APPLICATION OF TECHNIQUES TO IDENTIFY COAL-MINE AND POWER-GENERATION EFFECTS ON SURFACE-WATER QUALITY, SAN JUAN RIVER BASIN, NEW MEXICO AND COLORADO

By Carole L. Goetz, Cynthia G. Abeyta, and Edward V.Thomas

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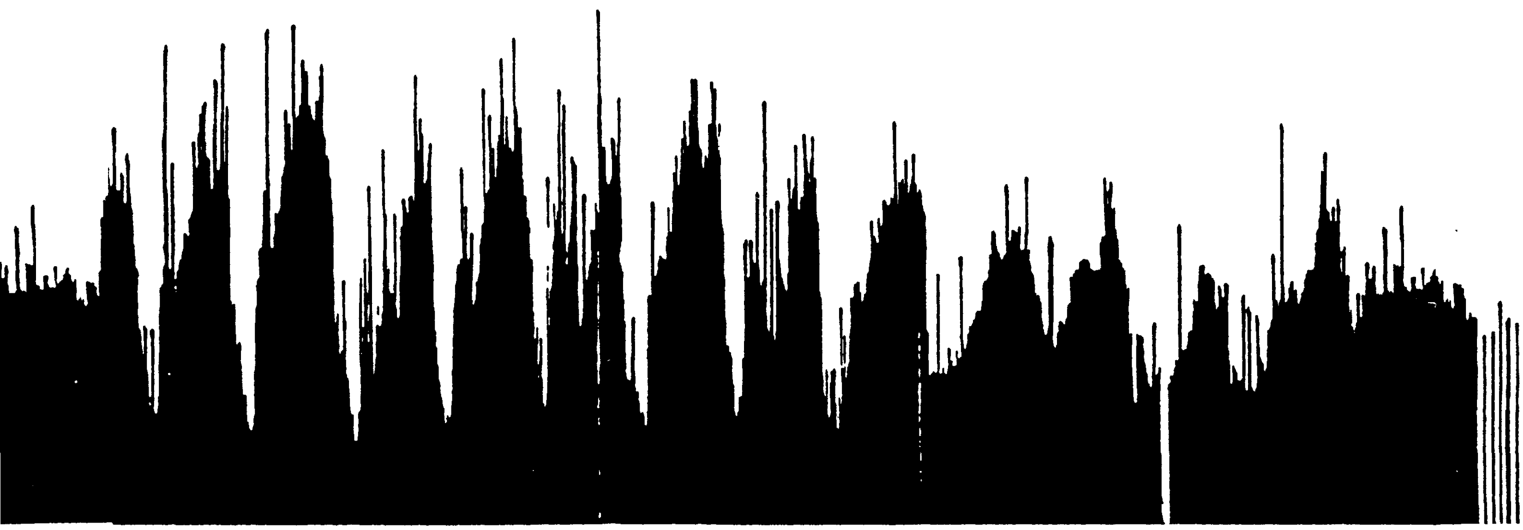

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CONVERSION FACTORS

For the convenience of readers who may want to use International System of Units (SI), the data may be converted by using the following factors.

Multiply inch-pound units	By	To obtain SI units
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
acre	0.004047	square kilometer
acre-foot	1,233	cubic meter
cubic foot per second	0.02832	cubic meter per second
ton, short	907.2	kilogram

Temperature

$$°C = (°F-32)/1.8$$
$$°F = (1.8 \times °C) + 32$$

Energy

British thermal unit (Btu)	1054.8	Joule

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ABSTRACT

Numerous analytical techniques were applied to determine water-quality changes in the San Juan River basin upstream of Shiprock, New Mexico. Eight techniques were used to analyze hydrologic data from 1935 through 1979. Data analyzed included precipitation, water quality, and streamflow. The eight methods used are: (1) Piper diagram, (2) time-series plot, (3) frequency distribution, (4) box-and-whisker plot, (5) seasonal Kendall test, (6) Wilcoxon rank-sum test, (7) SEASRS procedure, and (8) analysis of flow-adjusted, specific-conductance data and smoothing.

