Characteristics and Trends of Streamflow and Dissolved Solids in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah, and Wyoming

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Prepared in cooperation with the U.S. Bureau of Reclamation

U.S. DEPARTMENT OF THE INTERIOR
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By TIMOTHY D. LIEBERMANN, DAVID K. MUELLER, JAMES E. KIRCHER, and ANNE F. CHOQUETTE

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CONVERSION FACTORS

For use of readers who prefer to use metric (International System) units, conversion factors for inch-pound units used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
acre	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	1,233	cubic meter per annum
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton, short	907.2	kilogram
ton per year (ton/yr)	907.2	kilogram per annum

Temperature in degree Fahrenheit (°F) can be converted to degree Celsius (°C) as follows:

$$°C=5/9\ (°F - 32)$$

To convert discharge, multiply cubic foot per second (ft^3/s) by 1.983 to obtain acre-foot per day (acre-ft/d). Another term and abbreviation used in this report is:

milligram per liter (mg/L)

Characteristics and Trends of Streamflow and Dissolved Solids in the Upper Colorado River Basin, Arizona, Colorado, New Mexico, Utah, and Wyoming

By Timothy D. Liebermann, David K. Mueller, James E. Kircher, *and* Anne F. Choquette

Abstract

Annual and monthly concentrations and loads of dissolved solids and major constituents were estimated for 70 streamflow-gaging stations in the Upper Colorado River Basin. Trends in streamflow, dissolved-solids concentrations, and dissolved-solids loads were identified. Nonparametric trend-analysis techniques were used to determine step trends resulting from human activities upstream and long-term monotonic trends. Results were compared with physical characteristics of the basin and historical water-resource development in the basin to determine source areas of dissolved solids and possible cause of trends.

Mean annual dissolved-solids concentration increases from less than 100 milligrams per liter in the headwater streams to more than 500 milligrams per liter in the outflow from the Upper Colorado River Basin. All the major tributaries that have high concentrations of dissolved solids are downstream from extensive areas of irrigated agriculture. However, irrigation predated the period of record for most sites and was not a factor in many identified trends. Significant annual trends were identified for 30 sites. Most of these trends were related to transbasin exports, changes in land use, salinity-control practices, or reservoir development. The primary factor affecting streamflow and dissolved-solids concentration and load has been the construction of large reservoirs. Reservoirs have decreased the seasonal and annual variability of streamflow and dissolved solids in streams that drain the Gunnison and San Juan River basins. Fontenelle and Flaming Gorge Reservoirs have increased the dissolved-solids load in the Green River because of dissolution of mineral salts from the bank material. The largest trends occurred downstream from Lake Powell. However, the period of record since the completion of filling was too short to estimate the long-term effects of that reservoir.

INTRODUCTION

The Colorado River and its tributaries comprise one of the primary sources of water in the arid American West. The availability and quality of water have been central factors in settlement and development in the Colorado River basin and in neighboring arid regions. Much legislation and many legal agreements have been established to govern the distribution of water and to maintain water quality in the basin.

The Colorado River basin formally was divided into upper and lower basins by the Colorado River Compact of 1922 (Upper Colorado River Commission, 1950). The division occurs at the compact point, which was named Lee Ferry, Ariz. (pl. 1), located 1 mi downstream from the mouth of the Paria River and 1.4 mi downstream from the streamflow-gaging station at Lees Ferry, Ariz. The Upper Colorado River Basin comprises parts of the States of Arizona, Colorado, New Mexico, Utah, and Wyoming.

The Upper Colorado River Basin annually discharges about 7 million tons of dissolved solids from natural sources and sources related to human activities. This dissolved-solids load is a major concern to agricultural, municipal, and industrial users in the Lower Colorado River Basin.

"Dissolved solids" is the sum of the individual dissolved constituents present in water. Dissolved-solids concentration is the quantity of dissolved solids in a unit volume of water. In other reports on the Colorado River basin, dissolved-solids concentration often is referred to as "salinity." Dissolved-solids load is the product of dissolved-solids concentration and streamflow and represents the quantity of dissolved material transported downstream. In this report, the unit of measure for dissolved-solids concentration is milligrams per liter, and the unit of measure for dissolved-solids load is tons. The mass fraction of a dissolved constituent is the proportion of that constituent within the overall dissolved load.

In the Upper Colorado River Basin, the major dissolved constituents are the cations calcium, magnesium, sodium, and potassium; the anions sulfate, chloride, and bicarbonate; and electrically neutral silica. Compared to the sum of these major constituents, other dissolved constituents such as carbonate, nitrate, and organic-carbon compounds ordinarily are not present in substantial quantities. For calculating dissolved-solids concentration as the sum of the constituents, bicarbonate is converted to the equivalent quantity of carbonate that would remain in the evaporation residue. In this report, the term "carbonate equivalent" refers to the sum of carbonate and bicarbonate as carbonate. Where carbonate and bicarbonate data were missing, alkalinity was used to compute carbonate equivalent. Carbonate equivalent concentrations and loads were used in all subsequent analyses and are listed in tables of data in this report. Bicarbonate was the primary form of dissolved carbon at all sampling locations. The concentrations and loads of sodium and potassium also were combined in a single value in this report. Potassium generally accounted for only a small fraction of this sum.

As a river flows downstream, it naturally accumulates dissolved solids from diffuse and point sources. Diffuse sources add dissolved solids gradually throughout long reaches of the river; these contributions may come from overland flow, from ground-water movement through underlying soils and rocks, and from dissolution of materials in the stream channel. Natural point sources are primarily saline springs that discharge into the stream. Human activities that can produce sources of dissolved solids include municipal and industrial development, mining and drilling operations, disturbance or inundation of surface material, and operation of irrigation systems. Diffuse sources contribute more dissolved solids to the Colorado River system than do point sources (Iorns and others, 1965) and are more difficult to measure and control. Any process that increases the quantity of dissolved solids transported downstream may be called dissolved-solids loading.

Dissolved-solids concentration may increase because of the diversion of water that has a relatively small dissolved-solids concentration from the stream system. In the Upper Colorado River Basin, this concentrating effect primarily is caused by the export of water to other basins, evapotranspiration from irrigated agricultural lands, and evaporation from stream channels and reservoirs.

To address the concern about dissolved solids, Congress passed the Colorado River Basin Salinity Control Act of 1974 (amended in 1985), which authorized planning and construction of salinity-control projects in the Colorado River basin. The U.S. Bureau of Reclamation was named the lead agency for coordinating salinity-control activities.

As part of a cooperative agreement with the U.S. Bureau of Reclamation, the U.S. Geological Survey has undertaken studies to provide information that will help in evaluating and planning salinity-control needs. This report evaluates historical streamflow and dissolved solids in the Upper Colorado River Basin.

Purpose and Scope

The purposes of this report are to (1) determine annual and monthly concentrations and loads of dissolved solids and the major dissolved constituents for all streamflow-gaging stations in the Upper Colorado River Basin that had adequate periods of record; (2) determine sources of dissolved solids; (3) determine trends in streamflow, dissolved solids, and the major dissolved constituents during various periods of record; and (4) determine possible causes of trends.

This report describes the water resources of the drainage basin of the Colorado River upstream from Lee Ferry, Ariz. Dissolved solids were estimated at 70 streamflow-gaging stations in the Upper Colorado River Basin by using surface-water and water-quality records from the U.S. Geological Survey data base. Records through the end of the 1983 water year were evaluated.

Previous Investigations

The first description of the Colorado River basin was reported by John Wesley Powell (1875), documenting his expeditions during 1869 and 1871–72. Several U.S. Geological Survey publications in the early twentieth century have described the region, its water resources, and its potential for water use (La Rue, 1916, 1925; Follansbee, 1929; Woolley, 1930). Other comprehensive studies were compiled by Iorns and others (1965), the Upper Colorado Region State-Federal Inter-Agency Group (1971), and the U.S. Environmental Protection Agency (1971).

Using tree-ring dating techniques, precipitation trends and natural streamflow in the basin have been evaluated for the last 450 years (Stockton and Jacoby, 1976; Dracup, 1977). Using streamflow, reservoir storage, and depletion records, virgin streamflow at Lee Ferry, Ariz., has been estimated from 1896 to 1984 (Upper Colorado River Commission, 1984).

Numerous studies concerning dissolved-solids concentration and water quality in the basin have been done since the 1960's in response to international agreements, national legislation, and increasing demands for potable water. Ground-water investigations include those of Price and Arnow (1974), Taylor and others (1983), and Warner and others (1985). The U.S. Bureau of Reclamation has published biennial progress reports since 1963 documenting salinity, water use, and salinity-control measures (U.S. Department of the Interior, 1985).

Beginning in 1985, the U.S. Bureau of Reclamation and the U.S. Department of Agriculture jointly published an annual evaluation of salinity-control programs (U.S. Bureau of Reclamation, 1985b). Prior to 1985, their reports were published separately (for example, U.S. Bureau of Reclamation, 1983; U.S. Soil Conservation Service, 1983, 1984). The U.S. Environmental Protection Agency (1971) also has investigated mineral quality in the Colorado River basin. Analyses of trends in dissolved solids in the basin were done by Kircher and others (1984) and Moody and Mueller (1984).

Regional studies describing local hydrology and salinity effects have been done for several subbasins including the Green River basin (Bolke and Waddell, 1975; DeLong, 1977; Lowham and others, 1982); Price River basin (Mundorff, 1972; Ponce, 1975; Riley and others, 1982a, 1982b); San Rafael River basin (Mundorff and Thompson, 1982); Duchesne River basin (Mundorff, 1977); Dirty Devil River basin (Mundorff, 1979; Rittmaster and Mueller, 1985); Yampa River basin (Steele and others, 1979; Steele and Hillier, 1981; Turk and Parker, 1982; Adams and others, 1983; Parker and Norris, 1983); White River basin (Weeks and others, 1974; Hackbart and Bauer, 1982; Boyle and others, 1984; Lindskov and Kimball, 1984); Gunnison and Dolores River basins (Kircher and others, 1984); and the western Colorado area (Shen and others, 1981; Larrone and Shen, 1982; Whittig and others, 1982; Evangelou and others, 1984).

Acknowledgments

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DESCRIPTION OF STUDY AREA

The Upper Colorado River Basin encompasses 113,200 mi^2 in the States of Arizona, Colorado, New Mexico, Utah, and Wyoming (pl. 1). Of this, about 3,960 mi^2 is in the Great Divide basin of Wyoming, which does not contribute to the flow of the Colorado River. The Upper Colorado River Basin is about 550 mi long and 350 mi wide.

Stream System

The Colorado River begins high in the Rocky Mountains of Colorado and winds 640 mi to Lee Ferry, Ariz., before passing through the Grand Canyon, Lake Mead, and into Mexico, where its natural outlet is the Gulf of California. The Colorado River, by name, originally extended upward only to the mouth of the Green River in Utah. Upstream from that confluence, it was known as the Grand River. The Green River was considered the upper continuation of the Colorado River because it was longer and drained a larger area (La Rue, 1916). In 1921, a joint resolution of Congress changed the name of the Grand River to the Colorado River (Follansbee, 1929).

Although the mountainous headwater areas of the basin receive a large quantity of snow, most of the basin is semiarid or arid plains that do not contribute substantially to streamflow. Almost 85 percent of the streamflow originates in only 15 percent of the area (Stockton and Jacoby, 1976). Thus, the average runoff from the basin is very small, compared to the other major rivers that discharge into the ocean. The Colorado River at Lees Ferry, Ariz., has a mean annual streamflow about equal to that of the Delaware River, which drains an area about one-tenth the size of the Upper Colorado River Basin. The Columbia River basin (258,000 mi^2) in the Northwestern United States and Canada is about twice the size of the Upper Colorado River Basin, but the Columbia River has a mean annual streamflow more than 13 times greater than the Colorado River at Lees Ferry, Ariz. (data from Dunne and Leopold, 1978). Annual runoff from the Upper Colorado River Basin varies from 0.5 inches throughout much of the basin to more than 20 inches in the high mountains (fig. 1).

Physiography

The Upper Colorado River Basin encompasses parts of four major physiographic provinces (fig. 2): the Southern Rocky Mountains, the Wyoming Basin, the Middle Rocky Mountains, and the Colorado Plateau (Hunt, 1974). The Southern Rocky Mountains are a series of mountain ranges and intermontane basins trending north-south and comprising the highest part of the Continental Divide with elevations ranging from 5,000 ft to more than 14,000 ft. The Wyoming Basin consists of elevated semiarid basins with isolated mountains and elevations ranging from 5,000 ft to 7,000 ft. The Middle Rocky Mountains are an assortment of mountains and semiarid intermontane basins with features similar to the neighboring provinces. The elevations in the Middle Rocky Mountains range from 5,000 ft to more than 12,000 ft. The Colorado Plateau province has the highest plateaus on the continent with elevations ranging from about 3,100 ft to 11,000 ft. The Colorado Plateau province is semiarid and deeply incised by numerous canyons.

Geology

The geology of the study area is diverse; it is characterized predominantly by igneous and metamorphic rocks in the high mountains and sedimentary rocks elsewhere. The core of the Southern Rocky Mountains consists mainly of Precambrian granite, schist, and gneiss, capped in places by Tertiary volcanics. Sedimentary rocks contain predominantly sandstone, siltstone, and shale, and local occurrences of evaporite. Several widespread formations were deposited in marine or brackish environments resulting in bedded and disseminated sodium chloride (halite) and calcium sulfate (gypsum), as well as clay that has high concentrations of exchangeable sodium and magnesium (Whittig and others,

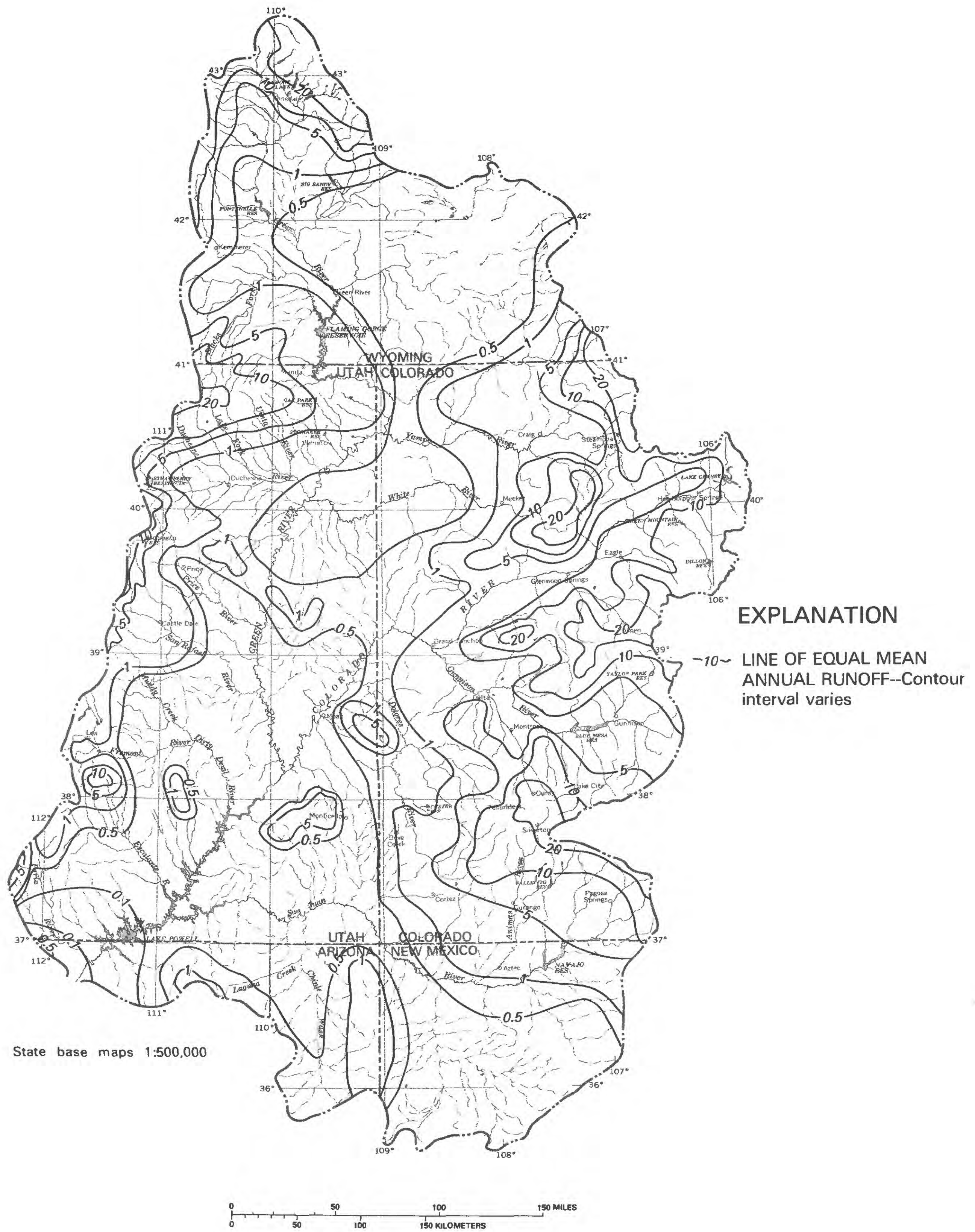


Figure 1. Mean annual runoff in Upper Colorado River Basin (modified from Gebert and others, 1987). Contours in inches.

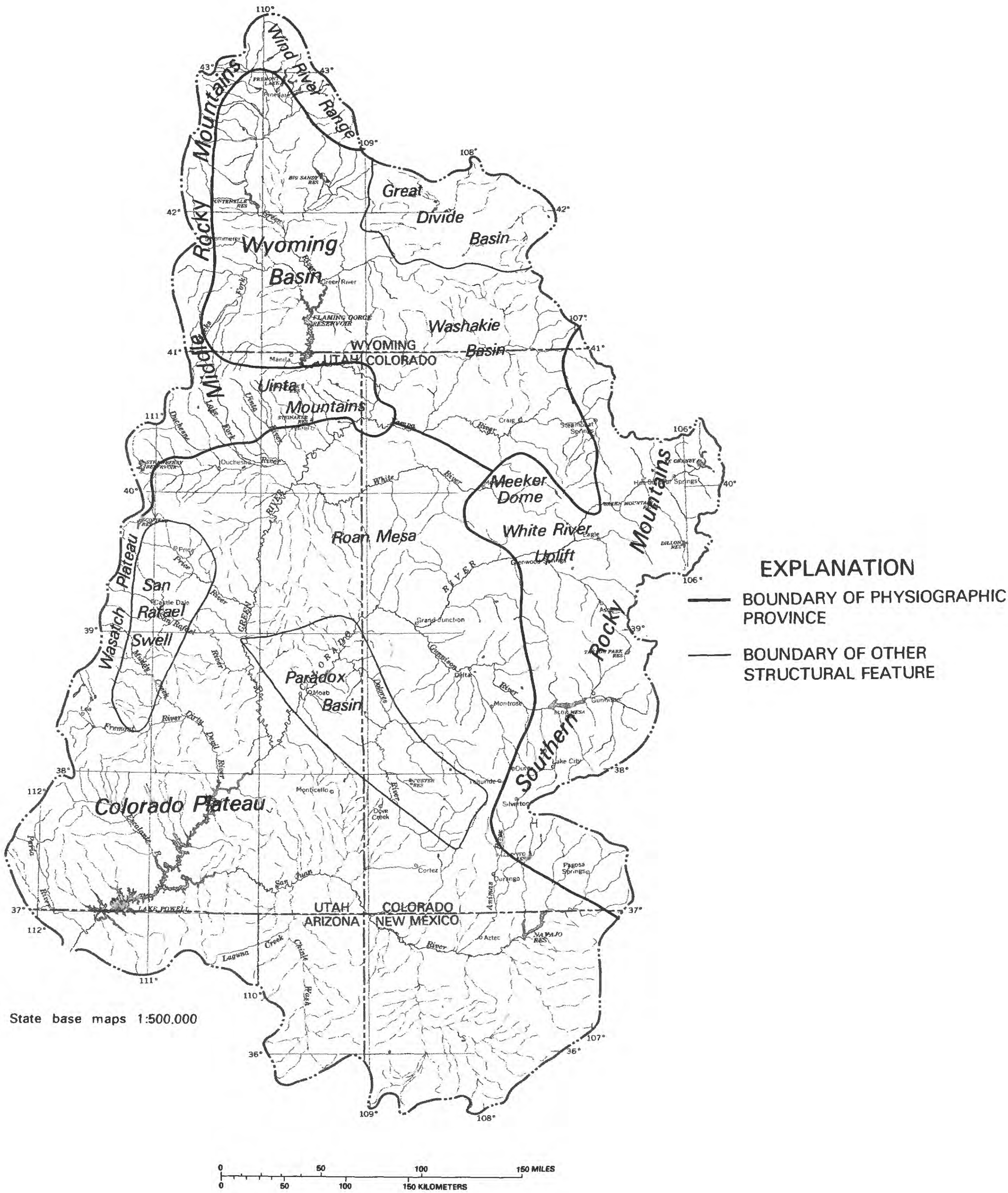


Figure 2. Major physiographic provinces and other features of Upper Colorado River Basin.

1982). Sedimentary formations also contain deposits of oil, oil shale, coal, and natural gas. Structural features, including anticlines, domes, and faults, expose large sequences of strata in the Upper Colorado River Basin. More than 200 formations have been identified (Iorns and others, 1965; Warner and others, 1985).

Several geologic units are major contributors of dissolved solids to streams in the Upper Colorado River Basin. Most important is the Upper Cretaceous Mancos Shale and equivalent formations such as the Tropic Shale. The upper members of the Mancos Shale consist of thick beds of marine shale that commonly form flat benches that underlie irrigated lands. The Mancos Shale contains gypsum, calcite (calcium carbonate), dolomite (calcium magnesium carbonate), and sodium-rich clay. Weathering of the Mancos Shale includes dissolution of gypsum, followed by cation exchange on the clay, resulting in water containing high concentrations of dissolved sulfate, sodium, and calcium (Rittmaster and Mueller, 1985). Mancos Shale is most widely exposed in the Roaring Fork, Gunnison, Uncompahgre, San Juan, Yampa, White, Price, San Rafael, Dirty Devil, and Dolores River basins (fig. 3).

The Paradox Member of the Pennsylvanian Hermosa Formation has formed a series of salt anticlines near the Colorado-Utah border, which contain large deposits of halite. Water interacting with these salt domes contains very high concentrations of dissolved sodium and chloride. The Eagle Valley Evaporite, of Pennsylvanian age, contains soluble salts and gypsum and is exposed in the Eagle River and Roaring Fork River basins. The Jurassic Carmel Formation contains deposits of halite. It is exposed in a narrow band across the Price, San Rafael, and Dirty Devil River basins.

Several coal-bearing formations occur in the Upper Colorado River Basin. These are mined in the Gunnison, Upper Green, Yampa, White, Price, San Rafael, Dirty Devil, and San Juan River basins. Water in these formations contains high concentrations of magnesium, sodium, and sulfate.

The Green River Formation is extensively exposed in southern Wyoming, northeastern Utah, and northwestern Colorado. This formation consists of Tertiary lacustrine deposits containing nahcolite (sodium bicarbonate), dolomite, and calcite, as well as the world's largest deposits of oil shale. The Parachute Creek Member of the Green River Formation crops out in the Piceance, Yellow, Parachute, and Roan Creek basins. Water in the Parachute Creek Member contains high concentrations of sodium, bicarbonate, and chloride. The Laney Member of the Green River Formation underlies irrigated agricultural land in the Big Sandy River basin.

The Tertiary Uinta Formation and its equivalent, the Bridger Formation, are exposed north and south of the Uinta Mountains near the Utah-Wyoming border. These formations contain gypsum and a thick, saline layer deposited during the final phase of the ancestral Lake Uinta. A large area overlying the Uinta Formation is irrigated in the Duchesne River basin.

Climate

Climate in the Upper Colorado River Basin is diverse because of physiographic features, prevailing wind patterns, and wide variations in elevation and latitude. Extremes of temperature may range from −50 to 115 °F. The basin generally is arid; annual precipitation averages 15.9 in. (Iorns and others, 1965), ranging from 60 in. in the higher mountains to less than 5 in. in the southern part of the basin.

The northern and high-mountain parts of the Upper Colorado River Basin are characterized by long, cold winters and short, warm summers. Many areas are covered by snow all winter, and 10-ft snowpacks are not unusual. Plateau and high-basin areas may have cold winters and hot summers; the southern end of the basin has mild winters and very hot summers. Mountainous areas generally receive most of their precipitation as snow; the lower areas have dry winters and receive most of their precipitation from summer thunderstorms.

DEVELOPMENT OF WATER RESOURCES

The Upper Colorado River Basin is sparsely populated; the average density is about six persons per square mile. Population has increased from 288,000 in 1930 to 664,000 in 1982 (U.S. Bureau of Census, 1982). The largest increase occurred from 1970 to 1980, when the population increased by 55 percent (fig. 4). The basin is primarily rural; only five towns had populations greater than 10,000 in 1982, and only 40 percent of the population lived in towns with more than 1,000 people. Farmington, N. Mex., with a population of 36,000, was the basin's largest town in 1982.

Several metropolitan areas outside the Upper Colorado River Basin have a marked effect on water and land use in the basin. They increase the demand for water, energy, and food produced in the basin. The cities of Denver and Colorado Springs, Colo., Albuquerque, N. Mex., and Salt Lake City, Utah, are dependent on water diverted from the Upper Colorado River Basin.

Irrigation

Most of the water used in the Upper Colorado River Basin is for irrigated agriculture. Crops that are irrigated include livestock feed, fruit, and vegetables. The practice of irrigation in the basin began with the first settlements. After the passage of the Reclamation Act in 1902 (Follansbee, 1929), the irrigated area increased substantially to a total of 1.3 million acres by 1910. Since then the total irrigated acreage has not increased appreciably, but usually has fluctuated between about 1.4 and 1.6 million acres (U.S. Bureau of Census, 1984). Most of the irrigated lands (fig. 5) are in river valleys or on plateaus and are supplied by extensive

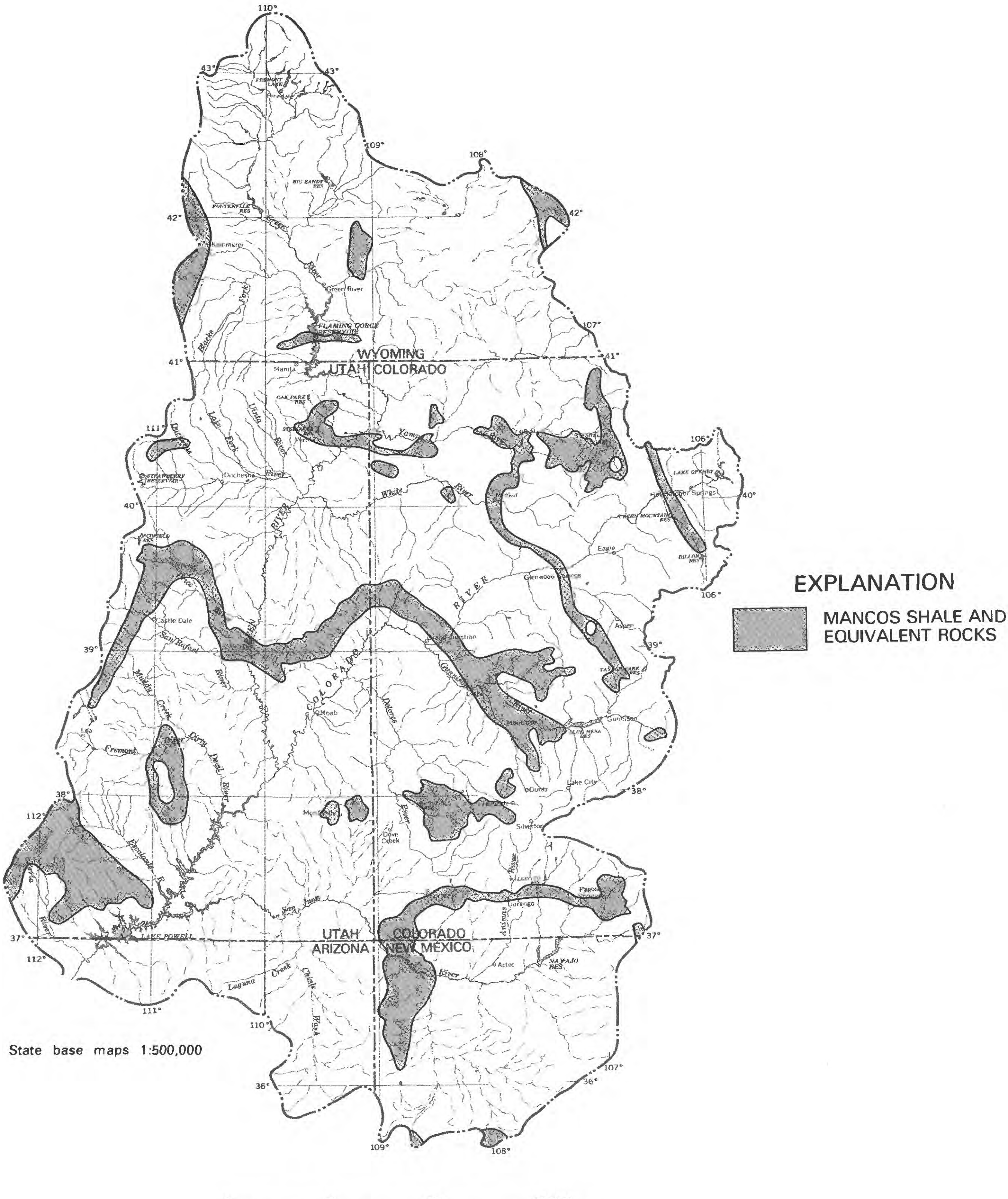


Figure 3. Major exposures of Mancos Shale and equivalent rocks in the Upper Colorado River Basin (modified from Rocky Mountain Association of Geologists, 1972).

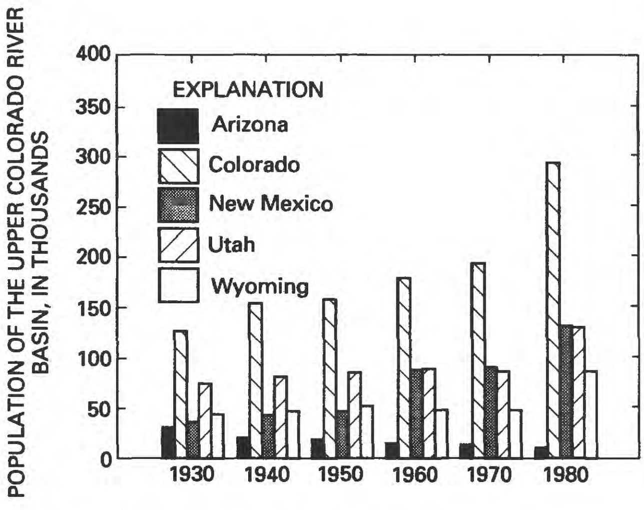


Figure 4. Changes in population between 1930 and 1980 in Upper Colorado River Basin (data from the U.S. Bureau of Census, 1982).

systems of canals and ditches. Consumptive use by crops averaged 1.8 million acre-ft/yr during the 1973–82 water years, about 13 percent of the annual virgin streamflow of the Colorado River at Lees Ferry, Ariz., during the same period (U.S. Bureau of Reclamation, written commun., 1985). Virgin streamflow is the streamflow that would have occurred in the absence of human intervention upstream. It is an estimate of all water consumptively used or exported from the basin.

Irrigated agriculture is the largest source of dissolved solids related to human activities in the Upper Colorado River Basin. Irrigation-return flows generally have a higher dissolved-solids concentration than the applied water, because of the loading effect of salt dissolution in the soil-aquifer system and the concentrating effect of evapotranspiration. Many areas in the basin did not contribute substantially to runoff, and thus to dissolved-solids loading, until the advent of irrigation. Because irrigation practices began before streamflow and water-quality records were initiated, the increase in dissolved-solids loading in the basin can only be estimated.

Transbasin Exports and Imports

Although much of the Upper Colorado River Basin is arid, large volumes of water are exported to other basins. Diversions began in 1892 when the Grand River Ditch was constructed in the headwaters of the Colorado River near Grand Lake, Colo. Total exports averaged less than 2,000 acre-ft/yr at the turn of the century. Exports increased to approximately 100,000 acre-ft by 1920, 200,000 acre-ft by 1940, and 500,000 acre-ft by 1955 (fig. 6). During the 1973–82 water years, annual transbasin exports averaged 739,000 acre-ft, about 5 percent of the virgin streamflow of the Colorado River at Lees Ferry, Ariz. For the same period, 54 percent of the total exports went to the Platte River basin, 17 percent went to the Arkansas River basin, 15 percent went to the Rio Grande basin, and 14 percent went to the Great Basin in Utah. Diversions that export water from the Upper Colorado River Basin are listed in table 1.

Transbasin exports from the Upper Colorado River Basin tend to increase the downstream concentration of dissolved solids. Exports primarily are from the headwater regions, where dissolved-solids concentrations are low. The removal of this relatively pure water from the headwater regions leaves less water for dilution downstream.

Historically, only one transbasin diversion has brought water into the Upper Colorado River Basin. The Tropic and East Fork Canal has diverted water from the Great Basin into the Paria River basin since 1892, averaging 4,800 acre-ft annually during 1974–83 (Upper Colorado River Commission, 1984).

Reservoirs

The first artificial reservoirs in the Upper Colorado River Basin were constructed during the 1890's, primarily for water storage and irrigation. Strawberry Reservoir, completed in 1912, was the first reservoir that had a capacity greater than 100,000 acre-ft; it stored water for delivery through Strawberry Tunnel to the Great Basin in Utah. Reservoirs were important for settlement as well as for agriculture because they increased the year-round availability of water in a region characterized by general aridity and seasonal streamflow resulting from snowmelt. Completion of the Colorado River Storage Project during the the 1960's increased the combined capacity of reservoirs in the basin to about 38 million acre-ft, more than three times the mean annual flow measured at Lees Ferry, Ariz. Lake Powell, formed by Glen Canyon Dam, is by far the largest reservoir and has a total capacity of 27 million acre-ft. It is about the size of Lake Mead, which is formed by Hoover Dam in the Lower Colorado River Basin. Eighty-two reservoirs in the Upper Colorado River Basin have a normal capacity greater than 5,000 acre-ft (table 2).

The major effects of reservoirs on streamflow are associated with the regulation of streamflow and evaporation losses from the water surface. Reservoir regulation tends to decrease the seasonal variability in streamflow; it increases the low-flow volumes during late summer, autumn, and winter and decreases the peak flows occurring during the snowmelt season, April through June. However, discharge patterns downstream from reservoirs become more complex when the timing and magnitude of releases are controlled by power-generation requirements or by diversion projects. Evaporation from Lake Powell during 1973–82 averaged

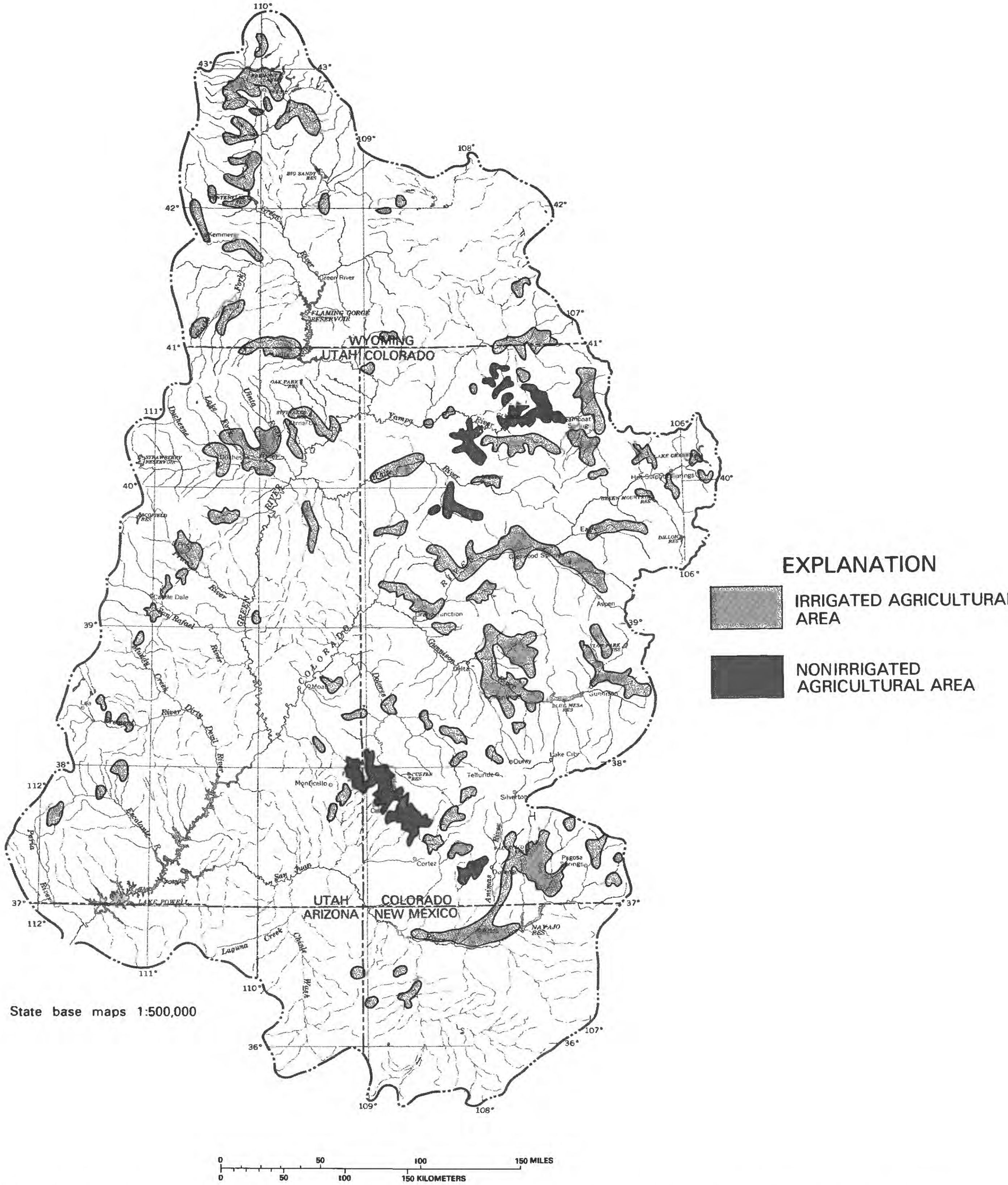


Figure 5. Major agricultural areas in Upper Colorado River Basin (modified from Upper Colorado Region State-Federal Inter-Agency Group, 1971).

