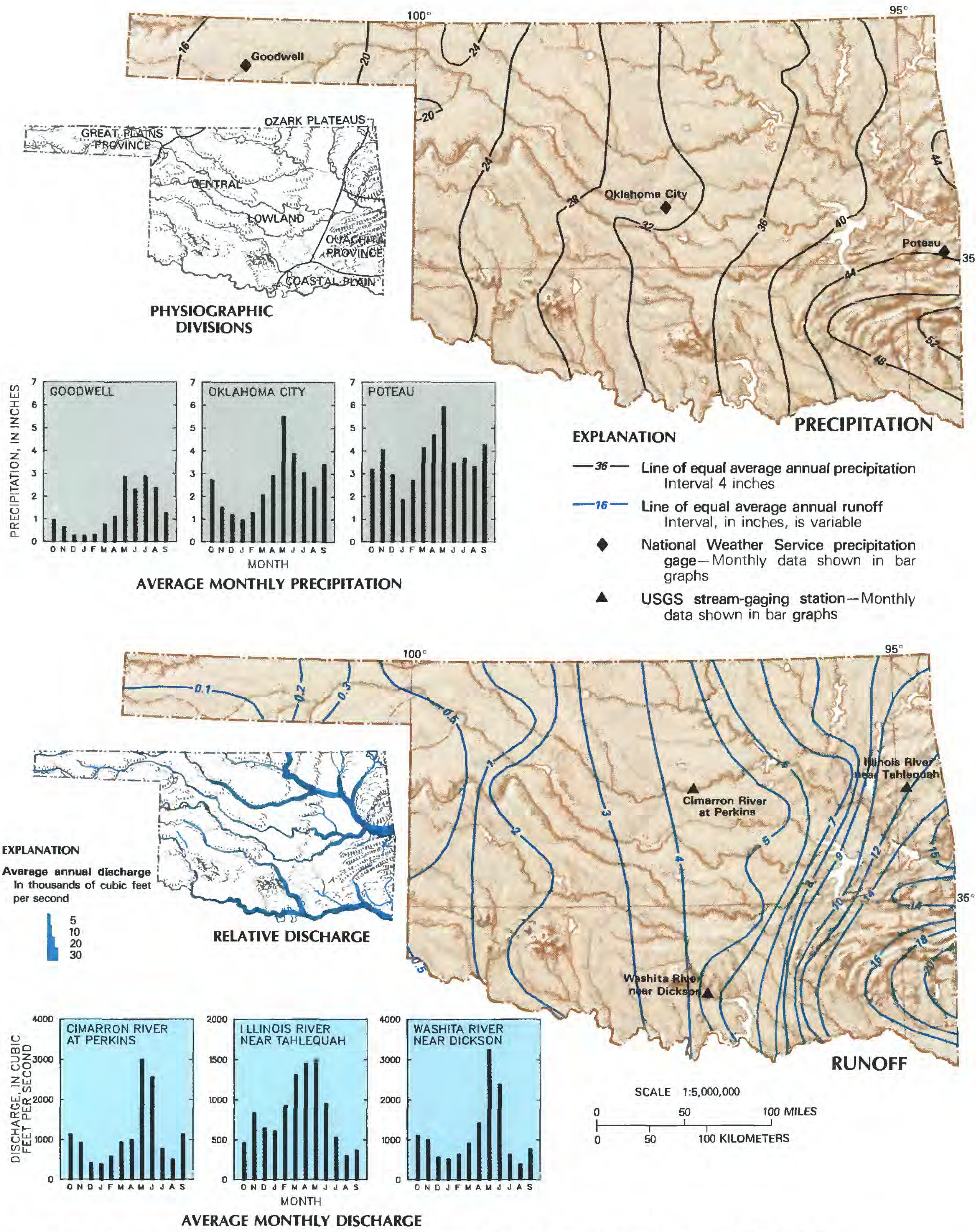

Figure 1. Average annual precipitation and runoff in Oklahoma and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Oklahoma

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; mg/L = milligrams per liter. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	ARKANSAS-WHITE-RED REGION Arkansas River basin, Salt Fork Arkansas River and Cimarron River basin, Verdigris River and Grand (Neosho) River basins, and Canadian River basins[1]							
1.	Salt Fork Arkansas River at Tonkawa (07151000).	4,528	1942-82	6.68	730	69,400	Appreciable	Salinity limits use. Average dissolved solids is 3,100 mg/L.
2.	Cimarron River at Perkins (07161000).	17,852	1940-82	8.73	1,180	174,000	None	Salinity limits use. Average dissolved solids is 5,100 Periodic flooding.
3.	Arkansas River at Tulsa (07164500).	74,615	1926-64 1965-82	155 346	6,550 6,940	324,000 165,000	Moderete Appreciable	
4.	Verdigris River near Claremore (07176000).	6,534	1936-62 1965-82	3.06 15.4	3,720 3,720	178,000 46,400	Moderate Appreciable	
5.	Illinois River near Tahlequah (07196500).	959	1936-82	16.8	867	141,000	Negligible	
6.	Little River near Sasakwa (07231000).	865	1943-65 1966-82	.69 .08	398 242	66,800 23,300	None Appreciabla	
7.	Beaver River at Beaver (07234000).	7,955	1938-82	.03	95.9	68,100	. . . do . . .	Undependable flow limits use. Analysis includes period since impoundment of Optima Reservoir (1978).
8.	Fourche Maline near Red Oak (07247500).	122	1939-63 1966-82	.10 .12	126 133	51,400 17,900	None Appreciable	Regulation by floodwater retarding structures.
	Red River basin[2], Washita River basin							
9.	North Fork Red River near Headrick (07305000).	4,244	1946-82	0.39	266	54,200	Appreciable	Analysis based on period of record since reguletion begen. Salinity limits use. Average dissolved solids is 4,660 mg/L.
10.	Red River near Gainesville (07316000).	30,782	1947-82	97.6	2,750	180,000	Moderate	Analysis based on period of record since regulation began. Salinity limits use. Average dissolved solids is 2,140 mg/L.
11.	Washita River near Dickson (07331000).	7,202	1929-60 1962-82	33.7 4.87	1,540 1,140	117,000 64,200	Negligible Appreciable	Municipel supply water is treated by desalination process.
12.	Muddy Boggy Creek near Farris (07334000).	1,087	1938-82	.14	880	61,200	Moderate	Major water use is water supply.
13.	Red River at Arthur City, Tex. (07335500).	44,531	1945-82	375	7,890	174,000	Appreciable	Analysis based on period of record since regulation began.

[1] Includes parts or all of the Upper Cimarron, Arkansas-Keystone, Lower Cimarron, Lower Arkansas, Neosho—Verdigris, Lower Canadian and North Canadian Subregions (Seaber, and others, 1984).

[2] Includes parts or all of the Red Headwaters, Red—Washita, and Red—Sulphur Subregions (Seaber, and others, 1984).

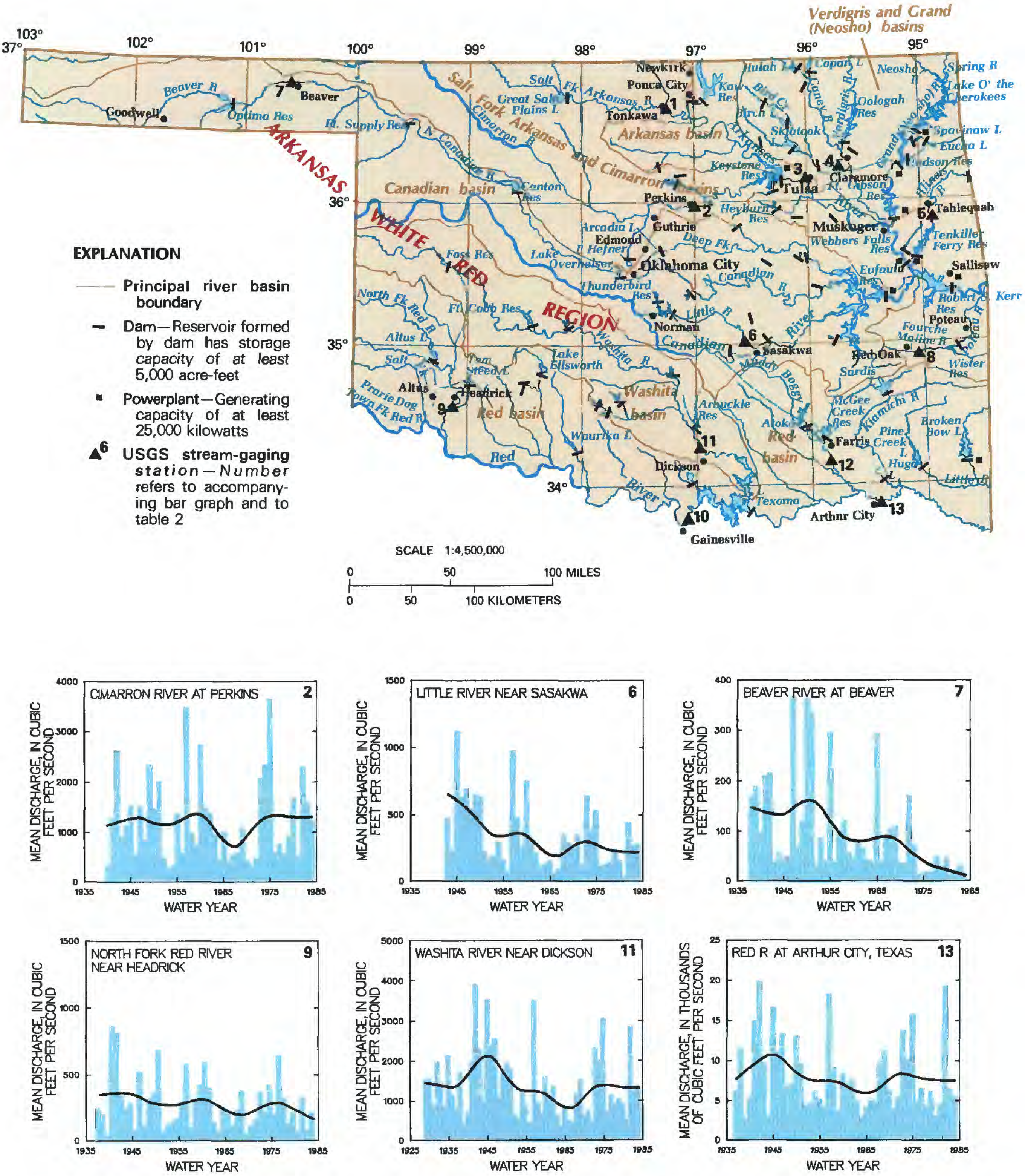

Figure 2. Principal river basins and related surface-water resources development in Oklahoma and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

area of the Verdigris basin is 8,303 mi², of which 4,290 mi² are in Oklahoma. Flat, rolling hills dominate the topography. The combined reservoir capacity of both basins is 2,880,000 acre-ft or 938,000 Mgal.

Although Oologah Reservoir supplies water for navigation, flood control and water supply are even more important. The effects of this regulation near Claremore (table 2, site 4) have been to decrease the 100-year flood peak by 74 percent and increase the 7-day, 10-year low flow by 400 percent. Other multipurpose impoundments in the Verdigris River basin are: Birch Lake (completed in 1977), Copan Lake (1983), Hulah Lake (1951), and Skiatook Lake (1985).

The Grand (Neosho) River is called the Neosho River in Kansas downstream to the point where the Spring River joins, and the Grand River downstream of that point to the Arkansas River. The Grand River follows a winding course through a chain of reservoirs before entering the Arkansas River. The basin has 12,520 mi² of drainage area, of which 6,781 mi² are in Oklahoma; 35 percent, or 164 miles, of the river's total length is in Oklahoma. The terrain consists of low mountains with rocky stream channels.

In addition to fulfilling downstream navigation needs, the Grand River has been developed for hydroelectric power and water supply by the Grand River Dam Authority. The combined hydroelectric-power output capacity for Lake O' the Cherokees (completed in 1940), Hudson Reservoir (1964), and Fort Gibson Reservoir (1953) is 231,400 kilowatts. Water for municipal supply is exported from Eucha Lake (completed in 1952) and Spavinaw Lake (1924) to Tulsa.

Canadian River Basin.—The Canadian River flows easterly into Oklahoma from Texas, meanders southeasterly 411 miles and drains 19,487 mi² in Oklahoma before joining the Arkansas River below Eufaula Reservoir. The major tributaries are the North Canadian River (including the Deep Fork) and the Little River.

Surface-water development has been limited in the western half of the Canadian River basin because of inconsistent supply, saline water, and inadequate dam sites. Municipal, industrial, and agricultural users have had to depend on ground-water supplies.

Five major reservoirs—Fort Supply (completed in 1942), Canton (1948), Eufaula (1948), Thunderbird (1948), and Optima (1978)—were constructed for flood control and water supply and have a combined storage capacity of 2,710,000 acre-ft or 883,000 Mgal. Eufaula Reservoir also provides hydroelectric power and sediment control as an aid to navigation. Arcadia Lake (under construction) will serve as water supply for Edmond and flood control for the Deep Fork. Thirteen additional municipal water-supply impoundments that have more than 5,000 acre-ft or 1,630 Mgal of storage have been built in central Oklahoma on tributary streams.

Thunderbird Reservoir on the Little River has provided flood protection for downstream reaches by decreasing the 100-year flood by 65 percent near Sasakwa (table 2, site 6). Because municipal supply is the primary use and municipal return flow is exported to the Canadian River, the average annual discharge near Sasakwa has decreased from 398 ft³/s or 257 Mgal/d to 242 ft³/s or 156 Mgal/d. The 15-year moving average discharge (fig. 2) shows a steady decrease, probably due to population increase in the Norman area.

In the panhandle, irrigation pumping and diversions from the Beaver River have steadily decreased the annual discharge at Beaver (fig. 2, site 7) since 1937. Apportionment of water rights for Optima Reservoir (completed in 1978), downstream from Beaver, became an issue when residents and communities filed applications seeking more water than the expected yield (Oklahoma Water Resources Board, 1984b).

In much of the western part of the basin, streams have been fully allocated, and little water is available for future development (U.S. Geological Survey, 1984). Many urban areas have water demands that exceed their water supplies and are continually acquiring additional surface-water rights as they become available.

Red River Basin

At the 100th meridian, the Prairie Dog Town Fork Red River flowing eastward from Texas, forms the southern border of Oklahoma. At the confluence of the Prairie Dog Town Fork with the Salt Fork, the waterway continues as the Red River proper, spanning 517 miles from Texas to Arkansas. Thirty-four percent, or 22,971 mi², of Oklahoma is drained by the Red River and its northern tributaries.

Lake Texoma (completed in 1944), one of the largest multipurpose reservoirs in the United States, regulates the Red River. Prior to regulation, the maximum recorded discharge of the Red River at Arthur City (table 2, site 13) was 201,000 ft³/s or 130,000 Mgal/d on May 21, 1935. Since regulation, records indicate that the 100-year flood peak discharge is 174,000 ft³/s or 112,000 Mgal/d. The average discharge for the period since regulation is 7,890 ft³/s or 5,100 Mgal/d. Additional impoundments that have been built for flood control, water supply, irrigation, fish and wildlife propagation, and recreation are Altus Lake (completed in 1948), Atoka Lake (1964), Pine Creek Lake (1969), Broken Bow Lake (1970), Hugo Lake (1971), Tom Steed Lake (1975), Waurika Lake (1977), and Sardis Lake (1982). The combined reservoir capacity in the Red River basin is 4,510,000 acre-ft or 1,470,000 Mgal.

Water from streams draining southeastern Oklahoma is in demand because the water quality is superior to that of streams draining southwestern Oklahoma. Urban growth has necessitated water transfer from areas of surplus water resources. Oklahoma City imports 60 acre-ft or 19.5 Mgal of water per day from Atoka Lake on Boggy Creek for municipal supply. An additional reservoir (McGee Creek) is under construction to supply water to Oklahoma City. In the southwest, natural brine discharges increase the chloride concentration so that several streams are unusable for municipal and irrigation supply (Stoner, 1982a).

Agriculture is important to the Red River basin, but without irrigation the farming economy is endangered. The W. C. Austin Project in the North Fork drainage near Altus supplies 36,000 acre-ft or 11,700 Mgal of water to about 47,000 acres to augment sparse precipitation.

Washita River Basin.—The Washita River flows southeasterly from west-central to south-central Oklahoma. The channel meanders 575 miles through gently rolling terrain; at the Arbuckle Mountains the channel narrows and deepens before emerging onto the flat coastal plain along the Red River. The basin drainage area is 7,945 mi^2, of which 95 percent is in Oklahoma.

The threat of devastating floods such as the May 19, 1957, peak discharge of 98,000 ft^3/s or 63,300 Mgal/d at Dickson has been reduced by upstream regulation. The most significant surface-water development in the basin was construction of about 1,100 floodwater-retarding structures that regulate streamflow in about 47 percent of the basin. These structures and additional flood protection by Foss Reservoir (completed in 1961), Fort Cobb Reservoir (1959) and Arbuckle Reservoir (1967) have substantially reduced flood damages. They have a combined storage capacity of 360,000 acre-ft or 117,000 Mgal.

The average annual discharge since regulation near Dickson (table 2, site 11) is 1,140 ft^3/s or 737 Mgal/d. Although the 7-day, 10-year flow is 4.87 ft^3/s or 3.14 Mgal/d, an extended period of no flow was recorded in 1956. Average annual discharge can be misleading. The extremes indicate considerable fluctuations in flow quantities. Because the surface-water supply is undependable, many municipalities depend, at least in part, on ground water.

Water use has reduced the average annual flow and 7-day, 10-year low flow. Dry-land farming was practiced for years because of an insufficient irrigation supply. Water stored in Fort Cobb Reservoir and in the floodwater-retarding structures is now used to irrigate cotton, peanuts, wheat, and hay.

Poor cultivation practices had turned the once clear running Washita channels into a silt-filled drainage. Extensive flood-prevention and conservation programs are contributing to a decrease in erosion and stream sedimentation.

Large sulfate concentrations resulting from natural dissolution of gypsum in the basin affect the suitability of the water for public supply (Stoner, 1982b). Foss Reservoir is used for municipal supply, but the water must be treated by a desalination process.

SURFACE-WATER MANAGEMENT

Oklahoma's surface-water resources are managed by the Oklahoma Water Resources Board. The use of surface water in Oklahoma is governed by a modified doctrine of prior appropriation. The Water Resources Board administers a permitting program for surface-water withdrawals for all of Oklahoma except the drainage of the Grand River which is under the jurisdiction of the Grand River Dam Authority, a separate State entity. Permits are required for all but domestic use.

Oklahoma is a member of four interstate compacts with neighboring states that govern waters of the Arkansas and the Red River basins. The primary purpose of the compacts is to apportion the waters among the States fairly and to provide a forum for the exchange of information and resolution of controversy between members.

The "Oklahoma Comprehensive Water Plan" (Oklahoma Water Resources Board, 1980) was adopted by the first session of the Thirty-Eighth Legislature in 1981. The focal point of the Water Plan entails eight regional plans of development that maximize water resources development without water transfer. One of the key recommendations contained in the plan was establishment of a means to finance water-resources development. State voters approved the concept to use money from a water-development fund as collateral for investment certificates that are sold to raise money for water projects at the local level. The fund also serves as a source of funding for the State match on any Federal projects. The U.S. Geological Survey participates in a cooperative program with the Oklahoma Water Resources Board in which surface-water data collection and analysis are performed to aid in the accomplishment of surface-water management objectives.

Many of the State's waterworks were constructed prior to the adoption of the Water Plan. These single to multipurpose projects have been developed and are managed by the U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Soil Conservation Service, Grand River Dam Authority, and numerous cities and towns.

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OREGON
Surface-Water Resources

Surface water is of prime importance in Oregon; it comprises about 84 percent of the total water use in the State. Western Oregon has a good supply of surface water, whereas surface water is a limited resource in eastern Oregon. There is a large variation in the distribution of surface water seasonally and areally throughout the State. The period of low flow occurs in late summer. Many of the smaller streams in eastern Oregon are dry by summer's end, but the larger streams, which follow a similar seasonal pattern, still flow in late summer. Reservoir storage is necessary throughout the State to augment summer flows with captured winter and spring runoff.

Irrigation comprises 88 percent of the total water used in Oregon; surface water provides 85 percent of the water used for irrigation. Many of the major cities, such as Portland, Salem, Eugene, Corvallis, Pendleton, Coos Bay, and Astoria, depend on surface water as their primary source of supply. Oregon is second only to Washington in the amount of water used for hydroelectric power. In fact, Oregon and Washington used more water for hydroelectric power than all of the eastern States combined (Solley and others, 1983). Surface-water withdrawals in Oregon for various purposes and related statistics for 1985 are given in table 1.

The efficient use of surface-water supplies is severely limited because of the competitive and sometimes incompatible demands for surface water. These competitive demands involve municipal supplies, irrigation, Indian lands, industry, recreation, fisheries, and hydroelectric power. The establishment of minimum flows for instream use is a current critical issue, as is the sustained flooding of Malheur and Harney Lakes.

GENERAL SETTING

Oregon is divided into nine physiographic divisions (fig. 1, Dicken, 1965), four of which are in western Oregon (the Willamette Valley, the Coast Range, the Cascade Renge, and the Klamath Mountains) and five are in eastern Oregon, the Blue Mountains, the Deschutes-Umatilla Plateau, the High Lava Plain, the Basin and Range, and the Owyhee Upland). The hydrology of Oregon is influenced by five mountain ranges; the Cascade Range is a natural divide between eastern and western Oregon. Surface runoff patterns generally are uniform in western Oregon, whereas runoff patterns in the eastern part of the State differ widely. The Columbia and the Snake Rivers bring water that originates in other States and Canada into Oregon; however, most streams originate within the State and with flows that result from the rain and snow of winter storm fronts that move eastward from the Pacific Ocean. Atmospheric circulation provides the basic west-to-east movement, but the topography of the land largely determines where the precipitation falls (Phillips and others, 1965). Up to 160 inches of rain falls annually on the western slopes of the Coast Range, which intercepts the eastward-moving storms from the Pacific Ocean (fig. 1). The eastern side of the mountains receives much less precipitation. Farther to the east, storms that reach the western side of the Cascade Range release much of the remaining moisture. Average annual precipitation is about 40 inches in the Willamette Valley between the Coast Range and the Cascade Range. Some parts of eastern Oregon record less than 10 inches of precipitation annually. The average annual precipitation over the entire State is about 27 inches. Average annual runoff is 20 inches (Busby, 1966). The remaining 7 inches evaporates, transpirates, or is consumed by human activities.

Table 1. Surface-water facts for Oregon

[Data 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 SURFACE WATER, 1980	
Number (thousands)	941
Percentage of total population	36
From public water supply systems:	
Number (thousands)	851
Percentage of total population	33
From rural self-supplied systems:	
Number (thousands)	90
Percentage of total population	3
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	6,800
Surface water only (Mgal/d)	5,700
Percentage of total	84
Percentage of total excluding withdrawals for thermoelectric power	84
Category of use	
Public-supply withdrawals:	
Surface water Mgal/d	160
Percentage of total surface water	3
Percentage of total public supply	70
Per capita (gal/d)	190
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	19
Percentage of total surface water	0.3
Percentage of total rural domestic	13
Per capita (gal/d)	211
Livestock:	
Surface water (Mgal/d)	19
Percentage of total surface water	0.3
Percentage of total livestock	73
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	440
Percentage of total surface water	8
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	85
Excluding withdrawals for thermoelectric power	84
Irrigation withdrawals:	
Surface water (Mgal/d)	5,000
Percentage of total surface water	88
Percentage of total irrigation	85
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	490,000

PRINCIPAL RIVER BASINS

Oregon is located in three water-resources regions—the Pacific Northwest, California, and Great Basin (fig. 2). Most of the river basins in the State are in the Pacific Northwest Region. The Klamath River basin is included in the California Region. A few very small ephemeral streams are in the Great Basin Region and are not discussed. The Snake and the Columbia Rivers, which follow State borders, originate in other States and in Canada, but all other major streams except the Owyhee River are mainly within the State. Most of these river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

PACIFIC NORTHWEST REGION

Oregon Closed Basins Subregions

The Silvies and the Donner und Blitzen Rivers are the primary sources of flow into the closed Malheur and Harney Lakes basin. The basin is the largest closed basin in Oregon, with an area of 5,300 mi² (square miles). The average elevation of the basin floor is about 4,100 feet above sea level. Average annual flow in the Silvies River, which drains the Strawberry Mountains from the north, is extremely variable, ranging from 591 ft³/s (cubic feet per second) or 382 Mgal/d (million gallons per day) in 1983 to 15 ft³/s or 10 Mgal/d in 1934 (fig. 2). In dry years, irrigation of hay crops and pasture completely depletes its flow. The monthly average hydrograph is typical of streams in eastern Oregon that are derived almost entirely from snowmelt (fig. 1). More than 90 percent of the total annual flow occurs in April, May, and June. The Donner und Blitzen River, which drains the Steens Mountains, also derives its flow from snowmelt, but springs in the permeable basalt along the river canyon provide high summer base flow. Much of this river's flow is used for irrigation and for operation of the Malheur National Wildlife Refuge. Very little water reaches Malheur Lake, and no water runs off to Harney Lake (at the lowest part of the basin), in dry years; as a result, Harney Lake is frequently dry, and Malheur Lake is dry during successive dry years (fig. 2). The quality of water in Malheur Lake is suitable for most uses, but, because evaporation concentrates the dissolved salts from inflowing streams, the water of Harney Lake is not usable for agriculture or fisheries. Recently, 2 years of above-average snowpack (1983-84) have resulted in record high runoff into Malheur and Harney Lakes. As a result, the two lakes, which normally are two separate water bodies, have combined into one lake that covers 170,000 acres; during previous years with high runoff, the composite lake covered only about 50,000 acres. The level of the composite lake reached 4,102 feet above sea level, which is about 7 feet higher than had been observed in the previous 50 years. Most of the wildlife habitat has been flooded, and about 30 ranch families have been evacuated. Many of these ranches have been flooded for as long as 3 years, and possible solutions to the problem have become a major water issue in Oregon. A proposed solution involves diversion of water from Malheur Lake into the Malheur River basin. This proposal must address environmental concerns as to potential impacts on the water quality, sedimentation, and flooding in the Malheur River basin that potentially could result from the introduction of water from the Malheur–Harney basin.

Middle Snake Subregion

Owyhee River Basin.—The Owyhee River has a drainage area of 11,400 mi², about half of which is in Oregon; the other half is in Idaho and Nevada. The river enters the southeastern corner of Oregon from Idaho and flows northward through a deep canyon for 80 miles where it enters the 50-mile-long Owyhee Reservoir (fig. 2). The reservoir has a total capacity of more than 1 million acre-ft (acre-feet) or 326,000 Mgal (million gallons), and its waters are diverted to irrigate hay, fruit, sugar beets, corn, potatoes, and other crops. The reservoir provides good bass, crappie, and bluegill fishing. Only 1.25 inches of average annual runoff from the basin reaches the Owyhee Reservoir (Phillips and others, 1965). There is very little water-quality information for the area upstream from the reservoir. Below the reservoir the water quality is impacted by irrigation return flows and arsenic concentrations are introduced from ground-water seepage

Middle Columbia Subregion

The Umatilla River heads in the timbered Blue Mountains and the lower basin includes the rolling lands of the Deschutes-Umatilla Plateau. The river flows in a northwesterly direction before entering the Columbia River. The naturally low summer flows are supplemented by a storage reservoir on McKay Creek and by an off-channel reservoir fed by a diversion from the Umatilla River (Phillips and others, 1965). This stored water and the natural summer flows are almost completely depleted during low and even normal flow years. The water availability problems are magnified further by declining ground-water levels in parts of the basin. Most of the flow is diverted for irrigation during the summer in the lower basin and overland return irrigation flow carries contaminants that have an adverse effect on the water quality. The quality of the waters of the upper basin are suitable for most uses.

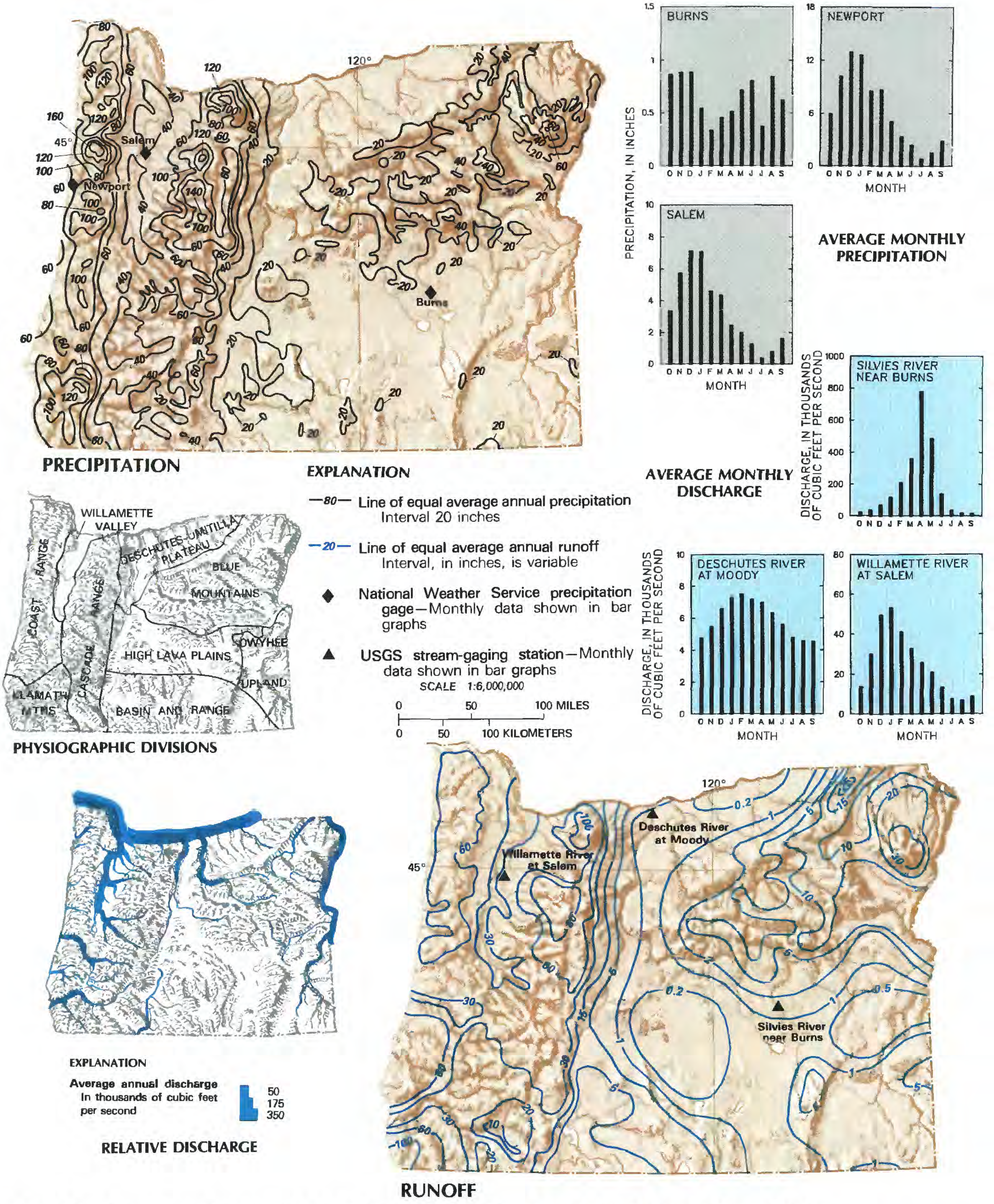

Figure 1. Average annual precipitation and runoff in Oregon and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from U.S. Weather Bureau, 1964; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Dicken, 1965.)

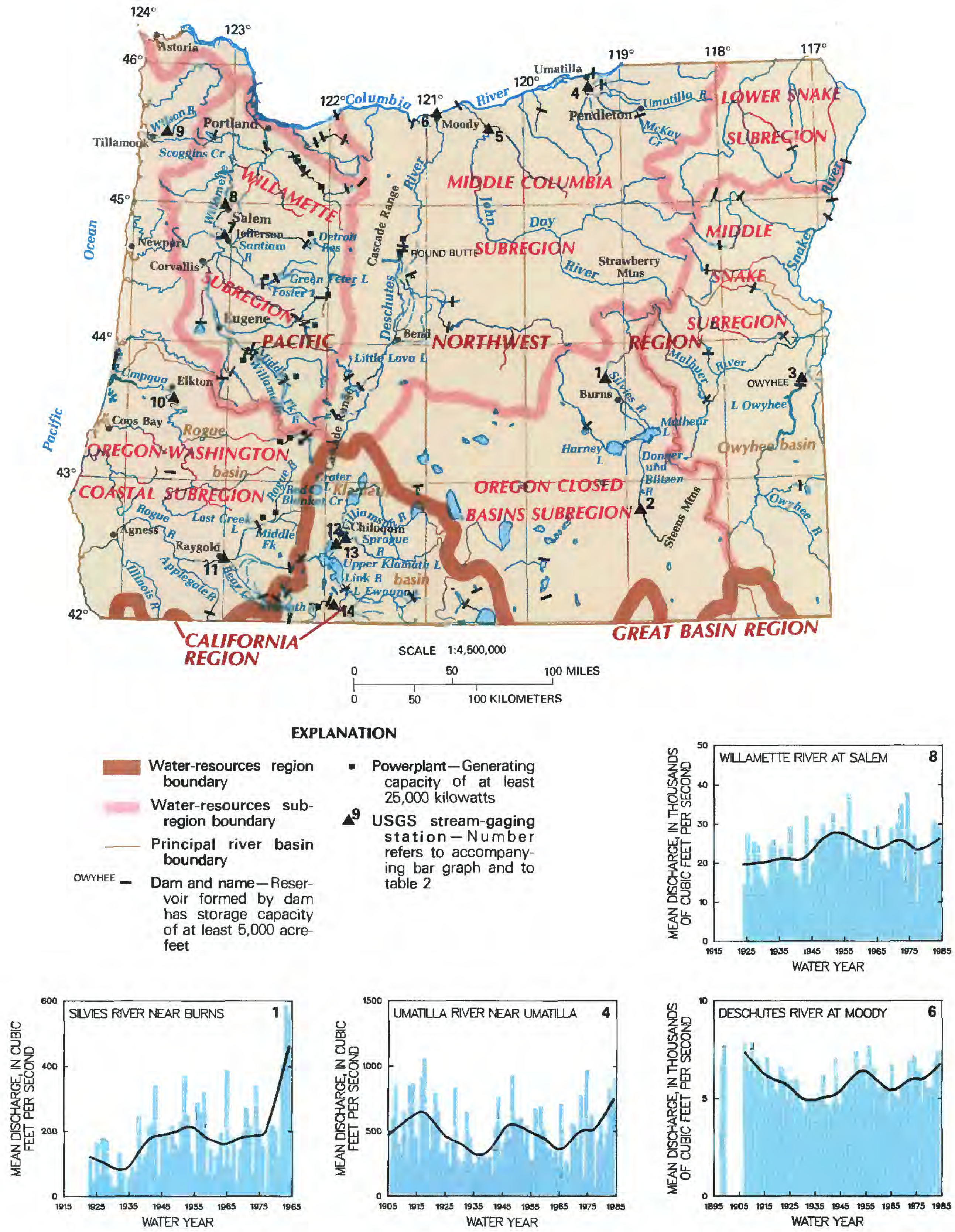

Figure 2. **Principal river basins and related surface-water resources development in Oregon and average discharges for selected sites.** Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

The Deschutes River heads at Little Lava Lake in south-central Oregon and flows 250 miles northward to the Columbia River (fig. 2). The Deschutes basin encompasses 10,500 mi² of land that is generally volcanic in origin. Sixty percent of the basin area is forested land.

The Deschutes River quality is very good in the forested areas. However, there are some problems with elevated temperatures and suspended sediment where water is diverted or returned from irrigated areas. Precipitation averages 90 inches per year in its upper reaches in the Cascade Mountain Range, but only averages about 9 inches in its lower reaches. The flow of the Deschutes River is more uniform than that of any river of its size in the United States (Phillips and others, 1965). The uniform flow rate is maintained by ground-water inflow; snowmelt and rainwater are intercepted by the spongelike pumice soil and porous lava rock and are stored in ground-water reservoirs. This ground water supplies many springs that maintain a high base flow throughout the year, as illustrated in the monthly average hydrograph in figure 1. About 40 percent of the basin is agricultural land and only about 5 percent of the total farmland is irrigated; however, irrigation accounts for the largest consumptive use of water in the basin. Most of the irrigated land is located in the middle of the basin. Six large canals near Bend divert most of the flow for irrigation. Hydroelectric power is produced at Bend and at Pelton and Round Butte Dams. Salmon and steelhead spawn in the Deschutes River and its tributaries; the river and its lakes provide excellent trout fishing.

Willamette Subregion

The Willamette River, with an average annual flow of 35,000 ft³/s or 22,600 Mgal/d and a drainage area of 11,200 mi², is the largest river within Oregon. The river heads in the Cascade Range and, upon entering the Willamette Valley, is bounded on the east by the Cascade Range and on the west by the Coast Range. From the headwaters of the Middle Fork, the Willamette flows 260 miles north and enters the Columbia River 100 miles upstream from the Pacific Ocean. The freshwater harbor at Portland provides an inland port for the Columbia River and Pacific Ocean traffic. Two-thirds of the population of Oregon reside in the basin. The basin contains the most fertile agricultural lands in the State. The flows of the river are highly controlled by 12 major reservoirs on streams draining the Cascade Range and by one on Scoggins Creek, which flows from the foothills of the Coast Range. These reservoirs are used for flood control, irrigation, and recreation and have a combined storage capacity of 2,560,000 acre-ft or 834,000 Mgal. The augmentation of low flows by the operation of these reservoirs is shown in table 2 in the 7-day, 10-year low-flow values. In the early 1920's, all industries and municipalities on the river dumped their untreated wastes directly into the river. These large loads of organically rich wastewaters resulted in severe problems associated with low dissolved-oxygen levels that persisted for many years. Since the 1950's, public involvement, legislation, and voluntary action by municipalities and industries has resulted in low-flow augmentation, basinwide secondary treatment of wastewaters, and the use of other waste-management practices that have greatly improved the quality of the water of the river (Hines and others, 1977). In addition to abating the pollution problems of the river, the State established a 150-mile stretch of river upstream of Portland as a natural, historic, scenic, and recreational greenway that protects the agricultural and other economic users of land along the river (Barlett, 1984).

Oregon-Washington Coastal Subregion

Rogue River Basin.—Except for small parts of some of its tributary streams, the Rogue River basin is entirely within Oregon. The Rogue River basin encompases 5,080 mi² and is about 210 miles long. The river heads on the slopes of Mount Mazama—a volcanic mountain whose caldera contains the 1,900-foot-deep Crater Lake. The river flows through the steep, densely timbered upper reaches and is impounded by Lost Creek Lake before it flows into the agricultural Rogue River Valley. The river joins with Bear Creek near the upper end of the valley and with the Applegate River at the lower end. It then follows a tortuous 100-mile path of winding

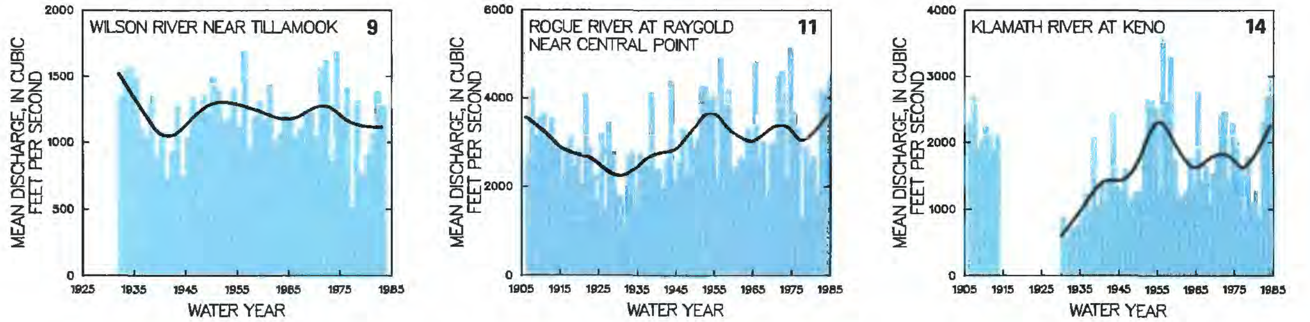

Figure 2. Principal river basins and related surface-water resources development in Oregon and average discharges for selected sites—Continued.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Table 2. Selected streamflow characteristics of principal river basins in Oregon

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
	PACIFIC NORTHWEST REGION **Oregon Closed Basins Subregion**							
1.	Silvies River near Burns (10335000).	934	1923-83	1.5	175	4,900	None	Diversions for irrigation during runoff period.
2.	Donner und Blitzen River near Burns (10396000).	200	1912-13, 1915-16, 1918-21, 1939-83	20	125	4,200	. . . do . . .	
	Middle Snake Subregion							
3.	Owyhee River below Owyhee Reservoir (13183000).	11,160	1930-83	1.7	380	. . . .	Appreciable	Divarsion of over 400,0000 acre-feet from Owyhee Dam in most years for irrigation below station.
	Middle Columbia Subregion							
4.	Umatilla River near Umatilla (14033500)	2,290	1928-83	1.3	456	19,700	Negligible	Many diversions for irrigetion.
5.	John Day River at McDonald Ferry (14048000).	7,580	1906-83	28	2,036	37,800	None	Many diversions for irrigation.
6.	Deschutes River at Moody (14103000).	10,500	1897-99, 1907-83	3,610	5,846	. . . .	Moderete	Lerge diversions for irrigation in upper basin.
	Willamette Subregion							
7.	Santiam River at Jefferson (1418900).	1,790	1909-53 1967-82	323 1,150	7,821 7,821	. . . .	Appreciable	Flow regulated since 1953 by Detroit Lake and since 1966 by Green Peter and Foster Lakes.
8.	Willamette River et Selem (14191000).	7,280	1911-41, 1969-82	2,720 5,160	23,650	. . . .	. . . do . . .	Flow reguleted by 12 reservoirs above station.
	Oregon-Washington Coastal Subregion **Rogue River basin**							
9.	Wilson River near Tillamook (14301500).	161	1932-83	51	1,205	36,700	None	Small diversions for domestic use.
10.	Umpque River near Elkton (14321000).	3,683	1906-83	797	7,517	276,000	Negligible	Diversions for irrigation.
11.	Rogue Rivar et Raygold (14359000).	2,053	1905-83	870	2,978	139,000	Moderate	Many diversions for irrigation.
	CALIFORNIA REGION **Klamath-Northern California Coastal Subregion** **Klamath River basin**							
12.	Sprague River near Chiloquin (11501000).	1,580	1922-83	127	584	13,300	None	Diversions for irrigation.
13.	Williamson River near Chiloquin (11502500).	3,000	1918-82	414	1,049	14,100	Negligible	Do.
14.	Klemath River at Keno (11509500).	3,920	1905-12, 1930-83	165	1,684	13,000	Moderate	Do.

canyons through a remote section of the Coast Range. On the western side of the range, the river joins with the Illinois River about 27 miles before the Rogue River enters the Pacific Ocean. The upper reaches of the Rogue River and the tributary streams of Middle Fork and Red Blanket Creek are used to produce hydroelectric power. The Lost Creek Lake (completed in 1977, storage capacity 465,000 acre-ft or 152,000 Mgal) and flood-control dams (completed in 1980, storage capacity 82,200 acre-ft or 26,800 Mgal) on the Applegate River also augment summer flow. The Rogue River has experienced devastating flooding in the past. A flow of 290,000 ft^3/s or 187,000 Mgal/d was measured during the December 1964 flood at the gaging station near Agness. State laws prohibit the building of dams that would interfere with fish passage on the middle and downstream sections of the Rogue River main stem.

The Rogue River has high quality water throughout the year. With the completion and operation of the Lost Creek Lake and Applegate Dam, summer flow has been agumented with an improvement of water quality during the last 10 years.

CALIFORNIA REGION

Klamath-Northern California Coastal Subregion

Klamath River Basin.—The Klamath River basin in Oregon has an area of 4,100 mi^2; the lower half of the basin is in California. The Cascade Range physiographic province forms the western boundary of the basin whereas the Basin and Range province comprises most of the basin (Dicken, 1965). Most of the basin is at an elevation of 4,000 to 5,000 feet above sea level. The principal headwater stream is the Williamson River, and its principal tributary is the Sprague River. The Williamson River flows into Upper Klamath Lake (84,000 acres), which is the largest lake wholly in Oregon (other than the presently flooded Malheur-Harney Lake). A large part of the inflow into Upper Klamath Lake is provided by springs. Seven springs, which either flow directly into Upper Klamath Lake or into its tributaries, account for a total average flow of about 1,000 ft^3/s or 646 Mgal/d. Water is diverted for power and irrigation from Upper Klamath Lake. The 2-mile-long Link River flows out of Upper Klamath Lake and into Lake Ewauna. Outflow of Lake Ewauna—the beginning of the Klamath River main stem—flows 34 miles before entering California. The John C. Boyle Powerplant is located 9 miles below Lake Ewauna. The inflow streams introduce nutrients to Upper Klamath Lake that produce an excessive growth of algae and depletes the dissolved-oxygen content of the water. The dissolved-oxygen content is below acceptable Federal limits for fish in parts of the lake, and the Link and the Klamath Rivers are adversely affected by algae in water flowing out of Upper Klamath Lake. Most of the runoff in the basin results from snowmelt that occurs from March through June. Summer flows are augmented by large springs above Upper Klamath Lake and by storage in the lake. A large amount of water is lost from the basin by evapotranspiration from marshes, lakes, and reservoirs. The Klamath River Basin Compact facilitates development and control of the water resources and provides for equitable distribution of the water to Oregon and California.

SURFACE-WATER MANAGEMENT

Oregon law gives the Director of the Oregon Water Resources Department (OWRD) the authority to issue permits to appropriate the State's surface and ground waters for beneficial uses. The OWRD also has the 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 interference with existing water rights, where joint voluntary action among users is inadequate. The OWRD is the principal cooperator with the U.S. Geological Survey in investigation of the State's surface-water resources. These activities include data collection, data analysis, and interpretive studies that together form an information base for surface-water planning and management. The Department of Environmental Quality is responsible for establishing and enforcing rules designed to prevent contamination of Oregon's surface-water resources.

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FOR ADDITIONAL INFORMATION

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Prepared by Larry L. Hubbard

PENNSYLVANIA
Surface-Water Resources

The history of Pennsylvania can be traced through the development of its water and related land resources. From its founding as a settlement in the port of Philadelphia, to its present position as a leading industrial, agricultural, and financial center, Pennsylvania's growth has depended on its varied and plentiful water resources. Pennsylvania contains about 45,000 miles of streams, more than 2,300 reservoirs, and 76 lakes (surface area greater than 20 acres).

Most streams in Pennsylvania have critical problems related to the quantity and quality of the resource. Flooding on many streams causes major damage to agriculture and urban developments. Droughts, especially during the 1960's, have been disastrous to the State, especially agriculture. Most streams are again experiencing below-average flows, which are causing water-supply problems in many areas, especially in the eastern part of the State. Surface-water pollution from point and nonpoint sources and from sedimentation also are significant problems.

In Pennsylvania, 81,000 Mgal/d (million gallons per day) or 125,300 ft³/s (cubic feet per second) were used for hydroelectric-power generation in 1980. Excluding hydroelectric-power generation, surface-water withdrawals represented 94 percent of the State's total water use. Fifty-six percent of the State's population relies on surface water for its water supply. Self-supplied industries—the largest users of surface water except for hydroelectric-power generation— withdrew 13,000 Mgal/d or 20,100 ft³/s during 1980. Surface-water withdrawals in Pennsylvania during 1980 for various purposes and related statistics are given in table 1.

GENERAL SETTING

The State includes parts of seven physiographic provinces, which form parallel belts from southeast to northwest (fig. 1). From southeast to northwest these provinces are: Atlantic Coastal Plain, Piedmont, Blue Ridge, New England, Valley and Ridge, Appalachian Plateaus, and Central Lowland.

Pennsylvania, near the center of the Temperate Zone, enjoys a moderate climate. The average annual temperature is about 50 °F (degrees Fahrenheit); average monthly temperatures range from about 29 °F in January and February to 72 °F in July. Long periods of extreme cold or heat are infrequent.

Because Pennsylvania is crossed by several major storm tracks, precipitation is plentiful; average annual precipitation ranges from about 36 inches in the north and west to about 48 inches in the east (fig. 1). All parts of the State receive snowfall during the winter. Precipitation in eastern Pennsylvania is distributed evenly throughout the year whereas the western part of the State receives most of the precipitation in the spring and summer. The eastern part of the State occasionally receives heavy rainfall from hurricanes. In Pennsylvania, about 25 inches, or almost half of the average annual precipitation, is returned to the atmosphere by evaporation or transpiration.

Like precipitation, runoff is extremely variable, both seasonally and annually as well as areally. Average annual runoff ranges from about 14 to 26 inches (fig. 1). A large part of the runoff results from snowmelt and from rainfall in the spring and early summer.

PRINCIPAL RIVER BASINS

Almost all of Pennsylvania is located in the Mid-Atlantic and Ohio Regions (Seaber and others, 1984) (fig. 2). Several small streams in the northwestern and north-central parts of the State are part of the Great Lakes Region. The principal river basins in the Mid-Atlantic and Ohio Regions are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other related information are given in table 2.

Table 1. Surface-water facts for Pennsylvania

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	6,620
Percentage of total population	56
From public water-supply systems:	
Number (thousands)	6,620
Percentage of total population	56
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	16,000
Surface water only (Mgal/d)	15,000
Percentage of total	94
Percentage of total excluding withdrawals for thermoelectric power	83
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	1,300
Percentage of total surface water	9
Percentage of total public supply	87
Per capita (gal/d)	196
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	7
Percentage of total surface water	<0.1
Percentage of total livestock	11
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	13,000
Percentage of total surface water	90
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	96
Excluding withdrawals for thermoelectric power	86
Irrigation withdrawals:	
Surface water (Mgal/d)	140
Percentage of total surface water	0.9
Percentage of total irrigation	88
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	81,000

MID-ATLANTIC REGION

Delaware Subregion

Delaware River Main Stem.—The Delaware River enters northeastern Pennsylvania and flows approximately 270 miles southward, forming the eastern boundary of the State, before entering Delaware Bay (fig. 2). The area of the Pennsylvania part of the drainage basin is 6,465 mi² (square miles), which is 50 percent of its total drainage area. The Delaware River drains 14 percent of the State. Commercial navigation extends upstream as far as Trenton, N.J.

Streams and lakes throughout the Delaware River basin are used extensively for recreation—particularly in the Pocono Mountains. A substantial amount of the river's flow is diverted to several major metropolitan areas for water supply. Many heavy industries and port facilities are located along the lower Delaware, and surface-water use in this area is great.

Within Pennsylvania, the upper Delaware River is regulated by seven major reservoirs that are used primarily for recreation, public-water supply, and flood control. The combined storage capacity is 519,200 acre-ft (acre-feet) or 169,100 Mgal (million gallons).

The Delaware River must meet minimum flow requirements to prevent the encroachment of seawater upstream. During the 1960's drought, depletion of water supplies in the basin created a crisis. The Delaware River basin is currently experiencing another drought and restrictions have been placed on water use.

Water quality in the upper reaches is suitable for most uses. Erosion and resultant sedimentation are problems in the lower Delaware River basin. The extensive soil erosion is the result of past and present mining activities, agricultural practices, and construction activities. Below Trenton, N.J., the quality of the river is degraded by large quantities of inadequately treated industrial and municipal wastes discharged from Pennsylvania and New Jersey.

Schuylkill River Basin.—The Schuylkill River basin is about 80 miles long and 25 miles wide and encompasses an area of 1,912 mi² above its mouth at Philadelphia (fig. 2).

The lower reach of the Schuylkill River is the most urbanized area in the basin. Most of the basin's population is centered around Norristown and Philadelphia. Water demands are currently high and continue to grow rapidly. Total water use in 1980 was 624 Mgal/d or 965 ft³/s, of which 29 percent was for public-water supply, 39 percent for self-supplied industries, and 32 percent for thermoelectric-power generation.

The Schuylkill River is regulated by four major impoundments: Still Creek Reservoir (completed in 1933), Blue Marsh Reservoir (1979), Green Lane Reservoir (1956), and Lake Ontelaunee; their combined storage capacity is 83,700 acre-ft or 27,290 Mgal.

The major concern in the Schuylkill River basin is pollution by acid mine drainage. The headwaters of the river are in anthracite fields. As the river leaves the Appalachian Mountain physiographic section and enters the Great Valley section, the acidic waters are partially neutralized and diluted by alkaline waters of Tulpehocken and Maiden Creeks.

Susquehanna Subregion

Susquehanna River Main Stem.—From head to mouth, the Susquehanna River has a length of 444 miles, of which 273 miles are in Pennsylvania. Seventy-six percent (21,038 mi²) of the total drainage area is in Pennsylvania. The Susquehanna River basin encompasses 46 percent of the State (fig. 2).

Except for public-supply use in the metropolitan areas of Wilkes-Barre (46 Mgal/d or 71 ft³/s) and Scranton (44 Mgal/d or 68 ft³/s), a relatively small amount of surface water is used in the basin. Most water use in the lower basin is for thermoelectric-power generation.

Flooding is a major problem along the Susquehanna River. Two major floods have occurred recently—in 1972 and 1975. The maximum discharge of record (1890–1984) on the Susquehanna River at Harrisburg (table 2, site 9) was 1,020,000 ft³/s or 659,300 Mgal/d on June 24, 1972. This value exceeded the 100-year flood peak by 36 percent.

Water quality of the main stem, except for acid mine drainage from coal mined east of the river, is suitable for most uses. Nonpoint sources of nutrients and sediment problems in the lower basin are caused by runoff from agricultural areas.

West Branch Susquehanna River Basin.—The West Branch Susquehanna River drains an area of 6,979 mi² in north-central Pennsylvania before entering the Susquehanna River at Sunbury (fig. 2, site 8).

Water use in this river basin is comparatively small. The largest single water user—the Montour Electric power-generating plant—uses about 33 Mgal/d or 51 ft³/s.

Flow in the West Branch is regulated by six flood-control reservoirs, which have a combined capacity of 440,200 acre-ft or 143,400 Mgal. Peak runoffs along the river are reduced by the regulatory storage in the basin. Flood damage has been and continues to be a concern in communities along the river. Maximum discharge of record (1939–1984) on the West Branch Susquehanna River at Lewisburg (table 2, site 10) was 300,000 ft³/s or 194,000 Mgal/d on June 24, 1972.

Although coal has been very important to the local economy, mining operations have had an adverse impact on water resources. Water quality in the upper basin generally is unsuitable for most uses because of widespread acid mine drainage. Below Lock Haven, the generally alkaline tributary streams help neutralize the acid mine drainage. This basin has one of the lowest rates of erosion in the State—probably because the widespread forests trap sediment and the amount of disturbed and barren land susceptible to erosion is small.

Juniata River Basin.—The Juniata River basin, located entirely within Pennsylvania, has a total area of 3,405 mi² or 16 percent of the Susquehanna River basin in Pennsylvania (fig. 2).

Total surface-water use in the basin is 109 Mgal/d or 169 ft³/s; the major use is self-supplied industry (34 percent). The greatest increase in usage is expected to be for irrigation.

The Juniata River is regulated by Raystown Lake (completed in 1972 with 762,000 acre-ft or 248,300 Mgal of storage capacity), which was built primarily for flood control. The lake is also used for recreation and low-flow augmentation and to control downstream water temperatures.

Water quality of the Juniata River generally is suitable for most uses, however, degradation of water quality has been caused by discharges of municipal and industrial wastes and acid mine drainage. Usually, the degradation is localized and is diluted by the stream in a relatively short distance because the quantities of waste are usually small in proportion to the volume of streamflow. Some degradation of water quality from agricultural runoff has occurred in the lower part of the basin.

The Juniata River basin is ideally suited for many water-related recreational activities. Many of its streams are used for swim-

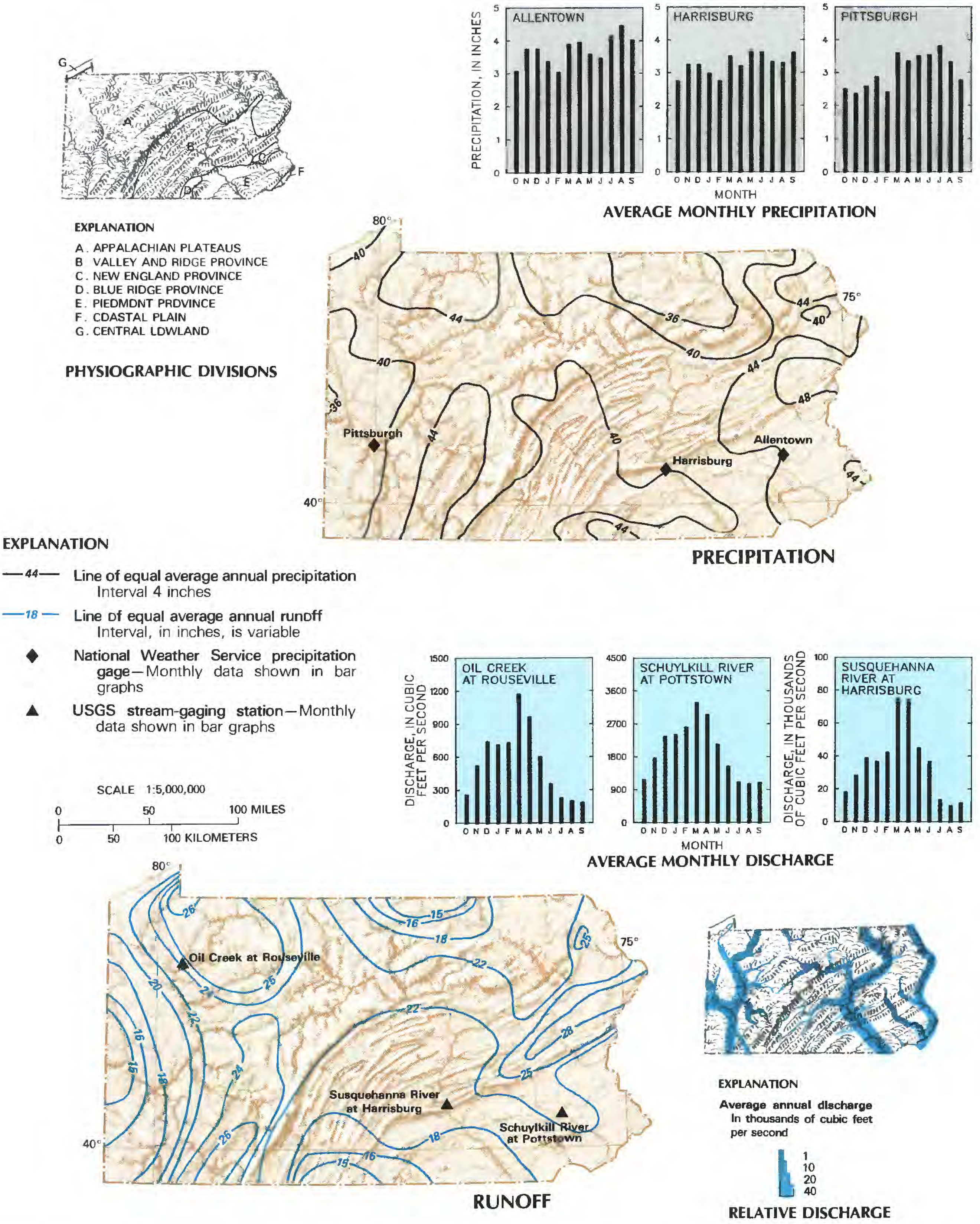

Figure 1. Average annual precipitation and runoff in Pennsylvania and average monthly data for selected sites, 1951–80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

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[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Pennsylvania State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				MID-ATLANTIC REGION DELAWARE SUBREGION Delaware River main stem				
1.	Bush Kill at Shoemakers (01439500).	117	1908-83	7.6	235	10,800	None	Recreational area.
2.	Delaware River at Belvidere, N.J. (01446500).	4,535	1922-83	920	7,890	220,000	Appreciable	
3.	Delaware River at Trenton, N.J. (01463500).	6,780	1913-83	. . . .	11,685	270,000	. . . do . . .	
				Schuylkill River basin				
4.	Schuylkill River at Landingville (01468500).	133	1947-83	28	292	14,600	None	Record not continuous.
5.	Schuylkill River at Pottstown (01472000).	1,147	1926-83	260	1,891	74,000	Moderate	
				SUSQUEHANNA SUBREGION Susquehanna River main stem				
6.	Susquehanna River at Towanda (01531500).	7,797	1913-83	550	10,600	105,000	Moderate	Regulated by seven flood-control reservoirs.
7.	Susquehanna River at Danville (01540500)	1,220	1899-1983	980	15,320	260,000	. . . do . . .	Regulated by eight flood-control reservoirs.
8.	Susquehanna River at Sunbury (01554000).	18,300	1937-83	1,600	26,520	530,000	. . . do . . .	Some regulation during low flow.
9.	Susquehanna River at Harrisburg (01570500).	24,100	1890-1983	2,556	34,350	750,000	. . . do . . .	Periodic flooding.
				West Branch Susquehanna River basin				
10.	West Branch Susquehanna River at Lewisburg (01553500).	6,847	1939-83	655	10,810	280,000	Moderate	Regulated by six flood-control reservoirs.
				Juniata River basin				
11.	Juniata River at Newport (01567000).	3,354	1899-1983	380	4,295	145,000	Moderate	Flow regulated since 1972.
				POTOMAC SUBREGION				
12.	Tonoloway Creek at Needmore (01613050).	10.7	1965-83	0.27	12.4	1,590	None	

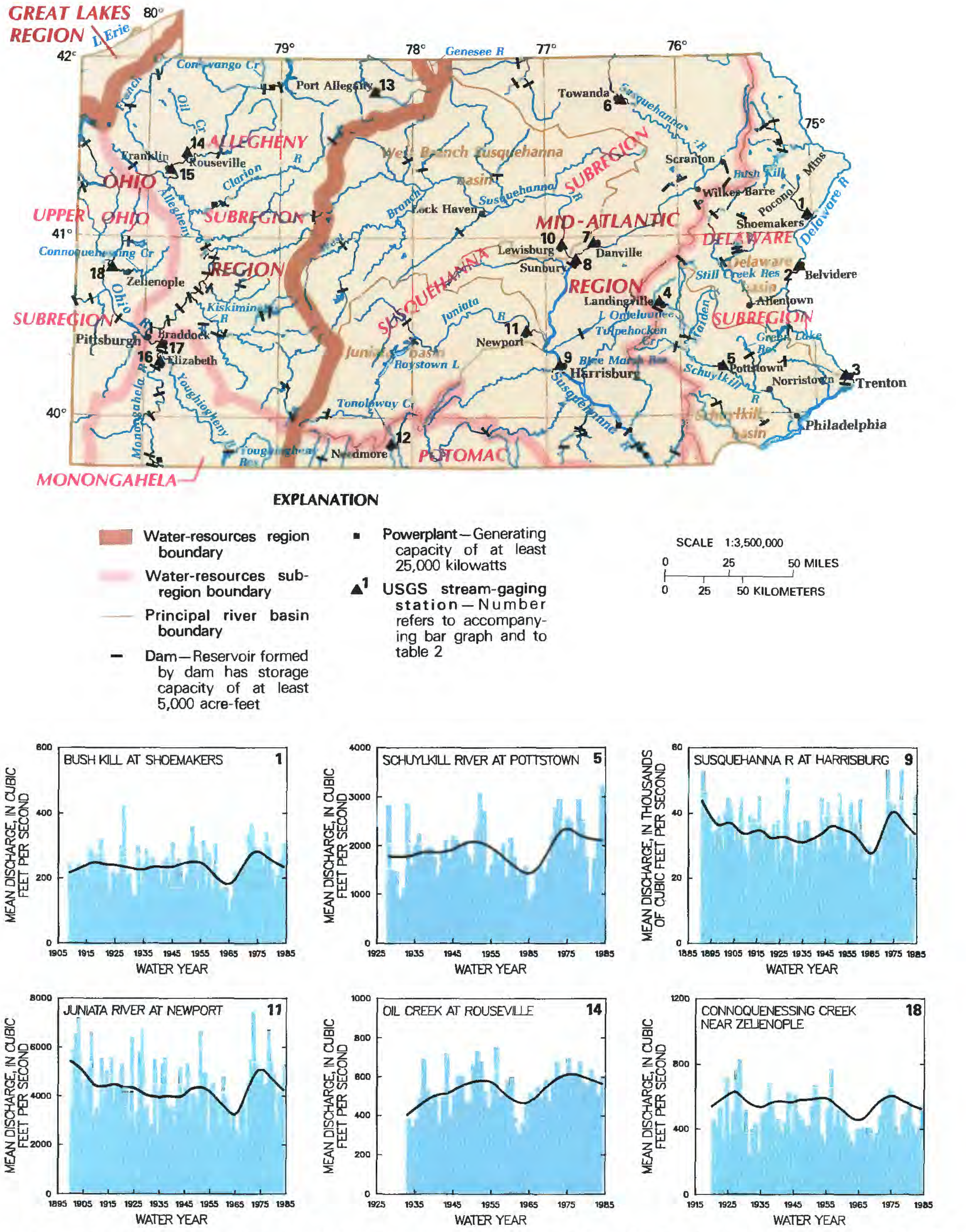

Figure 2. Principal river basins and related surface-water resources development in Pennsylvania and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Table 2. Selected streamflow characteristics of principal river basins in Pennsylvania—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Pennsylvania State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	OHIO REGION **ALLEGHENY SUBREGION**							
13.	Allegheny River at Port Allegany (03007800).	248	1974-83	24	476	9,300	None	
14.	Oil Creek at Rouseville (03020500).	300	1932-83	29	535	19,800	. . . do . . .	
15.	Allegheny River at Franklin (03025500).	5,982	1914-83	511	10,470	125,000	Moderate	Regulated by five flood-control reservoirs.
	MONONGAHELA SUBREGION							
16.	Monongahela River at Elizabeth (03075070).	5,340	1933-83	698	9,109	170,000	Appreciable	Flow regulated by locks and reservoirs.
17.	Monongahele River at Braddock (03085000).	7,337	1938-83	1,150	12,460	230,000	. . . do . . .	Flow regulated by locks and reservoirs and hydroelectric plants.
	UPPER OHIO SUBREGION **Ohio River main stem**							
18.	Connoquenessing Creek near Zelienople (03106000).	356	1919-83	11	464	19,450	Negligible	

ming and provide excellent trout and bass fishing. The main stem and larger tributaries are excellent for boating.