The San Juan River basin in northwestern New Mexico is an area of active and proposed coal mining. The effects of coal mining on the streams are of particular interest if the effects are large enough to be measured and separated from natural and cultural effects. The Navajo Reservoir, on the San Juan River upstream of the mined areas, began operation in 1963, the same year that mining began in the basin. The reservoir's effects on water quality in the San Juan River were successfully separated from other effects. Post-1963 changes in dissolved-solids concentration, dissolved-potassium concentration, specific conductance, suspended-sediment concentration, or suspended-sediment load in the San Juan River downstream from the surface coal mines were examined to determine if coal mining was having an effect on the quality of surface water. None of the analytical methods used to analyze the data showed any increase in dissolved-solids concentration, dissolved-potassium concentration, or specific conductance in the river downstream from the mines; some of the analytical methods used showed a decrease in dissolved-solids concentration and specific conductance.

Chaco River, an ephemeral stream tributary to the San Juan River, undergoes changes in water quality due to effluent from a power-generation facility. The discharge in the Chaco River contributes about 1.9 percent of the average annual discharge at the downstream station, San Juan River at Shiprock, N. Mex. The changes in water quality detected at the Chaco River station were not detected at the downstream Shiprock station.

It was not possible, with the available data, to identify any effects of the surface coal mines on water quality that were separable from those of urbanization, agriculture, and other cultural and natural changes. In order to determine the specific causes of changes in water quality, it would be necessary to collect additional data at strategically located stations.

INTRODUCTION

Public and regulatory agencies are concerned with how water quality has changed in the past and how it is likely to change in the future. The San Juan River basin in northwestern New Mexico was studied to determine if measurable water-quality changes have taken place, and if so, if individual causes of the changes could be distinguished. Of particular interest are the effects of actual and proposed coal-mining activities on water quality. Legal requirements of regulatory agencies have created a need to evaluate the hydrologic effects of coal mining.

The objectives of the study are to (1) apply analytical techniques that detect changes and determine if one or a combination of techniques could be used to separate individual land-use effects on water quality from cumulative effects, and (2) describe and quantify the effects, if any, of coal-mine activities on water quality of the San Juan River. A statistical approach for analyzing historical water-quality and streamflow data was used and included graphical and descriptive analyses of available data. Eight analytical techniques were used with specific objectives:

(1) Piper diagram	Displays water classification and mixing of waters.
(2) Time-series plot	Displays patterns and trends over time.
(3) Frequency distribution	Displays range and frequency of data values.
(4) Box-and-whisker plot	Displays mean, median, 75th and 25th percentiles, and range of data.
(5) Seasonal Kendall test	Removes the influence of seasonality and tests for a monotonic trend.
(6) Wilcoxon rank-sum test	Tests for differences between data from two time periods; no assumptions about how the data are distributed are required.
(7) SEASRS procedure	Removes the influence of seasonality and then tests for differences between data from two time periods; no assumptions about how the data are distributed are required.
(8) Flow-adjusted specific conductance	Removes the influence of streamflow and tests for changes in daily specific conductance between stations.