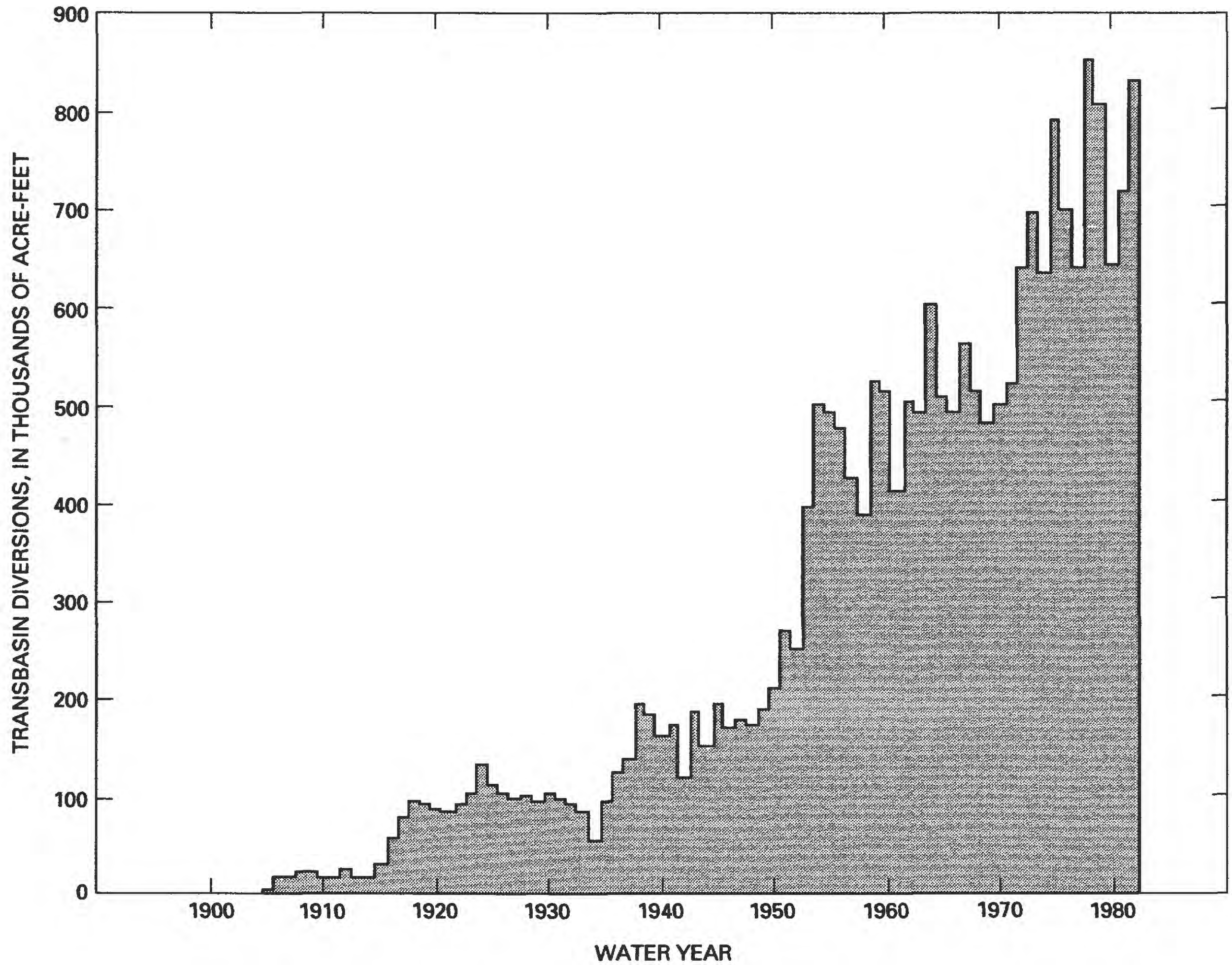


Figure 6. Annual transbasin exports from Upper Colorado River Basin, 1905 to 1983.

517,000 acre-ft/yr (U.S. Bureau of Reclamation, 1982; J. Osterberg, U.S. Bureau of Reclamation, oral commun., 1986), which was about 3 percent of the virgin streamflow of the Colorado River at Lees Ferry, Ariz., for the same period.

The major effects of reservoirs on dissolved solids are associated with evaporation, mixing and stratification in the water body, and chemical processes in the water body. Net evaporation from a water body removes water but leaves the dissolved solids behind. This increases the concentration of dissolved solids in the reservoir and ultimately in the water released. The mixing of low- and high-concentration inflow in a reservoir decreases seasonal variability in the outflow concentration and also decreases the year-to-year variability. However, stratification and density currents can limit the mixing that occurs.

The effects of chemical reactions in a large reservoir are difficult to quantify because of the problems of sampling a large, dynamic volume of water at various depths, the lack of sufficient inflow data for accurate mass balance, and the uncertainties associated with the modeling of geochemical reactions in a deep, heterogeneous water mass. Buchak and Edinger (1982) reported that the simple mixing of two waters, such as lake water and stream inflow, could cause calcite to precipitate in order to maintain chemical equilibrium. However, they concluded that the potential decrease in dissolved-solids load due to calcite precipitation in Lake Powell would be negligible in comparison to the total annual load. Several studies have indicated that precipitation of calcite and silica does occur in large reservoirs along the Colorado River (Smith and others, 1960, p. 185; Bolke and Waddell, 1975, p. 11).

The effects of leaching from the banks of a reservoir also are difficult to quantify. When a reservoir is drawn down, water from bank storage may reenter the reservoir. This water may have a high concentration of dissolved solids if it has been in contact with soluble minerals in the bank material.

Table 1. Diversions that export water from the Upper Colorado River Basin

[Data from U.S. Bureau of Reclamation, written commun., 1985; H.E. Petsch, U.S. Geological Survey, written commun., 1985; °-min-s, degrees-minutes-seconds; - -, no record]

Conveyance name	State	Origin	Point of diversion Latitude (°-min-s)	Point of diversion Longitude (°-min-s)	Year placed in operation	Year record begins	Mean annual[1] export (acre-feet per year)
Alva B. Adams Tunnel	Colo.	Grand Lake, Colorado River	40-19-40	105-34-50	1947	1947	247,200
Azotea Tunnel	Colo.	Navajo River	36-51-12	106-40-18	1971	1971	106,600
Berthoud Pass Ditch	Colo.	Fraser River	39-47-55	105-46-35	1910	1910	536
Black Canyon Ditch	Utah	Cottonwood Creek	39-27-00	111-20-00	1906	1915	379
Boreas Pass Ditch	Colo.	Blue River	39-24-40	105-58-05	1909	1933	49
Busk-Ivanhoe Tunnel	Colo.	Fryingpan River	39-14-55	106-28-15	1925	1925	5,850
C.H. Boustead Tunnel	Colo.	Fryingpan River	39-16-39	106-26-09	1972	1972	41,470
Candland Ditch	Utah	Huntington Creek	39-33-00	111-19-00	1906	1950	200
Cedar Creek Tunnel	Utah	Cottonwood Creek	39-27-00	111-20-00	1906	1914	373
Cheyenne Diversion	Wyo.	Little Snake River	41-02-27	106-55-15	1964	1964	7,050
Coal Fork Ditch	Utah	Cottonwood Creek	39-30-00	111-19-00	1906	1949	263
Columbine Ditch	Colo.	Eagle River	39-22-45	106-13-40	1931	1931	1,690
Don La Font Ditches	Colo.	Piedra River	37-34-20	107-00-00	1940	1940	191
Duchesne Tunnel	Utah	Duchesne River	40-35-33	111-00-07	1953	1954	18,180
Ephraim Tunnel	Utah	Cottonwood Creek	39-19-47	111-25-51	1906	1937	4,350
Eureka Ditch	Colo.	Colorado River	40-20-00	105-43-40	1940	1940	12
Ewing Ditch	Colo.	Eagle River	39-21-40	106-18-15	1880	1908	1,020
Fairview Tunnel[2]	Utah	Huntington Creek	39-40-03	111-18-41	1949	1949	2,340
Fuchs Ditch	Colo.	Los Pinos River	37-40-50	107-19-30	1937	1937	261
Grand River Ditch	Colo.	Colorado River	40-28-40	105-45-10	1892	1896	17,540
H.D. Roberts Tunnel	Colo.	Blue River	39-27-42	105-40-32	1963	1963	67,720
Hobble Creek Ditches	Utah	Strawberry River	40-18-00	111-15-00	1906	1906	1,201
Homestake Tunnel	Colo.	Eagle River	39-16-50	106-26-26	1967	1967	24,310
Hoosier Pass Tunnel	Colo.	Blue River	39-21-35	106-04-35	1952	1952	8,000
Horseshoe Tunnel	Utah	Cottonwood Creek	39-22-00	111-27-00	1906	1950	600
J. August Ditch	Utah	Ferron Creek	39-18-00	111-27-00	1906	1940	200
Larkspur Ditch	Colo.	Tomichi Creek	38-24-00	106-15-00	1935	1935	244
Larsen Tunnel	Utah	Cottonwood Creek	39-21-00	111-27-00	1925	1941	945
Madsen Ditch	Utah	Ferron Creek	39-19-00	111-27-00	1906	1940	35
Moffat Water Tunnel	Colo.	Fraser River	39-54-10	105-38-50	1936	1936	59,720
Reeder Ditch	Utah	Cottonwood Creek	39-23-00	111-23-00	1924	1930	270
Spring City Tunnel	Utah	Cottonwood Creek	39-25-34	111-21-51	1939	1939	2,210
Strawberry Tunnel	Utah	Strawberry Reservoir	40-09-40	111-14-40	1915	1915	67,820
Tabor Ditch	Colo.	Cebolla Creek	37-56-00	107-10-50	1928	1928	837
Tarbell Ditch	Colo.	Cochetopa Creek	38-00-00	106-48-00	1914	--	413
Treasure Pass Ditch	Colo.	Wolf Creek	37-28-50	106-48-10	1929	1929	322
Twin Creek Tunnel	Utah	Cottonwood Creek	39-28-00	111-20-00	1906	1950	225
Twin Lakes Tunnel	Colo.	Roaring Fork River	39-05-00	106-32-30	1935	1935	42,330
Vidler Tunnel	Colo.	Blue River	39-27-28	105-47-22	1971	1971	316
Weminuche Pass Ditch	Colo.	Los Pinos River	37-40-50	107-19-30	1937	1937	1,490
Williams Creek Ditch	Colo.	Squaw Pass Creek	37-36-00	107-13-00	1938	1938	84
Willow Creek Ditch	Utah	Strawberry River	40-20-00	111-14-00	1906	1906	1,388
Wurtz Ditch	Colo.	Eagle River	39-21-15	106-21-05	1932	1932	2,910

[1]For water years 1973-82.

[2]Known from 1949 to 1967 as Fairview Ditch.

Mining and Energy Resources

Mining brought the first settlers to the region, and it is still the major industry in many areas. Molybdenum, vanadium, copper, nickel, uranium, lead, zinc, oil shale, coal, and oil and gas resources all occur in the Upper Colorado River Basin (Upper Colorado Region State-Federal Inter-Agency Group, 1971). Railroad development and increases in population spurred the mining of coal. Coal pro-

Table 2. Reservoirs with a normal capacity greater than 5,000 acre-feet located in the Upper Colorado River Basin
[Data from N.E. Spahr, U.S. Geological Survey, written commun., 1985; °-min-s, degrees-minutes-seconds]

Reservoir	State	Latitude (°-min-s)	Longitude (°-min-s)	Location (river basin)	Year completed	Normal capacity (acre-feet)
Big Sand Wash Reservoir	Utah	40-17-36	110-13-48	Lake Fork	1965	12,050
Big Sandy Reservoir	Wyo.	42-15-18	109-25-48	Big Sandy River	1952	39,700
Blue Lake #1	Colo.	37-53-00	107-46-00	San Miguel River	1911	6,014
Blue Mesa Reservoir	Colo.	38-27-13	107-20-00	Gunnison River	1966	940,700
Bottle Hollow Reservoir	Utah	40-17-24	109-52-06	Uinta River	1970	11,100
Boulder Lake	Wyo.	42-50-12	109-42-24	Boulder Creek	1964	22,280
Brown's Draw Reservoir	Utah	40-25-24	110-07-12	Cottonwood Creek	1981	6,750
Bush Creek Reservoir	Wyo.	42-08-00	108-29-18	Bush Creek	1945	17,267
Cleveland Reservoir	Utah	39-34-42	111-14-18	Spring Creek	1908	5,340
Crawford Reservoir	Colo.	38-39-18	107-35-42	Smith Fork	1951	14,395
Crystal Reservoir	Colo.	38-30-38	107-37-25	Gunnison River	1976	25,236
Currant Creek Reservoir	Utah	40-20-00	111-03-06	Currant Creek	1977	15,670
Desert Lake	Utah	39-22-00	112-29-00	Huntington Creek	1926	7,300
Dillon Reservoir	Colo.	39-37-14	106-03-53	Blue River	1963	252,678
Eden Valley Reservoir #1	Wyo.	42-13-36	109-23-06	Little Sandy Creek	1910	18,490
Electra Lake	Colo.	37-32-48	107-48-24	Animas River	1976	23,254
Electric Lake	Utah	39-36-12	111-12-54	Huntington Creek	1974	31,500
Elk Head Reservoir	Colo.	40-33-48	107-22-36	Elk Head Creek	1979	11,500
Flaming Gorge Reservoir	Utah	40-54-24	109-25-12	Green River	1964	3,787,000
Fontenelle Reservoir	Wyo.	42-02-00	110-04-00	Green River	1964	345,300
Fremont Lake	Wyo.	42-55-00	109-50-00	Pine Creek	1934	20,600
Gould Reservoir	Colo.	38-36-12	107-35-36	Iron Creek	1954	9,000
Grass Valley Reservoir	Colo.	39-36-24	107-39-36	Harvey Gap	1920	5,058
Green Mountain Reservoir	Colo.	39-52-42	106-19-45	Blue River	1943	154,000
Groundhog Lake	Colo.	37-47-24	108-17-36	Dolores River	1938	21,711
Gurley Reservoir	Colo.	38-02-06	108-15-00	San Miguel River	1961	10,039
Homestake Reservoir	Colo.	39-22-06	106-27-48	Homestake Creek	1964	43,600
Huntington North Reservoir	Utah	39-21-06	110-57-12	Huntington Creek	1966	5,420
Jackson Gulch Reservoir	Colo.	37-24-06	108-16-30	West Mancos River	1949	9,980
Jerry Creek #2 Reservoir	Colo.	39-11-24	108-06-42	Plateau Creek	1977	6,320
Joes Valley Reservoir	Utah	39-17-18	111-16-12	Cottonwood Creek	1966	62,460
Johnson Reservoir	Utah	38-36-30	111-38-00	Fremont River	1900	10,350
Juniata Reservoir	Colo.	38-58-06	108-17-06	Kahnah Creek	1979	5,752
Lake Avery	Colo.	39-58-18	107-38-48	Big Beaver Creek	1964	7,658
Lake Catamount	Colo.	40-21-54	106-48-00	Yampa River	1974	7,422
Lake Granby	Colo.	40-08-36	105-52-54	Colorado River	1950	540,000
Lake Powell	Ariz.	36-56-12	111-29-00	Colorado River	1964	27,000,000
Lemon Reservoir	Colo.	37-22-48	107-39-42	Florida River	1963	40,100
Long Park Reservoir	Utah	40-54-30	109-52-06	Sheep Creek	1980	13,700
Mahoney Reservoir	Wyo.	41-57-36	107-29-24	Separation Creek	1910	6,119
Many Farms Lake	Ariz.	36-21-48	109-36-30	Chinle Wash	1943	12,500
Mc Chivvis Reservoir	Colo.	40-07-06	107-01-12	Watson Creek	1962	7,141
Meadow Creek Reservoir	Colo.	40-03-06	105-45-18	Meadow Creek	1975	5,750
Meeks Cabin Reservoir	Wyo.	41-01-36	110-34-48	Blacks Fork	1971	32,470
Midview Reservoir	Utah	40-11-12	110-10-06	Duchesne River	1937	5,800
Mill Meadow Reservoir	Utah	38-29-42	111-34-06	Fremont River	1954	5,232
Miller Flat Reservoir	Utah	39-32-24	111-14-30	Miller Flat Creek	1949	5,560
Millsite Reservoir	Utah	39-05-48	111-11-06	Ferron Creek	1971	18,000
Miramonte Reservoir	Colo.	37-58-24	108-20-06	Naturita Creek	1978	6,851
Moon Lake	Utah	40-33-42	110-29-24	Lake Fork	1938	49,500
Morgan Lake	N. Mex.	36-41-36	108-29-06	Chaco River and San Juan River	1960	36,550
Morrow Point Reservoir	Colo.	38-27-05	107-32-12	Gunnison River	1968	117,200
Narraquinepp Reservoir	Colo.	37-29-00	108-37-30	Narraquinnep Canyon	1956	18,960
Navajo Reservoir	N. Mex.	36-48-28	107-36-31	San Juan River	1963	1,708,600
New Fork Lake Reservoir	Wyo.	43-05-06	109-58-00	New Fork River	1928	20,340

Table 2. Reservoirs with a normal capacity greater than 5,000 acre-feet located in the Upper Colorado River Basin—Continued

Reservoir	State	Latitude (°-min-s)	Longitude (°-min-s)	Location (river basin)	Year completed	Normal capacity (acre-feet)
Oak Park Reservoir	Utah	40-44-36	109-37-12	Big Brush Creek	1938	6,249
Overland Reservoir #1	Colo.	39-04-42	107-38-42	Peters Creek	1951	5,990
Paonia Reservoir	Colo.	38-56-36	107-21-12	Muddy Creek	1962	20,950
Pearl Lake	Colo.	40-46-48	106-53-18	Lester Creek	1975	5,657
Pelican Lake	Utah	40-11-00	109-40-48	Uinta River	1967	11,850
Red Creek Reservoir	Utah	40-18-12	110-50-54	Red Creek	1960	5,700
Rifle Gap Reservoir	Colo.	39-37-48	107-45-42	Rifle Creek	1967	13,600
Ruedi Reservoir	Colo.	39-21-50	106-49-06	Fryingpan River	1968	102,500
Scofield Reservoir	Utah	39-47-12	111-07-30	Price River	1946	73,600
Shadow Mountain Reservoir and Grand Lake	Colo.	40-12-24	105-50-24	Colorado River	1947	18,400
Silver Jack Reservoir	Colo.	38-14-42	107-32-36	East Fork Cimarron River	1971	13,520
Sixty-seven Reservoir	Wyo.	42-35-24	110-12-30	Spring Creek	1942	5,211
Starvation Reservoir	Utah	40-11-26	110-26-28	Strawberry and Duchesne Rivers	1970	167,000
Steamboat Lake	Colo.	40-47-30	106-56-48	Willow Creek	1966	23,064
Steinaker Reservoir	Utah	40-30-00	109-32-00	Ashley Creek	1961	38,170
Stillwater Reservoir #1	Colo.	40-01-48	107-07-12	Yampa River	1939	6,088
Strawberry Reservoir	Utah	40-08-24	111-06-12	Strawberry River	1912	1,106,500
Summit Reservoir	Colo.	37-25-18	108-23-12	Tributary of Lost Canyon Creek	1939	5,954
Taylor Park Reservoir	Colo.	38-49-07	106-36-24	Taylor River	1935	106,200
Vallecito Reservoir	Colo.	37-23-00	107-34-30	Los Pinos River	1941	129,700
Vega Reservoir	Colo.	39-13-30	107-48-40	Plateau Creek	1959	33,800
Viva Naughton Reservoir	Wyo.	41-57-48	110-39-30	Hams Fork	1961	42,393
Williams Fork Reservoir	Colo.	40-02-06	106-12-18	Williams Fork	1959	93,637
Williams Reservoir	Colo.	37-30-12	107-13-30	Williams Creek	1958	10,084
Willow Creek Reservoir	Colo.	40-08-49	105-56-31	Willow Creek	1953	10,600
Willow Lake	Wyo.	42-59-30	109-54-30	Lake Creek	1931	22,630
Yamcolo Reservoir	Colo.	40-03-18	107-02-48	Bear River	1980	9,080

duction peaked during World War I, then declined until the late 1960's, when demand from electric utilities and industry caused a resurgence of production from surface mining (Green and others, 1980). Oil and gas have been produced in the Upper Colorado River Basin since the early 1900's. The world's largest deposits of oil shale occur in the central area of the Green River basin.

Mining and energy resources development can contribute dissolved solids to water in the Upper Colorado River Basin. Abandoned oil and gas wells can serve as conduits for deep, saline water to mix with shallow ground water which then discharges to streams. Also, the leaching of solutes from coal spoils can contribute large quantities of dissolved solids to streams (McWhorter and others, 1975).

LEGISLATION AFFECTING WATER RESOURCES

Water use in the Upper Colorado River Basin is controlled by law and by formal agreements among users. Some legal constraints are designed to protect the quality of water by limiting dissolved-solids concentrations.

Water Allocation

In 1922, representatives of the States in the Colorado River basin drafted the Colorado River Compact, which was approved by Congress in 1928 (Upper Colorado River Commission, 1950). The Compact formally divided the basin into the Upper Colorado River Basin and the Lower Colorado River Basin at Lee Ferry, Ariz., along the main stem of the Colorado River. Those parts of the Colorado River basin that naturally drain into the Colorado River upstream from Lee Ferry, Ariz., were included in the Upper Colorado River Basin and the remainder were included in the Lower Colorado River Basin. A distinction also was made between the States of the upper division (Colorado, New Mexico, Wyoming, and Utah) and the States of the lower division (Arizona, California, and Nevada). The flow of the Colorado

River was apportioned to provide exclusive beneficial consumptive use of 7.5 million acre-ft annually to each basin, and the Lower Colorado River Basin was given the right to increase its annual beneficial consumptive use by 1 million acre-ft. The States of the upper division guaranteed to "***not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75 million acre-ft for any period of 10 consecutive years***". The Compact also made provisions for obligations to Indian tribes and stipulated that if flow proved insufficient to satisfy any treaty obligations to Mexico, "***the burden of such deficiency shall be equally borne by the Upper basin and the Lower basin." Such an obligation was fulfilled by the Water Treaty of 1944 with the United Mexican States, which guaranteed 1.5 million acre-ft of water annually to Mexico.

The Upper Colorado River Basin Compact of 1948 apportioned the water of the Upper Colorado River Basin among the five States having drainage areas that contribute to the flow of the Colorado River upstream from Lee Ferry, Ariz. Annual consumptive use was allocated as follows: 50,000 acre-ft to Arizona, and of the remaining portion, 51.75 percent to Colorado, 11.25 percent to New Mexico, 23 percent to Utah, and 14 percent to Wyoming.

Although it did not directly apportion flow, the Colorado River Storage Project Act of 1956 (Public Law 84-485) resulted in major effects on the flow in the entire Colorado River basin. It authorized construction of the Glen Canyon Dam, the Flaming Gorge Dam, the Navajo Dam, and the Wayne N. Aspinall (formerly known as Curecanti) Unit, which is composed of Blue Mesa, Morrow Point, and Crystal Reservoirs on the Gunnison River.

Water Quality

The Water Quality Act of 1965 (Public Law 89-234) was an amendment to the Federal Water Pollution Control Act of 1948. It required States to adopt water-quality standards for their interstate waters, but did not require numeric criteria for dissolved-solids concentrations. A second set of amendments, Public Law 92-500, was enacted in 1972. The U.S. Environmental Protection Agency's interpretation of this law required the establishment of numeric criteria for dissolved-solids concentration in the Colorado River. The Colorado River Basin Salinity Control Forum was established to develop these criteria and a plan of implementation. The Forum recommended that numeric dissolved-solids criteria be set at the calculated flow-weighted concentrations that existed during the 1972 calendar year (Colorado River Basin Salinity Control Forum, 1975). These were approved by the seven basin States and the U.S. Environmental Protection Agency in 1976. The criteria are dissolved-solids concentrations of 723 mg/L downstream from Hoover Dam, Arizona-Nevada, 747 mg/L downstream from Parker Dam, Arizona-California, and 879 mg/L upstream from Imperial Dam, Arizona-California.

An outcome of the 1972 meeting between President Nixon and Mexican President Echeverria was the signing of Minute 242 of the International Boundary and Water Commission pledging to find a solution for Mexico's problems with saline Colorado River water. It was agreed that the difference between the average annual salinity at Morelos Dam (at the Mexican border) and at Imperial Dam (the last major control structure upstream from the Mexican border) should not exceed "115 $\pm$ 30 parts per million" (Upper Colorado River Commission, 1973).

Congress passed the Colorado River Basin Salinity Control Act (Public Law 93-320) in 1974 authorizing the construction of 4 salinity-control projects and the development of plans for 12 others. The 1984 amendment to the act (Public Law 98-589) provided authority to the U.S. Bureau of Reclamation and the U.S. Department of Agriculture to install the salinity controls needed to meet the numeric criteria through the year 2005. The amendment established cost effectiveness as an underlying decision-making criterion for implementation of a project, authorized construction of several projects, and authorized the Secretary of Agriculture to establish a voluntary on-farm salinity control program with landowners (U.S. Bureau of Reclamation, 1985b).

METHODS OF DATA ANALYSIS

The primary source of the data used in this report was the U.S. Geological Survey's National Water Data Storage and Retrieval System (WATSTORE) (Hutchison, 1975). All daily values of streamflow and specific conductance and analyses of water quality were retrieved from this data base. Data describing streamflow-gaging stations, such as location and elevation, were obtained from WATSTORE and U.S. Geological Survey data reports. Much of the data for reservoirs, diversions, and agricultural projects were obtained from the U.S. Bureau of Reclamation project data reports (U.S. Water and Power Resources Service, 1981), and additional data were obtained from the U.S. Department of the Interior progress report (1985) and the Upper Colorado River Commission (1950–84) annual reports.

Daily data collection in the Upper Colorado River Basin by the U.S. Geological Survey began in 1894 when streamflow-gaging stations were established along the Colorado and Gunnison Rivers near Grand Junction, Colo., and along the Green River near Green River, Wyo., and Green River, Utah (U.S. Geological Survey, 1954). Daily monitoring of specific conductance began in 1935 when once-daily measurements were recorded at stations along the Colorado River near Cameo, Colo., and Cisco, Utah, and along the Gunnison River near Grand Junction, Colo.

Systematic sampling of water quality in the Upper Colorado River Basin began in 1926, when 10 samples were analyzed from the Colorado River at Lees Ferry, Ariz. (Collins and Howard, 1928). By 1984, water at 566 different sites had been sampled at least once for dissolved-solids concentration, and 214 streamflow-gaging stations had at least 25 dissolved-solids analyses.

Selection of Streamflow-Gaging Stations

Seventy streamflow-gaging stations (hereinafter referred to as sites) were selected for analysis in this report (table 3, pl. 1). Minimum criteria for selection were that a site have a sustained period of analyses for dissolved solids and a concurrent record of daily values of streamflow. Other selection criteria included the length and completeness of record, the availability of daily values of specific conductance, and a geographic location along a major stream or in an area of special interest. The period of record for several sites was increased by combining the records of adjacent sites. For this study, about 1,500 site-years of dissolved-solids data were compiled.

Estimation of Dissolved Solids

Annual and monthly dissolved-solids concentrations and loads and mass fractions of major ionic constituents were estimated using the computerized method described by Liebermann and others (1987). Data were retrieved from the U.S. Geological Survey's data base (Hutchison, 1975). The data available in WATSTORE included mean daily streamflow, mean daily specific conductance, and periodic chemical analyses. These data were evaluated to locate potential errors that, if uncorrected, might degrade the accuracy of subsequent regression analyses and lead to erroneous results.

The corrected data were used to estimate the daily loads of dissolved solids and selected ionic constituents. Loads were computed using the linear regression

$$\ln(\hat{L}) = \hat{b}_0 + \hat{b}_1 \ln(Q) + \hat{b}_2 \ln(SC) \qquad (1)$$

where

$\ln(\hat{L})$ = the estimated natural logarithm of load;
$\ln(Q)$ = the natural logarithm of streamflow;
$\ln(SC)$ = the natural logarithm of specific conductance; and
$\hat{b}_0, \hat{b}_1, \hat{b}_2$ = regression coefficients.

If specific conductance was not available, load was computed as a function of streamflow only:

$$\ln(\hat{L}) = \hat{b}_0 + \hat{b}_1 \ln(Q) \qquad (2)$$

Equation 2 may not be appropriate for sites immediately downstream from a large reservoir. In order to ensure the applicability of equation 1 for such sites, missing values of specific conductance were estimated by linear interpolation between the last observation preceding the missing record and the first observation following the missing record. Missing values of specific conductance were estimated for 3 of the 70 sites evaluated in the Upper Colorado River Basin: site 34, Green River near Greendale, Utah (downstream from Flaming Gorge Reservoir); site 61, San Juan River near Archuleta, N. Mex. (downstream from Navajo Reservoir); and site 69, Colorado River at Lees Ferry, Ariz. (downstream from Lake Powell). For each site, missing specific-conductance values were estimated only for the period when streamflow was regulated.

The observed dissolved-solids and constituent loads used to calibrate the regression models (eqs 1 and 2) were computed as the product of streamflow and the dissolved-solids or constituent concentration. For specific sampling dates, constituent loads were calculated for dissolved calcium, magnesium, sodium plus potassium, the carbonate equivalent of alkalinity, chloride, and sulfate. For each site the regression models were evaluated on three-year groups of data. The calibrated models then were used to estimate daily loads for the central year of the group. The daily loads were summed to produce the monthly values used in subsequent analyses. Daily streamflows also were summed to produce monthly values. The flow-weighted mean monthly concentrations of dissolved solids and ionic constituents then could be computed by division of the monthly load by the monthly streamflow. The monthly load and streamflow were summed to produce annual values, from which flow-weighted mean annual concentrations were computed. A complete tabulation of the monthly and annual time series of streamflow, load, and concentration at the 70 sites is included in a separate data report (Liebermann and Nordlund, 1988).

Flow-Adjusted Concentration

For most sites in the Upper Colorado River Basin, concentration of dissolved constituents is related to streamflow. As streamflow increases, concentration decreases; as streamflow decreases, concentration increases. This relation can affect subsequent trend analyses of the data, because a significant trend in concentration may be entirely the result of a corresponding trend in streamflow. To distinguish a trend in concentration caused by changing supply rates or sources, the effect of streamflow first must be removed. The resulting flow-adjusted concentrations then may be analyzed for trends over time.

Residuals from regression of dissolved-solids concentration as a function of streamflow commonly are used as flow-adjusted concentrations. In this report, the regression model assumed to relate concentration to streamflow for all the sites was:

$$\ln(\hat{C}) = \hat{b}_0 + \hat{b}_1 \ln(Q) \qquad (3)$$

Table 3. Streamflow-gaging stations for which dissolved solids were estimated
[°-min-s, degrees-minutes-seconds; - -, not applicable]

Site number (on plate 1)	U.S. Geological Survey station number	Station name	Latitude (°-min-s)	Longitude (°-min-s)	Elevation (feet)	Drainage area (square miles)	Period of water-quality record (complete water years)
1	09013000	Alva B. Adams Tunnel at East Portal near Estes Park, Colo.[1]	40-14-20	105-48-15	8,250	--	1976-83
2	09034500	COLORADO RIVER at Hot Sulphur Springs, Colo.	40-05-00	106-05-15	7,670	825	1947-83
3	09069000	Eagle River at Gypsum, Colo.	39-39-00	106-57-06	6,276	944	1947-83
4	09070500	COLORADO RIVER near Dotsero, Colo.	39-38-40	107-04-40	6,130	4,394	1959-83
5	09071100	COLORADO RIVER near Glenwood Springs, Colo.	39-34-12	107-13-34	5,900	4,560	1942-83
6	09085000	Roaring Fork River at Glenwood Springs, Colo.	39-32-37	107-19-44	5,721	1,451	1959-83
7	09093500	Parachute Creek at Parachute, Colo.	39-27-11	108-03-33	5,100	198	1975-82
8	09093700	COLORADO RIVER near DeBeque, Colo.	39-21-45	108-09-07	4,940	7,370	1973-82
9	09095000	Roan Creek near DeBeque, Colo.	39-27-12	108-18-59	5,380	321	1975-80
10	09095500	COLORADO RIVER near Cameo, Colo.	39-14-20	108-16-00	4,814	8,050	1934-83
11	09105000	Plateau Creek near Cameo, Colo.	39-11-00	108-16-10	4,836	592	1969-79
12	09149500	Uncompahgre River at Delta, Colo.	38-44-31	108-04-49	4,926	1,129	1959-80
13	09152500	Gunnison River near Grand Junction, Colo.	38-59-00	108-27-00	4,628	7,928	1934-83
14	09152900	Adobe Creek near Fruita, Colo.	39-08-13	108-41-48	4,520	15	1974-80
15	09153300	Reed Wash near Loma, Colo.	39-11-01	108-47-12	4,470	29	1974-83
16	09163340	Mack Wash near Mack, Colo.	39-15-57	108-50-32	4,615	16	1974-82
17	09163490	Salt Creek near Mack, Colo.	39-13-18	108-53-32	4,440	436	1974-83
18	09163500	COLORADO RIVER near Colorado-Utah State line	39-07-45	109-01-36	4,325	17,843	1962-83
19	09177000	San Miguel River at Uravan, Colo.	38-21-26	108-42-44	5,000	1,499	1974-79
20	09180000	Dolores River near Cisco, Utah	38-47-50	109-11-40	4,165	4,580	1952-83
21	09180500	COLORADO RIVER near Cisco, Utah	38-48-38	109-17-34	4,090	24,100	1929-83
22	09188500	GREEN RIVER at Warren Bridge, near Daniel, Wyo.	43-01-08	110-07-03	7,468	468	1962-82
23	09205000	New Fork River near Big Piney, Wyo.	42-34-02	109-55-46	6,800	1,230	1966-83
24	09209400	GREEN RIVER near La Barge, Wyo.	42-11-34	110-09-45	6,520	3,910	1964-81
25	09211200	GREEN RIVER below Fontenelle Reservoir, Wyo.	42-01-16	110-02-57	6,378	4,280	1968-83
26	09214500	Little Sandy Creek above Eden, Wyo.	42-14-12	109-18-44	6,750	134	1976-81
27	09216000	Big Sandy River below Eden, Wyo.	42-00-37	109-34-57	6,450	1,610	1962-80
28	09216050	Big Sandy River at Gasson Bridge, near Eden, Wyo.	41-56-43	109-41-04	6,350	1,720	1975-83
29	09216562	Bitter Creek above Salt Wells Creek, near Salt Wells, Wyo.	41-38-52	108-59-50	6,330	829	1977-81
30	09217000	GREEN RIVER near Green River, Wyo.	41-30-59	109-26-54	6,060	9,740	1952-83
31	09222000	Blacks Fork near Lyman, Wyo.	41-27-08	110-10-20	6,380	821	1963-83
32	09224700	Blacks Fork near Little America, Wyo.	41-32-46	109-41-34	6,128	3,100	1955-83

33	09229500	Henrys Fork near Manila, Utah	41-00-45	109-40-20	6,060	520	1955-83
34	09234500	GREEN RIVER near Greendale, Utah	40-54-30	109-25-20	5,594	15,090	1957-83
35	09235300	Vermillion Creek near Hiawatha, Colo.	41-00-54	108-38-39	6,610	196	1976-81
36	09244410	Yampa River below diversion, near Hayden, Colo.	40-29-18	107-09-33	6,380	1,430	1975-82
37	09250600	Wilson Creek near Axial, Colo.	40-18-56	107-47-50	6,300	20	1975-80
38	09251000	Yampa River near Maybell, Colo.	40-30-10	108-01-45	5,900	3,410	1951-83
39	09259700	Little Snake River near Baggs, Wyo.	41-00-11	107-55-11	6,050	3,020	1965-68
40	09260000	Little Snake River near Lily, Colo.	40-32-50	108-25-25	5,685	3,730	1951-83
41	09261000	GREEN RIVER near Jensen, Utah	40-24-34	109-14-05	4,758	25,400	1962-83
42	09279500	Duchesne River at Duchesne, Utah	40-09-51	110-23-34	5,494	660	1962-69
43	09302000	Duchesne River near Randlett, Utah	40-12-56	109-46-58	4,756	4,247	1957-83
44	09304800	White River below Meeker, Colo.	40-00-48	108-05-33	5,928	1,024	1974-83
45	09306200	Piceance Creek below Ryan Gulch near Rio Blanco, Colo.	39-55-16	108-17-49	6,070	506	1971-83
46	09306222	Piceance Creek at White River, Colo.	40-05-16	108-14-35	5,705	652	1971-83
47	09306255	Yellow Creek near White River, Colo.	40-10-07	108-24-02	5,535	262	1974-82
48	09306300	White River above Rangely, Colo.	40-06-26	108-42-44	5,270	2,773	1975-81
49	09306430	Evacuation Creek near Watson, Utah	39-57-08	109-09-31	5,050	284	1975-81
50	09306500	White River near Watson, Utah	39-58-46	109-10-41	4,947	4,020	1951-83
51	09306850	Bitter Creek at mouth, near Bonanza, Utah	39-57-56	109-24-59	4,770	398	1975-83
52	09306900	White River at mouth, near Ouray, Utah	40-03-54	109-38-06	4,655	5,120	1975-83
53	09314500	Price River at Woodside, Utah	39-15-50	110-20-45	4,600	1,540	1949-83
54	09315000	GREEN RIVER at Green River, Utah	38-59-10	110-09-02	4,040	40,590	1929-83
55	09324500	Cottonwood Creek near Orangeville, Utah	39-16-00	111-07-45	6,050	208	1976-83
56	09328100	San Rafael River at San Rafael Bridge Campground, near Castle Dale, Utah	39-04-51	110-39-56	5,100	1,284	1975-83
57	09328500	San Rafael River near Green River, Utah	38-51-30	110-22-10	4,190	1,628	1947-83
58	09333500	Dirty Devil River above Poison Spring Wash, near Hanksville, Utah	38-05-50	110-24-27	3,850	4,159	1969-76
59	09335000	Colorado River at Hite, Utah	37-48-30	110-26-55	3,440	72,340	1951-56
60	09352900	Vallecito Creek near Bayfield, Colo.	37-28-39	107-32-35	7,906	72	1963-83
61	09355500	SAN JUAN RIVER near Archuleta, N. Mex.	36-48-05	107-41-51	5,655	3,260	1956-83
62	09364500	Animas River at Farmington, N. Mex.	36-43-17	108-12-05	5,280	1,360	1955-83
63	09365000	SAN JUAN RIVER at Farmington, N. Mex.	36-43-22	108-13-30	5,230	7,240	1962-82
64	09367950	Chaco River near Waterflow, N. Mex.	36-43-28	108-35-27	4,980	4,350	1977-83
65	09368000	SAN JUAN RIVER at Shiprock, N. Mex.	36-47-32	108-43-54	4,849	12,900	1958-83
66	09370800	Mancos River near Cortez, Colo.	37-06-27	108-27-43	5,685	302	1977-82
67	09372000	McElmo Creek near Colorado-Utah State line	37-19-27	109-00-54	4,890	346	1978-81
68	09379500	SAN JUAN RIVER near Bluff, Utah	37-08-49	109-51-51	4,048	23,000	1930-83
69	09380000	COLORADO RIVER at Lees Ferry, Ariz.	36-51-53	111-35-15	3,106	107,540	1942-83
70	09382000	Paria River at Lees Ferry, Ariz.	36-52-20	111-35-38	3,123	1,410	1948-50

[1]Water is diverted from Grand Lake, but streamflow is measured at East Portal in the South Platte River basin.

where

$\ln(\hat{C})$ = estimated natural logarithm of dissolved-solids concentration;

$\ln(Q)$ = natural logarithm of streamflow; and

$\hat{b}_0$ and $\hat{b}_1$ = regression coefficients.