Potomac Subregion

The Pennsylvania part of the Potomac River basin contains headwater streams that flow through Maryland and enter the main stem of the Potomac River. The area of the basin in Pennsylvania is 1,584 mi² or about 11 percent of the total area drained by the Potomac (fig. 2). Only 3 percent of Pennsylvania is drained by the Potomac River.

The western part of the basin is sparsely populated, and most of the area is very mountainous and heavily forested.

Surface-water use in the basin is relatively small (30.8 Mgal/d or 48 ft³/s) but is projected to increase to 37 Mgal/d or 57 ft³/s by 1990. The greatest increase in usage is expected to be for irrigation—from 21.2 Mgal/d or 33 ft³/s in 1980 to 25.2 Mgal/d or 39 ft³/s in 1990.

Floods have caused some damage in the basin, but this region has sustained the least flood damage of any basin in the State. The quality of both surface and ground waters in the basin is generally suitable for most uses. Nutrient enrichment of streams and lakes from agricultural runoff is a concern in parts of the basin.

OHIO REGION

Allegheny Subregion

The Allegheny River begins high on the western slope of the Allegheny Ridge in north-central Pennsylvania, enters New York for a short distance, and then turns southward to Pittsburgh where it joins the Monongahela River to form the Ohio River (fig. 2). The Pennsylvania part of the Allegheny River basin has an area of 9,798 mi^2 or 83 percent of its total drainage area. The most important tributaries are the Kiskiminetas River, the Clarion River, French Creek, and Conewango Creek. The Allegheny River basin drains 22 percent of the State.

Surface-water use in the basin totaled 1,958 Mgal/d or 3,030 ft^3/s in 1980. The major users are self-supplied industries and thermoelectric-powerplants.

Storage capacity is mostly in the upper basin, upstream from Pittsburgh. The principal reservoirs have a combined capacity of 2,069,000 acre-ft or 674,100 Mgal. These impoundments are used primarily for flood control but also are important for recreation and low-flow augmentation.

The abundance of coal and associated deep and strip-mining activities have created serious acid mine-drainage problems in much of the basin. Stream quality in the upper reaches of the basin is degraded by oil brine and industrial discharges associated with the petroleum industry.

Monongahela Subregion

The Monongahela River basin in Pennsylvania has an area of 2,737 mi^2 (fig. 2). Six percent of Pennsylvania is drained by the Monongahela River. The headwaters of the Monongahela River are in West Virginia; it then flows northward into the Ohio River at Pittsburgh. All of the Monongahela River in Pennsylvania is navigable.

The Monongahela River and the Youghiogheny River—a principal tributary—are regulated by four major impoundments. Tygart Reservoir (completed in 1938) and Youghiogheny Reservoir (1943) are used primarily for flood control, but also are important for low-flow augmentation and recreation. Lake Lynn (completed in 1926) and Deep Creek Reservoir (1925) are used for hydroelectric power. The combined storage capacity of these impoundments is 704,300 acre-ft or 229,500 Mgal.

This basin sustains some of the greatest flood damage of any basin in the State; millions of dollars in damage occur each year. Most of the damage occurs along the Monongahela River near Pittsburgh.

Acid mine drainage from coal and associated mining activities has created serious water-quality problems in the river. Mining also has indirectly created a supply problem because of heavy demands for water by steel and related industries and by thermoelectric power-generation facilities, whose water use exceeds 3,000 Mgal/d or 4,640 ft^3/s. The most critical water-supply problem is the conflict between water-supply requirements during low-flow periods and the need to maintain flow for navigation. Currently, reservoir releases are used to maintain sufficient flow for navigation purposes during low flows. Because the navigation servitude takes precedence over all water use during low flow, a public water supplier in need of increased withdrawals could be denied a permit for additional surface-water usage.

Upper Ohio Subregion

Ohio River Main Stem.—The Ohio River drains 3,080 mi^2 in Pennsylvania (fig. 2). Most of this area is underlain by bituminous-coal reserves. Total surface-water use for the basin is one of the highest in the State—2,120 Mgal/d or 3,280 ft^3/s. Major water users are self-supplied industries (42 percent) and thermoelectric-power generation (50 percent).

Because of urbanization and the location of communities along the river, this basin experiences a significant amount of flood damage. Surface-water quality is primarily degraded by acid mine drainage, although discharges of municipal and industrial wastes also cause some degradation. Erosion and sedimentation rates are relatively high and result in an average annual sediment yield greater than 500,000 tons. The majority of this soil loss is caused by mining throughout the basin.

OTHER RIVER BASINS

Small parts of two subregions in Pennsylvania drain into the Great Lakes Region—The Eastern Lake Erie-Lake Erie and Southwestern Lake Ontario Subregions. The Eastern Lake Erie-Lake Erie Subregion is a 509-mi^2 strip of land about 15 miles wide along Lake Erie that is used extensively for recreation and is the source of water for most of the area's population. The Southwestern Lake Ontario Subregion consists of a small part of the Genesee River's headwaters (99 mi^2) in north-central Pennsylvania.

SURFACE-WATER MANAGEMENT

Since 1971, the Pennsylvania Department of Environmental Resources (PADER) has been the State agency responsible for developing water-management policies and practices. A comprehensive "State Water Plan," developed by PADER, forms the basis for water-resource management in the State. Several offices and bureaus within the Department conduct hydrologic studies of surface-water resources independently and in cooperation with the U.S. Geological Survey.

Two Federal-interstate compact commissions—the Delaware River Basin Commission (DRBC) and the Susquehanna River Basin Commission (SRBC)—were established for resources planning and regulation in the eastern two-thirds of the State. The Ohio, the Potomac, and the Lake Erie basins are not subject to equivalent regulatory structures.

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PUERTO RICO
Surface-Water Resources

Puerto Rico and its outlying islands comprise a land area of about 3,471 mi^2 (square miles). Although small in size, Puerto Rico has diverse topography, geology, and abundant surface-water resources. More than 100 streams flow to the ocean.

Surface water provides approximately 73 percent of the population's freshwater needs. Total surface-water runoff in Puerto Rico is about 1,500 Mgal/d (million gallons per day) or 2,320 ft^3/s (cubic feet per second), of which about 1,100 Mgal/d or 1,700 ft^3/s are usable (U.S. Geological Survey, 1984). Although this quantity is more than ample to supply current and anticipated needs, available resources usually are not located near areas of demand, and local water shortages can occur, especially during periods of below-normal rainfall.

Hydroelectric-power generation at nearly half of the 27 reservoirs on the island is the principal instream use of water in Puerto Rico. In 1980, instream water use was 38 percent of the estimated total use (440 Mgal/d or 681 ft^3/s) (Gomez-Gomez and others, 1983). However, hydroelectric power produces less than 1 percent of the electric power consumed on the island. Surface water also provides about 480 Mgal/d or 743 ft^3/s (67 percent) of the total water withdrawn for offstream use; ground water provides the rest (240 Mgal/d or 371 ft^3/s). The principal offstream uses are for public supplies (280 Mgal/d or 433 ft^3/s) and irrigation (180 Mgal/d or 279 ft^3/s). Surface-water withdrawals for various uses in Puerto Rico in 1980 are given in table 1.

The surface-water issues of greatest priority in Puerto Rico are adequacy of supplies, extensive flooding along the coastal valleys, elevated fecal-coliform bacteria counts in most streams, increasing eutrophication of reservoirs and coastal streams, saltwater intrusion, and sedimentation in reservoirs.

GENERAL SETTING

Puerto Rico's principal streams flow from a central mountain range—the Cordillera Central—to the sea through a complex system of small rivers. The length of the principal streams, measured from headwaters to the ocean, ranges from about 7 miles (Rio Canas) in the south coast area to about 60 miles (Rio de La Plata) in the north coast area. Many of the streams along the south coast area have almost no flow during the dry season. Along the north coast area, flow is perennial. Only seven watersheds in Puerto Rico have drainage areas larger than 100 mi^2. Base flows are generally less than 100 ft^3/s or 64.6 Mgal/d.

Average annual precipitation varies greatly, both geographically and seasonally (fig. 1). Annual precipitation averages about 75 inches on the northern coast, compared to less than 35 inches in the south. Extremes of as much as 250 inches are recorded in the rain forest of Luquillo (eastern Puerto Rico) and as little as 30 inches in the Valle de Lajas (southwestern Puerto Rico). The variability in precipitation during the year is islandwide, as shown in bar graphs for Morovis, Paraiso, Villalba, and San Sebastian in figure 1. The precipitation pattern at all sites is similar: a generally dry period that begins in December and usually ends in March or April; a spring rainfall period in April and May; an erratic, semidry period in June and July; and a wet season from August through November. The largest total monthly rainfall generally occurs during May and September.

Table 1. Surface-water facts for Puerto Rico

[Data 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 SURFACE WATER, 1980	
Number (thousands)	2,317
Percentage of total population	73
From public water-supply systems:	
Number (thousands)	1,830
Percentage of total population	58
From rural self-supplied systems:	
Number (thousands)	487
Percentage of total population	15
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	720
Surface water only (Mgal/d)	480
Percentage of total	67
Percentage of total excluding withdrawals for thermoelectric power	67
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	280
Percentage of total surface water	58
Percentage of total public supply	80
Per capita (gal/d)	153
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	15
Percentage of total surface water	3
Percentage of total rural domestic	42
Per capita (gal/d)	30
Livestock:	
Surface water (Mgal/d)	3
Percentage of total surface water	0.6
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	3
Percentage of total surface water	0.6
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	0.1
Excluding withdrawals for thermoelectric power	0.8
Irrigation withdrawals:	
Surface water (Mgal/d)	180
Percentage of total surface water	38
Percentage of total irrigation	64
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	440

Puerto Rico is in the pathway of the tropical storms and hurricanes that move through the Caribbean. The island has been affected by more than 100 storms since 1493 (Salivia, 1972). The hurricane season is from June through October. Tropical storms in the vicinity of Puerto Rico often result in severe flooding. The most significant recent floods occurred in 1970 and 1975. The floods of October 5-10, 1970, resulted in damages to most of eastern Puerto Rico and discharge yields in excess of 3,000 (ft^3/s)/mi^2 (cubic feet per second per square mile) (Haire, 1972). In 1975, precipitation during tropical storm Eloisa exceeded 25 inches in 48 hours throughout southwestern Puerto Rico. Extreme floods with recurrence intervals of almost 100 years were recorded.

A significant part of the rainfall in Puerto Rico evapotranspires. Average annual pan evaporation ranges from about 80 inches in coastal areas to about 50 inches in the interior (actual evapotranspiration is estimated to be about 80 percent of pan evaporation). Average monthly pan evaporation varies seasonally, ranging from a high of about 6 to 8 inches during June and July, and a low of about 3 to 5 inches during November and December (Black and Veatch, and R. A. Domenech and Associates, 1971).

Runoff varies greatly geographically and seasonally in response to precipitation fluctuations and reservoir regulation (fig. 1). Average annual runoff ranges from about 20 inches in the north, because of regulation and withdrawals for public supply, to about 150 inches in the rain forest of Luquillo. The average monthly discharges for the selected sites in figure 1 also show the runoff variability. The lowest average monthly discharges at Rio Grande de Manati, Rio Fajardo, Rio Portugues, and Rio Grande de Anasco (table 2, sites 3, 9, 13, and 15) are 166 ft^3/s or 107 Mgal/d, 34 ft^3/s or 22 Mgal/d, 6.1 ft^3/s or 3.9 Mgal/d, and 100 ft^3/s or 64.6 Mgal/d, respectively. In general, two periods of runoff occur. A large part of the runoff occurs during August through December, and a second period of intense runoff occurs during April and May (fig. 1).

PRINCIPAL RIVER BASINS

Puerto Rico and its outlying islands are located in the Caribbean Region, Puerto Rico Subregion (fig. 2). The surface waters in Puerto Rico have been subdivided into four major areas (U.S. Water Resources Council, 1978). The northern coastal area extends from Rio Grande to Quebrada Fajardo, the eastern coastal area from Rio Fajardo to Cano Santiago, the southern coastal area from Rio Maunabo to Rio Loco, and the western coastal area from Quebrada Boqueron to Rio Grande de Anasco.

These areas are described below; their locations and long-term variations in streamflow at representative gaging stations are shown in figure 2. Streamflow characteristics and other related information are given in table 2. The effect of reservoir construction is not noticeable from figure 2. Streamflow records do not show changes in streamflow patterns due to reservoir construction because none of the recording gages were installed prior to dam construction.

CARIBBEAN REGION

Puerto Rico Subregion

North Coast Area.—The northern coast of Puerto Rico is a tropical area characterized by karst topography that developed on a series of limestone formations that strike east-west and dip about 5° to the north. The limestone of the northern coast covers an area about 80 miles long from Aguada to Loiza Aldea and as much as 15 miles wide near Arecibo, encompassing about 620 mi^2 or one-fifth of the land area of Puerto Rico.

The principal streams of the northern coast are the Rio Grande de Loiza, the Rio de La Plata, the Rio Grande de Manati, and the Rio Grande de Arecibo. The Rio Grande de Loiza flows entirely through volcanic rocks into the alluvial valleys east of Metropolitan San Juan; it is the principal source of water for the city. The Rio de La Plata and the Rio Grande de Arecibo are regulated for water supply and power generation. The Rio Grande de Manati is the largest unregulated river basin in Puerto Rico. The other principal streams flow from the volcanic rocks of the Cordillera Central through the limestone hills to the ocean. Stretches of two smaller streams west of Arecibo (the Rio Tanama and the Rio Camuy) flow underground through a complex of limestone caves and deep canyons. All the streams in the area are sources of water supply.

East of Arecibo, large swampy areas have formed on the northern coastal plain, Cano Diburones between the Rio Grande de Manati and the Rio Grande de Arecibo, and Laguna Tortuguero, between the Rio Grande de Manati and the Rio Cibuco. Both are notable for the large amounts of nearly freshwater that they discharge.

The population of the northern coastal area is about 2.2 million, of which about 1.0 million live in Metropolitan San Juan. Surface-water withdrawals are about 230 Mgal/d or 356 ft^3/s for public-supply uses (Gomez-Gomez and others, 1984). The discharge of sewage effluents to streams and to the ocean total about 37.6 Mgal/d or 58 ft^3/s. Most of the sewage receives only partial treatment because of overloading at the treatment plants.

Industrial, agricultural, and domestic water demands in several basins along the northern coast are rapidly approaching maximum available supplies. In the Rio Cibuco basin, most of the available ground-water and surface-water supplies are committed to agriculture, domestic, and industrial uses. Between the Rio Grande de Manati and the Rio Grande de Arecibo, ground-water resources in the Barceloneta area can support only limited additional development. The development of water supplies in the Rio Grande de Manati and the Rio Grande de Arecibo is contemplated in a massive plan to provide water to Metropolitan San Juan through the year 2020 (Vazquez and others, 1983).

Six reservoirs with capacities that exceed 5,000 acre-ft (acre-feet) or 1,630 Mgal (million gallons) have been built since 1913 in the northern coastal area: Loiza (12,700 acre-ft or 4,140 Mgal), La Plata (20,000 acre-ft or 6,520 Mgal), Carite (10,700

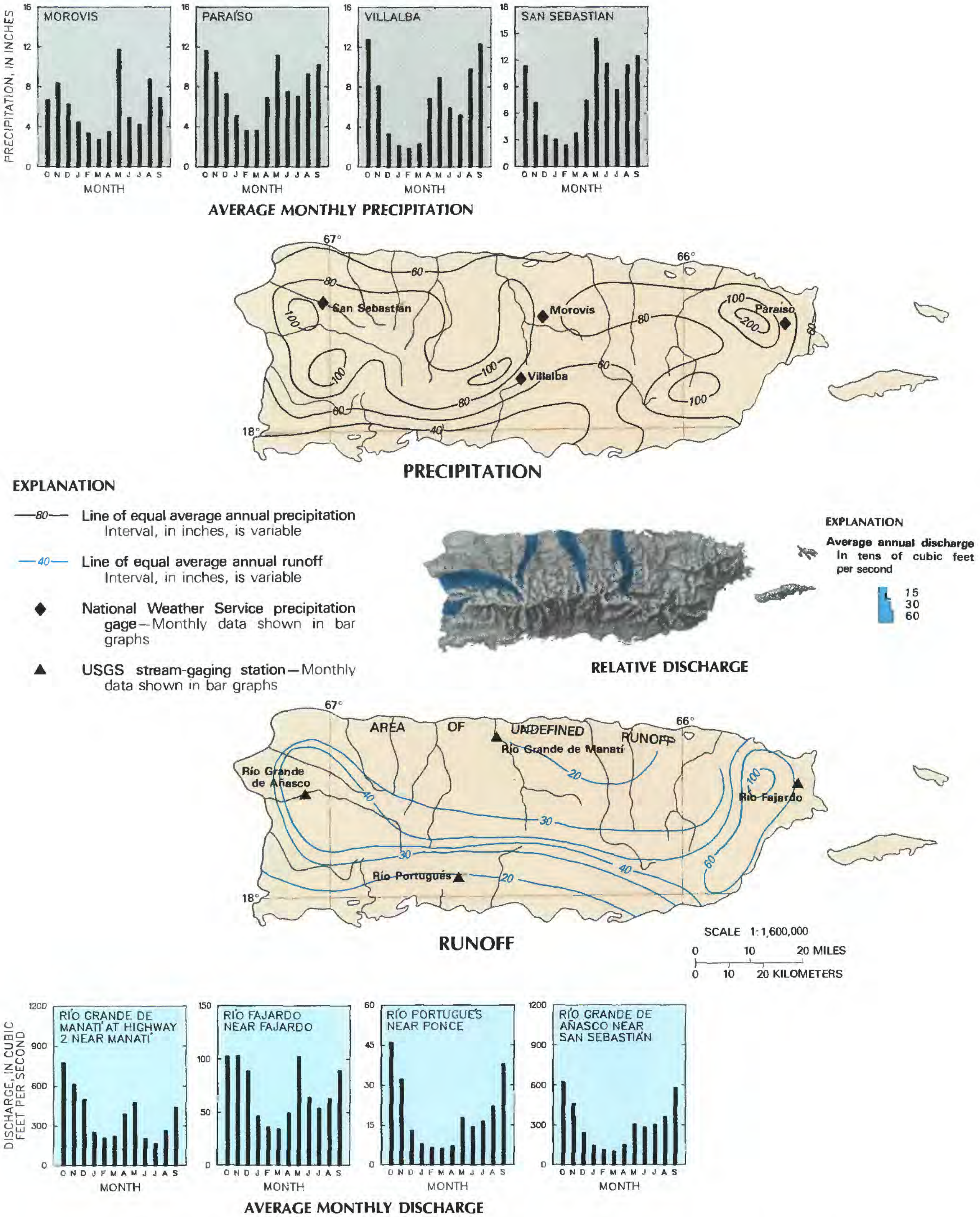

Figure 1. Average annual precipitation and runoff in Puerto Rico and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA, files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files.)

acre-ft or 3,490 Mgal), Guajataca (29,300 acre-ft or 9,550 Mgal), Caonillas (43,200 acre-ft or 14,100 Mgal), and Dos Bocas (16,800 acre-ft or 5,480 Mgal). The principal reservoirs (Loiza, La Plata, and Carite) are used mainly to supply water for domestic uses to the San Juan Metropolitan area. Lago Guajataca is used mainly for the Isabela District Irrigation system, but also supplies most of the domestic needs of Isabela and Aguadilla. Lagos Caonillas and Dos Bocas are used mainly to generate hydroelctric power.

The effect of flow regulation is indicated when streamflow characteristics between sites are compared. Average discharges for the Rio Grande de Arecibo at Central Cambalache and the Rio de La Plata at Toa Alta (table 2, sites 2 and 5), are 510 ft^3/s or 330 Mgal/d and 276 ft^3/s or 178 Mgal/d while the 7-day, 10-year low flows are 90 ft^3/s or 58 Mgal/d and 7.8 ft^3/s or 5.0 Mgal/d, respectively. It is evident that flow regulation for hydroelectric power production helps sustain flow while regulations for public water supply drains water availability. The effect of reservoir construction, however, is not represented in the discharge summaries in figure 2 because none of the data shown were collected prior to dam construction.

Elevated concentrations of suspended solids are a severe problem that affects most of the streams and reservoirs in Puerto Rico, especially in the northern coastal area. Poor soil-conservation and farming practices induce high erosion and sedimentation rates, particularly during periods of above-average flows. Lago Loiza Reservoir has lost more than 50 percent of its original capacity (Quinones-Marquez, 1980).

Agricultural activities in the area (farming and cattle breeding) are point and nonpoint sources of nutrients (nitrogen and phosphorus) and fecal bacteria. Nutrient concentrations greater than 0.5 mg/L (milligram per liter) are found in the Rio de La Plata, the Rio Hondo, the Rio de Bayamon, and the Rio Grande de Loiza. Fecal-coliform bacteria counts exceed 1,000 cols/100 mL (colonies per 100 milliliters) at most streams. Counts of from 100,000 to 1,000,000 cols/100 mL frequently occur at the Rio Hondo, the Rio de Bayamon, the Rio Piedras, the Rio Caguitas, and the Quebrada Blasina. The general water quality of the streams in the area, however, is suitable for most uses, including water supply, after suitable treatment to remove bacteria.

Floods occur about once every 5 years along most of the coastal valleys of the principal streams in the area. The greatest 100-year flood in the area determined from gaging station records is 255,000 ft^3/s or 145,000 Mgal/d at the Rio Grande de Manati at Highway 2 near Manati (table 2, site 3). The areas most significantly affected by floods include the lower valleys of the Rio de La Plata, the Rio Cibuco, the Rio Grande de Manati, and the Rio Grande de Arecibo. Less frequent, but more severe floods occur in the Rio Puerto Nuevo (Metropolitan San Juan) and the Rio Grande de Loiza areas. Flood-control studies at most of the lower basins have been completed by the U.S. Army Corps of Engineers.

East Coast Area.—Rivers in this area generally flow in steep-sided valleys in the interior and in narrow, discontinuous swamps and marshes along the coast. The population of the area is about 145,000. Fajardo is the principal town with about 25,000 habitants (1984 census). Surface-water withdrawals in 1984 were about 20 Mgal/d or 31 ft^3/s, mostly for domestic uses. Sewage discharge effluents to streams and the ocean are about 3.2 Mgal/d or 5.0 ft^3/s. The geology of the area is dominated by volcanic and intrusive rocks. Narrow alluvial valleys are present near the coast and overlie plutonic and intrusive igneous rocks.

Frequent flooding occurs in the lower reaches of the Rio Fajardo and the Rio Humacao. The greatest 100-year flood in the area determined from gaging station records is 45,400 ft^3/s or 29,300 Mgal/d at the Rio Fajardo near Fajardo (table 2, site 9). The flood of 1960 at the Rio Humacao resulted in more than 100 deaths (Bogart and others, 1964). The Rio Humacao is now partially channelized. Flood control studies and a proposed reservoir for the Rio Fajardo have been prepared by the U.S. Army Corps of Engineers. The 15-year moving average of annual discharge suggests an upward trend (fig. 2, site 9).

Fecal-coliform bacteria counts as high as 100,000 cols./100 mL occur frequently in the lower Rio Humacao basin. Nitrogen and phosphorus concentrations that total from 0.1 to 0.5 mg/L are common in the Rio Fajardo and the Rio Humacao. In spite of this, the general water quality of the streams in the area is suitable for most uses, including water supply, after suitable treatment to remove bacteria.

South Coast Area.—This area is characterized by basins with steep gradients and turbulent streams, which originate in the mountainous uplands and discharge to the Caribbean Sea through wide valleys and coalescing alluvial deposits (fig. 2). Unconsolidated deposits of coarse permeable sand and gravel in the alluvial valleys cover an extensive area 3 to 4 miles wide and about 40 miles long.

The population of the area is about 510,000. Ponce is the largest city, with a population of about 160,000 in 1984 (the third largest in Puerto Rico). About 32 Mgal/d or 50 ft^3/s of surface water is used for public supply. Sewage discharge to the ocean and streams is about 3.8 Mgal/d or 5.9 ft^3/s.

Table 2. Selected streamflow characteristics of principal river basins in Puerto Rico

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Puerto Rico agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				CARIBBEAN REGION PUERTO RICO SUBREGION North Coast area				
1.	Rio Culebrinas at Hwy 104 near Moca (50147800).	71.2	1967–85	20.0	299	111,000	Negligible	Withdrawals of 2.4 Mgal/d for public-water supply.
2.	Rio Grande de Arecibo at Central Cambalache (50029000).	[1]200	1969–84	90.0	510	. . . .	Appreciable	Regulated 13.9 miles upstream to provide water for Lago Dos Bocas Hydropower Plant. Withdrawals of 6.5 Mgal/d for public-water supply. High stages affected by overbank flow.
3.	Rio Grande de Manati at Hwy 2 near Manati (50038100).	[2]197	1970–85	60.0	375	255,000	Moderate	Withdrawals of 6.6 Mgal/d for public-water supply.
4.	Rio Cibuco at Vega Baja (50039500).	[3]99.1	1973–85	[1]8.2	125	45,800	. . . do . . .	
5.	Rio de la Plata at Toa Alta (50046000).	[4]200	1960–85	7.8	276	202,000	Appreciable	Regulated 10 miles upstream at La Plata Reservoir to provide water (62.0 Mgal/d) for public-water supply.
6.	Rio Grande de Loiza near Caguas (50055000).	89.8	1960–85	14.0	219	131,000	Moderate	
7.	Rio Herrera near Colonia Dolores (50062500).	2.75	1966–73	[1]1.4	9.47	[1]5,430	Negligible	
8.	Rio Espirutu Santo near Rio Grande (500063800).	8.62	1966–85	5.0	57.0	22,400	. . . do . . .	Withdrawals of 1.0 Mgal/d for public-water supply.
				East Coast area				
9.	Rio Fajardo near Fajardo (50071000).	14.9	1961–85	3.5	68.9	45,400	Moderate	Withdrawals of 6.0 Mgal/d for public-water supply.
				South Coast area				
10.	Rio Grande de Patillas near Patillas (50092000).	18.3	1966–85	5.4	60.9	40,500	Negligible	
11.	Rio Inabon at Real Abajo (50112500).	9.70	1964–70 1971–85	1.3	18.6	15,100	. . . do . . .	Withdrawals of 0.13 Mgal/d for public-water supply.
12.	Rio Cerrillos near Ponce (50114000).	17.8	1964–85	3.1	35.8	22,200	. . . do . . .	
13	Rio Portugues near Ponce (50115000).	8.82	1964–85	1.5	18.2	21,800	. . . do . . .	Withdrawals of 0.06 Mgal/d for public-water supply.
				West Coast area				
14.	Rio Guanejibo near Hormigueros (50138000).	120	1973–85	[1]5.9	220	[1]160,000	Negligible	Withdrawals of 2.89 Mgal/d for public-water supply.
15.	Rio Grande de Anasco near San Sebastian (50144000).	[5]134	1963–85	38.0	304	83,600	Appreciable	Transbasin diversion (except during floods) to Rio Yauco basin for hydroelectric power and irrigation above Lago Yahuecas, Lago Guayo, Lago Prieto, and Lago Toro. Withdrawals of 1.50 Mgal/d for public-water supply.

[1] Estimated.

[2] Drainage area includes 38 mi^2 which are partly or entirely noncontributing and excludes 6.0 mi^2 upstream from Lago El Guineo and Lago de Matrullas.

[3] Drainage area includes 25.4 mi^2 which do not contribute directly to surface runoff.

[4] Drainage area excludes 8.2 mi^2 upstream form Lago Carite, flow from which is diverted to the Rio Guamani.

[5] Drainage area includes 39.7 mi^2 from headwaters of Lago Yahuecas (17.05 mi^2), Lago Guayo (9.67 mi^2), Lago Prieto (9.50 mi^2), and Lago Toro (3.5 mi^2) which does not contribute to surface runoff except at high stages.

Four reservoirs with capacities that exceed 5,000 acre-ft or 1,630 Mgal have been built since 1913. Lago Patillas (14,400 acre-ft or 4,690 Mgal) and Lago Guayabal (6,500 acre-ft or 2,120 Mgal), are part of the South Coast District Irrigation system. Lago Lucchetti (15,700 acre-ft or 5,120 Mgal) is part of Valle de Lajas District Irrigation system. Lago Toa Vaca (50,700 acre-ft or 16,500 Mgal) provides flood control to the area. All the reservoirs are used for irrigation and public-water-supply. Irrigation canals divert water from the main channels of the Rio Grande de Patillas, the Rio Guamani, the Rio Jacaguas, the Rio Coamo, the Rio Yauco, and the Rio Loco. Construction of two additional reservoirs is now in progress.

Severe contamination of surface waters with fecal-coliform bacteria occur at the Rio Guayanilla (more than 100,000 cols/100 mL) and the Rio Grande de Patillas (from 100,000 to 1,000,000 cols/100 mL sample). Nitrogen and phosphorus concentrations that total more than 0.5 mg/L are typical at the Rio Coamo and the Rio Jacaboa. In spite of this, the general water quality of the streams in the area is suitable for most uses, including water supply, after suitable treatment to remove bacteria.

Floods are frequent along the alluvial valleys of the southern coast. Significant floods occurred in 1960, 1970, and 1975. The floods of 1975 were the worst of record near Guayanilla and Yauco. Flood-control measures have been implemented near Ponce on the Rio Portugues, and the Rio Bucana. The greatest 100-year flood in the area determined from gaging station records is 40,500 ft^3/s or 26,200 Mgal/d at the Rio Grande de Patillas near Patillas (table 2, site 10).

West Coast Area.—This area is characterized by broad alluvial valleys that overlie volcanic rocks and limestone lenses. Except for the Rio Grande de Anasco, the rivers have short reaches and steep slopes.

The population of the area is about 260,000. Mayaguez is the principal city, with about 80,000 habitants (1984 census). Surface water provides about 21.8 Mgal/d or 34 ft^3/s for public supply. Sewage-treatment plants discharge about 4.6 Mgal/d or 7.2 ft^3/s to streams and the ocean.

The main reservoir in the area is Lago Guayo, which was completed in 1956 and has a storage capacity of 16,900 acre-ft or 5,510 Mgal. It is used for power generation and irrigation.

The highest fecal-coliform-bacteria counts occur in the Rio Guanajibo and the Rio Grande de Anasco (10,000 to 100,000 cols/100 mL). Nitrogen and phosphorus concentrations total more than 0.5 mg/L in all three major streams in the area. However, the general water quality of the streams in the area is suitable for most uses, including water supply, after treatment to remove bacteria.

SURFACE-WATER MANAGEMENT

Puerto Rico's surface-water resources are managed through a State Water Plan administered by the Puerto Rico Department of Natural Resources (DNR). Law No. 23 of January 1973, charged the Puerto Rico Department of Natural Resources with the responsibility for implementing the operational phase of the public environmental policy of Puerto Rico. Law No. 23 also provided for centralization of operational functions and implementation of regulations that had previously been dispersed throughout many governmental agencies. In addition, a new Water Law (No. 136 of June 3, 1976) assigned to the Secretary of DNR the responsibility to plan and regulate the use of and to improve, conserve, and develop the waters of Puerto Rico. Regulations for the appropriation, use, conservation, and administration of the water resources of Puerto Rico became effective on December 13, 1984.

The highlights of the regulations include: prior appropriation rights as of June 3, 1976, are recognized; construction permits are required for any installation designed to extract water from a stream or aquifer; a mechanism of users fee was established for all use categories; Commonwealth agencies are exempt from users fees; recharge of water to aquifers is regulated; "critical areas" may be established; and emergency situations may be declared.

Numerous Commonwealth and Federal agencies and educational institutions are involved in the use, planning, management, and investigation of Puerto Rico's water resources. The responsibilities with respect to water resources are shared by five agencies and public corporations: Puerto Rico Department of Natural Resources (permits and management); Puerto Rico Environmental Quality Board (water quality control); Puerto Rico Aqueduct and Sewer Authority (water supply); Puerto Rico Department of Health (drinking-water quality); and the Puerto Rico Industrial Development Company (water use in industry). These five agencies are the principal cooperators in the water-resources investigation program with the Caribbean District of the U.S. Geological Survey.

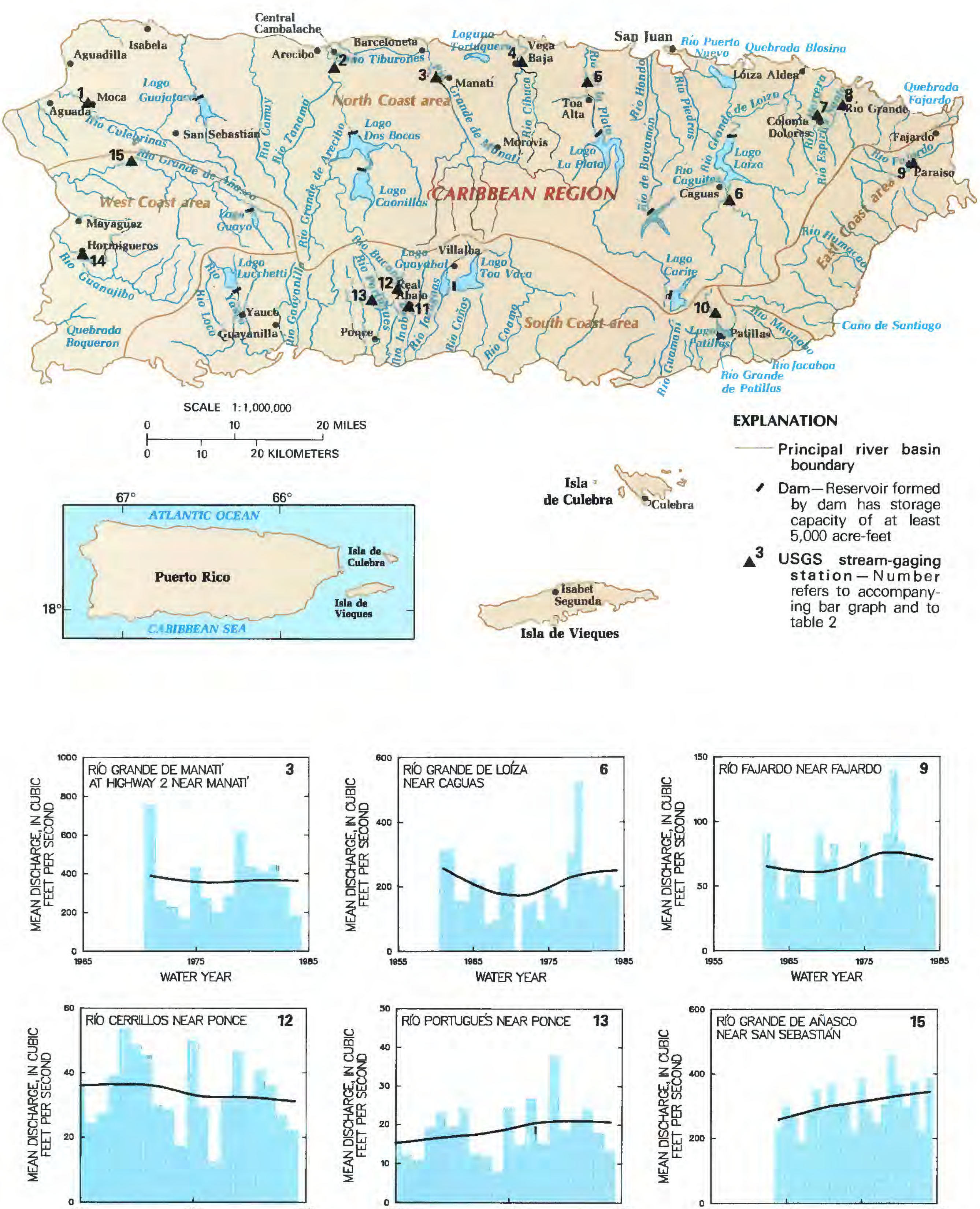

Figure 2. Principal river basins and related surface-water resources development in Puerto Rico and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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RHODE ISLAND
Surface-Water Resources

Rhode Island's surface-water resources are abundant and well developed, and have been a significant factor in making Rhode Island one of the Nation's most industrialized States. During the 19th century, many dams and reservoirs were constructed to provide water power and process water for textile mills and other industries. Industry dominated use of the State's surface-water resources. Today, self-supplied industrial use of surface water accounts for less than 20 percent of total freshwater use in Rhode Island (table 1). Most dams are no longer used to generate power or to regulate streamflow for process water, and the mill-owned reservoirs are used chiefly for recreation. Surface water is now used mainly for public supply. In 1980, surface water accounted for 82 percent, 140 Mgal/d (million gallons per day) or 217 ft³/s (cubic feet per second), of total withdrawals from surface-water and ground-water sources; of this amount, 79 percent was used for public-water supply. About three-fourths of the State's population depends on surface water for drinking water supplies.

The quality of water in streams is generally suitable for most uses, especially in headwater areas. Preservation and improvement of the quality of surface water is an issue of great concern to Rhode Island's citizens and public officials. In 1984, 90 percent of the State's stream miles met State designated-use, water-quality criteria, and 80 percent of those miles were suitable for fish habitat and swimming (Rhode Island Department of Environmental Management, 1984).

GENERAL SETTING

Rhode Island is in the New England Upland and Seaboard Lowland sections of the New England physiographic province (fig. 1). Topographic relief is moderate. The western two-thirds of the State is a hilly upland where land surface averages 200 to 600 feet above sea level and, reaches a maximum elevation of 812 feet at its northwestern edge. North and east of Narragansett Bay, the topography is gently rolling with elevations of less than 200 feet above sea level. Rhode Island measures only about 50 miles north to south and about 30 miles east to west, but it contains 383 lakes, ponds, and reservoirs, and more than 700 miles of rivers (Rhode Island Water Resources Board, 1970a). These water bodies comprise about 4 percent of the State's inland area.

Rhode Island's climate is temperate; summer temperatures are comfortable and winters are relatively mild. Annual precipitation averages 45 to 48 inches over most of the State, ranging from 42 inches on Block Island to 48 inches in the southwestern part of the State (fig. 1). Precipitation is distributed rather uniformly throughout the year, averaging 3 to 4 inches in most months. Average annual snowfall ranges from about 20 inches in the southern part of the State to 40 to 55 inches in the western third of the State.

Approximately half of the precipitation runs off to streams either directly as overland runoff or indirectly as ground-water inflow to streams; the remainder returns to the atmosphere by evapotranspiration. Evapotranspiration losses occur chiefly during the growing season (April through October); these losses impart a seasonal pattern to runoff (fig. 1). Average monthly runoff is highest from December through May and lowest from June through November. Average annual runoff ranges from 28 inches in the southern part of the State to 25 inches in the northern part. The variation in runoff from year to year shown in the graphs in figure 2 is directly related to variations in precipitation. No persistent trends in runoff are evident.

Table 1. Surface-water facts for Rhode Island

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	723
Percentage of total population	76
From public water-supply systems:	
Number (thousands)	723
Percentage of total population	76
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	170
Surface water only (Mgal/d)	140
Percentage of total	82
Percentage of total excluding withdrawals for thermoelectric power	82
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	110
Percentage of total surface water	79
Percentage of total public supply	85
Per capita (gal/d)	152
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	0.1
Percentage of total surface water	<0.1
Percentage of total livestock	50
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	23
Percentage of total surface water	16
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	66
Excluding withdrawals for thermoelectric power	66
Irrigation withdrawals:	
Surface water (Mgal/d)	4.5
Percentage of total surface water	3
Percentage of total irrigation	90
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	23

PRINCIPAL RIVER BASINS

All the river basins in Rhode Island are in the New England Region and, except for a small area along the western border of the State, are in the Massachusetts–Rhode Island Coastal subregion (fig. 2). Rhode Island's major streams discharge into Narragansett Bay and Block Island Sound. The principal rivers in Rhode Island are the Blackstone, the Pawtuxet, and the Pawcatuck (fig. 2). These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

NEW ENGLAND REGION
Massachusetts-Rhode Island Coastal Subregion

Blackstone River Basin.—The Blackstone River originates in the upland areas of south-central Massachusetts, flows southeastward to Rhode Island and discharges into a tidal estuary at the head of Narragansett Bay (fig. 2). Upstream from tidewater, the river drains an area of 478 mi² (square miles), 22 percent of which is in Rhode Island. The drainage area in Rhode Island includes 50 ponds, lakes, and reservoirs and 116 miles of streams. The largest tributary to the Blackstone River is the Branch River, which drains much of northwestern Rhode Island. It enters the Blackstone River near the Massachusetts-Rhode Island State line.

The first successful cotton mill in the United States was built on the Blackstone River just north of Providence in 1793. Thirty years later, more than 100 textile mills were using Rhode Island streams for water power, process water, and waste disposal. The Blackstone River became one of the most highly developed rivers in the Nation; its main stem and tributaries in Rhode Island average one dam for every mile of stream. Public-supply systems distribute most of the surface water used in the basin today. The Arnolds Mills Reservoir (completed in 1927) and Diamond Hill Reservoir (completed 1887; raised to its present elevation in 1969), with a combined total capacity of 11,000 acre-ft (acre-feet) or 3,582 Mgal (million gallons), are the source of water for the largest public-supply system in the Rhode Island part of the basin.

The Blackstone and the Branch Rivers are contaminated by municipal and industrial wastewater. Organic compounds are the principal contaminants; they cause local deficiencies in dissolved oxygen during low flow and elevated coliform-bacteria counts during both high and low flows. Expansion and upgrading of sewage-collection and treatment facilities and elimination of several industrial-waste discharges during the past two decades have considerably improved the quality of water in these rivers. Nevertheless, several reaches of the Branch River and all of the Blackstone River were unsuitable for water-contact activities in 1984 because of bacterial contamination. The inorganic-chemical content of the water in both rivers is comparatively low, making the quality of the water suitable without treatment for many uses other than drinking. Concentrations of dissolved solids in the Branch and the Blackstone Rivers generally are less than 100 mg/L (milligrams per liter) and 200 mg/L, respectively.

The largest flood on the Blackstone River since at least 1645 occurred during a hurricane in August 1955. Intense rains and failure of a dam in Massachusetts resulted in a maximum discharge of 32,900 ft^3/s or 21,300 Mgal/d, at the U.S. Geological Survey stream gage at Woonsocket (fig. 2, site 2); this flow is 1.7 times greater than the 100-year flood flow at this station (table 2, site 2). Construction of a flood-control reservoir upstream in Massachusetts and other smaller-scale, flood-control structures in Rhode Island following the 1955 flood, have reduced the potential for flood damage. However, several residences and commercial and industrial structures in the flood plain remain susceptible to damage by flooding.

Pawtuxet River Basin.—The Pawtuxet River drains most of central Rhode Island and its 230-mi^2 drainage area is entirely within the State. The upper, western part of the basin is hilly, largely forested, and relatively undeveloped. The lower, eastern part of the basin has gently rolling topography and is highly urbanized. The river discharges into the headwaters of Narragansett Bay just south of Providence. The basin contains 80 ponds and reservoirs, including the Scituate and the Flat River Reservoirs—two of the largest bodies of freshwater in the State. These reservoirs are the sources of two principal tributaries—the North and the South Branches of the Pawtuxet River—that join to form the main stem of the Pawtuxet River 11 miles upstream from its mouth.

The surface-water resources of the Pawtuxet River basin are highly developed. There are 143 dams on its 181 miles of streams. The Flat River Reservoir, completed about 1875, with a usable capacity of 5,700 acre-ft or 1,870 Mgal, was constructed to provide hydropower and process water for textile mills. The Scituate Reservoir, completed in 1926, was constructed to provide water for the public supplies of Providence and adjacent communities. This reservoir and five smaller feeder reservoirs with a combined usable capacity of 121,900 acre-ft or 39,700 Mgal supplied 37 percent of all offstream freshwater withdrawals in Rhode Island in 1980.

Construction of a second public-supply reservoir is planned for the southern part of the basin. The combined yield of this proposed reservoir (26 Mgal/d or 40 ft³/s) and that of the Scituate Reservoir (72 Mgal/d or 111 ft³/s) is expected to meet foreseeable public-supply needs of central and eastern Rhode Island. The new reservoir would be used mainly to supply communities outside of the Pawtuxet River basin.

The flow of the Pawtuxet River is affected by regulated releases from the Scituate Reservoir and, to a lesser extent, from the Flat River Reservoir. Out-of-basin transfers from the Scituate Reservoir reduce the average annual discharge of the Pawtuxet River. However, releases from both the Flat River and Scituate Reservoirs during dry weather cause a higher flow per unit drainage area in the Pawtuxet than in any other major stream in Rhode Island. The 7-day, 10-year low flow of the Pawtuxet River at Cranston (table 2, site 4) is 73 ft³/s or 46 Mgal/d, which is equivalent to a discharge of 0.36 (ft³/s)/mi² (cubic feet per second per square mile). The 7-day, 10-year low flow of the virtually unregulated Wood River at Hope Valley (table 2, site 6) in the Pawcatuck River basin is 0.28 (ft³/s)/mi². Average annual runoff per unit area is virtually the same in both areas.

Headwaters of the basin are relatively free of pollution. Downstream from the Scituate and the Flat River Reservoirs, however, streamflow is degraded by industrial and municipal wastewater and by seepage from a landfill. Concentrations of dissolved solids in the lower reaches of the main stem often exceed 200 mg/L and, at times, exceed 500 mg/L. In 1984, all of the main stem and the lower reaches of its two principal tributaries were unsuitable for water-contact activities. Development of the new water-supply reservoir is expected to result in increased

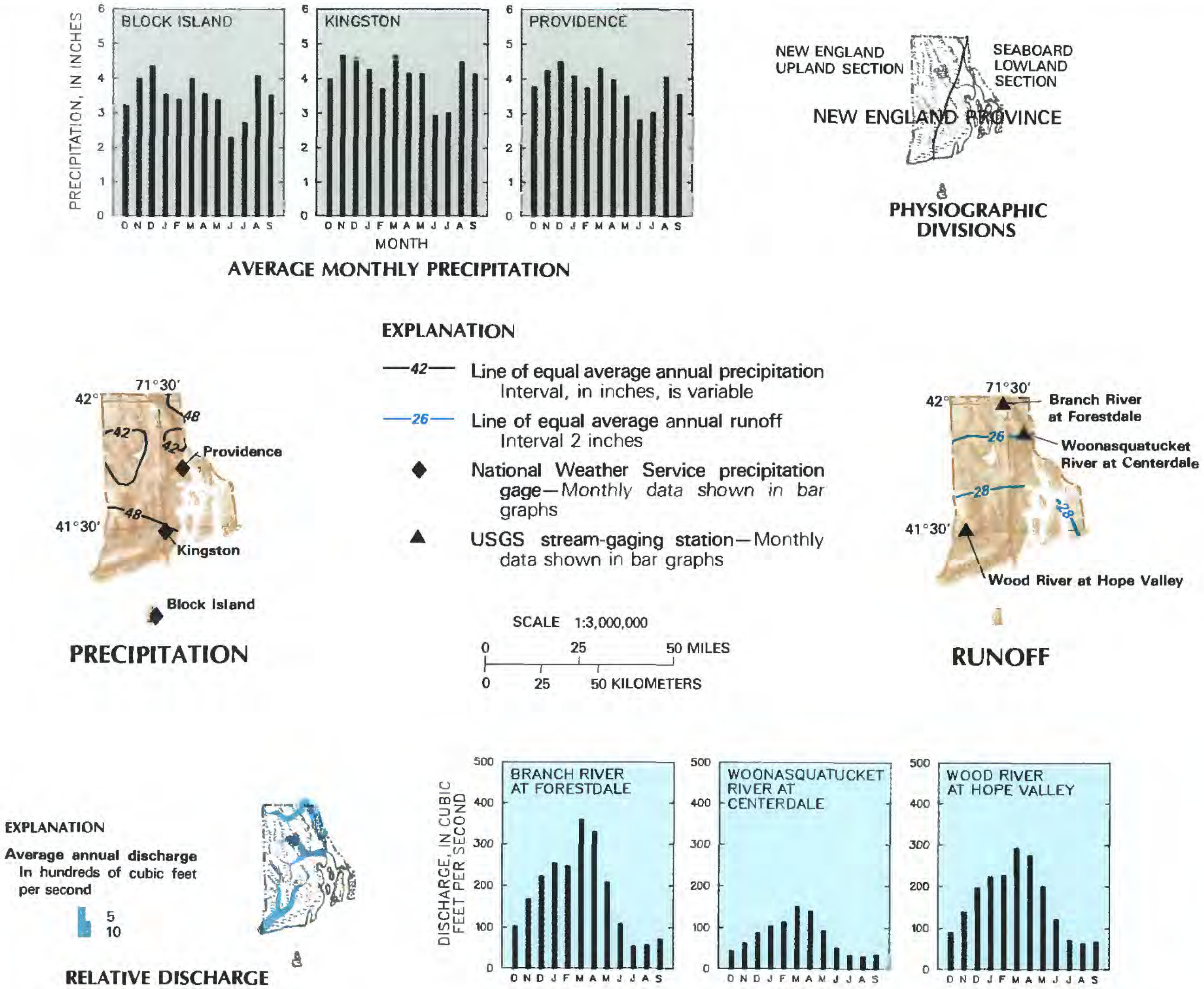

Figure 1. Average annual precipitation and runoff in Rhode Island and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

wastewater discharge in the lower basin, which, when combined with reduced streamflow caused by additional out-of-basin transfers, could increase pollution problems in the lower basin.

Construction on the flood plain of the Pawtuxet River has made the area susceptible to extensive damage by floods. The greatest flood recorded is that of February 1886, which occurred prior to construction of the Scituate Reservoir. More recent floods, such as that of June 1982, would have caused more extensive damage had they occurred at a time when the Scituate and the Flat River Reservoirs were full—although neither is designed to provide flood storage.

Pawcatuck River Basin.—The Pawcatuck River and its tributaries drain most of southern Rhode Island west of Narragansett Bay. The river originates in the southeastern corner of the basin, flows southwestward for 33 miles on a course approximately parallel to the Rhode Island coastline, and discharges into Block Island Sound at the Connecticut State line. The river is affected by tides for a distance of 5 miles upstream from its mouth. The drainage area above its mouth is about 317 mi^2, 20 percent of which is in southeastern Connecticut. The basin is rural, thinly populated, and largely forested; less than 10 percent of its area is urbanized. In the northern half of the basin, the terrain is hilly; in the southern half, rolling hills are interspersed with many low, swampy areas. The basin contains 63 ponds and reservoirs, and there are 92 dams on its 188 miles of streams. Most of the dams were built prior to the 20th century to provide power for mills; only a few are now used to regulate streamflow.

Prior to Pleistocene glaciation, southward-flowing tributaries of the Pawcatuck River discharged directly into Block Island Sound. These streams were blocked by a narrow, 100-foot-high ridge of glacial deposits aligned approximately parallel to, and just inland from, the coast. The redirected flow behind this natural dam resulted in formation of the Pawcatuck River.

Surface-water use in the basin is relatively minor. A few industries use streams for process water, and a small amount of water is pumped directly from streams to irrigate crops—chiefly potatoes and turf. All public supplies are obtained from wells that tap sand and gravel aquifers in stream valleys. Ground-water resources in the basin are abundant, relatively untapped, and in excess of basin needs. Export of ground water from the basin to nearby communities in need of additional water supply would reduce streamflow, especially low flows.

The quality of water in most reaches of the Pawcatuck River and its tributaries is suitable for human consumption and most other uses. Concentrations of dissolved solids in streamflow generally are less than 100 mg/L and seldom exceed 150 mg/L. About 5 percent of the river miles in the basin were degraded by industrial wastewater in 1984 to the extent that the water was unsuitable for drinking.

Floods are infrequent in the basin because of the large number of ponds and reservoirs, extensive swamps, highly permeable soils in valleys, and low stream gradients. Moreover, when floods have occurred, they have done little damage because of the low level of urban development in the basin.

Table 2. Selected streamflow characteristics of principal river basins in Rhode Island

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				NEW ENGLAND REGION MASSACHUSETTS-RHODE ISLAND COASTAL SUBREGION Blackstone River basin				
1.	Branch River at Forestdale (01111500).	91.2	1941-83	13	171	7,110	Negligible	Regulation moderate prior to 1957.
2.	Blackstone River at Woonsocket (01112500).	416	1930-83	100	763	19,200	Appreciable	Regulated by powerplants and reservoirs. Some flow diverted from adjacent basins for public supply.
				Pawtuxet River basin				
3.	South Branch Pawtuxet River at Washington (01116000).	63.8	1942-83	16	130	2,890	Moderate	Diversion from pond for public supply prior to 1972.
4.	Pawtuxet River at Cranston (01116500).	200	1941-83	73	345	5,220	Appreciable	Diversion from Scituate Reservoir to adjacent basins for public supply.
				Pawcatuck River basin				
5.	Pawcatuck River at Wood River Jct. (01117500).	100	1942-83	28	194	2,090	Negligible	Occasional regulation during low flow. Moderate regulation prior to 1969.
6.	Wood River at Hope Valley (01118000).	72.4	1942-83	20	156	2,630	. . . do . . .	Occasional regulation at low flow. Moderate regulation prior to 1948.
7.	Pawcatuck River at Westerly (01118500).	295	1942-83	67	576	6,850	. . . do . . .	Ground-water withdrawals for public supply reduce streamflow.

SURFACE-WATER MANAGEMENT

During the 19th century, associations of mill owners, who were granted stream flowage rights by the State legislature, became the principal managers of the State's surface-water resources. Regulation of streamflow by mill associations still occurs but to a much smaller extent. A few old mill dams have been renovated to provide hydroelectric power—mostly for resale to power companies. Present-day management of the State's surface-water resources mainly is the responsibility of public agencies.

State law establishes a general water-resources-development policy that assigns to water supply the highest priority among all possible uses of the State's water resources. (Rhode Island Statewide Planning Program, 1982, p. 28).

The Rhode Island Water Resources Board is designated to oversee development of surface-water and ground-water resources. The Rhode Island Department of Environmental Management is responsible for classifying and protecting the quality of surface water and ground water, and for regulating modifications of freshwater swamps, marshes, bogs, flood plains, streams, and ponds.

Municipal and private public-water-supply agencies manage surface-water resources by impounding water in reservoirs, by regulating releases to streams, and by transferring water from one basin to another.

Much of the hydrologic information used to manage Rhode Island's surface-water resources is obtained from hydrologic studies by the U.S. Geological Survey in cooperation with State and local agencies such as the Rhode Island Water Resources Board, the Rhode Island Department of Environmental Management, and the Narragansett Bay Water Quality Commission.

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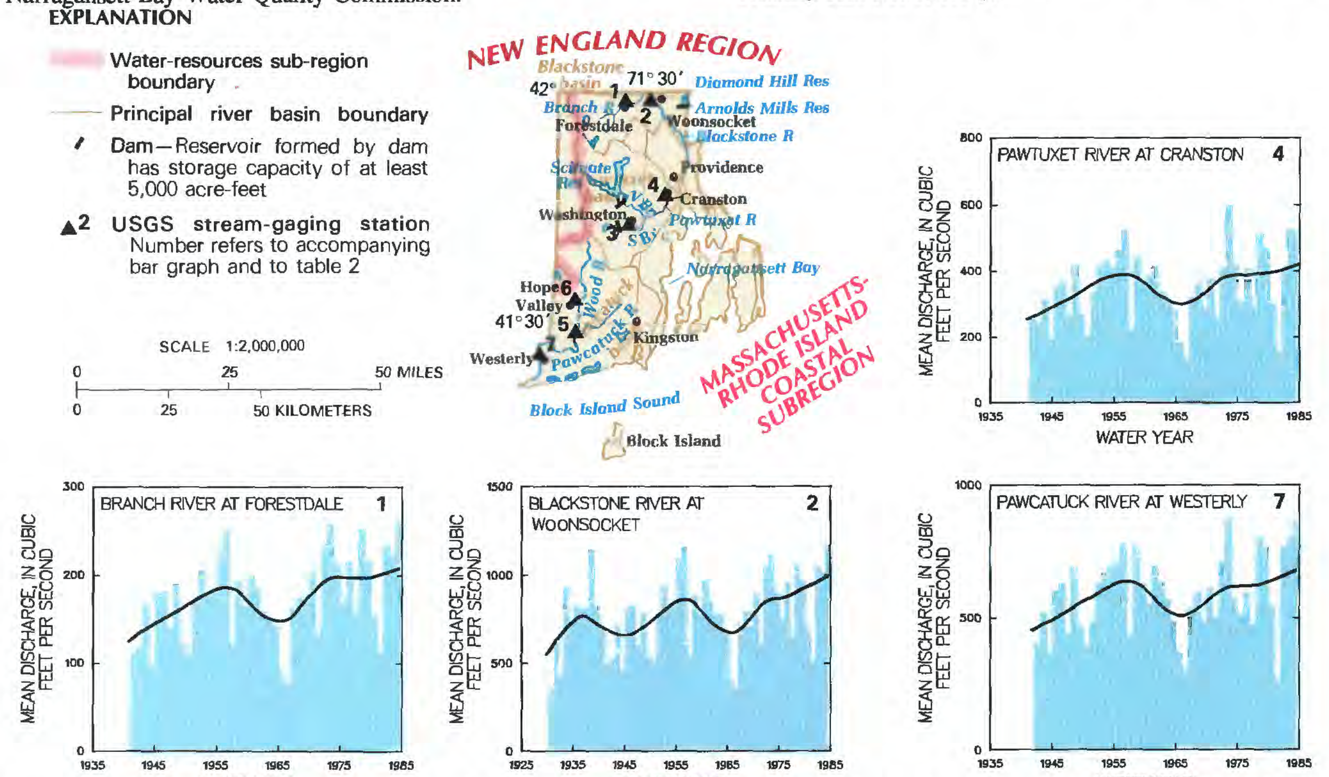

Figure 2. Principal river basins and related surface-water resources development in Rhode Island and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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South Carolina
Surface-Water Resources

South Carolina has an average streamflow of about 51,000 ft³/s (cubic feet per second) or 33,000 Mgal/d (million gallons per day) and 60 lakes with surface areas greater than 200 acres. Plentiful surface-water resources suitable for most uses have been the focal point of industrial, municipal, and recreational activities in the State. Between 1970 and 1980, total offstream water use in South Carolina nearly doubled to 5,780 Mgal/d or 8,940 ft³/s. This amount is projected to increase to about 8,550 Mgal/d or 13,200 ft³/s by the year 2020 (South Carolina Water Resources Commission, 1983). Surface water serves 59 percent of the State's population and supplies 96 percent of the total freshwater needs. Ground water is used to some extent throughout South Carolina, but is most heavily used in the Coastal Plain. By far the largest offstream surface-water use in 1980 was for the production of thermoelectric power (78.5 percent); withdrawals for self-supplied industry and public supply were 15.4 percent and 5.4 percent, respectively. Thirty-five hydroelectric powerplants provide about 7 percent of all electricity used in South Carolina and about 25 percent of the total generating capacity. Surface-water withdrawals in South Carolina in 1980 for various purposes and related statistics are given in table 1.

Table 1. Surface-water facts for South Carolina

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Source: South Carolina Water Resources Commission, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	1,842
Percentage of total population	59
From public water-supply systems:	
Number (thousands)	1,842
Percentage of total population	59
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
Freshwater Withdrawals	
Surface water and ground water, total (Mgal/d)	5,800
Surface water only (Mgal/d)	5,600
Percentage of total	96
Percentage of total excluding withdrawals for thermoelectric power	85
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	300
Percentage of total surface water	5.4
Percentage of total public supply	78
Per capita (gal/d)	162
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	4.6
Percentage of total surface water	0.1
Percentage of total livestock	45
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	5,200
Percentage of total surface water	94
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	99
Excluding withdrawals for thermoelectric power	95
Irrigation withdrawals:	
Surface water (Mgal/d)	41
Percentage of total surface water	0.7
Percentage of total irrigation	74
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	63,000

The quality of South Carolina's surface water is generally excellent and suitable for most uses; 84 percent of the river miles of the State's streams meet Federal standards. The water is soft and has a low buffering capacity. The most prevalent water-quality problem is fecal contamination from point and nonpoint sources, which affects recreational use in some streams. Other water-quality problems include low concentrations of dissolved oxygen in Coastal Plain streams, elevated concentrations of suspended solids in Piedmont streams, and eutrophic conditions in many lakes. Additional surface-water concerns include excessive sedimentation in streams and reservoirs, widespread growth of aquatic plants in about 50,000 acres of rivers and lakes, debates over instream use during low-flow periods, and the loss of wetlands because of development.