DESCRIPTION OF THE STUDY AREA

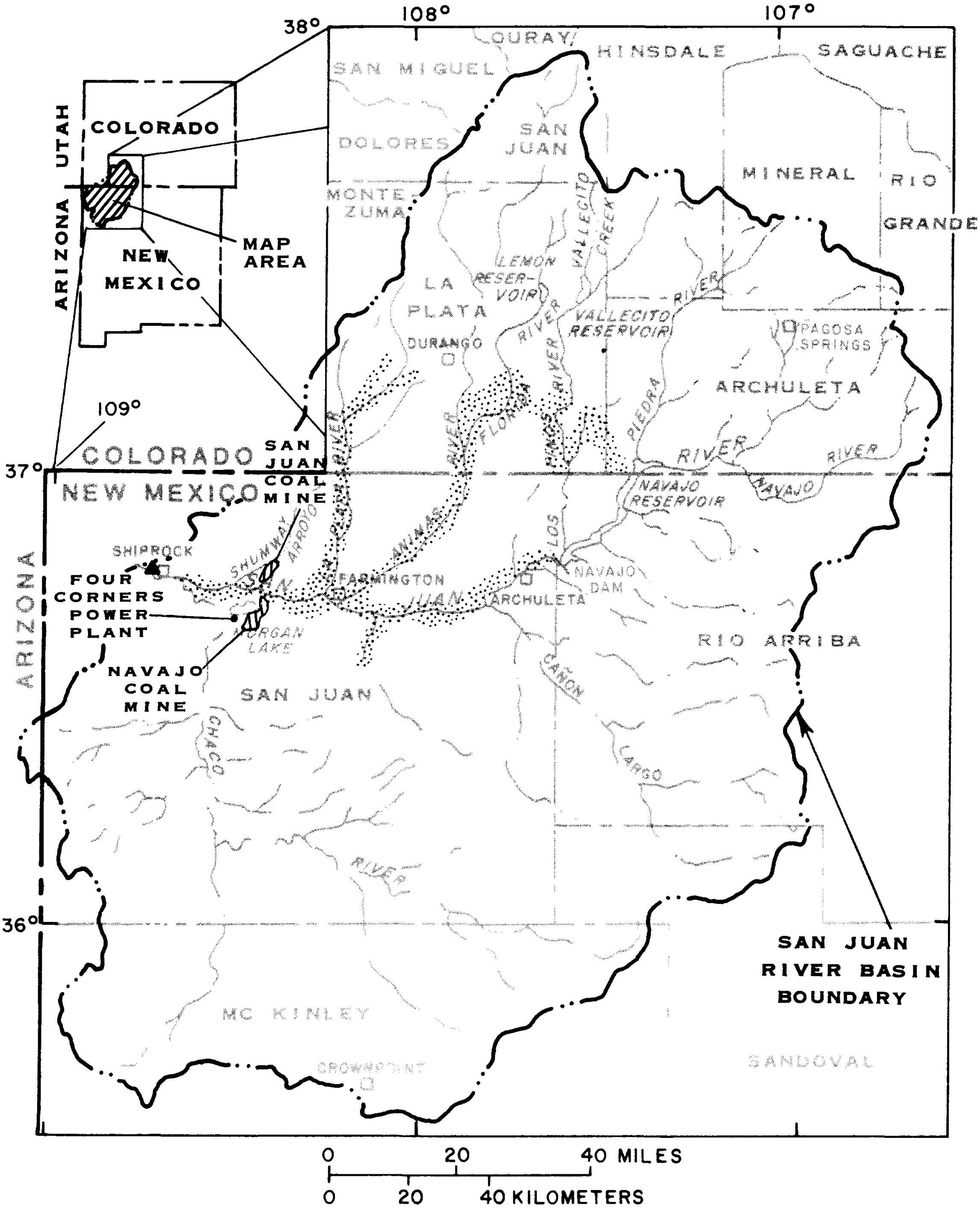
The study area is the San Juan River watershed upstream from Shiprock, N. Mex. (fig. 1). The watershed at Shiprock includes approximately 12,900 square miles - a diverse land, from its deserts in New Mexico to its 14,000-foot mountain peaks in Colorado. The watershed includes high-mountain, cobble streams in the north and ephemeral sand channels in the south. The San Juan River is the second largest tributary to the Colorado River. A number of reservoirs are in the watershed, including Navajo Reservoir on the San Juan River upstream of Archuleta, N. Mex. Water is used for agriculture, power generation, industrial and public supply, and recreation.

Streamflow and water-quality data are collected by various Federal, State, and local agencies. Streamflow and water-quality data used for this study include: (1) data maintained on file (WATSTORE) by the U.S. Geological Survey; and (2) data collected and analyzed by Four Corners Power Plant and maintained on file by the New Mexico Environmental Improvement Division (fig. 2 and table 1). Climatic, socioeconomic, agricultural, and mineralogical data were obtained from the National Oceanic and Atmospheric Administration, the U.S. Census Bureau, and reports by various agencies. The sites where water-quality data were collected are shown in figure 2 and listed in table 1. Sites where precipitation and stream discharge were measured are shown in figure 3 and listed in table 2. Because several organizations collected the data, sampling was done at different times and results were reported in different ways. Water-quality analyses were made in different laboratories, sometimes using different analytical techniques. All data sources contained some missing record.