Detransformation of the regression model enabled estimation of dissolved-solids concentration in the original units:

$$\hat{C} = \exp(\hat{b}_0) Q^{\hat{b}_1} \exp(1/2\hat{\sigma}^2) \quad (4)$$

where

$\exp(1/2\hat{\sigma}^2)$ = the bias-correction factor (Miller, 1984), and

$\hat{\sigma}^2$ = the estimated residual variance from calibration of the model (eq 1).

The residuals, or flow-adjusted concentrations, were computed as the difference between the observed dissolved-solids concentrations and the corresponding estimates ($\hat{C}$) from equation 4. Flow-adjusted concentrations were computed for both the monthly and annual time series for all sites.

Nonparametric Trend Analysis

Trend analyses were made to test for significant changes in streamflow and water quality during the period of record. Nonparametric (rank or distribution-free) analyses were used rather than parametric (least-squares regression) analyses, because water-quality data commonly do not meet the assumptions of parametric analyses (Hirsch and others, 1982). Hirsch and others reported that, even when all the normality assumptions were met, the nonparametric Kendall test was almost as powerful as parametric analyses based on least-squares regression. They also reported that when skewness or seasonality were introduced, the seasonal Kendall test was better than regression, and that the effects of serial correlation were no worse on the seasonal Kendall test than on the regression test.

Nonparametric analyses were applied to the monthly and annual time series of streamflow, dissolved-solids concentration, dissolved-solids load, and flow-adjusted concentration for all sites having 10 or more years of dissolved-solids records. Determination of trend significance was based on the following criteria: $p \leqslant 0.01$, highly significant; $0.01 < p \leqslant 0.05$, significant; $0.05 < p \leqslant 0.10$, marginally significant; $p > 0.10$, not significant; where p is the attained, two-sided significance level for the test.

The seasonal Kendall test (Crawford and others, 1983) was used to identify monotonic trends. The result of this test is analogous to the slope of the least-squares regression line (parametric) when the independent variable is measured in years. Analyses of annual data yielded the median annual change during the period of record, with an associated significance level for the change. Analyses of monthly data yielded the median annual change for each month of the year. For example, dissolved-solids concentration may have decreased by 3 mg/L per year during January, may have increased by 1 mg/L per year during June, and may not have changed significantly during September. Testing for trends in both the annual and monthly time series was necessary because the significance of trends in the two time series may be different. For example, a site may have no significant trend in annual streamflow, but may have an increasing trend in monthly streamflow during January and a decreasing trend in monthly streamflow during June.

The Mann-Whitney-Wilcoxon rank-sum test (Crawford and others, 1983) was used to identify changes in the annual and monthly data caused by an intervention in the watershed. An intervention is some definable change that has an effect on streamflow or water quality. Interventions identified in the study area included construction of reservoirs, implementation of salinity-control projects, and initiation of transbasin diversions. The data for a specific site were divided into two periods: preintervention and postintervention. The Mann-Whitney-Wilcoxon test analyzes the significance of the difference between the median values of the two periods and is analogous to the Student's *t*-test for the significance of the difference between two means. The statistic used to estimate the change in the median between the two periods is called the step trend. It is the median of the differences calculated from all possible combinations of the values for the two periods. The step trend is a unbiased estimate of the change in median and is a less variable estimator than the simple difference between the medians of the two periods.

Thirteen sites were tested for step trends caused by an upstream intervention. Results of the analyses for annual data are summarized in table 4. Each site had a substantial period of record before and after the intervention. Construction of a large reservoir or transbasin diversion system was the major intervention at 12 sites, and 1 site was evaluated for intervention due to a salinity-control project. Other salinity-control projects in the Upper Colorado River Basin were too recent to enable adequate intervention analysis. In addition to the step-trend analysis, the monotonic-trend analysis was done for the preintervention period and the postintervention period for each of these sites.

CHARACTERISTICS AND TRENDS OF STREAMFLOW AND DISSOLVED SOLIDS

The study area was divided into three major regions: the region drained by the Colorado River and tributaries upstream from the confluence with the Green River, the region drained by the Green River and its tributaries, and the region from the confluence of the Green and Colorado Rivers to Lee Ferry, Ariz., including the San Juan River and tributaries and all tributaries to the Colorado between the

Table 4. Annual step trends for sites affected by major interventions in the Upper Colorado River Basin

[mg/L, milligrams per liter; HS, highly significant ($p \leq 0.01$); S, significant ($0.01 < p \leq 0.05$); MS, marginally significant ($0.05 < p$ 0.10); - -, not significant ($p > 0.10$)]

Site (table 3, plate 1)	Principal intervention	Preintervention period of record (water years)	Postintervention period of record (water years)	Streamflow			Dissolved solids: Concentration			Dissolved solids: Load		
				Significance level	Step trend (acre-feet)	Percent[1]	Significance level	Step trend (mg/L)	Percent[1]	Significance level	Step trend (tons)	Percent[1]
5	Alva B. Adams Tunnel/Lake Granby	1942-49	1950-83	S	-330,000	18	HS	39	17	--	--	--
10	Alva B. Adams Tunnel/Lake Granby	1934-49	1950-83	MS	-385,000	13	--	--	--	MS	-89,000	6
13	Blue Mesa Reservoir	1934-65	1966-83	--	--	--	--	--	--	MS	-119,000	8
21	Alva B. Adams Tunnel/Lake Granby	1929-49	1950-65	--	--	--	--	--	--	MS	-594,000	14
21	Blue Mesa Reservoir	1950-65	1966-83	--	--	--	--	--	--	--	--	--
30	Fontenelle Reservoir	1952-63	1964-83	--	--	--	--	--	--	S	118,000	26
34	Flaming Gorge Reservoir	1957-62	1965-83	--	--	--	HS	112	29	S	346,000	55
43	Expansion of Strawberry Reservoir	1957-72	1973-83	--	--	--	--	--	--	--	--	--
50	Meeker well plugged	1951-68	1969-83	--	--	--	HS	-89	19	--	--	--
54	Flaming Gorge Reservoir	1929-62	1965-83	--	--	--	HS	29	7	MS	330,000	14
57	Joes Valley Reservoir	1947-65	1966-83	--	--	--	--	--	--	--	--	--
61	Navajo Reservoir	1956-61	1964-83	--	--	--	--	--	--	--	--	--
68	Navajo Reservoir	1930-61	1964-83	--	--	--	MS	47	11	--	--	--
69	Lake Powell filling	1942-62	1966-80	S	-2,705,000	24	--	--	--	HS	-1,588,000	19

[1]Percent of preintervention median.

confluence and Lee Ferry, Ariz. (pl. 1). These regions are called the Grand, Green, and San Juan regions.

This section contains a summary and analysis of the historical streamflow and water-quality records at the 70 selected sites. The analysis includes determination of annual and monthly means and results of trend analyses. Predominant cations and anions are reported, based on fraction of the dissolved-solids load. Bicarbonate is considered the primary form of dissolved carbon in the carbonate-equivalent fraction. Sodium is considered the primary component of the sodium-plus-potassium fraction.

Significant differences between the preintervention and postintervention periods at sites downstream from major interventions are reported as the step trends in the median values. The percentage change from the preintervention median also is reported. Monotonic trends are reported as the annual rate of change of the median value during the period of analysis. An estimate of the percentage change in median from the beginning to the end of the period also is reported. This change is computed using the ratio of the total change during the period over the estimated median at the beginning of the period:

$$\Delta m = 100 \left\{ \frac{n|T|}{M - T(n+1)/2} \right\} \quad (5)$$

where

Δm = the change in median, in percent;
n = the number of years;
T = the monotonic trend per year; and
M = the median for the entire period.

The denominator $[M - T(n+1)/2]$ estimates the median value for the beginning of the period. The median dissolved-solids concentration was used for evaluating the percentage change in flow-adjusted concentration. For sites having records divided into preintervention and postintervention periods, the monotonic trends for each period are presented. Trends are not reported if the period of record for a site is less than 10 years.

The period of record for the 70 sites ranges from 3 to 55 years. Therefore, results commonly cannot be compared between sites because of differences in the period of record. Streamflow hydrograph analyses were based on the entire period of record for streamflow and not confined to the period of concurrent water-quality record. For this reason streamflow analyses may have a different period of record than the dissolved-solids analyses throughout the report.

Grand Region

Most of the streamflow of the Colorado River in the Grand region originates on the western slope of the Rocky Mountains in Colorado. Areas in Utah contribute only minor quantities to the total streamflow from this region. The drainage area in the Grand region is about 27,000 mi^2. The Grand region comprises 24 percent of the total drainage area in the Upper Colorado River Basin; it contributes 47 percent of the streamflow and 51 percent of the total dissolved-solids load that leaves the Upper Colorado River Basin at Lee Ferry, Ariz. The major tributaries in the Grand region are the Eagle, Roaring Fork, Gunnison, and Dolores Rivers.

Data from 21 sites were evaluated for the Grand region (pl. 1). Long-term mean annual runoff, streamflow, dissolved-solids concentration and load, and major-constituent load were determined at each of these sites (table 5). Collins diagrams of chemical composition at several sites are shown in figure 7. The carbonate plus bicarbonate concentration in these diagrams was computed from the carbonate equivalent of alkalinity, and assuming that bicarbonate is the dominant species. Significant annual monotonic trends in the data for sites in the Grand region are reported in table 6. For purposes of discussion, the Grand region was divided into three subregions: the upper Colorado, the Gunnison, and the lower Colorado (pl. 1).

Upper Colorado Subregion

The upper Colorado subregion includes the drainage area of the Blue, Eagle, Roaring Fork, and Fraser Rivers and tributaries, and Plateau, Roan, Parachute, and Rifle Creeks. The upper Colorado subregion also includes the main-stem Colorado River from its headwaters in the mountains to the confluence with the Gunnison River.

Numerous reservoirs and diversions affect the streamflow in this subregion. The Alva B. Adams Tunnel/Lake Granby diversion and storage system is the largest transbasin export in the entire Upper Colorado River Basin. The Alva B. Adams Tunnel and Shadow Mountain Reservoir were completed in 1947, but major diversions did not begin until the completion of Lake Granby in 1950. Lake Granby stores water from the main stem of the Colorado River during the snowmelt season. Water then is pumped into Shadow Mountain Reservoir, which is continuous with Grand Lake. Diversions from Grand Lake via the Alva B. Adams Tunnel to the South Platte River basin are large during all months, except June, and average about 250,000 acre-ft/yr (table 1).

Homestake Tunnel and Reservoir have diverted water from the Eagle River basin since 1967. The Moffat Water Tunnel has diverted water from the Fraser River basin since 1936. The H.D. Roberts Tunnel, operating in conjunction with Dillon Reservoir, has diverted water from the Blue River basin since 1963. The Twin Lakes Tunnel (1935) and the C.H. Boustead Tunnel (1972) divert water from the Roaring Fork River basin. Ruedi Reservoir (1968) provides regulation of streamflow downstream from the diversions to the C.H. Boustead Tunnel.

Table 5. Mean annual values of runoff, streamflow, dissolved-solids concentrations and loads, and major-constituent loads—Grand region
[Periods of record for some sites are divided into preintervention and postintervention periods; asterisks indicate main-stem sites; mg/L, milligrams per liter; - -, not applicable]

Site (table 3, plate 1)	Period of record (water years)[1]	Runoff (inches)	Streamflow (acre-feet)	Streamflow (cubic feet per second)	Dissolved solids: Flow-weighted concentration (mg/L)	Dissolved solids: Load (tons)	Major-constituent loads (tons): Calcium	Magnesium	Sodium plus potassium	Carbonate equivalent[2]	Chloride	Sulfate
1	1976-83	--	229,000	317	29	9,000	2,100	400	1,000	4,100	100	1,400
2*	1947-83	4.45	196,000	270	70	19,000	4,450	800	2,000	9,300	400	1,800
3	1947-83	9.10	410,000	566	288	160,000	32,300	6,400	14,300	30,600	18,300	58,400
4*	1959-83	6.16	1,444,000	1,990	213	418,000	86,000	18,000	38,400	112,000	36,200	128,000
5*	1942-49	7.58	1,844,000	2,550	231	579,000	98,600	21,800	82,400	125,000	105,000	146,000
5*	1950-83	6.39	1,553,000	2,140	267	565,000	95,700	20,000	81,500	120,000	105,000	142,000
6	1959-83	11.20	867,000	1,200	245	288,000	66,400	11,100	19,500	73,900	20,500	97,000
7	1975-82	2.18	23,000	32	528	17,000	2,060	1,300	2,300	5,400	300	5,200
8*	1973-82	6.33	2,490,000	3,440	395	1,336,000	184,000	42,200	247,000	229,000	324,000	310,000
9	1975-80	2.49	43,000	59	568	33,000	3,720	2,800	4,700	11,600	400	9,800
10*	1934-49	6.96	2,990,000	4,130	364	1,481,000	212,000	52,300	258,000	275,000	331,000	354,000
10*	1950-83	6.22	2,671,000	3,690	398	1,446,000	203,000	47,400	261,000	260,000	330,000	345,000
11	1969-79	3.94	124,000	172	340	57,000	8,330	4,100	8,000	24,500	1,300	11,200
12	1959-80	3.32	200,000	276	1,260	344,000	51,200	16,400	35,400	31,500	3,800	205,000
13	1934-65	3.87	1,636,000	2,260	610	1,357,000	204,000	69,700	144,000	181,000	22,400	736,000
13	1966-83	4.00	1,691,000	2,330	557	1,281,000	196,000	68,900	127,000	176,000	19,700	694,000
14	1974-80	19.30	15,000	21	1,220	25,000	3,610	1,200	3,200	2,200	2,700	12,600
15	1974-83	45.50	70,000	97	1,360	130,000	18,300	7,000	15,000	10,400	13,300	66,200
16	1974-82	23.10	18,000	26	914	23,000	3,250	900	3,200	2,100	3,500	10,000
17	1974-83	2.92	68,000	94	1,360	125,000	16,000	6,700	15,300	9,600	11,500	66,200
18*	1962-83	4.56	4,340,000	5,990	583	3,438,000	486,000	162,000	463,000	483,000	368,000	1,480,000
19	1974-79	2.79	223,000	308	330	100,000	19,600	5,800	5,600	19,300	1,600	48,000
20	1952-83	2.38	582,000	803	584	462,000	48,500	14,300	97,800	54,900	132,000	114,000
21*	1929-49	4.19	5,391,000	7,440	580	4,255,000	563,000	203,000	621,000	592,000	443,000	1,830,000
21*	1950-65	3.57	4,595,000	6,340	615	3,843,000	521,000	170,000	565,000	487,000	501,000	1,600,000
21*	1966-83	3.72	4,784,000	6,600	565	3,677,000	494,000	160,000	547,000	525,000	514,000	1,440,000

[1]All mean values are based only on those water years having estimates of the major constituents.
[2]Carbonate equivalent is computed from alkalinity; bicarbonate is the primary dissolved form.

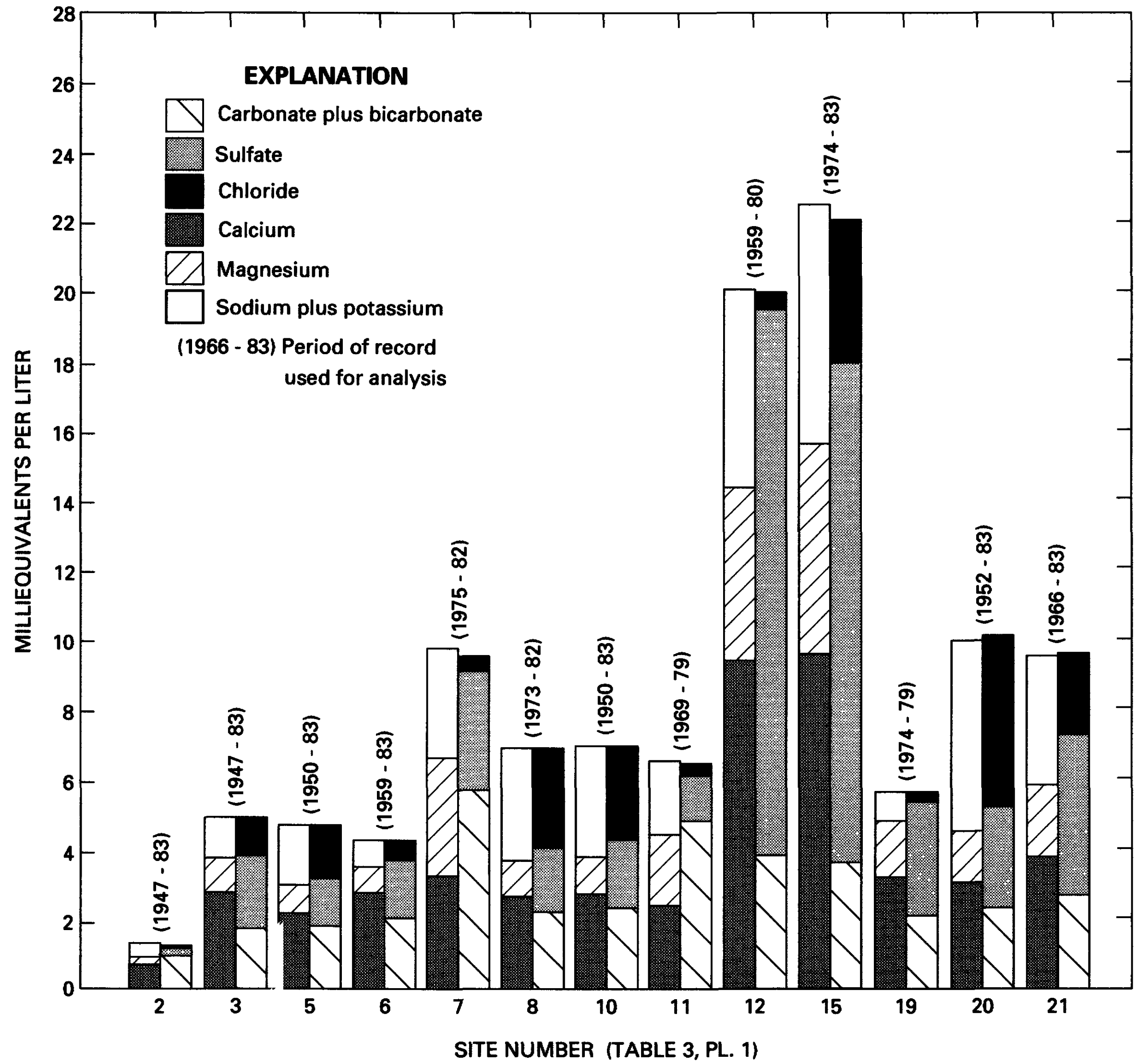


Figure 7. Mean chemical composition of dissolved solids at selected sites in Grand region. Cations on left, anions on right.

Alva B. Adams Tunnel at East Portal near Estes Park, Colo. (site 1)

The gaging station at site 1 (table 3, pl. 1) monitors water exported from Grand Lake. Although samples collected at this site do not represent an actual streamflow, they do represent the water quality in the headwaters of the Colorado River. During 1976–83, the flow-weighted dissolved-solids concentration averaged 29 mg/L (table 5), the lowest of any site in the entire Upper Colorado River Basin. Chemical composition is predominantly calcium and bicarbonate. About 9,000 tons of dissolved solids is removed annually from Grand Lake through the tunnel. However, the principal effect of this diversion is to remove relatively pure water from the stream system.

Colorado River at Hot Sulphur Springs, Colo. (site 2)

The streamflow at site 2 (table 3, pl. 1) is about 32 percent of its preintervention quantity, mainly because of exports through the Moffat Water Tunnel and the Alva B. Adams Tunnel (fig. 8*A*). The mean annual flow-weighted dissolved-solids concentration is 70 mg/L and the mean annual streamflow is 196,000 acre-ft (table 5). Monthly dissolved-solids concentration is relatively constant, varying between 59 and 89 mg/L. Calcium and bicarbonate are the predominant ions throughout the year. From 1947 to 1983, annual monotonic-trend analyses indicated a significant increase in median annual dissolved-solids concentration of 0.4 mg/L per year (table 6). This trend represents

Table 6. Selected annual monotonic-trend-analysis results—Grand region

[Sites having less than 10 years of dissolved-solids data are not reported; *n*, number of years of dissolved-solids data; acre-ft/yr, acre-feet per year; mg/L, milligrams per liter; tons/yr, tons per year; HS, highly significant (p ⩽ 0.01); S, significant (0.01 < p ⩽ 0.05); MS, marginally significant (0.05 < p ⩽ 0.10); - -, not significant (p > 0.10)]

Site (table 3, plate 1)	Period of record (water years)	*n*	Annual trend in streamflow: Significance level	Annual trend in streamflow: Trend (acre-ft/yr)	Annual trend in streamflow: Percent[1]	Annual trend in dissolved solids — Concentration: Significance level	Concentration: Trend (mg/L)	Concentration: Percent[1]	Load: Significance level	Load: Trend (tons/yr)	Load: Percent[1]	Flow-adjusted concentration: Significance level	Flow-adjusted concentration: Trend (mg/L)	Flow-adjusted concentration: Percent[1]
2	1947-83	37	--	--	--	S	0.4	22	--	--	--	--	--	--
3	1947-83	37	--	--	--	S	-1.9	21	HS	-1,250	26	HS	-2.1	23
4	1959-83	25	--	--	--	S	-2.4	24	--	--	--	HS	-1.0	11
5	1950-83	34	--	--	--	--	--	--	--	--	--	--	--	--
6	1959-83	25	--	--	--	--	--	--	--	--	--	--	--	--
8	1973-82	10	--	--	--	--	--	--	--	--	--	--	--	--
10	1934-49	16	--	--	--	MS	-5.8	21	--	--	--	--	--	--
10	1950-83	34	--	--	--	--	--	--	--	--	--	--	--	--
11	1969-79	11	--	--	--	--	--	--	--	--	--	--	--	--
12	1959-80	22	--	--	--	HS	-20.4	30	S	-3,810	22	HS	-19.3	28
13	1934-65	32	--	--	--	--	--	--	--	--	--	S	-2.8	13
13	1966-83	18	--	--	--	S	-16.1	39	--	--	--	HS	-9.9	26
15	1974-83	10	S	1,620	26	S	-38.4	25	MS	-2,770	19	MS	-37.0	25
17	1974-83	10	S	2,220	40	--	--	--	--	--	--	--	--	--
18	1962-83	22	--	--	--	MS	-11.2	34	--	--	--	HS	-4.8	16
20	1952-83	32	--	--	--	--	--	--	HS	4,990	46	HS	4.7	24
21	1929-49	21	--	--	--	--	--	--	--	--	--	--	--	--
21	1950-65	16	--	--	--	--	--	--	--	--	--	--	--	--
21	1966-83	18	--	--	--	--	--	--	--	--	--	MS	-2.9	9

[1]Percent change during period of record.

a 22-percent increase in median annual concentration during the 37-year period. The monotonic trend in median annual streamflow since 1947 was not statistically significant, perhaps because of the large annual variability and the large streamflow volume during 1983.

Eagle River at Gypsum, Colo. (site 3)

Although the streamflow at site 3 (table 3, pl. 1) is comparable to the Colorado River preintervention streamflow at site 2, the dissolved-solids concentration is much higher. The mean annual flow-weighted dissolved-solids concentration is 288 mg/L, and the mean annual streamflow is about 410,000 acre-ft (table 5). Sources of dissolved solids include mining operations and surface outcrops of Pennsylvanian sedimentary formations. Outcrops of the Eagle Valley Evaporite contain thick salt beds (Warner and others, 1985). During the snowmelt season (May–July), calcium and bicarbonate are the predominant ions. Calcium and sulfate predominate during the remainder of the year. The Homestake Tunnel has only slightly affected the streamflow of the Eagle River (fig. 8*B*).

Although streamflow has not changed significantly, dissolved solids decreased during 1947–83. Annual monotonic-trend analyses indicated a significant decrease in median annual dissolved-solids concentrations of 1.9 mg/L per year, and highly significant decreases in values of median annual dissolved-solids load of 1,250 tons/yr and flow-adjusted concentration of 2.1 mg/L per year (table 6). During the 37-year period, these trends represent a 21-percent decrease in median annual concentration, a 26-percent decrease in median annual load, and a 23-percent decrease in median annual flow-adjusted concentration. Median annual flow-adjusted concentrations of all major constituents also decreased. The cause of the decrease is unknown, but may be related to the change from mining and agricultural land uses to recreational land use.

Colorado River near Dotsero, Colo. (site 4)

Streamflow at site 4 averages approximately 1.4 million acre-ft/yr, and the mean annual flow-weighted dissolved-solids concentration is about 213 mg/L (table 5). Calcium and bicarbonate are the predominant ions throughout the year. Sulfate also is a predominant ion during the low-flow season because of the large load contributed by the Eagle River. During 1959–83, annual monotonic-trend analyses indicated a significant decrease in median annual dissolved-solids concentration of 2.4 mg/L per year and a highly significant decrease in median annual flow-adjusted concentration

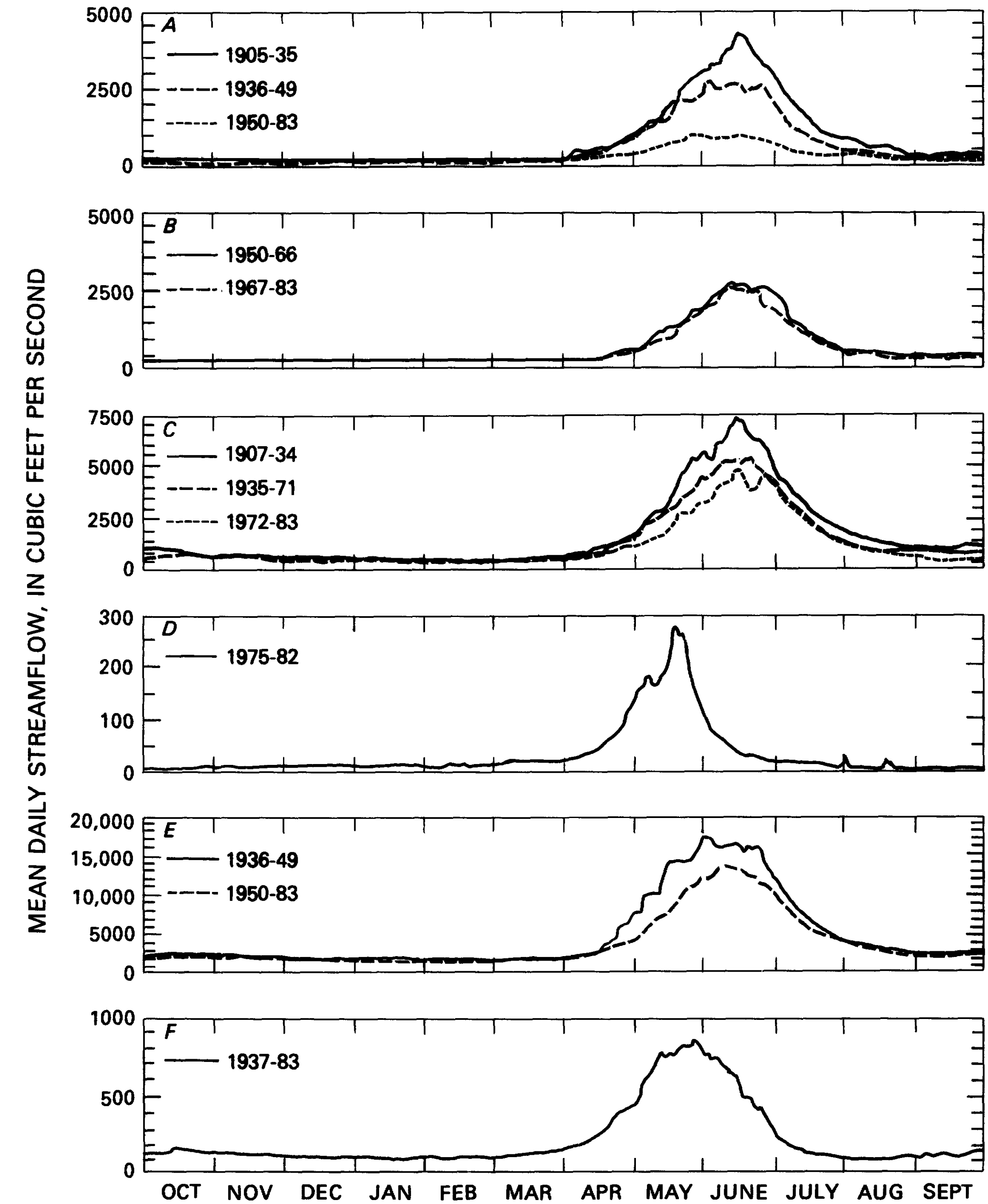


Figure 8. Mean daily streamflow at selected sites in upper Colorado subregion of Grand region (see pl. 1). *A*, Site 2, Colorado River at Hot Sulphur Springs, Colo. *B*, Site 3, Eagle River at Gypsum, Colo. *C*, Site 6, Roaring Fork River at Glenwood Springs, Colo. *D*, Site 7, Parachute Creek at Parachute, Colo. *E*, Site 10, Colorado River near Cameo, Colo. *F*, Site 11, Plateau Creek near Cameo, Colo.

of 1 mg/L per year (table 6). During the 25-year period, these trends represent a 24-percent decrease in median annual concentration and a 11-percent decrease in median annual flow-adjusted concentration. These decreases are comparable to the annual monotonic trends at site 3, along the Eagle River, which is the major tributary upstream.

Colorado River near Glenwood Springs, Colo. (site 5)

Site 5 (table 3, pl. 1) is located at the Shoshone Power Plant, 10 mi downstream from site 4 and 6 mi upstream from the town of Glenwood Springs. Streamflow is comparable to streamflow at site 4, but approximately 150,000 tons of dissolved solids is added annually between sites 4 and 5, 70 percent as dissolved sodium and chloride. Most of this dissolved-solids load is contributed by very saline, thermal springs between the towns of Dotsero and Glenwood Springs (Iorns and others, 1965; Warner and others, 1985). Dissolved-solids concentration at site 5 averages 18 mg/L higher in dissolved sodium and 30 mg/L higher in dissolved chloride than at site 4. Calcium and bicarbonate are the predominant ions during the snowmelt season. Sodium, calcium, and chloride are predominant during the low-flow season. The mean monthly loads of dissolved sodium and chloride are relatively constant throughout the year.

The period of record was divided into a preintervention period (1942–49) and a postintervention period (1950–83), based on the Alva B. Adams Tunnel/Lake Granby exports. The annual step trend in streamflow was −330,000 acre-ft, a significant decrease of 18 percent from the preintervention median streamflow (table 4). The annual step trend in dissolved-solids concentration was 39 mg/L, a highly significant increase of 17 percent from the preintervention median concentration. Dissolved-solids load did not change significantly. Monthly step trends indicated a significant decreasing streamflow and a highly significant increasing dissolved-solids concentration during the snowmelt season when water is stored in Lake Granby (fig. 9).

Annual monotonic-trend analysis for the preintervention period indicated increased streamflow and decreased dissolved-solids concentration during January through March. No significant annual monotonic trends were indicated for the postintervention period.

Roaring Fork River at Glenwood Springs, Colo. (site 6)

Site 6 (table 3, pl. 1) has a mean annual flow-weighted dissolved-solids concentration of 245 mg/L (table 5). The high mountains that form the headwaters region of the Roaring Fork River are the source of large volumes of water. The mean annual streamflow of the Roaring Fork River is about 867,000 acre-ft (table 5). Approximately 35,000 acres of irrigated farmland is in the downstream reaches of the river basin, which contain outcrops of Cretaceous sedimentary rocks. Mancos Shale, which contains relatively soluble deposits of gypsum (calcium sulfate) and trona (sodium carbonate and sodium bicarbonate), is exposed in a large area along the river and may be responsible for higher dissolved-solids concentrations. The Eagle Valley Evaporite also is exposed. The predominant ions are calcium and bicarbonate during the snowmelt season and calcium and sulfate during the low-flow season. The Twin Lakes Tunnel and C.H. Boustead Tunnel/Ruedi Reservoir each have caused decreases in peak flow at this site (fig. 8*C*). Large quantities of gypsum were leached from the bank material shortly after construction of Ruedi Reservoir (J.W. Yahnke, U.S. Bureau of Reclamation, written commun., 1982). No statistically significant annual monotonic trends were detected for this site.

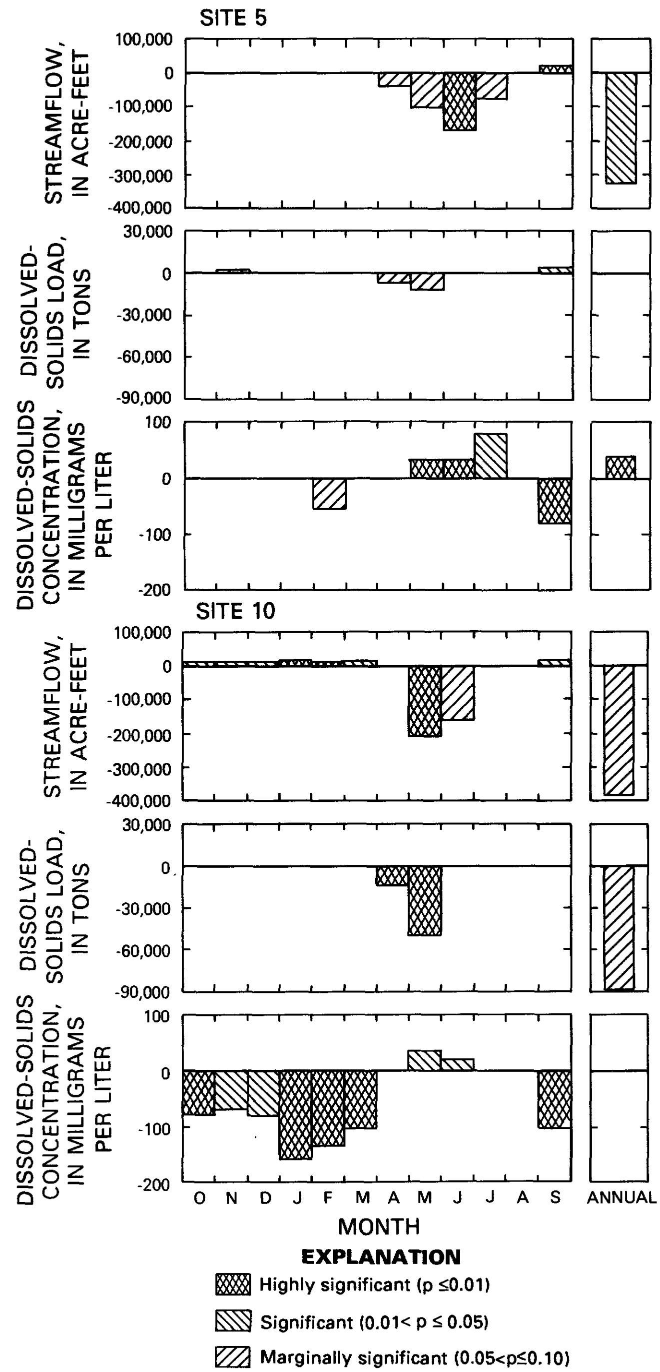


Figure 9. Step trends at site 5 (Colorado River near Glenwood Springs, Colo.) from 1942–49 to 1950–83 and at site 10 (Colorado River near Cameo, Colo.) from 1934–49 to 1950–83.

Parachute Creek at Parachute, Colo. (site 7)

Site 7 (table 3, pl. 1) has a mean annual flow-weighted dissolved-solids concentration of 528 mg/L and a mean annual streamflow of 23,000 acre-ft (table 5). Parachute Creek drains Roan Mesa located north of the Colorado River. In the drainage basin, Tertiary sedimentary rocks are exposed, including the Parachute Creek Member of the Green River Formation, which contains oil-shale deposits. Magnesium and calcium are the predominant cations during the high-streamflow season (April–June). Sodium and magnesium predominate during low streamflow. Bicarbonate is a predominant anion throughout the year. During the low-flow season sulfate also is predominant. Streamflow has a large snowmelt peak in May (fig. 8*D*); this occurs earlier than sites upstream, which are at higher elevations. Characteristics of streamflow are very similar to those at site 9 (Roan Creek near DeBeque, Colo.).