GENERAL SETTING

South Carolina is located in the Blue Ridge, Piedmont, and Coastal Plain physiographic provinces (fig. 1). Streamflow varies areally, seasonally, and annually depending on physiography, geology, rainfall, evapotranspiration, and land use.

Average annual precipitation is 80 inches in the Blue Ridge Province, decreases to about 48 inches over much of the Piedmont and Coastal Plain provinces, and increases to about 50 inches near the coast. Rainfall is greatest during the summer and least in the fall as shown in the bar graphs in figure 1.

Annual potential evapotranspiration ranges from 29.6 inches near Spartanburg to 46.6 inches at the southern tip of the State. Most evapotranspiration occurs during the summer (3.5 to 4.9 inches per month) and the least occurs during the winter (0.35 to 1.0 inch per month).

Average annual runoff ranges from 10 inches in the Coastal Plain to about 50 inches in the Blue Ridge province (fig. 1). Because precipitation is greater and more uniformly distributed throughout the year in the Blue Ridge province, its streams generally have greater average annual flows and well-sustained base flows when compared to streams in other parts of the State. Streams in the upper Coastal Plain also have well-sustained base flows.

Streams in the lower parts of the Piedmont and Coastal Plain are characterized by highly variable flows, small average annual flows, and poorly sustained base flows. Precipitation amounts below the State average and high rates of evapotranspiration during late summer and fall cause some streams to go dry periodically in these areas. This contrast in base flows in different parts of the State is illustrated by comparing the 7-day, 10-year low flows of representative streams per square mile of drainage area (table 2). The low flow per square mile of the Edisto River (table 2, site 12), which drains the Upper Coastal Plain, is 0.162 (ft³/s)/mi² (cubic feet per second per square mile) compared to 0.001 (ft³/s)/mi² for the Waccamaw River (site 5), which drains an area entirely in the lower part of the Coastal Plain.

PRINCIPAL RIVER BASINS

South Carolina is entirely in the South Atlantic-Gulf Region (Seaber and others, 1984). The principal river basins in the State are the Lower Pee Dee (Pee Dee Subregion), the Santee and the Edisto-South Carolina Coastal (Edisto-Santee Subregion), and the Savannah (Ogeechee-Savannah Subregion). These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Selected streamflow characteristics and other pertinent information are given in table 2.

SOUTH ATLANTIC-GULF REGION

Pee Dee Subregion

Lower Pee Dee River Basin.—The Pee Dee Subregion has a total drainage area of 18,500 mi² (square miles), approximately 7,860 mi² of which are in South Carolina. The Lower Pee Dee basin has five major river subbasins: the Pee Dee, the Little Pee Dee–Lumber, the Lynches, the Black, and the Waccamaw–Carolina Coastal–Sampit. Surface-water development is limited to navigational and flood control projects. Because topographic relief is low, this basin has only one major reservoir—Lake Robinson (completed in 1959 with 31,000 acre-ft (acre-feet) or 10,100 Mgal (million gallons) of storage). Major cities in this basin are Florence, Sumter, and Myrtle Beach. A combination of low flows in the Coastal Plain, drainage from swamps, and pollution from point and nonpoint sources lower concentrations of dissolved oxygen and increase concentrations of nutrients and fecal-coliform bacteria in several areas. Maintenance of low flows for agricultural use is an increasing concern in the basin.

The Pee Dee River has a large, perennial flow as a result of regulation upstream in North Carolina. Approximately 33 Mgal/d or 51 ft^3/s are diverted from the Pee Dee through a large canal to the Waccamaw River.

The Lynches, the Black, and the Little Pee Dee–Lumber River subbasins are primarily rural and undeveloped. Surface water, used mostly for irrigation, accounts for only 14 percent of total water withdrawals. A 52-mile segment of the Little Pee Dee River is eligible for the State Scenic Rivers Program. Occasional flooding and infestations of aquatic plants in the Black and the Pocotaligo Rivers are the only significant surface-water problems.

The Waccamaw–Carolina Coastal–Sampit subbasin drains into Winyah Bay, a large and important estuary. The subbasin is characterized by extensive cypress and hardwood swamps and a flourishing economy based on agriculture and tourism. Excluding steampower use, ground water supplies 99 percent of the area's needs. Fecal contamination restricts recreational use in some areas of the subbasin.

Edisto-Santee Subregion

Santee River Basin.—Approximately 10,600 mi^2 of the 15,300-mi^2 Santee River basin is in South Carolina. The Santee River basin contains the Saluda, the Broad, the Catawba–Wateree, the Congaree, and the Lower Santee River subbasins. Nearly half (46 percent) of the population of South Carolina resides in the Santee River basin which contains such major cities as Greenville, Spartanburg, Rock Hill, and Columbia. Eight of the fifteen largest reservoirs in South Carolina by capacity are in the basin: Lake Murray (completed in 1930), Lake Marion (1950), Wateree Lake (1919), Lake Wylie (1905), Lake Greenwood (1940), Fishing Creek Reservoir (1916) Poinsett Reservoir (1961), and Monticello Reservoir (1977); their combined storage capacity is 4,960,000 acre-ft or 1,620,000 Mgal.

The Saluda River originates in the Blue Ridge province and flows across the Piedmont province before joining the Broad River to form the Congaree River near Columbia. Surface-water demands in this subbasin periodically exceed available supplies. The quality of the Little Saluda and the Reedy Rivers is often degraded by municipal wastewater discharges. Regulation of flows from Lake Greenwood has increased the variability of flows in the Saluda River (fig. 2), which has adversely affected some instream uses. Five miles of the Middle Saluda River are protected under the State Scenic Rivers Program and 10 miles of the Saluda River below Lake Murray are eligible for the program.

The northwestern part of the Broad River subbasin includes part of the industrialized Interstate Highway 85 corridor, but the remainder of the subbasin is mostly rural. High flows on Brushy Creek, a tributary to the Enoree River, near Greenville, cause occasional flood damage to developed areas in the watershed. The Broad River has reliable flow with quality suitable for most uses.

The Catawba–Wateree subbasin is one of the most developed basins in the State; several hydroelectric dams and flood-control facilities regulate flows in the basin. Municipal wastewater from North Carolina has adversely affected Sugar Creek and the Catawba River and may threaten some water use activities in Fishing Creek Reservoir and Wateree Lake, the two most eutrophic lakes in the State.

The Congaree River subbasin contains a mixture of densely populated urban and sparsely populated rural areas. Extensive, scenic swamplands have made a 45-mile segment of the main stem river eligible for the State Scenic Rivers Program.

The Lower Santee subbasin has undergone extensive hydrologic modification in the last 40 years. Formed at the confluence of the Congaree and the Wateree Rivers, the Santee flows directly into Lake Marion—the State's largest reservoir (in area), with a capacity of 1,400,000 acre-ft or 456,000 Mgal. Since 1941, most of the water in Lake Marion has been diverted to the Cooper River. However, a recently completed rediversion project will restore 80 percent of the previously diverted flow back into the Santee River. Current water quality and some water-use activities may be significantly altered after streamflows are increased in the Santee River. Another major problem is the extensive aquatic plant growth in upper Lake Marion, which severely restricts recreational use.

Edisto–South Carolina Coastal Basin.—This basin has a drainage area of 8,210 mi^2, all of which is in South Carolina. The three principal river systems in this basin are the Ashley–Cooper River subbasin, the Combahee–Coosawhatchie River subbasin, and the Edisto River subbasin. Development is limited mostly to navigation and flood-control projects, with the exception of Lake Moultrie and a few small reservoirs used for water supply. Water quality is suitable for most uses, although low concentrations of dissolved oxygen, elevated water temperatures, and low-flow conditions occur during the summer.

The tidally affected Ashley and the Cooper Rivers discharge into Charleston Harbor. The Charleston metropolitan area makes extensive use of the surface-water resources in this predominantly urban subbasin and a 19-mile segment of the Ashley River is eligible for the State Scenic Rivers Program because of its historical significance. The Santee–Cooper Project diverts water from Lake Marion and the Santee River into Lake Moultrie (completed in 1941) for power generation, which was crucial to the defense industry and general economic development of the area. The diversion increased both the average annual flow of the Cooper River and the amount of sediment carried into Charleston Harbor, which increased sediment deposition and dredging costs in the harbor (Patterson, 1983). A new rediversion canal and hydroelectric power facility is now operational and will reduce the Cooper River average annual flow from 15,600 ft^3/s or 10,100 Mgal/d to about 3,000 ft^3/s or 1,940 Mgal/d, while preserving the power generation and recreational use of the lakes. However, decreased streamflow in the Cooper River will reduce its waste assimilative capacity and increase the potential for saltwater encroachment into the Back River Reservoir. Currently, reservoirs and the transfer of 72 Mgal/d or 111 ft^3/s from the Edisto subbasin supply surface-water needs in the Ashley–Cooper subbasin.

The Combahee–Coosawhatchie and the Edisto River subbasins, which drain the Coastal Plain, are mostly rural. These subbasins contain the most extensive estuarine waters in the State. Fresh surface water in the Edisto subbasin is plentiful. However, surface water provides only 18 percent of the water used in the Combahee–Coosawhatchie subbasin.

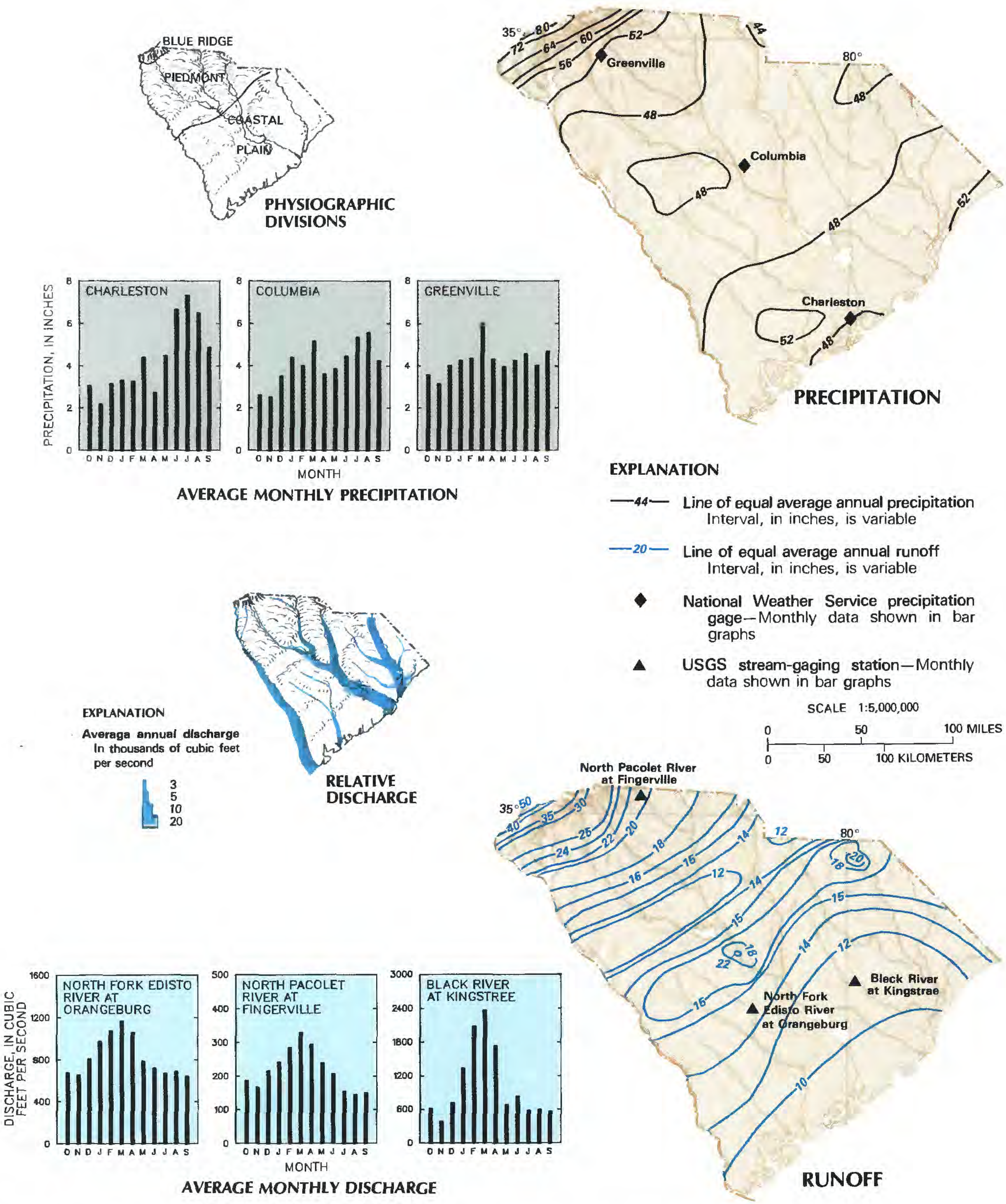

Figure 1. Average annual precipitation and runoff in South Carolina and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA), monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in South Carolina

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second; . . . .=insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
	SOUTH ATLANTIC-GULF REGION **PEE DEE SUBREGION** **Lower Pee Dee River basin**							
1.	Pee Dee River at Peedee (02131001).	8,830	1938-83	[1]1,500	9,850	[1]160,000	Appreciable	Flow regulated since 1911.
2.	Lynches River at Effingham (02132000).	1,030	1925-83	132	1,035	22,100	Negligible	
3.	Little Pee Dee River at Galivants Ferry (02135000).	2,790	1943-83	315	3,243	31,300	. . . do . . .	
4.	Black River at Kingstree (02136000).	1,252	1920-83	5.7	942	39,100	. . . do . . .	
5.	Waccamaw River near Longs (02110500).	1,110	1950-83	0.99	1,223	17,300	. . . do . . .	
	EDISTO-SANTEE SUBREGION **Santee River basin**							
6.	North Pacolet River at Fingerville (02154500).	116	1931-83	43	215	13,100	Negligible	
7.	Broad River at Richtex (02161500).	4,850	1925-83	[1]970	6,250	[1]210,000	Appreciable	Flow regulated since 1901.
8.	Saluda River near Columbia (02169000).	2,520	1925-83	[1]260	2,929	[1]70,000	. . . do . . .	Flow regulated since 1929.
9.	Wateree River near Camden (02148000).	5,070	1904-10, 1925-83	[1]490	6,444	[1]225,000	. . . do . . .	Flow regulated since 1919.
10.	Congaree River at Columbia (02169500).	7,850	1939-83	[1]1,800	9,425	[1]220,000	. . . do . . .	Flow regulated since 1929. About 58 ft^3 diverted above station by Columbia for municipal supply.
11.	Lake Marion-Moultrie Diversion Canal (02170500).	. . . .	1943-83	2,320	15,125	. . . .	. . . do . . .	Canal diverts water from Lake Marion to Lake Moultrie for generation of power and for navigation.
	Edisto-South Carolina Coastal basin							
12.	Edisto River near Givhans (02175000).	2,730	1939-83	442	2,711	29,200	Negligible	About 112 ft^3/s diverted above station for Charleston municipal supply.
13.	Salkehatchie River near Miley (02175500).	341	1951-83	33	356	4,390	. . . do . . .	
	OGEECHEE-SAVANNAH SUBREGION **Savannah River basin**							
14.	Savannah River at Augusta, Ga. (02197000).	7,508	1883-1891, 1896-1906, 1925-1983	[1]4,700	10,300	. . . .	Appreciable	Flow regulated since 1951.

[1] Analysis based on records collected since regulation began.

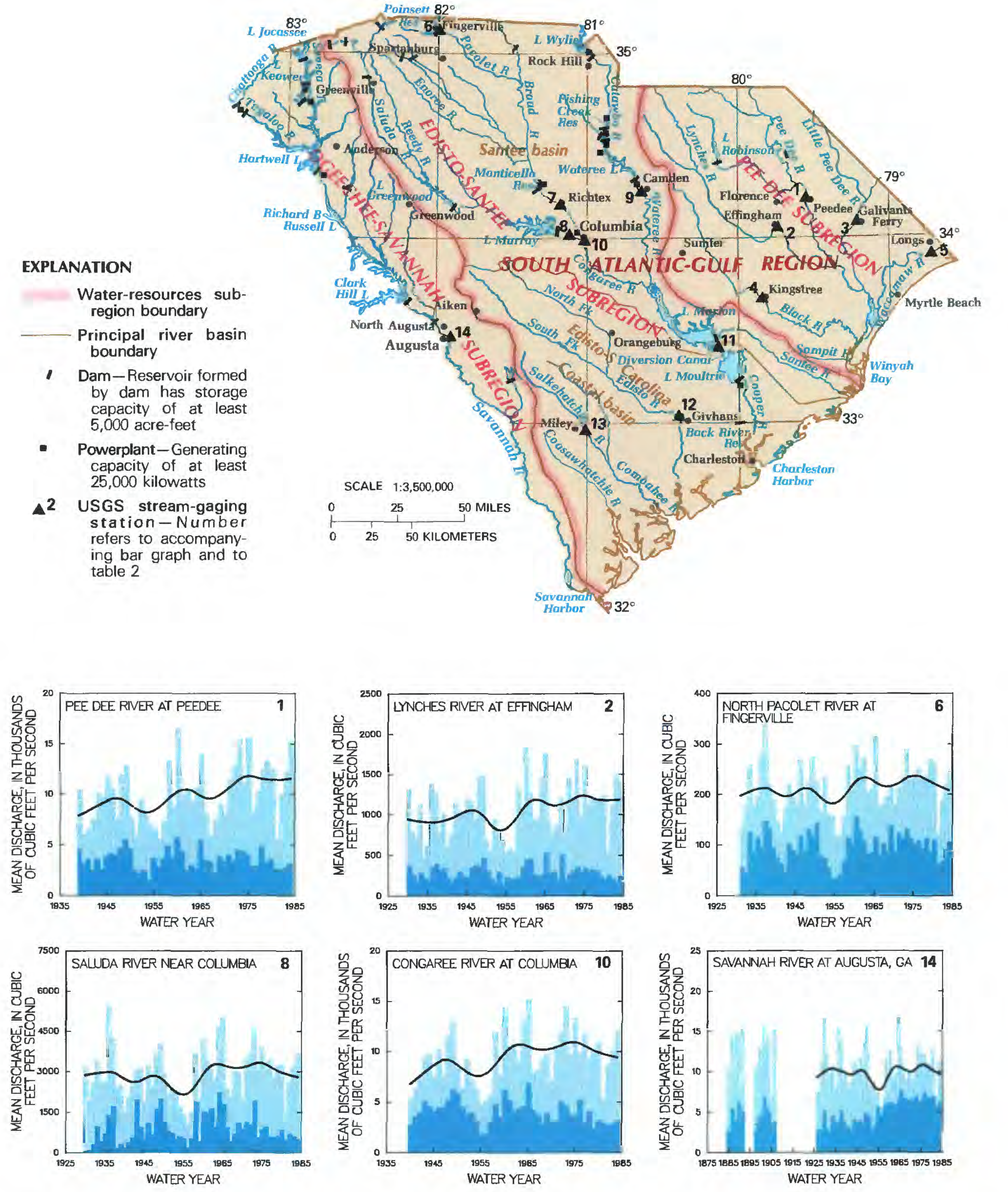

Figure 2. Principal river basins and related surface-water resources development in South Carolina and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development modified from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Ogeechee-Savannah Subregion

Savannah River Basin.—From headwaters in the mountainous Blue Ridge province, the Tugaloo and the Seneca Rivers converge to form the Savannah River. The Savannah River is the State boundary between Georgia and South Carolina as it flows southeasterly about 314 miles to the Atlantic Ocean. A tributary, the Chattooga River, is the only Federally designated National Wild and Scenic River in South Carolina. Segments of the Whitewater and the Thompson Rivers, which drain into Lake Jocassee, are under consideration for the State Scenic Rivers Program. The drainage area of the basin is about 10,400 mi^2, approximately 4,500 mi^2 of which is in South Carolina. Major population centers include Aiken, Anderson, Greenwood, and North Augusta, although the basin is predominantly rural. Since 1950, five large multipurpose reservoirs have been built on the upper Savannah River and its major tributaries: Lake Jocassee (completed in 1974), Lake Keowee (1971), Hartwell Lake (1962), Clarks Hill Lake (1954), and Richard B. Russell Lake (1985); combined storage capacity of these reservoirs is 8,270,000 acre-ft or 2,700,00 Mgal.

Surface-water development in the lower part of the basin is limited to navigational projects in the Savannah River from Savannah Harbor to Augusta, Ga. Since 1951, regulation upstream has resulted in higher, better sustained low flows, as shown in the bar graphs of annual 30-day minimum flows in figure 2. Total water use, surface-water withdrawals, and withdrawals for thermoelectric production are greater in this basin than in any other basin in the State. Approximately 6 Mgal/d or 9.3 ft^3/s is transferred to the Combahee-Coosawhatchie basin for public supply. Water quality in the reservoirs and main-stem river usually meets State designated water-use standards. Some of the more significant water-quality problems include elevated concentrations of polychlorinated biphenyls in Lake Hartwell and saltwater encroachment in the lower Savannah River.

SURFACE-WATER MANAGEMENT

The South Carolina Water Resources Planning and Coordination Act of 1967 established the South Carolina Water Resources Commission (WRC) and made that agency responsible for the development and coordination of a comprehensive State water policy. The WRC and Federal Energy Regulatory Commission regulate streamflow requirements through various licensing and permitting programs. In addition, several other State agencies have statutory responsibilities in specific areas of State water policy, including the Department of Health and Environmental Control, the Coastal Council, the Land Resources Conservation Commission, and the Wildlife and Marine Resources Department. The riparian, reasonable-use doctrine is the basis for surface-water law in South Carolina. State permits are not required for surface-water withdrawals. However, the South Carolina Water Use Reporting and Coordination Act (enacted in 1982) requires every user of 100,000 gal/d (gallons per day) or more of water to file a water-use report with the WRC. The Drought Response Act of 1985 authorizes the WRC to develop a plan for regulating nonessential water use during a drought emergency. Also in 1985, legislation was enacted which gives the WRC authority to regulate and permit interbasin transfers of surface water.

The U.S. Geological Survey routinely monitors streamflow and reservoirs and provides technical assistance to surface-water users in cooperation with several State and Federal agencies. The Department of Health and Environmental Control also measures streamflow periodically at several water-quality sampling stations not measured by the U.S. Geological Survey.

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FOR ADDITIONAL INFORMATION

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SOUTH DAKOTA
Surface-Water Resources

Except for the Missouri River, which has a large, sustained flow of water suitable for most uses, many streams in South Dakota do not provide a dependable water supply. Storage is necessary to contain spring runoff to augment low flows which occur during late summer, fall, and winter. Water quality of tributary streams generally is suitable for most uses during high flows, but commonly is unsuitable for many uses during low flows. Seasonal variation in quantity, rather than quality, is the principal constraint on use.

Instream water use of 67,000 Mgal/d (million gallons per day) or 104,000 ft^3/s (cubic feet per second) for hydroelectric-power generation represented 99 percent of the estimated total water use in South Dakota in 1980. Virtually all of the hydroelectric power was generated by four U.S. Army Corps of Engineers dams (Oahe, Big Bend, Fort Randall, and Gavins Point) located on the Missouri River (fig. 2). Excluding hydroelectric-power generation, surface-water withdrawals represented 52 percent of the total withdrawals in 1980. The largest use of surface water in 1980 was for irrigation of about 233,400 acres (compared to about 122,300 acres in 1970). Major irrigated crops are corn, alfalfa, beans, small grains, and hay and pasture. Twenty-three percent of the population of South Dakota is served by surface water. Information concerning surface-water withdrawals in South Dakota in 1980 is given in table 1.

Droughts, especially those of the 1930's, 1950's, and 1970's, have been disastrous to agriculture—the State's dominant industry. Large-scale development of water resources to stabilize agricultural production is a primary objective of State government.

GENERAL SETTING

South Dakota is located in the Great Plains and Central Lowland physiographic provinces (fig. 1). The Missouri River system drains the entire State except for a small area (about 3 percent of the State) in the northeastern corner. The river's course forms most of the boundary between the unglaciated region to the west and the glaciated region to the east.

Average annual precipitation in South Dakota ranges from about 16 inches in the west to about 24 inches in the Black Hills (southwest part of the State) and in the southeast (fig. 1); about 70 percent occurs during the growing season (May through October). Seasonal snowfall, which averages from 25 to 45 inches, usually accumulates from November or December through March (Spuhler and others, 1971). Average annual lake evaporation ranges from about 48 inches in the southwest to about 38 inches in the northeast; about 75 percent occurs during the growing season (National Oceanic and Atmospheric Administration, 1982).

Like precipitation, runoff is extremely variable, both seasonally and annually, as well as areally. The average annual runoff varies from about 0.2 inch in the northeast to about 2 inches in the Black Hills (fig. 1). A large percentage of runoff occurs as a result of snowmelt and rainfall in the spring and early summer (fig. 1).

PRINCIPAL RIVER BASINS

The rivers of South Dakota are almost entirely in the Missouri Region (Seaber and others, 1984), except for several small streams in the extreme northeastern corner of the State that are part of the Upper Mississippi and the Souris-Red-Rainy Regions. These northeastern streams are not discussed.

Ten rivers in South Dakota are principal tributaries to the Missouri River: the Little Missouri, the Grand, the Moreau, the Cheyenne, the Bad, the White, and the Keya Paha Rivers (the western tributaries that drain the Great Plains physiographic province) and the James, the Vermillion, and the Big Sioux Rivers (the eastern tributaries that drain the Central Lowland physiographic province) (fig. 1). The main stem of the Missouri River and the western and eastern tributaries are discussed below; their locations and long-term variations in streamflow at representative gaging stations are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for South Dakota

[Data 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 U.S. Geological Survey, 1985]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	162
Percentage of total population	23
From public water-supply systems:	
Number (thousands)	134
Percentage of total population	19
From rural self-supplied systems:	
Number (thousands)	28
Percentage of total population	4
OFFSTREAM USE, 1980 **FRESHWATER WITHDRAWALS**	
Surface water and ground water, total (Mgal/d)	690
Surface water only (Mgal/d)	360
Percentage of total	52
Percentage of total excluding withdrawals for thermoelectric power	52
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	24
Percentage of total surface water	7
Percentage of total public supply	32
Per capita (gal/d)	179
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	1.4
Percentage of total surface water	0.4
Percentage of total rural domestic	6
Per capita (gal/d)	50
Livestock:	
Surface water (Mgal/d)	11
Percentage of total surface water	3
Percentage of total livestock	12
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	22
Percentage of total surface water	6
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	46
Excluding withdrawals for thermoelectric power	45
Irrigation withdrawals:	
Surface water (Mgal/d)	310
Percentage of total surface water	86
Percentage of total irrigation	67
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	67,000

MISSOURI REGION
Missouri River Main Stem

The Missouri River is the major source of surface water in South Dakota; the sum of the average recorded flow of all streams tributary to the Missouri within the State is only 12 percent of the average recorded flow of the Missouri at Sioux City, Iowa. The main stem of the Missouri is within the Missouri–Oahe, Missouri–White, and Missouri–Big Sioux Subregions (Seaber and others, 1984).

About 24 percent of the Missouri River basin upstream from Sioux City is located in South Dakota. The river is almost entirely regulated in the State by Oahe Dam (completed in 1962), Big Bend Dam (completed in 1964), Fort Randall Dam (completed in 1953), and Gavins Point Dam (completed in 1955) that impound slightly more than 31 million acre-ft (acre-feet), or about 10,000,000 Mgal (million gallons), of water and that provide almost 1.5 million kilowatts of power-generation capacity (fig. 2). The river also is regulated in Montana and North Dakota before it enters South Dakota. The magnitude of the regulation provided by these dams is indicated by the 100-year flood discharges (table 2) for the Missouri River at Pierre, at Fort Randall Dam, at Yankton, and at Sioux City, Iowa (based on the period of record subsequent to regulation) which are only about 25 percent of the maximum discharges recorded at these stations prior to construction of the dams. The maximum discharge of record (water years 1929–83) on the Missouri River at Sioux City, Iowa was 441,000 ft^3/s (or 285,000 Mgal/d) on April 14, 1952.

The major uses of water from the main stem, other than power generation, are irrigation, municipal and industrial supplies, rural-domestic supplies, fish and wildlife propagation, and recreation. During 1980, more than 137,000 acres were irrigated in the main-stem basin in South Dakota, whereas only about 23,300 acres were irrigated during 1970 (South Dakota Department of Water and Natural Resources, written commun., 1980).

Diversion and use of stored Missouri River water in the State continues to be a major issue. Downstream States have expressed opposition to the proposed interbasin diversion of Missouri River water from South Dakota to Wyoming for energy development.

Western Tributaries

Major western tributaries of the Missouri River include the Little Missouri (Missouri–Little Missouri Subregion), the Grand and the Moreau (Missouri–Oahe Subregion), the Cheyenne (Cheyenne Subregion), the Bad and the White (Missouri–White Subregion), and the Keya Paha (Niobrara Subregion) Rivers. The deep valleys and canyons, buttes, and broad uplands of western South Dakota result in well-defined drainage in these basins.

Even though high flows during the spring and early summer can cause flooding, and low flows during late summer, fall, and winter can limit potential uses of most western tributaries, surface water provides important benefits to western South Dakota for irrigation; municipal, industrial, and rural supplies; livestock watering; recreation; and fish and wildlife propagation. Approximately 83 percent of the total irrigation in western South Dakota during 1980 (including 73,373 acres in Federally-developed projects) was from surface water.

The Little Missouri River originates in Wyoming and flows through northwestern South Dakota before entering the Missouri River in North Dakota. Only about 9 percent of the 9,500-mi^2 (square mile) drainage area is located in South Dakota. All irrigation in the basin in South Dakota during 1980 (720 acres) was from surface water.

About 87 percent of the 5,700-mi^2 drainage basin of the Grand River is located in South Dakota. Shadehill Reservoir, which was completed in 1951 and has a storage capacity of about 357,000 acre-ft or about 116,000 Mgal, provides water to irrigate 3,000 acres (U.S. Bureau of Reclamation, 1984). Irrigation in the basin in South Dakota during 1980 (about 5,210 acres) was entirely from surface water.

The drainage area of the Moreau River (about 5,400 mi^2) is entirely within South Dakota. Irrigation in the basin during 1980 (476 acres) was solely from surface water.

The Cheyenne River, the largest of the western tributaries, drains about 25,500 mi^2, about 55 percent of which is within South Dakota. Some Black Hills streams have a sustained flow and, therefore, differ markedly from most other streams in the State. The Rapid City flood of 1972, which occurred on Rapid Creek (a tributary of the Cheyenne River), gained national attention because of the loss of 237 lives and $160 million in property damage (Schwarz and others, 1975). Irrigation development by the U.S. Bureau of Reclamation within the Cheyenne River basin in South Dakota includes the Belle Fourche Project (57,068 acres), the Angostura Unit (12,218 acres), and the Rapid Valley Unit (8,900 acres) (U.S. Bureau of Reclamation, 1984). Rapid City obtains its municipal water supply from Pactola Reservoir (completed in 1956) which has a storage capacity of 99,000 acre-ft or 32,300 Mgal and Deerfield Reservoir (completed in 1947) which has a storage capacity of 15,700 acre-ft or 5,100 Mgal (U.S. Bureau of Reclamation, 1984). Surface-water irrigation in the South Dakota part of the Cheyenne River basin during 1980, including the Federal projects mentioned above, was reported to be about 104,000 acres, or about 96 percent of the total irrigation in the basin.

The entire drainage area of the Bad River, about 3,120 mi^2, is located in South Dakota. Sediment accumulation in the river channel is of major concern. Surface-water irrigation of about 2,590 acres during 1980 represented about 77 percent of the total irrigation in the basin.

The White River, so named because of its large concentrations of clay and sandstone particles that are eroded from the South Dakota Badlands, has a drainage area of 10,200 mi^2, 80 percent of which is in South Dakota. Sediment accumulation in the river channel is of major concern. Surface-water irrigation of about 12,330 acres in South Dakota during 1980 represented 52 percent of the total irrigation in the basin.

The Keya Paha River—a tributary of the Niobrara River (which flows into the Missouri River in Nebraska)—has a drainage area of about 1,730 mi^2 in South Dakota. Surface-water irrigation of about 2,720 acres in 1980 represented about 23 percent of the total irrigation in the Niobrara basin in South Dakota.

Eastern Tributaries

The James (James Subregion), and the Vermillion and the Big Sioux Rivers (Missouri–Big Sioux Subregion)—the principal eastern tributaries to the Missouri River—are prairie streams with similar characteristics. The topography of the stream basins is characterized by low, rolling hills and potholes typical of glaciated areas. Drainage patterns in the northern parts of the James and the Big Sioux River basins are not integrated, and large areas do not contribute directly to surface runoff. However, many of these areas serve as important aquifer recharge areas.

High flows during the spring and early summer can cause extensive flooding of agricultural land, and low flows during late summer, fall, and winter can limit potential uses of the eastern tributaries. Aside from these limitations, surface water provides important, although sometimes limited, irrigation; livestock-watering; municipal, industrial, and rural supplies; recreational opportunities; and excellent fish and wildlife habitat. The lack of sustained streamflow, and the presence of adequate ground water in many areas, is evidenced by the fact that only 10 percent of the total irrigation in the eastern tributary basins during 1980 was from surface water.

About 65 percent, or 14,000 mi^2, of the James River basin is located in South Dakota. The river has one of the flattest slopes (about 0.3 foot per mile in South Dakota) of any river of similar length in North America. Because of its flat slope and limited channel capacity as it flows across the Lake Dakota Plain (a glacial lakebed), streamflows with a recurrence interval of only 10 years can flood about 23,600 acres of agricultural land (U.S. Bureau of Reclamation, 1977). A hydraulic and mechanical dredging program has been started to decrease the flooding potential (South Dakota Department of Water and Natural Resources, 1983). In 1970, U.S. News and World Report called the James River one of the most polluted streams in the United States, primarily because water contained in pools during periods of no flow is subject to contamination from a variety of sources (Bartlett, 1984). Since that time, significant improvements in the water quality of the James River have been achieved through the efforts of the State. The river serves as the primary source of municipal water for the city of Huron and as a supplemental source for the city of Mitchell. About 13,700 acres (17 percent) of the irrigation in the basin in South Dakota during 1980 was from surface water.

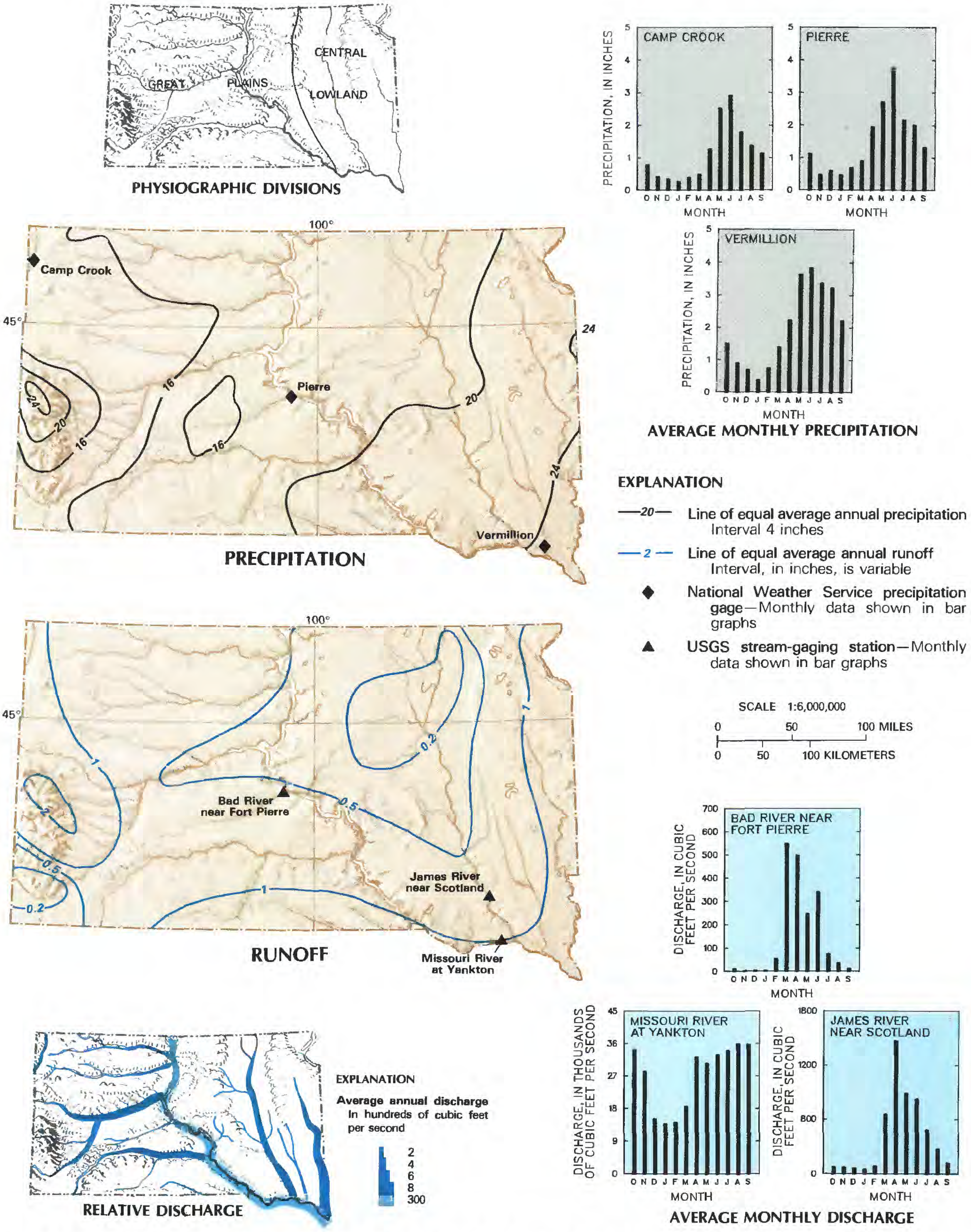

Figure 1. Average annual precipitation and runoff in South Dakota and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in South Dakota

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and South Dakota State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				MISSOURI REGION **Missouri River main stem[1]**				
1.	Missouri River near Mobridge (06358500).	208,700	[2]1928-62	3,500	21,560	471,000	Appreciable	Major water uses include hydroelectric-power generation, irrigation, rural water and municipal-industrial supply, fish and wildlife propagation, and recreation. Dissolved solids between 500 and 600 mg/L.
2.	Missouri River at Pierre (06440000).	243,500	1929-65	[3]2,100	21,860	[3]97,500	. . . do . . .	Do.
3.	Missouri River at Fort Randall Dam (06453000).	263,500	1947-83	[3]1,450	25,230	[3]99,000	. . . do . . .	Do.
4.	Missouri River at Yankton (06467500).	279,500	1930-83	[3]5,980	26,430	[3]92,400	. . . do . . .	Do.
5.	Missouri River at Sioux City, Iowa (06486000).	314,600	1929-83	[3]6,380	29,360	[3]115,000	. . . do . . .	Do.
				Western tributaries[4]				
6.	Little Missouri River at Camp Crook (06334500).	1,970	[5]1903-83	0.2	136	13,300	Negligible	Major water use is irrigation. Undependable flow limits use.
7.	Grand River at Little Eagle (06357800).	5,370	1958-83	[3]0.3	238	[3]24,400	Appreciable	Major water use is irrigation.
8.	Moreau River near Whitehorse (06360500).	4,880	1954-83	0.0	202	44,900	Negligible	Major water use is irrigation. Undependable flow limits use.
9.	Cheyenne River at Cherry Creek (06439300).	23,900	1960-83	[3]26.1	827	[3]84,600	Appreciable	Major water uses include irrigation and municipal-industrial supplies.
10.	Bad River near Fort Pierre (06441500).	3,107	1928-83	0.0	147	47,000	Negligible	Major water use is irrigation. Undependable flow limits use. Periodic flooding.
11.	White River near Oacoma (06452000).	10,200	1928-83	0.5	531	49,200	. . . do . . .	Major water use is irrigation. Undependable flow limits use.
12.	Keya Paha River at Wewela (06464500).	1,070	[5]1937-83	3.6	68.9	8,680	. . . do . . .	Major water use is irrigation. Undependable flow limits use.
				Eastern tributaries[6]				
13.	James River near Scotland (06478500).	20,300	1928-83	1.5	372	23,600	Moderate	Major water uses include irrigation, municipal-industrial supply, fish and wildlife propagation, and recreation. Undependable flow limits use. Periodic flooding.
14.	Vermillion River near Wakonda (06479000).	1,680	1945-83	0.9	125	6,050	. . . do . . .	Undependable flow limits use. Periodic flooding.
15.	Big Sioux River at Akron, Iowa (06485500).	8,360	1928-83	18.8	901	73,200	Negligible	Periodic flooding.

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[1] Within the Missouri-Oahe, Missouri-White, and Missouri-Big Sioux Subregions (Seaber, and others, 1984).

[2] Station discontinued subsequent to construction of Oahe Dam in 1962.

[3] Analysis based on period of record after regulation began.

[4] Within the Missouri-Oahe, Missouri-Little Missouri, Cheyenne, Missouri-White, and Niobrara Subregions (Seaber, and others, 1984).

[5] Period of record not continuous.

[6] Within the James and Missouri-Big Sioux Subregions (Seaber, and others, 1984).

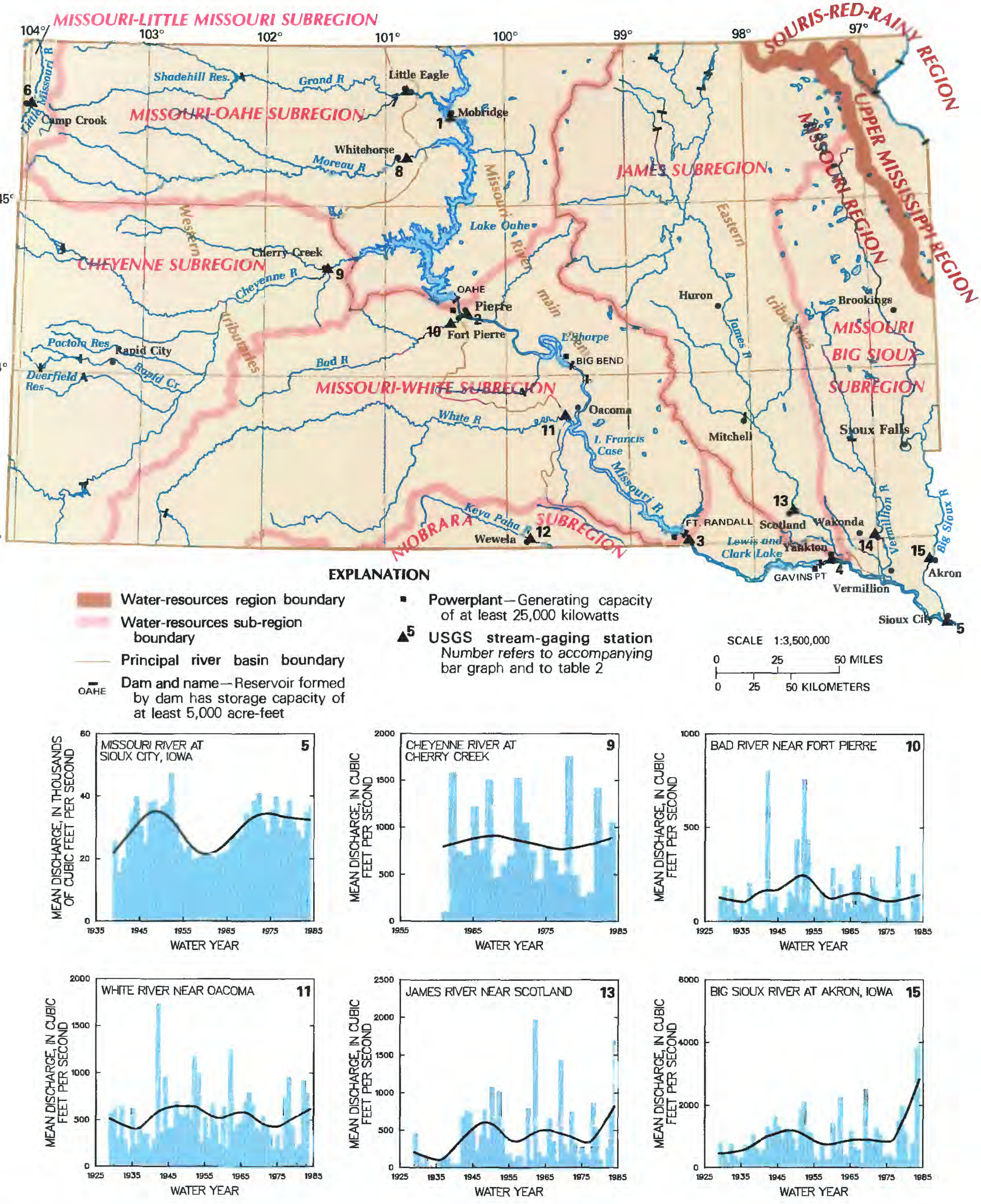

Figure 2. Principal river basins and related surface-water resources development in South Dakota and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

The entire 2,180-mi² drainage area of the Vermillion River is located within the State. Flooding of agricultural land and periods of no flow are major problems. No major municipal withdrawals are made from the river. Less than 1 percent (about 120 acres) of the irrigation in the basin during 1980 was from surface water.

The State contains about 70 percent of the 9,570-mi² Big Sioux River drainage area. Flooding of agricultural land along the Big Sioux River is a major concern. Conversely, the river usually does not flow during periods in the fall and winter upstream from Brookings. No major municipal withdrawals are made from the river. However, Sioux Falls obtains municipal water from the Big Sioux aquifer, and there is significant ground-water and surface-water interaction between the Big Sioux River and the aquifer. Only 5 percent (about 3,220 acres) of the irrigation in the basin in South Dakota during 1980 was from surface water.

SURFACE-WATER MANAGEMENT

South Dakota's surface-water resources are managed through a State Water Plan administered by the South Dakota Department of Water and Natural Resources (1984). The Department's Office of Water Policy provides technical policy analyses required to implement the State Water Plan, to improve water-resource management decisions, and to monitor Federal legislation and policies that affect South Dakota's water resources. The Department's Division of Water Development guides the planning, development, and implementation of water-resource projects to ensure maximum benefit to the public. This includes providing assistance to management organizations such as irrigation, watershed, water-user, water-development, and drainage districts. The Department's Division of Water Rights is charged with licensing and with other functions associated with regulation and management of the waters of the State.

The use of surface water in South Dakota is managed under the doctrine of prior appropriation. The State maintains the position that it has a right to use its equitable proportion of surface water from interstate streams.

The Flood Control Act of 1944, also known as the Pick-Sloan Missouri Basin Program, is a multipurpose program designed to provide benefits for the entire Missouri River basin. The six main-stem dams (four of which are located in South Dakota) have prevented about $2 billion worth of flood damages since their construction (U.S. Army Corps of Engineers, oral commun., 1985). Although substantial flood-control and navigation benefits of the program have been achieved as a result of the construction of the six dams, similar benefits have not been achieved in developing irrigation and municipal water supplies. For example, South Dakota gave up the use of more than 520,000 acres for the main-stem dams and reservoirs in return for 961,210 acres of irrigation development (U.S. Bureau of Reclamation, 1944). However, South Dakota has received only 24,118 acres of irrigation development (the Angostura, Rapid Valley, and Shadehill Units) from the program (U.S. Bureau of Reclamation, 1984). The State considers the Pick-Sloan Missouri Basin Program to be the cornerstone for planning and implementation of major water-resource development in South Dakota.

The U.S. Geological Survey collects hydrologic data and performs research relating to surface water quality and quantity in cooperation with local and State agencies and in support of other Federal agencies (U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Bureau of Indian Affairs, and U.S. Fish and Wildlife Service).

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TENNESSEE
Surface-Water Resources

Tennessee generally is considered to be a water-rich State, but the supply of water varies seasonally, annually, and areally (Alexander and others, 1984). Surface-water quality generally is suitable for most uses throughout the State. Approximately 150,000 Mgal/d (million gallons per day) or 232,000 ft^3/s (cubic feet per second) of surface water is used to generate hydroelectric power (table 1) at 24 dams; reservoirs also are used for flood control, navigation, recreation, and water supply.

Surface water provides approximately 9,600 Mgal/d or 14,900 ft^3/s or 96 percent of the total water withdrawn for offstream use; ground water provides the remaining 400 Mgal/d or 619 ft^3/s or 4 percent of the total freshwater withdrawals. Industrial supplies (9,300 Mgal/d or 14,400 ft^3/s) and public supplies (310 Mgal/d or 480 ft^3/s) are the principal offstream surface-water uses. Fifty-two percent of the population of Tennessee relies on surface water for domestic supply. Additional information on surface-water use in Tennessee is given in table 1.

Enactment of the Tennessee Valley Authority (TVA) in 1933 caused a dramatic increase in shipment along the Tennessee River and in population and industrialization. Development of surface-water resources by the TVA provided flood control and electric power, for the first time, to the rural population of the Tennessee Valley. Even though the river has been extensively developed with a succession of dams and lakes, the entire region remains scenic and prosperous.

The U.S. Army Corps of Engineers has extensively developed the surface-water resources in the Cumberland River basin. Construction of locks and dams enabled river traffic and industrialization along the Cumberland to increase dramatically. Similarly, increased power-generation capacity and water supplies were provided for the growing population and expanding economy. The beautiful lakes and parks provide recreation for many of the people in the Cumberland River basin.

The availability and quality of water for municipal and large, self-supplied commercial and industrial users in Tennessee are primary concerns of State government. Development and implementation of viable programs for dealing with water-supply shortages also are concerns (Alexander and others, 1984).

GENERAL SETTING

Tennessee is located in eight physiographic provinces (fig. 1). The topography of the State is diverse, ranging from rolling hills and broad flood plains in the Coastal Plain province in western Tennessee to steep mountains and deep narrow valleys in the Valley and Ridge and Blue Ridge provinces in eastern Tennessee. Annual precipitation ranges from approximately 47 inches in the west to 80 inches in the mountains in the east, and averages about 48 inches statewide. Precipitation does not exhibit a strong seasonal pattern; however, December through April tend to have the highest monthly rainfalls, and August through October tend to have the lowest monthly rainfalls (fig. 1).

Runoff varies geographically and seaonally in Tennessee as a result of precipitation patterns (fig. 1). During the winter and early spring (December through April), soils are frozen or saturated and evapotranspiration rates are low; these conditions result in high rates of runoff. Flooding is common during this period. The summer months (June through September) have lower runoff rates because of increased evapotranspiration and absorptive capacity of the soils. The majority of the runoff results from rainfall. Average annual runoff varies from approximately 18 to 40 inches (fig. 1). Examples of the seasonal runoff pattern for unregulated rivers are shown by bar graphs (fig. 1) for the Hatchie River at Bolivar, the Harpeth River near Kingston Springs, and the Clinch River above Tazewell.

Population centers and industrial development are located along the principal rivers where ample water supplies and navigation routes are available. Most agricultural activity is concentrated in western Tennessee and in valleys adjacent to the major streams in middle and eastern Tennessee where fertile, productive soils are present; however, little surface water is used for irrigation.

Table 1. Surface-water facts for Tennessee

[Data 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 SURFACE WATER, 1980	
Number (thousands)	2,402
Percentage of total population	52
From public water-supply systems:	
Number (thousands)	2,270
Percentage of total population	49
From rural self-supplied systems:	
Number (thousands)	132
Percentage of total population	3
OFFSTREAM USE, 1980 FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	10,000
Surface water only (Mgal/d)	9,600
Percentage of total	96
Percentage of total excluding withdrawals for thermoelectric power	82
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	310
Percentage of total surface water	3
Percentage of total public water	3
Per capita (gal/d)	137
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	11
Percentage of total surface water	0.1
Percentage of total rural domestic	41
Per capita (gal/d)	85
Livestock:	
Surface water (Mgal/d)	24
Percentage of total surface water	0.2
Percentage of total livestock	41
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	9,300
Percentage of total surface water	97
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	89
Irrigation withdrawals:	
Surface water (Mgal/d)	6.1
Percentage of total surface water	0.1
Percentage of total irrigation	51
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	150,000

PRINCIPAL RIVER BASINS

Tennessee is in the Ohio, Tennessee, and lower Mississippi Regions (fig. 2). The Cumberland and the Tennessee Rivers, which drain the central and eastern parts of the State, are the principal rivers within Tennessee. The Mississippi River, which forms the State's western boundary, drains the western part of Tennessee. The Cumberland and the Tennessee River basins and Mississippi main stem are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

OHIO REGION
Cumberland Subregion

Cumberland River Basin.—Headwaters of the Cumberland River originate in Kentucky. The main stem of the Cumberland River in Tennessee (fig. 2) is almost entirely regulated by five dams—four in Tennessee, Cordell Hull (completed in 1967), Old

Hickory (completed in 1954), Cheatham (completed in 1953), and Barkley (completed in 1964) and one in Kentucky, with combined reservoir storage of slightly more than 9.1 million acre-ft (acre-feet) or 2,970,000 Mgal (million gallons); the dams have approximately 914,000 kW (kilowatts) of power-generation capacity. Major tributaries to the Cumberland River in Tennessee include the Clear Fork, the New, the Obey, the Caney Fork, the Stones, the Harpeth, and the Red Rivers. Reservoirs on the Obey, the Caney Fork, and the Stones River (Lakes Dale Hollow, Great Falls, Center Hill, and J. Percy Priest, respectively) have a combined storage of approximately 4.5 million acre-ft or 1,470,000 Mgal and have approximately 248,860 kW of power-generation capacity. The drainage area of the Cumberland River at its most downstream point in Tennessee (Barkley Dam) is 17,598 mi^2 (square miles).

Principal uses of water from the Cumberland River and its major tributaries, other than power generation, are municipal and industrial supplies, rural-domestic supplies, fish and wildlife propagation, and recreation. The Cumberland River main stem also provides a navigable waterway for shipping into central Tennessee.

Flood damage has been and continues to be a concern in communities along the river. Maximum discharge of record (1922–85) on the Cumberland River at Celina (table 2, site 3) was 145,000 ft^3/s or 93,700 Mgal/d on December 29, 1926. Flood control is a primary purpose of reservoirs in the basin. Regulation by the reservoirs, most of which began in 1943, tends to reduce magnitudes of flood peaks along the main stem of the river; however, flooding is still a problem. Regulation also has reduced the variability in average annual discharge of the Cumberland River at Celina (site 3), as shown in figure 2.

The surface-water quality in the Cumberland River basin is generally stable and suitable for most uses. Locally, water quality in the upper part of the basin is severely impacted by nonpoint sources associated with coal mining. Surface mining can cause increased sedimentation and increased mineralization of water in streams. These conditions may limit the domestic, municipal, industrial, and recreational use of the water. The lower part of the basin has significant water-quality problems resulting from a combination of several factors. Low dissolved-oxygen concentrations in reservoir releases, the combined effect of numerous municipal and industrial waste discharges, and combined sewer bypasses in the Nashville area often result in water-quality violations of State standards. Future upgrading of existing municipal waste treatment facilities should improve the surface-water quality in the Cumberland River basin.

TENNESSEE REGION

Upper Tennessee, Middle Tennessee-Hiwassee, Middle Tennessee-Elk, and Lower Tennessee Subregions

Tennessee River Basin.—The Tennessee River is formed by the confluence of the French Broad and the Holston Rivers above Knoxville in eastern Tennessee and is the fifth largest river in America. The main stem of the Tennessee River is totally regulated within the State by six dams—Fort Loudoun (completed in 1943), Watts Bar (completed in 1942), Chickamauga (completed in 1940), Nickajack (completed in 1967), Pickwick (completed in 1938), and Kentucky (completed in 1944) with a combined reservoir storage of slightly more than 10.2 million acre-ft or 3,320,000 Mgal; the dams provide approximately 753,670 kW of power-generation capacity. Major tributaries to the Tennessee River in Tennessee include the Hiwassee, the Ocoee, the Little Tennessee, the Clinch, the Elk, the Duck, and the Big Sandy Rivers. Fifteen principal reservoirs on the major tributaries have a combined storage of approximately 8.8 million acre-ft or 2,870,000 Mgal and provide approximately 1,011,380 kW of power-generation capacity. The drainage area of the Tennessee River at its most downstream point in Tennessee (Kentucky Dam) is approximately 40,200 mi^2.

The surface-water quality in the Tennessee River basin is generally stable and suitable for most uses. Some water-quality problems in the basin are results of nonpoint source runoff from farmland, industry and municipal wastes, lake eutrophication, and low dissolved oxygen concentrations in reservoir releases (Tennessee Valley Authority, 1980). Problems associated with reservoir releases also include increased levels of iron and manganese and rapidly fluctuating temperatures. Each conditon has the potential to affect water uses below all the reservoirs, particularly during severe or extended drought. Water-quality problems exist in certain local areas; however, the overall trend in water quality is toward improvement due to efforts of the Tennessee Division of Water Management, U.S. Environmental Protection Agency, and other agencies concerned with improving the quality of the State's water resources.

Principal uses of water from the Tennessee River and its major tributaries, other than power generation, are municipal and industrial supplies, rural-domestic supplies, fish and wildlife propagation, and recreation. The Tennessee River is the largest navigable waterway in Tennessee and provides shipping access into Tennessee.

Flood damage has been and continues to be a concern in communities along the river. Maximum discharge of record (1874–1985) on the Tennessee River at Chattanooga (table 2, site 11) was 410,000 ft^3/s or 265,000 Mgal/d on March 1, 1875. Flood control is a primary purpose of reservoirs in the basin. Regulation by the reservoirs tends to reduce magnitudes of flood peaks along the main stem of the river; however, flooding is still a problem. Variability in average annual discharge of the Tennessee River at Chattanooga (site 11) is shown in figure 2.

LOWER MISSISSIPPI REGION

Lower Mississippi-Hatchie Subregion

Lower Mississippi River Basin.—The Mississippi River forms the western boundary of Tennessee and provides direct drainage for about one-fourth of the State. The river is an important navigation route to the large metropolitan area of Memphis.

Major use of water from the main stem and its tributaries, other than navigation, is recreation; little water is withdrawn for irrigation. Use of the water for industrial, municipal, and rural-domestic supplies are constrained by sediment loads and by waste disposal at upstream sources. At these locations, adequate supplies of ground water are available for most uses.

Generally low stream gradient contributes to the frequency and severity of flooding, which has been and continues to be a concern in communities along the river and its tributaries. Maximum discharge of record (1929–85) on the Obion River at Obion (fig. 2, site 16) was 99,500 ft^3/s or 64,300 Mgal/d on January 24, 1937, and maximum discharge of record (1929–85) on the Hatchie River at Bolivar (fig. 2, site 17) was 61,600 ft^3/s or 39,800 Mgal/d on March 18, 1973. Flooding of similar magnitude can recur because western Tennessee lacks flood-control reservoirs. For example, the 100-year flood on the Obion River at Obion (1,852-mi^2 drainage area) is 92,800 ft^3/s or 60,000 Mgal/d (table 2, site 16) or a runoff yield of 50 (ft^3/s)/mi^2 (cubic feet per second per square mile), and the 100-year flood on the Hatchie River at Bolivar (1,480-mi^2 drainage area) is 68,000 ft^3/s or 43,900 Mgal/d (table 2, site 17) or a runoff yield of 46 (ft^3/s)/mi^2. Frequent flooding of lower magnitude occurs several times annually.

The quality of surface water in the Mississippi River basin in Tennessee has been degraded by sedimentation from farmland, by discharge of wastewater, and by agricultural chemicals. Locally, sediment transport from farmland and nutrient enrichment resulting from crop-production activities adversely affect stream water for municipal and industrial uses. The effects of municipal and industrial discharges on surface-water quality are also a concern in Tennessee. Foremost among such sources of discharges, in the Mississippi River

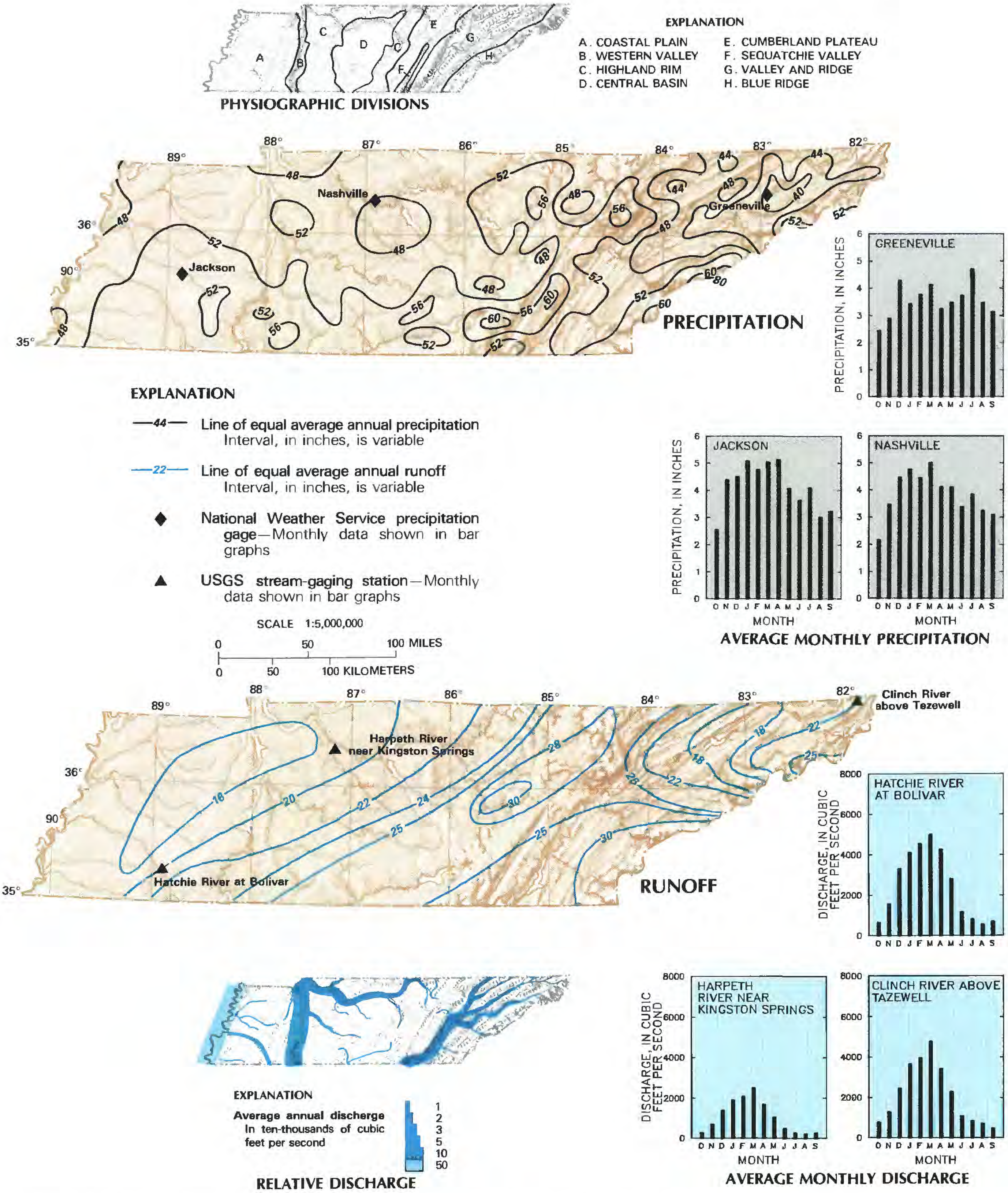

Figure 1. Average annual precipitation and runoff in Tennessee and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946, and Miller, 1974.)

basin, are municipal sewage treatment plants in and near urban centers and chemical processing and production plants. The overall trend in water quality is toward improvement owing to efforts by State and Federal agencies to decrease the effects of municipal and industrial wastes.