During the past few decades, the San Juan River has been impounded and regulated by the Navajo Dam, and the basin has undergone changes in population, irrigated agriculture, mining, and power generation. Any or all of these changes may affect streamflow or water quality.

Water Use

The largest water use in the San Juan River basin is for agriculture. According to a report by the Colorado Water Conservation Board and U.S. Department of Agriculture (1974, p. IV-6 to IV-7), agriculture accounted for nearly 93 percent of total water depletion during 1965 and was projected to equal 77 percent of total depletion in 1980. The second largest water use is for electric-power generation, accounting for less than 4 percent of the total water depletion during 1965 and projected to equal 16 percent of total depletion in 1980. Since agriculture and electric-power generation use the most water, return flow from farms and power-generating plants possibly could affect surface-water quality.



EXPLANATION

AREA OF IRRIGATED AGRICULTURE

▲ U.S. GEOLOGICAL SURVEY STREAMFLOW AND WATER-QUALITY GAGING STATION, SAN JUAN RIVER AT SHIPROCK

Figure 1.--San Juan River basin upstream from Shiprock, N. Mex.

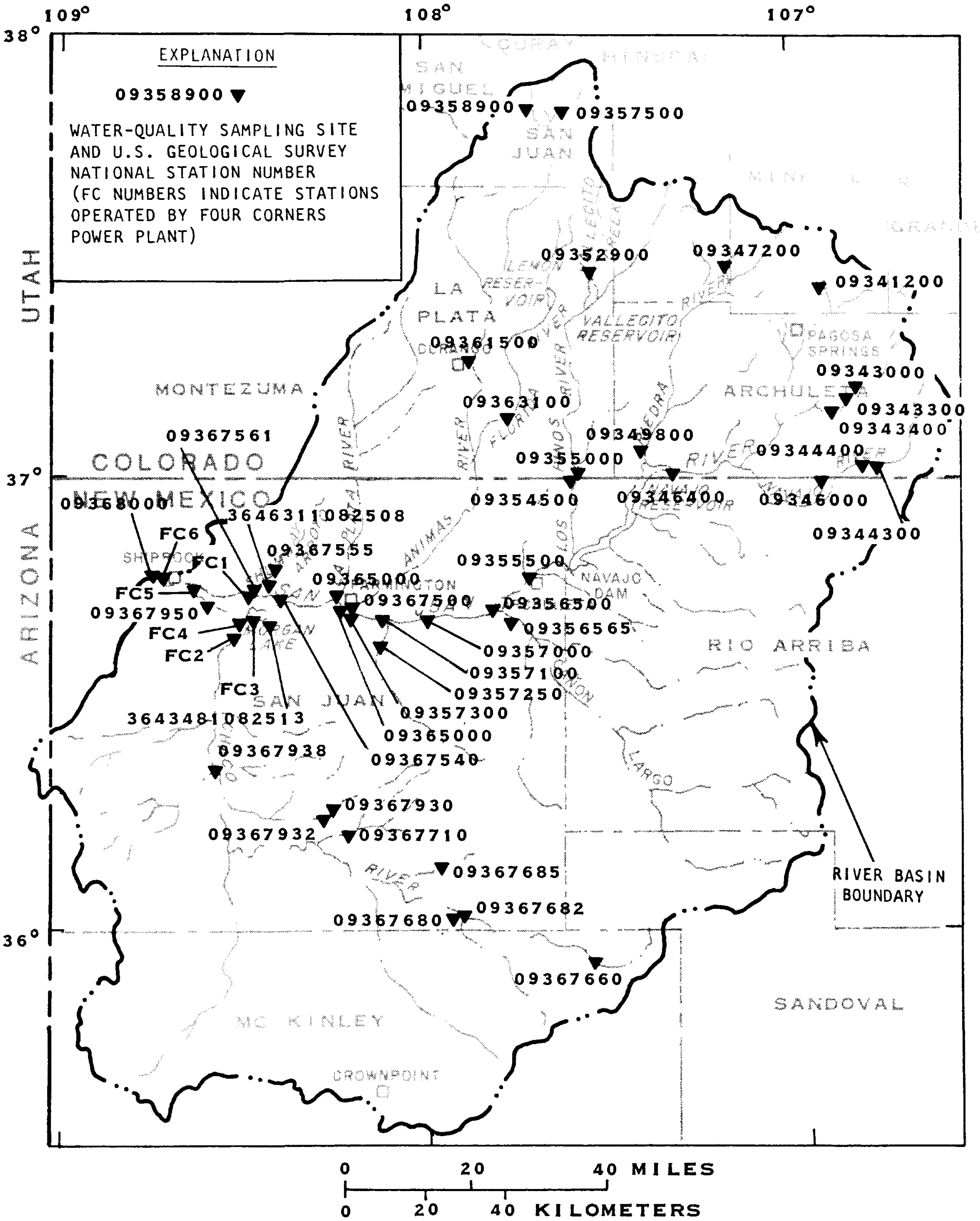


Figure 2.--Location of water-quality sampling sites.

Table 1. **Water-quality and sediment-sampling sites used in this report**

[Eight- and fifteen-digit station numbers are U.S. Geological Survey national station numbers; station numbers prefixed FC are stations operated by Four Corners Power Plant]

Station number (see fig. 2)	Station name	Latitude-longitude identification number
09341200	Wolf Creek near Pagosa Springs, Colo.	372647106530O
09343000	Rio Blanco near Pagosa Springs, Colo.	371246106473 8
09343300	Rio Blanco below Blanco Div. Dam, near Pagosa Springs, Colo.	371211106484 5