Colorado River near DeBeque, Colo. (site 8)

Mean annual flow-weighted dissolved-solids concentration at site 8 (table 3, pl. 1) averaged about 395 mg/L, and mean annual dissolved-solids load was about 1.34 million tons during 1973–82 (table 5). The predominant ions are calcium and bicarbonate during the snowmelt season and sodium and chloride during the low-flow season. Large quantities of dissolved solids are added to the Colorado River in the reach between sites 5 and 8. No statistically significant annual monotonic trends were detected at this site.

The reach of the Colorado River between the towns of Dotsero and Glenwood Springs, Colo., represents the largest single source of dissolved solids in the Upper Colorado River Basin. The dissolved-solids load contributed in that reach was estimated by subtracting mean annual dissolved-solids loads at sites 4, 6, and 7 from the mean annual dissolved-solids load at site 8 and further subtracting dissolved-solids loads from other known, small-stream inflows that have an estimated dissolved-solids concentration of 600 mg/L. This resulted in an estimate of 475,000 tons/yr of dissolved solids contributed in the reach between Dotsero and Glenwood Springs, Colo. Seventy-three percent of this dissolved-solids load is dissolved sodium and chloride, which represents 17 percent of the dissolved-sodium and 38 percent of the dissolved-chloride loads leaving the Upper Colorado River Basin. Other estimates of the mean annual dissolved-solids load contributed by the thermal springs include 440,000 tons (U.S. Department of the Interior, 1985), 534,000 tons (Warner and others, 1985), and 476,000 tons (Iorns and others, 1965).

Roan Creek near DeBeque, Colo. (site 9)

Streamflow characteristics at site 9 are similar to those at site 7. Both sites record runoff from Roan Mesa; however, streamflow and dissolved-solids load are greater at site 9 because of its larger drainage area. Dissolved-solids concentration and chemical composition are similar at both sites.

Colorado River near Cameo, Colo. (site 10)

Streamflow hydrographs for site 10 (table 3, pl. 1) depict the cumulative effect of reservoirs and transbasin exports (fig. 8*E*). The snowmelt-runoff peak has decreased, and a slight increase in flow has occurred during the remainder of the year. A base flow of about 500 ft^3/s is maintained throughout the year. The effect of development before 1935 is not depicted because of the lack of streamflow-gaging data. Chemical composition of streamflow is related to the primary sources of dissolved solids in the region. During the snowmelt season, calcium and bicarbonate are the predominant ions. During the base-flow period, when the thermal springs in the Glenwood Springs and Dotsero areas contribute a greater proportion of the streamflow, sodium and chloride are predominant.

The period of record was divided into a preintervention period (1934–49) and a postintervention period (1950–83), based on the Alva B. Adams Tunnel/Lake Granby exports. The annual step trend in streamflow was about −385,000 acre-ft, a marginally significant decrease of 13 percent from the preintervention median (table 4). This change was comparable in magnitude to the decrease at site 5. In contrast to site 5, the annual step trend in dissolved-solids load was about −89,000 tons, a marginally significant decrease of 6 percent, but dissolved-solids concentration did not change significantly. These differences apparently resulted from decreases in dissolved-solids concentration at site 10 during the base-flow period (September–March), which did not occur at site 5 (fig. 9). The decreases in dissolved-solids concentration may have been caused by the cumulative effect of upstream reservoirs, which also produced small, but significant, increases in streamflow at site 10 during the base-flow period.

Annual monotonic-trend analysis for the preintervention period indicated a marginally significant decrease in median annual dissolved-solids concentration of 5.8 mg/L per year (table 6). This trend represents a 21-percent decrease in median annual concentration during the 16-year period. Monthly trends indicated enhanced streamflow and corresponding decreases in dissolved-solids concentration during the low-flow season. Although no significant annual monotonic trends were indicated for the postintervention period, monthly trends again indicated increased streamflow and decreased dissolved-solids concentration during the low-flow season.

Plateau Creek near Cameo, Colo. (site 11)

The water at site 11 (table 3, pl. 1), which is drained from Grand Mesa along the southern side of the Colorado River, is less saline than that of Parachute and Roan Creeks (sites 7 and 9) and has a larger proportion of dissolved bicarbonate. The mean annual flow-weighted dissolved-solids concentration is about 340 mg/L, and the mean annual streamflow is about 124,000 acre-ft (table 5). The site is downstream from many small reservoirs and about 25,000 acres of irrigated farmland; its streamflow hydrograph is characterized by a late-May snowmelt peak and a well-sustained base flow (fig. 8*F*). The Tertiary Wasatch Formation and Cretaceous Ohio Creek Member of the Hunter Canyon Formation that underlie much of the drainage basin do not contain large quantities of soluble material; streamflow contains relatively high concentrations of dissolved magnesium and bicarbonate but low concentrations of dissolved sulfate. During the snowmelt season, calcium and bicarbonate are the predominant ions. Sodium, calcium, magnesium, and bicarbonate predominate during the low-flow season. No statistically significant annual monotonic trends were detected during 1969–79.

Gunnison Subregion

The drainage area of the Gunnison subregion (pl. 1) is about 8,000 mi^2. The Gunnison River is the largest tributary to the Colorado River in Colorado and originates in high mountainous terrain. Irrigation in the Gunnison subregion began about 1890, and more than 200,000 acres was irrigated during 1986, of which about 90,000 acres is along the Uncompahgre River, about 20,000 acres is along Tomichi Creek in the upper Gunnison area, and most of the remainder is near the town of Delta, Colo., in the lower reaches of the Gunnison basin. The large Uncompahgre and lower Gunnison areas are underlain by Mancos Shale. Irrigation water applied to land underlain by Mancos Shale causes weathering and dissolution of mineral salts from the soils and underlying shale. As a result, the water returns to the river with a larger dissolved-solids load than it had before it was diverted (Iorns and others, 1965). Annual agricultural dissolved-solids loading has been estimated at 360,000 tons from the Uncompahgre Valley and 480,000 tons from the lower Gunnison area (U.S. Department of the Interior, 1985), which makes the Gunnison subregion the largest agricultural source of dissolved solids in the Upper Colorado River Basin.

Three small transbasin diversions, the Larkspur, Tabor, and Tarbell ditches export water from the Gunnison River subregion to the Arkansas River and Rio Grande basins. Large volumes of water are diverted within the subregion through the Gunnison Tunnel, which transports water from the Gunnison River to the Uncompahgre Valley. Diversions through the tunnel began in 1910, totaled 117,000 acre-ft during 1915, 250,000 acre-ft during 1930, and 352,000 acre-ft during 1950. Taylor Park Dam was built in 1935 for storage as part of the Uncompahgre Project.

Three large dams were built for power generation and water storage on the main stem of the Gunnison River as part of the Colorado River Storage Project. Together the reservoirs constitute the Wayne N. Aspinall Unit, formerly known as the Curecanti Unit. The largest and farthest upstream is Blue Mesa Reservoir; the others are Morrow Point Reservoir and Crystal Reservoir.

Uncompahgre River at Delta, Colo. (site 12)

Streamflow at site 12 (table 3, pl. 1) is affected by imports from the Gunnison Tunnel from April through October and by substantial evapotranspiration from irrigated croplands. The streamflow hydrograph for site 12 is characterized by a modest snowmelt-runoff peak during May and June and a prominent irrigation-return flow period lasting from September through mid-November (fig. 10*A*). Calcium and sulfate are the predominant ions during the entire year. Dissolved sulfate makes up about 60 percent of the dissolved-solids load. The river also transports large loads of dissolved sodium, magnesium, and bicarbonate, but only a small load of dissolved chloride. Annual flow-weighted dissolved-solids concentration averages about 1,260 mg/L (table 5).

Annual flow of the Uncompahgre River at site 12 did not change significantly during 1959–80, but dissolved-solids concentration and load have decreased since the late 1960's. Annual monotonic-trend analyses indicated highly significant decreases in median annual values of dissolved-solids concentration of 20.4 mg/L per year and flow-adjusted concentration of 19.3 mg/L per year, and a significant decrease in median annual dissolved-solids load of 3,810 tons/yr (table 6). During the 22-year period, these trends represent a 30-percent decrease in median annual concentration, a 28-percent decrease in median annual flow-adjusted concentration, and a 22-percent decrease in median annual load. All major constituents, except dissolved bicarbonate, decreased significantly in concentration and flow-adjusted concentration. Flow-adjusted concentration decreased during all months. The reason for this decline is unknown, but it may be related to regulation and storage by Blue Mesa Reservoir, which is downstream from the irrigated areas in the upper reaches of the Gunnison River and upstream from the diversion point of the Gunnison Tunnel.

Gunnison River near Grand Junction, Colo. (site 13)

Streamflow hydrographs for site 13 (table 3, pl. 1) are shown in figure 10*B*. During 1897–1906, a flattening of the snowmelt-runoff peak from diversions for agriculture occurred; the peak further decreased after 1906 because of irrigation diversions through the Gunnison Tunnel. Regulation by reservoirs in the Wayne N. Aspinall Unit after 1965 has not decreased the annual flow of the Gunnison River but has approximately halved the flow during the snowmelt season and doubled the flow during the base-flow period. Streamflow and dissolved-solids concentration are less variable throughout the year, and from year to year. As at site 12, the dissolved-solids composition is predominantly calcium and sulfate, with small quantities of sodium, magnesium, and bicarbonate. Although the chemical composition of streamflow is similar to that of the Uncompahgre River, the dissolved-solids concentration is lower because of dilution from the main stem of the Gunnison River.

The period of record at site 13 was divided into a preintervention period (1934–65) and a postintervention period (1966–83), based on the completion of Blue Mesa Dam. The annual step trends in streamflow and dissolved-solids concentration were not significant, but a marginally significant decrease of 119,000 tons in dissolved-solids load

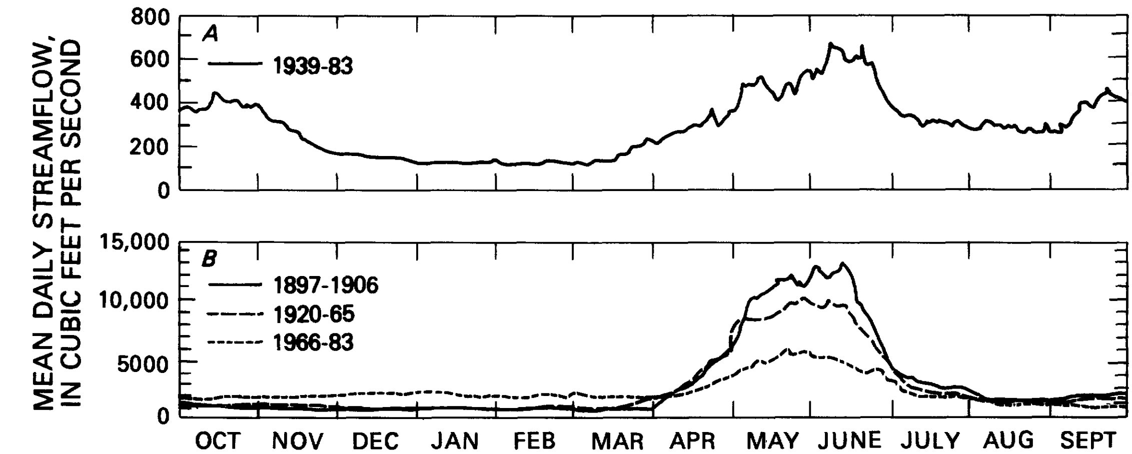


Figure 10. Mean daily streamflow at selected sites in Gunnison subregion of Grand region. *A*, Site 12, Uncompahgre River at Delta, Colo. *B*, Site 13, Gunnison River near Grand Junction, Colo.

was identified (table 4). This decrease is 8 percent of the preintervention median. It corresponds in magnitude with the decrease in the load at site 12 on the Uncompahgre River, which is tributary to the Gunnison River upstream from site 13. Monthly step-trend decreases in dissolved-solids concentration of about 600 mg/L occurred during the low-flow season of August through March; corresponding increases in streamflow also occurred (fig. 11). Streamflow and dissolved-solids load decreased during the snowmelt period of May and June, and dissolved-solids concentration increased slightly during May.

Annual monotonic-trend analysis for the preintervention period indicated a significant decrease in median annual flow-adjusted concentration of 2.8 mg/L per year, a 13-percent decrease in the median during the 32-year period. During the postintervention period, annual monotonic-trend analyses indicated a significant decrease in median annual dissolved-solids concentration of 16.1 mg/L per year and a highly significant decrease in median annual flow-adjusted concentration of 9.9 mg/L per year. These trends represent a 39-percent decrease in median annual concentration and a 26-percent decrease in median annual flow-adjusted concentration during the 18-year period. The postintervention trends may be related to the completion of Morrow Point and Crystal Reservoirs downstream from Blue Mesa Reservoir.

Lower Colorado Subregion

The lower Colorado subregion includes the drainage areas of the Dolores River and its tributaries and the Colorado River between Grand Junction, Colo., and the confluence with the Green River. About 70,000 acres is irrigated along the Colorado River in the Grand Valley near Grand Junction. Irrigation water for about 32,000 acres is supplied by the Grand Valley Canal (constructed before 1900) and Redlands Power Canal. The remaining area is supplied by the Government Highline Canal built by the Federal Grand Valley Project in 1917. This canal takes water diverted from a dam across the Colorado River upstream from Grand Junction and transports it to cropland parallel to the river for 55 mi. Total irrigation diversions averaged 400,000 acre-ft/yr by the early 1930's. Consumptive use by irrigation has been estimated at 247,000 acre-ft/yr (U.S. Bureau of Reclamation, 1985a). Most of the irrigated land in the Grand Valley is underlain by Cretaceous Mancos Shale, which is a source of mineral salts dissolved in irrigation-return flow. The U.S. Bureau of Reclamation (1985a) estimated that 580,000 tons of dissolved solids per year is added to the Colorado River in the Grand Junction area. As part of the Colorado River Basin Salinity Control Program, the lining of canals and laterals has been started. The completed project will decrease the dissolved-solids input by an estimated 140,000 tons/yr. Stage I of the project, affecting about 10 percent of the irrigated area, was completed in April 1983.

Approximately 28,000 acres is irrigated within the San Miguel River basin and about 7,000 acres in the remainder of the Dolores River basin. About 116,000 acre-ft of water is exported annually from the Dolores River to Montezuma Valley in the San Juan River basin for irrigation of 37,000 acres (U.S. Forest Service and others, 1976). The Dolores Project, under construction since 1977, will export an additional 81,000 acre-ft/yr of water to the San Juan River basin.

The Dolores River channel crosses Paradox Valley, one of a series of collapsed salt anticlines in the Paradox Basin. The river flows directly across the soluble Paradox Member of the Hermosa Formation, which is composed of about 14,000 ft of halite and halite-rich shale. As specified in Title II of the Colorado River Basin Salinity Control Act, construction of salinity-control facilities in the Paradox Valley

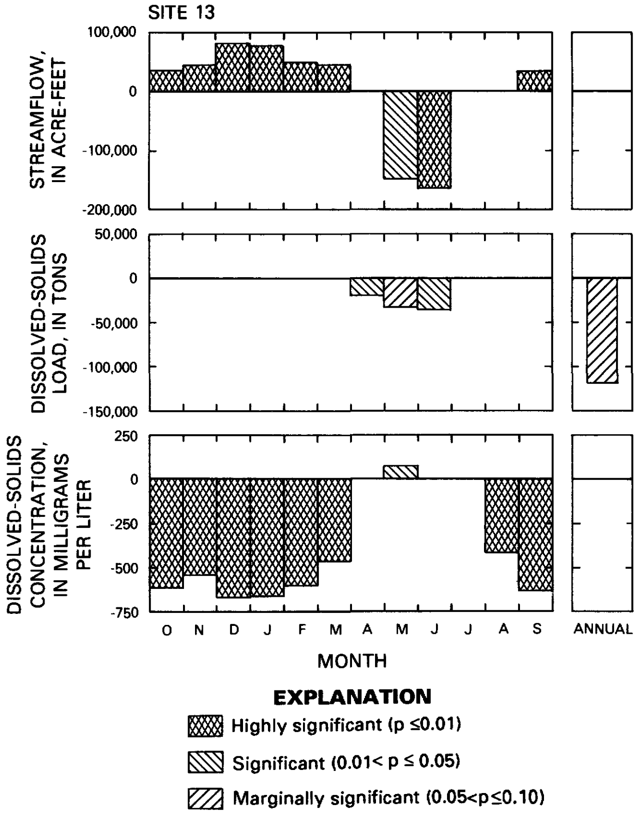


Figure 11. Step trends at site 13 (Gunnison River near Grand Junction, Colo.) from 1934–65 to 1966–83.

area was authorized, the goal of which was to remove 180,000 tons of dissolved solids per year from the Dolores River.

Adobe Creek near Fruita, Colo. (site 14)

Streamflow at site 14, like streamflow at sites 15, 16, and 17 (table 3, pl. 1), is composed almost entirely of irrigation-return flows and excess irrigation waters from the Grand Valley agricultural area. During 1974–80, mean annual flow-adjusted dissolved-solids concentration averaged 1,220 mg/L (table 5). Calcium and sulfate are the predominant ions throughout the year. Sodium and magnesium constitute a large fraction of the cation composition from November through March. Dissolved sulfate comprises about 49 percent of the dissolved-solids load. This composition is typical of agricultural return flow from areas underlain by gypsiferous shale.

Reed Wash near Loma, Colo. (site 15)

The streamflow hydrograph for site 15 (table 3, pl. 1) during 1974–83 shows the effect of irrigation waters in the streams that drain the Grand Valley agricultural area (fig. 12*A*). Irrigation waters return to the stream system rather quickly, but accumulate large dissolved-solids loads. Mean monthly dissolved-solids concentration ranged from 970 mg/L during May to 4,000 mg/L during January. As at site 14, streamflow is artificially large because of the water imported into the local area.

Reed Wash drains an area affected by the Grand Valley Unit of the Colorado River Basin Salinity Control Project. Construction of salinity-control features in Grand Valley began in 1980. The period of record at site 15 was not long enough for an annual step-trend analysis, but several annual monotonic trends were detected for 1974–83. Trends indicated significant increases in median annual streamflow of 1,620 acre-ft/yr (table 6) as a result of small increases in streamflow for September through November, possibly from extension of the period of application of irrigation water. Annual monotonic trends indicated a significant decrease in median annual dissolved-solids concentration of about 38 mg/L per year and a marginally significant decrease in median annual flow-adjusted concentration of 37 mg/L per year, as a result of decreases for August through January in the constituents that are dominant in irrigation-return flow (dissolved calcium, magnesium, and sulfate). A marginally significant decrease in median annual dissolved-solids load of 2,770 tons/yr also was detected. During the 10-year period of record, these trends represent a 26-percent increase in median annual streamflow, a 25-percent decrease in median annual dissolved-solids concentration, a 25-percent decrease in median annual flow-adjusted concentration, and a 19-percent decrease in median annual dissolved-solids load.

Mack Wash near Mack, Colo. (site 16)

Site 16 (table 3, pl. 1) is just downstream from Highline Lake and upstream from most of the Grand Valley irrigated area. Therefore, it has a lower dissolved-solids concentration, and its streamflow hydrograph indicated the pattern of releases from Highline Lake.

Salt Creek near Mack, Colo. (site 17)

Most of the drainage basin of Salt Creek is outside the irrigated area of Grand Valley, but the streamflow hydrograph for site 17 (table 3, pl. 1) indicates that most of the water is from irrigation-return flow (fig. 12*B*). Because Mack Wash discharges into Salt Creek, streamflow at site 17 is affected by reservoir releases from Highline Lake, upstream from site 16. During 1974–83, mean annual flow-weighted dissolved-solids concentration at site 17 averaged 1,360 mg/L (table 5). Annual monotonic-trend analyses indicated a significant increase in median annual streamflow of 2,220 acre-ft/yr (table 6), resulting from increased monthly streamflow during August. This trend represents a 40-percent increase in median annual streamflow for the 10-year period.

Although the volumes of streamflow at sites 14, 15, 16, and 17 in the Grand Valley are different, the mean annual dissolved-solids concentrations and the seasonal fluctuations of streamflow and dissolved-solids concentration are similar. Calcium and sulfate are the predominant ions during every

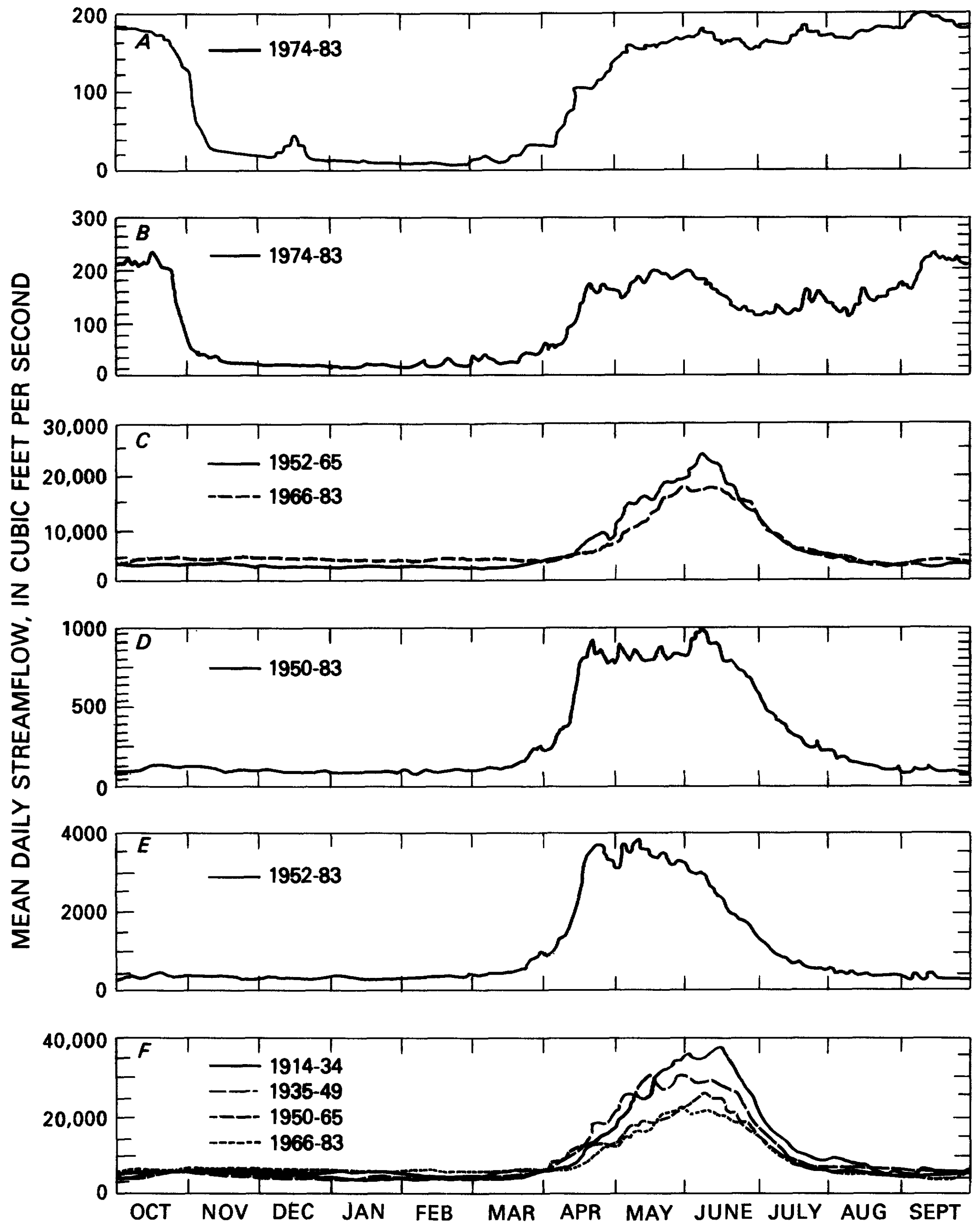


Figure 12. Mean daily streamflow at selected sites in lower Colorado subregion of Grand region. *A*, Site 15, Reed Wash near Loma, Colo. *B*, Site 17, Salt Creek near Mack, Colo. C, Site 18, Colorado River near Colorado-Utah State line. *D*, Site 19, San Miguel River at Uravan, Colo. *E*, Site 20, Dolores River near Cisco, Utah. *F*, Site 21, Colorado River near Cisco, Utah.

month. Sodium also is a predominant cation during the low-flow season. Leaching from the underlying Mancos Shale contributes large quantities of calcium, magnesium, and sulfate. The source water from the Colorado River contains large quantities of sodium and chloride from upstream thermal springs, and the concentration of these constituents in irrigation-return flow is increased because of evapotranspiration. The combined mean annual dissolved-solids load from sites 14, 15, 16, and 17 is about 303,000 tons (table 5). Other sites in the Grand Valley where irrigation-return flow was measured have a combined annual streamflow of 77,000 acre-ft. Assuming a mean dissolved-solids concentration of 1,300 mg/L, the combined annual dissolved-solids load at these sites may be estimated as 136,000 tons. Therefore, the annual dissolved-solids load in measured flow from the Grand Valley is about 439,000 tons. The total load of dissolved solids from the Grand Valley irrigation area is larger because of contributions from ungaged irrigation-return flows and from seepage directly into the Colorado River. Estimates of the mean annual dissolved-solids load from the Grand Valley unit include 497,000 tons, of which 441,000 tons was attributed to agriculture (Iorns and others, 1965), and 580,000 tons (U.S. Bureau of Reclamation, 1985a).

Colorado River near Colorado-Utah State line (site 18)

The streamflow hydrograph for site 18 (table 3, pl. 1) depicts the cumulative effect of transbasin exports, irrigation-return flow, and reservoir regulation (fig. 12*C*). The period after 1966 depicts a decreased snowmelt-runoff peak and increased fall and winter flow, mainly due to storage in and releases from the large reservoirs on the Gunnison River. Mean annual streamflow averaged about 4.3 million acre-ft and dissolved-solids load averaged about 3.4 million tons (table 5). During the snowmelt season, calcium, sulfate, and bicarbonate are the prodominant ions. During the low-flow season, calcium, sodium, and sulfate predominate. Increased dissolved-solids concentration during September and October, when the proportion of dissolved sulfate is largest, indicates the presence of irrigation-return flow. Proportions of dissolved sodium and chloride, which are more indicative of natural base-flow contributions, are largest from January through March. The period of record (1962–83) includes four years of data prior to completion of Blue Mesa Dam.

Annual monotonic-trend analysis indicated a marginally significant decrease in median annual dissolved-solids concentration of 11.2 mg/L per year and a highly significant decrease in median annual flow-adjusted concentration of 4.8 mg/L per year (table 6). During the period of record, these trends represent a 34-percent decrease in median annual dissolved-solids concentration and a 16-percent decrease in median annual flow-adjusted concentration. Flow-adjusted concentration of every constituent except dissolved chloride decreased significantly. These trends correspond with the decreases detected after 1965 in the Gunnison subregion, which does not contribute large quantities of dissolved chloride to the Colorado River.

San Miguel River at Uravan, Colo. (site 19)

The streamflow hydrograph for site 19 (table 3, pl. 1) shows a flattening of the snowmelt-runoff peak caused by diversions for irrigation (fig. 12*D*). Chemical composition of dissolved solids is predominantly dissolved sulfate (fig. 7). Dissolved sodium and chloride are present only in minor proportions. Calcium, bicarbonate, and sulfate are the predominant ions during the snowmelt season, and calcium and sulfate are predominant in base flow. Although a large area is irrigated upstream from the site, the area is not underlain by Mancos Shale; therefore, the dissolved-solids concentration at site 19 is not high and averaged about 330 mg/L during 1974–79 (table 5).

Dolores River near Cisco, Utah (site 20)

The streamflow hydrograph for site 20 (table 3, pl. 1) is similar to the hydrograph for site 19 (fig. 12*E*). Streamflow at site 20 is depleted by irrigation in the San Miguel River basin and by diversions to the Montezuma Valley. The mean annual concentrations of major constituents is about the same as that for site 19, except for much higher concentrations of dissolved sodium and chloride. Calcium and bicarbonate are the predominant ions during the snowmelt season. Sodium and chloride are predominant during low streamflow. Mean monthly dissolved-solids concentration often exceeds 2,000 mg/L.

Of the 362,000 tons of dissolved solids contributed annually by the Dolores River, excluding the San Miguel River, 223,000 tons is dissolved sodium and chloride. Almost all of this contribution may be attributed to dissolution from salt anticlines, primarily where the Dolores River crosses Paradox Valley. Other estimates of the mean annual dissolved-solids load contributed by Paradox Valley are 200,000 tons (U.S. Forest Service and others, 1976) and 205,000 tons (U.S. Department of the Interior, 1985). A minor but concentrated source of salt loading to the Dolores River is Salt Creek, which drains the Sinbad Valley anticline. The low-flow dissolved-solids concentration at a site on Salt Creek near Gateway, Colo., is 40,000 mg/L, of which 92 percent is dissolved sodium and chloride. The Dolores River contributes 8.7 percent of the dissolved sodium load and 18.6 percent of the dissolved chloride load leaving the Upper Colorado River Basin.

Annual monotonic-trend analysis for the period of record, 1952–83, indicated highly significant increases in median annual dissolved-solids load of 4,990 tons/yr and median annual flow-adjusted concentration of 4.7 mg/L per year (table 6). These trends represent a 46-percent increase in median annual dissolved-solids load and a 24-percent increase in median annual flow-adjusted concentration during the 32-year period. The increase in flow-adjusted concentration primarily consisted of sodium and chloride, indicating the source might be loading from the salt anticlines. Testing of brine wells in the Paradox Valley during 1978–83 may have contributed to this increase in loading, because the brine, which was pumped into storage ponds, seeped into the Dolores River. Climatic variation also may have been a factor. The 2 years with the highest annual streamflow and dissolved-solids loads (1972 and 1983) occurred during the last 11 years of the 33-year period of record. The 2 years with the highest dissolved-solids concentrations and very low annual streamflow (1977 and 1981) also occurred toward the end of the period of record.

Colorado River near Cisco, Utah (site 21)

Site 21 (table 3, pl. 1) is the farthest downstream site in the Grand region. The streamflow hydrograph for this site depicts the progressive depletion and regulation of flow in the Grand region since streamflow-gaging records began in 1914 (fig. 12*F*). Since 1966, mean annual streamflow has averaged about 4.8 million acre-ft and mean annual dissolved-solids load has averaged about 3.7 million tons (table 5). Chemical composition is affected by irrigation-return flows from Mancos Shale areas, such as the Grand Valley, and inflow from the saline springs in the Dotsero–Glenwood Springs area and the Dolores River basin. During snowmelt runoff, calcium, sulfate, and bicarbonate are the predominant ions; during base flow, sodium and sulfate predominate. Because of inflow from the Dolores River, the proportion of chloride is larger at site 19 than at site 18 upstream.

The period of record was separated into three intervals: A preintervention period (1929–49), a middle period (1950–65), and a postintervention period (1966–83). The intervals were divided based on construction of the Alva B. Adams Tunnel/Lake Granby (1950, when full operation of the project began) and Blue Mesa Reservoir (1966). Annual step trends resulting from Alva B. Adams Tunnel/Lake Granby between 1929–49 and 1950–65 indicated a significant decrease in dissolved-solids load of 594,000 tons/yr (table 4). This decrease was 14 percent of the preintervention median. The loads of dissolved sulfate, bicarbonate, and sodium decreased during the snowmelt season, and the dissolved chloride load decreased during the low-flow season. Annual step-trend analysis, for changes resulting from Blue Mesa Reservoir between the periods 1950–65 and 1966–83, detected no significant changes in annual medians, except for a decrease in dissolved-sulfate load of 137,000 tons/yr. Monthly step trends indicated that from September through March, streamflow increased and dissolved-solids concentration decreased, probably due to increased reservoir regulation (fig. 13).

Annual monotonic trends were analyzed for the three intervals at site 21. For the preintervention period, increased streamflow and decreased dissolved-solids concentration were detected during the low-flow season. These trends corresponded to trends detected at sites 5 and 10 and probably are from winter releases from Green Mountain and Taylor Reservoirs. No statistically significant annual trends were detected for the preintervention and middle periods. For the postintervention period, a marginally significant decrease in median annual flow-adjusted concentration of 2.9 mg/L per year was detected (table 6). This trend represents a 9-percent decrease in the median annual flow-adjusted concentration during the 18-year period (1966–83) and corresponded to similar decreases in the Gunnison River subregion.

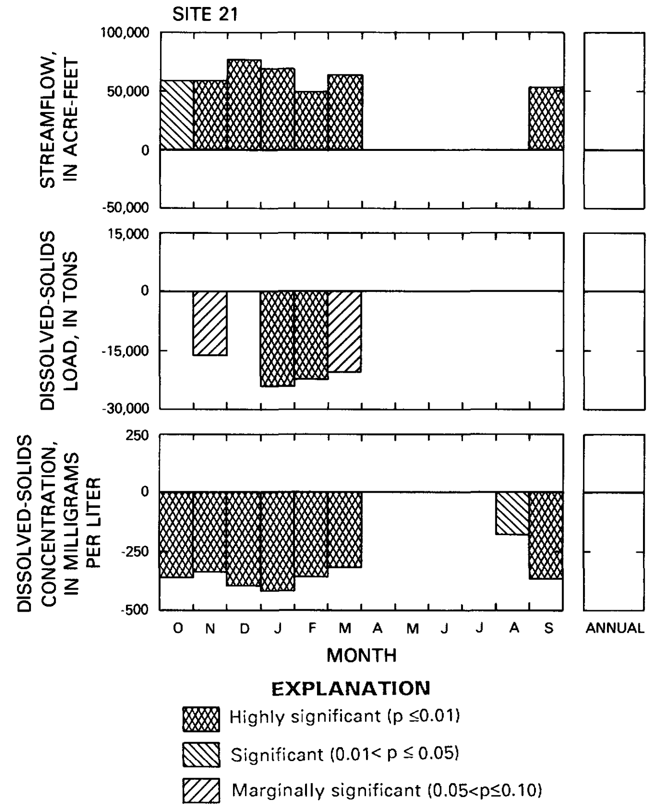


Figure 13. Step trends at site 21 (Colorado River near Cisco, Utah) from 1950–65 to 1966–83.

General Trends in the Grand Region

Annual streamflow in the Grand region has been progressively depleted by transbasin exports. Exports and reservoir regulation have decreased streamflow during the snowmelt-runoff season, and slightly increased streamflow during the winter along the main stems of the Colorado and Gunnison Rivers.

Annual step-trend analysis indicated decreases in streamflow in the Grand region. The Alva B. Adams Tunnel/Lake Granby export, which is the largest depletion in the entire Upper Colorado River Basin, was the probable cause of changes in streamflow and dissolved-solids concentration at site 5 (Colorado River near Glenwood Springs, Colo.) and changes in streamflow and dissolved-solids load at site 10 (Colorado River near Cameo, Colo.). The filling of Blue Mesa Reservoir decreased the monthly variability of streamflow, dissolved-solids concentration, and dissolved-solids load in the Gunnison River and may have contributed to decreasing annual monotonic trends in concentration and load. Significant decreases in dissolved-solids concentration and load also were detected in the Eagle River basin. Dissolved-solids load, mainly dissolved sodium and chloride, increased in the Dolores River basin. Annual step trends at the most downstream site in the Grand Region (site 21, Colorado River near Cisco, Utah) indicated a decrease in dissolved-solids load associated with initiation of the Alva B. Adams Tunnel/Lake Granby exports, and annual monotonic trends indicated a recent decrease in median annual flow-adjusted dissolved-solids concentration, which may be related to the trends in the Eagle and Gunnison Rivers.

Green Region

Most of the flow of the Green River in the Green region originates on the western slope of the Rocky Mountains in Colorado and Wyoming. The drainage area of the Green region is about 45,000 mi^2 and occupies parts of Colorado, Wyoming, and Utah (pl. 1). The Green region contains about 41 percent of the total drainage area of the Upper Colorado River Basin and contributes 39 percent of the streamflow and 34 percent of the dissolved-solids load. Compared to the streamflow at Lees Ferry, Ariz., water of the Green region has relatively high concentrations of dissolved magnesium and bicarbonate and low concentrations of dissolved chloride, resulting from the predominance of Tertiary rocks. The major tributaries in the Green region are the New Fork, Big Sandy, Yampa, Duchesne, White, Price, and San Rafael Rivers, and the Blacks Fork and Henrys Fork.

Data for 36 sites were evaluated in the Green region (pl. 1). Long-term mean annual runoff, streamflow, dissolved-solids concentrations and loads, and major-constituent loads were determined at each of these sites (table 7). The chemical composition of streamflow at selected sites in the Green region is shown in figure 14. Selected annual monotonic-trend-analysis results for the Green region are listed in table 8. For purposes of discussion, the Green region was divided into four subregions: the upper Green, the middle Green, the White, and the lower Green (pl. 1).

Upper Green Subregion

The upper Green subregion includes all of the drainage area upstream from the streamflow-gaging station on the Green River near Greendale, Utah, exclusive of the Great Divide basin. The major drainages in the upper Green subregion include the New Fork and Big Sandy Rivers, and Blacks Fork, Hams Fork, and Henrys Fork and tributaries. About 200,000 acres is irrigated upstream from La Barge, Wyo., including large tracts along the Green River in the vicinity of Pinedale, Wyo., along the New Fork River (62,000 acres), and in the Piney Creek basin. A number of small reservoirs store water in the New Fork River basin.

The Big Sandy River begins in the southern Wind River Range, in central Wyoming, but most of its drainage basin is very arid. The Eden Valley Project to supply irrigation water was begun in 1950 and completed in 1960. Some 20,000 acres is irrigated in the basin, and water is stored in Big Sandy and Eden Valley Reservoirs. The average growing season lasts only 90 days. The agricultural area is underlain by the Laney Member of the Green River Formation. Shallow aquifers annually discharge an estimated 116,000 tons of dissolved solids from saline seeps into the Big Sandy River (U.S. Department of the Interior, 1985).