SURFACE-WATER MANAGEMENT

Tennessee's surface-water resources are managed at the State level by the Governor's Safe Growth Team, the Tennessee Department of Health and Environment, the Tennessee Wildlife Resources Agency, and the Tennessee Department of Conservation. The Office of Water Management, in the Department of Health and Environment, is charged with developing a State Water Management Plan to ensure maximum public benefit; the Office also is responsible for enforcing the regulations adopted by the State.

The Tennessee Office of Water Management consists of four divisions:

1. The Division of Water Pollution Control which issues National Pollutant Discharge Elimination System (NPDES) permits for discharge of wastes into streams. This Division enforces the

Table 2. Selected streamflow characteristics of principal river basins in Tennessee

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and Tennessee State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
				OHIO REGION **CUMBERLAND SUBREGION** **Cumberland basin**				
1.	New River at New River (03408500).	382	1934-85	0.47	741	63,500	None	Water quality affected by coal mining.
2.	Wolf River near Byrdstown (03416000).	106	1942-85	5.19	192	31,400	. . . do . . .	Recreational area and water supply.
3.	Cumberland River at Celina (03417500).	7,307	1924-85	850	11,830	78,000	Appreciable	Industrial supply, power generation, and water supply. Regulation began in 1943. Low flow and 100-year flood analyses based on period of record since regulation began. Furnished by the U.S. Army Corps of Engineers.
4.	West Fork Stones River near Smyrna (03428500).	237	1965-85	9.0	440	57,400	None	Recreational area and water supply.
5.	Harpeth River near Kingston Springs (03434500).	681	1924-85	25.4	986	69,700	. . . do . . .	State scenic river and water supply.
6.	Red River at Port Royal (03436100).	935	1961-85	66.6	1,351	18,000	. . . do . . .	Water supply.
				TENNESSEE REGION **UPPER TENNESSEE, MIDDLE TENNESSEE-HIWASSEE, MIDDLE TENNESSEE-ELK, AND LOWER TENNESSEE SUBREGIONS** **Tennessee basin**				
7.	Nolichucky River at Embreeville (03465500).	805	1919-85	224	1,370	72,600	None	Water supply.
8.	Little River near Maryville (03498500).	269	1951-85	54.8	535	37,200	Moderate	Water supply and recreational area.
9.	Obed River near Lancing (03539800).	518	1958-68, 1974-85	1.3	1,062	84,400	None	Water supply and recreational area.
10.	South Chickamauga Creek near Chickamauga (03567500).	428	1928-78, 1980-85	88.3	698	35,100	Moderate	Industrial supply.
11.	Tennessee River at Chattanooga (03568000).	21,400	1874-1985	10,000	37,100	257,000	Appreciable	Industrial supply and power generation. Regulated since 1936. Low flow and 100-year flood analyses based on period of record since regulation began. Furnished by the Tennessee Valley Authority.
12.	Elk River near Prospect (03584500).	1,784	1905-07, 1920-85	330	3,076	128,000	Moderate	Water supply and power generation. Regulation began in 1945.
13.	Duck River at Hurricane Mills (03603000).	2,557	1925-85	303	4,121	114,000	. . . do . . .	Regulated since 1976. Water supply and recreational area.
14.	Buffalo River near Lobelville (03604500).	707	1927-85	174	1,196	88,900	None	Recreational area and water supply.
15.	Big Sandy River at Bruceton (03606500).	205	1929-85	35.5	294	18,900	. . . do . . .	Water supply.

entire body of regulations associated with NPDES permits, and regulates the placement of structures of discharge into any stream.

2. The Division of Water Supply administers and regulates the State's Safe Drinking Water Act for public supply.
3. The Division of Ground Water Protection regulates wastewater disposal into the ground-water system.
4. The Division of Construction Grants and Loans allocates Federal and State funds for construction of water treatment plants and reviews construction plans.

The Tennessee Office of Water Management requires registration of streamflow withdrawals of 50,000 gal/d or 0.08 ft³/s or more in the State. This registration is required by a State water-use law that became effective in 1965.

The TVA partly manages streamflow along the main stem of the Tennessee River with a series of dams and reservoirs that were constructed primarily for navigation, flood control, and power generation. The U.S. Army Corps of Engineers partly manages streamflow along the main stem of the Cumberland River with a series of dams and reservoirs that were constructed primarily for flood control, navigation, power generation, and recreation.

The U.S. Geological Survey collects hydrologic data and performs research in flood magnitude and frequency, low-flow characteristics, and surface-water quality in cooperation with local and State agencies and in support of other Federal agencies (Department of Energy, U.S. Army Corps of Engineers, and the Tennessee Valley Authority).

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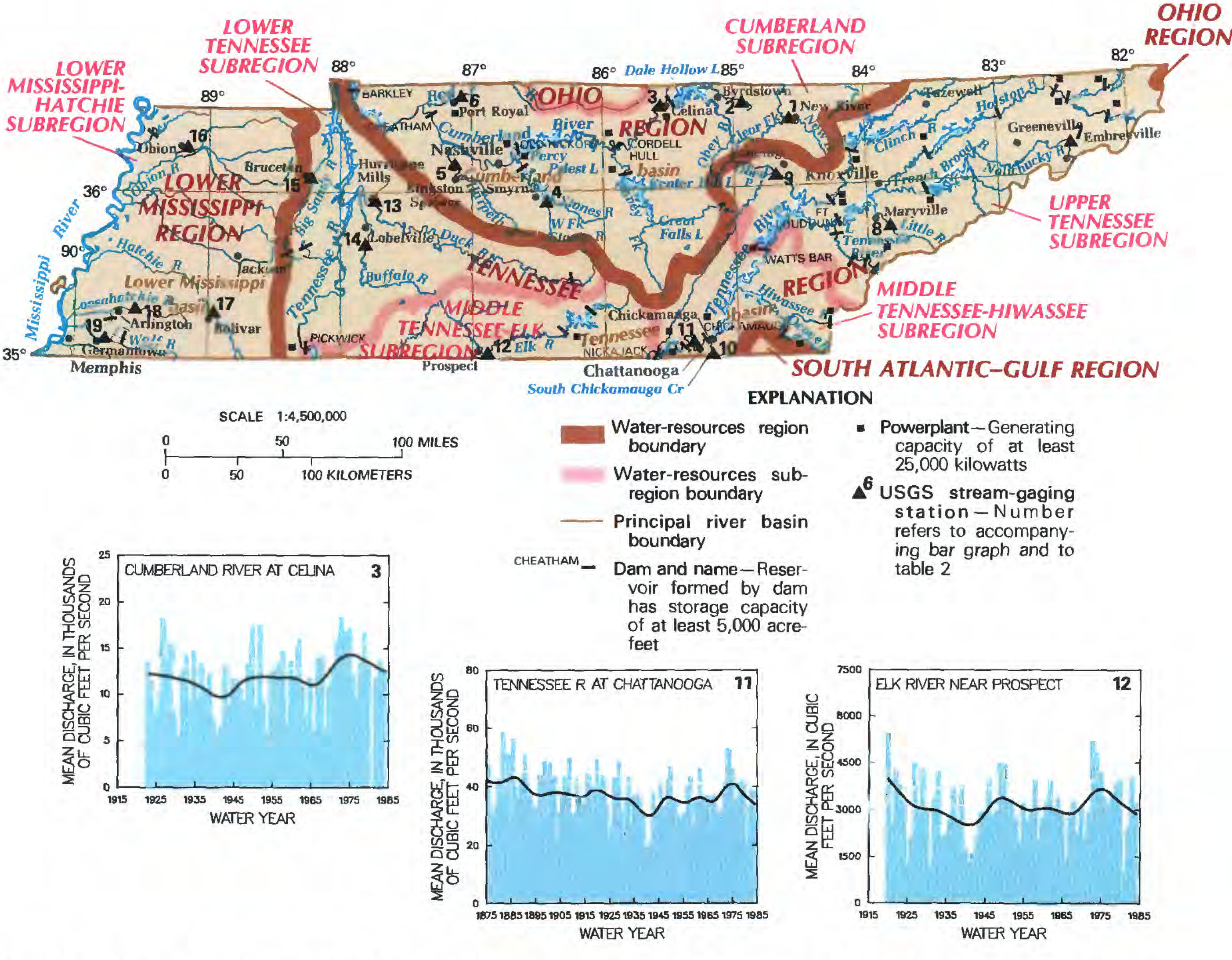

Figure 2. *Principal river basins and related surface-water resources development in Tennessee and average discharges for selected sites.*

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

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Table 2. Selected streamflow characteristics of principal river basins in Tennessee—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second. Sources: Reports of the U.S. Geological Survey and Tennessee State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				LOWER MISSISSIPPI REGION Lower Mississippi-Hatchie Subregion Lower Mississippi basin				
16.	Obion River at Obion (07026000).	1,852	1929-58, 1966-85	266	2,702	92,800	None	Water quality affected by high suspended-sediment content, and pollution. Overbank flooding occurs annually.
17.	Hatchie River at Bolivar (07029500).	1,480	1929-85	126	2,428	68,000	. . . do . . .	Federal and State wildlife refuge area. Overbank flooding occurs annually.
18.	Loosahatchie River near Arlington (07030240).	262	1969-85	71	364	24,000	. . . do . . .	Water quality affected by high suspended-sediment content and pollution. Overbank flooding occurs annually.
19.	Wolf River at Germantown (07031650).	699	1969-85	200	1,040	42,100	. . . do . . .	Water quality affected by high suspended-sadiment content and pollution. Overbank flooding occurs annually.

FOR ADDITIONAL INFORMATION

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Prepared by Clarence H. Robbins and R. H. Bingham

TEXAS
Surface-Water Resources

A substantial part of the economy of Texas depends on the State's surface-water supplies, and that dependence is expected to increase in the future. Texas has a 400-mile coastline on the Gulf of Mexico, from which more than $1.25 billion of seafood is harvested each year. In addition, the State has more than 3,700 streams with a total length of about 80,000 miles. Texas, second in volume of inland water, has more than 6,000 mi² (square miles) of lakes, reservoirs, and streams. Rapidly declining ground-water levels in the High Plains irrigation areas, in El Paso, and in the Waco-Dallas-Fort Worth area; and land-surface subsidence caused by ground-water withdrawals in the Houston-Galveston area are limiting withdrawals in those areas (U.S. Geological Survey, 1984, p. 215). During 1980, almost 40 percent of all water used in Texas, including 61 percent of public-water supplies and 51 percent of domestic supplies, came from surface-water sources (table 1). More than 7 million people, or about half of the State's population, are served by surface-water supplies. In addition, 77 percent of the self-supplied industrial and 51 percent of water supplies for livestock were derived from surface water (Texas Department of Water Resources, 1984). Hydroelectric powerplants had a capacity of 546 megawatts. Surface-water withdrawals in Texas in 1980 for various purposes and related statistics are given in table 1.

Table 1. Surface-water facts for Texas

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; > = greater than. Source: Solley, Chase, and Mann, 1983; Texas Department of Water Resources unpublished Data, 1985]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	7,308
Percentage of total population	51
From public water-supply systems:	
Number (thousands)	7,083
Percentage of total population	50
From rural self-supplied systems: (Includes individual systems and public-supply systems for communities with less than 1,000 population)	
Number (thousands)	225
Percentage of total population	2
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	16,000
Surface water only (Mgal/d)	6,300
Percentage of total	39
Percentage of total excluding withdrawals for thermoelectric power	38
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	1,300
Percentage of total surface water	21
Percentage of total public supply	61
Per capita (gal/d)	183
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	63
Percentage of total surface water	1
Percentage of total rural domestic	17
Per capita (gal/d)	119
Livestock:	
Surface water (Mgal/d)	111
Percentage of total surface water	2
Percentage of total livestock	51
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	1,400
Percentage of total surface water	23
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	77
Excluding withdrawals for thermoelectric power	76
Irrigation withdrawals:	
Surface water (Mgal/d)	3,300
Percentage of total surface water	54
Percentage of total irrigation	30
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	>9,800

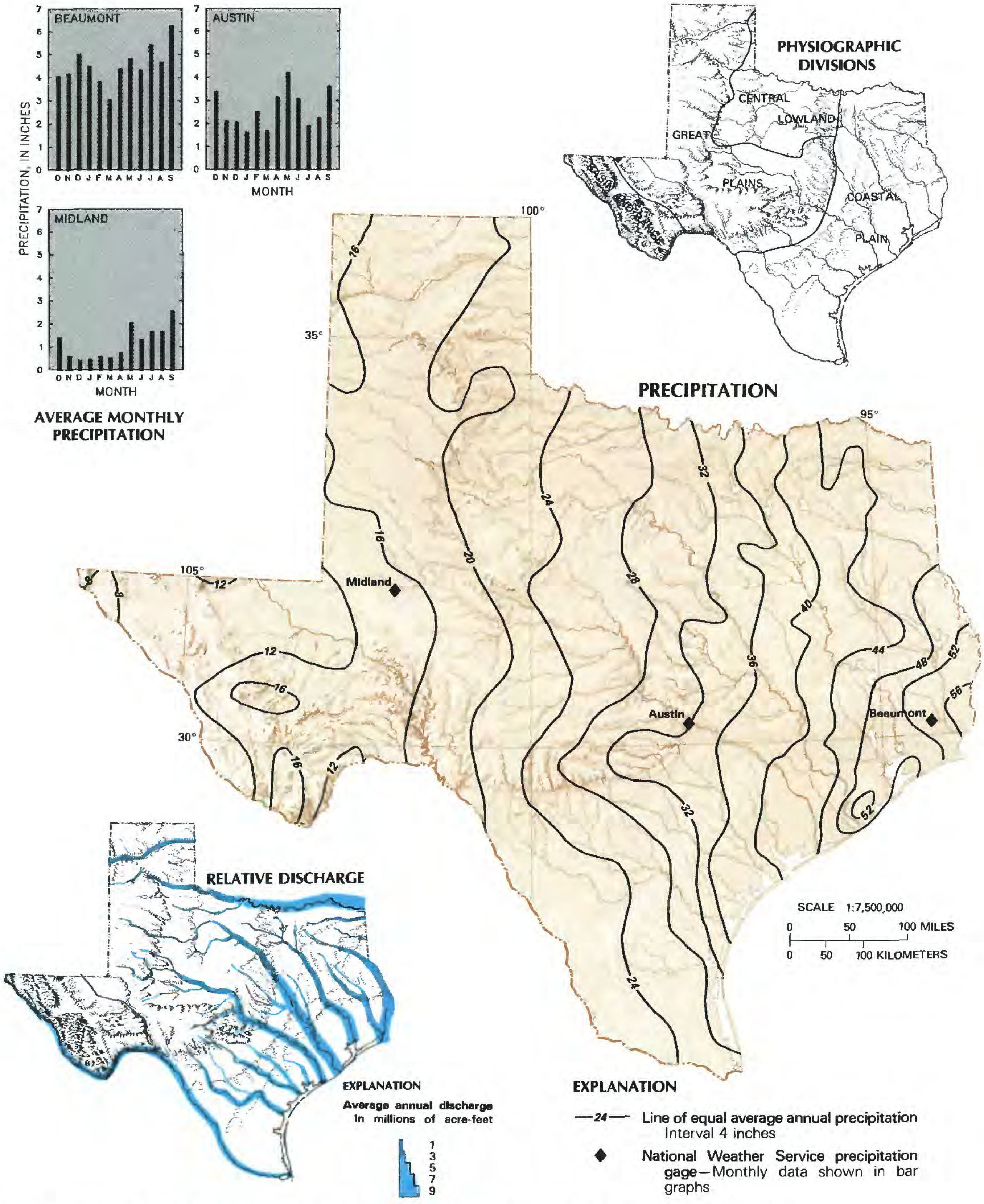
Texas has two of nature's persistent hydrologic dilemmas—droughts and floods. At least 14 significant droughts of differing severity and geographical extent have occurred in Texas since 1900 (Texas Department of Water Resources, 1984). The most severe drought on record occurred during 1950-56, when 94 percent of the State's counties were classified as disaster areas. Devastating floods have occurred in most areas of Texas; flash floods from intense rainstorms are common and unpredictable, and tidal surges and flooding associated with tropical storms are common in the flat lowlands of the Coastal Plain physiographic province (fig. 1).

All major rivers in the State are regulated, to varying degrees, by control structures or reservoirs. Presently, Texas has 184 major reservoirs with a capacity of 5,000 acre-ft (acre-feet) or 1,630 Mgal (million gallons) or greater, and 5 more are under construction. Texas' share of the conservation storage of these 189 reservoirs is an estimated 32,300,000 acre-ft or 10,530,000 Mgal, with an additional 17,500,000 acre-ft or 5,700,000 Mgal of flood-control storage (Texas Department of Water Resources, 1984). Yet, with all these surface-water resources, available storage capacity from reservoirs in much of the State barely will be sufficient to meet the State's present water demands during critical droughts (Texas Department of Water Resources, 1984). However, shortages will occur in some parts of the State during moderate droughts because the reservoirs are not connected to a central distribution system.

Natural processes and human activities affect the quality of a significant part of the State's surface waters. Excessive concentrations of sodium chloride from salt springs and salt flats in the upstream reaches of the Red, the Brazos, the Colorado, and the Pecos Rivers commonly make river and reservoir water unfit for most uses (Rawson, 1974); in some areas, oil-and gas-exploration and production activities contribute to this problem. Treated sewage effluent is a significant percentage of the flow in the Trinity River downstream from Dallas-Fort Worth and in the San Antonio River downstream from San Antonio. The number and severity of surface-water-quality issues are increasing as a consequence of increasing urban and industrial development in the Houston-Galveston area. Another concern to the State is the potential effect of upstream water development on freshwater inflows to the bays and estuaries—coastal waters that sustain commercial and sport fishing, navigation, commercial shell dredging, and diverse recreational activities.

GENERAL SETTING

The varied landscape of Texas is characterized by four major physiographic provinces (fig. 1). The Coastal Plain province, which rises from sea level to about 550 feet above sea level near the base of the Balcones Escarpment, is a rolling to hilly rangeland. The Central Lowland province is a level to rolling prairie, with oak and juniper woodland and prairie in the east that grades to mesquite woodlands and prairie in the west. The Great Plains province primarily consists of the Edwards Plateau region in the south and the High Plains region in the north. The Edwards Plateau, which ranges from 700 feet above sea level at the top of the Balcones Escarpment to about 2,600 feet in the west, is a deeply dissected, rolling to mountainous area underlain by cavernous to dense limestone. Many spring-fed, perennially flowing streams issue from the limestone. The High Plains, which is part of an alluvial mantle that extends eastward from the Rocky Mountains, is a level, relatively treeless, semiarid prairie with a maximum elevation of about 4,500 feet above sea level. Flat-lying, porous soils limit surface runoff in many areas. Large tracts of irrigated farmland dominate land use throughout most of the High Plains. The Basin and Range province consists of forested mountains as high as 8,000 feet above



EXPLANATION

Average annual discharge in millions of acre-feet

1
3
5
7
9

EXPLANATION

—24— Line of equal average annual precipitation Interval 4 inches

◆ National Weather Service precipitation gage—Monthly data shown in bar graphs

Figure 1. Average annual precipitation and runoff in Texas and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Admistration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

sea level that alternate with arid, gravel-filled valleys. Throughout Texas, the natural vegetation grades from dense forests in the east to treeless, grassy prairies in the west.

Although evaporation of water from the Gulf of Mexico is the largest source of precipitation in Texas, the geologic and topographic differences among the provinces greatly affect the distribution and variation in precipitation and runoff throughout the State. Average annual precipitation progressively decreases from about 56 inches along the eastern border near the Gulf of Mexico to about 8 inches on the leeward side of the mountains along the far western border (fig. 1). Annual precipitation averages 54 inches at Beaumont (fig. 1), and the summer rainfall maximum shown at this station typifies the seasonal rainfall maximum in the eastern part of the State along the Gulf of Mexico and in the Basin and Range province. Annual precipitation averages about 32 inches at Austin and 14 inches at Midland (fig. 1), and the May and September rainfall maximums shown at these stations are typical of those in the Great Plains and Coastal Lowland provinces in the central part of the State (Carr, 1967).

Statewide, evaporation losses account for about 42 percent of the precipitation. The average annual lake-surface evaporation rates for Texas range from 45 inches along the eastern

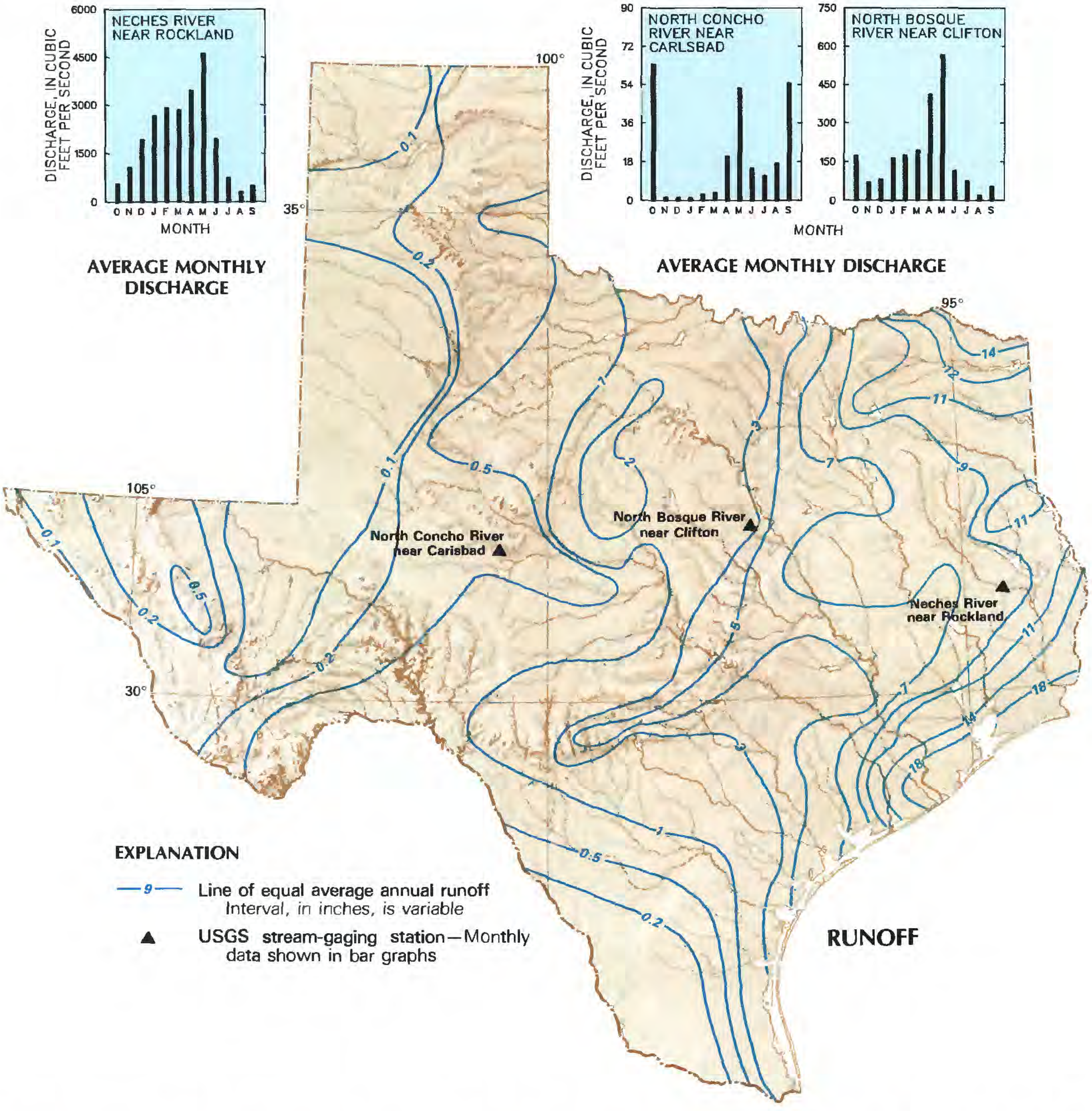


Figure 1. Average annual precipitation and runoff in Texas and average monthly data for selected sites, 1951-80—Continued.

boundary to 95 inches near the "Big Bend" area in the southwest (Larkin and Bomar, 1983). Consequently, potential evaporation exceeds precipitation, except for the eastern part of the Coastal Plain province (fig. 1).

Runoff patterns vary seasonally and geographically throughout Texas (fig. 1). In the arid areas of the Basin and Range lowlands and the High Plains, average annual runoff is less than 0.1 inch whereas runoff exceeds 18 inches in the southeastern part of the Coastal Plain. The increase in runoff on the Balcones Escarpment caused by increased springflow is shown in figure 1 by the "hair pin"-shaped, westerly extension of the 5-inch-runoff line in central Texas near Austin; the decreased runoff south of this area is caused partly by streamflow losses to subsurface recharge from streams that traverse the Balcones fault zone at the base of the escarpment. The graphs of average monthly discharges in figure 1 primarily reflect precipitation patterns in the area.

PRINCIPAL RIVER BASINS

Surface water in Texas is located in three hydrologic regions: The Arkansas-White-Red Region, which contains the principal Canadian-Red River basin; the Texas-Gulf Region, which contains the principal Sabine-Neches-Trinity-San Jacinto, the Brazos-Colorado, and the Lavaca-Guadalupe-Nueces River basins; and the Rio Grande Region, which contains the principal Rio Grande basin (Seaber and others, 1984). The water-resources subregions to which these river basins correspond are indicated in footnotes in table 2. Most rivers in Texas drain to the southeast, and many flow through two or more physiographic provinces where their runoff and flood characteristics can change abruptly. These principal river basins are described below; their locations, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

ARKANSAS-WHITE-RED REGION

Canadian-Red River Basin

The Canadian and the Red Rivers originate in the High Plains of New Mexico and drain the northern part of Texas (fig. 2). The upstream reaches of both rivers are subject to infrequent flooding, and both contain saline water from natural sources.

The Canadian River is 906 miles long; has a total drainage area of 47,705 mi², of which 12,700 mi² is in the High Plains area in Texas; and contains 2 major reservoirs in Texas. Lake Meredith, completed in 1965, is the largest reservoir, and supplies water to 11 cities for municipal and manufacturing uses by means of the Canadian River aqueduct system. Since 1952, development and use of this river have been governed by the Canadian River Compact.

The Red River is 1,360 miles long, forms part of the Texas-Oklahoma and Texas-Arkansas boundaries, and has a total drainage area of 93,450 mi², of which 24,463 mi² is in Texas. The river was named for the reddish-colored silt transported by the stream from its headwaters. It was a menace to early settlers and ranchers because of its treacherous currents and long reaches underlain by dangerous quicksand. Major flooding rarely occurs in the Great Plains and Central Lowland provinces; but, in the Coastal Plain province, the increased precipitation and flatter terrain contribute to a greater flood potential. Since 1980, the use of water in the Red River basin by Texas has been governed by the Red River Compact. However, actual distribution of water among the States of Oklahoma, Arkansas, Louisiana, and Texas is difficult to administer because of ungaged areas, timeliness of streamflow data, and uncertainty of travel time and flow losses. There are 22 major reservoirs in the basin (fig. 2); the most significant is Lake Texoma, which was completed in 1943 for flood control and hydroelectric-power generation and is the largest lake wholly or partly in Texas. The average discharge of the Red River where it leaves Texas is about 11,700 ft³/s (cubic feet per second), or 7,560 Mgal/d. The upstream reaches of the Red River contain elevated concentrations of salt and other minerals that limit water use; some tributaries contain saline water with dissolved-solids concentrations that exceed 25,000 mg/L (milligrams per liter). During 1980, 55 percent of the surface water used in the Red River basin was for irrigation and 29 percent was for municipal supplies (Texas Department of Water Resources, 1984).

TEXAS-GULF REGION

Sabine-Neches-Trinity-San Jacinto River Basin

The Sabine, the Neches, the Trinity, and the San Jacinto Rivers drain the relatively flat, subhumid area of the Coastal Plain province (fig. 2). Flooding is a major problem in this principal basin, where hurricane-induced surge tides and torrential rains cause damaging floods, particularly along the downstream reaches of the Trinity and the San Jacinto Rivers.

The Sabine River is 360 miles long, forms part of the State boundary between Texas and Louisiana, and has a total drainage area of 9,756 mi², of which about 76 percent is in Texas. The Sabine River has an average discharge of about 7,600 ft³/s or 4,910 Mgal/d at its mouth. Since 1954, Texas' use of water from the basin has been governed by the Sabine River Compact. Flow in the basin is controlled by 12 major reservoirs, including Lake Tawakoni and Toledo Bend Reservoir, which is the fifth largest reservoir in the United States with a total capacity of 4,477,000 acre-ft or 1,460,000 Mgal. Toledo Bend was completed in 1966 for hydroelectric-power generation, water conservation, municipal and industrial supply, and irrigation. Water from Lake Tawakoni (completed in 1960) is exported from the Sabine River basin to supplement supplies for the municipalities of Dallas, Commerce, and Terrell.

The Neches River is 416 miles long and has a drainage area of 10,011 mi², all of which is in Texas. Because the basin lies in an area that receives substantial rainfall, the average discharge of the Neches near its mouth is about 6,610 ft³/s or 4,270 Mgal/d, and large-magnitude floods occur on an average of once every 5 years. The effect of the early 1950's drought on streamflow in the basin is evident on the discharge graph of the Neches River near

Table 2. Selected streamflow characteristics of principal river basins in Texas

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Contributing drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				ARKANSAS-WHITE-RED REGION **Canadian-Red River basin[1]**				
1.	Canadian River near Amarillo (07227500).	15,376	1939-83	0.3	331	135,000	Moderate	Low flow controlled by New Mexico reservoirs.
2.	Red River near Terral, Okla. (07315500).	22,787	1939-83	76.4	2,117	. . . .	Appreciable	Many diversions for municipal, oilfield, and irrigation uses.
				TEXAS-GULF REGION **Sabine-Neches-Trinity-San Jacinto River basin[2]**				
3.	Trinity River at Dallas (08057000).	6,106	1903-83	20.5	1,530	. . . .	Appreciable	Flow controlled by seven upstream reservoirs.
4.	Trinity River at Romayor (08066500).	17,186	1969-83	64	7,417	. . . .	Appreciable	Flow is regulated by Livingston Reservoir.
5.	Neches River near Rockland (08033500).	3,636	1962-83	27.6	1,974	68,400	Negligible	At times low flow may be regulated by reservoirs.
				Brazos-Colorado River basin[3]				
6.	Salt Fork Brazos River near Aspermont (08082000).	2,496	1940-83	0.0	108	52,900	Negligible	National stream-accounting network station.
7.	Brazos River near South Bend (08088000).	13,107	1939-83	0.0	836	. . . .	. . . do . . .	Small diversions for municipal supply and oilfield uses.
8.	North Bosque River near Clifton (08095000).	968	1968-83	0.0	167	73,200	. . . do . . .	City of Clifton diverts flow and discharges effluent upstream from station.
9.	Colorado River at Colorado City (08121000).	1,585	1953-83	0.0	38.9	. . . .	Appreciable	Diversions from Lake J. B. Thomas since 1952.
10.	Llano River near Junction (08150000).	1,849	1916-83	17.8	194	363,000	Negligible	Diversion upstream from station for irrigation.
11.	Colorado River at Wharton (08162000).	30,600	1939-83	224	2,685	. . . .	Appreciable	Many diversions for irrigation, municipal supply, and other uses.
				Lavaca-Guadalupe-Nueces River basin[4]				
12.	Guadalupe River at Spring Branch (08167500).	1,315	1923-83	0.1	311	158,000	Negligible	Several small diversions for irrigation.
13.	Nueces River at Laguna (08190000).	737	1924-83	9.6	148	408,000	Moderate	Do.
14.	Nueces River near Three Rivers (08210000).	15,427	1916-83	0.0	848	116,000	. . . do . . .	Flow loss by infiltration to aquifer in Balcones fault zone.
				RIO GRANDE REGION **Rio Grande basin[5]**				
15.	Pecos River near Girvin (08446500).	29,560	1940-83	3.3	84.2	23,300	Moderate	Flow regulated by Red Bluff Reservoir.

[1] Within the Upper Canadian, Lower Canadian, North Canadian, Red Headwaters, Red-Washita, and Red-Sulphur Subregions (Seaber,and others, 1984).

[2] Within the Sabine, Neches, Trinity, and Galveston Bay-San Jacinto Subregions (Seaber, and others, 1984).

[3] Within the Brazos Headwaters, Middle Brazos, Lower Brazos, Upper Colorado, and Lower Colorado-San Bernard Coastal Subregions (Seaber, and others, 1984).

[4] Within the Central Texas Coastal and Nueces-Southwestern Texas Coastal Subregions(Seaber, and others, 1984).

[5] Within the Rio Grande-Mimbres, Rio Grande Amistad, Rio Grande Closed Basins, Upper Pecos, Lower Pecos, Rio Grande-Falcon, and Lower Rio Grande Subregions (Seaber, and others, 1984).

Rockland (fig. 2, site 5). Ten reservoirs have been constructed in the Neches River basin primarily for municipal and industrial supplies and for storage. The Sam Rayburn Reservoir, the second largest lake in the State (completed in 1965) is used for flood control and hydroelectric-power generation. During 1980, about 68 percent of the surface water used in the basin was for self-supplied industries (Texas Department of Water Resources, 1984).

The Trinity River is 550 miles long and has a drainage area of 17,969 mi², all of which is in Texas. The Trinity River basin contains more large cities (Dallas, Fort Worth, Arlington, and Irving, to name a few), greater population (3.2 million), and more extensive industrial development than any other river basin in Texas. A 6-foot-deep navigation channel that extends from the mouth upstream about 41 miles was completed in 1925 and was maintained until 1940; maintenance of the navigation channel resumed in 1968. The basin contains 27 major reservoirs (fig. 2), and 4 more are under construction; this basin contains 17 percent of the total surface area of reservoirs in the State, and recreational use of these reservoirs is substantial. The average discharge of the Trinity near its mouth is 7,417 ft³/s or 4,790 Mgal/d. Along the upper reaches of the river, reservoirs that supply municipal and industrial water for the Dallas–Fort Worth area contain water suitable for most uses. However, the treated effluent from municipal wastewater-treatment plants constitutes most of the nutrient-enriched and oxygen-depleted low flows of the Trinity from south of Dallas (table 2, site 3) for 250 miles to Livingston Reservoir. During 1980, 72 percent of the surface water used in the Trinity River basin was for municipal supplies (Texas Department of Water Resources, 1984).

Although only 85 miles long, the San Jacinto River is a valuable source of water. Its drainage area is 3,976 mi², all of which is in Texas. The basin is subject to intense rainstorms and to severe flooding throughout the year. Houston, the third largest port in the Nation and home for 1.5 million people, is an industrial center that dominates the surface-water resources in the basin. Surface water for municipal supplies in the Houston area comes from two reservoirs along the upstream reaches of the river—Lake Conroe (completed in 1973) and Lake Houston (completed in 1954), where the quality of water is suitable for most uses. However, rapid urban development is causing concern about the potential degradation of water quality in Lake Houston. The Houston Ship Channel extends from the Port of Houston into the San Jacinto River and Galveston Bay to the Gulf of Mexico. Treated sewage effluents and industrial effluents from chemical and petrochemical manufacturing, oil production, and shipping are discharged to the Houston Ship Channel and tributary streams and create water-quality concerns.

Because of the large amount of rainfall, this basin has the most plentiful supplies of water in the State; consequently, some planners in water-short areas periodically propose to transport water to their areas. As expected, water managers in their basins want to reserve the water for growth.

Brazos-Colorado River Basin

The Brazos and the Colorado Rivers have many similarities: They both begin in the High Plains of New Mexico, enter and traverse Texas in adjacent and parallel basins, and discharge to the Gulf of Mexico (fig. 2); they both acquire large concentrations of dissolved salts from natural sources in their upstream reaches; and they both are appreciably regulated.

The Brazos River is 840 miles long and has a drainage area of 45,573 mi², of which 42,800 mi² is in Texas. Much of the early Anglo-American colonization of Texas occurred in the Brazos River Valley. Agriculture dominates land use within the basin, and the Brazos River annually deposits an estimated 104,250 tons of eroded topsoil at its mouth (Texas Department of Water Resources, 1984). Saline water, primarily of natural origin, in the northwestern part of the Brazos basin is a major concern (Rawson and others, 1968); flows of the Salt Fork Brazos (table 2, site 6) and the main stem Brazos River upstream from Possum Kingdom Reservoir are too saline for most beneficial uses. The average daily load of dissolved solids in the Salt Fork Brazos is estimated to be 1,760 tons (Texas Department of Water Resources, 1984). As a result of this salinity, water in three main stem reservoirs—Possum Kingdom (completed in 1941), Granbury (completed in 1969), and Whitney (completed in 1951), with a combined conservation storage capacity of 1,340,000 acre-ft or 437,000 Mgal)—is unsuitable for municipal supplies without costly treatment. The basin contains 40 major reservoirs (fig. 2) that are operated primarily for flood control and water supply. Average discharge of the Brazos River near its mouth is about 7,320 ft³/s or 4,730 Mgal/d. The effect of the early-1950's drought in streamflow in the basin is shown in the discharge graph of the North Bosque River near Clifton (fig. 2, site 8). During 1980, about 60 percent of the municipal supplies in the basin were obtained from surface water (Texas Department of Water Resources, 1984).

The Colorado River is 865 miles long and drains an area of 42,318 mi², virtually all in Texas. In 1839, the area where the Colorado River flows from the Balcones Escarpment was selected as the site for the new capital of the Republic of Texas, and the city of Austin was built; presently the population of the Austin area is increasing at one of the fastest rates of any city in the Nation. All the principal tributaries of the Colorado, except Pecan Bayou, are spring-fed, perennially flowing streams that originate in the Edwards Plateau. Floods are a recurring issue, particularly near the coast where hurricane-related damage occurs on the average of 2 years of every 5 (Texas Department of Water Resources, 1984). Water stored in Lake J. B. Thomas (completed in 1952 with 202,300 acre-ft or 65,900 Mgal of storage capacity) in the northwestern part of the basin is suitable for most uses; dissolved-solids concentrations generally do not exceed 400 mg/L. The discharge graph of the Colorado River at Colorado City (fig. 2, site 9) shows the effect of water impoundment in Lake J. B. Thomas beginning in 1952

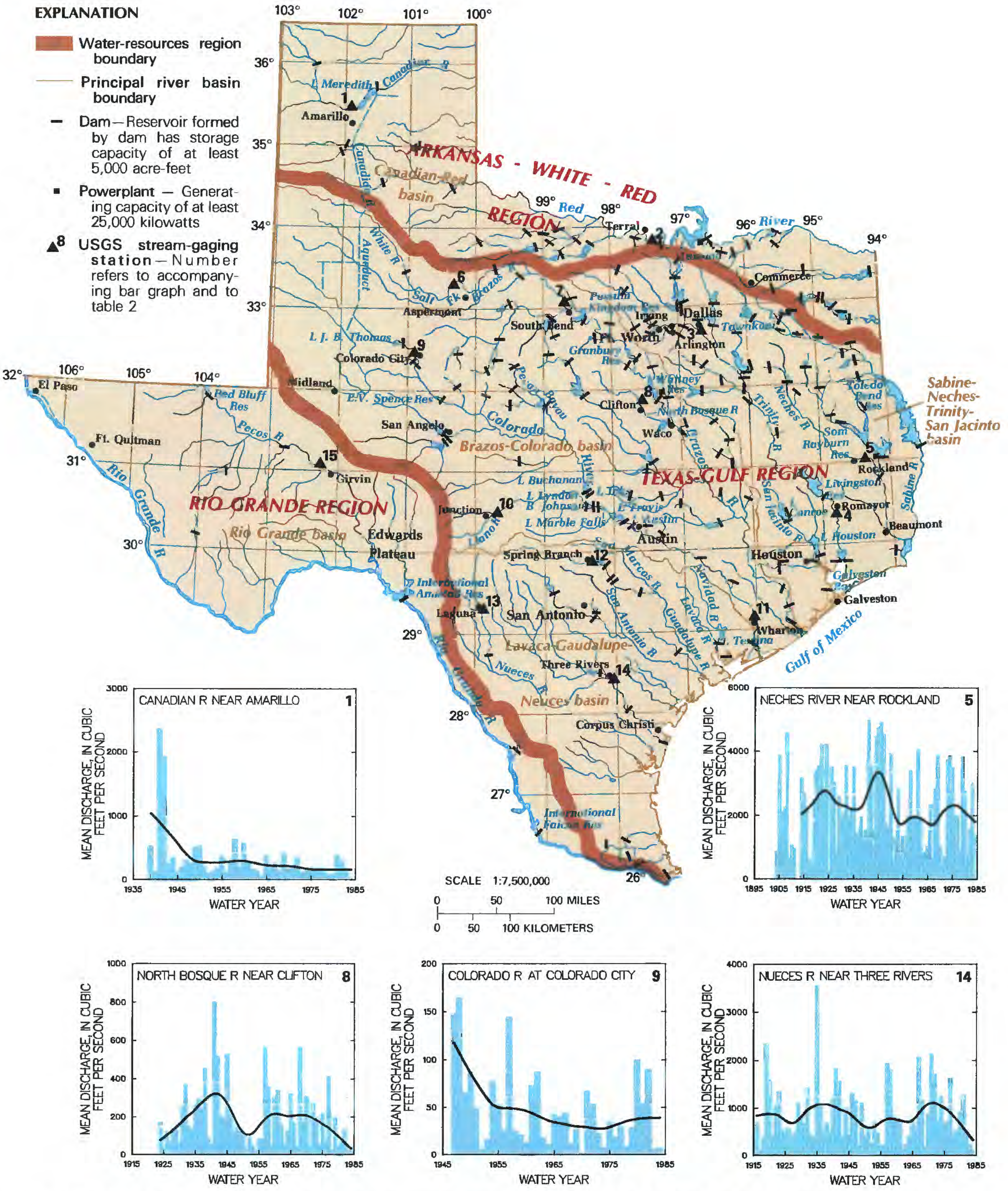


Figure 2. Principal river basins and related surface-water resources development in Texas and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

and the effect of the 1950's drought. The Colorado River between Lake J. B. Thomas and Lake E. V. Spence (completed in 1969) receives saline inflows both from natural and manmade sources; dissolved-solids concentrations in this reach during low flow have been as much as 10,000 mg/L, but recent salinity-control measures taken by the Colorado River Municipal Water District have significantly improved the water quality of the river (Rawson, 1980). Allocation of water between upper and lower water-management districts has recently been resolved with the approval of the construction of Stacy Reservoir near San Angelo.

The Colorado River basin contains 25 major reservoirs, including the Highland Lakes system west of Austin that consists of Lakes Buchanan, Inks, Lyndon B. Johnson, Marble Falls, Travis, and Austin. This 150-mile-long chain of lakes, with a combined conservation storage capacity of 2,585,600 acre-ft or 842,000 Mgal, is used for water supply, hydroelectric-power generation, and recreation. Average discharge of the Colorado River near its mouth is 2,395 ft^3/s or 1,500 Mgal/d. Surface water is used for 73 percent of the municipal supplies in the basin, and 48 percent of the surface water used is for irrigation (Texas Department of Water Resources, 1984).

Lavaca-Guadalupe-Nueces River Basin

The Lavaca River basin, with a drainage area of 2,305 mi^2, is located in the Coastal Plain province. The Lavaca and its major tributary, the Navidad River, contain water suitable for most uses; concentrations of dissolved solids seldom exceed 500 mg/L. Flooding and tidal surges from tropical storms are common along the coast. The only major reservoir in the basin—Lake Texana (completed in 1980 with 61,100 acre-ft or 52,500 Mgal of storage capacity)—is used for municipal and industrial supplies. Maintaining sufficient freshwater flow into the bays and estuaries to maintain their health is of concern to many coastal citizens.

The Guadalupe and the Nueces Rivers, and most of their major tributaries, originate in the Edwards Plateau and cross the Balcones fault zone at the base of the Balcones Escarpment before they reach the Coastal Plain (fig. 1). The fault zone is a permeable area of fractured limestone in the outcrop area of the Edwards aquifer. As many streams in these river basins cross the fault zone, much of their flow percolates through the fractured limestone and recharges the Edwards aquifer.

The Guadalupe River is 250 miles long and drains an area of about 10,250 mi^2, all of which is in Texas. The Guadalupe and its main tributaries—the San Marcos, the Comal, and the San Antonio Rivers—are spring-fed, perennially flowing rivers with fairly steady flows. Generally, the quality of surface water in the basin is suitable for most uses; concentrations of dissolved solids usually are less than 500 mg/L and often are less than 300 mg/L. Floods during the hurricane season (June through November) occur in the basin on an average of once in every 3 years. There are nine reservoirs in the basin; they are operated primarily for flood control, irrigation, and hydroelectric-power generation. During 1980, about 63 percent of the surface water used in the basin was for self-supplied industries (Texas Department of Water Resources, 1984). The San Marcos and the Comal Rivers issue from headwater springs with extensive recreational areas. Rare fauna and flora in the streams below springs depend on the water for their existence. If and when ground-water withdrawals or droughts cause the springs to stop flowing, their existence would be endangered. The Comal River, only 2.5 miles long, is the shortest river in Texas, and one of the shortest that carries an equivalent discharge of water (298 ft^3/s or 193 Mgal/d) in the United States. Part of the San Antonio River is diverted and channeled through San Antonio and is the setting of the renowned "Paseo del Rio," or "River Walk," an attractive assortment of hotels, sidewalk cafes, and shops. During low flow, however, the San Antonio River downstream from the city consists almost entirely of treated municipal sewage and industrial effluent.

The Nueces River is 315 miles long and has a drainage area of 16,950 mi^2. A substantial part of the streamflow in the northern part of the basin enters the Edwards aquifer as the streams cross the Balcones fault zone. Most tributaries of the Nueces are ephemeral (flow only during or immediately after rainstorms); in many instances, the entire flows of these tributaries recharge the aquifer (Land and others, 1983). Although a substantial amount of water used in the basin is ground water, three major reservoirs in the basin provide water for municipal supplies (mainly for Corpus Christi) and for irrigation. During 1980, about 83 percent of the surface water used in the basin was for irrigation (Texas Department of Water Resources, 1984). The water is suitable for most uses.

RIO GRANDE REGION

Rio Grande Basin

With a length of 1,896 miles, the Rio Grande is the fourth longest river in the United States; the 889-mile reach in Texas forms the international boundary between the United States and Mexico. Total drainage area of the Rio Grande is 182,215 mi^2, of which 48,259 mi^2 is in Texas. The Pecos River, a major tributary of the Rio Grande, originates in New Mexico and drains about 27,000 mi^2 in Texas.

Early Indian civilizations and some of the earliest European settlements in North America were developed along the Rio Grande Valley, where the river was used for irrigation. The earliest irrigated area in Texas, and one of the earliest in the United States, is along the river near El Paso; irrigation is still the predominant water use. In 1980, there were 33 active irrigation districts in the four-county Lower Rio Grande Valley region, in addition to numerous private and industrial irrigation systems. About 86 percent of the surface water used in the basin was for irrigation (Texas Department of Water Resources, 1984).

Allocation of the surface water in the Rio Grande basin is governed by two interstate compacts and two international treaties. A treaty signed by the United States and Mexico in 1906 provided for the delivery of 60,000 acre-ft (19,500 Mgal) annually to Mexico upstream from Fort Quitman; and a 1945 treaty allocated the waters from Fort Quitman to the Gulf of Mexico, and allowed for the construction of three major storage reservoirs (only two were built, however). The International Falcon Reservoir (completed in 1953) and the International Amistad Reservoir (completed in 1968) were built under the 1945 treaty to provide for conservation storage and flood control; Texas' share of conservation storage in both reservoirs is 3,465,000 acre-ft or 1,129,000 Mgal. The International Boundary and Water Commission administers the treaty obligations. The Rio Grande Compact, approved by Texas, New Mexico, and Colorado in 1939, allocated the uncommitted water in the Rio Grande upstream from Fort Quitman. Since 1949, Texas' share of the Pecos River has been regulated by the Pecos River Compact. Even though compacts are established, disagreement among members on the need for upstream States to release water for the downstream States is common.

Dissolved-solids concentration of the Rio Grande as it enters Texas at El Paso ranges from 500 to about 3,000 mg/L; the smallest concentrations occur in the spring and summer when reservoirs in New Mexico release water, and the largest concentrations occur in winter during low flow (Texas Department of Water Resources, 1984). Between El Paso and Fort Quitman, most of the streamflow consists of treated municipal effluent and irrigation return flows, and the annual discharge-weighted dissolved-solids concentration ranges from 300 to 4,400 mg/L. The Pecos River contributes a substantial quantity of saline water to the Rio Grande; the annual discharge-weighted average concentrations of dissolved solids of the Pecos near Girvin exceed 14,000 mg/L (Texas Department of Water Resources, 1984). Between the International Amistad and Falcon Reservoirs, however, water quality improves markedly, and the discharge-weighted average concentration of dissolved solids is about 500 mg/L. In the Lower Rio Grande Valley, there is concern that pesticides used on farms is contaminating the surface-water and ground-water supplies. One of the pesticides is DDT, which is still being used in Mexico.

SURFACE-WATER MANAGEMENT

Surface water that flows in public watercourses in Texas is considered public property, whereas ground water is considered private property. The use of surface water is administered by the State through a system of water rights. Riparian domestic and livestock uses of surface water are exempt from appropriation permit requirements. Other users follow the principal of "first in time, first in right" which establishes the seniority of each recognized water right, with the condition that the rights can be revoked if the waters are not used. In 1967, the Water Rights Adjudication Act (Sec. 11.301 et seq., Texas Water Code) was enacted by the State to require a recording of claims of water rights that were then (1967) unrecorded, to limit the exercise of those claims to actual use, and to provide for the adjudication and administration of water rights.

Water management in Texas also involves the overlapping jurisdiction of Federal, State, regional, and local governments, each having water-management responsibilities. The United States has two treaties with Mexico to govern the international waters of the Rio Grande, and Texas is involved in five interstate compacts with neighboring States to manage water resources of the five boundary rivers. Of the 10 State agencies that administer water law and policy in Texas, the Texas Department of Water Resources has the major responsibilities, including development of a State Water Plan. Acting as the legislative arm of the Department, the Texas Water Development Board establishes general policies and rules to implement the statutory requirements and makes loans for water-quality protection; acting as the judicial arm of the Department, the Texas Water Commission adjudicates water rights and approves plans to appropriate State surface water, construct levees, and dispose of treated wastewater and industrial solid wastes. The Department's Executive Director and staff monitor water quality and water rights and provide enforcement when warranted. In addition, the Texas Department of Health regulates the quality of water for public supplies, and the Texas Railroad Commission regulates disposal of wastes associated with petroleum production.

Local governments, regional water authorities, utility districts, and private companies sponsor, construct, operate, and maintain water-supply, water-quality protection, and flood-protection projects and facilities. Currently, there are 1,092 public municipal water systems, 800 rural water-supply corporations, and 750 investor-owned public water-supply systems operating in Texas. In addition, there are 28 river authorities and regional water-supply districts; 950 water-supply, irrigation, and municipal utility districts; 45 flooding and drainage organizations, and 56 drainage districts throughout the State involved with management of surface-water resources (Texas Department of Water Resources, 1984).

A common requirement for all of the water-management agencies is timely and reliable hydrologic data. These data have been, and continue to be, almost solely collected by the U.S. Geological Survey. In cooperation with State and local agencies, the U.S. Geological Survey collects hydrologic data and conducts hydrologic studies in cooperation with various Federal, State, and local agencies. The Survey maintains a computerized data base and operates a real-time data collection network of gaging stations.

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TRUST TERRITORY OF THE PACIFIC ISLANDS, SAIPAN, GUAM, AND AMERICAN SAMOA

Surface-Water Resources

Surface water is vital to the people of Guam, American Samoa, and the Trust Territory of the Pacific Islands for public and rural domestic supplies. Ground water is developed for public supply only on the islands of Guam, Saipan (Commonwealth of the Northern Mariana Islands), Moen (Truk), Gagil-Tamil (Yap), and Tutuila (American Samoa). About 20 percent of the 110,000 residents on Guam rely on surface supplies; average offstream withdrawals from surface and ground-water sources amounts to nearly 33 Mgal/d (million gallons per day) or 51 ft^3/s (cubic feet per second), 7 Mgal/d or 11 ft^3/s of which is from surface sources. On some islands of the Trust Territory, public supplies are obtained from rainfall-catchment basins and streamflow. Public-supply systems on the major islands outside of Guam use about 5 Mgal/d or 7.7 ft^3/s of surface water (table 1). A growing population is increasing the demand. A shortage of water may develop because of a lack of distribution facilities and because much of the surface water, although excellent in chemical quality, is degraded by pathogenic organisms. Even now, shortages are common during periods of deficient rainfall, such as occurred during the drought of 1982–83. The locations of the islands are shown in figure 1. Statistics on area, population, rainfall, runoff, and surface-water quality and use are given in table 1.

Table 1. Area, population, rainfall, runoff, dissolved solids of streamflow, and water use: Guam, American Samoa, and the Trust Territory of the Pacific Islands

[Abbreviations: Mi^2 = square miles; mg/L = milligrams per liter; Mgal/d = million gallons per day; . . . . = insufficient data or not applicable. Sources: Data from files and reports of the U.S. Geological Survey.]

Island group Principal islands	Land area (mi^2)	Population (thousand)	Average annual rainfall (inches)	Average annual runoff (inches)	Maximum dissolved solids[1] (mg/L)	Approximate surface water used (Mgal/d)
Guam	212	110	85	55	235	[2]7.0
American Samoa:						
Tutuila	53	30	125–250	81–200	113	0.8
Tau	1.2	15	. . . .	. . . .	. . . .	. . . .
Republic of Palau	190	12	. . . .	. . . .	. . . .	2.0
Babelthuap	153	. . . .	. . . .	110	66	. . . .
Koror	3.6	9	148	. . . .	. . . .	. . . .
Commonwealth of the Northern Marianas Islands	. . . .	15	. . . .	. . . .	. . . .	. . . .
Saipan	48	12	81	26	253	[3]0.4
Tinian	41	0.9	. . . .	. . . .	. . . .	. . . .
Rota	33	1.3	. . . .	. . . .	. . . .	. . . .
Federated States of Micronesia:						
State of Yap	38	8	122	55	. . . .	0.1
Yap	. . . .	. . . .	. . . .	. . . .	241	. . . .
Gagil–Tamil	. . . .	. . . .	. . . .	. . . .	83	. . . .
Maap	4.1	. . . .	. . . .	. . . .	. . . .	. . . .
Rumung	1.6	. . . .	. . . .	. . . .	. . . .	. . . .
State of Truk	45.7	38	. . . .	. . . .	368	0.2
Tol	13	6.8	. . . .	61	. . . .	. . . .
Moen	7.2	10.0	144	70	. . . .	. . . .
Dublon	3.4	3.2	117	56	. . . .	. . . .
State of Pohnpei	129	22	[4]191	167–205	82	1.7
State of Kosrae	42	6	[4]200	145	125	[5]. . . .
Republic of the Marshall Islands	69	31	77–136	0	. . . .	[6]1.0

[1] Maximum measured in the island group.

[2] By U.S. Navy.

[3] From springs.

[4] On the coast. Computed from runoff to be 340 inches in the mountainous interior of Pohnpei and 225 inches in the interior of Kosrae.

[5] No central system.

[6] From rain catchment.

GENERAL SETTING

Guam and American Samoa are United States territories; the Trust Territory of the Pacific Islands includes about 2,100 other tropical islands in the Caroline, Mariana, and Marshall groups between the Equator and the Tropic of Cancer. About 25 islands have an area of more than 1 mi^2 (square mile); smaller islands number in the hundreds (fig. 1). These islands are organized into several separate political entities on the basis of common cultural characteristics. Some entities are scheduled to become quasi-independent under pending agreements with the United States Government, and all are virtually self-governing.

Traditionally, island inhabitants have relied heavily on the ocean for transportation and food, and have obtained water for domestic supplies and irrigation of small areas from individual rain catchments or small streamflow diversions. In recent years, as island populations have become concentrated in commercial and governmental centers, transport by air has supplanted ocean transport for most inhabitants. Inhabitants now rely on prepared foods distributed by commercial outlets, and water is supplied through centralized systems for most of the population.

Rainfall ranges from about 80 to about 340 inches per year (van der Brug, 1983a, b; 1984a, b, c; 1985). As can be seen by the bar graph in figure 1, there is no consistent pattern in monthly rainfall. Several islands are of volcanic origin and have interior ridges that reach elevations from a few hundred to about 2,000 feet above sea level; these ridges are the headwaters of perennial streams.

Runoff is fairly uniformly distributed areally within each volcanic island group, except on Pohnpei (formerly Ponape) and in American Samoa where runoff varies with elevation. Runoff from volcanic islands ranges from about 55 inches per year on Yap to about 200 inches in the mountains of Pohnpei. Many small coral islands and atolls have no streamflow; Saipan and Guam have large areas underlain by very porous limestone where little or no streamflow occurs.

On the western islands of Guam, Yap, Palau, and Saipan, rainfall and runoff tend to be lowest early in the year (fig. 1). Streamflow begins to increase in May or June, and the highest average monthly discharge occurs some time from July through October, depending on location. On Guam the high occurs in September; in the Palau Islands the high occurs in July, and on Yap the high flow is distributed nearly uniformly from August through October. On Pohnpei and Kosrae, streamflow is characterized by a series of alternating high and low periods; the difference between the highs and lows is less pronounced on these islands than it is in the western islands. In American Samoa, the low flow occurs in July and September; the highest flow occurs in December.

Changes in streamflow are represented by the moving average on bar graphs in figure 2. Records collected in Guam and American

Samoa show little net change in the last 30 years. The apparent decline on Babelthuap and Pohnpei is due to climatic conditions. The decline is more than can be accounted for by diversions.

Municipalities on the islands of Guam, Saipan, Moen, Yap, Pohnpei, Koror (in the Republic of Palau), and Tutuila have central water-supply systems. Some of these are supplied from small streamflow reservoirs that hold from a few hundred thousand to a few million gallons. Supply and distribution systems commonly use old leaky pipelines, some of which were constructed as temporary lines during World War II. Water use by residents is often unrestricted and water-conservation measures are difficult to regulate.

Surface water generally is of suitable quality for most uses; the water is soft with a dissolved-solids concentration generally less than 300 mg/L (milligrams per liter). Concentrations of most measured constituents except iron are lower than the limit recommended by the World Health Organization (1971). The average iron concentration in the Trust Territory is 134 μg/L (micrograms per liter), but concentrations as high as 1,000 μg/L have been detected. The desirable limit for iron is 100 μg/L and undesirable effects may result from concentrations of more than 300 μg/L. Elevated coliform bacteria counts have been detected in some streams and reservoirs, but few if any coliform have been found in central distribution systems. High coliform bacteria counts, however, may be present in water supplies of villages and local residences that are not connected to central systems.

A drought in 1982 and 1983 resulted in below normal runoff during much of the 1983 water year. Rainfall in Guam from January through May 1983 was the lowest on record; van der Brug estimated recurrence intervals that ranged from 125 to 250 years for the amounts of precipitation in the various island groups. Monthly average rainfalls averaged about 28 percent of normal to the west of 155 E longitude and 13 percent of normal to the east of this longitude. Runoff for the first 5 months of 1983 ranged from 3 to 8 percent of normal throughout most of the Trust Territory. Islands that rely on surface-water supplies were severely impacted by the drought. Even those that depend on ground water for their main source of supply experienced problems from large drawdowns and saltwater intrusion. In several wells, chloride concentrations increased markedly during the drought. For example, the average chloride concentration of ground water on Moen increased from 78 to 410 mg/L between February 10 and April 20, 1983 (van der Brug, 1986). Human and animal wastes caused waterborne disease. A cholera epidemic occurred in Truk, and hepatitis was prevalent in some islands. Water shortages were common; central water systems resorted to (1) pumping water from swamps that had been used previously for growing taro, (2) delivering water by tank truck, (3) storing water in used oil drums, and (4) imposing severe restrictions. Crop damage, especially to taro and coconuts, was severe enough to cause shortages. Recovery was still occurring in 1985.

Typhoons frequently originate near the western part of the Trust Territory, but the storms usually follow a path that leads away from most of the islands. With the notable exception of the Mariana Islands, only rarely does a typhoon strike land, but when this does happen the island that is struck may be devastated by wind, rain, and flooding.

PRINCIPAL ISLAND GROUPS

Physiographic and Water Resource regions are not defined for the islands. The largest streams drain about 20 mi². Streams have a large average discharge per unit of drainage area. Selected streamflow characteristics are given in table 2.

GUAM

Guam has an area of 212 mi² and is the largest and southernmost of the Mariana Islands. Rainfall on Guam ranges from about 80 inches on the coastal lowlands to about 100 inches in the mountains of southern Guam. Annual pan evaporation is 77 inches. All streams are in the southern (volcanic) half of the island; the northern half is composed of limestone from which little water runs off. Small quantities of water were diverted from the Ylig River (fig. 2, site 3) for municipal use until the drought in 1983. The U.S. Naval Station on Guam diverts about 7 to 9 Mgal/d or 11 to 14 ft³/s from Fena Valley Reservoir and springs upstream from the reservoir. This system supplies water primarily to military residents. Two small springs are used for the water supply of a village near the southwestern side of the island. The Ugum River (fig. 2, site 2) has been studied as a possible source of an additional 2 to 4 Mgal/d or 3 to 6 ft³/s. Surface supplies are suitable for most uses; dissolved-solid concentrations range from 110 to 235 mg/L, two-thirds of which is calcium carbonate hardness. Guam suffered the least of any island during the 1983 drought because of its well-developed central water supply, which relies mostly on ground water.

AMERICAN SAMOA

American Samoa includes five volcanic islands and two atolls. Tutuila is the largest island, and has an area of 53 mi². Rainfall is abundant from November through April (fig. 1). Average annual rainfall ranges from 125 to 200 inches in the lowlands, and averages more than 250 inches in the mountains. Despite the abundant rainfall, water supplies from surface sources become critically deficient during droughts. Increasing population, expansion of the tuna-canning industry, and increasing tourism are creating a large demand for water. The scarcity of reservoir sites hinders further development of surface-water supplies. Surface water is of excellent chemical quality, indicated by dissolved-solids concentrations of 50 to 113 mg/L and calcium carbonate hardness of 13 to 52 mg/L. The water may often be contaminated by pathogenic organisms; however, as indicated by fecal counts ranging from 1,000 to 10,000 cols/100 mL (colonies per 100 milliliters). Water is highly colored from humic acid. At times, polluted streams contaminate ground-water wells.

REPUBLIC OF PALAU

The Republic of Palau consists of 350 islands with a combined area of 190 mi² and a combined population of 12,000. Six islands have areas of more than 3 mi²; most are merely limestone ridges. Streams are present only on volcanic islands; perennial streams are found only on Babelthuap, which has an area of 153 mi². Precipitation averages 148 inches on the island of Koror and is probably about the same on Babelthuap. Approximately 70 percent of the precipitation runs off. The average runoff of Babelthuap is approximately 8 (ft³/s)/mi² (cubic feet per second per square mile) of drainage area. The central water system diverts water from two rivers on Babelthuap to supply about 2 Mgal/d or 3 ft³/s for the 10,000 people who live on Koror and the southern end of Babelthuap.

COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS

The Northern Mariana Islands include a chain of 14 islands and have a combined population of 15,000; the three largest—Saipan, Tinian, and Rota—have areas of 48, 41, and 33 mi², respectively. Saipan is the population, commercial, and educational center and the seat of government. Average annual rainfall is 81 inches, but most of this percolates into the limestone and little streamflow occurs. Small streams drain the central part of Saipan, and perennial springs are common. Two springs on Saipan and one on Rota are the only surface-water sources in the northern Marianas that are developed for water supply. Tinian has virtually no surface water. The dissolved-solids concentration in one sample from the S. F. Talofofo Stream on Saipan (fig. 2, site 1) was 253 mg/L with a calcium carbonate hardness of 130 mg/L. Water from six springs on Saipan had higher concentrations of dissolved solids (310 to 1,516 mg/L) and calcium carbonate (170 to 465 mg/L).

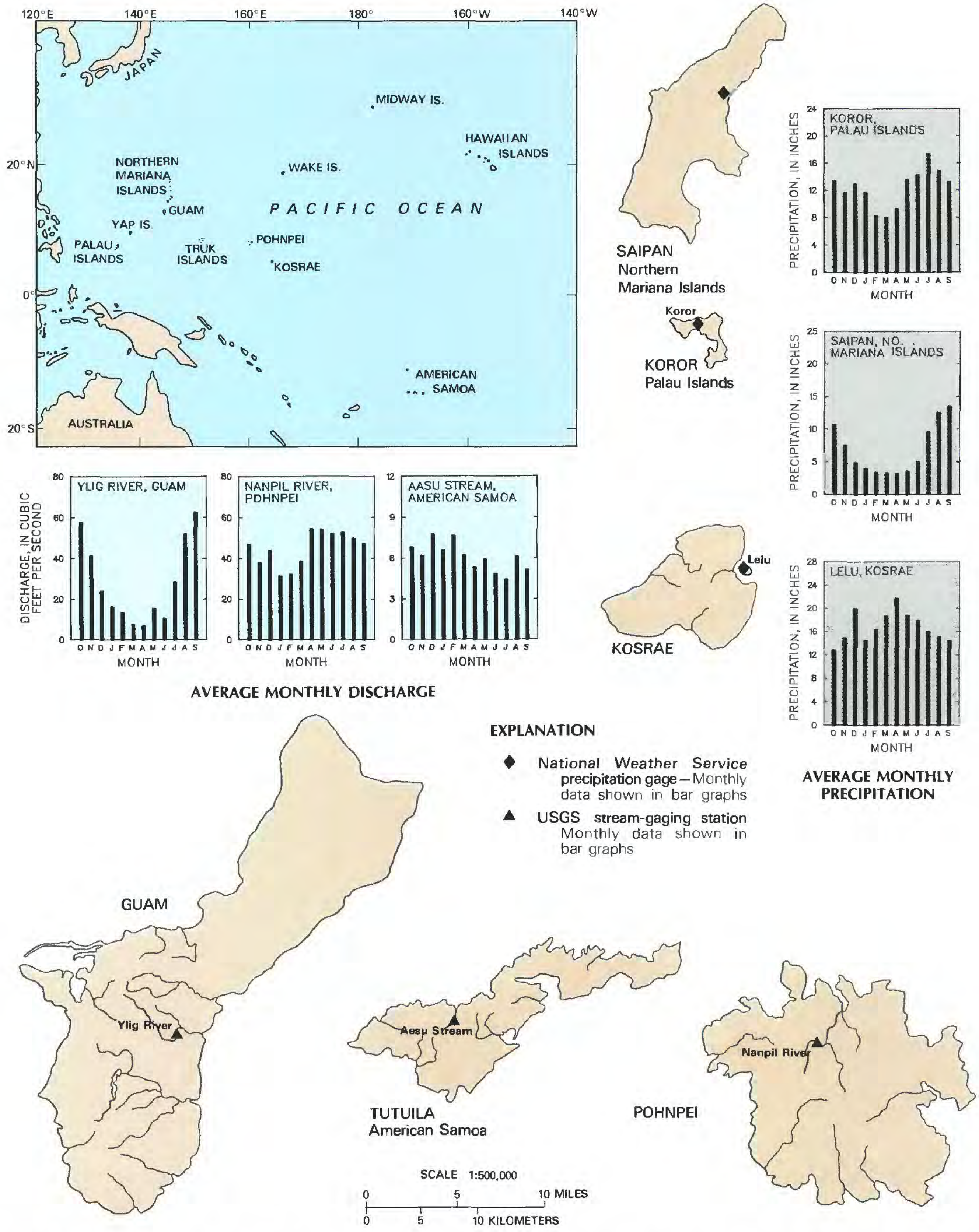

Figure 1. Location of Guam, American Samoa, and islands of the Trust Territory of the Pacific Islands. Bar graphs show average monthly precipitation and discharge for selected sites.

(Sources: Precipitation—data from Van der Burg, 1983a, b; 1984 a, b, c; 1985; 1986. Discharge-annual runoff data and monthly discharge from U.S. Geological Survey files.)

FEDERATED STATES OF MICRONESIA

State of Yap.—The State of Yap consists of four major islands—Yap, Gagil-Tamil, Maap, and Rumung—that have a total population of 8,000. Average annual rainfall is 122 inches and pan evaporation is 75 inches. Streams are perennial on Gagil-Tamil, but those on Yap Island drain less than 0.25 mi² and go dry for several days to weeks each year. The central water system diverts streamflow at a rate of about 0.3 Mgal/d. Dissolved-solids concentrations in streams range from 48 to 241 mg/L on Yap, and 23 to 83 mg/L on Gagil-Tamil. Coliform counts in excess of 24,000 cols/100 mL were found in samples from one reservoir. Rain catchments are used to supply water for many individual homes.

State of Truk.—The State of Truk includes about 100 islands; the total area is about 45.7 mi². Most of the area is in the Truk atoll, which consists of 19 volcanic islands, and about 65 coral islets scattered in an 820-mi² lagoon that is enclosed by a 125-mile-long barrier reef. The five largest islands have areas that range from 1.6 to 13 mi²; all others have areas of less than 1 mi². Tol is the largest of the islands; Moen is the administrative, commercial, educational, and transportation center of the islands. The State of Truk has a total population of 38,000. Most of the population (about 25,000) live on the six major volcanic islands of the Truk atoll. Average annual rainfall ranges from 117 inches on Dublon to 144 inches on Moen; 40 to 50 percent of this runs off. Surface water is of good chemical quality and is suitable for most uses. The dissolved-solids concentration is less than 370 mg/L. Water on Moen is soft and has iron concentrations of 70 to 310 mg/L. The central system for Moen draws part of its water from a 90-acre rainfall catchment basin and from a small streamflow reservoir. The system diverts an average of about 150,000 gal/d (gallons per day) or 0.2 ft³/s. The demand for water on Moen probably will always exceed the supply.

STATE OF POHNPEI

The State of Pohnpei, which includes the main island of Pohnpei and seven small atolls, has a population of 22,000. Average annual rainfall is 191 inches at the coast, and is estimated to be about 340 inches in the upper part of the Nanpil River—one of the

Table 2. Selected streamflow characteristics of selected river basins in Guam, American Samoa, and the Trust Territory of the Pacific Islands

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is the peak flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Dreinage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	Remarks
				SAIPAN				
1.	S. F. Talofofo Stream (16801000).	0.64	1968-84	0.0	1.35	. . . .	None	
				GUAM				
2.	Ugum River (16854500).	5.76	1977-84	3.6	23.3	. . . .	None	
3.	Ylig River (16858000).	6.48	1952-84	0.2	28.0	5,980	. . . do . . .	
4.	Pago River (16865000)	5.67	1951-82	0.2	26.3	12,300	do.	
				PALAU				
5.	Diongradid River (16890600).	4.45	1969-84	3.2	32.4	2,870	None	
6.	Tabecheding River (16890900).	6.07	1970-84	1.7	48.4	4,910	. . . do . . .	
				YAP				
7.	Qaringeel Stream (16892400).	0.24	1968-84	0.1	1.07	696	None	
				TRUK				
8.	Wichen River (16893800).	0.57	1968-83	0.02	3.05	1,060	None	
				POHNPEI				
9.	Nanpil River (16897600).	3.00	1970-84	1.8	44.6	10,000	None	
				KOSRAE				
10.	Malem River (16899750).	0.76	1971-81, 1982-84	0.3	6.71	2,760	. . . .	Slight diversion.
				AMERICAN SAMOA				
11.	Aasu Stream (16920500).	1.03	1958-84	0.4	6.05	586	. . . .	Slight diversion.
12.	Afuelo Stream (16948000).	0.25	1958-84	0.03	1.45	683	. . . .	Do.

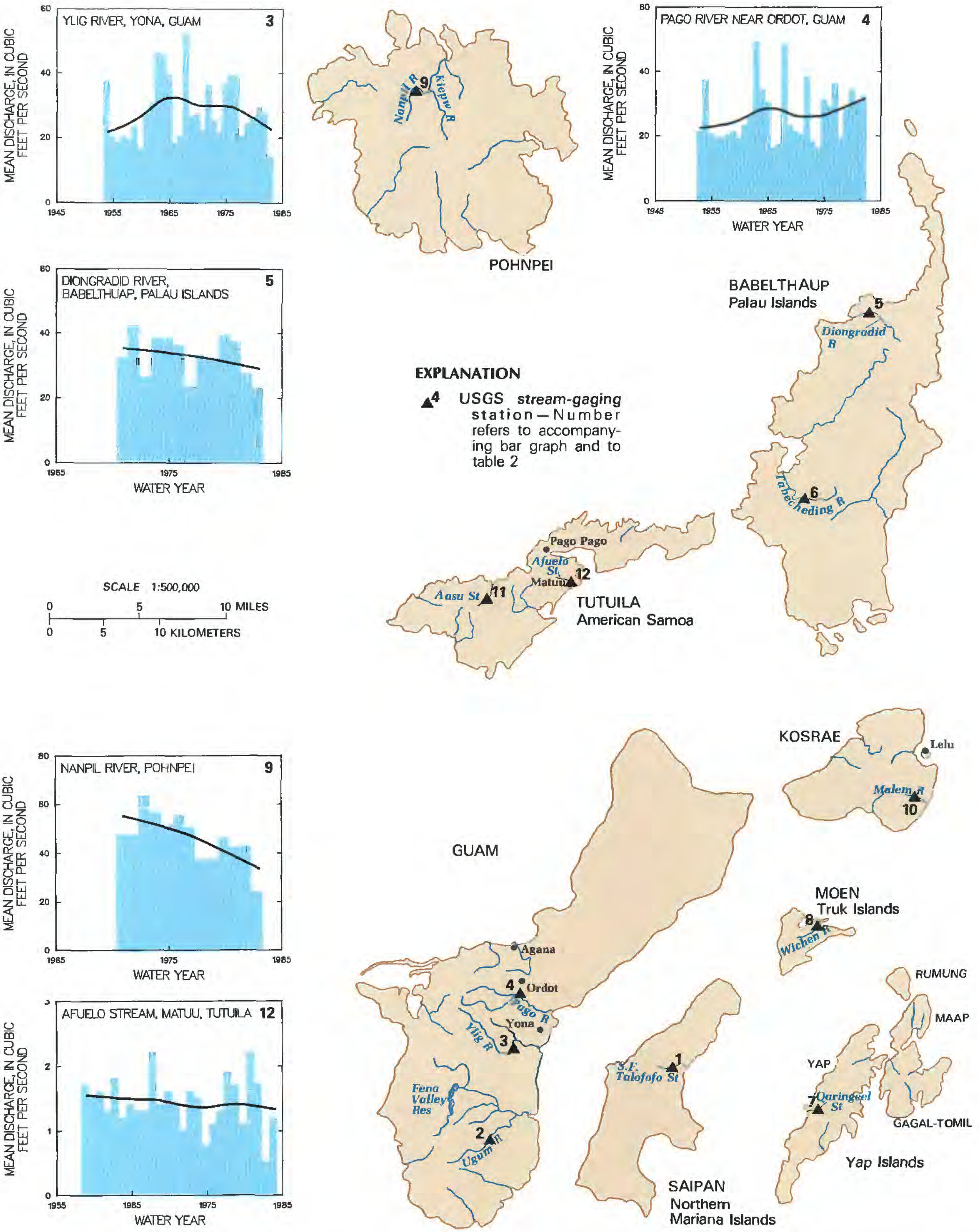

Figure 2. Principal islands and streamflow stations in Guam, American Samoa, and the Trust Territories and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Source: Data from U.S. Geological Survey files.)

many streams that radiate from the center of the volcanic cone. The Nanpil River (fig. 2, site 9), a tributary to the Kiepw River, has the highest average discharge per square mile, (15.1 ft^3/s or 9.8 Mgal/d) of any stream in the Trust Territory. The peak discharge of the Kiepw River below the Nanpil River in 1976 was determined to be 26,000 ft^3/s or 16,800 Mgal/d from an 11.2 mi^2 drainage area. The central water system, which serves about 8,000 people, diverts 1.2 to 1.7 Mgal/d or 1.9 to 2.6 ft^3/s from the Nanpil River. Hydroelectric power has been considered for Pohnpei, but a lack of reservoir sites in the narrow, steep-sloped basins has prevented development of powerplants. Water quality is generally suitable for most uses; dissolved-solids concentrations ranged from 15 to 82 mg/L. The iron content ranged from 22 to 230 mg/L.

STATE OF KOSRAE

The State of Kosrae is a volcanic island of about 42 mi^2, and is the easternmost of the Caroline Islands. The small adjacent island of Lelu has about one-third of the 6,000 people in the State. The annual rainfall of about 200 inches for coastal areas is distributed fairly uniformly throughout the year. Perennial streams drain radially from the interior, and the average discharge is 11 (ft^3/s)/mi^2. Water is of good quality; dissolved-solid concentrations range from 27 to 125 mg/L. There is no central water supply on Kosrae, but eight reservoirs on small streams supply water for local villages. Normally, the quantity of water is sufficient.

REPUBLIC OF THE MARSHALL ISLANDS

The Republic of the Marshall Islands includes 34 atolls, 870 reefs, and 1,152 islands with a total area of 69 mi^2 and a population of 31,000. Average annual rainfall is 77 inches on Ujelang, 103 inches on Kwajalein, and 136 inches on Majuro, but there is virtually no surface runoff. Kwajalein and Majuro depend on rainfall-catchment basins for water during about 8 months per year. These catchments are fed by runoff from airport runways. The Kwajalein catchment supplies about 500,000 gal/d or 0.8 ft^3/s and the Majuro catchment supplies about 400,000 gal/d or 0.6 ft^3/s. Kwajalein also used a saltwater conversion plant until a ground-water skimming system was completed recently.

SURFACE-WATER MANAGEMENT

The governments of Guam, American Samoa, and the various groups in the Trust Territory have not enacted specific legislation or regulation for surface-water management. The Trust Territory Environmental Protection Board monitors the quality of water resources on Saipan and the Trust Territory islands. Each island group has its own Public Works Department that operates its central water-supply system. 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 1). The GEPA is responsible for planning activities and for development of regulations to ensure the conservation of Guam's water resources. The U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers construct and replace water systems.

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, the U.S. Department of the Navy, and local governments, has collected streamflow and other hydrologic data on one or more of the Pacific Islands since 1951 (U.S. Geological Survey, 1962; 1971; 1977; 1973–84; van der Brug, 1983a, b; 1984a, b, c; 1985). The Geological Survey has also provided technical assistance to local governments. Local agencies that cooperate with the Geological Survey are: Guam Environmental Protection Agency, Government of Guam; Department of Public Works, Government of American Samoa; Office of the High Commissioner, Trust Territory of the Pacific Islands; Department of the Public Works, Commonwealth of the Northern Mariana Islands; Federated States of Micronesia, States of Yap, Truk, Pohnpei, and Kosrae; Republic of Palau; and the Republic of the Marshall Islands.

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U.S. VIRGIN ISLANDS
Surface-Water Resources

Surface-water resources are negligible in the U.S. Virgin Islands (USVI). Rain is the only natural source of freshwater on the islands. Although average annual rainfall in the USVI is about 45 inches, high evapotranspiration rates reduce the quantity of surface water available for use (Jordan and Cosner, 1973; Jordan, 1975). During the rainy season, about 280 small impoundments with a combined storage capacity of 1,535 acre-ft (acre-feet) or 500 Mgal (million gallons) store storm runoff. Irrigation uses are negligible, but wells and small impoundments supply an estimated 100,000 gal/d (gallons per day) or 0.15 ft³/s (cubic feet per second) for livestock watering (U.S. Water Resources Council, 1978). Water quality is generally suitable for most uses during periods of high flows, but is unsuitable for many uses during low flows.

Most streams in the USVI are intermittent. However, Bonne Resolution Gut and Turpentine Run at St. Thomas (fig. 1) have perennially flowing reaches. Since the late 1960's, Turpentine Run base flow consists predominantly of sewage effluent. In these reaches, about one-half to three-fourths of the flow is storm runoff, and the remainder is ground-water seepage. Base flow in other reaches of the streams is meager and ceases during the dry season (February and March).

In 1980, 5 Mgal/d (million gallons per day) or 7.7 ft³/s, or about 82 percent of the total water supply in the USVI was from surface-water sources, including water from seawater conversion, cisterns, and rainfall catchments (table 1). Of this amount, about 3.5 Mgal/d or 5.4 ft³/s (70 percent) was used for public supply. Fifty-eight percent of the population of the USVI relies on surface water. Increasing water demands have been met by seawater conversion plants.

Flooding is one of the major surface-water issues in the USVI. On April 18, 1983, St. Thomas and St. John experienced the most intense storm in recorded history (Curtis, 1984). Rainfall intensities of 2.5 in/h (inches per hour) and a total rainfall of more than 16 inches in 18 hours were recorded. Almost instantaneous runoff caused widespread flooding near the coastlines of both islands. Flood damages were estimated to be $12 to to $13 million. Flooding in the USVI has intensified as a result of changes in channel conditions, alteration of waterway openings at roads, changes in runoff characteristics of the streams caused by increased urbanization, and other cultural developments.

Table 1. Surface-water facts for the U.S. Virgin Islands

[Data may not add to totals because of independent rounding Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Torres—Sierra and Dacosta, 1984; Francois, Thompson, and Ayayi, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	55
Percentage of total population	58
From public water-supply systems:	
Number (thousands)	31
Percentage of total population	33
From rural self-supplied systems:	
Number (thousands)	24
Percentage of total population	25
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	6.1
Surface water only (Mgal/d)	[1]5.0
Percentage of total	82
Percentage of total excluding withdrawals for thermoelectric power	82
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	3.5
Percentage of total surface water	70
Percentage of total public supply	88
Per capita (gal/d)	113
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	1.4
Percentage of total surface water	28
Percentage of total rural domestic	70
Per capita (gal/d)	58
Livestock:	
Surface water (Mgal/d)	0.1
Percentage of total surface water	2
Percentage of total livestock	100
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	0
Excluding withdrawals for thermoelectric power	0
Irrigation withdrawals:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total irrigation	0
INSTREAM USE ,1980	
Hydroelectric power (Mgal/d)	0

[1] Includes seawater conversion, cisterns, and rainfall catchments.

GENERAL SETTING

The USVI form part of the Lesser Antilles Islands, which separate the Caribbean Sea from the Atlantic Ocean. The three principal islands (St. Thomas, St. John, and St. Croix) have a combined area of 132 mi² (square miles). The physiography, geology, hydrology, and climate of all three islands are very similar.

On St. Thomas, most of the land surface slopes and extends seaward from a central ridge 500 to 1,500 feet high along the length of the island. St. John is formed mainly by a ridge that trends east-west; slopes to the north descend steeply to the sea. The ridge ranges from 500 to 1,277 feet above sea level. The northwestern part of St. Croix is a rugged mountainous area underlain chiefly by volcanic rocks. To the south and southwest, the mountainous area is bordered by a gently rolling plain underlain by limestone and marl and mantled by alluvium. The crest generally ranges from 600 to 1,000 feet above sea level.

On all three islands, the mountainous areas are separated by narrow, steepsided valleys that are natural drainageways for storm runoff. These drainageways are dry for long periods in most reaches, or contain flow only after heavy rainfall. As a result, floodwaters recede rapidly and inundation usually lasts less than 1 day. In the uplands, streambeds consist of rocks that range in size from small cobbles to large boulders. On the coastal plains, stream gradients are low and the valleys broad; streambeds contains few boulders, and deposits of sand and gravel are common.

Average annual precipitation is similar geographically and seasonally throughout the islands (fig. 1). In general, two seasons of precipitation occur. The late summer and early fall wet season (August through November) and a secondary wet season, usually in May. Rainfall in the USVI ranges from about 30 inches in the flat lowlands in St. Croix, to about 55 inches on the mountain peaks in St. John (fig. 1). Most rainfall occurs during brief showers. Heavy, intense rains result from the passage of tropical depressions, tropical storms, and hurricanes.

More than 90 percent of the precipitation evaporates or is transpired by vegetation. Bowden and others (1969) computed monthly potential evaporation and soil-moisture deficiency at six stations on St. Croix. Computed annual potential evaporation ranges from 58 to 69 inches and averages 62 inches. Actual annual evapotranspiration (derived from potential evapotranspiration and observed changes in soil moisture over time) ranges from 41 to 46 inches and averages 43 inches. Bowden's data show a soil-moisture deficiency 9 to 11 months of the year at the different stations (Jordan and Cosner, 1973).

Annual runoff in the USVI ranges from about 2 to 8 percent of the rainfall during a year of average precipitation. From 0.5 to 2 inches of water annually runs off to the sea, and the amount varies from basin to basin, depending on topography, soil-moisture conditions, exposure to prevailing clouds, and vegetation cover. The base flow of streams with perennial reaches is often equal in volume to that of storm runoff. Base flow, however, usually infiltrates into alluvial deposits in the lower reaches of the streams with little discharge to the sea. On St. Croix, runoff is stored in ponds and used to supply water to cattle or for irrigation. Historical reports, geologic evidence, and testimony of long-time residents indicate that streamflow was once greater that at present (Jordan and Cosner, 1973). The long-term decline in ground-water levels and in streamflow is attributed to changes in land and water use (Solley and others, 1983).

PRINCIPAL BASINS

The USVI are in the Caribbean Region, Virgin Islands Subregion (Seaber and others, 1984). Nearly all streams in the USVI discharge to the sea. Major streams that drain large parts of the islands are Bonne Resolution Gut and Turpentine Run (St. Thomas), Guinea Gut (St. John), and Jolly Hill Gut (St. Croix). These stream basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other related information are given in table 2.

The major surface-water quality problems that affect aquifers in the USVI are contamination by sewage-effluent discharge to the streams, and septic tanks. Storm runoff, containing oils and lead from leaded gasoline, recharge the shallow small aquifers in urbanized areas. Turpentine Run on St. Thomas exemplifies these problems.

CARIBBEAN REGION

U.S. Virgin Islands Subregion

St. Thomas.—St. Thomas has an area of 28 mi^2. Bonne Resolution Gut drains an area of 0.49 mi^2 on the northern coast of St. Thomas. The drainage basin is typical of the steep-gradient valleys that extend from the central ridge to the sea. It is the only stream on St. Thomas, other than Turpentine Run, that has a perennial flow in a 1,000-foot-long reach in the middle of its course. Flow is maintained by ground water that issues from a series of small seeps in saprolite and weathered volcanic rock. The average annual flow of Bonne Resolution Gut at Bonne Resolution (fig. 2, table 2, site 1) is 0.24 ft^3/s or 0.16 Mgal/d.

Bonne Resolution Gut is regulated by a dam and pumping station that supplies about 10,000 gal/d or 0.02 ft^3/s for irrigation of truck crops. Farm ponds function as useful sources of water for stock and for the irrigation of small truck-garden plots. Approximately 40 ponds with a total estimated capacity of 276 acre-ft or 90 Mgal have been constructed on St. Thomas. The ponds are maintained by storm runoff, which otherwise would flow to the sea. Runoff from individual storms commonly exceeds 10 percent of rainfall in the basin and is as much as 30 percent when rainfall is excessive and soil-moisture demands are low.

Turpentine Run in eastern St. Thomas drains an area of 3.4 mi^2. About two-thirds of the drainage basin is in the interior and is surrounded by high hills. Discharge to the sea is through a relatively narrow V-shaped valley, 200 feet wide at its narrowest place. The valley widens as it approaches the sea, and it empties

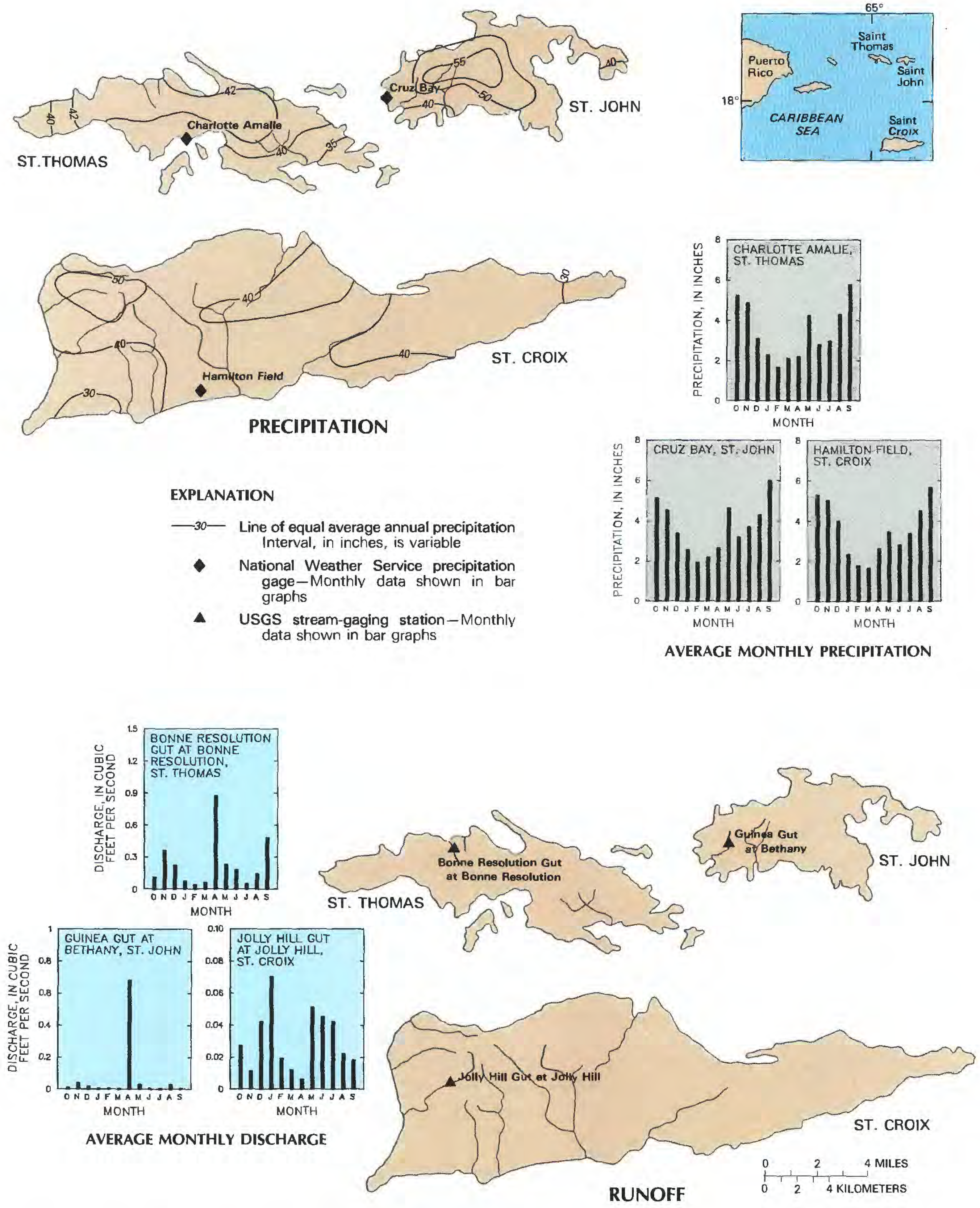

Figure 1. Average annual precipitation and runoff in U.S. Virgin Islands and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual and monthly data from National Oceanic and Atmospheric Administration files. Discharge—annual runoff data from U.S. Geological Survey files.)

into Mangrove Lagoon. About 3,000 feet from the sea, a tributary valley drains a 0.5-mi^2 subbasin. The average annual flow of Turpentine Run at Mariendal (fig. 2, table 2, site 2) is 1.07 ft^3/s or 0.71 Mgal/d. Since the late 1960's, a large part of the flow consists of sewage effluent.

Turpentine Run is not regulated. During periods of near-normal rainfall, storm runoff contributes the greater part of the total annual discharge. However, storm runoff prevails for only a few days each year. Monthly rainfall of about 4 inches is necessary to maintain base flow. When rainfall is less, base flow declines sharply. Once base flow has begun to decline, rainfall in excess of 4 inches in each of 2 or 3 consecutive months is necessary to reverse the downward trend. The quantity of water is adequate for crop irrigation, livestock watering, and wildlife, except during some periods of low flow.

St. John.—St. John has an area of 20 mi^2. Guinea Gut drains a small basin (0.72 mi^2) on the southwestern coast of St. John. Flows are small, and the stream becomes intermittent during droughts. Most of the base flow is from springs. The spring-fed pool on Guinea Gut probably is the source of the greatest discharge on the island. It also is less affected by drought than other springs. The average annual flow of Guinea Gut at Bethany (fig. 1, table 2, site 3) is 0.08 ft^3/s or 0.05 Mgal/d.

Guinea Gut is not regulated. Water use is minimal because of a lack of storage. A few farm ponds have been built in St. John, but most are unsuccessful, probably because of leakage through the permeable, alluvial bottom sediments.

St. Croix.—St. Croix has an area of 84 mi^2. Jolly Hill Gut drains about 4.5 mi^2 of the island and reportedly was once a perennial stream. It flows from the Northside Range to a freshwater pond on the northern edge of Frederiksted and then to the sea. At present, the stream usually flows in only a short reach near Jolly Hill. The average annual flow of Jolly Hill Gut at Jolly Hill (fig. 2, table 2, site 4) is 0.02 ft^3/s or 0.01 Mgal/d.

Storm runoff is usually a major part of streamflow. The rainstorms that produce runoff generally are short, but of high intensity and seldom exceed 5 percent of the rainfall. An estimated 15,000 gal/d or 0.02 ft^3/s is diverted from the stream for irrigation of truck crops when water flows. Because rainfall is seldom sufficient to saturate the soil, runoff occurs infrequently; when runoff does occur, variations in soil-moisture conditions cause considerable variations in the amount of runoff. Crop irrigation, rural-domestic

Table 2. Selected streamflow characteristics of principal river basins in U.S. Virgin Islands

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second. Sources: Reports of the U.S. Geological Survey U.S. Virgin Islands]

Site no. (*see fig. 2*)	Gaging station			Streamflow characteristics				
	Name and USGS no.	*Drainage area* (mi^2)	*Period of analysis*	*7-day, 10-year low flow* (ft^3/s)	*Average discharge* (ft^3/s)	*100-year flood* (ft^3/s)	*Degree of regulation*	Remarks
				CARIBBEAN REGION U.S. VIRGIN ISLANDS SUBREGION St. Thomas				
1.	Bonne Resolution Gut at Bonne Resolution (50252000).	0.49	1963-68, 1979-81, 1982	0	0.24	[1]1,650	None	Public supply.
2.	Turpentine Run at Mariendal (50276000).	2.97	1963-69, 1979-80, 1982	0	1.07	[1]9,710	. . . do . . .	Livestock and irrigation.
				St. John				
3.	Guinea Gut at Bethany (50295000).	0.37	1963-67, 1983	0	0.08	[1]946	None	Livestock and irrigation.
				St. Croix				
4.	Jolly Hill Gut at Jolly Hill (50345000).	2.10	1963-69, 1983	0	0.02	[2]223	None	Livestock and irrigation.

[1] Discharge represents highest recorded. Data available are not adequate to determine a discharge-frequency relation, but it is estimated to have exceeded the 100-year flood (Curtis, 1984).

[2] Discharge represents highest recorded.

supplies, livestock watering, and maintenance of wildlife habitats are the major uses of water from Jolly Hill Gut.

SURFACE-WATER MANAGEMENT

In the USVI, the Department of Conservation and Cultural Affairs is responsible for administering and enforcing all laws relating to water resources and water pollution (Title 3, Chapter 22, of the U.S. Virgin Islands Code, as of June 4, 1968). Other agencies involved with the management of the water resources are the Virgin Islands Public Works Department, the Virgin Islands Water and Power Authority, and the Virgin Islands Planning Office. These agencies have been the principal cooperators in the water-resources investigation program with the Caribbean District of the U.S. Geological Survey.

The Virgin Islands Public Works Department designates the Commissioner of Public Works to supervise and control the construction, repair, maintenance, operation, and administration of the drinking-water systems (Title 30, Section 51, of the U.S. Virgin Island Code). The Virgin Islands Water and Power Authority (WAPA), established in 1964, produces and distributes electrical energy and provides potable water from its water-distillation systems (Title 30, Section 103, of the U.S. Virgin Island Code).

The Virgin Islands Planning Office was established for water-management planning (Chapter 5, Title 12, of the U.S. Virgin Island Code). The U.S. Virgin Islands law requires all dwellings, apartments, and hotels to have a minimum cistern storage of 10 gal/ft^2 (gallons per square foot) of roof area for one-story buildings, and 15 gal/ft^2 of roof area for two-story buildings or higher. All other buildings are required to have cisterns with a minimum usable capacity of 4.5 gal/ft^2 of roof area, except churches and warehouses, which are not required to conform to this standard (Jordan and Cosner, 1973).

In the USVI, all waters are publicly owned and are subject to appropriation. Under this policy, prior rights to water are given precedence. These prior rights may be nullified by the government of the USVI (Commissioner of Conservation and Cultural Affairs), if it is determined that the exercise of such rights would imperil health or welfare by endangering, imparing, or destroying available sources of water. Under Section 153 of Title 12, appropriation permits are not required if pumpage is less than 530 gal/d or 0.01 ft^3/s for beneficial use (Gomez-Gomez and Heisel, 1980).

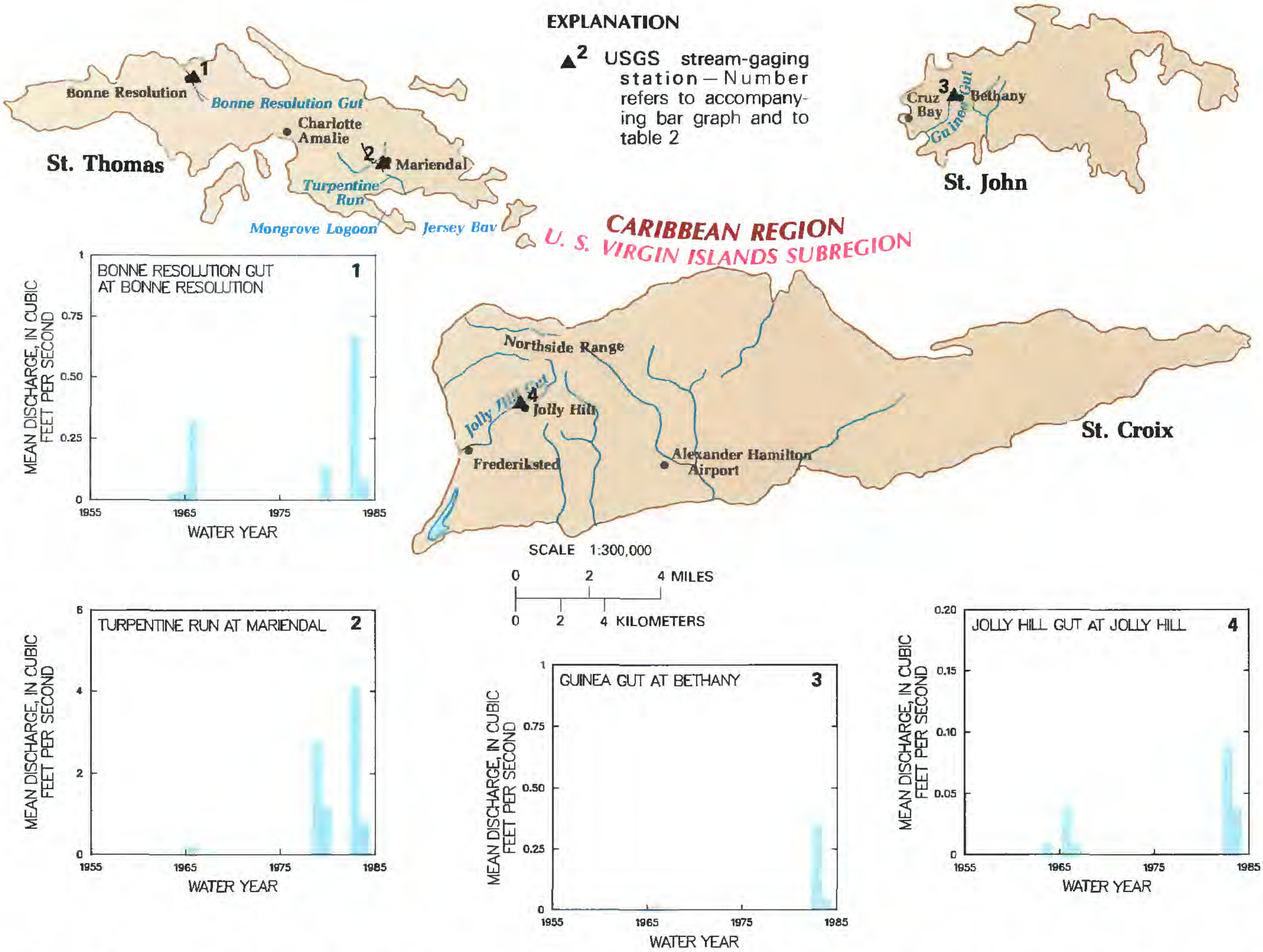

Figure 2. Principal river basins and related surface-water resources development in U.S. Virgin Islands and average discharges for selected sites. Bar graphs show average discharge by water year at selected stream-gaging sites. (Source: Data from U.S. Geological Survey files.)

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UTAH
Surface-Water Resources

Surface water is the primary water source in the State. It currently provides about 81 percent of the offstream water used in Utah, and provides freshwater for more than one-third of the State's population of about 1.5 million. The major use of surface water is irrigation. About 86 percent of the irrigation is from surface-water sources, with about 81 percent of the surface-water withdrawals being used for irrigation. Though secondary to ground water, surface water is an important source for public supply. More than one-third of Utah's population depends on surface water for its freshwater supply; about 34 percent of the public supply is from surface-water sources. Information concerning surface-water withdrawals in Utah in 1980 is given in table 1.

Most Utah streams do not have a sustained flow large enough to provide a dependable water supply. Thus, reservoirs are necessary to store runoff for low-flow augmentation. The quality of the water in most streams that flow from the mountains is suitable for most uses. A major source of surface-water deterioration is the return flow of water used for irrigation, especially in parts of eastern and southern Utah (Colorado River basin streams) during low-flow periods where the irrigated soils are developed on salt-bearing shale formations. Thus, during low flow, both the quantity and quality of streams may be constraints on their use. Accordingly, major water-resource development to stabilize the surface-water supply is a primary objective of State government.

GENERAL SETTING

The eastern one-half of Utah is primarily in the Middle Rocky Mountains and Colorado Plateaus physiographic provinces and the western one-half of the State is primarily located in the Basin and Range physiographic province (fig. 1). The Middle Rocky Mountains and Colorado Plateaus provinces are areas of mountain ranges, high plateaus, and broad basins, which locally have been deeply incised primarily 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.

Average annual precipitation in Utah ranges from about 5 inches on the Great Salt Lake Desert to more than 60 inches on the highest mountains (fig. 1). In most of the State, the seasonal distribution of precipitation is relatively uniform, with the winter precipitation normally consisting of snow. The 1961-80 (April 1) average water content of the snowpack in the mountains exceeded 40 inches in some parts of the State (U.S. Soil Conservation Service, 1985). Since the mid-1960's, statewide precipitation has been greater than the 30-year average (1951-81), especially during 1980-84.

Average annual evapotranspiration ranges from 32 inches in the northern part of Utah to 58 inches in the southwestern corner (Kohler and others, 1959, plate 2). Evapotranspiration during the growing season (May through October) ranges from 75 to 80 percent of the total (Kohler and others, 1959, plate 4).

Average annual runoff ranges from less than 0.1 inch in the western part of the State to more than 30 inches in the mountains (fig. 1). Although precipitation is fairly evenly distributed throughout the year, most runoff generally occurs in May and June (fig. 1). Most runoff results from melting of the large snowpack in the mountains.

PRINCIPAL RIVER BASINS

UPPER COLORADO REGION

The upper Colorado Region is the major source of surface water in Utah. The major rivers of Utah primarily are within the Upper Colorado and Great Basin Regions (Seaber and others, 1984). Several streams in the southwestern part of the State are in the Lower Colorado Region—primarily, the Virgin River. A few small streams in the northwestern corner of the State are in the Pacific Northwest Region. The streams in the Snake River Basin region are not discussed in the text, although water-use data for this region are included in table 1. The principal regions and the main stem of the Colorado River and its main tributaries are discussed below; their location, and long-term variations in streamflow at representative gaging stations are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Utah

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day. Sources: Holmes and others, 1982; Hooper and Schwarting, 1982; Solley, Chase, and Mann, 1983; and Gates, 1985]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	560
Percentage of total population	37
From public water-supply systems:	
Number (thousands)	550
Percentage of total population	36
From rural self-supplied systems:	
Number (thousands)	10
Percentage of total population	0.7
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	4,100
Surface water only (Mgal/d)	3,400
Percentage of total	81
Percentage of total excluding withdrawals for thermoelectric power	81
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	130
Percentage of total surface water	4
Percentage of total public supply	34
Per capita (gal/d)	229
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	3.3
Percentage of total surface water	0.1
Percentage of total rural domestic	11
Per capita (gal/d)	330
Livestock:	
Surface water (Mgal/d)	9
Percentage of total surface water	0.3
Percentage of total livestock	22
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	518
Percentage of total surface water	15
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	89
Excluding withdrawals for thermoelectric power	82
Irrigation withdrawals:	
Surface water (Mgal/day)	2,700
Percentage of total surface water	81
Percentage of total irrigation	86
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	3,400

Four principal rivers are tributaries to the Colorado River in the Upper Colorado River basin in Utah: the Dolores, the Green, the Dirty Devil, and the San Juan (table 2). Their lower reaches are all located in the Colorado Plateaus physiographic province (fig. 1).

That region comprises more than 40 percent of the State (fig. 2), yet it contains only about 4 percent of the population and about one-fourth of the irrigated lands. The Central Utah project, presently under construction, will store excess runoff from the Upper

Colorado Region for transfer to the Great Basin Region, where nearly 96 percent of the State's population resides.

Colorado River Main Stem

The Colorado River is the most significant source of water in Utah. It flows from Colorado and meanders through the southeastern part of Utah for about 300 miles before it enters Lake Powell near the State's southern border. About one-third of the Upper Colorado River basin upstream from Lake Powell is located in Utah. There are no major uses of the river, other than for recreation and fish and wildlife propagation, in that part of the basin. Water conveyed to Lake Powell is stored for hydroelectric-power generation and downstream uses.

Upper Colorado-Dolores Subregion

Dolores River Basin.—The Dolores River basin has a drainage area of about 4,600 mi^2 (square miles), only about 200 mi^2 of which are in Utah. It is a major tributary to the Colorado River, but practically no water from the river is used in the State.

Great Divide-Upper Green and Lower Green Subregions

Green River Basin.—The Green River is the largest tributary to the Colorado River in Utah. Its drainage area comprises nearly 50 percent of the Upper Colorado River Region, and it contributes about 40 percent of the flow of the Colorado River basin at Lake Powell. About 40 percent of the Green River basin is in Utah. The Green River is regulated by Flaming Gorge Reservoir, located at the Utah-Wyoming border, where the Green River enters the State.

The major uses of the water from the main stem are power generation, fish and wildlife propagation, and recreation. During 1980, about 1,100 Mgal/d (million gallons per day), or 1,700 ft^3/s (cubic feet per second) was used to generate hydroelectric power at Flaming Gorge; this is about one-third of the total water used for hydroelectric-power generation in Utah.

Surface water in the Green River basin is withdrawn by users primarily from the tributaries rather than the Green River. Four rivers are principal tributaries to the Green River in Utah—the White, the Duchesne, the Price, and the San Rafael. Except for the White River, the drainage areas of these rivers are entirely within the State. The main use of water in the Green River basin is for irrigation of some 230,000 acres primarily in the Duchesne, the Price, and the San Rafael River basins.

Two major water-supply issues in the Green River basin are related to Indian water rights and energy (coal and oil shale) development. Indian water rights primarily is an issue in the White and the Duchesne River basins. The oil shale resources are in the White River basin, and most of the coal resources are in the Price and the San Rafael River basins.

Upper Colorado-Dirty Devil and San Juan Subregions

Two major tributaries to the Colorado River downstream from the Green River basin are the Dirty Devil and the San Juan Rivers. All of the Dirty Devil River basin and 15 percent of the San Juan River basin are in the State. The primary use of the Dirty Devil River is for irrigation; other than for recreation, there is very little use of the San Juan River in Utah.

LOWER COLORADO REGION

Lower Colorado-Lake Mead Subregion

Only about 5 percent of Utah is in the Lower Colorado Region. The only major river in Utah within this basin is the Virgin River (table 2, site 11), which drains about two-thirds of the basin. The Virgin River originates in the Colorado Plateaus physiographic province and flows to the Basin and Range physiographic province (fig. 1).

The primary uses of surface water in this subregion are irrigation (50 Mgal/d or 77 ft^3/s), self-supplied industry (9 Mgal/d or 14 ft^3/s), and public supply (5 Mgal/d or 7.7 ft^3/s). The irrigation water is applied to about 18,000 acres. In the future, public supply may become a major use in this basin. The southwestern part of the Virgin River basin, near St. George, is an area undergoing rapid urbanization, primarily because the area has become a very desirable retirement community as well as a winter recreation area.

GREAT BASIN REGION

Five principal rivers are in the Great Basin in Utah—the Bear, the Weber, the Jordan, the Sevier, and the Beaver (table 2). The Bear, the Weber, and the Jordan Rivers all originate in the Middle Rocky Mountains physiographic province and flow to the Basin and Range province (fig. 1). The Sevier and the Beaver Rivers originate in the Colorado Plateaus physiographic province and flow to the Basin and Range province. All of the Weber, the Jordan, the Sevier, and the Beaver River basins and 44 percent of the Bear River basin are entirely in the State. The Bear River originates in Utah and flows through Wyoming, reenters and leaves Utah, and flows through Idaho before flowing back into Utah and the Great Salt Lake.

The Great Basin Region is a closed basin—that is, streams do not flow to any of the oceans, but only to closed lakes in the basin. The Bear, the Weber, and the Jordan Rivers all flow to Great Salt Lake, whereas the Sevier River flows to Sevier Lake; the Beaver River would flow to the lower Sevier River with sufficient sustained flow. However, even during the wet years of 1983 and 1984, flow of the Beaver River was not sufficient to reach the lower Sevier River.

Bear and Great Salt Lake Subregions

There are three main inflows to the Great Salt Lake: the Bear, the Weber, and the Jordan Rivers. The Bear River has two main tributaries in Utah—the Little Bear and the Logan Rivers. The Bear River is the largest river, with respect to discharge, in the Western Hemisphere that does not flow to an ocean (Bartlett, 1984, p. 305). The Weber River has one main tributary—the Ogden River and the Jordan River, which has two main tributaries—the Spanish Fork and the Provo River (table 2)—with both flowing into Utah Lake. The Jordan River is the outflow from Utah Lake and discharges to the the Great Salt Lake.

The Great Salt Lake is unique among lakes in the Western Hemisphere because of its size and salt concentrations. The lake occupies a low part of the desert area of western Utah and is a closed lake with no outlet to the sea. It varies considerably in size depending on climatic conditions (Arnow, 1984).

About 86 percent of the population of Utah is located along the Wasatch Range on the eastern side of Utah Lake and Great Salt Lake. About one-half of Utah's irrigated land and about two-thirds of the surface water used for hydroelectric power is used in this area. Thus, the main offstream uses of surface water are for irrigation, self-supplied industries, and public supply. Because of the population concentration, the major water issues relate to adequacy of supplies for future needs, and flooding, particularly of the lands adjacent to Utah Lake and Great Salt Lake.

Plans for meeting the increased needs for public supply include completion of the Bonneville Unit of the Central Utah Project, including the construction of the proposed Jordanelle Reservoir. When completed, the Central Utah Project will allow the transfer of water from the Upper Colorado River basin to the Great Basin. The Jordanelle Reservoir, with a planned storage of 320,000 acre-ft (acre-feet) or 104,000 Mgal (million gallons), will be constructed on the upper Provo River (a tributary to Utah Lake and the Jordan River). Parts of the Central Utah Project, including the

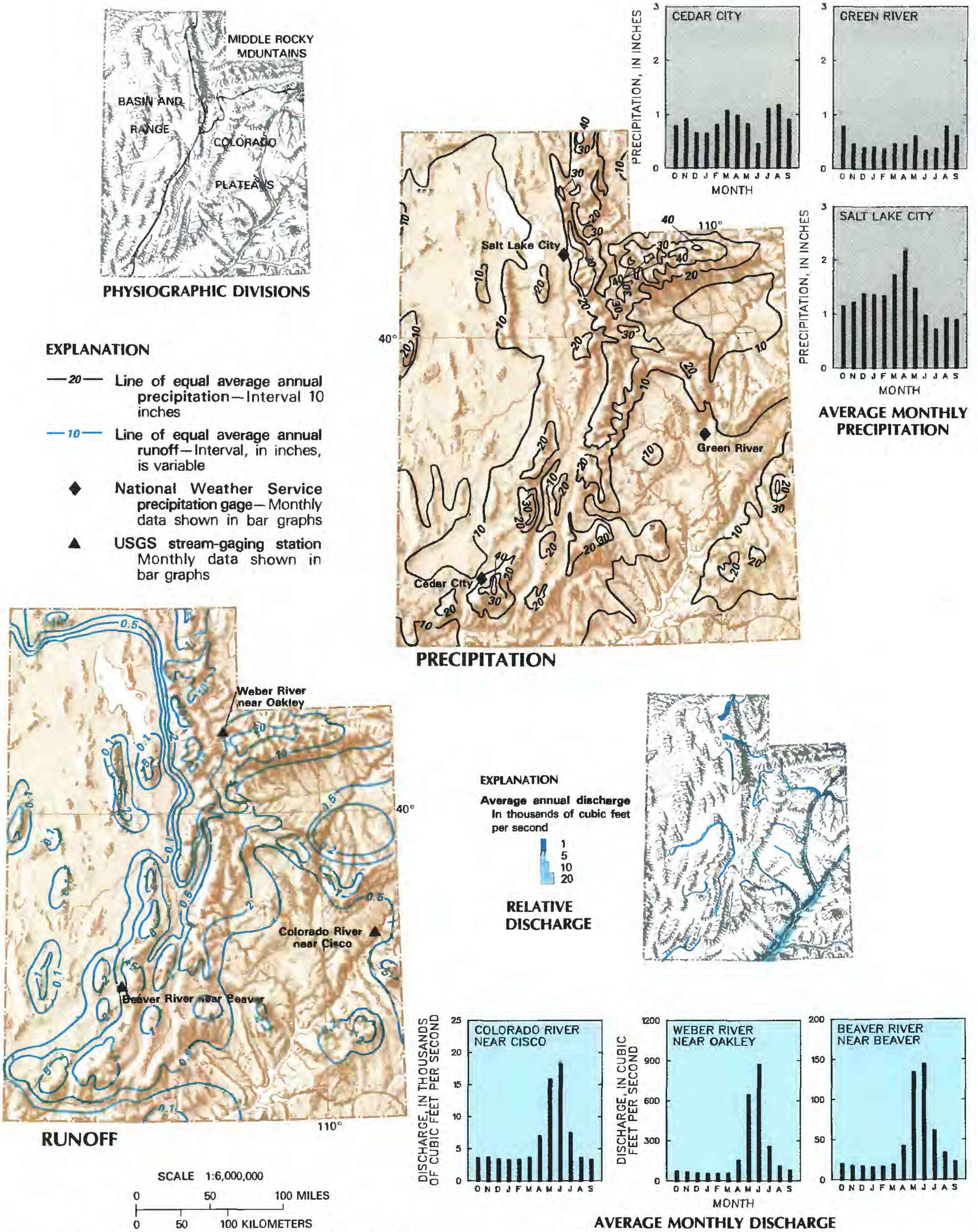

Figure 1. Average annual precipitation and runoff in Utah and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric administration (NOAA); monthly data from NOAA files. Runoff— annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Utah

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second; mg/L = milligrams per liter; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	UPPER COLORADO REGION **Colorado River main stem[1]**							
1.	Colorado River near Cisco (09180500).	[2]24,100	1895–1984	1,100	7,563	87,600	Moderate	Major water use is recreation. A major inflow to Lake Powell. Dissolved solids between between 200 and 1,500 mg/L.
	UPPER COLORADO—DOLORES SUBREGION **Dolores River basin**							
2.	Dolores River near Cisco (09180000).	[2]4,580	1951–84	19	785	23,600	Moderate	Very little use in Utah. Dissolved solids between 200 and 6,000 mg/L.
	GREAT DIVIDE—UPPER GREEN AND LOWER GREEN SUBREGIONS **Green River basin**							
3.	Green River near Jensen (09261000).	[2]29,660	[3]1904–84	480 [4]743	4,396 [4]4,456	38,200	Appreciable	Major water use is hydroelectric-power generation, fish and wildlife propagation, and recreation. Dissolved solids between 200 and 600 mg/L.
4.	Green River at Green River (09315000).	[2]44,850	[1]1895-1984	730 [4]1,214	6,316 [4]5,977	66,600	. . . do . . .	Major water uses are fish and wildlife propagation and recreation. A major inflow to Lake Powell. Dissolved solids between 200 and 800 mg/L.
5.	Duchesne River near Randlett (09302000).	4,247	1943–84	14	582	12,100	. . . do . . .	Major water use is irrigation. Dissolved solids between 100 and 2,500 mg/L.
6.	White River near Watson (09306500).	[2]4,020	[3]1904-79	130	695	9,100	Negligible	Major water uses are fish and wildlife propagation and recreation. Dissolved solids between 300 and 2,000 mg/L.
7.	Price River at Woodside (09314500).	1,540	1946-84	.2	115	10,200	Moderate	Major water use is irrigation. Dissolved solids between 500 and 7,000 mg/L.
8.	San Rafael River near Green River (09328500).	1,628	[3]1909–84	0	152	11,400	Negligible	Major water use is irrigation. Dissolved solids between 500 and 7,000 mg/L.
	UPPER COLORADO—DIRTY DEVIL AND SAN JUAN SUBREGIONS							
9.	Dirty Devil River above Poison Springs, Wash, near Hanksville (09333500).	4,159	1948–84	0	99.1	35,200	Negligible	Major water use is irrigation. Dissolved solids between 600 and 2,000 mg/L.
10.	San Juan River near Bluff (09379500).	[2]23,000	1915–84	60	2,542	62,300	Appreciable	Major use is recreation. A major inflow to Lake Powell. Dissolved solids between 150 and 1,200 mg/L.
	LOWER COLORADO REGION **LOWER COLORADO—LAKE MEAD SUBREGION**							
11.	Virgin River at Virgin (09406000).	[3]934	1909–84	38	208	20,400	Negligible	Major water uses are irrigation and municipal-industrial public supply. Dissolved solids between 300 and 1,000 mg/L.

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[1] Within the Upper Colorado–Dolores and Upper Colorado–Dirty Devil Subregions (Seaber, Kapinos, and Knapp, 1984).

[2] Approximate.

[3] Period of analysis not continuous.

[4] Since completion of Flaming Gorge Reservoir in 1963.

Table 2. Selected streamflow characteristics of principal river basins in Utah—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; mg/L = milligrams per liter; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				GREAT BASIN REGION BEAR AND GREAT SALT LAKE SUBREGIONS				
12.	Bear River near Randolph (10026500).	1,616	1944–84	5.8	204	3,040	Appreciable	Major water uses are irrigation, hydroelectric-power generation, and fish and wildlife propagation. Dissolved solids between 300 and 1,000 mg/L.
13.	Bear River near Collinston (10118000).	6,267	1889–1984	11	1,510	11,000	. . . do . . .	Major water uses are irrigation, hydroelectric-power generation, and fish and wildlife propagation. Dissolved solids between 300 and 1,000 mg/L.
14.	Little Bear River near Paradise (10106000).	198	1937–84	12	92.8	1,990	Moderate	Major water use is irrigation. Dissolved solids between 200 and 400 mg/L.
15.	Logan River above State Dam, near Logan (10109000).	214	1896–1984	15	273	2,160	Negligible	Major water uses are irrigation and municipal supply. Dissolved solids between 150 and 400 mg/L.
16.	Weber River near Oakley (10128500).	162	1905–84	37	221	3,450	. . . do . . .	Major water uses are irrigation, municipal-industrial supply, fish and wildlife propagation, and recreation. Dissolved solids between 100 and 400 mg/L.
17.	Weber River at Gateway (10136500).	1,627	[3]1890–1984	58	581	7,370	Appreciable	Major water uses are irrigation, municipal-industrial supply, fish and wildlife propagation, and recreation. Dissolved solids between 100 and 400 mg/L.
18.	Ogden River below Pineview Dam, near Ogden (10140000).	321	1938–59	.2	86.2	2,600	. . . do . . .	Major water uses are irrigation, municipal-industrial supply, fish and wildlife propagation, and recreation. Dissolved solids between 100 and 400 mg/L.
19.	Jordan River at Narrows, near Lehi (10167000).	3,010	1913–84	1.0	381	1,240	. . . do . . .	Major water uses are irrigation, municipal-industrial supply, and fish and wildlife propagation. Dissolved solids between 500 and 1,000 mg/L.
20.	Spanish Fork near Lakeshore (10152000).	675	[3]1904–84	0	91.4	2,110	Moderate	Major water uses are irrigation, and fish and wildlife propagation. Dissolved solids between 300 and 1,000 mg/L.
21.	Provo River at Provo (10163000).	673	[3]1903–84	.5	198	2,320	Appreciable	Major water uses are irrigation, municipal-industrial supply, and fish and wildlife propagation. Dissolved solids between 150 and 400 mg/L.

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[1] Within the Upper Colorado—Dolores and Upper Colorado—Dirty Devil Subregions (Seaber, Kapinos, and Knapp, 1984).

[2] Approximate.

[3] Period of analysis not continuous.

[4] Since completion of Flaming Gorge Reservoir in 1963.

Table 2. Selected streamflow characteristics of principal river basins in Utah—Continued

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second; mg/L = milligrams per liter; . . . . = insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
	ESCALANTE DESERT—SEVIER LAKE SUBREGION Sevier River basin							
22.	Sevier River at Hatch (10174500).	340	[3]1911–84	36	127	1,760	*Negligible*	*Major water use is* irrigation. Dissolved solids between 150 and 400 mg/L.
23.	Sevier River near Sigurd (10205000).	3,375	1914–84	.4	102	1,660	Appreciable	Major water use is irrigation. Dissolved solids between 300 and 1,000 mg/L.
24.	Sevier River near Lynnyl (10224000).	5,966	[3]1914–84	7.2	210	2,470	. . . do . . .	Major water use is irrigation. Dissolved solids between 500 and 3,000 mg/L.
25.	Beaver River near Beaver (10234500).	91.0	1914–84	12	52.2	1,270	Negligible	Major water uses are irrigation, municipal-industrial supply, and fish and wildlife propagation. Dissolved solids between 50 and 200 mg/L.

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[1] Within the Upper Colorado—Dolores and Upper Colorado—Dirty Devil Subregions (Seaber, Kapinos, and Knapp, 1984).
[2] Approximate.
[3] Period of analysis not continuous.
[4] *Since completion of Flaming Gorge Reservoir in 1963.*

Jordanelle Reservoir, have been vigorously opposed by environmentalist groups.

In September 1982, precipitation at Salt Lake City was the greatest ever recorded for that month. This resulted in severe flooding in the area and caused Utah Lake and Great Salt Lake to begin rising earlier than normal. Runoff from an excessively large snowfall in the basin during 1983-84 caused both lakes to rise and stay above normal levels. Utah Lake rose to a level of 4.94 feet above compromise level (the level at which flooding around the lake begins) in 1983 and has stayed above compromise level. The lake rose to 5.46 feet above compromise level in 1984 and to 3.54 feet above in 1985. Flooding has caused considerable damage to parks, buildings, and farmland around the lake.

From September 1982 through June 30, 1983, the Great Salt Lake rose 5.1 feet (Arnow, 1985, p. 31). The lake rose an additional 5.0 feet (Arnow, 1985, p. 31) from September 1983 through July 1, 1984. These are the two highest individual-year increases in lake level ever recorded. Because the decline during the summer of 1984 was small, there was a net lake-level rise of 9.6 feet during a 2-year period; this is the largest 2-year rise in the period of record of the lake. In fact, the level of the lake reached 4,209.25 feet above sea level in 1984 and 4,209.95 feet above sea level in 1985—the highest lake levels since 1877. The recorded extremes of the lake are a high of 4,211.5 feet above sea level in 1873 and a low of 4,191.35 feet in 1963 (Arnow, 1985, p. 31).

The 9.6-foot rise of 1983 and 1984 inundated 680 mi^2 of land. This caused considerable damage to highways, railroads, industries, parks, beaches, and wildlife refuges around the lake. The capital damage to these facilities was approximately $212 million (Utah Division of Water Resources, 1984, p. 3–41). The 1985 rise flooded another 60 mi^2 and caused additional property damage. The State is studying alternatives for controlling the level of the Great Salt Lake. These include pumping lake water to the desert west of the lake, building reservoirs on the Bear River, and constructing dikes in areas subject to flooding.

Escalante Desert-Sevier Lake Subregion

The principal use of water in the Escalante Desert-Sevier Lake Subregion is for irrigation. This region only accounts for 8 percent of the State's population, but nearly one-fourth of the State's irrigated lands.

Sevier River Basin.—Although surface water accounts for 86 percent of the irrigation water statewide, in this basin, surface water only accounts for about 60 percent of the irrigation supply. The major streams in this subregion are the Sevier and the Beaver Rivers, which are a part of the Sevier River basin. The Sevier and the Beaver Rivers are regulated with facilities that store excess water from the spring snowmelt for later use during periods of little or no runoff. The Sevier River is one of the most completely consumed rivers in the United States. More than 99 percent of the total precipitation in the drainage area, 6.5 million acre-ft or 2,120,000 Mgal, is consumed in the basin (Bartlett, 1984, p. 326). The Sevier and the Beaver Rivers are shown in figure 2, with streamflow characteristics and other pertinent information given in table 2. The other small streams within this basin are very unreliable water sources.

Water supply, flooding, and effects of energy development are the major issues within this basin. Energy development has included the construction of a major coal-fired thermoelectric plant near Delta along the downstream reach of the Sevier River. Water for operation of this plant is purchased from farmers who previously used the water for irrigation. With the completion of the Central Utah Project, the planned transfer of water from the Upper Colorado River Basin to this basin will provide a much more dependable surface-water supply.

During 1983 and 1984, flooding was a major issue in this basin. In 1983, a dam on the Sevier River failed, which caused failure of another dam downstream; these failures caused severe flooding of communities and farmland along the downstream reach of the Sevier River.