09343400	Rio Blanco at U.S. Highway 84, near Pagosa Springs, Colo.	370830106502 4
09344300	Navajo River above Chromo, Colo.	370155106435 6
09344400	Navajo River below Oso Dam, near Chromo, Colo.	370148106441 6
09346000	Navajo River above Edith, Colo.	370010106542 5
09346400	San Juan River near Carracas, Colo.	370049107184 2
09347200	Middle Fork Piedra River near Pagosa Springs, Colo.	372912107094 6
09349800	Piedra River near Arboles, Colo.	370518107235 0
09352900	Vallecito Creek near Bayfield, Colo.	372839107323 5
09354500	Los Pinos River at La Boca, Colo.	370034107355 6
09355000	Spring Creek at La Boca, Colo.	370040107354 7
09355500	San Juan River near Archuleta, N. Mex.	364805107415 1
09356500	San Juan River near Blanco, N. Mex.	364350107485 0
09356565	Cañon Largo near Blanco, N. Mex.	364124107452 1
09357000	San Juan River at Bloomfield, N. Mex.	364200107591 0
09357100	San Juan River at Hammond Bridge, near Bloomfield, N. Mex.	364122108054 2
09357250	Gallegos Canyon near Farmington, N. Mex.	363852108073 0
FC1	San Juan River near Hogback, N. Mex.	-
09357300	San Juan River above Animas River at Farmington, N. Mex.	364310108124 5
09357500	Animas River at Howardsville, Colo.	374959107355 6
09358900	Mineral Creek above Silverton, Colo.	375104107433 1
09361500	Animas River at Durango, Colo.	371645107524 7
09363100	Salt Creek near Oxford, Colo.	370823107451 0
09364500	Animas River at Farmington, N. Mex.	364317108120 5
09365000	San Juan River at Farmington, N. Mex.	364322108133 0
09367500	La Plata River near Farmington, N. Mex.	364423108145 1
09367540	San Juan River near Fruitland, N. Mex.	364425108240 9
09367555	Shumway Arroyo near Fruitland, N. Mex.	364823108234 2

Table 1. Water-quality and sediment-sampling sites used in this report - Concluded