About 76,000 acres is irrigated in the Blacks Fork basin. The basin contains numerous reservoirs. The largest is Viva Naughton Reservoir on Hams Fork, with a capacity of about 42,000 acre-ft. Most of the irrigated land is on the Blacks Fork and Smiths Fork, upstream from site 31. About 9,000 acres is irrigated in the Henrys Fork basin, which contains numerous small lakes and reservoirs. In the Blacks Fork and Henrys Fork basins, irrigation is on alluvium underlain by the Tertiary Bridger Formation.

Fontenelle Reservoir, on the Green River between the towns of La Barge and Fontenelle, Wyo., was built to provide storage for irrigation water; however, the purpose of the reservoir was changed to supply water for the anticipated energy development in the area. The reservoir has inundated outcrops of the Laney Member and the Wilkins Peak Member of the Green River Formation. In 1960, substantial deposits of trona (sodium carbonate and sodium bicarbonate) were found in the area later inundated by the reservoir. In 1983, the reservoir was drained because of concern caused by observations of unstable conditions, including seepage around the left abutment caused by cavernous dissolution.

Flaming Gorge Reservoir was completed in 1964 and has a capacity of 3.8 million acre-ft. It is the second largest reservoir in the Upper Colorado River Basin and is located on the Green River between Green River, Wyo., and Greendale, Utah. Filling began in November 1962, and very little water was released from the reservoir during the 1963 water year. The reservoir was two-thirds full by the end of 1965, but it did not reach 90 percent of capacity until 1972. Flaming Gorge Reservoir also has inundated outcrops of the Laney Member of the Green River Formation. A chemocline developed during the first few years of operation, producing a stable saline layer in the bottom of the reservoir. The chemocline began to diminish following the conversion to a selective withdrawal operation in 1978 (Miller and others, 1983). During the high-flow year of 1983, the low gates were opened, and the saline water was flushed out of the reservoir.

Green River at Warren Bridge, near Daniel, Wyo. (site 22)

The streamflow hydrograph for site 22 (table 3, pl. 1) shows a well-defined snowmelt-runoff peak during June and a period of steady base flow (fig. 15*A*). The predominant ions are calcium and bicarbonate during the snowmelt-runoff season and calcium and sulfate during the base-flow season. Mean annual runoff averages 15.3 in., and the mean annual flow-weighted dissolved-solids concentration is 147 mg/L (table 7). During 1962–82, annual monotonic-trend analyses indicated a significant decrease in median annual dissolved-solids load of 615 tons/yr (table 8), mostly as a result of decreases in dissolved calcium and bicarbonate. During the

Table 7. Mean annual values of runoff, streamflow, dissolved-solids concentrations and loads, and major-constituent loads—Green region
[Periods of record for some sites are divided into preintervention and postintervention periods; asterisks indicate main-stem sites; mg/L, milligrams per liter]

Site (table 3, plate 1)	Period of record (water years)[1]	Runoff (inches)	Streamflow (acre-feet)	Streamflow (cubic feet per second)	Dissolved solids: Flow-weighted concentration (mg/L)	Dissolved solids: Load (tons)	Major-constituent loads (tons): Calcium	Magnesium	Sodium plus potassium	Carbonate equivalent[2]	Chloride	Sulfate
22*	1962-82	15.3	383,000	528	147	76,000	19,300	4,100	1,700	22,600	500	28,100
23	1966-83	8.66	568,000	785	80	62,000	14,400	2,900	6,300	30,500	1,600	6,200
24*	1964-81	6.04	1,259,000	1,740	173	295,000	63,400	18,100	22,200	122,000	5,000	64,700
25*	1968-83	5.52	1,260,000	1,740	220	377,000	76,700	21,900	31,500	138,000	7,400	101,000
26	1976-81	2.08	15,000	21	146	3,000	460	80	500	600	100	1,200
27	1962-80	.46	40,000	55	1,510	82,000	8,400	2,900	13,500	5,600	2,400	49,000
28	1975-83	.59	55,000	76	2,170	163,000	14,000	7,100	28,400	9,700	3,200	100,000
29	1977-81	.11	4,800	7	1,310	8,500	500	400	1,800	800	900	4,100
30*	1952-63	2.16	1,125,000	1,550	293	448,000	74,100	24,800	49,900	129,000	8,700	162,000
30*	1964-83	2.60	1,348,000	1,860	309	566,000	89,400	31,200	65,200	150,000	12,700	217,000
31	1963-83	2.72	119,000	164	697	113,000	13,200	4,300	18,500	17,200	6,900	52,800
32	1955-83	1.39	230,000	318	580	181,000	23,800	8,100	28,000	35,700	12,300	73,500
33	1958-83	2.26	63,000	87	616	53,000	8,600	3,700	3,800	10,000	1,400	25,200
34*	1957-62	1.72	1,387,000	1,910	372	702,000	106,000	35,500	90,700	165,000	28,700	276,000
34*	1965-83	2.00	1,609,000	2,220	491	1,073,000	148,000	58,200	136,000	203,000	40,500	488,000
35	1976-81	.22	2,300	3	921	2,900	300	200	500	600	60	1,300
36	1975-82	9.16	698,900	965	90	85,000	17,000	5,200	9,100	30,300	2,800	20,700
37	1975-80	1.10	1,600	2	787	1,700	200	100	200	400	200	600
38	1951-83	5.93	1,078,000	1,490	152	223,000	38,500	13,500	25,200	73,800	8,900	63,200
39	1965-68	2.47	398,000	550	138	75,000	15,200	3,600	8,400	30,800	1,600	15,100
40	1951-83	2.03	403,000	557	195	107,000	17,700	4,100	15,700	37,800	4,500	27,100
41*	1962-83	2.33	3,156,000	4,360	341	1,461,000	207,000	82,400	190,000	318,000	64,800	599,000
42	1962-69	7.87	277,000	383	189	71,000	14,500	5,000	4,300	26,300	1,800	19,000
43	1957-83	1.76	398,000	549	650	351,000	39,200	20,700	51,100	65,800	22,900	152,000
44	1974-83	8.41	460,000	634	284	178,000	35,700	9,600	14,500	47,800	11,400	58,500
45	1971-83	.70	19,000	26	926	24,000	2,000	1,800	4,000	6,900	400	8,500
46	1971-83	.65	23,000	31	1,240	38,000	1,900	2,200	9,300	12,300	1,200	11,100
47	1974-82	.10	1,400	2	2,140	4,100	60	200	1,300	1,400	200	900
48	1975-81	2.97	440,000	607	391	234,000	36,600	12,500	30,200	59,200	15,800	79,800
49	1975-81	.07	1,100	2	1,720	2,600	200	100	500	200	30	1,500
50	1951-68	2.23	478,000	659	467	303,000	46,500	14,100	42,900	71,700	32,400	95,700
50	1969-83	2.36	507,000	699	382	263,000	40,200	14,700	32,900	68,500	16,300	90,600
51	1975-83	.07	1,400	2	6,740	13,000	500	800	2,600	400	180	8,300
52	1975-83	1.88	514,600	710	419	300,000	41,600	16,000	40,300	78,200	16,100	108,000
53	1949-83	1.08	89,000	123	1,990	240,000	20,100	13,300	37,800	19,300	5,000	145,000
54*	1929-62	1.89	4,091,000	5,650	420	2,337,000	339,000	121,000	318,000	536,000	129,000	894,000
54*	1965-83	2.02	4,365,000	6,030	463	2,747,000	355,000	150,000	372,000	564,000	123,000	118,000
55	1976-83	6.54	73,000	100	225	22,000	4,500	2,200	1,200	11,400	500	2,400
56	1975-83	1.34	92,000	127	1,340	167,000	16,400	10,400	23,700	17,300	2,900	96,800
57	1947-83	1.03	90,000	124	1,570	192,000	18,800	10,600	27,600	16,100	3,500	116,000

[1]All mean values are based only on those water years having estimates of the major constituents.
[2]Carbonate equivalent is computed from alkalinity; bicarbonate is the primary dissolved form.

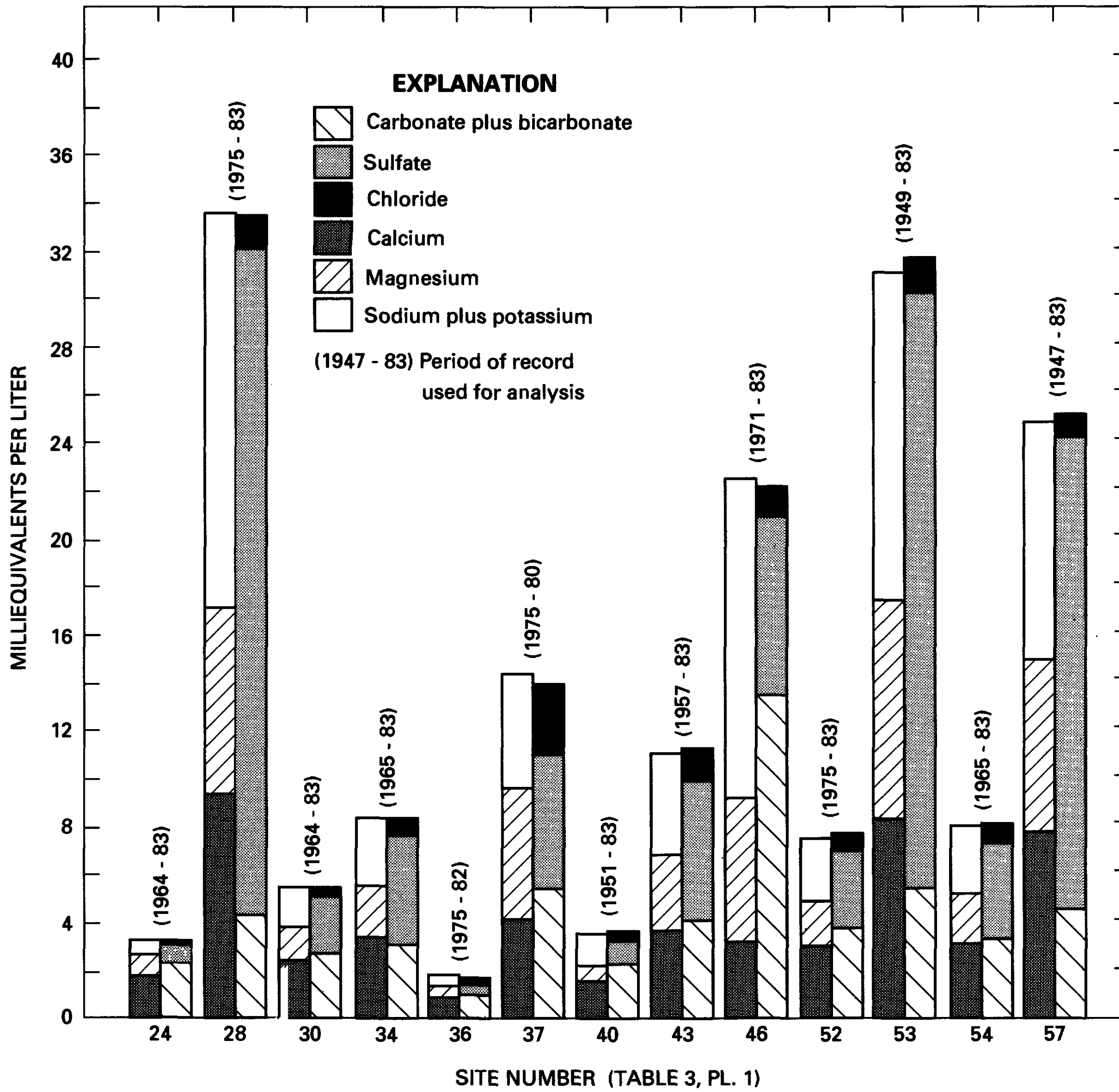


Figure 14. Mean chemical composition of dissolved solids at selected sites in Green region. Cations on left, anions on right.

21-year period of record, this trend represents a 15-percent decrease in the median annual dissolved-solids load. However, dissolved-solids concentration and flow-adjusted concentration did not change significantly.

New Fork River near Big Piney, Wyo. (site 23)

Site 23 (table 3, pl. 1) has a larger drainage area and greater annual streamflow than site 22 (fig. 15*B*); however, mean annual runoff at site 23 (8.7 in.) is less than at site 22. Even though site 23 is downstream from a large agricultural area, the mean annual flow-weighted concentration of dissolved solids (80 mg/L) is about half of that at site 22 (table 7). The predominant ions are calcium and bicarbonate, and chemical composition is relatively constant throughout the year. No statistically significant trends were detected during 1966–83.

Green River near La Barge, Wyo. (site 24)

The predominant ions at site 24 (table 3, pl. 1) are calcium and bicarbonate throughout the year, although the proportion of dissolved sulfate increases during the low-flow season (fig. 14). Concentrations of dissolved sodium and chloride are very low. No statistically significant trends were detected during 1964–81.

Green River below Fontenelle Reservoir, Wyo. (site 25)

Site 25 (table 3, pl. 1) is located 1 mi downstream from Fontenelle Dam. Streamflow was regulated by releases from the reservoir from 1964 to 1983, except from September 1965 through November 1967, when the reservoir was drained to repair a leak. Reservoir regulation decreased streamflow from May through July and increased streamflow

Table 8. Selected annual monotonic-trend-analysis results—Green region

[Stations with less than 10 years of dissolved-solids data are not reported; *n*, number of years of dissolved-solids data; acre-ft/yr, acre-feet per year; mg/L, milligrams per liter; tons/yr, tons per year; HS, highly significant ($p \leq 0.01$); S, significant ($0.01 < p \leq 0.05$); MS, marginally significant ($0.05 < p \leq 0.10$); - -, not significant ($p > 0.10$)]

Site (table 3, plate 1)	Period of record (water years)	*n*	Annual trend in streamflow: Significance level	Trend (acre-ft/yr)	Percent[1]	Annual trend in dissolved solids — Concentration: Significance level	Trend (mg/L)	Percent[1]	Load: Significance level	Trend (tons/yr)	Percent[1]	Flow-adjusted concentration: Significance level	Trend (mg/L)	Percent[1]
22	1962-82	[2]20	--	--	--	--	--	--	S	-615	15	--	--	--
23	1966-83	18	--	--	--	--	--	--	--	--	--	--	--	--
24	1964-81	18	--	--	--	--	--	--	--	--	--	--	--	--
25	1968-83	16	--	--	--	--	--	--	--	--	--	--	--	--
27	1962-80	[2]18	MS	1,140	79	--	--	--	S	1,740	53	S	13.9	17
30	1952-63	12	--	--	--	--	--	--	MS	-15,600	34	--	--	--
30	1964-83	20	--	--	--	--	--	--	--	--	--	--	--	--
31	1963-83	21	--	--	--	--	--	--	--	--	--	--	--	--
32	1955-83	[2]28	--	--	--	--	--	--	--	--	--	S	3.1	16
33	1955-83	[2]28	--	--	--	HS	-9.4	41	--	--	--	HS	-5.0	20
34	1965-83	19	--	--	--	--	--	--	--	--	--	--	--	--
38	1951-83	33	--	--	--	HS	.9	21	S	3,380	65	HS	1.2	29
40	1951-83	33	S	6,440	71	--	--	--	MS	1,310	50	--	--	--
41	1962-83	22	--	--	--	--	--	--	--	--	--	--	--	--
43	1957-83	27	--	--	--	--	--	--	--	--	--	--	--	--
44	1974-83	10	--	--	--	--	--	--	--	--	--	HS	-3.5	12
45	1971-83	13	--	--	--	--	--	--	--	--	--	--	--	--
46	1971-83	13	--	--	--	HS	-44.1	34	--	--	--	MS	-24.2	20
50	1951-68	18	--	--	--	--	--	--	--	--	--	--	--	--
50	1969-83	15	--	--	--	--	--	--	--	--	--	--	--	--
53	1949-83	[2]31	--	--	--	S	-33.2	37	--	--	--	HS	-23.1	28
54	1929-62	34	--	--	--	--	--	--	--	--	--	--	--	--
54	1965-83	19	--	--	--	--	--	--	--	--	--	--	--	--
57	1947-83	37	--	--	--	--	--	--	--	--	--	--	--	--

[1]Percent change during period of record.

[2]One or more years of data are missing within the period of record. Percentage changes are calculated on the entire period.

from August through March (fig. 15*C*). The dissolved-solids concentration is less variable than at site 24; calcium and bicarbonate are the predominant ions throughout the year. Flow-weighted dissolved-solids concentration and load are greater than at site 24, and there is a larger sulfate load. No statistically significant trends were detected during 1968–83.

Little Sandy Creek above Eden, Wyo. (site 26)

Mean daily streamflow at three sites in the Big Sandy River basin are shown in figure 15*D*. The streamflow hydrograph for site 26 (table 3, pl. 1), upstream from the irrigated area, indicates snowmelt beginning in April and peaking in June, and very low streamflow from August through February. Dissolved-solids concentration was relatively small, even during the low-flow season, and the flow-weighted concentration averaged about 146 mg/L during 1976–81 (table 7). Calcium, sodium, and sulfate are the predominant ions throughout the year, and bicarbonate also is a predominant anion during the snowmelt-runoff season. The proportion of dissolved sulfate increased during the low-flow season. No trends were analyzed at this site because of the short period of record.

Big Sandy River below Eden, Wyo. (site 27)

Mean daily streamflow at site 27 (table 3, pl. 1) is much larger than at site 26 because of the larger drainage area; however, the seasonal pattern is remarkably different (fig. 15*D*). Beginning about May, snowmelt runoff is diverted almost totally for irrigation; irrigation-return flows dominate during the remainder of the year. Mean annual flow-weighted dissolved-solids concentration is large; during 1962–80, it averaged 1,510 mg/L (table 7). Annual dissolved-solids load averaged about 82,000 tons. Sodium and sulfate composed 76 percent of the dissolved-solids load.

Annual monotonic-trend analyses indicated a marginally significant increase in median annual streamflow of 1,140 acre-ft/yr (table 8). Median annual dissolved-solids load increased significantly, as a result of large increases in base flow during September through February. Median annual dissolved-solids load significantly increased by 1,740 tons/yr, and median annual flow-adjusted concentration significantly increased by 13.9 mg/L per year. These increases represent a 79-percent change in median annual streamflow, a 53-percent change in median annual load, and a 17-percent change in median annual flow-adjusted concentration during the period of record. Based on the monthly time series of streamflow and dissolved-solids load, irrigation-return flows increased until about 1966 and since then have remained relatively stable.

Big Sandy River at Gasson Bridge, near Eden, Wyo. (site 28)

Site 28 (table 3, pl. 1) is about 10 mi downstream from site 27. Streamflow is similar at the two sites but averages 21 ft^3/s greater at site 28 (fig. 15*D*) because of irrigation-return flows that enter the stream by seepage through shallow aquifers. Mean annual dissolved-solids load increased from 82,000 tons at site 27 to 163,000 tons at site 28 (table 7). Dissolved sodium and sulfate composed 82 percent of the increased dissolved-solids load. The mean annual dissolved-sulfate load of 100,000 tons almost equaled the dissolved-sulfate load of the Green River at site 25, with a drainage area of 4,280 mi^2, compared to only 1,720 mi^2 at site 28.

Bitter Creek above Salt Wells Creek, near Salt Wells, Wyo. (site 29)

The headwaters of Bitter Creek are not in a mountainous region but are in a semiarid area along the southwest border of the Great Divide Basin. Consequently, streamflow of Bitter Creek at site 29 (table 3, pl. 1) has only a modest, early snowmelt-runoff season (fig. 15*E*). The stream dries up during the summer, except after thunderstorms, which produce short, intense flood peaks. Thunderstorms decrease as the weather cools during September, and the creek generally is dry through the winter months. The flow-weighted dissolved-solids concentration averaged about 1,300 mg/L during 1977–81 (table 7). Chemical composition, as in the Big Sandy River, is predominantly sodium and sulfate during all seasons. The proportions of dissolved sodium and chloride are larger and the proportions of dissolved calcium and sulfate are smaller than in Big Sandy River. There is no significant water use upstream from site 29. Downstream from the site, Salt Wells Creek converges with Bitter Creek, increasing streamflow and dissolved-solids concentration before the creek empties into the Green River. Lowham and others (1982) described the water chemistry of Salt Wells Creek in detail. They reported that the dissolved-solids concentration ranges from 100 mg/L in the headwaters to 3,000 mg/L near the mouth.

Green River near Green River, Wyo. (site 30)

Site 30 (table 3, pl. 1) is about 50 mi downstream from Fontenelle Dam, 0.1 mi downstream from Bitter Creek, and 4 mi upstream from the high-water line of Flaming Gorge Reservoir. Samples for water-quality analyses are collected upstream from the streamflow-gaging station and Bitter Creek. The seasonal pattern of streamflow has been altered slightly by regulation of flow at Fontenelle Reservoir (fig. 15*F*). The predominant ions are calcium and bicarbonate during the snowmelt-runoff season (May through August). Calcium, sodium, and sulfate predominate during the remainder of the year. The flow-weighted dissolved-solids concentration averaged 309 mg/L during 1964–83 (table 7).

The site was evaluated for annual step trends caused by Fontenelle Dam. The period of record was separated into preintervention (1952–63) and postintervention (1964–83) periods. The postintervention period generally has had larger streamflow, but because of the variability from year to year, the annual step trend in streamflow was not significant. The step-trend analysis indicated a significant increase in annual dissolved-solids load of 118,000 tons, a 26-percent change from the preintervention median load (table 4). Most of this increase was attributable to changes in sodium and sulfate loads, possibly from dissolution of minerals from the bank material of Fontenelle Reservoir and from increased dissolved-solids loads from the Big Sandy River. Monthly step trends indicated that streamflow and dissolved-solids load increased during the low-flow season because of releases from Fontenelle Reservoir (fig. 16). However, they did not decrease during the high-flow season because of the generally larger flows during the postintervention period, especially during 1983.

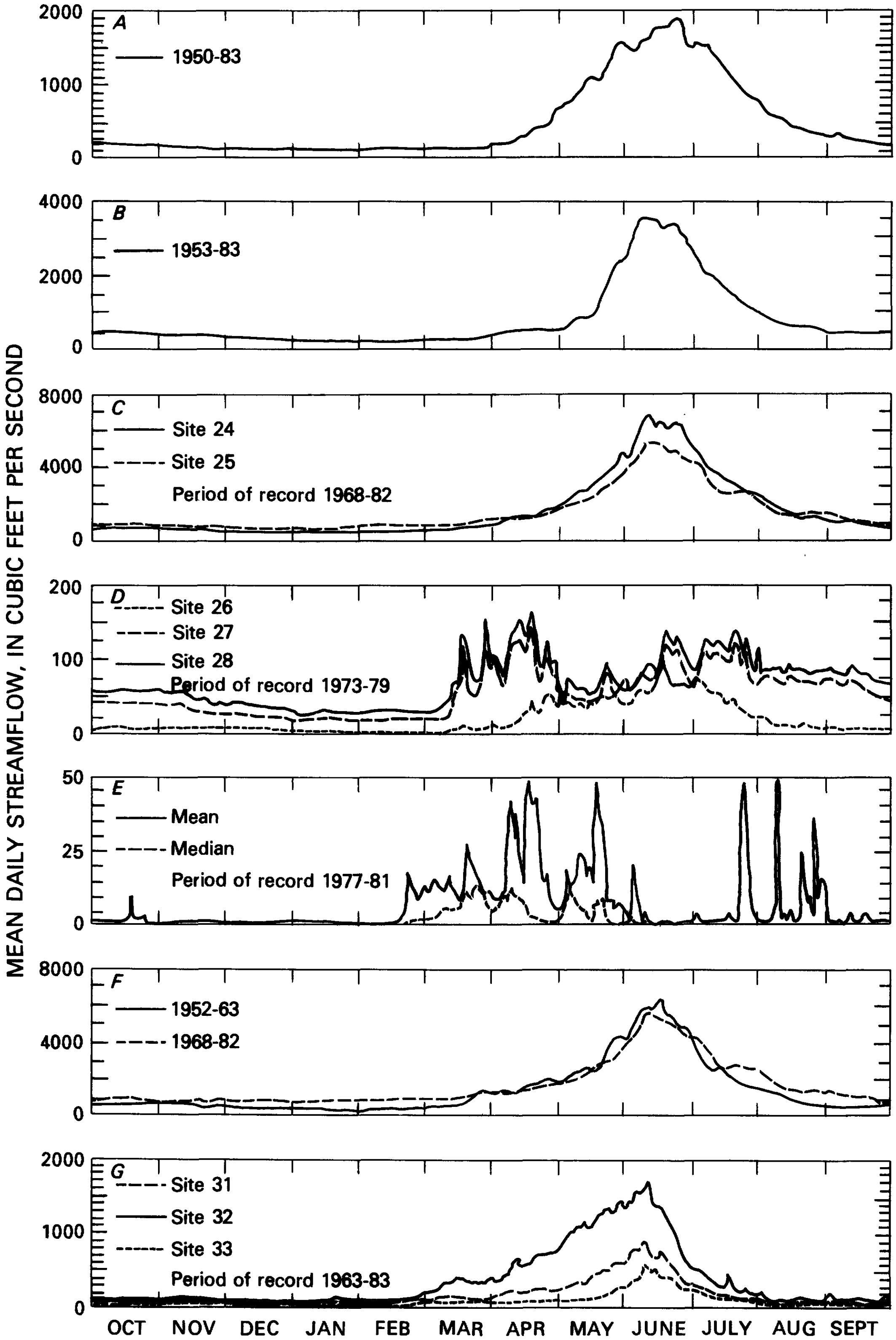
For the preintervention period, annual monotonic-trend analyses indicated a marginally significant decrease in dissolved-solids load of 15,600 tons/yr. This trend represents a 34-percent decrease in the median annual load during the 12-year period. This trend may be related to climate; several years of high streamflow occurred early in the period. No statistically significant annual monotonic trends were detected for the postintervention period.

Blacks Fork near Lyman, Wyo. (site 31)

Blacks Fork, upstream from site 31 (table 3, pl. 1), drains the northern slopes of the Uinta Mountains (fig. 2). Despite large tracts of irrigated land, flow regulation was not begun until late 1981 (Meeks Cabin Dam), and the streamflow hydrograph indicates a well-defined snowmelt-runoff peak during June (fig. 15*G*). The flow-weighted dissolved-solids concentration averaged 697 mg/L during 1963–83 (table 7). The predominant ions are sodium and sulfate throughout the year. Dissolved sodium and sulfate compose 70 percent of the dissolved-solids load during the low-flow season. This chemical composition is affected by return flow from irrigated land underlain by Cretaceous and Tertiary shale. No statistically significant trends were indicated for the period of record.

Blacks Fork near Little America, Wyo. (site 32)

The streamflow at site 32 (table 3, pl. 1) includes the streamflow at site 31 plus the streamflow of Hams Fork and


MEAN DAILY STREAMFLOW, IN CUBIC FEET PER SECOND
A
1950-83
B
1953-83
C
Site 24
Site 25
Period of record 1968-82
D
Site 26
Site 27
Site 28
Period of record 1973-79
E
Mean
Median
Period of record 1977-81
F
1952-63
1968-82
G
Site 31
Site 32
Site 33
Period of record 1963-83
OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT

Muddy Creek. Chemical composition is similar at sites 31 and 32 except that concentrations of dissolved sodium and sulfate are higher at site 31. Hams Fork and Muddy Creek dilute the dissolved-solids concentration downstream from site 31, resulting in a flow-weighted mean of 580 mg/L at site 32 during 1955–83 (table 7). The predominant ions are calcium and bicarbonate during the high-flow season (May and June) and sodium and sulfate during the low-flow season.

Annual monotonic-trend analyses indicated a significant increase in flow-adjusted concentration of 3.1 mg/L per year (table 8). This represents a 16-percent increase in the median annual flow-adjusted concentration during the period of record.

Henrys Fork near Manila, Utah (site 33)

Henrys Fork, like Blacks Fork upstream from site 31, drains the northern slopes of the Uinta Mountains. However, it does not have large tracts of irrigated agriculture. The streamflow hydrograph for site 33 (table 3, pl. 1) shows a modest snowmelt-runoff peak, which has a long period of sustained base flow (fig. 15*G*). Mean annual flow-weighted dissolved-solids concentration averaged 616 mg/L (table 7); the predominant ions are calcium and sulfate throughout the year. The water of Henrys Fork has a larger proportion of dissolved calcium and magnesium than the water of Blacks Fork and has a smaller proportion of dissolved sodium and chloride.

Annual monotonic-trend analyses indicated highly significant decreases in dissolved-solids concentration and flow-adjusted concentration during 1955–83. Median annual concentration decreased by 9.4 mg/L per year, and median annual flow-adjusted concentration decreased by 5.0 mg/L per year (table 8). These trends represent a 41-percent decrease in median annual concentration and a 20-percent decrease in median annual flow-adjusted concentration during the period of record.

Green River near Greendale, Utah (site 34)

Site 34 (table 3, pl. 1) is 0.5 mi downstream from Flaming Gorge Reservoir. Flow of the river has been completely controlled since filling of the reservoir began in November 1962. Prior to November 1962, the snowmelt-runoff peak was larger and somewhat earlier than the peak upstream at site 20 because of snowmelt inputs from the Blacks Fork and Henrys Fork basins. Since the initial filling period, seasonal variability has decreased (fig. 17). Mean daily streamflow is almost constant throughout the year; slight increases occur during late summer when excess storage is released and during the winter when the power demand is greater. Releases generally range between 1,000 and 4,500 ft^3/s. Large releases occurred during 1983 and 1984, when the spillway was used to prevent overflow of the dam. Dissolved-solids concentration at site 34 is remarkably constant, and calcium and sulfate are the predominant ions throughout the year. Prior to streamflow regulation, calcium and bicarbonate predominated during the high-flow season, and calcium, sodium, and sulfate predominated during the low-flow season.

The period of record was divided into a preintervention period (1957–62) and a postintervention period (1965–83), based on the initial filling of Flaming Gorge Reservoir. Annual step trends were highly significant for dissolved-solids concentration (112 mg/L) and significant for dissolved-solids load (346,000 tons). These trends represent a 29-percent increase from the preintervention median concentration and

Figure 15. Mean daily streamflow at selected sites in upper Green subregion of Green region. *A*, Site 22, Green River at Warren Bridge, near Daniel, Wyo. *B*, Site 23, New Fork River near Big Piney, Wyo. *C*, Site 24, Green River near La Barge, Wyo., and site 25, Green River below Fontenelle Reservoir, Wyo. *D*, Site 26, Little Sandy Creek above Eden, Wyo., site 27, Big Sandy Creek below Eden, Wyo., and site 28, Big Sandy River at Gasson Bridge, near Eden, Wyo. *E*, Site 29, Bitter Creek above Salt Wells Creek, near Salt Wells, Wyo. *F*, Site 30, Green River near Green River, Wyo. *G*, Site 31, Blacks Fork near Lyman, Wyo., site 32, Blacks Fork near Little America, Wyo., and site 33, Henrys Fork near Manila, Utah.

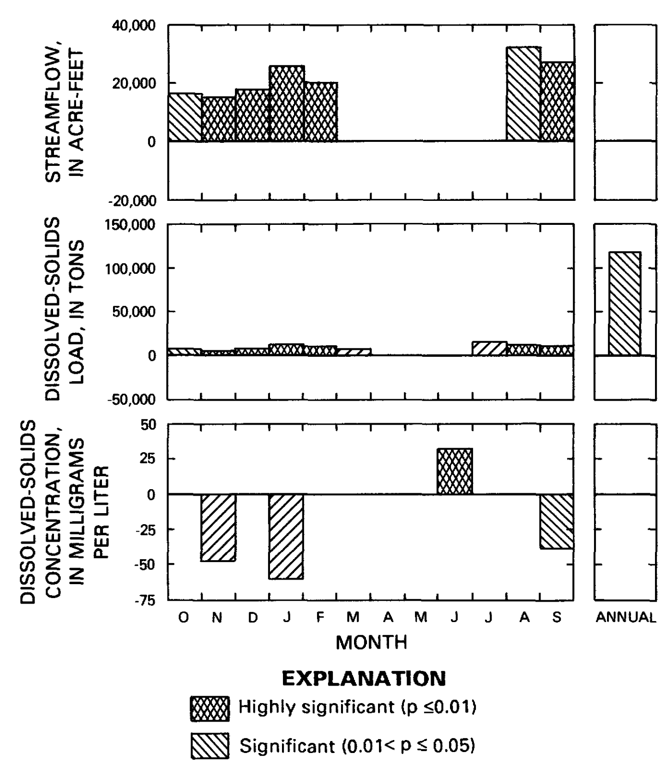


Figure 16. Step trends at site 30 (Green River near Green River, Wyo.) from 1952–63 to 1964–83.

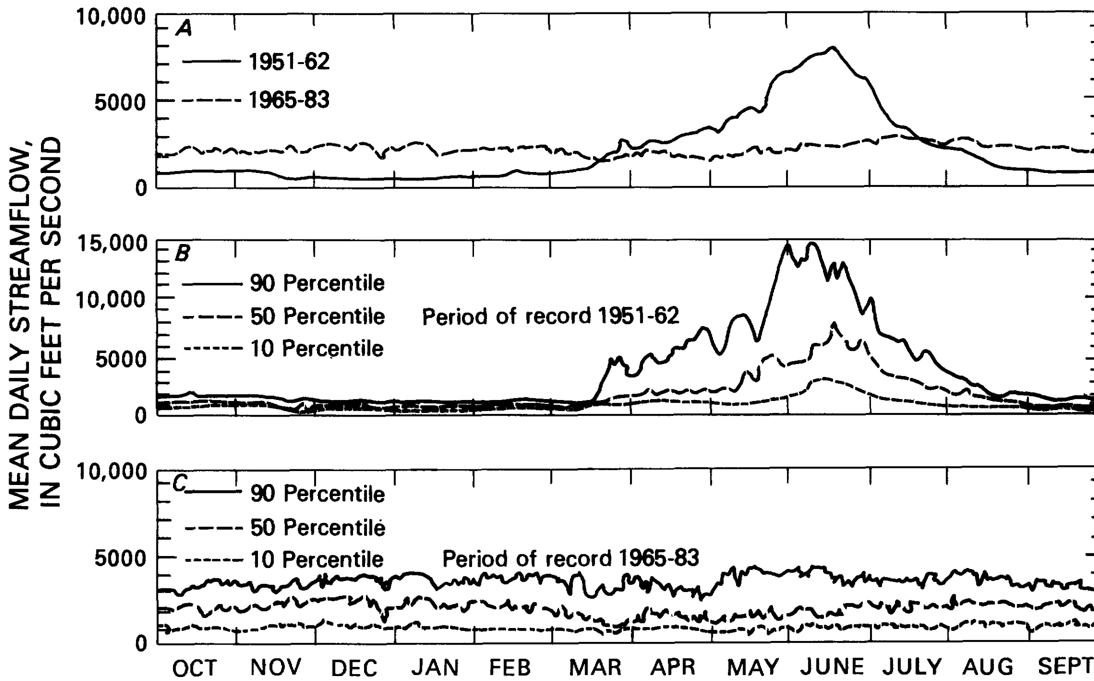


Figure 17. Daily streamflow at site 34 (Green River near Greendale, Utah) before and after the initial filling of Flaming Gorge Reservoir. *A*, Mean daily streamflow. *B*, Daily streamflow for selected non-exceedance probabilities before initial filling. *C*, Daily streamflow for selected non-exceedance probabilities after initial filling.

a 55-percent increase from the preintervention median load (table 4). The increase in dissolved-solids load may have been caused by several factors, including an increase in streamflow between the two periods and an increase in dissolved-solids loading upstream. At site 30, just upstream from Flaming Gorge Reservoir, median annual dissolved-solids loading increased by 118,000 tons at approximately the same time. Dissolution of minerals from the reservoir bank material is another potential source of increased dissolved-solids load. The net dissolved-solids load added from dissolution of bank material has been estimated to be 1.59 million tons during 1963–72, an annual average of 159,000 tons (Madison and Waddell, 1973; Bolke and Waddell, 1975). Because most of the increase was dissolved sulfate, the primary mineral involved was believed to be gypsum.

The preintervention period was not evaluated for annual monotonic trends because of the short period of record. No statistically significant annual monotonic trends were indicated during the postintervention period.

Middle Green Subregion

The middle Green subregion includes the Yampa River basin and tributaries and all the tributaries to the Green River between Greendale, Utah, and the confluence with the White River. About 7,100 acre-ft/yr is exported from the Little Snake River through the Cheyenne Diversion to supply water to the city of Cheyenne, Wyo. (table 1). It is the only transbasin export from the Colorado River basin in Wyoming. About 65,000 acres is irrigated upstream from Maybell, Colo., and about 21,000 acres is irrigated along the Little Snake River. Large deposits of coal are mined from Cretaceous deposits in the Yampa River basin. Surface mines are active along Trout Creek, Foidel Creek, Williams Fork, Wilson Creek, and along the southern side of the Yampa River between Steamboat Springs and Hayden, Colo. Much of the basin contains outcrops of the coal-bearing Mesaverde Group (Williams Fork and Iles Formations) and Mancos Shale. Coal-fired powerplants near Hayden and Craig, Colo., use about 13,000 acre-ft of water per year from the Yampa River.

Steinaker Reservoir provides late-season irrigation water for about 15,000 acres around Vernal, Utah. About 175,000 acres is irrigated in the Duchesne River basin. Since 1969, Starvation Reservoir on the Strawberry River has provided water for late-season irrigation near the town of Duchesne, Utah. In addition to the Strawberry River inflow, water from the Duchesne River is diverted into Starvation Reservoir. Moon Lake stores water for late-season irrigation of about 75,000 acres near the mouths of the Lake Fork and Uinta Rivers. The Strawberry and Duchesne Tunnels export water west to the Salt Lake City–Provo area in the Great Basin. Water for diversion through the Strawberry Tunnel has been supplied by Strawberry Reservoir since 1913. Some water from the upper Duchesne River basin is diverted into Strawberry Reservoir, and minimal water is released from the reservoir into the Strawberry River. As part of the Central Utah Project, the reservoir was enlarged in 1973 to a capacity of 1.1 million acre-ft (table 2). However, the remainder of the project has not been completed, and the reservoir had not been filled by 1983.