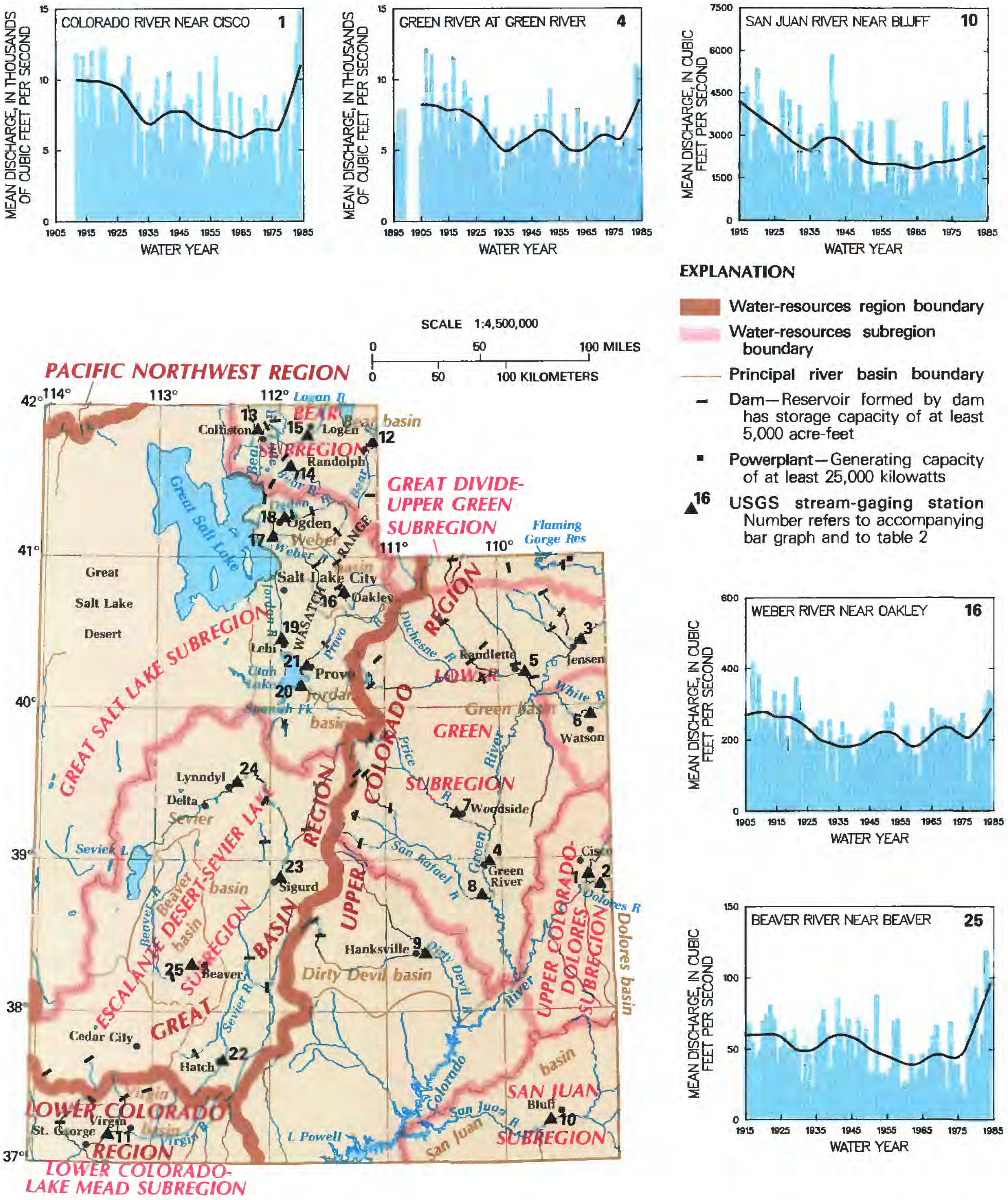

Figure 2. Principal river basins and related surface-water resources development in Utah and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Sevier Lake, like Utah Lake and Great Salt Lake, is a remnant of a once larger lake. In 1872, the area of Sevier Lake was 188 mi² (Gilbert, 1890, p. 224-225), and was dry, or nearly dry, since about 1880. During November 1982 through June 1984, however, excess runoff in the Sevier River basin exceeded upstream reservoir capacity, and more than 1 million acre-ft or 326,000 Mgal of water was conveyed to Sevier Lake. On May 22, 1984, the lake was reported to be 35 feet deep (Robert Morgan, Utah Division of Water Rights, oral commun., 1985) and the area of the lake was approximately the same size reported by Gilbert (1890, p. 225).

SURFACE-WATER MANAGEMENT

Surface-water resources available for use in Utah are the Colorado River, the Bear River, and the streams entirely within Utah. The Colorado River Compact of 1922, the Upper Colorado River Compact of 1949, and subsequent agreements and court decisions, provide for the apportionment of water from the Colorado River to States within the Colorado River Basin and for Mexico. The Bear River Compact of 1958, and subsequent agreements and court decisions, provide for the apportionment of water in the Bear River among Idaho, Utah, and Wyoming.

Surface-water use in Utah is regulated by the Utah Department of Natural Resources, Division of Water Rights. The right to use surface water in Utah is appropriated under the doctrine of prior appropriation, under which earlier users of water have priority over later users. The Utah Department of Natural Resources, Division of Water Resources, guides the planning and development of water-resources projects to ensure maximum public benefit. This includes providing technical assistance to management organizations such as mutual irrigation companies and municipalities. The Division of Water Resources also administers a fund that provides financial assistance to irrigation companies and municipalities for constructing or upgrading water-development projects. The U.S. Department of Interior, Bureau of Reclamation, has constructed a number of reservoirs and is responsible for their operation on the Colorado and Green Rivers.

Protection of surface-water quality, and prevention and control of surface-water pollution, are the responsibility of the Utah Department of Health, Division of Environmental Health. The U.S. Department of the Interior, Bureau of Reclamation, is responsible for controlling salinity in the Colorado River.

The U.S. Geological Survey, in cooperation with local, State, and Federal agencies, routinely monitors streamflow and reservoirs. They also provide technical and scientific assistance to surface-water users.

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VERMONT
Surface-Water Resources

Surface water is an important natural resource in Vermont. It serves as a source of water supply for about 46 percent of the State's total population of 511,000, and is a major source of water for industrial purposes. Public surface-water systems provide about 31 Mgal/d (million gallons per day) or 48 ft^3/s (cubic feet per second) to 210,000 people, about 40 percent of the population. Rural self-supplied systems provide about 2.6 Mgal/d or 4 ft^3/s to 29,000 people, about 6 percent of the population. Withdrawals for industrial uses total 260 Mgal/d or 402 ft^3/s. The amount of surface water used for hydroelectric-power generation (about 14,000 Mgal/d or 21,700 ft^3/s) is greater than for all other uses combined. Surface-water withdrawals in Vermont in 1980 and related statistics are given in table 1.

Water-related recreation is a significant factor in the economy of the State. In general, the quality of surface water is suitable for most recreational purposes, but some treatment is required for human consumption. The water in about 84 percent of the more than 1,100 miles of streams in Vermont meets State water-quality standards. About 90 percent of those streams provide municipal water supplies (Vermont Agency of Environmental Conservation, 1982). Recreational use of lakes and streams generates much interest at the State and local level, and, although most of Vermont's lakes meet water-quality standards, there is much concern regarding acid precipitation and its effect on lakes. A related issue of statewide concern is excessive aquatic plant growth in several parts of Lake Champlain.

Table 1. Surface-water facts for Vermont

[Data 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 SURFACE WATER, 1980	
Number (thousands)	240
Percentage of total population	46
From public water-supply systems:	
Number (thousands)	210
Percentage of total population	40
From rural self-supplied systems:	
Number (thousands)	29
Percentage of total population	6
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	340
Surface water only (Mgal/d)	300
Percentage of total	87
Percentage of total excluding withdrawals for thermoelectric power	51
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	31
Percentage of total surface water	10
Percentage of total public supply	65
Per capita (gal/d)	150
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	2.6
Percentage of total surface water	0.9
Percentage of total rural domestic	15
Per capita (gal/d)	90
Livestock:	
Surface water (Mgal/d)	3.5
Percentage of total surface water	1
Percentage of total livestock	38
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	260
Percentage of total surface water	87
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	65
Irrigation withdrawals:	
Surface water (Mgal/d)	1.2
Percentage of total surface water	0.4
Percentage of total irrigation	81
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	14,000

GENERAL SETTING

Vermont, known for the Green Mountains and Lake Champlain, and for its rolling lowlands, farms, small communities, and many streams and ponds, is located in parts of three physiographic provinces (fig. 1). Fenneman (1946) subdivided Vermont into the Hudson Valley section of the Valley and Ridge province, the Champlain section of the St. Lawrence Valley province, and the New England Upland, White Mountain, Green Mountain, and Taconic sections of the New England province.

Precipitation averages about 40 inches statewide and ranges from about 33 inches in the Lake Champlain Valley and Connecticut Valley to about 53 inches in the Green Mountains. Precipitation is variable throughout the year, as represented by graphs of average monthly precipitation at Burlington , Chelsea, and Cavendish (fig. 1). Monthly precipitation ranges from about 1.7 inches to about 5.2 inches at long-term Vermont precipitation-gaging stations (National Oceanic and Atmospheric Administration, 1982). January and February tend to be the drier months of the year (fig. 1). Precipitation at Cavendish and Chelsea varies little during the rest of the year, but the summer is wetter, on the average, at Burlington.

Average annual runoff ranges from about 13 inches in the Lake Champlain Valley to about 33 inches in the southern Green Mountains. Runoff varies both seasonally and geographically (fig. 1). The high "spring" flows occur during March, April, and May and result from the melting snowpack and concurrent precipitation. The melting snowpack in the Green Mountains contributes to streamflow during June in some years. With the start of the growing season, water loss through transpiration increases dramatically, and warm temperatures enhance evaporation from soils and free-water surfaces. Much of the precipitation during the summer replaces soil moisture lost through evapotranspiration and maintains storage in regulated ponds and lakes. Thus, streamflow decreases progressively from June through August. Transpiration usually decreases and streamflow increases during September. Following the first killing frost, and if there is no soil moisture deficiency to satisfy, streamflow commonly increases from September through November or December, depending on when the snowpack starts to accumulate. From that time, flow generally decreases until snowmelt begins in March.

In general, the greatest flood flows known for any particular stream occurred during one or more of the floods of 1927, 1936, 1938, 1955, 1973, or 1984 (Thomson and others, 1964; U.S. Geological Survey, 1975-83). The larger flows resulted from rainstorms that accelerated snowmelt (1936), from hurricanes (1938 and 1955), or from major storms (1927, 1973, and 1984).

Agricultural droughts of varying lengths and severity are common and occur when soil moisture is deficient resulting in economic losses from reduced yields of crops, pastures, and forests. Droughts that cause water-supply deficiencies tend to persist from one year to the next as a consequence of longer periods of below-normal precipitation; the most recent such protracted drought occurred in the early to mid-1960's (Barksdale and others, 1966).

PRINCIPAL RIVER BASINS

The U.S. Water Resources Council has cataloged Vermont's rivers and streams into two regions—the New England to the east, which includes 46 percent of the State, and the Mid-Atlantic to the west, which includes 54 percent of the State (Seaber and others, 1984) (fig. 2). Within the New England Region, the Connecticut Subregion drains about 40 percent of the State and the St. Francois Subregion drains 6 percent in the northeastern corner of the State. In the Mid-Atlantic Region, the Richelieu Subregion drains 49 percent of the State and the Upper Hudson Subregion drains 5 percent in the southwestern corner of the State (Seaber and others, 1984).

NEW ENGLAND REGION

Connecticut Subregion

The Connecticut River—the longest river in New England (Bartlett, 1984)—forms the border between Vermont and New Hampshire for more than half of its length. It drains a long and narrow area of eastern Vermont starting at the international border with Canada south to the State boundary with Massachusetts. That narrow area varies in width from less than 10 miles to about 40 miles but comprises about 40 percent of the area of the State. The Connecticut River is a natural route for travel, trading, and commerce. Indians once gathered for fishing at the falls and rapids, which are common throughout the length of the river. Settlers located at the falls, because the falls were barriers to navigation and, thus, logical places for trading and commerce. From these settlements, people migrated to the mouths of the tributaries and eventually up the tributaries, which created the many scattered small communities for which Vermont is noted. The waterpower available at the falls was developed for use by textile mills and other industries. Many sites were later developed to generate hydroelectric power.

Headwaters of the Connecticut River drain the White Mountain section of the New England province. Two large tributaries—the Nulhegan and the Passumpsic Rivers—drain the Vermont part of the White Mountain section. A graph depicting the average discharge by water year for the Moose River at Victory, a tributary of the Passumpsic River, is shown in figure 2 (site 2). The 15-year weighted moving average of annual values for the Moose River at Victory provides a general indication of the variability of runoff from streams in this mountainous area.

Tributaries to the Connecticut River in middle and southern Vermont are the Wells, the Waits, the Ompompanoosuc, the White, the Ottauquechee, the Black, the Williams, the Saxtons, the West, and the Deerfield Rivers. The U.S. Army Corps of Engineers constructed and operates flood-control reservoirs on the Ompompanoosuc (completed in 1949), the Ottauquechee (1961), the Black (1960), and the West Rivers (1961), with capacities ranging from 34,000 to 71,000 acre-ft (acre-feet) or 11,100 Mgal (million gallons) to 23,100 Mgal. The headwaters of the White River basin drain part of the Green Mountain section, but the lower, larger part drains the New England Upland section and is typical of a drainage system on the eastern side of the Green Mountains. Comparison of average monthly discharge for the White River at West Hartford (fig. 1) and precipitation for Chelsea (fig. 1) (which is in the basin) and Cavendish (fig. 1) (which is south of the basin), shows the seasonal relation between runoff and precipitation.

The variation in average discharge by water year of the Connecticut River is shown by flow records for the station at North Walpole, N.H. (fig. 2, site 6). Flow is regulated by powerplants and by lakes, ponds, and flood-control reservoirs having a combined usable capacity of about 570,000 acre-ft or 186,000 Mgal. Regulation has a pronounced effect on daily and instantaneous flows, but, because there is little net change in storage in the reservoirs from year to year, there is little effect on average discharges by water year. Because the daily flows are affected by regulation, the 7-day, 10-year low-flow statistic (table 2) needs to be used with caution.

MID-ATLANTIC REGION

Richelieu Subregion

Most of western Vermont is part of the Lake Champlain drainage. Westward flowing tributaries to Lake Champlain include the Missisquoi, the Lamoille, and the Winooski Rivers. These streams begin in the New England Upland section, traverse the Green Mountain section of the New England province, and cross into the Champlain section of the St. Lawrence Valley province before discharging to Lake Champlain. Topography varies from rolling upland to mountainous, then changes sharply to gently rolling lowlands. Northern flowing tributaries to Lake Champlain are Otter Creek and other small streams. These begin in the Green Mountain and Taconic sections of the New England province, then flow across the Champlain section of the St. Lawrence Valley province to Lake Champlain.

The Lake Champlain Valley forms a natural north-south route that was traveled by Indians and settlers and was the scene of much trading, commerce, and warfare. Settlements, initially established along the major waterways, spread throughout the easily farmed lowlands, and then up the valleys of the tributaries. Farming still predominates in the lowlands, and a mixture of farming, recreation, and commercial forestry prevails in the mountains and uplands. Light industry, initially located at waterpower sites, is scattered throughout the subregion. Later, many of the waterpower sites were developed to generate hydroelectric power.

Flow at the Missisquoi River near East Berkshire (table 2; figs. 1 and 2, site 13,) is little affected by regulation, and its pat-

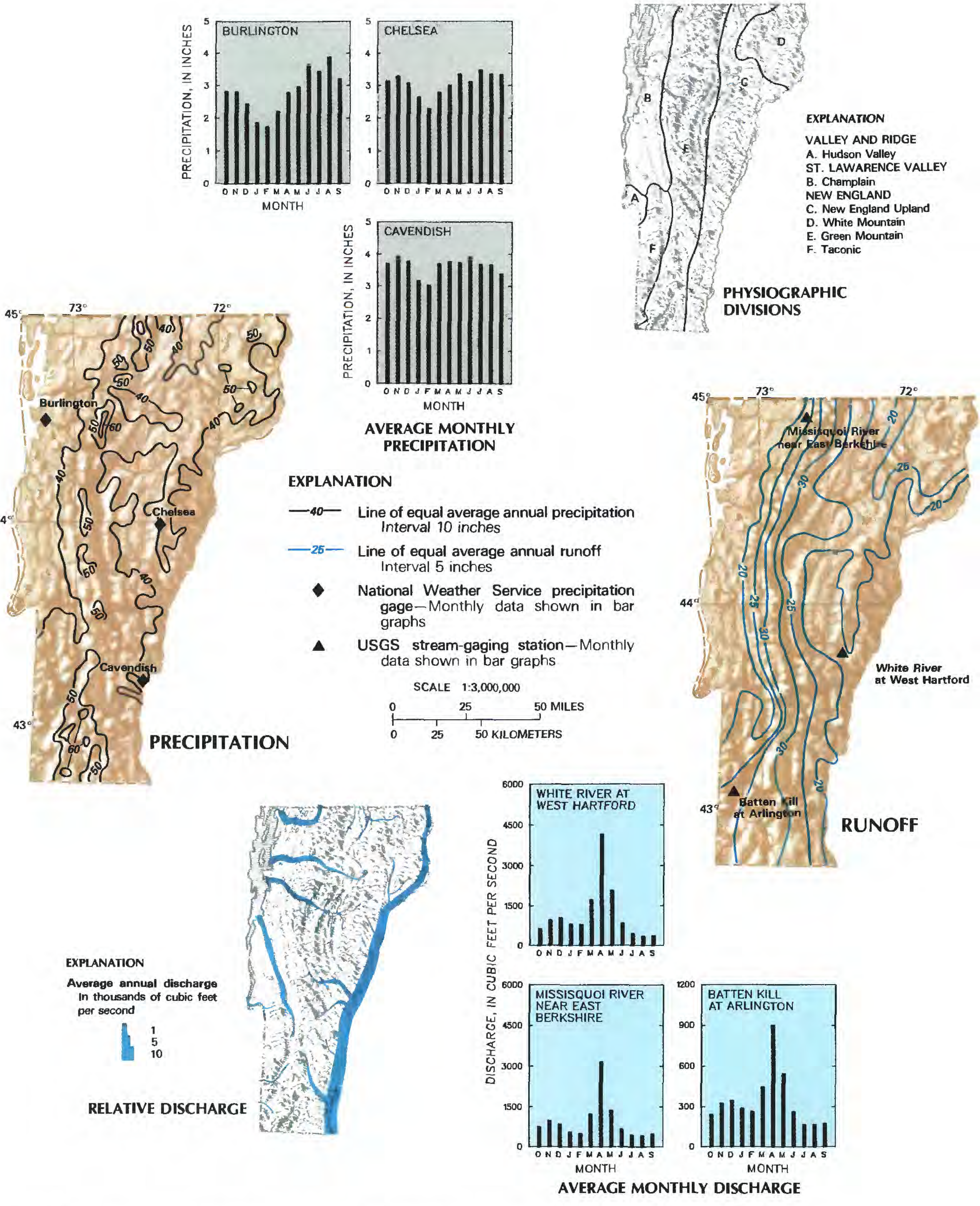

Figure 1. Average annual precipitation and runoff in Vermont and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data adapted from Knox and Nordenson, 1955; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

terns are typical of streams flowing from the northern Green Mountains. The drought of the mid-1960's had little impact on streamflows in northern Vermont (Barksdale and others, 1966) (fig. 2, site 13). However, during the mid-1970's, the area experienced high streamflows as shown by the 15-year weighted moving average of the annual values (fig. 2, site 13).

Average discharges by water year of Otter Creek at Center Rutland (site 8) and at Middlebury (site 9) are shown in figure 2. The flow of Otter Creek at Center Rutland is representative of streams that drain from the southern Green Mountains and northern Taconic Mountains. The flow of Otter Creek at Middlebury includes drainage from the Champlain lowland. Daily flows at Center Rutland are affected by regulation, by powerplants, and by the Chittenden Reservoir (completed in 1928 with a storage capacity of 19,000 acre-ft or 6,200 Mgal), but the average discharges by water year are only slightly affected by net changes in storage. Figure 2 shows

Table 2. Selected streamflow characteristics of principal river basins in Vermont

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi^2=square miles; ft^3/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day,[1] 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood[1] (ft^3/s)	Degree of regulation	
				NEW ENGLAND REGION CONNECTICUT SUBREGION				
1.	Connecticut River at North Stratford, N.H. (01129500).	799	1930-83	165	1,583	. . . .	Appreciable	Recreational, forestry products, agricultural, and light industrial areas. Hydroelectric powerplants.
2.	Moose River at Victory (01134500).	75.2	1947-83	5.7	143	4,460	None	Recreational and forestry products area.
3.	Passumpsic River at Passumpsic (01135500).	436	1928-83	88	739	17,200	Moderate	Recreational, forestry products, agricultural, and light industrial areas.
4.	White River at West Hartford (01144000).	690	1915-83	87	1,184	56,700	None	Recreational, agricultural, and forestry products area.
5.	Saxtons River at Saxtons River (01154000).	72.2	1940-82	3.8	120	9,510	. . . do . . .	Recreational, forestry products, and agricultural areas.
6.	Connecticut River at North Walpole, N.H. (01154500).	5,493	1942-83	993	9,380	. . . .	Appreciable	Recreational, agricultural, forestry products, and light industrial areas. Hydroelectric powerplants.
				ST. FRANCOIS SUBREGION				
7.	Black River at Coventry (04296000).	122	1951-83	19	201	4,220	Negligible	Recreational, forestry products, and agricultural areas.
				MID-ATLANTIC REGION RICHELIEU SUBREGION				
8.	Otter Creek at Center Rutland (04282000).	307	1928-83	79	551	13,700	Appreciable	Recreational, agricultural, light industrial, and some urban areas. Hydroelectric powerplants.
9.	Otter Creek at Middlebury (04282500).	628	1904-06, 1911-19, 1929-83	157	987	10,600	. . . do . . .	Recreational, agricultural, light industrial, and urban areas. Hydroelectric powerplants.
10.	Dog River at Northfield Falls (04287000).	76.1	1934-83	3.2	122	11,400	Negligible	Recreational, forestry products, and agricultural areas.
11.	Winooski River near Essex Junction (04290500).	1,044	1928-83	149	1,706	. . . .	Appreciable	Recreational, forestry products, agricultural, light industrial, and scattered urban areas. Hydroelectric powerplants.
12.	Lamoille River at East Georgia (04292500).	686	1929-83	158	1,239	23,900	Moderate	Recreational, forestry products, and agricultural areas.
13.	Missisquoi River near East Berkshire (04293500).	479	1911-83	57	925	21,000	None	Do.
				UPPER HUDSON SUBREGION				
14.	Batten Kill at Arlington (01329000).	152	1928-80	52	339	9,420	None	Recreational and forestry products areas.

[1] Based on record to 1981.

the effects of the drought of the mid-1960's and the high streamflows of the 1970's on the 15-year weighted moving average of the annual values.

SURFACE-WATER MANAGEMENT

The management of surface 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 surface-water resources.

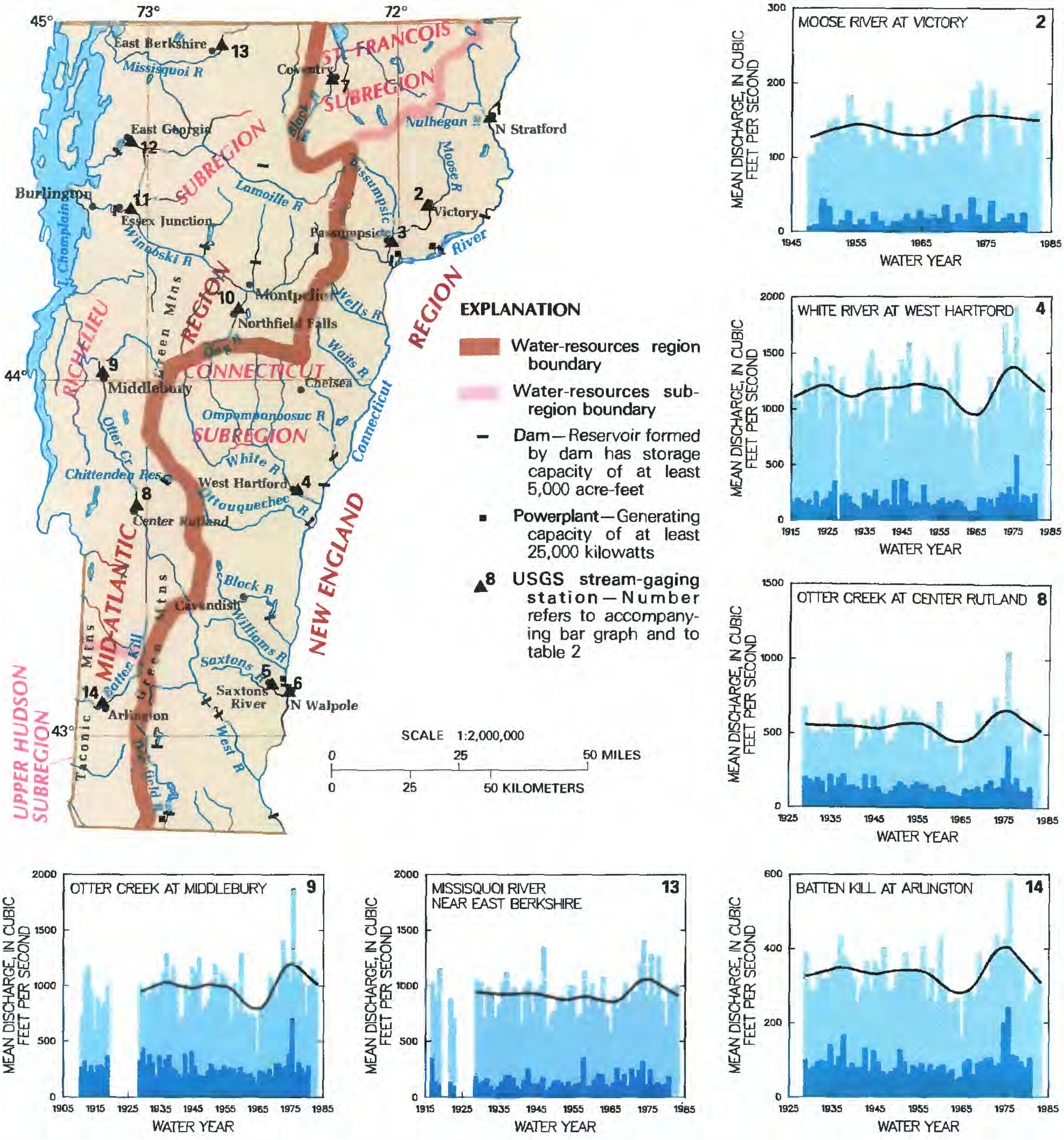

Figure 2. Principal river basins and related surface-water resources development in Vermont and average discharges for selected sites.

Bar graphs show average discharge (light blue) and 30-day minimum discharge (dark blue) by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Within the DWREE, water-management programs are divided among several units: Water Quality Management, Water Supply, Technical Review, Pollution Control, Construction, Solid Waste, Permits and Compliance, Monitoring and Surveillance, and Ground Water Management. Some of the programs address ground water or air pollution, but they also can involve surface-water management when resource issues are interrelated.

The Water Quality Management Unit addresses the broadest range of surface-water issues. Within the purview of this unit are: water-quality certification, stream gaging in cooperation with the U.S. Geological Survey, assimilative-capacity studies, and water-quality planning in cooperation with the U.S. Environmental Protection Agency.

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FOR ADDITIONAL INFORMATION

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VIRGINIA
Surface-Water Resources

Virginia is a water-rich State with abundant surface-water resources. The majority of the principal metropolitan areas of the State rely mainly on surface water as a source of public and industrial water supply. Surface water constitutes 70 percent of the total freshwater withdrawals (excluding withdrawals for thermoelectric-power generation) and provides freshwater, by means of public-supply systems, to about 59 percent (Kull, 1983) of Virginia's approximately 5.3 million residents (U.S. Bureau of the Census, 1983); ground water supplies the remaining 41 percent of the population by public and rural water-supply systems. The major uses of offstream surface water are for industrial supplies (90 percent) and public supplies (9 percent); surface water provides 83 percent of the total supply for public use. Non-consumptive uses of surface water include cooling water for thermoelectric-power generation and industrial processes, passageways for barges and ships, recreation potential such as swimming and boating, and wildlife habitat. The quality of surface water throughout the State generally is suitable for most uses except in relatively few areas. Surface-water withdrawals in Virginia in 1980 for various purposes and related statistics are given in table 1.

Major surface-water issues in Virginia include flooding, increased competition for withdrawals from the James and the Roanoke Rivers to meet public and industrial water-supply needs, and the continuing concerns regarding nutrient enrichment and pollution by heavy metals and organic substances.

GENERAL SETTING

Virginia lies within five physiographic provinces (fig. 1), each of which is characterized by distinctive geologic features and landforms that cause significant differences in the character of streams occurring in each province. These five physiographic provinces, from east to west, are the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau. The topography in each province is diverse, ranging from virtually flat in the Coastal Plain, to gentle hills and valleys in the central Piedmont, to higher relief and rugged terrain along the Blue Ridge and Appalachian crests, to rolling hills and valleys of the Valley and Ridge. Land-surface elevations range from sea level in the Coastal Plain along the coast to more than 5,000 feet above sea level in the mountains of the Blue Ridge.

The diversity in topography is reflected in the geographic distribution of climatic conditions within the State. Average annual precipitation ranges from about 36 to 52 inches. 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 (fig. 1). Precipitation, as shown in the bar graphs (fig. 1), does not exhibit a strong seasonal pattern during the year; thus, no wet or dry season is distinctive. Average annual evaporation from open bodies of water ranges from 45 to 55 inches, and 80 to 85 percent of this evaporation occurs from April through October (Virginia State Water Control Board, 1982, p. 33).

The distribution of runoff differs greatly among the physiographic provinces (fig. 1) and also exhibits appreciable differences between wet and dry years. In dry years, total runoff may range from about 3 inches to 10 inches in the southwestern part of the State—the area of highest runoff. In wet years, total runoff may range from about 16 inches to about 27 inches; thus, annual runoff may range from about 25 to 40 percent of precipitation (Virginia Department of Conservation and Economic Development, 1965, p. 46). Average monthly streamflows are generally greatest in March and least during the summer (fig. 1, bar graph).

Table 1. Surface-water facts for Virginia

[Data 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; Kull, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	3,157
Percentage of total population	59
From public water-supply systems:	
Number (thousands)	3,157
Percentage of total population	59
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
Freshwater Withdrawals	
Surface water and ground water, total (Mgal/d)	5,600
Surface water only (Mgal/d)	5,200
Percentage of total	93
Percentage of total excluding withdrawals for thermoelectric power	70
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	490
Percentage of total surface water	9
Percentage of total public supply	83
Per capita (gal/d)	156
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	23
Percentage of total surface water	0.4
Percentage of total livestock	90
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	4,700
Percentage of total surface water	90
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	76
Irrigation withdrawals:	
Surface water (Mgal/d)	19
Percentage of total surface water	0.4
Percentage of total irrigation	71
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	26,000

PRINCIPAL RIVER BASINS

Streams in Virginia contribute flow to four major hydrologic regions and seven subregions (fig. 2). The northern half of the State is in the Mid-Atlantic Region, which has two subregions in Virginia: The Potomac subregion, which consists of the Shenandoah River basin and several minor tributaries to the Potomac River, and the Lower Chesapeake subregion, which consists of the Rappahannock, the York, and the James River basins in addition to miscellaneous small tributaries. Southern and southeastern Virginia are part of the South Atlantic-Gulf Region. In Virginia, this region is composed of the Chowan-Roanoke and the Pee Dee Subregions. The Ohio Region is located in the southwestern part of the State and is separated into two subregions: The Kanawha (the New River) and the Big Sandy-Guyandotte (the Levisa and the Russell Forks). The Clinch, the Powell, and the Holston River basins, also located in the southwestern part of the State, are in the upper Tennessee Subregion of the Tennessee Region. Six principal subregions and selected river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MID-ATLANTIC REGION

Potomac Subregion

The Potomac Subregion is comprised of the Shenandoah River basin west of the Blue Ridge and several smaller streams east of the Blue Ridge. Fourteen percent of the State's area is in this subregion. Although the Potomac River lies just outside Virginia (its southern shoreline forms the northern boundary of the State), 39 percent of the total Potomac River drainage area is in Virginia. The Shenandoah River headwaters begin in the mountains along the Virginia-West Virginia State line and flow north in two major branches—the North Fork and the South Fork. These two rivers join at Front Royal to form the Shenandoah River. Most of the rocks in the basin are limestones, sandstones, and shales, and the waters contain elevated concentrations of dissolved carbonates compared with other streams in the State. Surface waters in the subregion, however, are suitable for most uses except in the South Fork Shenandoah River. Residual mercury from past long-term industrial wastewater discharges is a chronic problem in the South Fork Shenandoah River. Thus, a limit has been placed on fish consumed from the river because of its elevated mercury concentration. The river receives considerable recreational use, such as fishing, swimming, canoeing, and whitewater rafting. Urbanization in the Washington, D.C., area has had a major impact on the small tributaries to the Potomac River through increased nutrient and sediment loadings, increased runoff, and growing water-supply demands.

Lower Chesapeake Subregion

The basins of the lower Chesapeake Subregion, which comprise about 41 percent of the State, drain a wide variety of physiographic areas. The Rappahannock River, which drains about 8 percent of the State, heads on the eastern flank of the Blue Ridge and flows eastward across the Piedmont and Coastal Plain to the Chesapeake Bay. There has been no significant development in the Rappahannock River basin except near Fredericksburg. Municipal water supply and irrigation are the major water uses. Reaches near the confluence of the Rapidan River with the Rappahannock River have been given a "scenic river" designation, and development has been restricted to preserve the rustic quality of the river.

The York River basin drains about 7 percent of the State. The York River begins on the Piedmont and flows eastward and southward into the Chesapeake Bay. Major tributaries of the York are the Pamunkey and the Mattaponi Rivers. Flooding is frequent along the wide flood plains of the Mattaponi River but damage is slight because of the small amount of development that has occurred. The North Anna and the South Anna Rivers join to form the Pamunkey River just below the Fall Line. Lake Anna is a major reservoir on the North Anna River with a storage capacity of 305,000 acre-ft (acre-feet) or 99,400 Mgal (million gallons). It was constructed in the 1970's to serve as a cooling pond for a nuclear powerplant. In recent years, irrigation usage in the Pamunkey River basin has increased significantly. The Pamunkey River has also been considered as a potential source of municipal water by communities on the James-York peninsula.

Drainage basins of the James River and its tributaries comprise nearly 25 percent of the State. The main river channel crosses four physiographic provinces on its way to the Chesapeake Bay: The Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain. Major tributaries to the James are the Jackson and the Cowpasture Rivers which join to form the James, the Maury, the Piney, the Rivanna, and the Appomattox Rivers.

The James River served as the main transportation artery in the State from colonial times until the development of the railroads after the Civil War. The James River and Kanawha Canal eventually extended 200 miles westward from Richmond to Buchanan. It carried agricultural and mineral resources eastward and manufactured goods westward. Major cities such as Lynchburg, Charlottesville, Richmond, and Petersburg developed along the James and its tributaries. Today most of the land use in the basin is agricultural; however, there are large industrial and manufacturing complexes along the lower James at Richmond, Hopewell, and Norfolk.

Numerous dams have been constructed on the James to aid navigation, divert water for municipal and industrial uses, provide flood protection, and generate hydroelectric power. Major water-quality issues include the persistence of kepone in the aquatic environment of the lower James, which resulted from dumping (discontinued) of this pesticide in the James at Hopewell; toxic metals in sediments of the Elizabeth River, a minor tributary to the James River at Norfolk; and the leaching of copperas (mining) wastes resulting in fishkills on the Piney River. With the exception of these issues, surface water within this subregion is generally suitable for most uses.

The Chesapeake Bay is an ancient river valley that was covered by rising waters from melting glaciers at the end of the Pleistocene Era. The development of major urban areas near tributaries to the Bay and the subsequent municipal and industrial wastes discharged into these tributaries have caused major changes in the fauna and flora of the Bay. These changes, in turn, have adversely affected the fishing and shellfish industries that developed where the freshwaters of streams entered the saline waters of the Bay.

SOUTH ATLANTIC-GULF REGION

Chowan-Roanoke Subregion

The Chowan-Roanoke Subregion is the principal component of the South Atlantic-Gulf Region in Virginia. It comprises 27 percent of the State and is composed of two major basins—the Roanoke River and the Chowan River-Dismal Swamp.

The Roanoke basin drains about 15 percent of the State. The Roanoke River begins on the western flank of the Blue Ridge Mountains, then flows northward along the Valley and Ridge province. It cuts through the Blue Ridge Mountains at Roanoke and flows eastward across the Piedmont. Major tributaries join the main stem as it flows across the Piedmont. The largest tributary is the Dan River which starts in the Blue Ridge Mountains and flows south into North Carolina before turning north to join the Roanoke at Kerr Reservoir. A large hydroelectric project is located at Philpott Lake (completed in 1950, storage capacity of 247,400 acre-ft or 80,600 Mgal) on the Smith River, a major tributary to the Dan River. Several other hydroelectric dams are located on the Roanoke River including ones at Smith Mountain Lake (completed in 1963, storage capacity of 1,517,000 acre-ft or 494,000 Mgal), Leesville Lake (completed in 1962, storage capacity of 94,960 acre-ft or 30,900 Mgal), and Kerr Reservoir (completed in 1950, storage capacity of about 2,770,000 acre-ft or 903,000 Mgal). Surface-water issues in the Roanoke River basin include sedimentation in the reservoirs, flooding along the Dan River, and the proposed interbasin transfer of water from Lake Gaston to the Norfolk-Virginia Beach area in southeastern Virginia.

The Chowan River and adjacent Dismal Swamp basins drain 11 percent of the State. The Nottoway and the Blackwater Rivers join at the Virginia-North Carolina State line to form the Chowan River. The Meherrin River joins the Chowan River from the west before the main river empties into Albemarle Sound. The streambed slopes of rivers in the Chowan basin are much less than most others in the State. The rivers tend to have flatter, longer lasting flood flow peaks rather than the sharp flood flow peaks common in the remainder of the State. Lake Drummond, encompassing 5

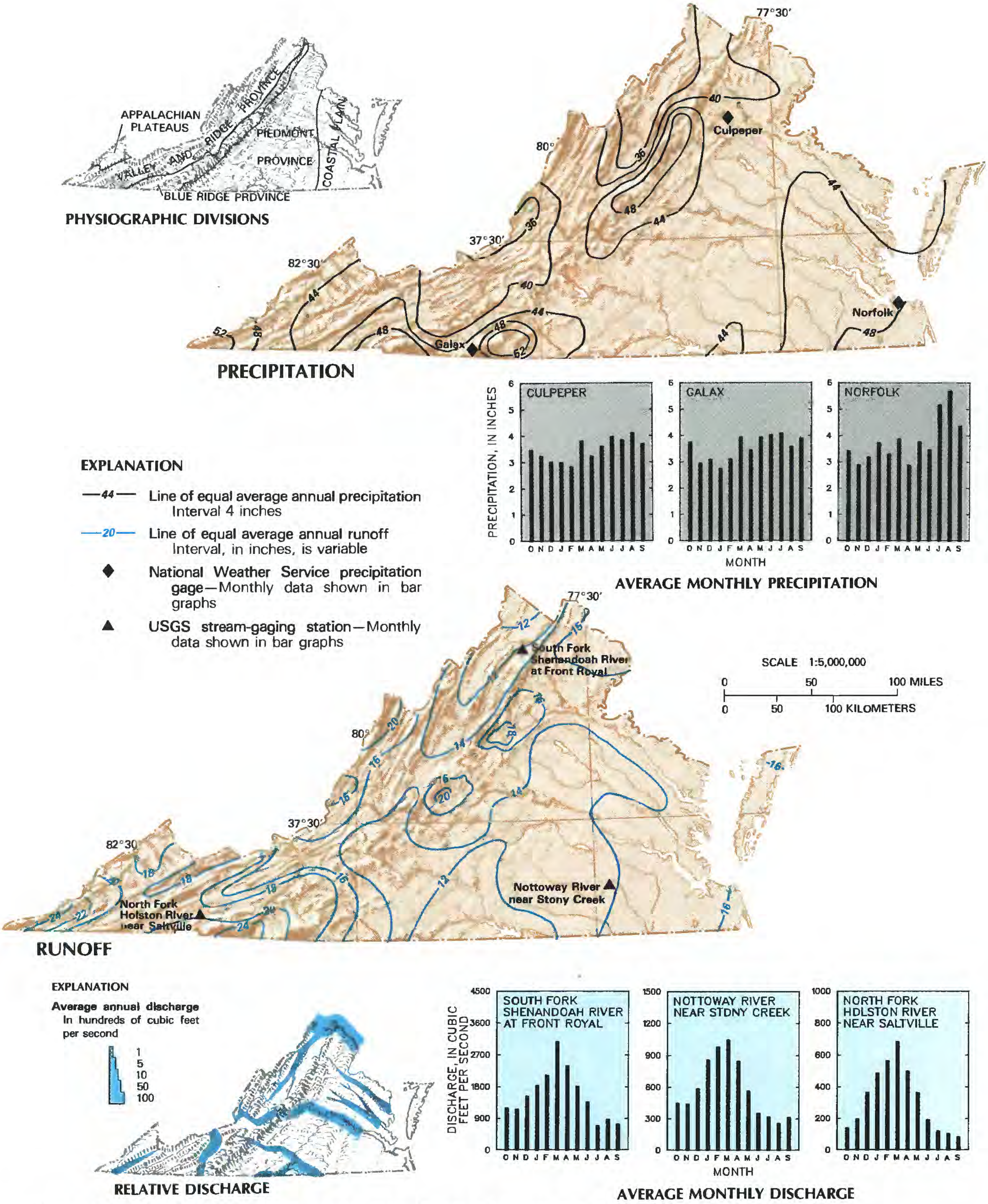

Figure 1. Average annual precipitation and runoff in Virginia and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

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Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	
				MID-ATLANTIC REGION **Potomac Subregion**				
1.	South Fork Shenandoah River at Front Royal (01631000).	1,642	1899-1906, 1930-84	243	1,590	143,000	Negligible	Typical of streams in northern Valley and Ridge Province. Major water uses include hydroelectric, municipal, industrial, fish and wildlife propagation, and recreation.
2.	Accotink Creek near Annandale (01654000).	23.5	1947-84	0.84	27.7	14,500	Appreciable	Basin has undergone change from semi-rural to suburban-urban during period of record.
				Lower Chesapeake Subregion				
3.	Pamunkey River near Hanover (01673000).	1,081	1941-71	33	915	38,500	Negligible	Prior to construction of Lake Anna Dam.
			1972-84	70	1,144	. . . .	Appreciable	Subsequent to construction of Lake Anna Dam. Major water uses include irrigation, municipal-industrial, thermoelectric cooling, and fish propagation.
4.	Cowpasture River near Clifton Forge (02016000).	461	1925-84	54	525	28,000	Negligible	Typical of streams west of Blue Ridge.
5.	James River at Cartersville (02035000).	6,257	1898-1979	584	7,060	264,000	. . . do . . .	Prior to construction of Gathright Dam.
			1980-84	670	. . . .	. . . .	Moderate	Low flow augmented by releases from Gathright Dam since 1979. Major uses include industrial, hydroelectric, recreation, and municipal.
				SOUTH ATLANTIC-GULF REGION **Chowan-Roanoke Subregion**				
6.	Nottoway River near Stony Creek (02045500).	579	1929-84	12.8	564	25,700	Negligible	Major uses include irrigation, fish propagation and recreation. Typical of streams on Southern Piedmont.
7.	Blackwater River near Franklin (02049500).	617	1944-84	1.4	643	11,700	Moderate	Typical Coastal Plain stream with extremely low flows during late summer. Some water diverted upstream of gage for municipal and irrigation purposes.
8.	Smith River near Philpott (02072000).	216	1946-50	. . . .	354	. . . .	Negligible	Prior to Philpott Dam.
			1951-84	58	268	. . . .	Appreciable	Subsequent to Philpott Dam. Major water use is hydroelectric power generation and municipal.
				OHIO REGION **Kanawha Subregion**				
9.	New River at Allisonia (03168000).	2,202	1929-84	725	3,220	131,600	Moderate	Major water uses are hydroelectric, industrial, and municipal. Some daily regulation by powerplant 25 miles upstream.
				Big Sandy-Guyandotte Subregion				
10.	Russell Fork at Haysi (03208500).	286	1926-50	0.81	326	41,700	Negligible	Prior to major strip-mining in basin.
			1951-84	2.3	337	74,300	Appreciable	Subsequent to major development of coal strip-mining activities. Major water use in basin, mining.
				TENNESSEE REGION **Upper Tennessee Subregion**				
11.	North Fork Holston River near Saltville (03488000).	222	1907-08, 1920-84	24	302	20,500	Negligible	Typical stream in southern valley and ridge province.

mi² (square miles) in the Dismal Swamp, is the largest natural lake in Virginia. Large nutrient loads and eutrophication have been problems on the Chowan River. Water is pumped from both the Nottoway and the Blackwater Rivers and transported out of the basin to reservoirs in the Norfolk area to supplement local municipal water-supply sources. Surface waters within this subregion are generally suitable for most uses.

OHIO REGION

Kanawha Subregion

The Kanawha Subregion contains the New River and its tributaries, which drain about 8 percent of the State. The river begins in the Blue Ridge and flows south into North Carolina, then back north into Virginia. The middle and lower reaches of the New River flow mainly over limestones and shales and the upper reach over igneous and metamorphic rocks. Several small dams are located on the New River; plus one major reservoir, Claytor Lake (completed in 1939, storage capacity of 230,100 acre-ft or 75,000 Mgal).

Big Sandy-Guyandotte Subregion

The Big Sandy-Guyandotte Subregion drains about 2 percent of the State through the Levisa Fork and its major tributary, the Russell Fork. This subregion is important to Virginia because, along with the Powell and the Clinch River basins of the adjacent upper Tennessee Subregion, it is the location of current coal mining activities. Strip mining has steadily increased since the early 1950's. Discharge data for the Russell Fork at Haysi (fig. 2, table 2, site 10) reflect a steady increase in base-flow levels since that time. Flooding can be a problem because much of the local commerce,

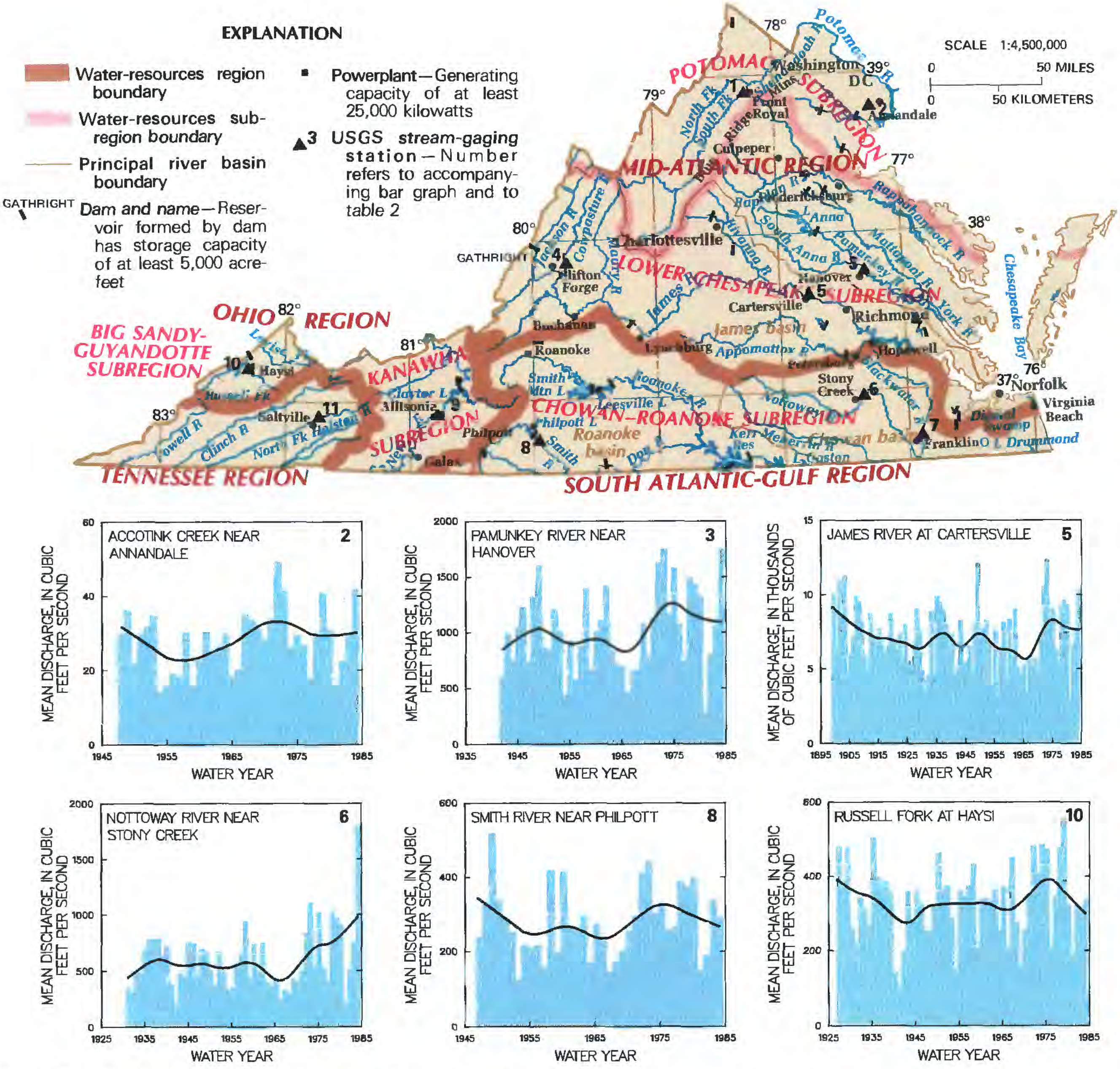

Figure 2. Principal river basins and related surface-water resources development in Virginia and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

industry, and residential areas are located in narrow bands along the stream valleys. Surface waters within the subregion are suitable for most uses.

TENNESSEE REGION

Upper Tennessee Subregion

The upper Tennessee Subregion comprises 8 percent of the State. This subregion contains the Holston, the Clinch, and the Powell Rivers. The Holston River lies in the Valley and Ridge physiographic province and mainly drains limestones and other sedimentary rocks.

The Clinch River lies along the western side of the Valley and Ridge physiographic province and drains limestones to the east and a number of small streams from the coal mining areas along the Appalachian Plateaus to the west. The Powell River, a major tributary to the Clinch, also receives drainage from coal mined areas along its northern and western sides. Acid-mine drainage generally is not a serious problem because of the high neutralizing capacity of the regional carbonate rock. Thus, surface waters are generally suitable for most uses. Flooding is a problem in some communities, especially in the coal-mining areas where development in the stream valleys has been considerable. In recent years, proposed interbasin transfer of water through a coal-slurry pipeline has raised some political, technical, and economic questions.

SURFACE-WATER MANAGEMENT

In the absence of statutory law, the basic principle applying to surface-water management in Virginia is the common law riparian rights. Virginia legislation directs the State Water Control Board (SWCB) to formulate State water-resources policy with responsibilities for planning the development, conservation, and use of Virginia's water resources.

The water-quality classification and protection of the surface waters are the responsibility of the SWCB under State law. The SWCB is also charged with administration of the National Pollutant Discharge Eliminations System (NPDES) permitting system and Section 401 of the Clean Water Act of 1977 (P.L. 95-217). Use of surface waters for public supply purposes is regulated by the Virginia Department of Health (VDH). The VDH reviews water-supply development plans, establishes water-supply quality standards, and monitors the quality of water delivered to consumers to ensure that it meets standards.

A number of Federal legislative acts authorize various State and Federal agencies to regulate different aspects of surface waters in Virginia. The statutes include the Wild and Scenic Rivers Act (P.L. 90-542), which reserves historical flows and prohibits new diversions or water resource developments around selected river reaches; the Federal Power Act (16 U.S.C. 791a-823), which authorizes the Federal Energy Regulatory Commission to license waterpower projects; and the Clean Water Act (P.L. 95-217), which provides for the establishment of various standards and procedures to control runoff and discharge of pollutants and especially Section 404 of this act which authorizes the regulation of dredge and fill permits through the U.S. Army Corps of Engineers.

The U.S. Geological Survey and the SWCB operate a cooperative network of stream gages throughout the State to provide information on current flow conditions for real-time management of water resources projects and long-term data to assess trends and flow statistics for planning and research purposes.

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FOR ADDITIONAL INFORMATION

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WASHINGTON
Surface-Water Resources

The supply of surface water in Washington (runoff averages about 26 inches per year) is adequate to satisfy the needs of man today and in the foreseeable future; however, its distribution is uneven both areally and seasonally. This distribution results in shortages in parts of eastern Washington and in summertime shortages and wintertime floods in western Washington. Reservoirs in the State help solve these supply problems by storing floodflows and releasing the water later to augment low flows. The Columbia River, for example, is now virtually 100 percent regulated by multipurpose dams.

Limitations to the full and efficient use of available surface-water supplies in Washington are imposed by competitive and often incompatible demands for the water. These demands are for municipal supplies, irrigation, industry, recreation, Indian tribes, fisheries, and hydropower. In Washington in 1980 the total surface-water withdrawal was 7,500 Mgal/d (million gallons per day) or 11,600 ft^3/s (cubic feet per second), 81 percent of which was used for irrigation. Although irrigation uses most of the surface water withdrawn in Washington, 51 percent of the population depends on surface water for supply. Limitations to water use caused by natural surface-water quality are practically negligible in Washington; however, irrigation water pumped from some deep basalt aquifers in the Columbia River basin has a high enough sodium content to be causing problems for farmers. There are also potential problems caused by irrigation return flows that are heavily laden with salts either leached from the soil or added by fertilizers. Pollution from domestic and industrial wastes exists in small, local areas; but, in general, streamflows are adequate for the dilution and assimilation of these wastes. Facts concerning surface-water withdrawals by category and other related statistics for Washington for 1980 are given in table 1.

GENERAL SETTING

Washington has four principal physiographic provinces—Pacific Border, Cascade-Sierra Mountains, Northern Rocky Mountains and Columbia Plateaus (Fig. 1). The varied topography of these provinces influences the rainfall and snowfall greatly and thereby influences the surface-water runoff. The provinces are shown in figure 1.

Washington has a distinctly varied climate that is caused by two features: (1) the Cascade Mountains and (2) the prevailing westerly winds from the Pacific Ocean. The north-south trending Cascades divide the State into the western part with a marine climate—with cool, wet winters and warm, relatively dry summers and into the eastern part with a more continental climate of cold winters and hot, dry summers.

Although the average annual precipitation in Washington is about 40 inches, the western part receives about 70 inches and the eastern about 20 inches. Locally, average annual precipitation ranges from only 7 inches in the driest part of eastern Washington to about 150 inches in the Olympic Mountains. The areal distribution of precipitation and the monthly variations at three selected sites are shown in figure 1. About two-thirds of the precipitation in Washington occurs in the fall and winter (October through March), either as rain at the lower elevations or as snow at the higher elevations. Heavy snowpacks and glaciers in the Olympic and Cascade Mountains are major sources of water for many rivers in Washington.

Evapotranspiration amounts to more than 22 inches in the Olympic and Cascade Mountains, between 12 and 22 inches in the Puget Trough, on the lower slopes of the mountains, and in the timbered areas of eastern Washington, and less than 12 inches in most of the Columbia Plateau. The evapotranspiration losses are directly related to precipitation and are higher in the wetter, cooler areas and are lower in the dryer, hotter areas where there is less water available to transpire or evaporate.

Table 1. Surface-water facts for Washington

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day.; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	2,125
Percentage of total population	51
From public water-supply systems:	
Number (thousands)	2,100
Percentage of total population	51
From rural self-supplied systems:	
Number (thousands)	25
Percentage of total population	0.6
OFFSTREAM USE, 1980 **FRESHWATER WITHDRAWALS**	
Surface water and ground water, total (Mgal/d)	8,200
Surface water only (Mgal/d)	7,500
Percentage of total	91
Percentage of total excluding withdrawals for thermoelectric power	91
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	510
Percentage of total surface water	7
Percentage of total public supply	63
Per capita (gal/d)	243
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	11
Percentage of total surface water	0.1
Percentage of total rural domestic	22
Per capita (gal/d)	440
Livestock:	
Surface water (Mgal/d)	2.0
Percentage of total surface water	<0.1
Percentage of total livestock	33
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	830
Percentage of total surface water	11
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	86
Excluding withdrawals for thermoelectric power	86
Irrigation withdrawals:	
Surface water (Mgal/d)	6,100
Percentage of total surface water	81
Percentage of total irrigation	96
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	940,000

The runoff in Washington falls into two general categories: (1) the snowmelt-runoff regime typical of the eastern part of the State; and (2) the rainfall-runoff regime that predominates in western Washington. Examples of monthly variations are shown in figure 1 as well as areas where various amounts of runoff occur, expressed as annual averages. The Naselle River is typical of the coastal streams whose major runoff occurs during the 4 months November through February; only about 10 percent runs off during the 5 months May through September. The runoff is closely related to precipitation and, because of the relatively low elevation, the heavy winter precipitation falls as rain and runs off quickly. Thunder Creek is a glacier-fed stream draining a high elevation where almost all winter precipitation falls as snow. The distribution of runoff is opposite to that of the Naselle, with the maximum runoff occurring in July and the high-runoff period extending from May through September. The period of low flow lasts all winter. The Colville River exhibits a typical runoff pattern for a stream in eastern Washington. Much of the winter precipitation falls as snow which does not melt until the warmer temperatures of spring cause the high runoff period to occur from April through June. By July the snow has melted and the streamflow becomes low.

Some basins are underlain by porous geologic formations that can store some of the precipitation which then is released to the stream as the flow decreases during the dry season. Other basins may be underlain by dense, impervious rock formations which can hold very little water and for these, when the dry season comes, the low-flow recession is pronounced and the streams may cease flowing altogether. The bar graphs in figure 2 indicate that, although there was a statewide rising trend in streamflow from 1945 to 1955 and a falling trend from 1955 to 1965, there has been no significant change in runoff during the last 50 years.

PRINCIPAL RIVER BASINS

Washington is entirely in the Pacific Northwest Region (fig. 2). West of the Cascade Mountains there are many relatively short, steep rivers flowing from the mountains into the ocean. Four river basins, the Chehalis, the Quinault, the Duwamish, and the Skagit were chosen as representative of western Washington streams. All of eastern Washington is drained by the Columbia River and in that area the Columbia River main stem and two of its tributaries, the Colville and the Yakima Rivers, were chosen as representative. These river basins are described below; their location, and long-term variations in streamflow characteristics at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

PACIFIC NORTHWEST REGION

Oregon-Washington Coastal Subregion

Chehalis River Basin.—The Chehalis River drains an area of 2,114 mi^2 (square miles) of which about 84 percent is forest land and 7 percent is farmland. The main stem and its main tributaries, the Newaukum, the Skookumchuck, the Satsop, and the Wynoochee Rivers, originate in relatively low mountains (fig. 2). Very little of the abundant precipitation falls as snow, and seasonal distribution of runoff is similar to that of rainfall. (See the Naselle River in fig. 1 for similar runoff pattern.) There is sufficient water supply within the basin for present and future needs, provided seasonal distribution problems are resolved. In 1976, the Washington State Department of Ecology (WDOE) adopted a basin management program for the Chehalis River establishing base flows to preserve instream uses. This resulted in closure of a large part of the basin to further appropriation of surface waters. Water rights issued since 1976 have virtually accounted for all the unappropriated waters in the basin. There is competition for the water from the forest-products industries, agriculture, municipalities, and the anadromous fisheries. The Chehalis River is only slightly regulated; there is a U.S. Army Corps of Engineers dam on the Wynoochee River for flood control and for augmenting summer low flows and a private storage dam on the Skookumchuck River to supply water to a coal-fired steamplant. The chemical quality of the water is good enough to be no constraint on the use of the water. It is soft, with concentrations of 40 mg/L (milligrams per liter) as calcium carbonate or less and dissolved constituents of 70 mg/L or less.

Puget Sound Subregion

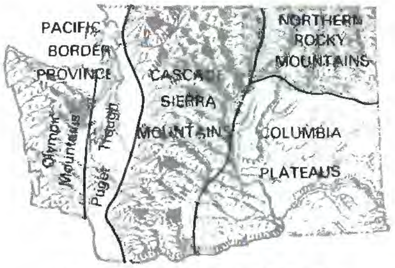
Duwamish River Basin.—The Duwamish River originates in the Cascade Mountains and flows westerly into the ocean at Seattle (fig. 2). It drains 483 mi^2 of which about 70 percent is forest land. It is called the Duwamish River for the first 11 miles above the mouth, and is called the Green River above that point. The upper 48 percent of the basin is city of Tacoma watershed land. Tacoma diverts about 108 ft^3/s or 70 Mgal/d for its municipal supply. The water is of excellent chemical quality, being soft (16 mg/L as calcium carbonate) with a dissolved constituents concentration of about 40 mg/L. Prior to the construction of Howard Hanson Dam in 1961, the lower 32 miles of the basin suffered flood damage most years. Since the dam has controlled the flooding, the lower valley has been occupied by light industry and truck gardens. The river supports both salmon and trout fisheries, but prior to construction of the dam they were impaired by the low flows in the river in late summer. Now the dam stores some of the spring snowmelt water and releases it later to augment the natural low flows. The discharge statistics in table 2 show the increase in the 7-day, 10-year low flow and the decrease in the 100-year flood at selected sites as a result of regulation.

Skagit River Basin.—The Skagit River (fig. 2) drains 3,130 mi^2 of which 400 mi^2 are in Canada. The basin is mostly mountainous, being almost entirely above 2,000-foot elevation except for the floors of the downstream reaches of the main stem and major tributaries. The average annual precipitation over the basin is about 100 inches (fig. 1) which falls mostly in the winter as rain and as snow in the higher elevations. Some tributaries are glacier-fed and their runoff is similar to that of Thunder Creek (fig. 1). There are important hydroelectric facilities in the upper basin and on a tributary, the Baker River. The lower basin and delta area have excellent soil and are used extensively for growing vegetables, berries, flower bulbs, and also corn and hay for dairy cows. The chemical quality of the water is excellent and is no restraint on the use of the water. The water is soft (30 mg/L as calcium carbonate) and has a concentration of dissolved constituents of 50 mg/L or less.