Station number (see fig. 2)	Station name	Latitude-longitude identification number
09367561	Shumway Arroyo near Waterflow, N. Mex.	364624108 2626
09367660	Chaco Wash at Star Lake Trading Post, N. Mex.	3556071073139
09367680	Chaco Wash at Chaco Canyon National Monument, N. Mex.	3601431075504
09367682	Gallo Wash at Chaco National Monument, N. Mex.	3602061075325
09367685	Ah-Shi-Sle-Pah Wash near Kimbeto, N. Mex.	3609181075647
09367710	De-Na-Zin Wash near Bisti Trading Post, N. Mex.	3613511081157
09367930	Hunter Wash at Bisti Trading Post, N. Mex.	3616371081512
09367932	Hunter Tributary at road crossing south of Bisti, N. Mex.	3615331081506
09367938	Chaco River near Burnham, N. Mex.	3621571083357
FC2	Chaco River upstream of power plant	-
FC3	Morgan Lake	-
FC4	Ash-pond effluent	-
FC5	Chaco River downstream of power plant	-
09367950	Chaco River near Waterflow, N. Mex.	3643281083527
09368000	San Juan River at Shiprock, N. Mex.	3647321084354
FC6	San Juan River at Shiprock, N. Mex.	-
364348-108251310	Navajo Mine 1978 Reclamation Plot	3643481082513
364631-108250810	San Juan Mine 1977 Graded Pile	3646311082508