Vermillion Creek near Hiawatha, Colo. (site 35)

Vermillion Creek drains an arid, geologically diverse area before emptying into the Green River in the northwestern corner of Colorado. Site 35 (table 3, pl. 1) has about one-third the streamflow of Vermillion Creek near its mouth, but the dissolved-solids concentrations are similar. Streamflow at site 35 is characterized by a small snowmelt-runoff peak, occasional flash floods, and minimal or no flow during the remainder of the year. Mean annual flow-weighted dissolved-solids concentration averages 921 mg/L (table 7). Sodium and sulfate are the predominant ions. Concentration and chemical composition do not vary greatly throughout the year.

Yampa River below diversion, near Hayden, Colo. (site 36)

Streamflow at site 36 (table 3, pl. 1) averages about 700,000 acre-ft/yr (table 7) and primarily is composed of snowmelt runoff that has minimal dissolved solids. The mean annual flow-weighted dissolved-solids concentration is 90 mg/L. Calcium and bicarbonate are the predominant ions throughout the year. Water from the Elk River, which drains the virtually insoluble Precambrian rocks of the Park Range, dilutes the dissolved-solids concentration of the Yampa River upstream from Hayden, Colo.

Wilson Creek near Axial, Colo. (site 37)

Wilson Creek is a tributary to Milk Creek and drains a small area underlain principally by the Williams Fork Formation. The streamflow hydrograph for site 37 (table 3, pl. 1) is characterized by a sharp snowmelt-runoff peak in mid-May that is unaffected by reservoirs or diversions (fig. 18*A*). Although the total runoff from the drainage basin is small, base flow is rather constant. The mean annual flow-weighted dissolved-solids concentration is 787 mg/L (table 7), predominantly as magnesium and sulfate. The proportions of dissolved sodium and chloride are larger than in the mainstem waters of the Yampa River at site 36. During the high-flow season, the concentrations of magnesium, calcium, sodium, bicarbonate, and sulfate are approximately equal. The proportions of sodium, sulfate, and, notably, magnesium increase during the low-flow season. Brine disposal from oil-drilling operations in the upper part of the drainage basin may have contributed substantial quantities of dissolved solids to the stream (Turk and Parker, 1982).

Yampa River near Maybell, Colo. (site 38)

The mean annual streamflow of the Yampa River at site 38 (table 3, pl. 1) exceeds 1 million acre-ft/yr (table 7). A large snowmelt-runoff peak occurs during May and June, followed by a long period of steady base flow (fig. 18*B*). Compared to the Yampa River at site 36, streamflow is 54 percent larger and mean annual dissolved-solids load is 162 percent larger, the increase principally being dissolved sulfate, bicarbonate, and calcium. The mean annual flow-weighted dissolved-solids concentration is 152 mg/L (table 7). Calcium and bicarbonate are the predominant ions during the high-flow season, and calcium, sodium, and bicarbonate predominate during the low-flow season.

For 1951–83, annual monotonic-trend analyses indicated highly significant increases in median annual dissolved-solids concentration of 0.9 mg/L per year and in median annual flow-adjusted concentration of 1.2 mg/L per year. Trends indicated a significant increase in median annual dissolved-solids load of 3,380 tons/yr (table 8). These increases represent a 21-percent change in median annual dissolved-solids concentration, a 29-percent change in flow-adjusted concentration, and a 65-percent change in dissolved-solids load during the 33-year period of record. Highly significant increasing trends were determined for annual flow-adjusted concentrations of magnesium, sodium, and sulfate. Flow-adjusted concentration increased significantly during all months except April and August.

Iorns and others (1965) reported that although contributions from rocks of Cretaceous and Tertiary age in the Yampa River basin had large proportions of dissolved magnesium, sodium, and sulfate, the dissolved-solids concentration of the river increased only moderately because the volume of runoff was small. These same constituents have increased flow-adjusted concentrations for site 38. The major land-use change in the Yampa River basin has been the expansion of coal-resource development since the early 1960's (Steele and others, 1979). Both gypsum, a sulfate mineral, and pyrite, which produces sulfate during oxidation, occur in the spoils of surface-mined coal. Turk and Parker (1982) reported that a principal effect of coal mining may be an increase in the relative concentration of dissolved sulfate in surface water. Increases in dissolved-solids and dissolved-sulfate concentrations at site 38 are moderately small, but they are significant. The proportion of dissolved sulfate increased from about 24 to 36 percent during 1951–83. The increase may have been caused by leaching of soluble minerals from spoils and disturbed lands. McWhorter and others (1975) reported that the dissolved-solids load from spoils at the Edna Mine in Colorado was 10 times greater than that produced upstream along Trout Creek. Runoff from spoils in the Yampa River basin produces three to six times the runoff from undisturbed land, and springs have been observed at the toe of spoils, changing intermittent streams into perennial streams. A typical spoils pile may yield annually 3 to 5 inches of runoff having a dissolved-solids concentration of 1,500 to 2,500 mg/L (R.S. Williams, U.S. Geological Survey, oral commun., 1985). Warner (in Steele and Hillier, 1981) reported that leachate from spoils could produce a slow spread of degraded ground water throughout a period of decades.

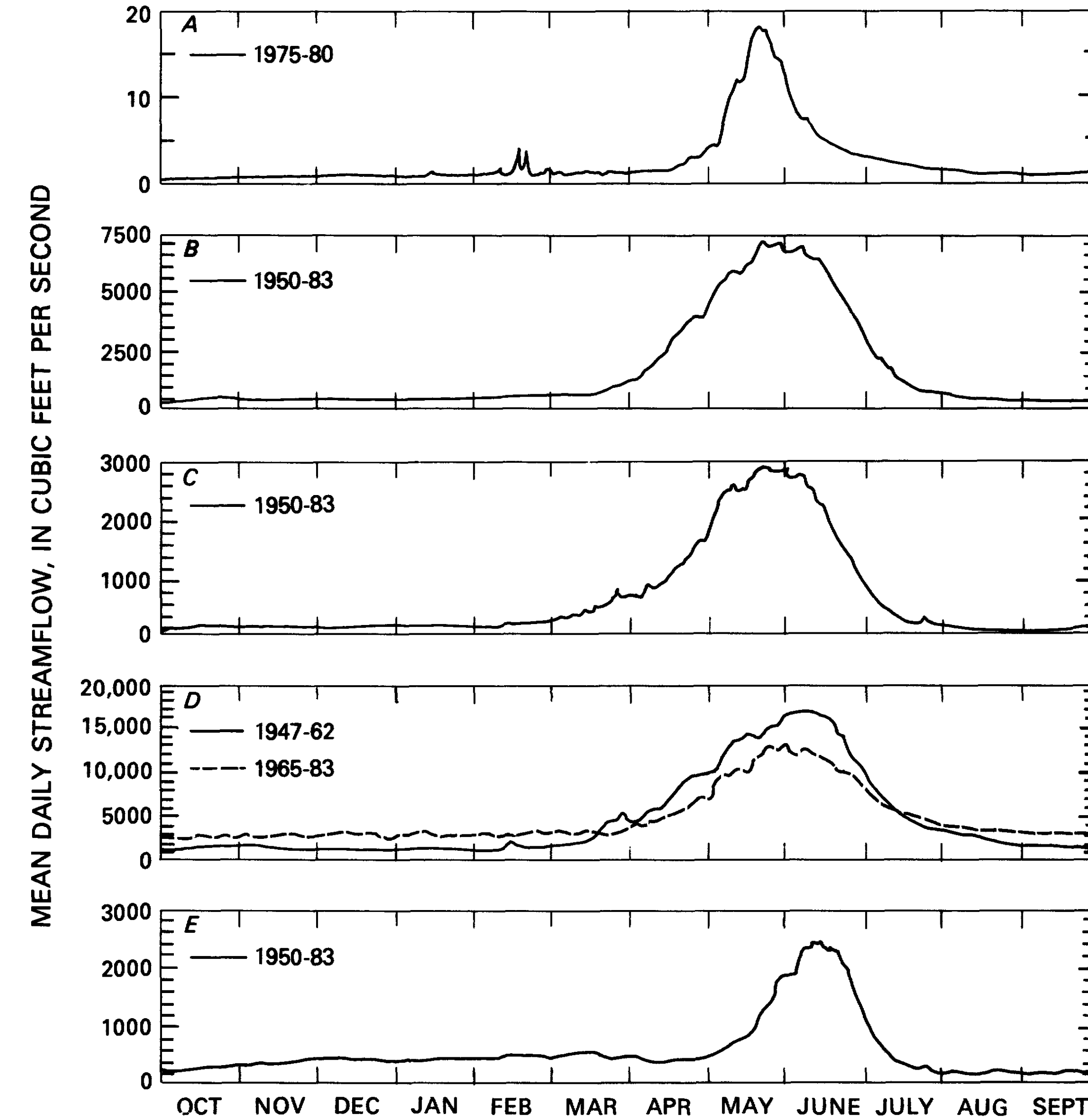


Figure 18. Mean daily streamflow at selected sites in middle Green subregion of Green region. *A*, Site 37, Wilson Creek near Axial, Colo. *B*, Site 38, Yampa River near Maybell, Colo. *C*, Site 40, Little Snake River near Lily, Colo. *D*, Site 41, Green River near Jensen, Utah. *E*, Site 43, Duchesne River near Randlett, Utah.

Little Snake River near Baggs, Wyo. (site 39)

The main fork of the Little Snake River begins in the mountains, but most of the river basin is in the semiarid Washakie basin. Site 39 (table 3, pl. 1) has a well-defined snowmelt-runoff peak, but the river often dries up in late summer from irrigation depletions. Calcium and bicarbonate are the predominant ions during March-September; calcium, sodium, and bicarbonate predominate during the base-flow months.

Little Snake River near Lily, Colo. (site 40)

The streamflow hydrograph for site 40 (table 3, pl. 1) shows a well-defined snowmelt-runoff peak, slightly flattened by irrigation withdrawals (fig. 18*C*). As at site 39, the river often dries up during late summer because of irrigation depletions. Mean annual streamflow at site 40 is 403,000 acre-ft, essentially the same as at site 39, but the mean annual flow-weighted dissolved-solids concentration increases from 138 mg/L to 195 mg/L between the two sites (table 7). The Little Snake River merges with the Yampa River downstream from Maybell, Colo., resulting in an annual streamflow for the Yampa River of about 1.5 million acre-ft, approximately equal to the annual streamflow at site 34 on the Green River. The chemical composition of the Little Snake River at site 40 is principally calcium, sodium, sulfate, and bicarbonate, which are contributed by the Tertiary formations in the Washakie basin. During August and September, when streamflow is at its minimum, the predominant ions are sodium and sulfate. The predominant ions are calcium and bicarbonate during the high streamflow months, April–July.

Annual monotonic-trend analysis for 1951–83 indicated a significant increase in median annual streamflow of 6,440 acre-ft/yr and a marginally significant increase in median annual dissolved-solids load of 1,310 tons/yr (table 8). During the 33 years of record, these increases represent a 71-percent change in median annual streamflow and a 50-percent change in median annual load.

Green River near Jensen, Utah (site 41)

Streamflow at site 41 (table 3, pl. 1) is a mixture of water released from Flaming Gorge Reservoir and water from the Yampa River. The decreased seasonal variability and enhanced low flows since 1962 are shown in figure 18*D*, but the figure also shows the substantial input from the Yampa River during the snowmelt-runoff season. Mean annual streamflow averages about 3.2 million acre-ft, and mean annual flow-weighted dissolved-solids concentration is 341 mg/L (table 7). The Yampa River dilutes the dissolved-solids concentration of the Green River by about 150 mg/L. Calcium, bicarbonate, and sulfate are the predominant ions during the high-flow season. Calcium, sodium, and sulfate predominate during the low-flow season. The period of record (1962–83) for dissolved solids coincides with the period following completion of Flaming Gorge Reservoir. No statistically significant trends were detected for this postintervention period.

Duchesne River at Duchesne, Utah (site 42)

Site 42 (table 3, pl. 1) is upstream from most of the irrigated land in the Duchesne River basin. Streamflow is depleted by the Duchesne Tunnel and by the diversions to Starvation Reservoir, which was completed in 1970, a few months before water-quality sampling was discontinued at the site. Mean annual flow-weighted dissolved-solids concentrations were not large, averaging 189 mg/L during water years 1962–69 (table 7). Calcium and bicarbonate are the predominant ions throughout the year. Streamflow at site 42 probably has decreased since 1970, because of offstream storage in Starvation Reservoir.

Duchesne River near Randlett, Utah (site 43)

Streamflow at site 43 (table 3, pl. 1) near the mouth of the Duchesne River is greatly depleted by transbasin exports and by consumptive use for irrigation. A considerable part of the base flow comes from agricultural return flows (fig. 18*E*). Mean annual streamflow is about 43 percent greater than at site 42, but mean annual dissolved-solids load increases fivefold, averaging 351,000 tons during 1957–83 (table 7). Streamflow is lowest and dissolved-solids concentration is highest during August through October. The mean annual flow-weighted dissolved-solids concentration at site 43 is 650 mg/L (table 7). Sodium and sulfate are the predominant ions most of the year; calcium and bicarbonate also become predominant during the high flow months (May–July). Most of the dissolved-solids load, especially dissolved sodium and sulfate, may be from irrigation-return flow through the Tertiary Uinta and Duchesne River Formations, which contain gypsum and other evaporites (Mundorff, 1977). Excess salinity in poorly drained agricultural soils has been increasing in magnitude in the basin. The dissolved-solids load at site 43 is the largest source of dissolved solids in the Green region. Furthermore, a large but unquantified dissolved-solids load from the lower Duchesne River basin enters the Green River by means other than the Duchesne River (Mundorff, 1977).

Because the enlarged part of Strawberry Reservoir had not been filled by 1983, annual step-trend analyses did not indicate any statistically significant trends. Annual monotonic-trend analyses for the entire period of record (1957–83) also did not indicate any statistically significant trends.

White Subregion

The White subregion includes a drainage area of about 5,000 mi^2. The headwaters of the White River are in the White River uplift, which is composed primarily of relatively insoluble Pennsylvanian and Permian rocks. The lower parts of the White subregion have abundant outcrops of relatively soluble Cretaceous and Tertiary sedimentary rocks, but dissolved-solids load is not large because little runoff is generated. About 33,000 acres is irrigated, including large tracts near the river upstream from Meeker, Colo., that are underlain by Mancos Shale. No transbasin exports occur from the White subregion, and no large reservoirs exist in the subregion.

Many drilling operations for oil and gas have occurred throughout the subregion. A major point source of dissolved solids existed in the Meeker Dome area, just north of the White River upstream from Meeker, Colo. Highly saline water from deep aquifers was seeping upward through abandoned and improperly plugged oil exploration wells drilled during the 1920's. Water from the Pennsylvanian and Permian Weber Formation was postulated to be rising through the deeper wells and discharging through the relatively shallow Meeker well (U.S. Bureau of Reclamation, 1983). Flow of about 3.2 ft^3/s that had a dissolved-solids concentration of 19,200 mg/L was measured at the Meeker well. The dissolved-solids load was 57,000 tons/yr, mostly as dissolved sodium and chloride (U.S. Department of the Interior, 1985). The well was plugged in October 1968. The next year, seepage again occurred in the area and had an estimated dissolved-solids load of 27,000 tons/yr. In 1980 and 1981, three more abandoned wells were plugged. Water levels in observation wells declined, and the resulting decrease in dissolved-solids load was estimated to be 18,000 tons/yr.

Much study has been done in the drainages of Piceance and Yellow Creeks to evaluate potential effects from the possible development of oil-shale deposits. The Uinta Formation is exposed throughout most of the area. The Parachute Creek Member of the Green River Formation is the principal bedrock aquifer in the area and is exposed along streams. Water in the Parachute Creek Member has high concentrations of dissolved sodium, bicarbonate, and chloride (Weeks and others, 1974). An area of about 5,000 acres is irrigated in the Piceance Creek and Yellow Creek basins, with about 4,000 acre-ft of water depleted from mid-March through November.

White River below Meeker, Colo. (site 44)

The streamflow hydrograph for site 44 (table 3, pl. 1) is characterized by substantial base flow and a snowmelt-runoff peak that is partially depleted by irrigation (fig. 19*A*). Ionic composition is predominantly calcium and bicarbonate during the high-flow season and calcium, sulfate, and bicarbonate during the low-flow season. Sulfate is the predominant component of dissolved-solids load because of the upstream irrigation on areas underlain by Mancos Shale and because of pyrite oxidation in the Green River Formation. The mean annual flow-weighted dissolved-solids concentration is 284 mg/L (table 7). During 1974–83, after the plugging of the Meeker well (1968), dissolved chloride averaged about 11,000 tons/yr out of a total dissolved-solids load of 178,000 tons/yr (table 7). The period after the plugging of the other three wells (1981–83) was too short for an intervention analysis. However, the proportions of sodium and chloride at site 44 decreased substantially during 1982 and 1983.

Annual monotonic-trend analyses indicated a highly significant decrease in median annual flow-adjusted concentration for the entire period of record. This decrease was 3.5 mg/L per year, representing a 12-percent change in the median annual concentration during the 10 years of record. Decreases in the flow-adjusted concentrations of calcium, sodium, and bicarbonate contributed to this trend.

Piceance Creek below Ryan Gulch near Rio Blanco, Colo. (site 45)

Site 45 is about 12 mi upstream from site 46 (table 3, pl. 1). The streamflow hydrographs for sites 45 and 46 on Piceance Creek show similar distributions; streamflow at the mouth (site 46) averaged 5 ft^3/s more than at site 45 upstream (fig. 19*B*). Agricultural depletions cause decreased streamflow during the irrigation season, notably during April; ground-water return flows make up most of the streamflow from November through February. Heavy snowfalls occasionally increase streamflow during February and March, and high-intensity thunderstorms occasionally increase streamflow during late summer (Weeks and others, 1974). No statistically significant annual monotonic trends were detected at this site.

Piceance Creek at White River, Colo. (site 46)

Mean annual flow-weighted dissolved-solids concentrations in Piceance Creek increase from 926 mg/L at site 45 to 1,240 mg/L at site 46 (table 7). Eighty-eight percent of this increase is a result of increases in sodium and bicarbonate concentrations. The relative proportions of sodium, bicarbonate, and chloride increase between the two sites. Sodium and bicarbonate are the predominant ions throughout the year at both sites. The proportion of calcium is small, and the equivalent concentration of magnesium exceeds that of calcium. The relatively high concentrations and the predominance of sodium and bicarbonate apparently result from subsurface flow through the Parachute Creek Member of the Green River Formation, which is connected to the surface by fracturing and is exposed in the lower reaches of the Piceance Creek basin.

Annual monotonic-trend analyses for 1971–83 indicated a highly significant decrease in median annual dissolved-solids concentration of 44.1 mg/L per year and a marginally significant decrease in median annual flow-adjusted concentration of 24.2 mg/L per year (table 8). During the 13 years of record, these decreases represent a 34-percent change in median annual concentration and a 20-percent change in median annual flow-adjusted concentration. Both trends may be caused by changes in irrigation practice associated with oil-shale leasing.

Yellow Creek near White River, Colo. (site 47)

Streamflow at site 47 (table 3, pl. 1) is generally less than 4 ft^3/s (fig. 19*C*). Occasional winter snowmelt events and summer thunderstorms generate flood peaks as large as 500 ft^3/s. Snowmelt runoff that occurs during April and May is diverted for irrigation. During most of the year, the flow-weighted dissolved-solids concentration is fairly constant, averaging 2,140 mg/L (table 7). Sodium and bicarbonate are the predominant ions throughout the year and account for 66 percent of the mean annual dissolved-solids load. Some irrigation-return flow is indicated during October and November. Chemical composition is very similar to that of Piceance Creek, except that little snowmelt is available to dilute ground-water inflow during the spring and early summer. The proportion of dissolved calcium is extremely small, only 1.4 percent of the total load of dissolved solids.

White River above Rangely, Colo. (site 48)

Streamflow at site 48 (table 3, pl. 1) has approximately the same volume and seasonal pattern as at site 44. Concentrations of sodium, bicarbonate, and sulfate are higher, and the mean annual flow-weighted dissolved-solids concentration averages 391 mg/L (table 7). The increased dissolved sodium and bicarbonate are contributed by Piceance and Yellow Creeks and by water discharged from the Parachute Creek Member of the Green River Formation. The increased

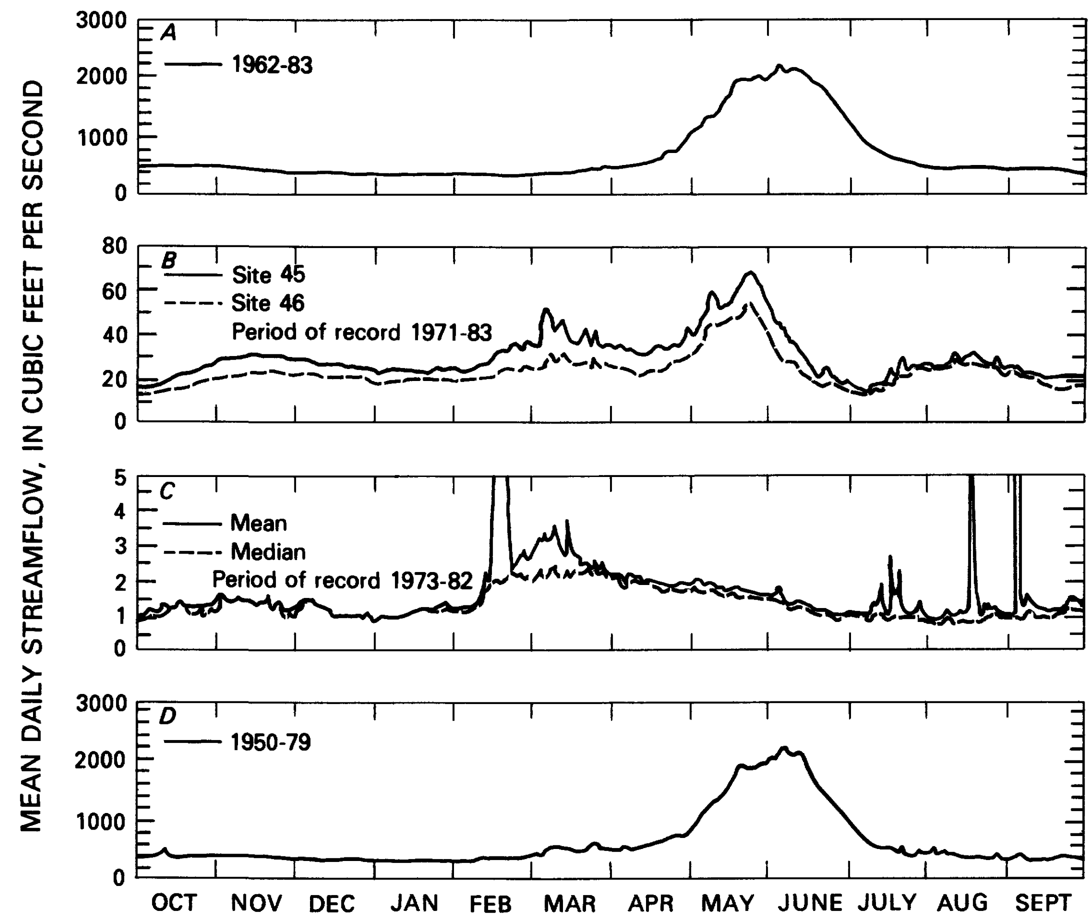


Figure 19. Mean daily streamflow at selected sites in White subregion of Green region. *A*, Site 44, White River below Meeker, Colo. *B*, Site 45, Piceance Creek below Ryan Gulch near Rio Blanco, Colo., and site 46, Piceance Creek at White River, Colo. *C*, Site 47, Yellow Creek near White River, Colo. *D*, Site 50, White River near Watson, Utah.

dissolved sulfate apparently is from dissolution of minerals in the Williams Fork Formation, which is exposed downstream from Yellow Creek. Calcium and bicarbonate are the predominant ions during the high-flow season. Calcium, bicarbonate, and sulfate are predominant during the low-flow season.

Evacuation Creek near Watson, Utah (site 49)

Runoff at site 49 (table 3, pl. 1) is very small. Evacuation Creek drains exposures of the Uinta Formation and the Parachute Creek Member of the Green River Formation. Snowmelt runoff along Evacuation Creek at site 49 peaks at about 2 ft^3/s during April and May. Other than during occasional floods, the creek is dry during most of the year, except in the vicinity of local seepage from the Green River Formation. Sodium and sulfate are the predominant ions throughout the year and account for 80 percent of the dissolved-solids load. Mean annual flow-weighted dissolved-solids concentration averaged 1,720 mg/L during 1975–81 (table 7).

White River near Watson, Utah (site 50)

Site 50 (table 3, pl. 1) is 1 mi downstream from the mouth of Evacuation Creek and about 8 mi downstream from the Colorado-Utah State line. During 1979–83, a streamflow-gaging station near the State line replaced the station near Watson; the two stations are considered equivalent for this report. Streamflow volume of the White River at site 50 is essentially the same as at sites 44 and 48 (table 7). There is substantial base flow, and the snowmelt-runoff peak is partially depleted by irrigation diversions (fig. 19*D*). During 1969–83, after the Meeker well was plugged, the mean annual flow-weighted dissolved-solids concentration averaged 382 mg/L, and the dissolved-solids load averaged 263,000 tons. During the high-flow season, calcium and bicarbonate are the predominant ions. During the low-flow season, calcium, sulfate, and bicarbonate are all equally dominant. Before the Meeker well was plugged, sodium also was a predominant cation during low flow.

The period of record was divided into a preintervention period (1951–68) and a postintervention period (1969–83), based on the plugging of the Meeker well in October 1968. Annual step-trend analyses indicated a highly significant decrease in annual dissolved-solids concentration of 89 mg/L (table 4). This trend represents a 19-percent decrease from the preintervention median concentration. Dissolved sodium and chloride make up 55 percent of the total decrease. No significant annual monotonic trends were identified for either the preintervention or postintervention periods.

Bitter Creek at Mouth, near Bonanza, Utah (site 51)

Bitter Creek, like Evacuation Creek, drains the Green River and Uinta Formations in the Uinta Basin. Bitter Creek is the largest single inflow to the White River downstream from site 50. Streamflow at site 51 (table 3, pl. 1) is very small, mostly occurring as surface runoff from summer thunderstorms. The mean annual flow-weighted dissolved-solids concentration is 6,740 mg/L (table 7), the highest of the 70 sites used for this report. Eighty-six percent of the mean-annual dissolved-solids load is dissolved sodium and sulfate.

White River at Mouth, near Ouray, Utah (site 52)

During 1975–83, the White River had an average annual net accumulation of about 11,000 acre-ft of streamflow and 40,000 tons of dissolved solids between site 50 and site 52 (table 3, pl. 1). Almost all of the increased dissolved-solids load was composed of sodium, sulfate, and bicarbonate from Bitter Creek and other small streams. The composition is predominantly calcium and bicarbonate during the high-flow season and sodium, calcium, sulfate, and bicarbonate during the low-flow season. Mean annual flow-weighted dissolved-solids concentration is 419 mg/L (table 7), which is less than at site 34 (491 mg/L) but is considerably greater than upstream on the Green River at site 38 (152 mg/L).

Lower Green Subregion

The lower Green subregion includes the drainages of the Price and San Rafael Rivers and all other tributaries to the Green River between the confluence of the White and Green Rivers and the confluence of the Green River with the Colorado River. About 41,000 acres is irrigated in the Price River basin, mainly near the town of Price, Utah. Runoff from the Wasatch Plateau is stored in Scofield Reservoir for irrigation releases, and some water is diverted into the Price River basin from Huntington Creek in the San Rafael River basin. Mancos Shale deposits underlie much of the agricultural area in the lower Price River basin and contribute large quantities of dissolved solids to the Price River. Accumulation of salts in agricultural land is a serious issue. Coking coal is produced in the Price River basin from underground mines; however, production declined during the 1960's and early 1970's (Mundorff, 1972).

The San Rafael River basin shares many characteristics with the Price River basin. It is very arid except for the headwaters in the Wasatch Plateau. About 42,000 acres is irrigated, primarily on Mancos Shale benches, in the vicinity of the towns of Huntington, Castle Dale, and Ferron, Utah (pl. 1). Water is stored for irrigation release in Joes Valley Reservoir and Electric Lake. Coal-fired powerplants in Emery County, Utah, use an estimated 24,000 acre-ft of water per year. There are many small transbasin exports westward to the Great Basin that date back to 1906. Downstream from the agricultural lands, the San Rafael River crosses the San Rafael Swell, an uplift area where upper Paleozoic and Mesozoic strata are exposed. These include the Curtis and Carmel Formations of Jurassic age, which contain deposits of gypsum and halite.

Price River at Woodside, Utah (site 53)

Streamflow at site 53 (table 3, pl. 1) is greatly affected by storage, diversions for public supply and agriculture, and irrigation-return flows. Water seldom is released from Scofield Reservoir during the winter, and the growing-season releases ordinarily are used entirely for irrigation. Because of irrigation diversions, median daily streamflow at site 53 lacks a snowmelt-runoff peak (fig. 20*A*). Occasional extreme-runoff years, when snowmelt greatly exceeds irrigation requirements, cause an increase in mean daily streamflow during April through June. Summer and autumn storms produce flash floods that have peak flows as large as 5,000 ft^3/s. Mean annual dissolved-solids load averages 240,000 tons (table 7), of which 76 percent is dissolved sodium and sulfate. During 1949–83, the mean annual flow-weighted dissolved-solids concentration was 1,990 mg/L (table 7). Sodium and sulfate are the predominant ions throughout the year, probably because of fairly continuous irrigation-return flows from the agricultural areas.

For 1949–83, annual monotonic-trend analyses indicated a significant decrease in median annual dissolved-solids concentration of 33.2 mg/L per year and a highly significant decrease in median annual flow-adjusted concentration of 23.1 mg/L per year (table 8). Decreases occurred during all months and for all constituents except dissolved bicarbonate, which is not strongly affected by contributions from the Mancos Shale. The decrease in dissolved-solids concentration represents a 37-percent change in the median annual concentration and may result from agricultural lands that have been taken out of production. The decrease in flow-adjusted concentration represents a 28-percent change in the median annual flow-adjusted concentration during the period of record. About 89 percent of this change was due to decreases in sodium and sulfate concentrations. Dissolved-solids load did not change significantly.

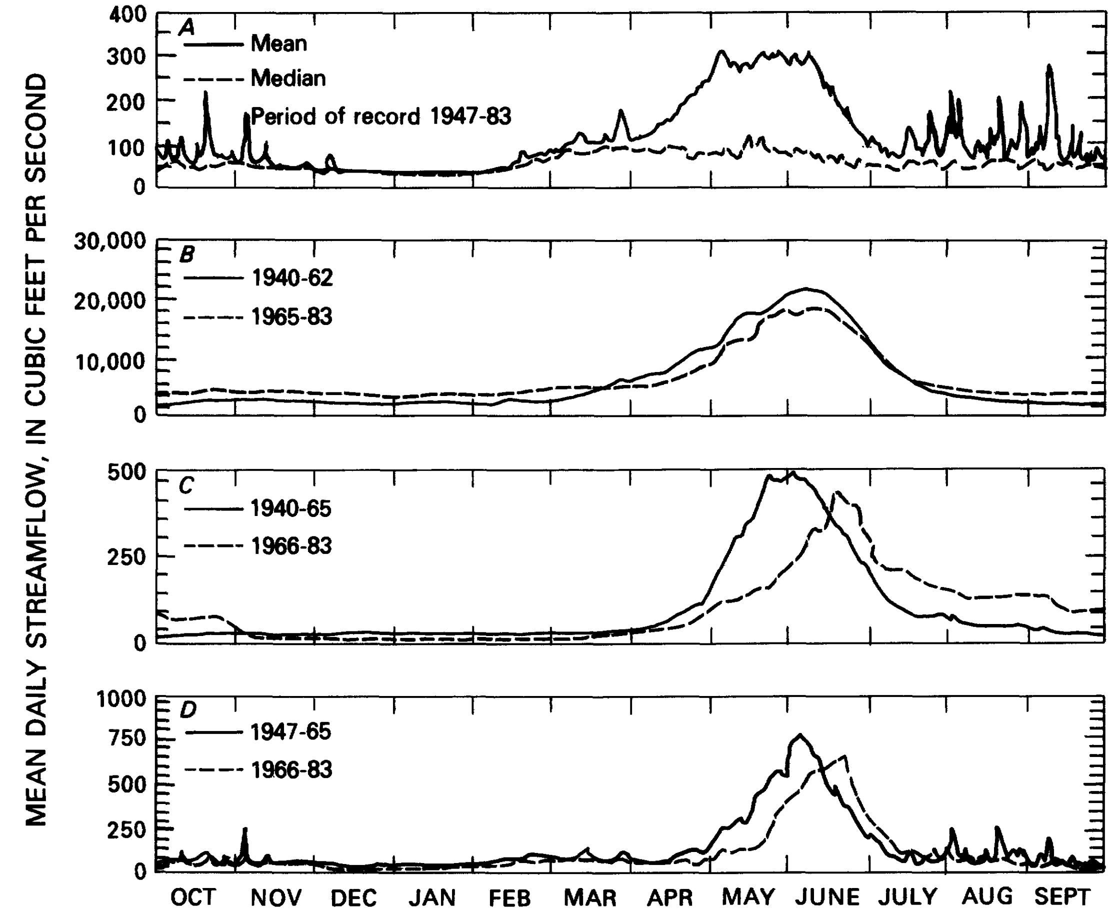


Figure 20. Mean daily streamflow at selected sites in lower Green subregion of Green region. *A*, Site 53, Price River at Woodside, Utah. *B*, Site 54, Green River at Green River, Utah. C, Site 55, Cottonwood Creek near Orangeville, Utah. *D*, Site 57, San Rafael River near Green River, Utah.

Green River at Green River, Utah (site 54)

Site 54 (table 3, pl. 1) is the site farthest downstream on the main stem of the Green River. The San Rafael River is the only major tributary of the Green River downstream from this site. Streamflow at site 54 is representative of the cumulative hydrology of almost the entire Green region. Mean daily streamflows during the period before construction of Flaming Gorge Dam (1929–62) and during the period after completion of initial filling (1965–83) are shown in figure 20*B*. The combined contributions from the Yampa and White Rivers are greater than the flow at site 34 and produce a snowmelt-runoff peak during May and June. Although storage in Flaming Gorge Reservoir decreases the snowmelt runoff, the main effect of regulation has been to double the streamflow during the low-flow season to about 3,500 ft^3/s. From 1965 to 1983, mean annual flow-weighted dissolved-solids concentration averaged 463 mg/L (table 7). Calcium and bicarbonate are the predominant ions during the high-flow season. Sodium, calcium, and sulfate predominate during the low-flow season (fig. 14). Since the reservoir was filled, mean annual dissolved-solids concentration has increased, primarily from increases in the dissolved-sulfate concentration. The variability of monthly dissolved-solids concentration and chemical composition has decreased.

The period of record was divided into a preintervention period (1929–62) and a postintervention period (1965–83). This division corresponds to the filling of Flaming Gorge Reservoir and approximately corresponds with the filling of Fontenelle Reservoir. Annual step-trend analyses indicated a highly significant increase in annual dissolved-solids concentration of 29 mg/L, despite increased streamflow (table 4). This was a 7-percent change from the preintervention median concentration. Trends indicated a marginally significant increase in annual dissolved-solids load of 330,000 tons, a 14-percent change from the preintervention median load (table 4). No statistically significant annual monotonic trends were identified for either the preintervention or postintervention periods (table 8).

Cottonwood Creek near Orangeville, Utah (site 55)

Cottonwood Creek is one of the three main tributaries that merge downstream from Castle Dale, Utah, to form the

San Rafael River. Site 55 (table 3, pl. 1) is downstream from Joes Valley Reservoir but upstream from diversions to the agricultural area of the San Rafael River basin. Construction of Joes Valley Reservoir preceded the beginning of water-quality sampling at this site. Streamflow of Cottonwood Creek at site 55 has been controlled almost completely by reservoir releases since 1966. Snowmelt runoff is stored in Joes Valley Reservoir during May, then released throughout the irrigation season; there is a sharp decline in streamflow at the end of October (fig. 20*C*). Because this site is upstream from the agricultural areas, mean annual flow-weighted dissolved-solids concentration is relatively low (225 mg/L; table 7), and it is almost constant throughout the year. Calcium and bicarbonate are predominant ions throughout the year; magnesium also becomes predominant during the low-flow season. The proportions of dissolved sodium and sulfate are small.

San Rafael River at San Rafael Bridge Campground, near Castle Dale, Utah (site 56)

Site 56 (table 3, pl. 1) is about 13 mi downstream from the confluence of Huntington, Cottonwood, and Ferron Creeks. It is downstream from almost all the agricultural land in the San Rafael River basin. Substantial quantities of dissolved solids from irrigation-return flows and from springs and seeps in the Curtis and Carmel Formations also enter the river upstream from this site. Mean annual streamflow is only slightly greater than at site 55, but dissolved-solids load increases almost eightfold. Dissolved sodium and sulfate compose 72 percent of the dissolved-solids load. Sodium and sulfate are the predominant ions throughout the year. Calcium and magnesium are approximately equal to sodium during the high-flow month of June. Streamflow during May remains relatively low because of irrigation diversions. Although the proportions of dissolved sodium and sulfate are much larger than at site 55, the available data do not indicate the relative magnitude of dissolved-solids load contributed by the irrigated Mancos Shale area versus natural dissolved-solids load from the San Rafael Swell area. However, based on the minimal runoff in the San Rafael Swell area, most of the dissolved-solids load may be leached from the Mancos Shale benches. Agricultural soils in the area have deteriorated from salt accumulation, and 4,600 acres was eliminated from agricultural use during 1976.

San Rafael River near Green River, Utah (site 57)

Site 57 (table 3, pl. 1) is about 20 mi upstream from the confluence with the Green River, in an area referred to as the San Rafael Desert. Comparison of data from this site and site 56 indicates that streamflow and dissolved-solids load increase slightly, but dissolved-solids concentration is about the same. The proportion of dissolved sulfate increases in the reach between the two sites. Since the filling of Joes Valley Reservoir, the snowmelt-runoff peak occurs later in the season; otherwise, streamflow has not changed greatly (fig. 20*D*).