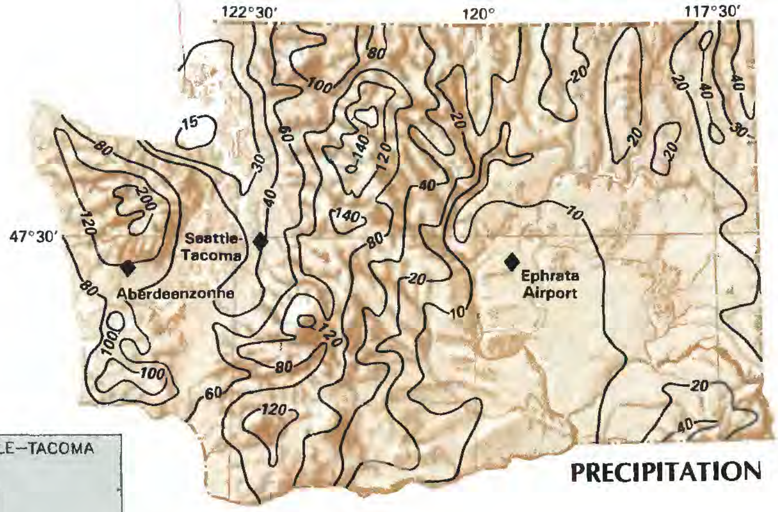
Upper Columbia Subregion

Colville River Basin.—The Colville River drains 1,020 mi^2 of forest and farmland in northeastern Washington before flowing into the Columbia River (fig. 2). It shows the typical runoff pattern for streams in eastern Washington. Although most of the precipitation falls in winter, it falls as snow and does not run off until the melting of the snowpack in the springtime (fig. 1). By July, the water supply becomes inadequate because the snow has melted and there is very little rainfall. The chemical quality of the water in the basin is typical of that in eastern Washington. The water is hard (164 mg/L as calcium carbonate) and the dissolved constituents are about 200 mg/L. The only hydroelectric powerplant in the basin is a small one (1,200 kilowatts) at the mouth of the Colville River. The economic growth, as reflected by population, has been very slight in the last 60 years. The population of Colville, the largest town in the basin, rose from 1,700 in 1920 to 4,600 in 1980. Inasmuch as only about 5 percent of the farmland is now irrigated, there is good potential for irrigating more in the future.

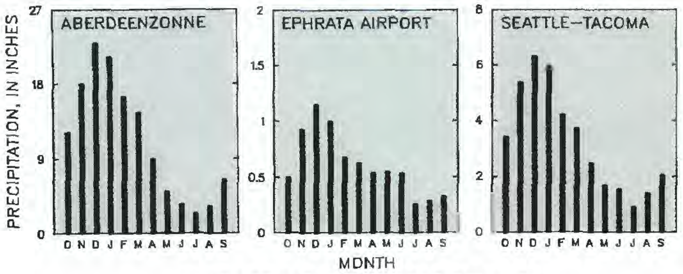
Columbia River Main Stem.—The Columbia River originates in Canada, flows about 500 miles in Canada and another 745 miles in Washington, and falls a total of 2,650 feet before flowing into the Pacific Ocean. It drains a total of 259,000 mi^2 of which 39,500 mi^2 are in Canada and 47,400 mi^2 are in Washington. There are now 13 hydroelectric dams on the main stem (11 in the U.S.) and it is the greatest power river in the world. Figure 1 shows how little precipitation falls in central eastern Washington through which the Columbia River flows. Grand Coulee Dam, with a usable storage capacity of 5,232,000 acre-ft (acre-feet) or 1,705,000 Mgal (million gallons), was completed in 1941 as the key feature in the vast Columbia Basin Irrigation project. The U.S. and Canada in September 1964 signed the Columbia Treaty, a plan to develop the Columbia River cooperatively for mutual benefit. One feature of the treaty was the building of a dam in Canada on the main stem 273 miles upstream from the border. It was completed in 1973 with a storage capacity of more than twice that of Grand Coulee Dam. The effect of that regulation may be seen in table 2 by noting the increase in the 7-day, 10-year low flow and the decrease in the 100-year flood flow for the Columbia River at international boundary. Washington has benefited from relatively inexpensive electricity generated at



PHYSIOGRAPHIC DIVISIONS



PRECIPITATION



AVERAGE MONTHLY PRECIPITATION

EXPLANATION

—80— Line of equal average annual precipitation
Interval, in inches, is variable

—30— Line of equal average annual runoff
Interval, in inches, is variable

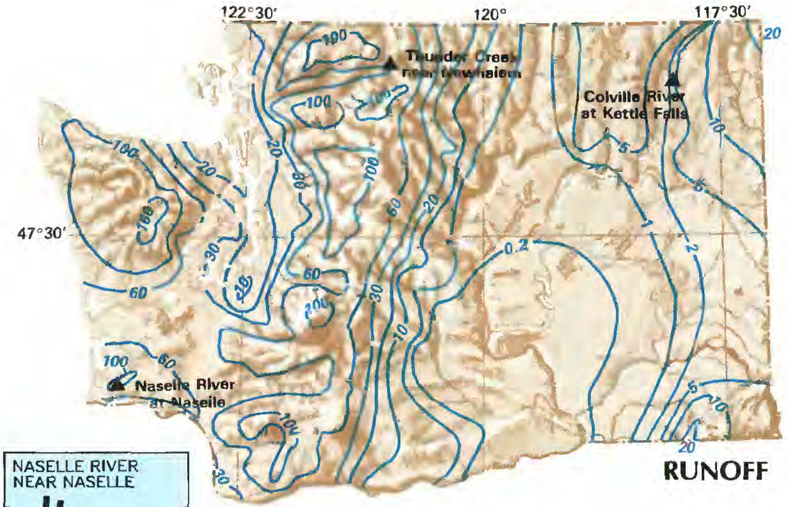
◆ National Weather Service precipitation gage—Monthly data shown in bar graphs

▲ USGS stream-gaging station—Monthly data shown in bar graphs

EXPLANATION

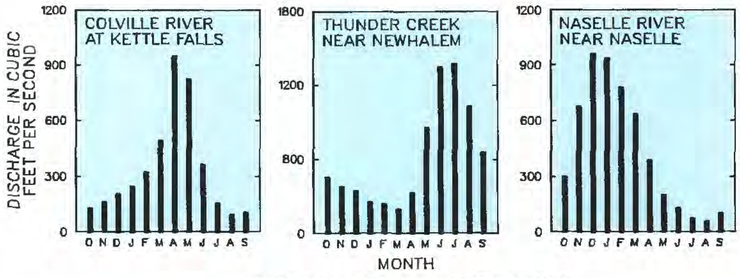
Average annual discharge
In thousands of cubic feet per second
5
10
50
100
175
250

RELATIVE DISCHARGE



RUNOFF

SCALE 1:6,000,000
0 50 100 MILES
0 50 100 KILOMETERS



AVERAGE MONTHLY DISCHARGE

Figure 1. *Average annual precipitation and runoff in Washington and average monthly data for selected sites, 1951-80.*

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA) and U.S. Weather Bureau, 1965; monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

private and Federal dams on the Columbia River ever since the first dam was completed in 1937. The aluminum industry was attracted to the area by the low rates, but there is currently some interest in Congress to increase the rates considerably which could influence the competitive nature of the alumimum plants in the world market. The higher rates may also make some farmland unprofitable where pumping of irrigation water is necessary. There are also unresolved legal questions concerning Indian water rights within the Columbia basin and competition for water among agriculture, hydropower, and fisheries.

Yakima Subregion

The Yakima River originates on the eastern slope of the Cascade Mountains and flows in a general southeasterly direction to the Columbia River (fig. 2). It drains an area of 6,155 mi^2 with the western part being quite wet and mountainous and the eastern part consisting of dry ridges and troughs. Only the uppermost reaches of the Yakima River have natural streamflows because of the extensive irrigation farther downstream. Five major storage reservoirs store about 60 percent of the average annual runoff. The federally developed Yakima Project was begun in 1907 and is one of the oldest and most successful irrigation projects in the United States. About 95 percent of all the farms in the basin are irrigated. The Yakima Valley is known nationally as an outstanding agricultural area especially for its tree fruit, grapes, hops, and vegetables. The chemical quality of the water in the upper Yakima River basin is of excellent quality (dissolved constituents of 70 mg/L or less) and is soft (30 mg/L as calcium carbonate). Near its mouth, the dissolved constituents increase to 180 to 250 mg/L and the water becomes moderately hard to hard (about 120 mg/L as calcium carbonate). The degradation of the chemical water quality of the Yakima River caused by raw or treated sewage effluents and by return flow from fertilized irrigated land is becoming an increasingly important issue. Other important issues are the unresolved legal questions concerning Indian rights to the water and fish within this basin.

SURFACE-WATER MANAGEMENT

Surface water in Washington is regulated chiefly by the Washington Department of Ecology (WDOE) and the Washington Department of Social and Health Services (DSHS). The Water Resources Act of 1971 (Chapter 90.54 of the Revised Code of

Table 2. Selected streamflow characteristics of principal river basins in Washington

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and Washington State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				PACIFIC NORTHWEST REGION OREGON-WASHINGTON COASTAL SUBREGION Chehalis River basin				
1.	Chehalis River near Grand Mound (12027500).	895	1930-83	116	2,853	55,800	Negligible	Low elevation. Timber and pastureland.
				Quinault River basin				
2.	Quinault River at Quinault Lake (12039500).	264	1912-83	350	2,861	54,100	None	Undeveloped valley in mountainous rain forest.
				PUGET SOUND SUBREGION Duwamish River basin				
3.	Green River near Auburn (12113000).	399	1937-61 1962-83	113 199	1,337 1,377	33,700 12,200	None Moderate	Regulated 32 miles upstream since 1961 for high and low flows.
				Skagit River basin				
4.	Skagit River near Mt. Vernon (12200500).	3,093	1941-83	4,770	16,700	157,000	Appreciable	Regulation increased during this period.
				UPPER COLUMBIA SUBREGION Colville River basin and Columbia River main stem				
5.	Columbia River at international boundary (12399500).	59,700	1939-72 1973-83	26,800 36,700	101,300 98,880	571,000 342,000	Moderate Appreciable	Regulation increased in 1973 by Mica Dam 273 miles upstream.
6.	Colville River at Kettle Falls (12409000).	1,007	1924-83	19	306	3,720	Negligible	Timber and pastureland.
7.	Columbia River at Grand Coulee Dam (12436500).	74,700	1939-83	35,100	111,500	616,000	Appreciable	Large irrigation project in eastern Washington began in 1939.
				YAKIMA SUBREGION				
8.	Yakima River at Kiona (12510500).	5,615	1934-83	704	3,640	52,000	Appreciable	Irrigated farmland, orchards, vineyards.

Washington (RCW)) directs the WDOE to develop and implement a comprehensive State water-resources program to ensure that the waters of the State are used for the best interests of the people. To manage the State's water resources, WDOE applies regulations, issues permits, and monitors appropriations that they have set based upon the doctrine of prior appropriation. They also manage shorelines of oceans and rivers, review applications for reservoir construction, review dam plans and make safety inspections, and license well drillers, and conduct technical investigations unilaterally and in cooperation with the U.S. Geological Survey.

WDOE is vested with exclusive authority to set instream flows and levels of State waters (RCW 90.03.247). The Department has now established instream flows on 88 major streams in the State and closed 187 streams and lakes to further consumptive appropria-

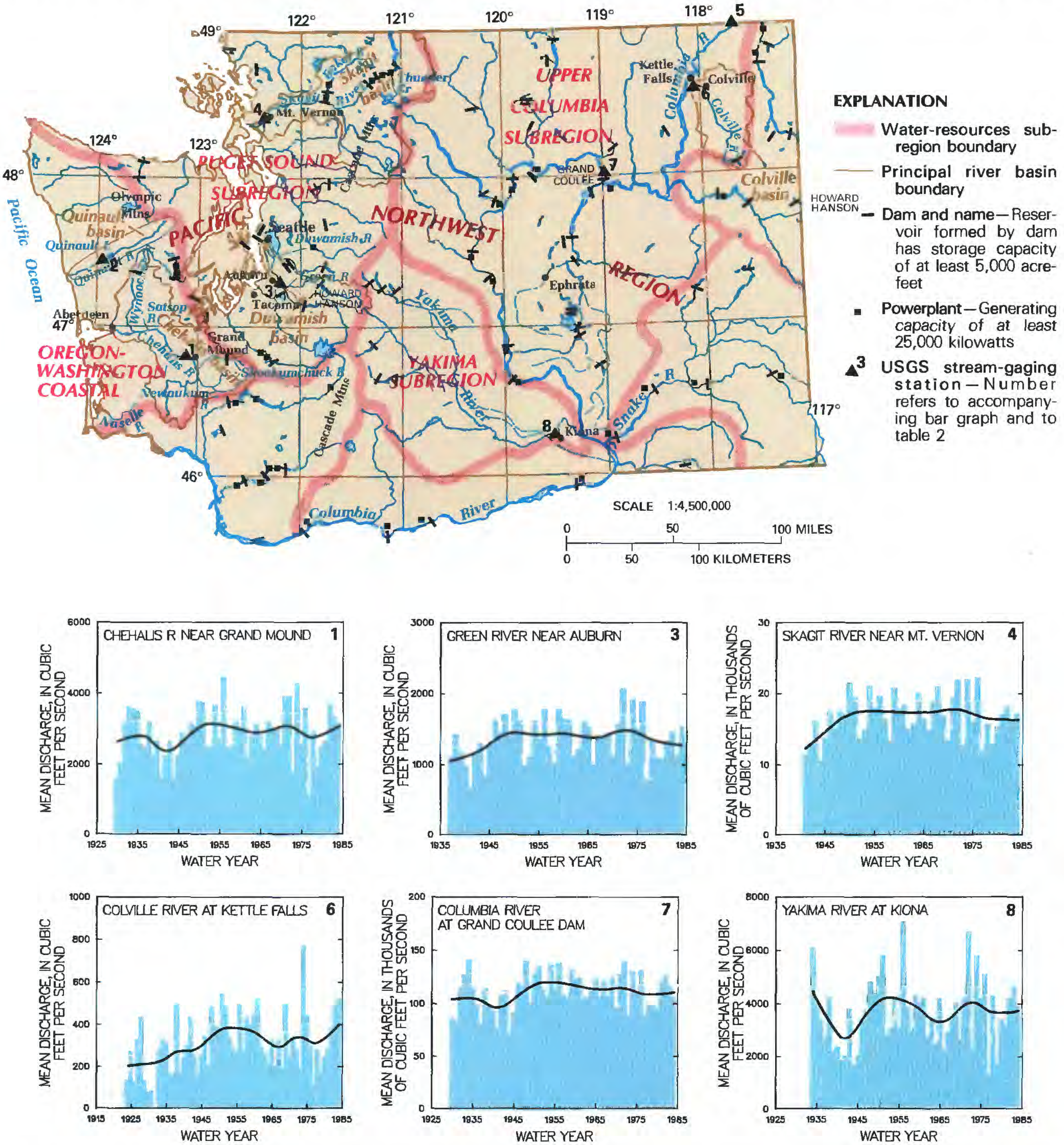


Figure 2. Principal river basins and related surface-water resources development in Washington and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

tion. When a stream is closed, no further water rights will be issued during the period of closure. Normally, closures are necessary only for the low-flow period of the year.

The protection of surface-water quality is the responsibility of both WDOE and DSHS. Under Chapter 90.48 of the RCW, WDOE has been designated the State water-pollution-control agency and is responsible for administering the Federal Clean Water Act. 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 and onsite sewage systems.

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Prepared by J. R. Williams

WEST VIRGINIA
Surface-Water Resources

West Virginia has abundant surface-water resources. Surface water supplies approximately 96 percent of freshwater used in the State and is the source of supply for about 47 percent of the population. The estimated available supply is 63,000 Mgal/d (million gallons per day) or 97,500 ft^3/s (cubic feet per second) of which less than 9 percent is withdrawn for offstream uses. Of the water withdrawn, less than 10 percent is consumed and not available for reuse (Lessing, 1982). In 1980, 98 percent of offstream withdrawals were for industrial use (5,300 Mgal/d or 8,200 ft^3/s), and most of the remaining 2 percent was for public supply (130 Mgal/d or 201 ft^3/s). Principal instream use of surface water is for hydroelectric power generation (21,000 Mgal/d or 32,500 ft^3/s). Surface-water withdrawals in West Virginia in 1980 for various purposes and related statistics are given in table 1.

Surface-water issues of greatest concern for State and local officials and for citizens of West Virginia include water-quality degradation, low flows of unregulated streams, and flooding. In general, surface-water quality is suitable for most uses; however, local reaches of some rivers in the State are contaminated by point and nonpoint discharges from manufacturing plants, municipal wastewater plants, coal mines, farms, areas of silviculture, and construction sites. Most streams in West Virginia do not provide a dependable water supply, and reservoir storage is necessary to contain runoff so that low flows may be augmented during the dry season. Flooding along the flat, narrow valley floors where most homes and businesses are built is a major problem, particularly along small, unregulated streams.

GENERAL SETTING

West Virginia is divided into three physiographic provinces, each with distinctive rock types and drainage patterns (fig. 1). The western and central parts of the State are in the Appalachian Plateaus province. The consolidated, mostly noncarbonate sedimentary rocks that underlie this area have been eroded by streams and rivers to form steep hills and deeply incised valleys. Surface-drainage patterns are dendritic and surface- and ground-water drainage divides, which generally coincide, are well defined. The eastern part of the State, except for the extreme eastern tip, is in the Valley and Ridge province. The consolidated noncarbonate and carbonate sedimentary rocks that underlie the area form a series of broad northeast-trending valleys and ridges. Surface drainage typically forms a trellis pattern. Surface-and ground-water drainage divides coincide and are clearly defined in noncarbonate areas, but are generally not clearly defined and do not coincide with surface drainage divides in carbonate areas. The Blue Ridge province includes only a very small area along the easternmost part of the State.

There is a significant orographic effect on the geographic distribution of precipitation in the State. Average annual precipitation increases from 40 inches along the western boundary of the State eastward to about 60 inches in the higher elevations in the mountainous east-central part of the State. On the eastern side of the mountains, a well-defined rain shadow reduces average annual precipitation to about 36 inches in the Eastern Panhandle (fig. 1). Precipitation does not exhibit a strong seasonal pattern but is distributed rather uniformly throughout the year. About 60 percent of the annual precipitation occurs from March through August. July is usually the wettest month, whereas September, October, and November are usually the driest. About 50 percent of the precipitation returns to the atmosphere by evapotranspiration. Thunderstorms are frequent during May through July and may produce intense local rainfall and cause severe flooding along unregulated streams.

Table 1. Surface-water facts for West Virginia

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Modified from Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	923
Percentage of total population	47
From public water-supply systems:	
Number (thousands)	921
Percentage of total population	47
From rural self-supplied systems:	
Number (thousands)	2
Percentage of total population	0.1
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	5,600
Surface water (Mgal/d)	5,400
Percentage of total	96
Percentage of total excluding withdrawals for thermoelectric power	80
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	130
Percentage of total surface water	2
Percentage of total public supply	72
Per capita (gal/d)	141
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.1
Percentage of total surface water	<0.1
Percentage of total rural domestic	0.6
Per capita (gal/d)	50
Livestock:	
Surface water (Mgal/d)	6.6
Percentage of total surface water	0.1
Percentage of total livestock	87
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	5,300
Percentage of total surface water	98
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	82
Irrigation withdrawals:	
Surface water (Mgal/d)	1.2
Percentage of total surface water	<0.1
Percentage of total irrigation	92
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	21,000

Runoff in West Virginia varies seasonally and geographically. Average annual runoff ranges from 12 inches in the Eastern Panhandle to about 40 inches in the higher mountainous areas and to about 16 inches in the western and southern parts of the State. The lowest amounts of runoff generally occur from June through November—a period of high evapotranspiration—and the greatest amounts of runoff generally occur from December through May—a period of low evapotranspiration. In the higher mountainous areas, where average annual snowfall accumulations are as much as 200 inches, runoff is significantly affected by spring snowmelt. Only a small part of annual precipitation infiltrates and recharges the ground-water reservoirs. In the noncarbonate, consolidated-rock areas of the State, annual recharge to ground-water reservoirs generally ranges from 2 to 6 inches. In the carbonate-rock areas, annual recharge ranges from 6 to 12 inches (William A. Hobba, U.S. Geological Survey, oral commun., 1985). The mid-1940's and 1960's were periods of reduced runoff, and the mid-1970's was a period of unusually high runoff (fig. 2). These long-term trends in runoff are similar throughout the State.

PRINCIPAL RIVER BASINS

Except for the Eastern Panhandle, which is in the Mid-Atlantic Region, all of West Virginia lies in the Ohio Region (Seaber and others, 1984). The Ohio Region in West Virginia is subdivided into five subregions—Monongahela, Upper Ohio, Kanawha, Big

Sandy–Guyandotte, and Middle Ohio. The Potomac Subregion is the only major basin in the Mid-Atlantic Region in the State (fig. 2). The principal river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

MID-ATLANTIC REGION

Potomac Subregion

The Potomac River drains about 15 percent of the land area in West Virginia or 3,460 mi² (square miles). About 25 percent of the subregion is in West Virginia. The present population in the subregion in West Virginia is about 130,000 (7 percent of the State total). Surface-water use is expanding to meet increasing demands for recreation, industrial and public supply, and irrigation.

The North Branch Potomac and the Potomac Rivers define the northern boundary of the State's Eastern Panhandle; the Potomac flows generally eastward from the Appalachian Plateaus, through the Valley and Ridge, and then through the Blue Ridge physiographic provinces (fig. 1). The South Branch Potomac River is the most important tributary to the Potomac River in West Virginia.

Major industries in the basin consist of coal and limestone mining, lumber and pulpwood harvesting, manufacturing, and canning and farming. The area is relatively rural. Forests cover 62 percent of the area; cropland, 12 percent; pasture, 15 percent; orchards and vineyards, 1 percent; and other land types, 10 percent.

The Stony River Reservoir, completed in 1915 with a controlled storage of 5,200 acre-ft (acre-feet) or 1,690 Mgal (million gallons), is used for water supply. The subregion also includes many small, flood-retarding dams that are used to decrease flood peaks and increase low flows (Hobba and others, 1972).

OHIO REGION

Monongahela Subregion

The Monongahela River drains 7,340 mi² in West Virginia, Pennsylvania, and Maryland. Fifty-seven percent of the subregion is in West Virginia. The Monongahela River is formed by the confluence of the West Fork and the Tygart Valley Rivers; its only major tributary is the Cheat River.

The western part of the subregion is characterized by low rolling hills that are drained by the main stem of the Monongahela and its tributaries. The eastern part is mountainous and is drained by the Cheat River (fig. 2). Except for the narrow flood plains along the major streams, very little land is flat. The major industries in the basin include coal mining; production of glass and pottery, cement, limestone, charcoal, and construction stone; timber; agriculture; and power generation.

Tygart Dam, completed in 1938 with a storage capacity of 285,000 acre-ft or 92,900 Mgal, is the only major flood-control dam in the basin (fig. 2). The full length of the Monongahela River is navigable for barge transportation through a system of locks and dams. Most of the river freight consists of coal, limestone, sand, and gravel.

The water available in the basin is adequate to meet present water-use needs and anticipated future demands. Only about 10 percent (4,800 Mgal/d or 7,430 ft³/s) of the average annual flow from the basin in West Virginia is withdrawn for offstream uses. However, water shortages occur in some areas that rely on relatively small streams for the principal water source. The 7-day, 10-year low flows range from 0.14 (ft³/s)/mi² (cubic feet per second per square mile) in the eastern part of the basin to zero in the western part (Friel and others, 1967).

A problem of major concern is the chemical quality of surface water. Many streams are acidic and highly mineralized because of drainage from coal-mining areas. Some local drainageways have become contaminated from industrial and municipal wastes.

Upper Ohio Subregion

Approximately one-third of the subregion (4,150 mi²) is in West Virginia; it extends from the tip of the Northern Panhandle to the Kanawha River basin (fig. 2). The principal river in the West Virginia part of the subregion is the Little Kanawha River.

The area along the Ohio River and lower reach of the Little Kanawha River is comprised of broad lowlands. The uplands are characterized by steep hills and narrow valleys, which are typical of the maturely dissected Appalachian Plateaus.

The Northern Panhandle and parts of the Little Kanawha basin are heavily mined for coal. The lowlands along the river are heavily urbanized and industrialized. Industries include manufacturing of coke, primary metals, metal fabricating, chemicals, and glass products. The Little Kanawha River basin is mostly rural compared to the heavily industrialized Ohio River lowlands. Oil and gas deposits are present almost everywhere throughout the basin.

Average annual runoff increases from 1.1 (ft³/s)/mi² in the western part of the basin to 3.0 (ft³/s)/mi² in the eastern part, primarily because of differences in topography and precipitation. The 7-day, 10-year low flow for the area is only about 0.001 (ft³/s)/mi² in the western part of the subregion (table 2, sites 7 and 8) (Bain and Friel, 1972).

The maximum flood of record on the Little Kanawha River occurred in March 1967 and caused widespread damage and destruction. Its recurrence interval was greater than 50 years. Burnsville Dam on the Little Kanawha, with a controlled storage of 61,700 acre-ft or 20,100 Mgal, was completed in 1978 as a multipurpose reservoir. The reservoir reduces flooding in downstream low-lying areas, increases the recreational potential, and supplements low flows (table 2).

Principal concerns are the potability and dependability of surface-water supplies, even though only a small fraction of the available streamflow is diverted for industry and public supply. Additional surface storage in the basin is needed to collect intermittent runoff and to augment the extremely low flows of drier months, and to improve the chemical quality by dilution.

Kanawha Subregion

The subregion drains 8,420 mi² in West Virginia (about 35 percent of the total land area in the State) and approximately 3,810 mi² in North Carolina and Virginia. The Kanawha River is formed at the confluence of the New and the Gauley Rivers in south-central West Virginia (fig. 2). It flows in a northwesterly direction and empties into the Ohio River. The Kanawha River is West Virginia's largest inland waterway, averaging 600 feet in width, and has an average annual flow of about 16,500 ft³/s or 10,700 Mgal/d.

Major tributaries to the Kanawha are the New, the Coal, the Elk, and the Gauley Rivers. The New River, which extends beyond West Virginia's eastern boundary and drains about 3,770 mi² in North Carolina and Virginia, is the largest tributary to the Kanawha River. The major tributary to the New River in West Virginia is the Greenbrier River (fig. 2).

The eastern part of the subregion lies in the Valley and Ridge physiographic province (fig. 1); the remainder is in the Appalachian Plateaus physiographic province. The only relatively flat areas in the basin are along the Ohio River and near the Kanawha River.

The Kanawha River was used to transport locally mined salt downstream to the "western territories" in 1808. The river has been navigable because of a series of locks and dams that have maintained a minimum pool since the late 1800's. The State's world-famous chemical industry settled in the Kanawha Valley because

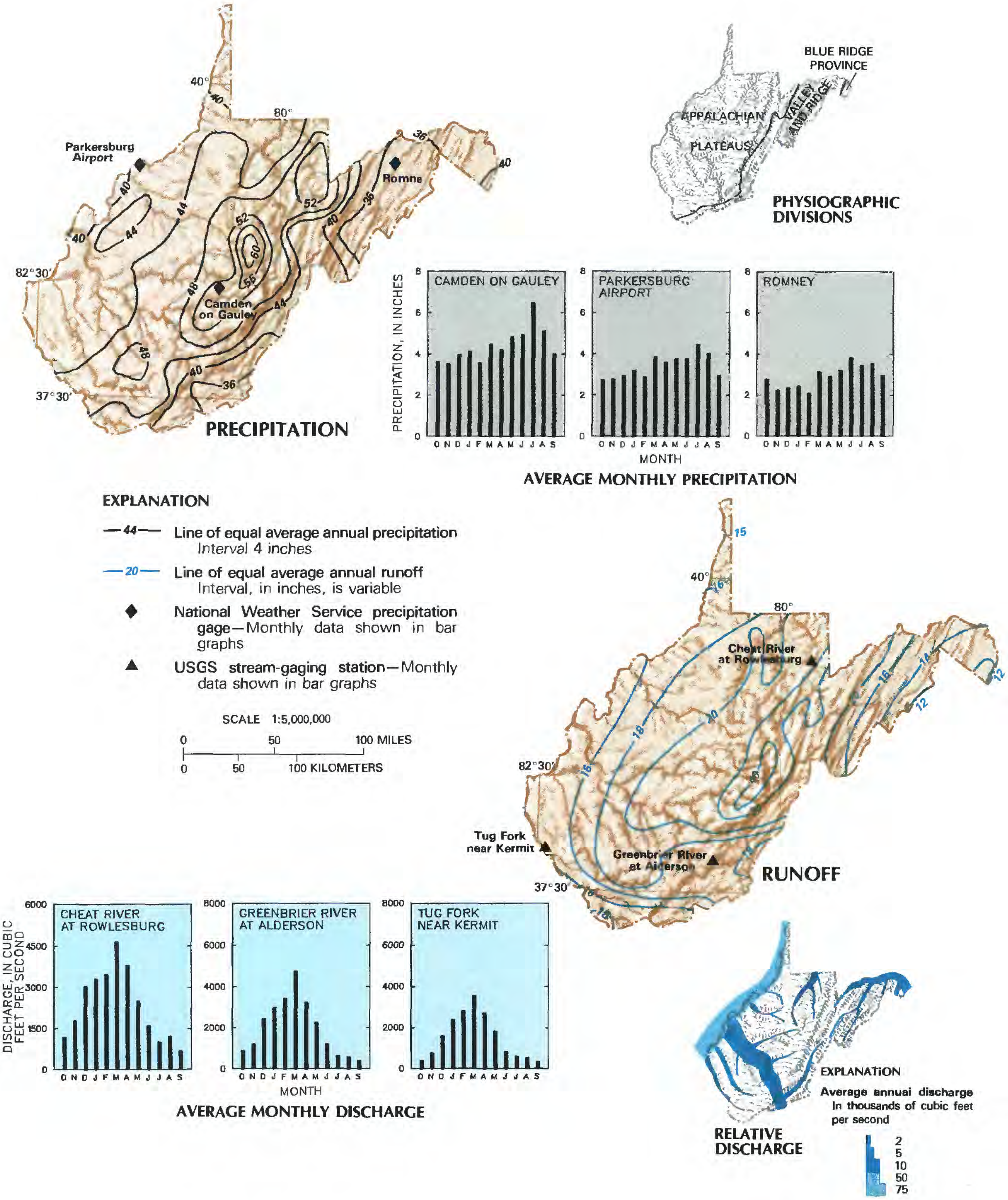

Figure 1. Average annual precipitation and runoff in West Virginia and average monthly data for selected sites, 1951-80.

(Sources: Precipitation modified from annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

of the natural salts, inexpensive river transportation, and coal, oil, and gas energy sources.

About 84 percent of the subregion is forested, 11 percent is used for agriculture, 2 percent is urban, and less than 1 percent is mined. Nearly one-third of the coal produced in West Virginia is mined from the Kanawha subregion.

The Greenbrier River (fig. 2) drains the only major basin in the State that has no coal mining, large factories, or large urban areas. Much of the Greenbrier subbasin is underlain by carbonate rocks.

The Coal and the Greenbrier Rivers are unregulated. The New, the Gauley, and the Elk Rivers are regulated by multipurpose dams and reservoirs that provide flood protection, recreation, and low-flow augmentation. Bluestone Lake on the New River was completed in 1952 and has a controlled storage of 600,100 acre-ft or 196,000 Mgal; Summersville Lake on the Gauley River was completed in 1971 and has a controlled storage of 390,800 acre-ft or 127,000 Mgal; and Sutton Lake on the Elk River was completed in 1961 and has a controlled storage of 261,200 acre-ft or 85,100 Mgal. The New River also is regulated by a reservoir in Virginia.

Table 2. Selected streamflow characteristics of principal river basins in West Virginia

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi^2 = square miles; ft^3/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and West Virginia State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				
	Name and USGS no.	Drainage area (mi^2)	Period of analysis	7-day, 10-year low flow (ft^3/s)	Average discharge (ft^3/s)	100-year flood (ft^3/s)	Degree of regulation	Remarks
				MID-ATLANTIC REGION POTOMAC SUBREGION				
1.	Patterson Creek near Haadsville (01604500).	219	1939–83	2.94	167	18,500	Negligible	Small flood-retarding dams.
2.	South Branch Potomac River near Springfield (01608500).	1,471	1929–83	70.9	1,296	132,000	. . . do . . .	Many small flood-retarding dams.
3.	Opequon Creek near Martinsburg (01616500).	272	1948–83	34.1	227	22,900	None	
				OHIO REGION MONONGAHELA SUBREGION				
4.	Tygart Valley River at Colfax (03057000).	1,366	1940–83	197	2,653	22,900	Appreciable	Flood control, recreation, and low-flow augmentation.
5.	Cheat River at Rowlesburg (03070000).	972	1924–83	38.7	2,274	72,200	None	
6.	*Big Sandy Creek* at Rockville (03070500).	200	1922–83	2.42	417	22,000	. . . do . . .	
				UPPER OHIO SUBREGION				
7.	Wheeling Creek at Elm Grove (03112000).	282	1941–83	0.64	336	27,000	None	
8.	Middle Island Creek at Little (03114500).	458	1929–83	0.51	659	28,000	. . do . . .	
9.	Little Kanawha River at Palestine (03155000).	1,515	1940–78 1979–83	4.10 38.0	2,089 2,287	56,200 51,200	. . . do . . . Appreciable	 Flood control, recreation, and low-flow augmentation.
				KANAWHA SUBREGION				
10.	Greenbrier River at *Alderson* (03183500).	1,364	1896–1983	53.9	1,994	74,500	None	Recreational area.
11.	Kanawha River at Kanawha Falls (03193000).	8,371	1878–1938 1939–83	1,333 1,818	12,700 12,840	318,000 167,000	. . . do . . Appreciable	 Flood control, industrial supply, low-flow augmentation, and power generation
12.	Elk River at Queen Shoals (03197000).	1,145	1929–59 1960–83	6.0 67.2	1,951 2,179	71,800 65,000	None Appreciable	 Flood control, public and industrial supply and recreation.
13.	Coal River at Tornado (03200500).	862	1962–83	13.3	1,233	50,700	None	
				BIG SANDY—GUYANDOTTE AND MIDDLE OHIO SUBREGIONS				
14.	Guyandotte River near Baileysville (03202400).	306	1969–83	33.3	447	50,900	None	
15.	East Fork Twelvepole *Creek near Dunlow* (03206600).	38.5	1965–83	0.07	54.4	5,170	. . . do . . .	
16.	Tug Fork near Kermit (03214000).	1,188	1935–83	40.2	1,414	101,000	. . . do . . .	

Three dams on the Kanawha River main stem maintain a minimum pool depth for barge navigation and generate hydropower (fig. 2).

The effect of Sutton Reservoir on low flows of the Elk River at Queen Shoals (table 2, site 12) can be seen in table 2. The several reservoirs upstream from the Kanawha River at Kanawha Falls (table 2, site 11) also provide major low-flow augmentation to improve the aquatic life in the river and its users in the downstream urbanized and industrialized areas.

Flooding continues to be a major problem in the smaller and unregulated tributaries of the subregion. As the area grows in population and industry, the flood problem worsens in the basin because more of the narrow flood plains are used for housing and industry. Although the quality of water in the Kanawha River main stem has significantly improved in recent years, it is a subject of major concern because the river receives waste from numerous industrial and urban complexes in the Kanawha Valley.

Big Sandy-Guyandotte and Middle Ohio Subregions

The major streams that drain these two subregions are the Big Sandy and the Guyandotte Rivers, and Twelvepole Creek. The Guyandotte River and Twelvepole Creek lie entirely in West Virginia. The Big Sandy, which originates outside West Virginia, drains parts of Kentucky and Virginia; it is formed by the confluence of Levisa Fork and Tug Fork. Tug Fork and the Big Sandy River form the West Virginia-Kentucky State line (fig. 2).

The topography of the subregions is typical of the Appalachian Plateaus. Because of steep land slopes, little development has occurred; forests comprise about 90 percent of the area, and agricultural and urban areas each comprise about 4 percent of the area. The remaining land use is classified as water, wetland, or barren. The basin's major industry is coal mining, which has affected streamflow quantity and quality by offstream diversions

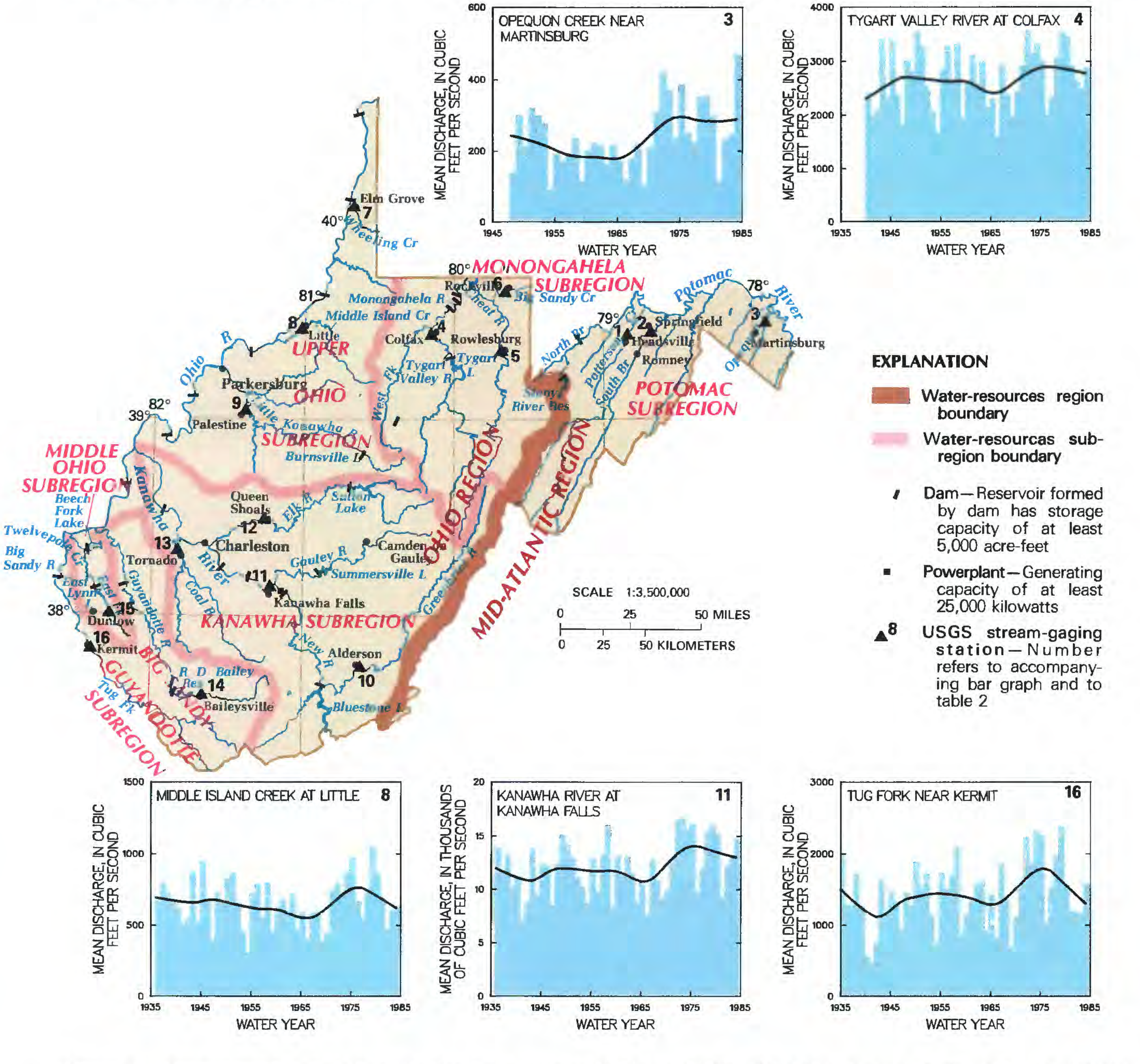

Figure 2. Principal river basins and related surface-water resources development in West Virginia and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

and mine drainage. Approximately 30 percent of the coal produced in West Virginia is mined from these subregions; most of the mining is in the southern half of the area where land slopes are steepest.

Low flow in the subregions is highly variable. The 7-day, 10-year low flow ranges from about 0.01 $(ft^3/s)/mi^2$ in the northwestern part to about 0.1 $(ft^3/s)/mi^2$ in the southern part (table 2, sites 14, 15, and 16). Average annual flows throughout the area range from about 1.3 to 1.5 $(ft^3/s)/mi^2$. The Guyandotte River has been regulated by R. D. Bailey Reservoir, with a controlled storage of 181,700 acre-ft or 59,200 Mgal, since 1980. Twelvepole Creek is regulated by two reservoirs—East Lynn Lake (completed in 1972 with a controlled storage of 70,800 acre-ft or 23,100 Mgal) and Beech Fork Lake (completed in 1977, with a controlled storage of 33,300 acre-ft or 10,800 Mgal). These reservoirs are operated for flood control and recreation. The Tug Fork is unregulated and routinely subject to flooding. The flood of April 1977 on the Tug Fork was the greatest of record, with an estimated recurrence interval greater than 100 years.

Flooding and stream quality are major areas of concern. The major water-quality problem is contamination of many streams by fecal coliform bacteria from human waste that exceeds West Virginia water-quality limits.

Ohio River Main Stem

The Ohio River, which flows through the subregions within the Ohio Region listed in table 2, forms the 277-mile-long Ohio–West Virginia State line, has been used for transportation and navigation since the earliest settlers arrived in the area. By 1929, the Ohio River was controlled by a series of locks and dams that provided a minimum navigation depth. There are seven locks and dams in the Ohio River in West Virginia (fig. 2). The average annual flow of the river is about 40,000 ft^3/s or 25,800 Mgal/d where it enters the State from Pennsylvania. Its average flow is about 80,000 ft^3/s or 51,700 Mgal/d where it leaves West Virginia at the Kentucky State line.

SURFACE-WATER MANAGEMENT

Surface-water resources of West Virginia are managed by public and private agencies. Flow is regulated for navigation, flood control, low-flow augmentation, hydroelectric-power generation, and recreation.

Water law in West Virginia is based on a modification of the riparian doctrine. State organizations, such as the Water Resources Board; the Department of Natural Resources, Division of Water Resources; and the State Department of Health, implement most of the regulatory, planning, and research programs for the protection and management of surface water in the State.

The State Natural Resources law of 1933, as revised by Chapter 133 of the Acts of 1961, created the Water Resources Board and the Division of Water Resources. The Division of Water Resources administers and enforces all laws relating to the conservation, development, protection, and use of the water resources 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.

The U.S. Geological Survey, in cooperation with the West Virginia Department of Natural Resources, Division of Water Resources, and other agencies, 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 surface-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 surface-water resources.

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FOR ADDITIONAL INFORMATION

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WISCONSIN
Surface-Water Resources

Wisconsin is a "water-rich" State that has 33,000 miles of rivers and streams; 14,947 lakes; and coastlines on two of the Great Lakes. In addition, the State contains about two quadrillion (2×10^{15}) gallons of ground water. Streamflow is characterized by high stable base flows and low flood peaks. Surface water provides 5,800 Mgal/d (million gallons per day) or 8,970 ft^3/s (cubic feet per second) or 90 percent of the total water withdrawn for offstream use (table 1). The largest use is for industrial supplies (4,900 Mgal/d or 7,580 ft^3/s) and public supplies (280 Mgal/d or 433 ft^3/s) which served 30 percent of the State's population. Withdrawals for thermoelectric power (4,600 Mgal/d or 7,120 ft^3/s) is the largest industrial use. Ground water provides 51 percent of the public-water supply. Instream use by hydroelectric plants is 71,000 Mgal/d or 110,000 ft^3/s at 72 dams; these plants produce 5 percent of the State's power requirements (Wisconsin Department of Energy, 1984).

The major surface-water issue in the State is the continued preservation of the abundance and excellent quality of the water in light of competing needs of water users. In areas where degradation of water quality has occurred, improvement is a high priority. Acid deposition is a potential threat to some lakes in Wisconsin; 967 of the clearwater lakes in the State are extremely sensitive to damage by acid precipitation.

Table 1. Surface-water facts for Wisconsin

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	1,420
Percentage of total population	30
From public water-supply systems:	
Number (thousands)	1,420
Percentage of total population	30
From rural self-supplied systems:	
Number (thousands)	0
Percentage of total population	0
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	5,800
Surface water only (Mgal/d)	5,200
Percentage of total	90
Percentage of total excluding withdrawals for thermoelectric power	54
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	280
Percentage of total surface water	5
Percentage of total public supply	49
Per capita (gal/d)	197
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0
Percentage of total surface water	0
Percentage of total rural domestic	0
Per capita (gal/d)	0
Livestock:	
Surface water (Mgal/d)	3.0
Percentage of total surface water	<0.1
Percentage of total livestock	4
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	4,900
Percentage of total surface water	94
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	98
Excluding withdrawals for thermoelectric power	78
Irrigation withdrawals:	
Surface water (Mgal/d)	3.0
Percentage of total surface water	<0.1
Percentage of total irrigation	4
INSTREAM USE,1980	
Hydroelectric power (Mgal/d)	71,000

GENERAL SETTING

Wisconsin is located in the Central Lowland and Superior Upland physiographic provinces (fig. 1). The area drained by the Mississippi River includes parts of the Central Lowland and Superior Upland provinces. The area drained by Lake Michigan is mainly in the Central Lowland province, with a small area in the Superior Upland province. The area drained by Lake Superior is entirely within the Superior Upland province.

The topography of Wisconsin was shaped by glaciers, except for the "Driftless Area" in the southwest. The glaciers created many kettles and potholes that formed the 14,947 lakes in the State.

Average annual precipitation in Wisconsin is generally about 32 inches, ranging from about 36 inches in the north to about 28 inches in the Green Bay area (fig. 1). Precipitation is greatest in June, July, and August and least in January and February. About 66 percent of the precipitation occurs during the growing season (May through October). Average seasonal snowfall (November through March) ranges from 40 inches in the southwest to 110 inches in the north-central part of the State. Average annual evaporation ranges from 28 inches in the northeast to 40 inches in the southwest; about 75 percent occurs during the growing season.

Runoff in the State is fairly uniform and ranges from an annual minimum of 6 inches in the west to about 14 inches in the north (fig. 1). Maximum runoff occurs during the snowmelt period of March or April in the south and in April in the north, and from thunderstorms in the months of May through August. The minimum runoff periods generally occur in August through September, but some northern streams have minimum runoff during January through February when most of the precipitation is in the form of snow and little or no melting occurs. Runoff patterns are significantly affected by the numerous lakes and wetlands in the glaciated parts of the State.

PRINCIPAL RIVER BASINS

The rivers in Wisconsin are in the Upper Mississippi Region and the Great Lakes Region (Seaber and others, 1984) (fig. 2). The Upper Mississippi Region includes five major subregions: St. Croix, Chippewa, Upper Mississippi-Black-Root, Wisconsin, and Rock; and parts of three other subregions that have larger drainage areas in surrounding States. The Great Lakes Region in Wisconsin is divided into three major subregions: Western Lake Superior, Southwestern Lake Michigan, and Northwestern Lake Michigan. These river basins are described below; their location, and long-term variations in streamflow at representative gaging stations, are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2. The significant droughts of 1931, 1934, 1958, 1964, and 1976 are evident on the graphs by the much lower annual discharge values.

UPPER MISSISSIPPI REGION
St. Croix Subregion

The St. Croix River in northwestern Wisconsin forms the border between Wisconsin and Minnesota for much of its length. It has a drainage area of 8,570 mi² (square miles). The total length of the St. Croix River is about 160 miles; principal tributaries in

Wisconsin are the Namekagon, the Clam, the Apple, the Willow, and the Kinnickinnic Rivers. Streamflow in the basin generally is characterized by high stable base flows and low flood peaks because of the highly permeable soils and the numerous wetlands and lakes. Flooding generally is not a problem in the basin; peak runoff events usually occur in the spring as a result of snowmelt.

Approximately 250 miles of the St. Croix and the Namekagon Rivers became part of the National Wild and Scenic Riverways System in 1968. The river system is extensively used for recreation over its entire length; canoeing, whitewater rafting, boating, fishing, and swimming are the most common uses.

The two main withdrawal uses of surface water are for cranberry culture and stock watering. Most of the water used for cranberry culture is for frost protection and harvesting and is nonconsumptive. Hydroelectric-power generation is the main instream use; power is generated at 13 hydroelectric plants in the basin.

The major water issue in the basin is the continued preservation of the excellent quality of the water. Although the basin is not presently threatened by development, conflicts sometimes arise between the needs of recreational users and the needs to preserve fish and wildlife habitat, hydroelectric-power generation, and irrigation.

Chippewa Subregion

The Chippewa River in northwestern Wisconsin extends 175 miles from its headwaters near the Michigan border to the Mississippi River. The drainage area is 9,435 mi^2 or 17 percent of the State. The principal tributaries are the Flambeau River and the Red Cedar River. The headwaters area of the basin has many lakes and wetlands, whereas the middle reach of the river is characterized by numerous rapids and several falls.

Most surface water withdrawn in the basin is for industrial use (72 percent)—primarily by four papermills. The next largest withdrawal (21 percent) is for irrigation. Stock watering accounts for the remainder of surface-water withdrawals (7 percent). The major instream use of water in the basin is hydroelectric-power generation at 23 plants.

Management of the surface waters in the basin for fish and wildlife habitat and recreation is extremely important because the area derives great economic gain from tourism. Recreational uses include boating, fishing, and swimming on the numerous lakes, flowages, and streams. Many of the streams are well known for whitewater canoeing and kayaking.

The major water issue in the basin is preservation of the water quality. Conflicts arise between the need to generate hydroelectric power and the needs of recreational users on large reservoirs in the basin, the most notable of which is Lake Chippewa, which was completed in 1923 with 230,000 acre-ft (acre-feet) or 75,000 Mgal (million gallons) of storage. This reservoir provides water for power generation and downstream industrial use and is well known for its excellent fishing.

Flow on the principal rivers is highly regulated by five upstream storage reservoirs that have a combined storage capacity of more than 470,000 acre-ft or 153,000 Mgal. Storage in the numerous wetlands and lakes in the headwaters area also stabilize flow. The effect of the droughts on streamflow, in particular during the 1930's, is illustrated in figure 2 where the annual discharge of the Chippewa River at Chippewa Falls is much lower than the average for this period.

Upper Mississippi-Black-Root Subregion

This subregion is located in west-central Wisconsin and includes two principal rivers—the Trempealeau River and the Black River. The Trempealeau River has a length of about 75 miles, and the Black River, about 125 miles. The Mississippi River forms the southwestern boundary of the basin and meanders within a broad valley between bluffs several hundred feet high. The profile of the river is shaped by a series of pools behind low-head navigation dams that provide a 9-foot-deep navigation channel.

The topography in the upper part of the Black River ranges from rolling terrain with thin soil cover (which increases runoff) to large wetland areas (where evapotranspiration reduces runoff). Topographic variations are responsible for some of the lowest low flows and highest flood discharges in the State (fig. 2). As shown in table 2, the Black River at Neillsville (site 3) has a 7-day, 10-year low flow of 7.5 ft^3/s or 4.8 Mgal/d and a 100-year flood of 39,000 ft^3/s or 25,200 Mgal/d.

Water required to cool three thermonuclear powerplants is the largest use of water in the basin on the Mississippi River (210 Mgal/d or 325 ft^3/s); these plants produce 2.29 billion kilowatt-hours of electricity. This withdrawal represents 96 percent of the surface-water withdrawals in the basin. The water withdrawn is returned to the river, which increases stream temperature.

Fish and wildlife habitat and recreation are important uses of surface water in the basin. Much of the Mississippi River consists of a series of national fish and wildlife refuges. The pools behind navigation dams on the Mississippi form large water bodies that are used extensively for swimming, boating, fishing, and hunting. A major water issue is prevention of water-quality degradation of the Mississippi River.

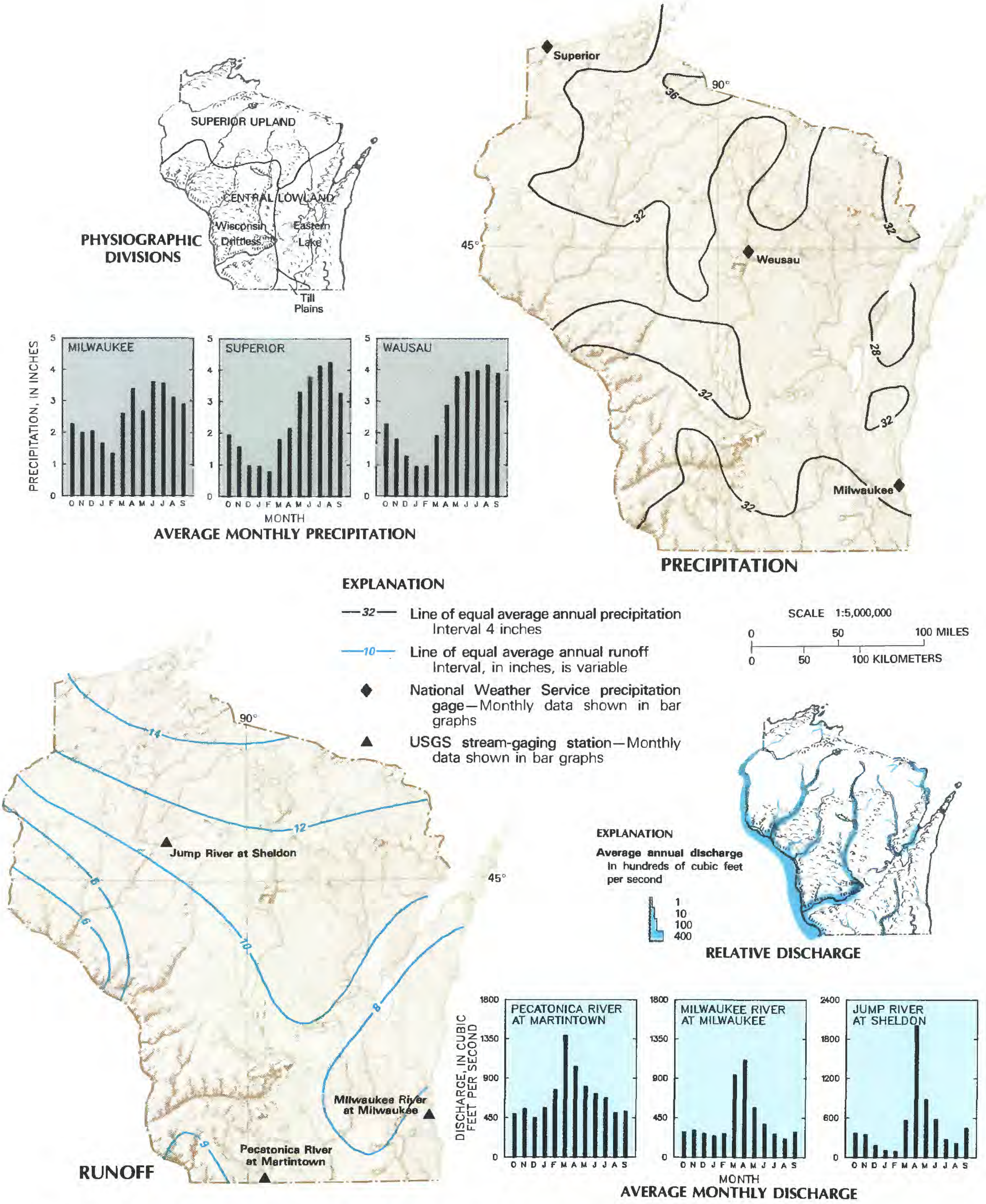

Figure 1. Average annual precipitation and runoff in Wisconsin and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from unpublished map compiled by D. A. Olson, National Oceanic and Atmospheric Administration (NOAA); monthly data from NOAA files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

Table 2. Selected streamflow characteristics of principal river basins in Wisconsin

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do. = ditto; mi² = square miles; ft³/s = cubic feet per second. Sources: Reports of the U.S. Geological Survey and Wisconsin State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	UPPER MISSISSIPPI REGION St. Croix Subregion							
1.	St. Croix River at St. Croix Falls (05340500).	6,240	1902–85	1,080	4,235	58,300	Negligible	Good quality, colored with very little pollution. Occasional flooding.
	Chippewa Subregion							
2.	Chippewa River at Chippewa Falls (05365500).	5,650	1888–1983	798	5,134	92,000	Appreciable	Generally good quality, highly colored. Some local pollution. Occasional flooding.
	Upper Mississippi—Black—Root Subregion							
3.	Black River at Naillsville (05381000).	749	1905–09, 1913–85	6.6	593	39,300	None	Good quality, some local pollution. Highly variable flow with some flooding.
	Wisconsin Subregion							
4.	Wisconsin River at Merrill (05395000).	2,760	1902–85	775	2,681	31,700	Appreciable	Generally good quality. Some reaches have degradation in quality from papermill and municipal waste discharges.
5.	Wisconsin River at Muscoda (05407000).	10,400	1913–85	2,790	8,662	80,400	. . . do . . .	Fair quality. Minor pollution from waste discharges. Flooding problems in Portage area.
	Rock Subregion							
6.	Rock River at Afton (05430500).	3,340	1914–85	200	1,800	14,700	Negligible	Generally good quality. Some degradation in quality by waste discharges. Flooding is a problem in lower reaches.
7.	Pecatonica River at Martintown (05434500).	1,034	1939–85	170	714	18,600	None	Good quality, little pollution. Flooding problems for several communities.
	GREAT LAKES REGION Western Lake Superior Subregion							
8.	Bad River near Odanah (04027000).	597	1914–22, 1948–85	65	620	22,100	None	Good quality, very littel pollution. Occasional flooding.
	Southwestern Lake Michigan Subregion							
9.	Milwaukee River at Milwaukee (04087000).	696	1914–85	24	411	14,000	Negligible	Fair to poor quality. Severe pollution problem in Milwaukee Harbor.
	Northwestern Lake Michigan Subregion							
10.	Peshtigo River at Peshtigo (04069500).	1,080	1953–83	211	1,240	9,790	Negligible	Generally good quality, very hard, some degradation from pollution.
11.	Fox River at Rapide Croche Dam near Wrightstown (04084500).	6,010	1898–1985	950	4,200	27,200	. . . do . . .	Generally poor quality in lower reach. Significant degradation in the past from waste discharge.
12.	Wolf River at New London (04079000).	2,260	1896–1985	466	1,740	17,100	. . . do . . .	Generally good quality. Frequent flooding problems for some communities.

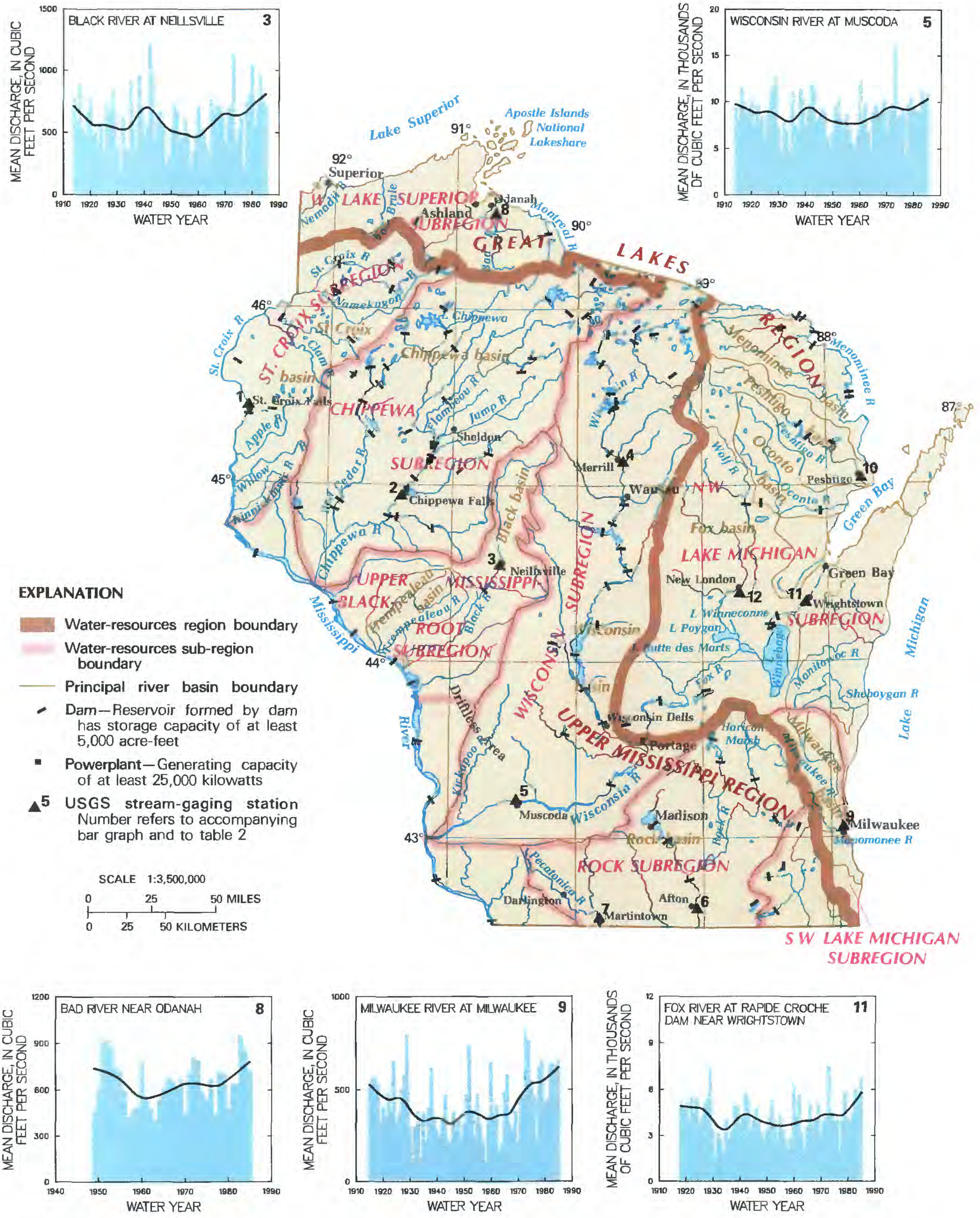

Figure 2. Principal river basins and related surface-water resources development in Wisconsin and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

Wisconsin Subregion

The Wisconsin River is the principal river in the State; it is the largest, the longest, and has the highest average discharge. It extends 440 miles from its headwaters at the Michigan border to its mouth at the Mississippi River. The drainage area is 11,560 mi² or 21 percent of the State. The area has one of the largest concentrations of lakes in the world; two counties contain 2,500 lakes.

The Wisconsin River has earned the local reputation of being "the hardest working river" (Copley, 1952) because of the use and reuse of its waters. Streamflow is regulated by 21 reservoirs and by many hydroelectric dams in the northern- and central-Wisconsin part of the basin; their total storage capacity is 400,000 acre-ft or 130,000 Mgal. The river is used for hydroelectric-power generation at 30 powerplants and by 15 papermills. In addition, the river provides opportunities for fishing, swimming, boating, canoeing, and waterfowl hunting.

The flow of the river is highly regulated by the large system of reservoirs that are owned and operated by the Wisconsin Valley Improvement Company—a privately chartered company that develops and controls the water resources of the river (Electric World, 1948). Although the main purpose of this company is to control the river for power production, the operation of the system has significant effect on reducing the severity of floods (Krug and House, 1980). The average annual flood peak was lowered by 20 percent and the 100-year flood peak by about 10 percent at Wisconsin Dells.

Flooding has been a problem on the Wisconsin River at Portage where, at times, the dikes have nearly been overtopped. Major flood discharges of record since 1935 were: 64,600 ft³/s or 41,800 Mgal/d on March 27, 1935; 72,200 ft³/s or 46,700 Mgal/d on Sept. 14, 1938; 61,700 ft³/s or 39,900 Mgal/d on April 11, 1951; 63,300 ft³/s or 40,900 Mgal/d on May 10, 1960, and 62,600 ft³/s or 40,500 Mgal/d on March 16, 1973. In addition, several communities have a history of serious flooding on the Kickapoo River—a tributary to the Wisconsin River.

The major water issue in the basin is the preservation and, in some reaches, improvement of water quality. The effect of acid precipitation is an extremely important issue because the basin contains most of the 967 clearwater lakes in the State that are extremely sensitive to damage by acid precipitation (0 to 40 microequivalents per liter of alkalinity). The basin is economically dependent on papermills and tourism, which, at times, can produce competing needs for use and regulation of the stream. In the lower reaches of the Wisconsin River, mercury from industrial waste discharges has been found in fish tissue. Considerable controversy developed after the construction of a flood-control dam on the Kickapoo River by the U.S. Army Corps of Engineers was stopped just before completion because a study showed that the lake formed by the dam would become eutrophic in a short time.

Rock Subregion

The Rock River is located in southern Wisconsin and extends about 330 miles from its headwaters in central Wisconsin to the Wisconsin–Illinois State line. The basin has a rolling landscape and a large number of wetlands and lakes. The most notable wetland is the 30,000-acre Horicon Marsh in the headwaters area of the river. The marsh is owned and operated by the U.S. Fish and Wildlife Service and by the Wisconsin Department of Natural Resources. The marsh is on a major flyway and provides refuge for large numbers of migrating geese and habitat for nesting ducks. The large number of wetlands and lakes affects the streamflow. Evapotranspiration in the wetlands significantly reduces low flow in many reaches of the Rock River, and storage or detention of runoff by the wetlands reduces flood peaks (fig. 1).

A major tributary to the Rock River is the Pecatonica River, which flows out of the "Driftless Area" of southwestern Wisconsin. Flooding is a problem for communities along the Pecatonica River Valley. The maximum discharge of record (1939–85) for the Pecatonica River at Darlington is 22,000 ft³/s or 14,200 Mgal/d on July 16, 1950, which is a unit discharge of about 80 (ft³/s)/mi² (cubic feet per second per square mile), as compared to the Rock River at Afton which has a maximum unit discharge of about 4 (ft³/s)/mi².

GREAT LAKES REGION

Western Lake Superior Subregion

This subregion extends from the Minnesota border along Lake Superior to the Michigan border. Most streams are smaller than in other subregions; the most predominant are the Nemadji, the Bois Brule, the Bad, and the Montreal Rivers.

Lake Superior, many inland lakes and numerous streams, and the Apostle Island National Lakeshore in the subregion provide abundant recreational opportunities. Many of the streams are used by migratory trout from Lake Superior.

The largest withdrawal use of water is for cooling at thermoelectric powerplants at Ashland and Superior. The water used for these plants is obtained from Lake Superior.

Areal variation in streamflow in the basin is significant. Streams such as the Bois Brule have very high stable base flow and low flood peaks, primarily because of the permeable soils and thick outwash deposits that mantle the area. Discharges of other streams, such as the Bad River (fig. 2, site 8), are not dependable during droughts and flood peaks tend to be comparatively high. This is caused by much less permeable soils and very little ground-water storage.

Southwestern Lake Michigan Subregion

The Southwestern Lake Michigan Subregion extends from Illinois along the Lake Michigan shoreline to Milwaukee and includes the Milwaukee River. The Milwaukee River is the largest stream in southeastern Wisconsin in size and importance. Its headwaters are in a morainal area that contains numerous kettle lakes and wetlands. The river flows through rolling, largely agricultural, rural landscape, which contains many small communities. It passes through Milwaukee and joins with the Menomonee and the Kinnickinnic Rivers and enters Lake Michigan at the Milwaukee Harbor.

Because the basin is heavily developed in the rural and urban areas, it has some of the more serious water-quality problems in the State. In the past, serious degradation of water quality occurred downstream of numerous sewage-treatment plants and outfalls from milk and cheese factories on the Milwaukee River. Most pollution from these point sources has been eliminated by building and upgrading sewage-treatment plants. Nonpoint sources, such as agricultural runoff in rural areas and street runoff in urban areas, continue to cause water-quality problems in the river and Milwaukee Harbor.

The city of Milwaukee is in the process of separating combined storm and sanitary sewers; this will alleviate the problems caused by the discharge of untreated sewage into the river during storms. In addition, the Wisconsin Department of Natural Resources has made the basin a "priority watershed," which will facilitate implementation of best-management practices to control pollution from rural nonpoint runoff.

Northwestern Lake Michigan Subregion

The Northwestern Lake Michigan Subregion extends from the Milwaukee River along the Lake Michigan shoreline to Michigan. Numerous rivers flow into Lake Michigan, including the Sheboygan, the Manitowoc, the Fox, the Oconto, the Peshtigo, and the Menominee Rivers.

The Fox River and its principal tributary—the Wolf River—are the dominant rivers in the Northwestern Lake Michigan Subregion. The headwaters of the Fox River are in south-central Wisconsin; the river flows northeastward where it combines with the Wolf River, which flows south from northeastern Wisconsin, and then into Lake Winnebago—the largest inland lake in the State. From Lake Winnebago, the Fox River falls about 185 feet in 37 miles to Green Bay; the fall is controlled by 18 navigation locks in this reach.

Water-related recreation is an important resource in the basin. The basin contains numerous lakes and many miles of excellent trout streams. The Wolf River also is well known for its canoeing and whitewater boating.

The basin contains 27 hydroelectric powerplants. Power generation has only a small effect on streamflow because most of the reservoirs are small. However, the Winnebago Pool, which consists of Lake Winnebago, Lake Butte des Morts, Lake Winneconne, and Lake Poygan, has a surface area of 180,000 acres and a storage capacity of 550,000 acre-ft or 179,000 Mgal. Flooding generally is not a problem except at New London, where floods have resulted from spring snowmelt.

The Fox River from Lake Winnebago to Green Bay has had a history of water-quality problems since the early 1900's. Effluent is discharged into this reach from 23 municipal sewage-treatment plants and from 36 industrial outfalls. The lower Fox River is the most industrialized stream in the State. A large number of papermills are located along the river. More than 100 hazardous chemicals have been identified in the lower Fox River, including polychlorinated biphenyls (PCB). Recent additions to sewage-treatment facilities and the requirement for an innovative cluster permit to discharge wastes have improved water quality significantly. A persistent problem is the accumulation of toxic materials and heavy metals in the bottom sediments over the years.

The other major rivers in the basin—the Oconto, the Peshtigo, and the Menominee—all have headwaters in north-central Wisconsin. This predominantly forested area contains numerous lakes and wetlands. Recreational water use, which includes many miles of trout streams and long stretches favorable for canoeing, is of prime importance for all three rivers in the area.

SURFACE-WATER MANAGEMENT

The surface-water resources of Wisconsin are managed by several public agencies and, in some cases, by private agencies. Flow in many rivers is regulated by companies that own and operate hydroelectric powerplants. Regulation of these plants is established by the Wisconsin Department of Natural Resources (WDNR) and by the Federal Energy Regulatory Commission (FERC). Waste-discharge permits and withdrawals of water for irrigation and public supplies also are regulated by WDNR

Wisconsin operates primarily under a riparian doctrine that grants to property owners adjacent to surface waters equal rights for reasonable and beneficial use of those waters. All streams and lakes in Wisconsin are owned by the public or held in trust for public use if they provide recreational benefits.

The U.S. Geological Survey collects hydrologic data and performs research in surface-water flow, occurrence, and water quality in cooperation with local and State agencies and in support of other Federal agencies (U.S. Army Corps of Engineers, U.S. Department of Energy, Federal Emergency Mitigation Agency, and U.S. National Park Service).

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FOR ADDITIONAL INFORMATION

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WYOMING
Surface-Water Resources

Surface water is abundant in some parts of Wyoming and is scarce in other parts (U.S. Geological Survey, 1984a). The mountainous areas of the State receive abundant precipitation, mostly in the form of winter snow; the plains and intermontane basins are semiarid. Most of the surface water in the State is committed under provisions of interstate compacts and court decrees; unused water is allowed to flow to downstream States. Reservoir storage of spring runoff from the mountains is needed to augment low flows during the remainder of the year. Surface water is of suitable quality for most uses in the State. Major surface-water issues in Wyoming include the competition among agriculture, municipalities, and industry for available water, and the need for additional storage facilities.

Perennial streams typify the mountainous areas of the State, whereas ephemeral streams are typical in the plains areas of the State. Most perennial streams in the semiarid plains originate in the mountains. Storage reservoirs regulate flow in many of the perennial streams, such as the Wind, the North Platte, the Green, the Bear, and the Snake Rivers. When available, water is diverted directly from many of the smaller, unregulated streams.

During 1980, about 91 percent—4,800 Mgal/d (million gallons per day) or 7,400 ft³/s (cubic feet per second)—of total freshwater withdrawals for offstream use in Wyoming were from surface-water sources (table 1). Of the water used from surface-water sources, about 94 percent—4,500 Mgal/d or 7,000 ft³/s—was for irrigation. In many areas of the State, surface-water supplies may be fully appropriated or remote from the area of need; therefore, ground water is the important source of supply. Only 1 percent of the withdrawals from surface water was used for public supply during 1980. Instream use accounted for 7,200 Mgal/d or 11,100 ft³/s.

GENERAL SETTING

Wyoming has been divided into five physiographic provinces (fig. 1): The Great Plains, Southern Rocky Mountains, Wyoming Basin, Middle Rocky Mountains, and Northern Rocky Mountains. More than three-fourths of the State consists of semiarid high plains and intermontane basins of the Great Plains, Wyoming Basin, and parts of the Middle Rocky Mountains provinces. Because of the variety of geographic and climatic conditions, surface-water resources differ considerably among these five provinces.

Average annual precipitation varies both geographically and seasonally in Wyoming (fig. 1) because of the diverse topography. Precipitation ranges from about 40 inches in the mountains to about 7 inches in some intermontane basins and some areas of the plains. Most precipitation in the mountains is snow, whereas most precipitation in intermontane basins and on the plains is rain from summer thunderstorms. The plains areas of the State receive the least precipitation during December through February, as seen by the bar graph for Cheyenne (fig. 1).

Much of the precipitation that falls in the State either evaporates or is transpired by vegetation. Average annual evaporation from lakes and reservoirs ranges from 28 inches in the northern mountains to 44 inches on the eastern plains (Geraghty and others, 1973). High evaporation and transpiration rates have a significant effect on storage reservoirs and on the quantity of irrigation water needed to grow various crops.

Runoff patterns in Wyoming vary greatly because of diverse topography and precipitation patterns (fig. 1). Average annual runoff in some mountainous areas exceeds 30 inches. Average annual runoff in much of the eastern plains of the State is less than 0.5 inch; runoff from some areas is less than 0.20 inch. Storage is required to provide dependable water supplies in the semiarid plains.

PRINCIPAL RIVER BASINS

Wyoming streams are in the Missouri, Upper Colorado, Great Basin, and Pacific Northwest Regions. Water in the streams in the Missouri Region eventually flows to the Gulf of Mexico. Water in streams in the Upper Colorado Region and in the Pacific Northwest Region eventually flows to the Pacific Ocean. Drainage in the Great Basin Region is internal and does not reach the sea. About 75.6 percent of the land area of Wyoming is in the Missouri Region; streams in this basin drain 73,680 mi² (square miles). Streams in the Upper Colorado Region drain 17,080 mi² or 17.5 percent of Wyoming. The Snake River in the Pacific Northwest Region drains 5,256 mi² in Wyoming, which is 5.4 percent of the State. The Bear River in the Great Basin Region drains 1,490 mi² or 1.5 percent of the State (Linford, 1975). The principal river basins are described below; their location and long-term variations in streamflow at representative gaging stations are shown in figure 2. Streamflow characteristics and other pertinent information are given in table 2.

Table 1. Surface-water facts for Wyoming

[Data may not add to totals because of independent rounding. Mgal/d = million gallons per day; gal/d = gallons per day; < = less than. Source: Solley, Chase, and Mann, 1983]

POPULATION SERVED BY SURFACE WATER, 1980	
Number (thousands)	215
Percentage of total population	46
From public water-supply systems:	
Number (thousands)	200
Percentage of total population	42
From rural self-supplied systems:	
Number (thousands)	15
Percentage of total population	3
OFFSTREAM USE, 1980	
FRESHWATER WITHDRAWALS	
Surface water and ground water, total (Mgal/d)	5,300
Surface water only (Mgal/d)	4,800
Percentage of total	91
Percentage of total excluding withdrawals for thermoelectric power	90
Category of use	
Public-supply withdrawals:	
Surface water (Mgal/d)	55
Percentage of total surface water	1
Percentage of total public supply	67
Per capita (gal/d)	275
Rural-supply withdrawals:	
Domestic:	
Surface water (Mgal/d)	0.8
Percentage of total surface water	<0.1
Percentage of total rural domestic	8
Per capita (gal/d)	53
Livestock:	
Surface water (Mgal/d)	12
Percentage of total surface water	0.2
Percentage of total livestock	79
Industrial self-supplied withdrawals:	
Surface water (Mgal/d)	270
Percentage of total surface water	6
Percentage of total industrial self-supplied:	
Including withdrawals for thermoelectric power	66
Excluding withdrawals for thermoelectric power	24
Irrigation withdrawals:	
Surface water (Mgal/d)	4,500
Percentage of total surface water	94
Percentage of total irrigation	92
INSTREAM USE, 1980	
Hydroelectric power (Mgal/d)	7,200

MISSOURI REGION
Upper Yellowstone Subregion

The headwaters of the Yellowstone River are in northwestern Wyoming. The Yellowstone River originates in rugged mountains near Yellowstone National Park and flows northerly for approximately 90 river miles before entering Montana (Linford, 1975). The major tributary to the Yellowstone River in this area is Clarks Fork Yellowstone River, which originates in Montana and flows southeasterly into Wyoming before reentering Montana. The population in this basin is very small; however, millions of tourists visit the area each year for recreational purposes.

Bighorn Subregion

The Wind River originates in rugged mountains just south of Yellowstone National Park and flows southeastward to Riverton (fig. 2). Near Riverton, it changes direction and flows northward through the Wind River Canyon, where the name changes to the Bighorn River, which flows into Montana. The Wind-Bighorn River drains parts of four different ranges of the Rocky Mountains, yet it flows through one of the most arid areas of the State. Boysen Reservoir (completed in 1951), north of Riverton on the Wind River, has a storage capacity of 802,000 acre-ft (acre-feet) or 261,000 Mgal (million gallons) and is used for irrigation, hydroelectric-power generation, and flood control.

Irrigation is the major use of surface water in the Bighorn River basin; about 510,000 acres are irrigated (Wyoming State Engineer, 1974). The average annual flow of the Wind River at Riverton is affected by considerable quantities of water diverted for irrigation and return flow from irrigated lands. Fivemile Creek near Shoshoni (fig. 2, site 3), drains an area irrigated by water diverted primarily from the Wind River upstream from Riverton. The average annual flow of the Bighorn River at Kane (fig. 2, site 4) is affected by storage in Boysen Reservoir, diversions for irrigation, and return flow from irrigated lands.

Most of the population in this basin is centered in small rural communities. The majority of the populace is employed in agriculture, oil and gas production, or tourism.

Powder-Tongue Subregion

The Powder River and the Tongue River are major tributaries to the Yellowstone River (fig. 2). The Powder River originates in central Wyoming and flows northward into Montana. Most of the western tributaries are perennial streams sustained by snowmelt along the eastern side of the Bighorn Mountains, but the eastern tributaries are ephemeral streams originating on the semiarid plains. The Tongue River originates in the scenic Bighorn Mountains and flows northeastward into Montana.

Piney Creek at Ucross (fig. 2, site 5) is typical of streams west of the Powder River. The average annual flow at Ucross reflects the effects of storage in several reservoirs and diversions for irrigation.

The majority of the area in the drainage basin is rangeland; only small areas adjacent to some of the perennial streams are irrigated. Large storage reservoirs for retaining spring runoff have not been constructed; consequently, water supplies during the dry summer months can be meager. Coal-mining and petroleum industries that operate in the basin also compete for the available water.

Only a few small rural communities are scattered throughout the basin. Energy development, tourism, and agriculture provide most jobs for residents of the area.

Cheyenne Subregion

The Cheyenne River basin in northeastern Wyoming is characterized by a lack of adequate surface-water supplies and some of the Nation's largest deposits of surface-minable coal. Most streams in this part of the State are ephemeral or intermittent and do not provide a dependable water supply. The major streams in the area are the Cheyenne River, which drains the area south of the Black Hills and flows eastward into South Dakota, and the Belle Fourche River, which drains areas west and north of the Black Hills and flows northeastward into South Dakota. Beaver Creek near Newcastle (fig. 1) has a flow pattern similar to most streams in the area except most streams have no flow for several months each year. There are usually two distinct periods of runoff. One occurs in the spring when the snow melts on the plains and the second occurs during the summer as a result of thunderstorms.

Coal mining is the largest industry in the area; production is expected to be 122 million tons per year by 1990 (Glass, 1980). Because water to operate coal-fired powerplants is not available, most of the coal is transported out of State. Oil and gas production and uranium mining are other important industries competing for available water.

Irrigation is not a common practice because the water supply is not reliable. Only small areas adjacent to some of the larger streams are irrigated. Keyhole Reservoir (completed in 1951), on the Belle Fourche River, has a storage capacity of 193,800 acre-ft or 63,200 Mgal but is used mainly for irrigation in South Dakota. Cattle and sheep production are the largest agricultural activities in the Cheyenne River basin.

North Platte Subregion

The North Platte River and its tributaries drain most of the southeastern quarter of Wyoming. The river originates in the mountains of Colorado and flows northward into Wyoming to the vicinity of Casper, where it turns southeastward and flows into Nebraska (fig. 2). The flow at the Wyoming-Nebraska State line is regulated by a series of upstream reservoirs on the main stem, the first of which began storing water in 1909. The reservoirs and their completion dates, in downstream order, are Seminoe (1939), Pathfinder (1909), Alcova (1938), Glendo (1957), and Guernsey (1927); they have a combined capacity of 3,052,000 acre-ft or 995,000 Mgal. These reservoirs store snowmelt runoff for later use on irrigated lands in Wyoming and Nebraska.

About 528,000 acres in this drainage basin are irrigated in Wyoming (Wyoming State Engineer, 1974). Major irrigated crops grown in the basin include hay, sugar beets, and corn; nonirrigated lands are used for dryland farming and livestock grazing.

Major tributaries to the North Platte River in Wyoming include the Encampment, the Medicine Bow, the Sweetwater, and the Laramie Rivers. These rivers originate in mountainous regions and have monthly runoff patterns that are similar to the Encampment River at mouth, near Encampment (fig. 1). Peak flows of these streams usually occur in May or June and result from snowmelt.

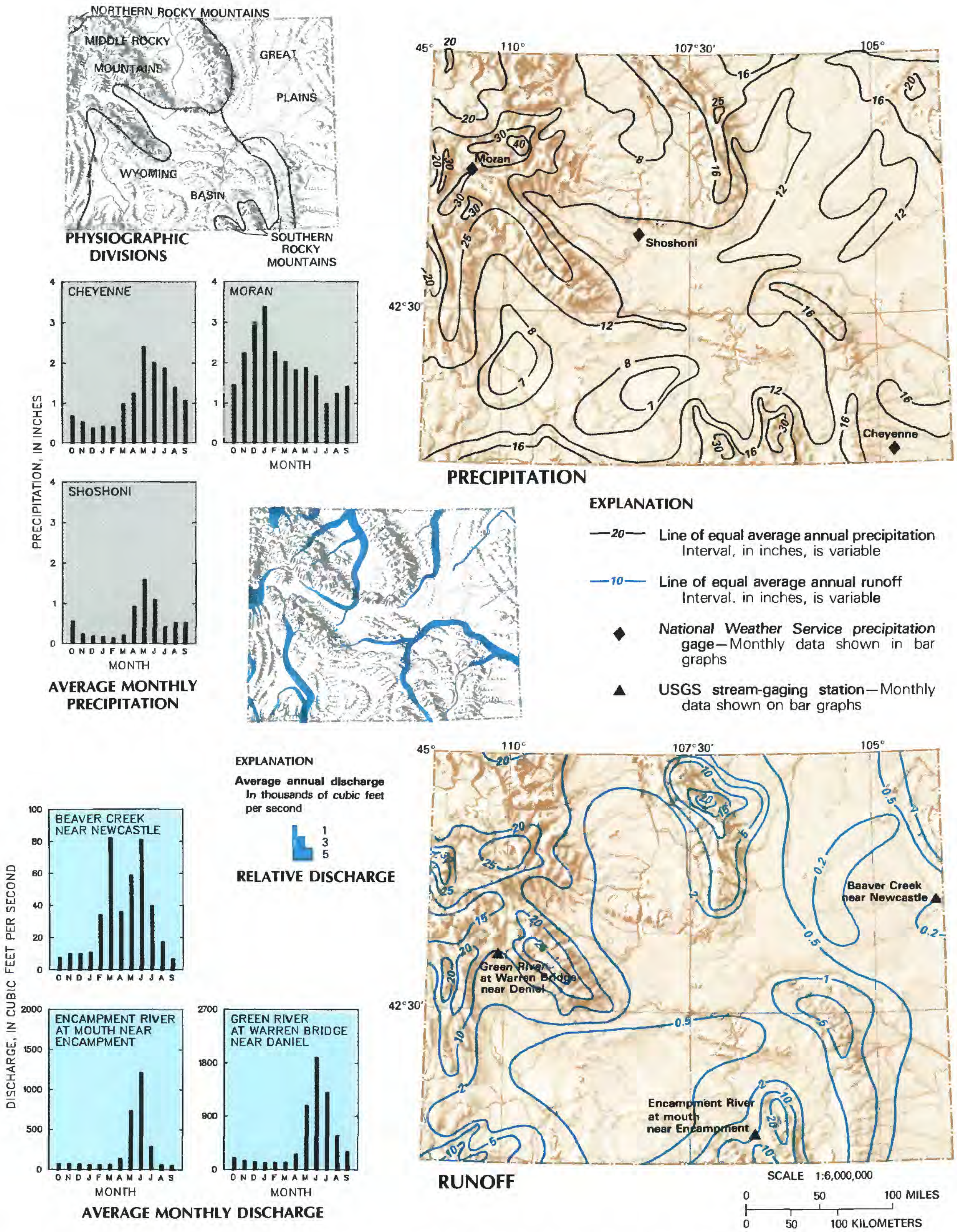
The largest city in the State, Casper, is located in central Wyoming on the North Platte River. Many of the companies that service the mining and mineral industries throughout the State are located in Casper. The other towns in the basin are small rural communities that serve local needs, usually agriculture.

Surface water in the basin is used for other purposes besides irrigation. Several large surface coal mines are in the Medicine Bow River basin. Considerable quantities of uranium have been mined in the Sweetwater River basin. Numerous oil and gas wells are producing in the basin, and hydroelectric power is generated at all of the previously mentioned dams on the North Platte River. Tourism also is important in the area; many mountainous streams are popular fishing streams, and reservoirs on the North Platte River are popular for fishing and boating.

UPPER COLORADO REGION

Great Divide-Upper Green Subregion

The Green River originates in the mountains of west-central Wyoming and flows southward into Utah (fig. 2). The topography of this area is characterized by mountains in the north and west and high plains and plateaus in the central and eastern parts of the basin. The Great Divide basin, which is a hydrologically closed basin with an area of 3,959 mi^2, also is considered part of the Upper Colorado Region. Average annual precipitation in the basin decreases from greater than 30 inches in the mountains to less than 7 inches throughout much of the Great Divide basin and the central part of the Green River basin (fig. 1).



EXPLANATION

—20— Line of equal average annual precipitation
Interval, in inches, is variable

—10— Line of equal average annual runoff
Interval, in inches, is variable

◆ National Weather Service precipitation gage—Monthly data shown in bar graphs

▲ USGS stream-gaging station—Monthly data shown on bar graphs

EXPLANATION

Average annual discharge
In thousands of cubic feet per second

1
3
5

Figure 1. Average annual precipitation and runoff in Wyoming and average monthly data for selected sites, 1951-80.

(Sources: Precipitation—annual data from J.D. Alyea, 1980; monthly data from National Oceanic and Atmospheric Administration files. Runoff—annual data from Gebert, Graczyk, and Krug, 1985. Discharge—monthly- and relative-discharge data from U.S. Geological Survey files. Physiographic diagram from Raisz, 1954; divisions from Fenneman, 1946.)

The Green River in Wyoming is regulated by Fontenelle Reservoir (completed in 1964 with a capacity of 344,800 acre-ft or 112,400 Mgal). The water is used for irrigation, industry, and hydroelectric-power generation. Flaming Gorge Reservoir (completed in 1962 with a capacity 3,789,000 acre-ft or 1,235,000 Mgal), is located astride the Wyoming-Utah State line and regulates the Green River in Utah. Both reservoirs provide excellent fishing and recreational opportunities.

Major tributaries to the Green River include the New Fork River, the Big Sandy River, and Blacks Fork. Most streams draining

Table 2. Selected streamflow characteristics of principal river basins in Wyoming

[Gaging station: Period of analysis is for the water years used to compute average discharge and may differ from that used to compute other streamflow characteristics. Streamflow characteristics: The 7-day, 10-year low flow is a discharge statistic; the lowest mean discharge during 7 consecutive days of a year will be equal to or less than this value, on the average, once every 10 years. The average discharge is the arithmetic average of annual average discharges during the period of analysis. The 100-year flood is that flow that has a 1-percent chance of being equaled or exceeded in a given year. Abbreviations: Do.=ditto; mi²=square miles; ft³/s=cubic feet per second; . . . . =insufficient data or not applicable. Sources: Reports of the U.S. Geological Survey and Wyoming State agencies]

Site no. (see fig. 2)	Gaging station			Streamflow characteristics				Remarks
	Name and USGS no.	Drainage area (mi²)	Period of analysis	7-day, 10-year low flow (ft³/s)	Average discharge (ft³/s)	100-year flood (ft³/s)	Degree of regulation	
	MISSOURI REGION **Upper Yellowstone Subregion**							
1.	Clarks Fork Yellowstone River near Belfry, Mont. (06207500).	1,154	1921-84	87	953	12,600	Negligible	Major water uses are irrigation and recreation.
	Bighorn Subregion							
2.	Wind River at Riverton (06228000).	2,309	1906-84	46	876	13,700	Appreciable	Major water use is for irrigation.
3.	Fivemile Creek near Shoshoni (06253000).	418	1941-42, 1948-83	20	157	4,530	. . . do . . .	Natural flow of stream is greatly effected by irrigation diversions and return flows.
4.	Bighorn River at Kane (06279500).	15,765	1928-84	329	2,285	31,900	. . . do . . .	Major water use is for irrigation.
	Powder-Tongue Subregion							
5.	Pinay Creek at Ucross (06323500).	267	1917-19, 1950-83	2.6	86.9	3,640	Appreciable	Major water use currently is irrigation; potential exists for industrial use.
	Cheyenne Subregion							
6.	Beaver Creek near Newcastle (06394000).	1,320	1945-84	0.05	31.3	8,530	Moderate	Numerous small reservoirs used for watering of livestock.
	North Platte Subregion							
7.	Encampment River at mouth, near Encampment (06625000).	265	1940-84	17	247	4,600	Moderate	Water uses include municipal, industrial, irrigation, and recreation.
8.	North Platte River at Wyoming-Nebraska state line (06674500).	22,218	1929-84	. . . .	2,766	17,700	Appreciable	Major water use is irrigation.
	UPPER COLORADO REGION **Great Divide-Upper Green Subregion**							
9.	Green River at Werren Bridge near Daniel (09188500).	468	1932-84	66	511	5,100	Negligible	Major water uses are irrigation and recreation.
10.	Blacks Fork near Millburna (09218500).	152	1940-84	9.5	163	2,760	Appreciable	Do.
	GREAT BASIN REGION **Bear Subregion**							
11.	Smiths Fork near Bordar (10032000).	165	1942-84	50	200	1,680	Negligible	Water uses include recreation and irrigation.
	PACIFIC NORTHWEST REGION **Upper Snake Subregion**							
12.	Snake River above reservoir near Alpine (13022500).	3,465	1937-39, 1954-84	1,031	4,638	32,200	Moderate	River is popular recreation site.

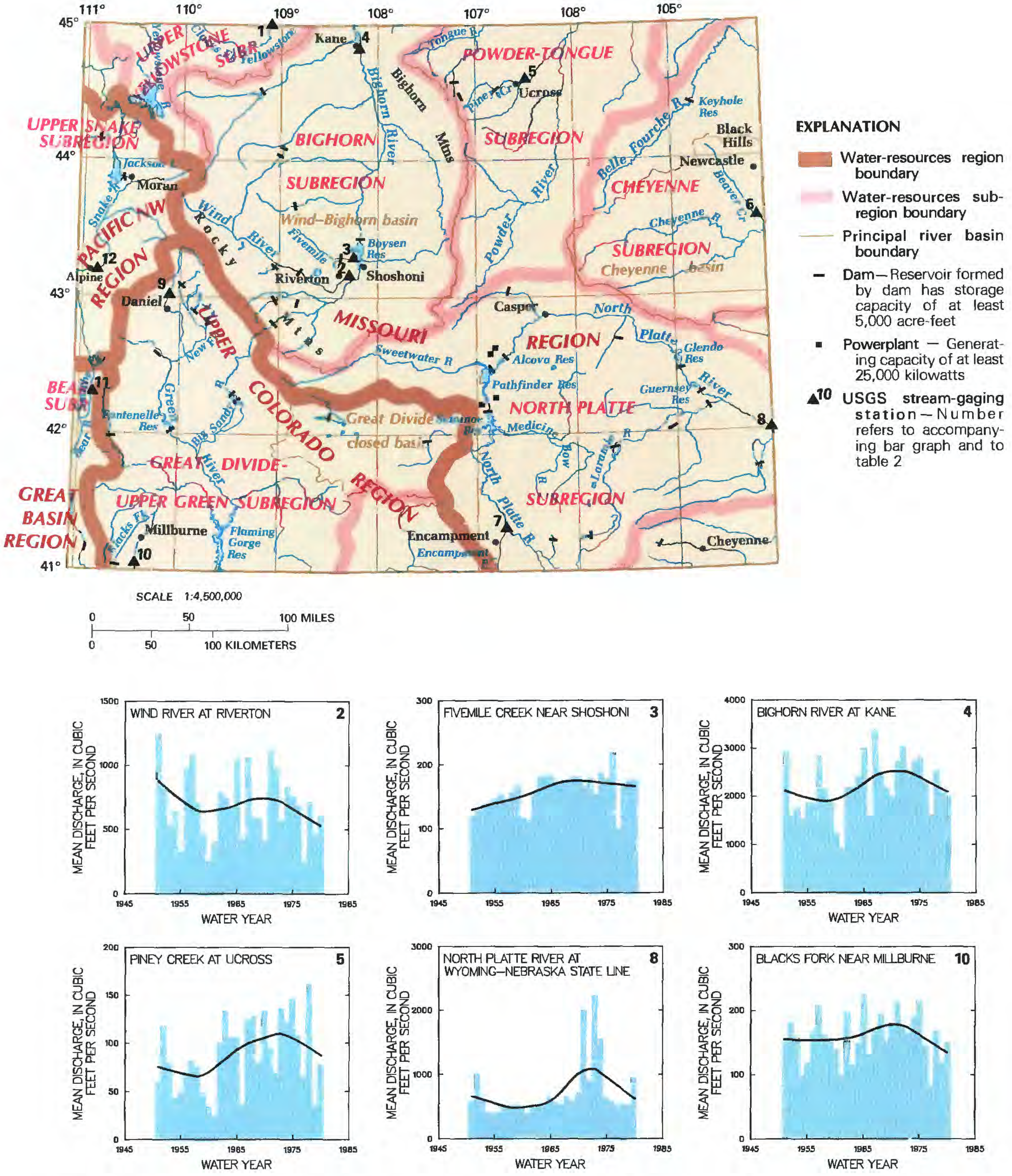


Figure 2. Principal river basins and related surface-water resources development in Wyoming and average discharges for selected sites.

Bar graphs show average discharge by water year at selected stream-gaging sites; the curve is a 15-year weighted moving average of the annual values. (Sources: Water-resources regions and subregions from Seaber and others, 1984; surface-water-resources development from Hitt, 1985; discharge data from U.S. Geological Survey files.)

the mountains in the north and west are perennial, whereas most streams draining the semiarid central and eastern parts of the basin, as well as the Great Divide Basin, are ephemeral.

About 303,000 acres are irrigated by surface water in the Green River basin (Wyoming State Engineer, 1974). Most of the irrigation is adjacent to the perennial streams in areas where snowmelt or storage reservoirs ensure adequate supplies. The primary crops raised on irrigated lands in the basin are forage crops. The average annual flow of Green River (site 9) near the upper end of the basin is 511 ft^3/s or 330 Mgal/d (fig. 1). The average annual flow of Blacks Fork near Millburne is 163 ft^3/s or 105 Mgal/d; this stream has been regulated since 1971 by an upstream reservoir (fig. 2).

Industries in the basin include trona (a mineral) mining, coal mining, oil and gas production, and thermoelectric power generation. The rangelands in the basin are used primarily for raising sheep and cattle.

GREAT BASIN REGION

Bear Subregion

The Bear River originates in the mountains of Utah and enters southwestern Wyoming. It flows northward, crossing the Wyoming-Utah State line several times, before leaving the State and entering Idaho and eventually flowing into Utah (fig. 1). Most of the streams in the basin are perennial and drain mountainous regions that have abundant winter snowfall. Smiths Fork near Border (table 2, site 11) is indicative of the average tributary streamflow in this basin.

Energy exploration and development has caused a large population influx in the basin during the last few years. The rapid population increase has created some issues regarding local water supplies. Irrigation of 54,000 acres (Wyoming State Engineer, 1974) also is a major use of surface water in the area.

PACIFIC NORTHWEST REGION

Upper Snake Subregion

The Snake River originates in the mountains of the southwestern part of Yellowstone National Park. It flows south through Teton National Park before flowing west and entering Idaho (fig. 2). The flow is regulated by Jackson Lake (completed in 1906 with a capacity 847,000 acre-ft or 276,000 Mgal), which is used to store water for irrigation projects in Idaho. The Snake River is the largest river in the State.

Tourism is the major industry in this basin because of the proximity of Yellowstone and Teton National Parks. The many streams and lakes in the basin attract fishermen and outdoor enthusiasts.

SURFACE-WATER MANAGEMENT

Interstate compacts and court decrees specify the quantities of water that must be allowed to flow out of Wyoming for downstream use and that which may be used within Wyoming. Various streams in Wyoming are administered by the Bear River, the Belle Fourche River, the Colorado River, the Upper Colorado River Basin, the Snake River, the Upper Niobrara River, and the Yellowstone River Compacts. The waters in the North Platte River basin are administered under the provisions of a United States Supreme Court decree.

The Wyoming State Engineer is in charge of administering water among and between appropriators under the prior appropriation doctrine. The concept of the prior appropriation doctrine is "first in time is first in right." In 1909, the legislature established preferred uses for Wyoming water. The preferred order is (1) domestic and stock water; (2) water for municipal purposes; (3) water for the use of steam engines and for general railway use, water for culinary, laundry, bathing, refrigeration, steam and hot water heating plants, and steam powerplants; (4) industrial purposes; (5) irrigation; and (6) hydropower (Trelease, 1978).

The U.S. Geological Survey routinely monitors streamflow and reservoirs. It also provides technical assistance to surface-water users in cooperation with several State and Federal agencies.

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GLOSSARY, CONVERSION FACTORS, WATER-RESOURCES REGIONS AND SUBREGIONS, AND STATISTICAL DATA ON MAJOR RIVERS

GLOSSARY

Absorption—Process by which substances in gaseous, liquid, or solid form are assimilated or taken up by other substances.

Acre-foot—Volume of water required to cover 1 acre of land (43,560 square feet) to a depth of 1 foot; equivalent to 325,851 gallons.

Adsorption—Adherence of gas molecules, ions, or molecules in solution to the surface of solids.

Alluvium—General term for deposits of clay, silt, sand, gravel, or other particulate rock material in a streambed, on a flood plain, on a delta, or at the base of a mountain.

Aquiculture—Art and science of farming organisms that live in water, such as fish, shellfish, and algae.

Aquifer—A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

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. The term "average" generally is reserved for average of record and "mean" is used for averages of shorter periods, namely, daily, monthly, or annual mean discharges.

Base flow—Sustained low flow of a stream. In most places, base flow is ground-water inflow to the stream channel.

Bedload—Sediment that moves on or near the streambed and in almost continuous contact with the bed.

Bed material—The sediment composing the streambed.

Bedrock—A general term for consolidated (solid) rock that underlies soils or other unconsolidated material.

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 between 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.

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.

Conjunctive use—Combined use of ground and surface waters.

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. Equivalent to 448.8 gallons per minute.

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.

DCP (Data-Collection Platform)—A radio that is used to transmit environmental data to a satellite relay system.

Discharge (hydraulics)—Rate of flow, especially fluid flow; a volume of fluid passing a point per unit time, commonly expressed as cubic feet per second, million gallons per day, or gallons per minute.

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.

Drainage basin—Land area drained by a river.

Drainage divide—Boundary between one drainage basin and another.

DRGS (Direct Readout Ground Station)—A station that can directly receive environmental data from an earth-orbiting satellite.

Ephemeral Stream—A stream or part of a stream that flows only in direct response to precipitation. It receives little or no water from springs, melting snow, or other sources. Its channel is at all times above the water table.

Eutrophication—The process by which water becomes enriched with plant nutrients, most commonly phosphorus and nitrogen.

Evaporation pan—An open tank used to contain water for measuring the amount of evaporation.

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.

Gage height—*See* Stage.

Gaging station—A site on a stream, canal, lake, or reservoir where systematic observations of gage height or water discharge are obtained by a gage, recorder, or similar equipment.

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.

GOES (Geostationary Operational Environmental Satellite)—A series of meteorological satellites operated by the National Oceanic and Atmospheric Administration.

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.

Hardness (water)—A property of water that causes the formation of an insoluble residue when the water is used with soap and a scale in vessels in which water has been allowed to evaporate. It is due primarily to the presence of ions of calcium and magnesium. Generally expressed as milligrams per liter as calcium carbonate ($CaCO_3$). A general hardness scale is:

Description	Milligrams per liter as $CaCO_3$
Soft	0–60
Moderately hard	61–120
Hard	121–180
Very hard	More than 180

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 and manufacturing uses such as steel, chemical and allied products, paper and allied products, mining, and petroleum refining. The water may be obtained from a public supply or may be self supplied.

Infiltration—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.

Interbasin transfer of water—*See* Water exports; water imports.

Interface—In hydrology, the contact zone between two fluids of different chemical or physical makeup.

Intermittent stream—A stream or part of a stream that flows only in direct response to precipitation. It receives little or no water from springs and melting snow, or other sources. It is dry for a large part of the year, generally more than 3 months.

Intermontane—Situated between or surrounded by mountains, mountain ranges, or mountainous regions.

Irrigation district—In the United States, a cooperative, self-governing public corporation set up as a subdivision of the State, with definite geographic boundaries, organized to obtain and distribute water for irrigation of lands within the district; created under authority of the State legislature with the consent of a designated fraction of the land-owners or citizens and has taxing power.

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.

Line-of-sight radio communication—Radio communications between points that require no obstructions, such as mountains, lie on the straight line path that joins the points.

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; an average of quantity.

Median—The middle item when items are arranged according to rank; an average of position.

Meteorburst data transmission—The name of a technique that relies on transitory micrometeor trails in the atmosphere to reflect radio transmissions between two widely separated points.

Millibar—A pressure unit of 100 pascals (newtons per square meter), convenient for reporting atmospheric pressure.

Nonpoint source of pollution—Pollution from broad areas, such as areas of fertilizer and pesticide application and leaking sewer systems, rather than from discrete points.

Normal—As used by the meteorological profession, average (or mean) conditions over a specific period of time; usually the most recent 30-year period; for example, 1951 to 1980.

Offstream use—Water withdrawn or diverted from a ground- or surface-water source for use.

Percolation—Slow laminar movement of water through openings within a porous earth material.

Perennial stream—A stream that normally has water in its channel at all times.

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.

Potential evapotranspiration—Water loss that will occur if at no time there is a deficiency of water in the soil for use by vegetation.

Precipitation—Includes rain, snow, hail, and sleet.

Prior appropriation—A concept in water law under which users who demonstrate earlier use of water from a particular source are said to have rights over all later users of water from the same source.

Public-supply withdrawals—Water withdrawn by public and private water suppliers for use within a general community. Water is used for a variety of purposes such as domestic, commercial, industrial, and public supply.

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.

Rainfall—Quantity of water that falls as rain only. Not synonymous with precipitation.

Reaeration—The replenishment of oxygen in water from which oxygen had been removed.

Real-time data—Data collected by automated instrumentation and telemetered and analyzed quickly enough to influence a decision that affects the monitored system.

Recharge (ground water)—Process of entry of water into 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.

Regulation of a stream—Artificial manipulation of the flow of a stream.

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 the precipitation that appears in surface-water bodies. It is the same as streamflow unaffected by artificial diversions, storage, or other human works in or on the stream channels.

Rural withdrawals—Water used in suburban or farm areas for domestic and livestock needs. The water generally is self supplied and includes domestic use, drinking water for livestock, and other uses such as dairy sanitation, evaporation from stock-watering ponds, and cleaning and waste disposal.

Safe yield (ground water)—Amount of water that can be withdrawn from an aquifer without producing an undesired effect.

Safe yield (surface water)—Amount of water that can be withdrawn or released from a reservoir on an ongoing basis with an acceptably small risk of supply interruption (reducing the reservoir storage to zero).

Saline water—Water that generally is considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. 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

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.

Sinkhole topography—*See* Karst.

Soft water—*See* Hardness (water).

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.

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. 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.

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.

Underground water—Subsurface water in the unsaturated and saturated zones.

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.

Water budget—An accounting of the inflow to, outflow from, and storage changes of water in a hydrologic unit.

Water content of snow—*See* Water equivalent of snow.

Water demand—Water requirements for a particular purpose, such as irrigation, power, municipal supply, plant transpiration, or storage.

Water equivalent of snow—Amount of water that would be obtained if the snow could be completely melted. Water content may be merely the amount of liquid water in the snow at the time of observation.

Water exports—Artificial transfer (pipes, canals) of freshwater from one region or subregion to another.

Water imports—Artificial transfer (pipes, canals) of freshwater to one region or subregion from another.

Water-resources region—Natural drainage basin or hydrologic area that contains either the drainage area of a major river or the combined areas of a series of rivers. In the United States, there are 21 regions of which 18 are in the conterminous United States, and one each in Alaska, Hawaii, and the Caribbean.

Water-resources subregion—The 21 water-resources regions of the United States are subdivided into 222 subregions. Each subregion includes that area drained by a river system, a reach of a river and its tributaries in that reach, a closed basin(s), or a group of streams forming a coastal drainage area.

Water rights—Legal rights to the use of water. *See* Prior appropriation; Riparian rights.

Water table—The top of the saturated zone in an unconfined aquifer. The water levels in wells that penetrate the uppermost part of an unconfined aquifer mark the position of the water table. *See also* Saturated zone.

Water-table aquifer—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.

CONVERSION FACTORS

[With particular reference to water-use and water-supply data]

Multiply	*By*	*To obtain*
	AREA	
acres	43,560	square feet (ft^{2})
	4,047	square meters (m^{2})
	0.001562	square miles (mi^{2})
	FLOW	
billion gallons per day (bgd)	1,000	million gallons per day (Mgal/d)
	1,121	thousand acre-feet per year (acre-ft/yr)
	1.547	thousand cubic feet per second (ft^{3}/s)
	694.4	thousand gallons per minute (gal/min)
	3.785	million cubic meters per day (m^{3}/d)
cubic feet per second (ft^{3}/s)	0.646317	million gallons per day (Mgal/d)
	448.831	gallons per minute (gal/m)
	724	acre-feet per year (acre-ft/yr)
million gallons per day (Mgal/d)	0.001	billion gallons per day (bgd)
	1.121	thousand acre-feet per year (acre-ft/yr)
	1.547	cubic feet per second (ft^{3}/s)
	0.6944	thousand gallons per minute (gal/m)
	0.003785	million cubic meters per day (m^{3}/d)
thousand acre-feet per year	0.0008921	billion gallons per day (bgd)
	0.8921	million gallons per day (Mgal/d)
	0.001380	thousand cubic feet per second (ft^{3}/s)
	0.6195	thousand gallons per minute (gal/min)
	0.003377	million cubic meters per day (m^{3}/d)

SELECTED WATER RELATIONSHIPS (approximations)

1 gallon = 8.34 pounds
1 million gallons = 3.07 acre-feet
1 cubic foot = 62.4 pounds
= 7.48 gallons
1 cubic foot per second per day = 86,400 cubic feet
= 1.98 acre-feet
= 646,317 gallons
= 0.646 million gallons
1 acre-foot (1 acre covered by 1 foot of water) = 325,851 gallons
43,560 cubic feet
1 cubic mile = 1.1 trillion gallons
3,379,200 acre-feet
1 inch of rain = 17.4 million gallons per square mile
27,200 gallons per acre
100 tons per acre

NAMES AND CODES OF THE WATER-RESOURCES REGIONS AND SUBREGIONS

NEW ENGLAND REGION (01)

- **0101,** St. John
- **0102,** Penobscot
- **0103,** Kennebec
- **0104,** Androscoggin
- **0105,** Maine Coastal
- **0106,** Saco
- **0107,** Merrimack
- **0108,** Connecticut
- **0109,** Massachusetts-Rhode Island Coastal
- **0110,** Connecticut Coastal
- **0111,** St. Francois

MID-ATLANTIC REGION (02)

- **0201,** Richelieu
- **0202,** Upper Hudson
- **0203,** Lower Hudson-Long Island
- **0204,** Delaware
- **0205,** Susquehanna
- **0206,** Upper Chesapeake
- **0207,** Potomac
- **0208,** Lower Chesapeake

SOUTH ATLANTIC-GULF REGION (03)

- **0301,** Chowan-Roanoke
- **0302,** Neuse-Pamlico
- **0303,** Cape Fear
- **0304,** Pee Dee
- **0305,** Edisto-Santee
- **0306,** Ogeechee-Savannah
- **0307,** Altamaha-St. Marys
- **0308,** St. Johns
- **0309,** Southern Florida
- **0310,** Peace-Tampa Bay
- **0311,** Suwannee
- **0312,** Ochlockonee
- **0313,** Apalachicola
- **0314,** Choctawhatchee-Escambia
- **0315,** Alabama
- **0316,** Mobile-Tombigbee
- **0317,** Pascagoula
- **0318,** Pearl

GREAT LAKES REGION (04)

- **0401,** Western Lake Superior
- **0402,** Southern Lake Superior-Lake Superior
- **0403,** Northwestern Lake Michigan
- **0404,** Southwestern Lake Michigan
- **0405,** Southeastern Lake Michigan
- **0406,** Northeastern Lake Michigan-Lake Michigan
- **0407,** Northwestern Lake Huron
- **0408,** Southwestern Lake Huron-Lake Huron
- **0409,** St. Clair-Detroit
- **0410,** Western Lake Erie
- **0411,** Southern Lake Erie
- **0412,** Eastern Lake Erie-Lake Erie
- **0413,** Southwestern Lake-Ontario
- **0414,** Southeastern Lake Ontario
- **0415,** Northeastern Lake Ontario-Lake Ontario-St.Lawrence

OHIO REGION (05)

- **0501,** Allegheny
- **0502,** Monongahela
- **0503,** Upper Ohio
- **0504,** Muskingum
- **0505,** Kanawha
- **0506,** Scioto
- **0507,** Big Sandy-Guyandotte
- **0508,** Great Miami
- **0509,** Middle Ohio
- **0510,** Kentucky-Licking
- **0511,** Green
- **0512,** Wabash
- **0513,** Cumberland
- **0514,** Lower Ohio

TENNESSEE REGION (06)

- **0601,** Upper Tennessee
- **0602,** Middle Tennessee-Hiwassee
- **0603,** Middle Tennessee-Elk
- **0604,** Lower Tennessee

UPPER MISSISSIPPI REGION (07)

- **0701,** Mississippi Headwaters
- **0702,** Minnesota
- **0703,** St. Croix
- **0704,** Upper Mississippi-Black-Root
- **0705,** Chippewa
- **0706,** Upper Mississippi-Maquoketa-Plum
- **0707,** Wisconsin
- **0708,** Upper Mississippi-Iowa-Skunk-Wepsipinicon
- **0709,** Rock
- **0710,** Des Moines
- **0711,** Upper Mississippi-Salt
- **0712,** Upper Illinois
- **0713,** Lower Illinois
- **0714,** Upper Mississippi-Kaskaskia-Meramec

LOWER MISSISSIPPI REGION (08)

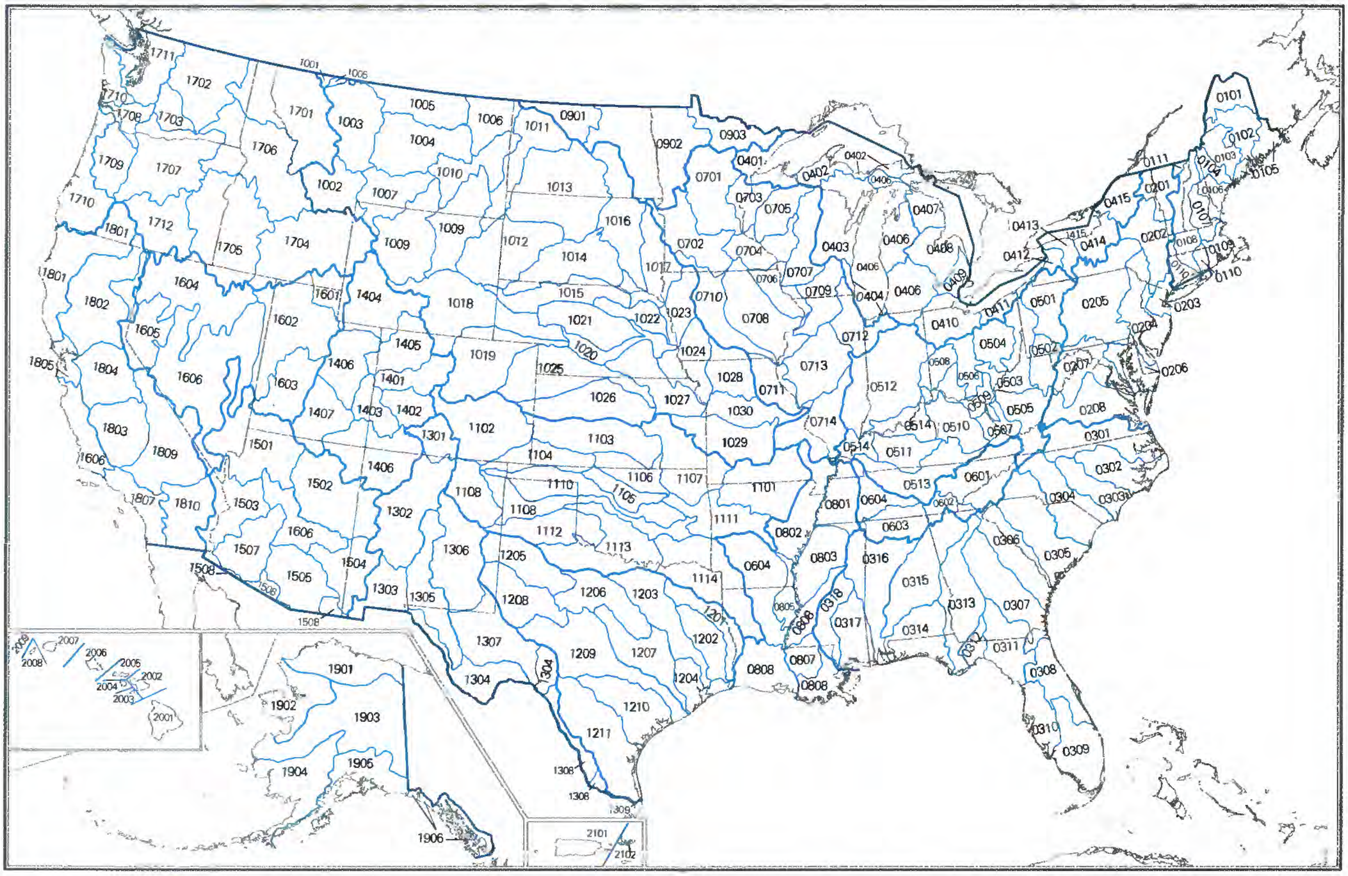
- **0801,** Lower Mississippi-Hatchie
- **0802,** Lower Mississippi-St. Francis
- **0803,** Lower Mississippi-Yazoo
- **0804,** Lower Red-Ouachita
- **0805,** Boeuf-Tensas
- **0806,** Lower Mississippi-Big Black
- **0807,** Lower Mississippi-Lake Maurepas
- **0808,** Louisiana Coastal
- **0809,** Lower Mississippi

SOURIS-RED-RAINY REGION (09)

- **0901,** Souris
- **0902,** Red
- **0903,** Rainy

MISSOURI REGION (10)

- **1001,** Saskatchewan
- **1002,** Missouri Headwaters
- **1003,** Missouri-Marias
- **1004,** Missouri-Musselshell
- **1005,** Milk
- **1006,** Missouri-Poplar
- **1007,** Upper Yellowstone
- **1008,** Bighorn
- **1009,** Powder-Tongue
- **1010,** Lower Yellowstone
- **1011,** Missouri-Little Missouri
- **1012,** Cheyenne
- **1013,** Missouri-Oahe



NAMES AND CODES OF THE WATER-RESOURCES REGIONS AND SUBREGIONS—Continued

1014, Missouri-White
1015, Niobrara
1016, James
1017, Missouri-Big Sioux
1018, North Platte
1019, South Platte
1020, Platte
1021, Loup
1022, Elkhorn
1023, Missouri-Little Sioux
1024, Missouri-Nishnabotna
1025, Republican
1026, Smoky Hill
1027, Kansas
1028, Chariton-Grand
1029, Gasconade-Osage
1030, Lower Missouri

Arkansas-White-Red Region (11)

1101, Upper White
1102, Upper Arkansas
1103, Middle Arkansas
1104, Upper Cimarron
1105, Lower Cimarron
1106, Arkansas-Keystone
1107, Neosho-Verdigris
1108, Upper Canadian
1109, Lower Canadian
1110, North Canadian
1111, Lower Arkansas
1112, Red Headwaters
1113, Red-Washita
1114, Red-Sulphur

Texas-Gulf Region (12)

1201, Sabine
1202, Neches
1203, Trinity
1204, Galveston Bay-San Jacinto
1205, Brazos Headwaters
1206, Middle Brazos
1207, Lower Brazos
1208, Upper Colorado
1209, Lower Colorado-San Bernard Coastal
1210, Central Texas Coastal
1211, Nueces-Southwestern Texas Coastal

Rio Grande Region (13)

1301, Rio Grande Headwaters
1302, Rio Grande-Elephant Butte
1303, Rio Grande-Mimbres
1304, Rio Grande-Amistad
1305, Rio Grande Closed Basins
1306, Upper Pecos
1307, Lower Pecos
1308, Rio Grande-Falcon
1309, Lower Rio Grande

Upper Colorado Region (14)

1401, Colorado Headwaters
1402, Gunnison
1403, Upper Colorado-Dolores
1404, Great Divide-Upper Green
1405, White-Yampa
1406, Lower Green
1407, Upper Colorado-Dirty Devil
1408, San Juan

Lower Colorado Region (15)

1501, Lower Colorado-Lake Mead
1502, Little Colorado
1503, Lower Colorado
1504, Upper Gila
1505, Middle Gila
1506, Salt
1507, Lower Gila
1508, Sonora

Great Basin Region (16)

1601, Bear
1602, Great Salt Lake
1603, Escalante Desert-Sevier Lake
1604, Black Rock Desert-Humboldt
1605, Central Lahontan
1606, Central Nevada Desert Basins

Pacific Northwest Region (17)

1701, Kootenai-Pend Oreille-Spokane
1702, Upper Columbia
1703, Yakima
1704, Upper Snake
1705, Middle Snake
1706, Lower Snake
1707, Middle Columbia
1708, Lower Columbia
1709, Willamette
1710, Oregon-Washington Coastal
1711, Puget Sound
1712, Oregon Closed Basins

California Region (18)

1810, Klamath-Northern California Coastal
1802, Sacramento
1803, Tulare-Buena Vista Lakes
1804, San Joaquin
1805, San Francisco Bay
1806, Central California Coastal
1807, Southern California Coastal
1806, North Lahontan
1809, Northern Mojave-Mono Lake
1810, Southern Mojave-Salton Sea

Alaska Region (19)

1901, Arctic Slope
1902, Northwest Alaska
1903, Yukon
1904, Southwest Alaska
1905, South Central Alaska
1906, Southeast Alaska

Hawaii Region (20)

2001, Hawaii
2002, Maui
2003, Kahoolawe
2004, Lanai
2005, Molokai
2006, Oahu
2007, Kauai
2008, Niihau
2009, Northwestern Hawaiian Islands

Caribbean Region (21)

2101, Puerto Rico
2102, Virgin Islands
2103, Caribbean Outlying Areas

LARGEST RIVERS IN THE UNITED STATES, IN DISCHARGE, DRAINAGE AREA, OR LENGTH

[Of the 32 rivers listed here, the 20 largest in three categories – discharge, drainage basin, and length – are ranked from 1 to 20; these ranks are shown in parentheses. Abbreviations: ft^3/s = cubic feet per second; mi^2 = square miles. All data have been rounded to no more than three significant figures. Sources of data: Stream discharge and drainage area – mainly U.S. Geological Survey reports and files; length – publications and files of U.S. Geological Survey, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, and the Tennessee Valley Authority; data for the St. Lawrence River from "Facts from Canadian Maps," Canada Department of Energy, Mines and Resources, 1972. Period of record for most rivers is 1951–80. Some data are provisional and subject to revision. Compiled by J.C. Kammerer, U.S. Geological Survey]

River	Location of mouth	Average discharge at mouth (1,000 ft^3/s)		Drainage area (1,000 mi^2)		Length from source to mouth (miles)		Source stream (name and location)	Water-resources region number at—	
									Source	Mouth
Arkansas	Arkansas	41.0	(16)	161	(9)	1,460	(6)	East Fork Arkansas River, Colorado (Lake County).	11	8
Atchafalaya (excluding about 167,000 ft^3/s diverted from Mississippi River).[1]	Louisiana	58.0	(11)	95.1	(11)	1,420	(8)	Tierra Blanca Creek, New Mexico (Curry County).	11	8
Brazos	Texas	(*)	- - -	45.6	(19)	1,280	(11)	Blackwater Draw, New Mexico (Curry County).	12	12
Canadian	Oklahoma	(*)	- - -	46.9	(18)	906	(16)	Canadian River, Colorado (Las Animas County).	11	11
Colorado	Mexico	(*)	- - -	246 (U.S.–Mexico)	(7)	1,450	(7)	Colorado River, Colorado (Grand County).	14	- - -
Colorado (of Texas)	Texas	(*)	- - -	42.3	- - -	862	(18)	Colorado River (of Texas), Texas (Dawson County).	12	12
Columbia	Oregon–Washington	265	(4)	258 (U.S.–Canada)	(6)	1,240	(12)	Columbia River, British Columbia Canada.	- - -	17
Copper	Alaska	59	(10)	24.4	- - -	286	- - -	Copper River at terminus of Copper Glacier, Alaska.	19	19
Gila	Arizona	(*)	- - -	58.2 (U.S.–Mexico)	(16)	649	- - -	Middle Fork Gila River, New Mexico (Catron County).	15	15
Kansas	Kansas	(*)	- - -	59.5	(15)	743	- - -	Arikaree River, Colorado (Elbert County).	10	10
Kuskokwim	Alaska	67	(9)	48	(17)	724	- - -	South Fork Kuskokwim River at terminus of unnamed glacier, Alaska.	19	19
Mississippi (excluding Atchafalaya–Red River basin).[1], [2]	Louisiana	593	(1)	1,150 (U.S.–Canada)	(1)	2,350	(2)	Mississippi River, Minnesota (Clearwater County).	7	8
Missouri[2]	Missouri	76.2	(6)	529 (U.S.–Canada)	(2)	2,540	(1)	Red Rock Creek, Montana (Beaverhead County).	10	10
Mobile	Alabama	67.2	(8)	44.6	- - -	774	(20)	Tickanetley Creek, Georgia (Gilmer County).	3	3
North Canadian	Oklahoma	(*)	- - -	17.6	- - -	800	(19)	Corrumpa Creek, New Mexico (Union County).	11	11
Nushagak	Alaska	36	(20)	13.4	- - -	285	- - -	Nushagak River, Alaska.	19	19
Ohio	Illinois–Kentucky	281	(3)	203	(8)	1,310	(9)	Allegheny River, Pennsylvania (Potter County).	5	5
Pecos	Texas	(*)	- - -	44.3	- - -	926	(15)	Pecos River, New Mexico (Mora County).	13	13
Platte	Nebraska	(*)	- - -	84.9	(13)	990	(14)	Grizzly Creek, Colorado (Jackson County).	10	10
Porcupine	Alaska	23	- - -	45.1 (U.S.–Canada)	(20)	569	- - -	Porcupine River, Yukon Territory, Canada.	- - -	19
Red[1]	Louisiana	56.0	(13)	93.2	(12)	1,290	(10)	Tierra Blanca Creek, New Mexico (Curry County).	11	8
Rio Grande	Mexico–Texas	(*)	- - -	336 (U.S.–Mexico)	(4)	1,760	(5)	Rio Grande, Colorado (San Juan County).	13	13
St. Lawrence (–Great Lakes).	Canada	348	(2)	396 (U.S.–Canada)	(3)	1,900	(4)	North River, Minnesota (Lake County).	4	- - -
Snake	Washington	56.9	(12)	108	(10)	1,110	(13)	Snake River, Wyoming (Teton County).	17	17
Stikine	Alaska	56	(13)	20 (U.S.–Canada)	- - -	379	- - -	Stikine River, British Columbia Canada.	- - -	19
Susitna	Alaska	51	(15)	20	- - -	313	- - -	Susitna River at terminus of Susitna Glacier, Alaska.	19	19
Susquehanna	Maryland	38.2	(18)	27.2	- - -	447	- - -	Hayden Creek, New York (Otsego County).	2	2
Tanana	Alaska	41	(16)	44.5	- - -	659	- - -	Nabesna River at terminus of Nabesna Glacier, Alaska.	19	19
Tennessee	Kentucky	68.0	(7)	40.9	- - -	883	(17)	North Fork French Broad River, North Carolina (Transylvania County).	6	6
Willamette	Oregon	37.4	(19)	11.4	- - -	309	- - -	Middle Fork Willamette River, Oregon (Douglas County).	17	17
Yellowstone	North Dakota	(*)	- - -	70.0	(14)	692	- - -	Yellowstone River, Wyoming (Park County).	10	10
Yukon	Alaska	225	(5)	328	(5)	1,980	(3)	Nisutlin River, Yukon Territory, Canada.	- - -	19

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*Less than 15,000 ft^3/s, and therefore not among the largest rivers in terms of discharge.

[1] In east-central Louisiana 50 miles northwest of Baton Rouge, the Red River flows into the Atchafalaya River, a distributary of the Mississippi River. The discharge of the Atchafalaya River, as shown in the table above, includes the entire discharge of the Red River, but excludes all water diverted into the Atchafalaya River from the Mississippi River. Thus, the respective discharges represent drainage from corresponding drainage areas.

[2] The total discharge from the entire 1,250,000-mi^2 Mississippi River system, including the Atchafalaya, Red, and Missouri River basins, averages 651,000 cubic feet per second. For the Mississippi River system as a whole, the longest continuous river channel is from the Missouri River headwater source in Montana to the mouth of the Missouri to the Gulf of Mexico, a combined length of about 3,710 miles.

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849