The period of record was divided into a preintervention (1947–65) and a postintervention (1966–83) period based on the filling of Joes Valley Reservoir. No statistically significant annual step trends or annual monotonic trends were detected in the data. Monthly step trends indicated a redistribution of streamflow, probably because of regulation by the reservoir. Streamflow decreased significantly during January, February, and May and increased significantly during July and October.

General Trends in the Green Region

The filling of Flaming Gorge Reservoir and, to some extent, Fontenelle Reservoir has decreased seasonal variability in streamflow along the main stem of the Green River. Streamflow at site 34 near Greendale, Utah, is virtually constant throughout most years. Significant increases in annual dissolved-solids concentration and load at site 34 resulted from dissolution of mineral salts in bed and bank material inundated by Fontenelle and Flaming Gorge Reservoirs, from irrigation-return flows in the Big Sandy River basin, and from increases in streamflow. The Eden Valley Project, begun during the 1950's, increased the dissolved-solids load of the Big Sandy River because of large irrigation-return flows.

The Yampa River contributes almost the same volume of water as does the Green River upstream from their confluence. Because the dissolved-solids concentration in the Yampa River is lower than in the Green River, the Yampa River inflow has a diluting effect. Increases in dissolved-solids load and concentration in the Yampa River may be related to surface mining of coal in the basin.

The White River contributes a large load of dissolved solids derived from natural and anthropogenic sources. Recent efforts to control the flow of saline ground water from several abandoned wells near Meeker, Colo., have produced a significant decrease in dissolved-solids concentration downstream.

The Price and San Rafael Rivers also transport large quantities of dissolved solids from agricultural sources. Streamflow has high concentrations of dissolved sodium and sulfate, resulting from irrigation-return flow from agricultural areas underlain by Mancos Shale and from contributions from the Carmel Formation. Reductions in irrigated area may have caused decreases in dissolved-solids concentration in the Price River.

At site 54 near Green River, Utah, near the downstream end of the Green region, step-trend analysis indicated decreasing seasonal variability. Dissolved-solids concentration increased by 29 mg/L because of changes upstream from Flaming Gorge Dam. Decreased concentration of dissolved chloride was caused by the decrease in dissolved-solids input from the Meeker Dome area.

San Juan Region

The San Juan region consists of the San Juan River drainage basin and the large arid area downstream from the confluence of the Green and Colorado Rivers. Most of the flow of the San Juan River originates on the western slope of the Rocky Mountains in Colorado. Streamflow contributed to the Colorado River in this region originates almost entirely in the San Juan River basin. The San Juan region contains 35 percent of the total drainage area of the Upper Colorado River Basin and contributes 16 percent of the streamflow and 14 percent of the dissolved-solids load. Lake Powell extends upstream to within about 20 mi of the confluence of the Green River, and it has inundated many features in the region, including the mouth of the San Juan River and the former town of Hite, Utah. Except for minor inputs from the Paria River, the flow of the Colorado River leaving the Upper Colorado River Basin is completely controlled by Glen Canyon Dam and Lake Powell. During 1966–80, the mean annual streamflow of the Colorado River at Lees Ferry, Ariz. (site 69) (table 3, pl. 1), was about 8.8 million acre-ft, mean annual flow-weighted dissolved-solids concentration was 564 mg/L, and the dissolved-solids load was about 6.7 million tons (table 9).

Data from 13 sites were evaluated for the San Juan region (pl. 1). Mean annual streamflows, dissolved-solids concentrations and loads, and major-constituent loads were determined at each of these sites (table 9). Chemical composition of streamflow for selected sites is shown in figure 21. Selected monotonic trend-analysis results are listed in table 10. The San Juan region was divided into two subregions: the San Juan and the main stem (pl. 1).

San Juan Subregion

The San Juan subregion consists of the entire San Juan River basin. Large tracts of land are irrigated along the San Juan and Animas Rivers in the vicinity of the towns of Farmington, Bloomfield, and Fruitland, N. Mex. Navajo Dam and Reservoir is the largest water-storage project in the San Juan region. Completed in 1963 and having a capacity of about 1.7 million acre-ft (table 2), Navajo Reservoir is the third largest reservoir in the Upper Colorado River Basin. The Navajo Indian Irrigation Project diverts water from the reservoir to supply Navajo Indian lands east of the Chaco River. Delivery of water to the Navajo Indian Irrigation Project began in 1976. Delivery during 1984 totaled 120,000 acre-ft, about one-half of the estimated depletion at full development.

Several diversions export water from the San Juan River basin to the Rio Grande basin. The largest is Azotea Tunnel, which has exported about 107,000 acre-ft/yr from the Navajo River and Rio Blanco drainages since 1971 (table 1), as part of the San Juan–Chama Project. Vallecito Reservoir, Lemon Reservoir, and Electra Lake provide water storage in the Los Pinos and Animas River drainages. Large volumes of irrigation water are imported to the McElmo Creek drainage from the Dolores River through the Montezuma Tunnel.

Vallecito Creek near Bayfield, Colo. (site 60)

Streamflow in the headwaters of the San Juan drainage generally has low dissolved-solids concentrations. Site 60 (table 3, pl. 1) has very large mean annual runoff, averaging 26.8 in., and very low mean annual flow-weighted dissolved-solids concentration, averaging 34 mg/L (table 9). The site is upstream from Vallecito Reservoir, and seasonal streamflow consists of a broad snowmelt-runoff peak followed by a gradual recession period and very little streamflow during the winter months (fig. 22*A*). Calcium and bicarbonate are the predominant ions throughout the year.

Analyses of annual monotonic trends indicated small but significant decreases in median annual dissolved-solids concentration of 0.3 mg/L per year and in median annual flow-adjusted concentration of 0.3 mg/L per year (table 10). These decreases represent a 17-percent change in the median annual concentration and in the median annual flow-adjusted concentration during the 21 years of record. Most of this change results from a decrease in dissolved sulfate. The cause of this decrease is not known.

San Juan River near Archuleta, N. Mex. (site 61)

Site 61 (table 3, pl. 1) is 7 mi downstream from Navajo Dam. About one-half of the total flow of the San Juan River enters the river upstream from this site. Streamflow has been completely regulated since June 1962. Although the initial filling period of the reservoir ended in June 1964, storage did not exceed 1 million acre-ft of its 1.7 million acre-ft capacity until 1968. The effect of reservoir storage and releases on streamflow is shown in figure 22*B*. Prior to 1962, streamflow was dominated by snowmelt runoff; after the initial reservoir filling, streamflow was almost constant. Although the seasonal variability in dissolved-solids concentration has been greatly decreased, the mean annual dissolved-solids concentration has not changed between the two periods. From 1964 to 1983, mean annual flow-weighted dissolved-solids concentration averaged 166 mg/L (table 9). Calcium and bicarbonate are the predominant ions throughout the year.

The period of record was divided into a preintervention period (1956–61) and a postintervention period (1964–83) (table 4), based on the initial filling of Navajo Reservoir. No annual step trends were statistically significant. There is no evidence of leaching or mineral precipitation in the reservoir. Monthly step trends in streamflow and dissolved-solids concentration and load indicate the decrease in seasonal variability after the initial filling of the reservoir (fig. 23*A*).

Annual monotonic-trend analyses of the postintervention period indicated a marginally significant decrease in median annual dissolved-solids concentration of 1.1 mg/L

Table 9. Mean annual values of runoff, streamflow, dissolved-solids concentrations and loads, and major-constituent loads—San Juan region
[Periods of record for some sites are divided into preintervention and postintervention periods; asterisks indicate main-stem sites; mg/L, milligrams per liter]

Site (table 3, plate 1)	Period of record (water years)[1]	Runoff (inches)	Streamflow (acre-feet)	Streamflow (cubic feet per second)	Dissolved solids: Flow-weighted concentration (mg/L)	Dissolved solids: Load (tons)	Major-constituent loads (tons): Calcium	Magnesium	Sodium plus potassium	Carbonate equivalent[2]	Chloride	Sulfate
58	1969-76	0.26	57,000	78	1,110	85,000	13,500	3,000	10,100	6,800	8,300	43,700
59	1951-56	2.17	8,380,000	11,600	580	6,616,000	887,000	321,000	950,000	1,020,000	659,000	2,780,000
60	1963-83	26.8	103,000	142	34	4,800	1,200	300	200	1,900	100	1,100
61*	1956-61	5.45	947,000	1,310	163	210,000	39,700	8,520	25,000	68,000	5,000	63,800
61*	1964-83	4.80	835,000	1,150	166	188,000	37,600	7,200	20,600	58,600	3,400	61,100
62	1955-83	8.06	585,000	807	263	209,000	46,800	6,500	17,100	49,000	9,000	80,800
63*	1962-82	3.43	1,327,000	1,830	256	462,000	89,900	12,800	52,300	107,000	11,900	188,000
64	1977-83	.13	31,000	42	801	33,000	3,600	900	6,200	2,800	2,200	17,800
65*	1958-61	2.09	1,440,000	1,990	324	634,000	110,000	17,300	82,400	123,000	25,100	276,000
65*	1964-83	2.00	1,379,000	1,900	324	607,000	107,000	19,100	76,000	121,000	18,300	274,000
66	1977-82	2.79	45,000	62	666	41,000	5,700	2,800	3,500	4,000	500	24,300
67	1978-81	1.99	37,000	51	2,210	110,000	13,700	8,400	9,300	7,400	2,300	69,100
68*	1930-61	1.39	1,710,000	2,360	413	961,000	165,000	36,000	115,000	180,000	27,000	438,000
68*	1964-83	1.26	1,545,000	2,130	467	981,000	149,000	40,800	120,000	173,000	33,600	465,000
69*	1942-62	2.01	11,520,000	15,900	539	8,443,000	1,220,000	381,000	1,170,000	1,430,000	752,000	3,490,000
69*	1966-80	1.53	8,754,000	12,100	564	6,714,000	885,000	311,000	983,000	954,000	640,000	2,940,000
69*	1981-83	1.98	11,360,000	15,700	520	8,039,000	1,040,000	382,000	1,190,000	1,200,000	765,000	3,460,000
70	1948-50	.23	17,000	24	1,340	32,000	3,700	1,500	4,200	2,600	600	19,100

[1]All mean values are based only on those water years having estimates of the major constituents.
[2]Carbonate equivalent is computed from alkalinity; bicarbonate is the primary dissolved form.

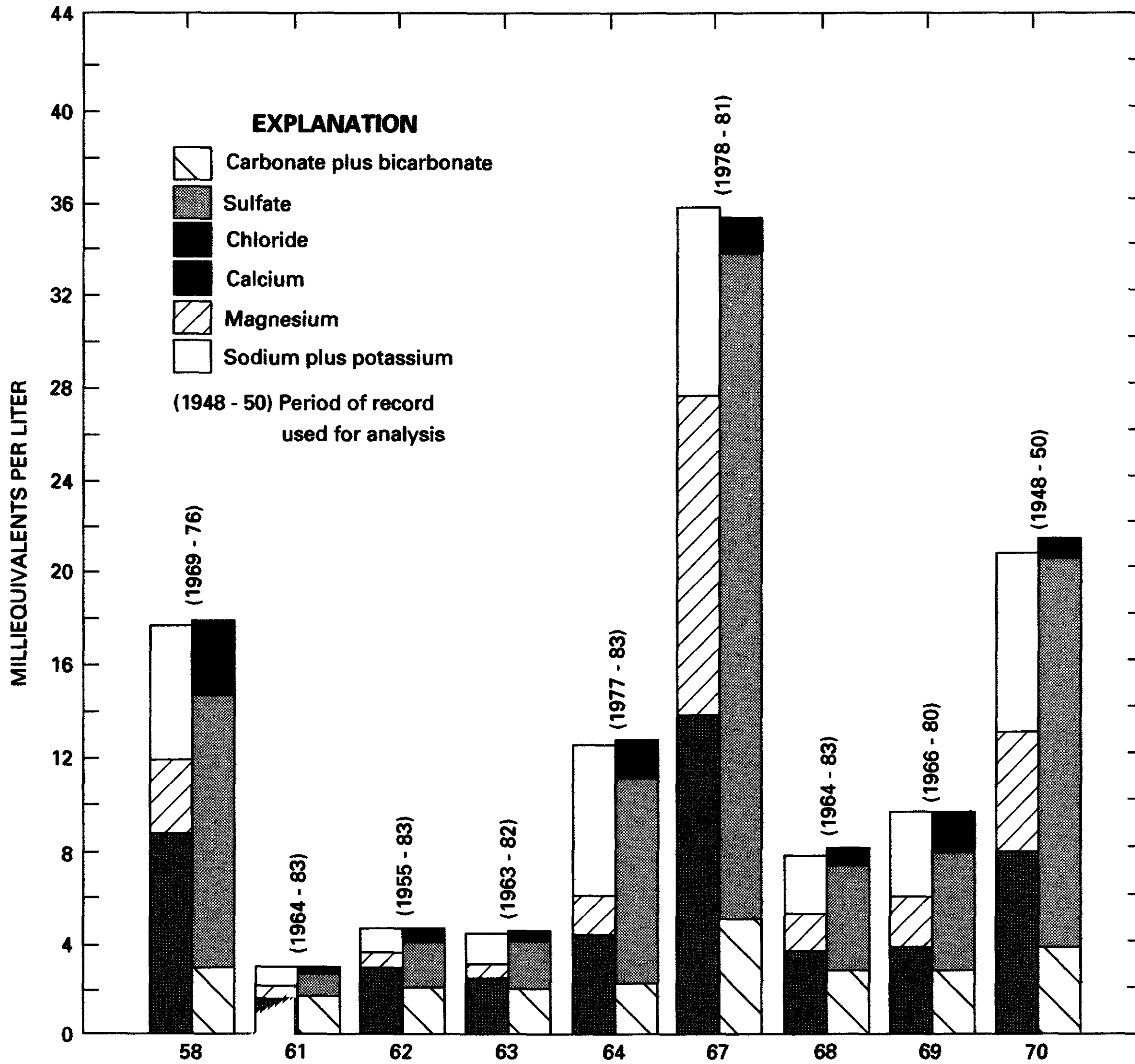


Figure 21. Mean chemical composition of dissolved solids at selected sites in San Juan region. Cations on left, anions on right.

per year (table 10). This trend represents a 12-percent change in the median annual concentration during the 20-year period.

Animas River at Farmington, N. Mex. (site 62)

The Animas River is the largest tributary of the San Juan River. At site 62 (table 3, pl. 1), near the mouth of the river, mean annual runoff averages about 8.1 in. (table 9). Streamflow is somewhat regulated by Lemon Reservoir and Electra Lake, and about 30,000 acres is irrigated upstream from the site. The streamflow hydrograph shows a typical snowmelt-runoff peak in June and steady base flow during the winter months (fig. 22*C*). Mean annual flow-weighted dissolved-solids concentration is greater than at site 61, averaging about 263 mg/L. Calcium and bicarbonate are the predominant ions during the high-flow season. Calcium and sulfate predominate during the low-flow season.

No statistically significant annual monotonic trends in streamflow or dissolved solids were detected during 1955–83. However, monthly concentrations of dissolved sodium and chloride decreased significantly, mainly during the low-flow season.

San Juan River at Farmington, N. Mex. (site 63)

Site 63 (table 3, pl. 1) is just downstream from the mouth of the Animas River. Irrigated area upstream from the site totals about 86,000 acres. Streamflow is controlled partly by Navajo Reservoir, and the period of record (1962–82) is essentially the same as the postintervention period for site 61. Streamflow is a combination of the regulated streamflow of the San Juan River and the seasonal streamflow of the Animas River. Streamflow peaks during June, and it is maintained at about 1,200 ft^3/s during the

Table 10. Selected annual monotonic-trend-analysis results—San Juan Region

[Sites having less than 10 years of dissolved-solids data are not reported; *n*, number of years of dissolved-solids data; acre-ft/yr, acre-feet per year; mg/L, milligrams per liter; tons/yr, tons per year; HS, highly significant ($p < 0.01$); S, significant ($0.01 < p \leqslant 0.05$); MS, marginally significant ($0.05 < p \leqslant 0.10$); - -, not significant ($p > 0.10$)]

Site (table 3, plate 1)	Period of record (water years)	*n*	Annual trend in streamflow: Significance level	Annual trend in streamflow: Trend (acre-ft/yr)	Annual trend in streamflow: Percent[1]	Annual trend in dissolved solids — Concentration: Significance level	Concentration: Trend (mg/L)	Concentration: Percent[1]	Load: Significance level	Load: Trend (tons/yr)	Load: Percent[1]	Flow-adjusted concentration: Significance level	Flow-adjusted concentration: Trend (mg/L)	Flow-adjusted concentration: Percent[1]
60	1963-83	21	--	--	--	S	-0.3	17	--	--	--	S	-0.3	17
61	1964-83	20	--	--	--	MS	-1.1	12	--	--	--	--	--	--
62	1955-83	29	--	--	--	--	--	--	--	--	--	--	--	--
63	1962-82	21	--	--	--	--	--	--	--	--	--	--	--	--
65	1964-83	20	--	--	--	MS	-3.7	20	--	--	--	S	-2.7	15
68	1930-61	32	--	--	--	--	--	--	--	--	--	S	-1.5	10
68	1964-83	20	--	--	--	MS	-7.1	26	--	--	--	S	-3.7	14
69	1942-62	21	--	--	--	S	7.3	33	--	--	--	S	3.3	14
69	1966-80	15	--	--	--	--	--	--	--	--	--	--	--	--

[1]Percent change during period of record.

low-flow season. Excluding the Animas River inflow, about 65,000 tons/yr of dissolved solids is added to the San Juan River in the reach between Archuleta and Farmington, N. Mex., mostly as dissolved sulfate. Irrigation-return flows from agricultural lands possibly are the source of this increase. Because of the upstream regulation, dissolved-solids concentration does not vary greatly throughout the year. No statistically significant annual monotonic trends were detected for this site.

Chaco River near Waterflow, N. Mex. (site 64)

The Chaco River drains a large, but arid, region south of the San Juan River and discharges into the San Juan River just upstream from Shiprock, N. Mex. Site 64 (table 3, pl. 1) is about 5 mi downstream from the Four Corners Powerplant, a large, coal-fired utility that began operating in 1967. Coal is supplied from a large strip mine upstream, where Upper Cretaceous deposits in the Fruitland Formation are overlain by Kirtland Shale. Water is pumped from the San Juan River to Morgan Lake, beside the powerplant, where it is used for cooling purposes. Wastewater from the plant drains from several holding ponds into the Chaco River, creating a perennial stream downstream from the powerplant. Base flow is maintained at about 15 ft^3/s. The remainder of the flow of the Chaco River is almost entirely from occasional, intense rainfall (fig. 22*D*). Mean annual flow-weighted dissolved-solids concentration averages 801 mg/L, and the mean dissolved-solids load is 33,000 tons/yr (table 9), 72 percent of which is sodium and sulfate.

San Juan River at Shiprock, N. Mex. (site 65)

Streamflow at site 65 (table 3, pl. 1) is about the same as at site 63, but dissolved-solids concentration and load are greater. Of the dissolved solids contributed in the reach, 74 percent is dissolved sodium and sulfate. During 1964–83, mean annual flow-weighted dissolved-solids concentration averaged 324 mg/L (table 9). Calcium, bicarbonate, and sulfate are the predominant ions during the high-flow season. Calcium and sulfate are predominant during the low-flow season. The proportion of dissolved sulfate in the dissolved-solids load increases from 32 percent at site 61 to 41 percent at site 63 and to 45 percent at site 65. The seasonal variability of streamflow and dissolved solids at site 65 markedly decreased after the closure of Navajo Reservoir.

The period of record was divided into a preintervention period (1958–61) and a postintervention period (1964–83) based on the initial filling of Navajo Reservoir. Because of the short preintervention period, step trends were not evaluated nor were monotonic trends evaluated for that period. Annual monotonic-trend analyses for the postintervention period indicated marginally significant decreases in median annual dissolved-solids concentration of 3.7 mg/L per year and significant decreases in median annual flow-adjusted concentration of 2.7 mg/L per year (table 10). These decreases represent a 20-percent change in the median annual concentration and a 15-percent change in the median annual flow-adjusted concentration during the 20-year period.

Mancos River near Cortez, Colo. (site 66)

Site 66 (table 3, pl. 1) is downstream from about 12,000 acres of irrigated land underlain by Mancos Shale. Navajo Wash drains additional irrigation area and discharges into the Mancos River downstream from the site. Therefore, the Mancos River contributes substantially more dissolved solids than reported for this site. Snowmelt runoff from the mountain headwaters results in a hydrograph peak from April through June. Calcium and sulfate are predominant throughout the year. Magnesium also becomes predominant during

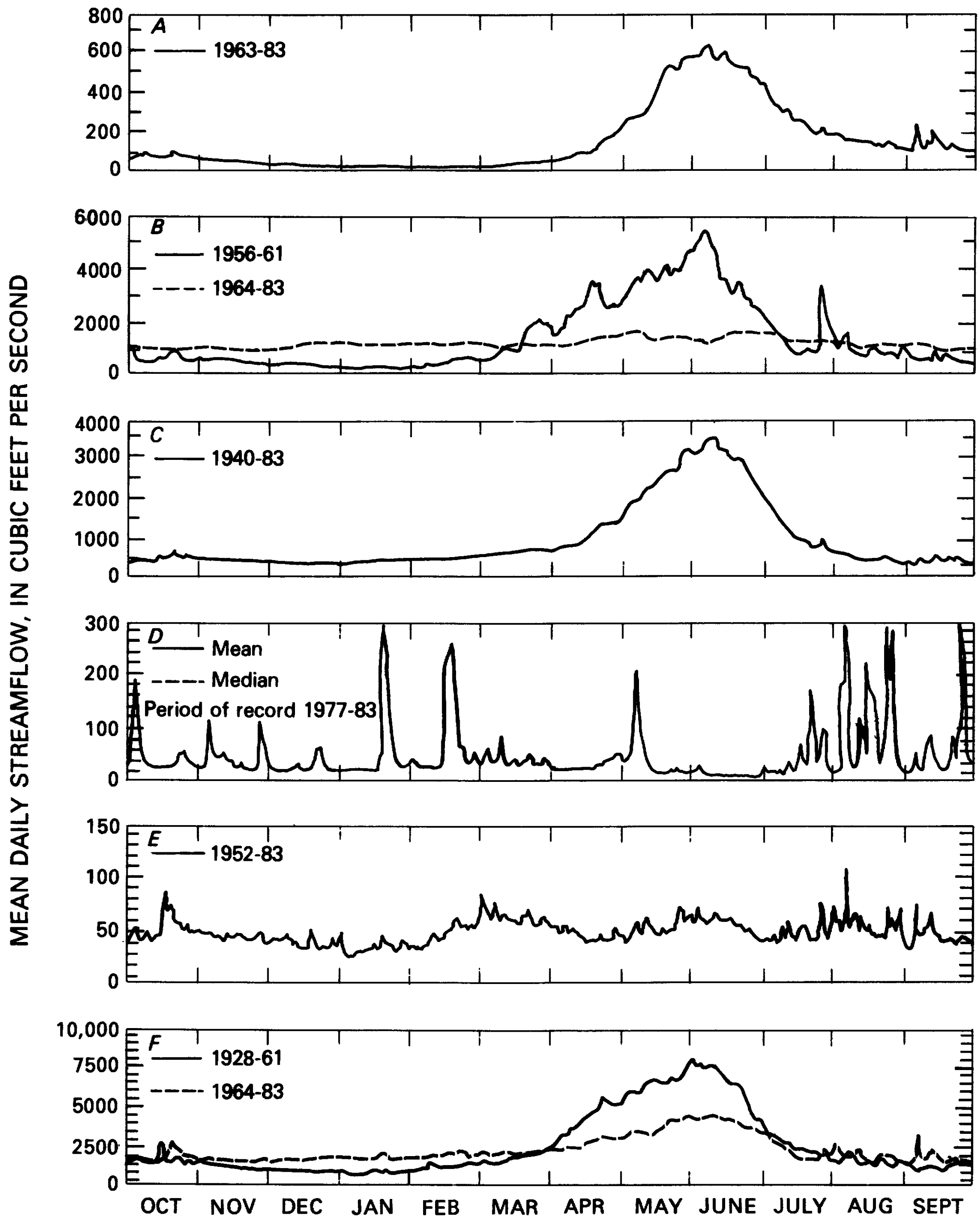


Figure 22. Mean daily streamflow at selected sites in San Juan subregion of San Juan region. *A*, Site 60, Vallecito Creek near Bayfield, Colo. *B*, Site 61, San Juan River near Archuleta, N. Mex. *C*, Site 62, Animas River at Farmington, N. Mex. *D*, Site 64, Chaco River near Waterflow, N. Mex. *E*, Site 67, McElmo Creek near Colorado-Utah State line. *F*, Site 68, San Juan River near Bluff, Utah.

October through March. Although dissolved-solids concentration during base flow averages about 1,800 mg/L, the large volume of snowmelt runoff decreases the average flow-weighted dissolved-solids concentration to 666 mg/L (table 9). Sulfate makes up 60 percent of the dissolved-solids load.

McElmo Creek near Colorado-Utah State line (site 67)

Site 67 (table 3, pl. 1) is downstream from about 33,000 acres of irrigated agriculture. McElmo Creek drains most of the Montezuma Valley irrigation area, which uses water

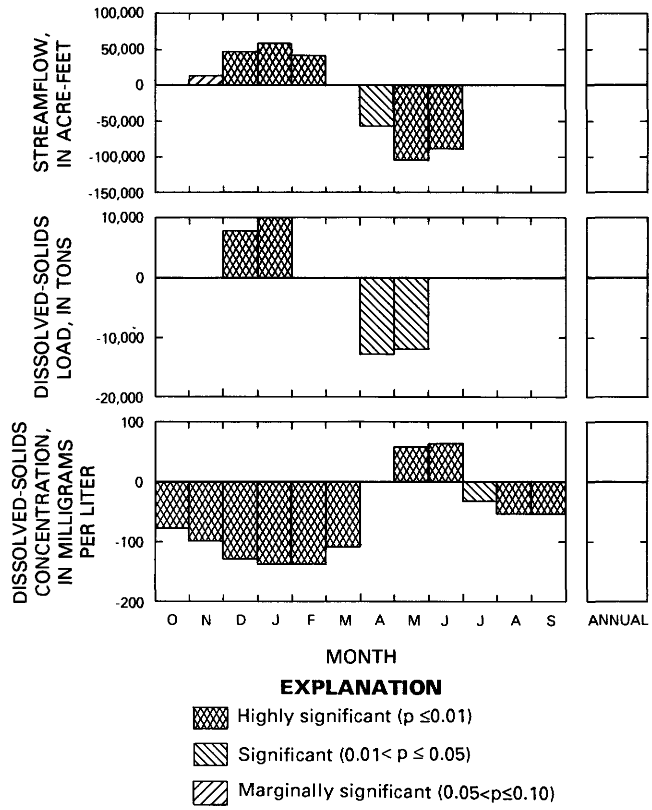


Figure 23. Step trends at site 61 (San Juan River near Archuleta, N. Mex.) from 1956–61 to 1964–83.

imported from the Dolores River basin. Although the chemical composition is similar to the water at site 66, the mean annual flow-weighted dissolved-solids concentration and load are much greater, averaging 2,210 mg/L and 110,000 tons (table 9). The streamflow hydrograph shows the effect of irrigation diversions. A snowmelt-runoff peak is absent, and most of the streamflow seems to be composed of irrigation-return flows (fig. 22*E*). Dissolved-solids concentration is almost constant throughout the year. Calcium, magnesium, and sulfate are the predominant ions. Sulfate is 63 percent of the dissolved-solids load.

San Juan River near Bluff, Utah (site 68)

Between sites 65 and 68 (table 3, pl. 1), the drainage area of the San Juan River almost doubles. Because most of the additional land is very arid, streamflow increases only slightly. However, mean annual dissolved-solids load increases by 374,000 tons (table 9). Excluding the measured inputs from the Mancos River (site 66) and McElmo Creek (site 67), which average 151,000 tons, dissolved-solids load in the reach increases by 223,000 tons/yr, 45 percent of which is dissolved sulfate. Mean annual streamflow at site 68 has decreased since the filling of Navajo Reservoir. Depletions that began after 1961 include evaporation and increased storage in the reservoir, the Azotea Tunnel diversions, Navajo Indian Irrigation Project diversions, and several smaller uses downstream from Navajo Reservoir. Resultant changes in seasonal streamflow are shown in figure 22*F*. Seasonal variations in streamflow and dissolved solids have decreased, but inflows, primarily from the Animas River, result in a modest snowmelt-runoff peak during May and June. Flow-weighted dissolved-solids concentrations averaged 467 mg/L during 1964–83 (table 9). Since the filling of Navajo Reservoir, calcium and sulfate have been the predominant ions throughout the year. Because of decreases in seasonal variability, dissolved bicarbonate is no longer the major anion during the high-flow season.

The period of record was divided into a preintervention period (1930–61) and a postintervention period (1964–83) (table 4), based on the initial filling of Navajo Reservoir. Annual step-trend analyses indicated a marginally significant increase in annual dissolved-solids concentration of 47 mg/L, which represents an 11-percent change from the preintervention median concentration. Most of this increase was due to changes in dissolved sodium and sulfate concentrations. These constituents were added principally in the reach downstream from the reservoir. A decrease in annual streamflow, although not statistically significant, limited the water available for dilution of dissolved solids at site 68.

Annual monotonic-trend analyses indicated a significant decrease in median annual flow-adjusted concentration of 1.5 mg/L per year, which represents a 10-percent change from the preintervention median concentration. During the postintervention period, trends indicated a marginally significant decrease in median annual dissolved-solids concentration of 7.1 mg/L per year and a significant decrease in median annual flow-adjusted concentration of 3.7 mg/L per year (table 10), mostly because of decreases in calcium, sodium, and sulfate. These decreases represent a 26-percent change in median annual concentration and a 14-percent change in median annual flow-adjusted concentration during the 20-year period.

A second step-trend analysis, using 1968–83 as the postintervention period, indicated no significant annual trends. For several years after Navajo Reservoir began to fill, releases were small, supplying less water to dilute the dissolved solids contributed downstream from the reservoir. After 1968, the reservoir was mostly full, more water was released, and dissolved-solids concentrations decreased. The reservoir, once filled, has affected seasonal variability but has not affected long-term mean values at site 68.

There are no additional sites on the San Juan River downstream from site 68. There are no perennial streams and virtually no irrigated agriculture in the reach, and dissolved-solids inputs probably are much smaller than those contributed in the reach between sites 65 and 68. Because of this, site 68 generally represents the entire input of the San Juan River to Lake Powell and the Colorado River.

Main-Stem Subregion

The main-stem subregion consists of the remainder of the San Juan region including the Dirty Devil and Paria Rivers and the main stem of the Colorado River. An area of about 19,000 acres is irrigated in the Dirty Devil River basin, which empties into the upper end of Lake Powell, upstream from the San Juan River. The Fremont River and Muddy Creek merge near Hanksville, Utah, to form the Dirty Devil River. Two small reservoirs, Johnson and Mill Meadow, store water for irrigation-season releases. The Carmel Formation and Mancos Shale are major contributors of dissolved solids to the stream system. As in the San Rafael and Price River basins to the north, large tracts of irrigated land are underlain by Mancos Shale.

Only about 3,300 acres is irrigated in the Paria River basin, which empties into the Colorado River downstream from Glen Canyon Dam. The Paria River basin receives the only transbasin import into the entire Upper Colorado River Basin. The Tropic and East Fork Canal has imported water from the Sevier River in the Great Basin since 1892. Annual imports averaged 4,840 acre-ft during 1974–83. The imports were used to irrigate land underlain by Tropic Shale.

Lake Powell is formed by Glen Canyon Dam, 16 mi upstream from Lees Ferry, Ariz. The reservoir extends more than 180 mi upstream and inundates more than 250 mi^2 of canyon and desert. Total storage capacity of the reservoir is about 27 million acre-ft. Evaporation from the lake surface averaged 517,000 acre-ft/yr during 1973–82 (U.S. Bureau of Reclamation, 1982; J. Osterberg, U.S. Bureau of Reclamation, oral commun., 1986). The 710-ft-high dam was begun in 1957 and completed in 1963. The reservoir serves multiple purposes; it is a major recreation area and a source of hydroelectric power. It provides flood control on the Colorado River and also is a water supply for meeting the terms of the Colorado River Compact during extended droughts. Storage began in Lake Powell on March 13, 1963, but the severe drought during 1963 and 1964 slowed the filling. The minimum power-pool elevation of 3,490 ft was reached in August 1964, and the Glen Canyon powerplant was placed in operation that September. Excess spring runoff during 1965 was passed on to Lake Mead, producing a maximum streamflow of 56,600 ft^3/s. The initial filling period ended July 31, 1965, when a normal streamflow release program was begun (fig. 24). At the end of water year 1965, Lake Powell was 31 percent full. Annual releases of 8 to 10 million acre-ft were maintained during water years 1966–79. Filling continued until June 22, 1980, when total storage reached 27 million acre-ft at a lake-surface elevation of 3,700 ft. This marked the end of the filling period, and since then, the reservoir has remained relatively full. Exceptionally large inflows during 1983 required releases over the dam's spillway, which provided a maximum streamflow of 92,600 ft^3/s. Releases during 1984 remained consistently between 25,000 and 30,000 ft^3/s, except for a period during June and July, when more than 2 million acre-ft was released to prevent overtopping of the dam. During the drought years of 1977 and 1981, releases from the reservoir exceeded inflow.

Dirty Devil River above Poison Spring Wash, near Hanksville, Utah (site 58)

Site 58 (table 3, pl. 1) is less than 20 mi upstream from the mouth of the Dirty Devil River. Although the headwaters are in the Wasatch Plateau, most of the basin is arid. Runoff is minimal, and streamflow is affected by agricultural diversions. Spring runoff is greatly depleted, and median flow in June and July is almost zero because of continued irrigation (fig. 25*A*). Intense storms and winter runoff supply most of the annual streamflow; spring runoff only occasionally exceeds depletions for irrigation. Most of the dissolved-solids load results from the dissolution of gypsum and halite and enters the stream from diffuse ground-water inflow. Calcium and sulfate are the predominant ions throughout the year. Sulfate is 51 percent of the dissolved-solids load, and chloride is 10 percent of the dissolved-solids load, an unusually large percentage. Mean annual flow-weighted dissolved-solids concentration was 1,110 mg/L during 1969–76 (table 9).

Colorado River at Hite, Utah (site 59)

Site 59 (table 3, pl. 1), upstream from the mouth of the San Juan River, has been inundated by the waters of Lake Powell. Water-quality data exist from 1951 through 1956 and seem to represent the preintervention period. Mean annual flow-weighted dissolved-solids concentration for the period was 580 mg/L (table 9). The dissolved-solids concentration in streamflow downstream from Hite, Utah, is diluted by the inflow of the San Juan River. Seasonal streamflow at site 59 indicated a well-defined snowmelt-runoff peak during May and June and an average base flow of about 5,000 ft^3/s throughout the winter months. Calcium, bicarbonate, and sulfate are the predominant ions during the high-flow season. Sodium and sulfate are the predominant ions during the low-flow season. Sulfate averages 42 percent of the dissolved-solids load throughout the year. The monthly load of chloride had much less variation than that of the other constituents, which indicates a relatively constant supply rate.

Colorado River at Lees Ferry, Ariz. (site 69)

The streamflow hydrograph for site 69 (table 3, pl. 1), prior to 1962, was characterized by a snowmelt-runoff season peaking during late May or early June at more than 50,000 ft^3/s, and a well-sustained base flow of 5,000 ft^3/s or more (fig. 25*B*). Daily streamflow during 1922–62 ranged from 1,000 to 124,000 ft^3/s. Mean monthly dissolved-solids concentration during 1942–62 varied from 300 mg/L during June to 1,000 mg/L during January. Calcium and bicarbonate were the predominant ions during the high-flow season (May and June). Sodium, calcium, and sulfate were predominant during the remainder of the year. Sulfate was 41 percent of the

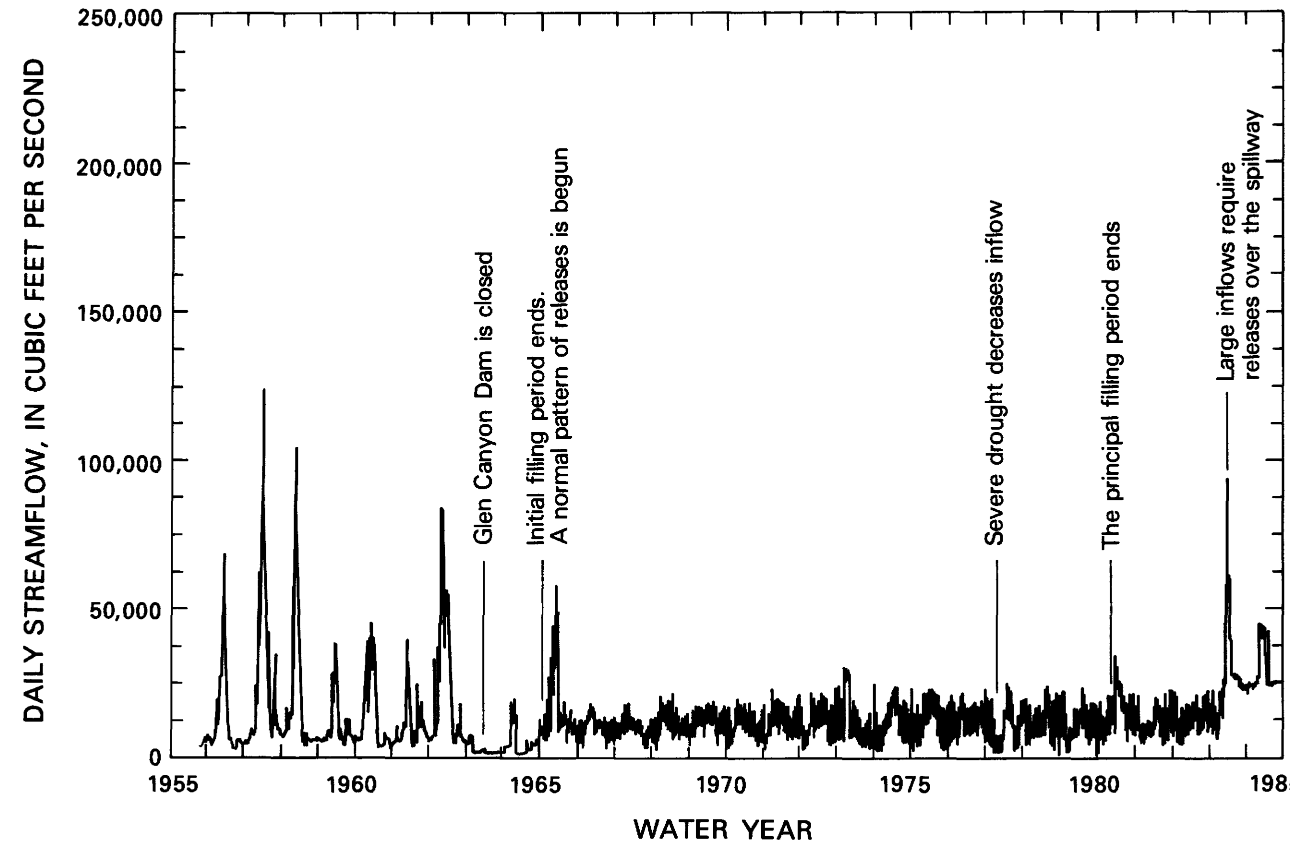


Figure 24. Daily streamflow at site 69 (Colorado River at Lees Ferry, Ariz.).

dissolved-solids load throughout the year. Mean annual streamflow averaged about 11.5 million acre-ft during 1942–62 (table 9). Annual inflows to Lake Powell during the principal filling period (1966–80) averaged 10.8 million acre-ft, and annual outflows were about 8.8 million acre-ft, representing a mean annual depletion of 2 million acre-ft. This depletion was a result of increased storage in the reservoir, losses through net evaporation, and losses to net bank storage. After normal operation was established in 1965, most releases of reservoir water were through the powerplant. Although day-to-day variations in release were large, the annual variations in daily streamflow were much less than in the past. During the principal filling period, streamflow had no snowmelt-season peak (fig. 25*C*). Slight increases in releases during the winter and summer months indicated seasonal increases in power demand for heating and air conditioning.

Streamflow releases during the initial filling period had relatively high dissolved-solids concentrations because of unusually low inflows. After 1968, the overall dissolved-solids concentration in the reservoir had stabilized. Mean annual dissolved-solids concentration at site 69 was not significantly affected by the reservoir. During 1966–80, the mean annual flow-weighted dissolved-solids concentration was 564 mg/L, an increase of less than 5 percent of the 1942–62 mean annual flow-weighted concentration (539 mg/L). Mean annual dissolved-solids load, however, decreased from about 8.4 to 6.7 million tons/yr (table 9), because of the decrease in streamflow. During the principal filling period, calcium, sodium, and sulfate were the predominant ions throughout the year. The monthly variation in dissolved-solids concentration, load, and chemical composition was very small. Since the end of the principal filling period, the record is too short for average conditions of streamflow and dissolved solids to be estimated accurately.

The period of record at site 69 was divided into a preintervention period (1942–62) and a postintervention period (1966–80) (table 4), based on the principal filling of Lake Powell. Annual step-trend analyses indicated a significant decrease in annual streamflow of 2,705,000 acre-ft and a highly significant decrease in annual dissolved-solids load of 1,588,000 tons between the two periods. These decreases represent a 24-percent change from the preintervention median streamflow and a 19-percent change from the preintervention median load. Dissolved-solids concentration did not change significantly, which indicates that the changes in streamflow and load were merely the result of increasing storage in the reservoir. Monthly step trends indicate a decrease in seasonal variability (fig. 26). Dissolved-solids concentration decreased by as much as 600 mg/L during the

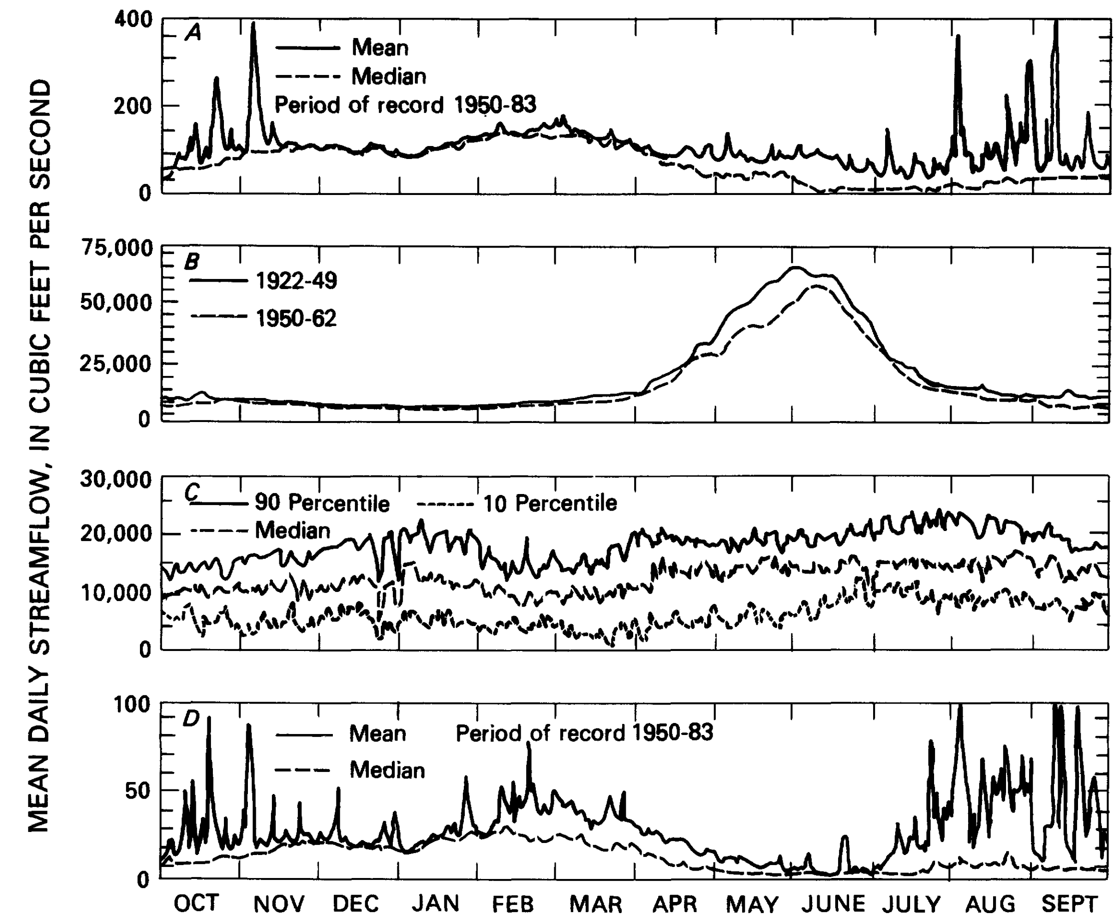


Figure 25. Mean daily streamflow at selected sites in main-stem subregion of San Juan region. *A*, Site 58, Dirty Devil River above Poison Spring Wash, near Hanksville, Utah. *B*, Site 69, Colorado River at Lees Ferry, Ariz. *C*, Site 69, Colorado River at Lees Ferry, Ariz., showing selected non-exceedance probabilities during the principal filling period (1966–80). *D*, Site 70, Paria River at Lees Ferry, Ariz.).

low-flow months, but did not change annually. A significant decrease of 27 mg/L in median annual bicarbonate concentration was indicated between the two periods. Although not statistically significant, the mean annual concentration of calcium decreased and all other constituents increased. Upstream changes in water use probably would not decrease the concentration of calcium and bicarbonate, and the estimated loss may be from precipitation of calcite in the reservoir.

Annual monotonic-trend analyses of the preintervention period indicated a significant increase in median annual dissolved-solids concentration of 7.3 mg/L per year (table 10). This represents a 33-percent change in median annual concentration during the 21-year period. Median annual flow-adjusted concentration also increased significantly by 3.3 mg/L per year, which represents a 14-percent change during the period of record. These increases result from increasing development and decreasing streamflow upstream in the Upper Colorado River Basin. No statistically significant annual monotonic trends were indicated for the principal filling period, except that concentrations of calcium and bicarbonate decreased by 1.04 mg/L per year, which may result from increasing calcite precipitation as the reservoir filled.

Paria River at Lees Ferry, Ariz. (site 70)

Site 70 (table 3, pl. 1) is near the confluence of the Colorado River, about 1 mi downstream from site 69. Although streamflow of the Paria River averages less than 0.5 percent of the streamflow of the Colorado River at site 69, flows at the two sites normally are added together to result in the official flow leaving the Upper Colorado River Basin at Lee Ferry, Ariz. Water-quality analyses for the Paria River are few, and dissolved-solids data are reported only to generally indicate dissolved-solids concentrations in the Paria River. Although streamflow and dissolved-solids load are less than those for site 58, areal runoff is comparable at both sites (table 9). The pattern of seasonal streamflow is similar at both sites, except that runoff from thunderstorms is a greater part of the total streamflow in the Paria River (fig. 25*D*). Mean annual flow-weighted dissolved-solids concen-

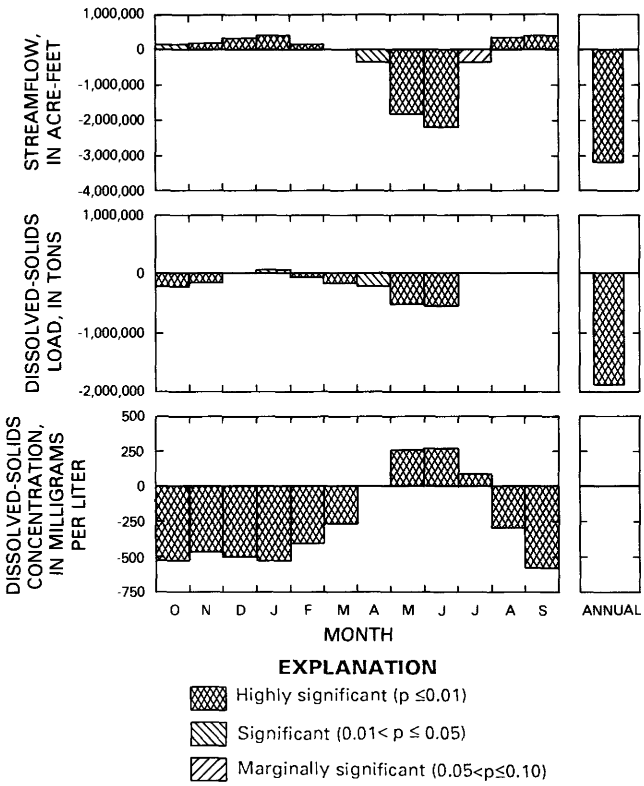


Figure 26. Step trends at site 69 (Colorado River at Lees Ferry, Ariz.) from 1942–62 to 1966–80.

tration during 1948–50 was 1,340 mg/L (table 9); sulfate was 61 percent of the dissolved-solids load. Unlike the Dirty Devil River basin, the Paria River basin does not contain large outcrops of the Carmel Formation, and the proportion of chloride is much lower, about 2 percent of the dissolved-solids load. Calcium, sodium, and sulfate are the predominant ions throughout the year. Annual dissolved-solids load from 1948 to 1950 averaged 32,000 tons (table 9).

General Trends in the San Juan Region

Annual streamflow of the San Juan River has not changed appreciably. Streamflow of the Colorado River at site 69 at Lees Ferry, Ariz., essentially represents the outflow of the entire Upper Colorado River Basin. Streamflow at Lees Ferry indicates changes throughout the basin, as well as the storage of inflows in Lake Powell and the complete regulation of outflows from Glen Canyon Reservoir.

Annual step-trend analyses at sites along the San Juan River indicate a decrease in monthly variability but little change in annual streamflow or dissolved solids. A marginally significant increase in dissolved-solids concentration at site 68 indicates that a change occurred during the filling of Navajo Reservoir.

Annual step-trend analyses for the Colorado River at site 69 at Lees Ferry, Ariz., indicate the decrease in streamflow and dissolved-solids load during the principal filling period of Lake Powell, as well as the virtual elimination of seasonal variability. Annual monotonic-trend analyses indicated that dissolved-solids concentration increased during the preintervention period, possibly resulting from increased development and exports upstream. Since 1942–62, however, dissolved-solids concentration has not changed significantly.

Lake Powell and Dissolved-Solids Outflow from the Upper Colorado River Basin

Because of its size and location, Lake Powell is the single most important anthropogenic feature affecting streamflow and dissolved solids in the Upper Colorado River Basin. Because of its capacity to store and mix inflows, the reservoir has decreased the seasonal and annual variability of streamflow and dissolved solids downstream from Glen Canyon Dam. Located at the downstream end of the Upper Colorado River Basin, releases from the reservoir effectively control the volume of water supplied to the Lower Colorado River Basin.

In terms of its effects on dissolved solids, Lake Powell primarily is a large mixing tank. After the initial filling period, the monthly dissolved-solids concentration in the outflow water stabilized within a narrow range (fig. 27). During water years 1971–83, monthly dissolved-solids concentrations in the outflow (site 69) ranged from 492 to 645 mg/L. Within that same period, concentrations in the inflow to Lake Powell (flow-weighted mean of sites 21, 54, 57, and 68) ranged from 261 to 904 mg/L, more than four times the range of the outflow concentration.

The mixing-tank concept was tested using a simple mass-balance procedure. Monthly inflow volumes and dissolved-solids loads were computed by summation of the streamflows and loads at sites 21, 54, 57, and 68. The measured volumetric storage change for Lake Powell was compared to the difference between the inflow and outflow volumes during the month. The dissolved-solids mass in storage was calculated as the product of the volume in storage (V_m) and the mean monthly outflow concentration at site 69 (C_m). Mass-balance equations could then be written for the change in volume:

$$V_m - V_{m-1} = Q_{I,m} - Q_{O,m} + U_{V,m} \qquad (6)$$

and the change in dissolved-solids load:

$$C_m V_m - C_{m-1} V_{m-1} = L_{I,m} - L_{O,m} + U_{L,m} \qquad (7)$$

where

V_m = the volume in storage at the end of month m;
V_{m-1} = the volume in storage at the end of the previous month ($m-1$);
$Q_{I,m}$ = the total inflow volume during month m;

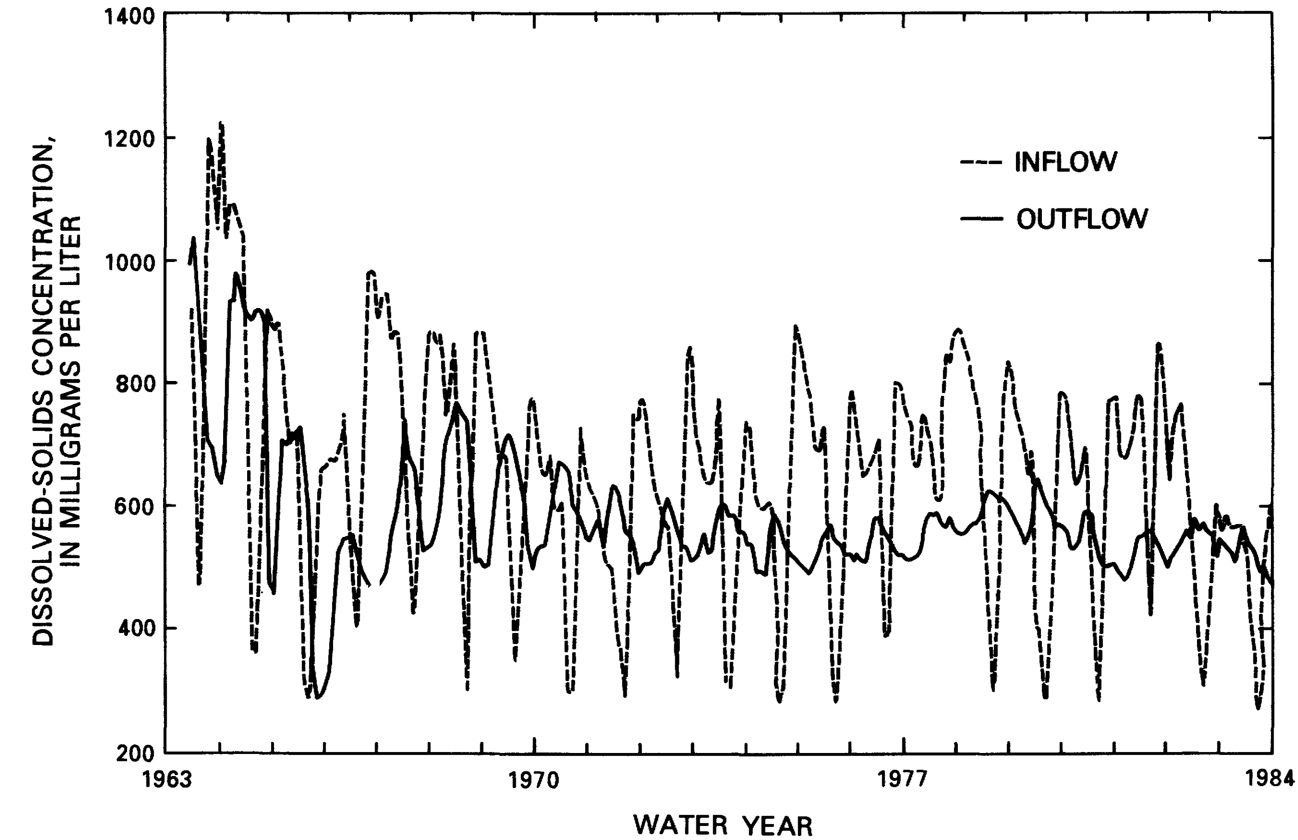


Figure 27. Monthly dissolved-solids concentration in Lake Powell inflow and outflow.

$Q_{O,m}$ = the outflow volume during month m;
$U_{V,m}$ = the unexplained change in volume during month m;
C_m = the flow-weighted mean dissolved-solids concentration in the outflow during month m;
C_{m-1} = the flow-weighted mean dissolved-solids concentration in the outflow during the previous month $(m-1)$;
$L_{I,m}$ = the total inflow dissolved-solids load during month m;
$L_{O,m}$ = the outflow dissolved-solids load during month m;
$U_{L,m}$ = the unexplained change in load during month m.

The unexplained changes in volume ($U_{V,m}$) and load ($U_{L,m}$) were defined to be negative if there was a loss in the reservoir during the month and positive if there was a gain. Unexplained losses of volume could be caused by evaporation or bank storage. Unexplained volume gains could be due to return flow from bank storage or unmeasured inflow. Over a long period, evaporation probably has the greatest effect. If equation 6 is accurate, the long-term mean value of U_V should be negative and approximately equal to the mean monthly evaporation. Monthly values of U_V are plotted in figure 28 for the period of record after July 1965, when the normal release program was implemented. The mean monthly unexplained change in volume for that period was −45,111 acre-ft, which indicates an annual loss of about 541,000 acre-ft from Lake Powell. A smoothed curve through the monthly values shows the annual deviation about this mean during the period. This loss closely corresponds to U.S. Bureau of Reclamation estimates of evaporation from the reservoir, which averaged about 517,000 acre-ft per year for 1973-82 (U.S. Bureau of Reclamation, 1982; J. Osterberg, U.S. Bureau of Reclamation, oral commun., 1986). Therefore, equation 6 seems appropriate for computing reservoir storage.

If the primary source of water loss in Lake Powell is actually evaporation, the dissolved-solids load would not be affected. A long-term gain or loss identified by the mean monthly unexplained change in load would indicate that a chemical process, such as salt dissolution or precipitation, was occurring in the reservoir. However, no consistent departure from zero was found in the values of U_L (fig. 29). The values were evenly distributed around zero, which indicates short-term fluctuations in mixing or inaccuracy of the mass balance given by equation 7. The mean monthly value was not significantly different from zero, and a smoothed curve showed no trend during the period. There-

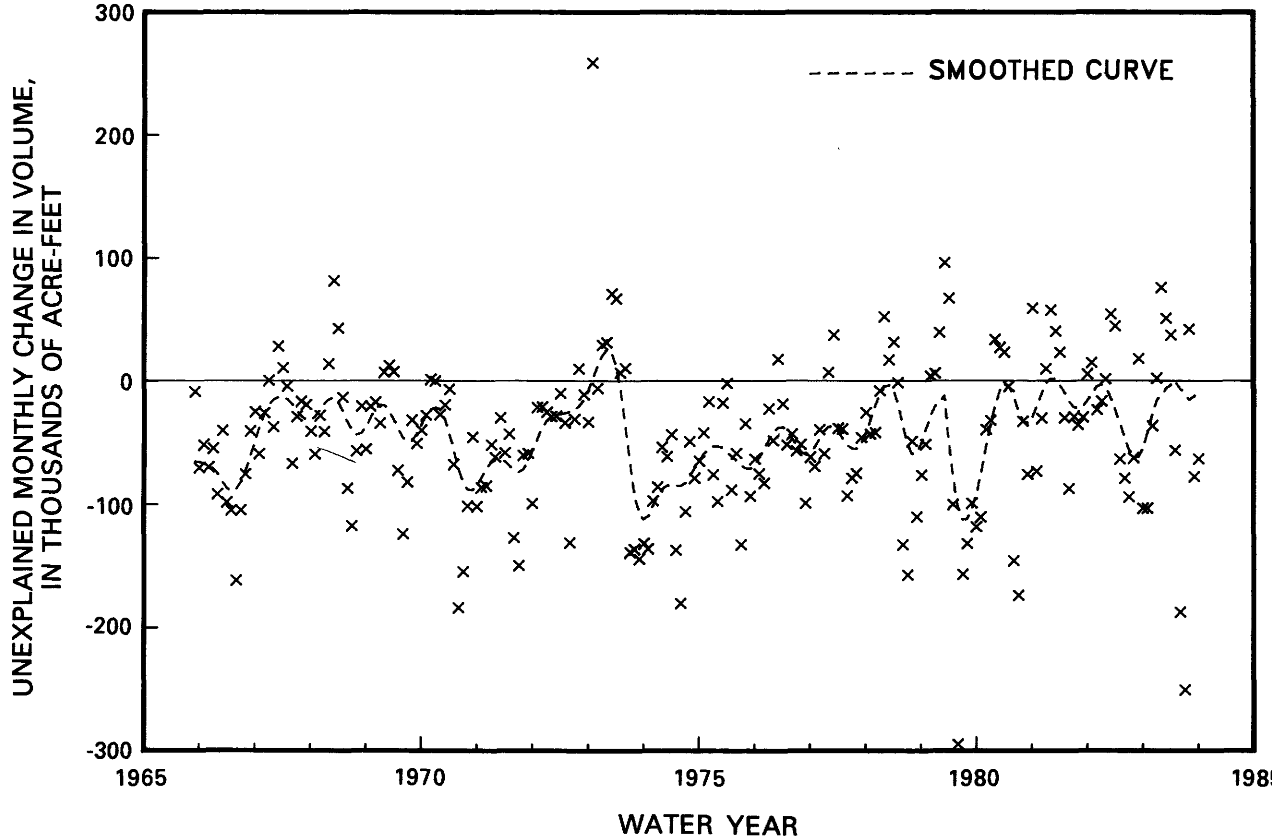


Figure 28. Monthly change in Lake Powell volume that is not explained by inflow-outflow mass balance.

fore, the mixing-tank concept seems appropriate for assessing the long-term effect of Lake Powell on dissolved-solids loads. Inflow volumes and loads are mixed in the reservoir, and the variability of the outflow dissolved-solids concentration has decreased. The loss or gain of dissolved solids within the reservoir could not be detected.

SUMMARY

Annual and monthly concentrations and loads of dissolved-solids and major constituents were estimated for 70 streamflow-gaging stations in the Upper Colorado River Basin. Trends in streamflow, dissolved-solids concentrations, and dissolved-solids loads were identified. Nonparametric trend-analysis techniques were used to determine long-term, monotonic trends and step trends that resulted from human activities upstream. Results were compared with physical characteristics of the basin and historical water-resource development in the basin to determine source areas of dissolved solids and possible cause of trends.

The mean annual dissolved-solids concentration of the Colorado River increases from less than 100 mg/L in the headwater streams to more than 500 mg/L at Lees Ferry, Ariz., downstream from Lake Powell. For the 70 sites analyzed in this report, mean annual flow-weighted concentration ranged from 29 mg/L near the headwaters of the Colorado River to 6,740 mg/L in Bitter Creek near Bonanza, Utah. In headwater streams, calcium and bicarbonate are the predominant dissolved constituents. Lower in the basin, in areas underlain by sedimentary rocks, large quantities of sulfate, sodium, and calcium are transported into the stream system. In many streams in the Colorado Plateau province, dissolved sulfate constitutes about 60 percent of the dissolved-solids load.

For sites on streams that have a mean annual streamflow greater than 25,000 acre-ft, the maximum dissolved-solids concentrations occurred downstream from areas where irrigated agriculture has major effects on streamflow and dissolved solids. Streams affected by irrigation return flow include the Big Sandy, Price, San Rafael, Uncompahgre, and Dirty Devil Rivers, McElmo and Salt Creeks, and Reed Wash. In the basins of these streams (except the Big Sandy River), large tracts of irrigated land are underlain by Mancos Shale. At sites downstream from these areas, sulfate is the predominant anion. Calcium or magnesium usually is the predominant cation in streams in the Grand region and the eastern side of the San Juan region. Sodium is the predomi-

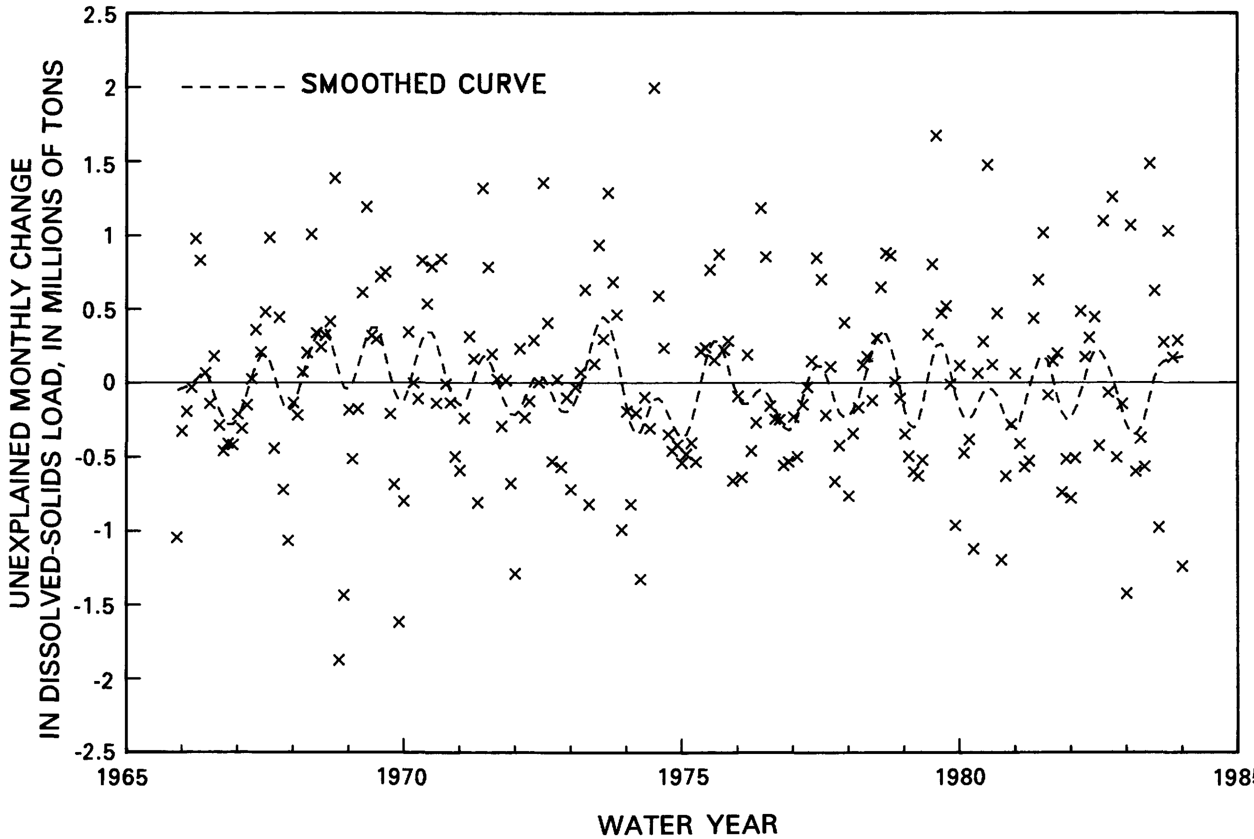


Figure 29. Monthly change in Lake Powell dissolved-solids load that is not explained by inflow-outflow mass balance.

nant cation on the western side of the Colorado Plateau in the Green and San Juan regions.

Large natural sources of dissolved-solids load include springs along the Colorado River in the Glenwood Springs, Colo., area (475,000 tons/yr) and along the Dolores River in the Paradox Valley area (223,000 tons/yr). Together, these sources account for 26 percent of the sodium and 57 percent of the chloride outflow from the entire Upper Colorado River Basin.

Tributary basins where irrigation occurs on areas underlain by Mancos Shale contribute large dissolved-solids loads. The largest of these loads came from the Uncompahgre River basin (344,000 tons/yr), the Price River basin (240,000 tons/yr), and the San Rafael River basin (192,000 tons/yr). The Grand Valley area, near Grand Junction, Colo., produces a dissolved-solids load of 439,000 tons/yr, almost entirely attributable to irrigation-return flow from Mancos Shale. Irrigation of areas overlying the Uinta and Green River Formations contributes to large dissolved-solids loads from the Duchesne River basin (351,000 tons/yr) and the Big Sandy River basin (163,000 tons/yr). Other tributaries that have large dissolved-solids loads are the Gunnison River (1,281,000 tons/yr, including the load from the Uncompahgre River), the Roaring Fork River (288,000 tons/yr), the Yampa River upstream from Maybell, Colo. (223,000 tons/yr), the Animas River (209,000 tons/yr), the White River upstream from Meeker, Colo. (178,000 tons/yr), and the Eagle River (160,000 tons/yr).

Significant trends in streamflow, dissolved-solids concentration, dissolved-solids load, or flow-adjusted concentration were identified for 30 sites in the Upper Colorado River Basin. The records for 10 of these sites were each divided into two periods to evaluate the step trends associated with specific human activities upstream. Monotonic trends were evaluated separately for the preintervention and postintervention periods at these sites and for the entire period of record for sites without identified interventions. No significant trends were found for 13 of the sites. Trend analyses were not done for 27 sites that had less than 10 years of record.

At the more upstream sites in the basin, trends seem to be related to increased transbasin diversions and to changes in land use. Downstream from the Alva B. Adams Tunnel/ Lake Granby diversion, streamflow and dissolved-solids load in the Colorado River have decreased. However, dissolved-solids concentration has increased at some Colorado River sites because the diverted water generally has a lower dissolved-solids concentration than in the downstream inflows. Dissolved-solids concentration and load have decreased in the Eagle River at Gypsum, Colo., where the upstream land use has changed from agriculture and mining to recreation. In the Yampa River basin, surface mining for coal has increased since the 1960's and may have contributed to increases in dissolved-solids concentration and load in the Yampa River near Maybell, Colo.

In the Big Sandy River basin, irrigation-return flows from the Eden Valley Project increased the annual dissolved-solids load in the Big Sandy River below Eden, Wyo., by more than 1,740 tons/yr per year, primarily as sodium and sulfate, from 1962 to 1981. In the Price River basin, the flow-weighted dissolved-solids concentration in the Price River at Woodside, Utah, decreased by 33.2 mg/L annually from 1949 to 1983. Eighty-nine percent of this change resulted from decreases in sodium and sulfate concentrations. This decrease may be the result of reductions of irrigated area in the basin.

Trends that indicate salinity-control effects were detected at two sites. Dissolved-solids concentration decreased by 89 mg/L at the White River near Watson, Utah, after the plugging of abandoned wells in the Meeker Dome area. At Reed Wash near Loma, Colo., which drains the area affected by salinity-control activities in the Grand Valley, annual dissolved-solids load decreased by about 2,770 tons annually during 1973–83, despite increasing streamflow. Salinity control in the Grand Valley also may have caused the decreases in flow-adjusted concentration from 1966 to 1983 at the Colorado River near Cisco, Utah.

The primary factor affecting trends in streamflow and dissolved solids in the Upper Colorado River Basin has been the construction of large reservoirs. Storage in a large reservoir enables mixing of inflows that may have large variations in volume and dissolved-solids concentration. This mixing can decrease the monthly and annual variability of streamflow and dissolved solids downstream from the reservoir. Chemical processes in the reservoir, such as mineral dissolution or precipitation, also can change the dissolved-solids characteristics downstream. In the Gunnison River, downstream from Blue Mesa Reservoir, streamflow has decreased and dissolved-solids concentration has increased during high flow (May–June). Conversely, streamflow has increased and dissolved-solids concentration has decreased during low flow (August–March). Overall, the monthly variability of streamflow and dissolved-solids concentration has diminished. This effect also is apparent farther downstream at the Colorado River near Cisco, Utah. Similar decreases in monthly variability have occurred at the San Juan River near Archuleta, N. Mex., downstream from Navajo Reservoir. No significant changes in annual streamflow or dissolved solids were found for this site.

Increases in dissolved-solids load have occurred in the Green River downstream from Fontenelle and Flaming Gorge Reservoirs. Both reservoirs inundated outcrops that contain gypsum (calcium sulfate). Sulfate accounted for most of the increase in dissolved-solids load at sites directly downstream from the reservoirs. Dissolved-solids concentration and load increased as far downstream as Green River, Utah, following the filling of the two reservoirs.

The largest step trends identified in the Upper Colorado River Basin occurred downstream from Lake Powell at Lees Ferry, Ariz. During the principal filling of the reservoir, streamflow decreased by about 2.7 million acre-ft/yr and dissolved-solids load decreased by about 1.6 million tons/yr. Although the annual dissolved-solids concentration did not change, the variability has been greatly diminished. Changes in monthly dissolved-solids concentration indicate a decrease in seasonal variability as well. Lake Powell functions like a large mixing tank, which diminishes the variations in streamflow and dissolved-solids outflow from the Upper Colorado River Basin. However, the period of record since the completion of filling was too short to estimate the long-term effects of that reservoir.

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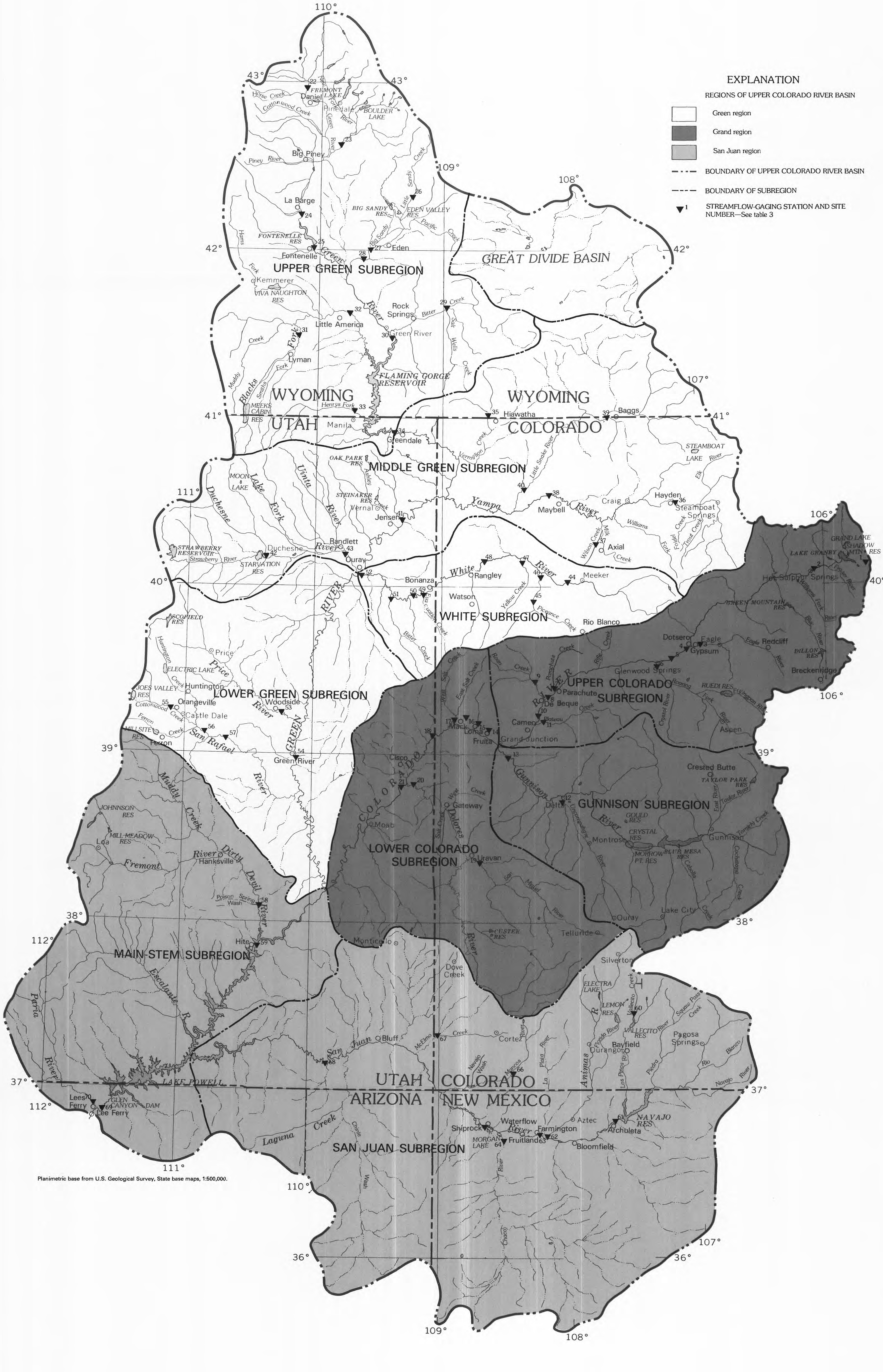

MAP SHOWING THE UPPER COLORADO RIVER BASIN REGIONS, SUBREGION BOUNDARIES, AND LOCATIONS OF STREAMFLOW-GAGING STATIONS