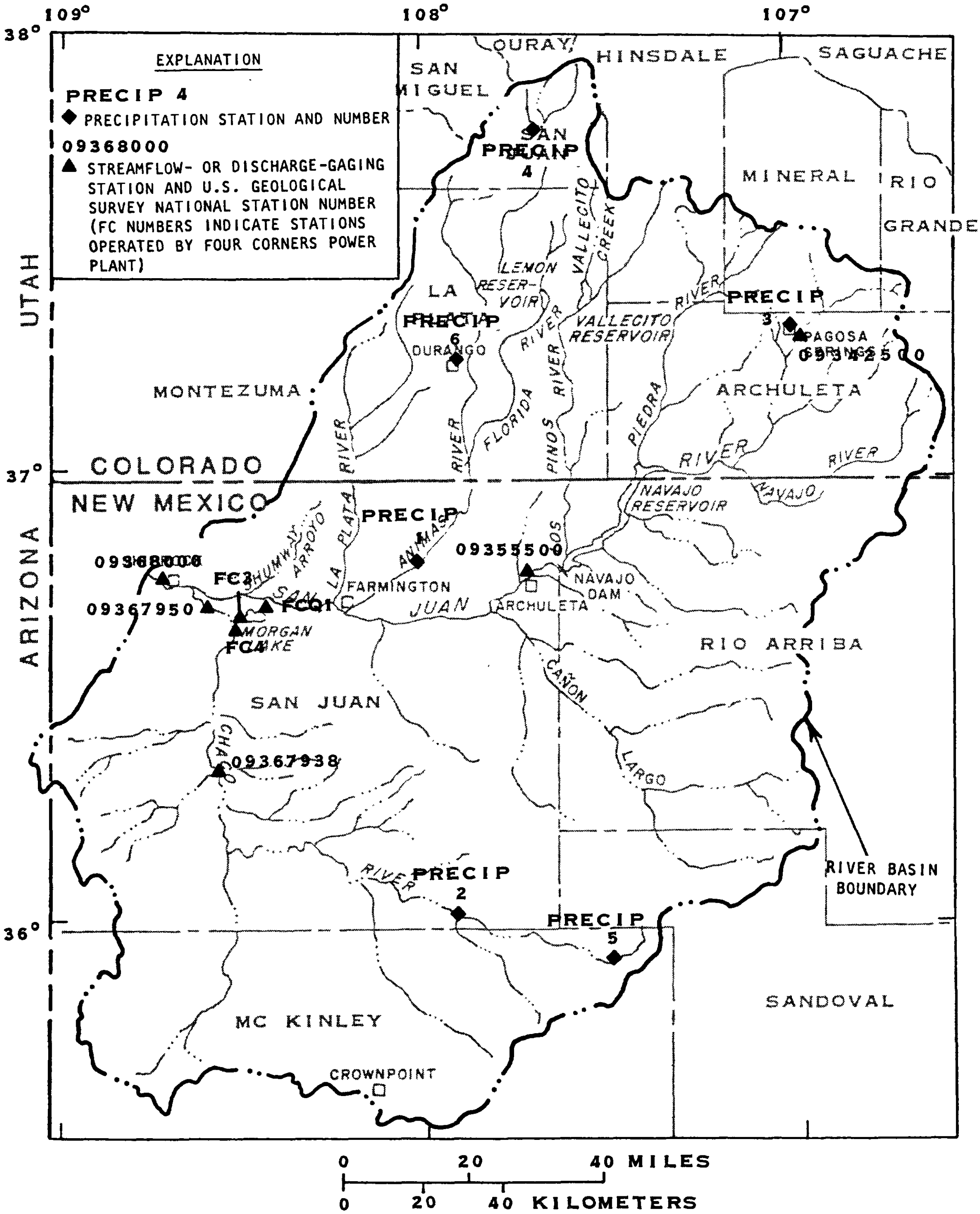


Figure 3.--Location of precipitation and streamflow- or discharge-gaging stations.

Table 2. Precipitation-measurement and discharge-measurement sites used in this report

[PRECIP station numbers are used in this report to represent National Oceanic and Atmospheric Administration precipitation-measurement stations; Eight-digit station numbers are U.S. Geological Survey national discharge-measurement station numbers; and FC station numbers are discharge-measurement stations operated by Four Corners Power Plant]

Station number	Station name	Latitude-longitude identification number
PRECIP1	Aztec Ruins National Monument, N. Mex.	3650001080000
PRECIP2	Chaco Canyon National Monument, N. Mex.	3602001075400
PRECIP3	Pagosa Springs, Colo.	3716001070100
PRECIP4	Silverton, Colo.	3748001074000
PRECIP5	Star Lake, N. Mex.	3556001072800
PRECIP6	Durango, Colo.	3717001075300
09342500	San Juan River at Pagosa Springs, Colo.	3715581070037
09355500	San Juan River at Archuleta, N. Mex.	3648051074151
FCQ1	San Juan River diversion to Morgan Lake, N. Mex.	-
09367938	Chaco River near Burnham, N. Mex.	3621571083357
FC3	Morgan Lake	-
FC4	Ash-pond effluent	-
09367950	Chaco River near Waterflow, N. Mex.	3643281083527
09368000	San Juan River at Shiprock, N. Mex.	3647321084354

Population

The population trend from 1860 through 1980 (fig. 4) indicates that population fluctuated between 10,000 and 20,000 from 1860 until 1900 (U.S. Department of Commerce, Bureau of the Census, 1860-1980). Population gradually increased from 32,000 in 1910 to 46,000 in 1950. Between the 1950 and the 1960 census, a population boom occurred, increasing the census count to more than 80,000 in 1960. From 1970 to 1980, population continued to increase dramatically, reaching 120,000 in 1980. The increasing population implies an increasing number of users of water-supply and sewerage systems. In the study area, the increasing population is accompanied by increasing urbanization that may affect streamflow and water quality.

Irrigated Cropland

Irrigated-cropland acreage is shown in figure 5. An increase of irrigated cropland from about 25,000 acres to 160,000 acres occurred from 1889 to 1949 (U.S. Department of Commerce, Bureau of the Census, 1860-1980). Irrigated cropland decreased to about 120,000 acres by 1959 and was about 150,000 acres in 1974. Most irrigated cropland is along stream valleys (fig. 1) where streamflow from the San Juan River and its tributaries is used as the source of irrigation water. Return flow of excess irrigation water may increase the dissolved-solids concentration in the San Juan River.

Reservoirs

Three large reservoirs, Lemon Reservoir, Vallecito Reservoir, and Navajo Reservoir (fig. 1), supply water for irrigation and provide recreation sites. Lemon Reservoir is on the Florida River, a tributary to the Animas River. Its capacity of 40,100 acre-feet is about 1.4 times the mean annual discharge of the Florida River entering the reservoir. It began operation in 1964. Vallecito Reservoir, on the Los Pinos River, began operation in 1941. Its capacity of 126,300 acre-feet is about 0.5 times the mean annual discharge of the Los Pinos River entering the reservoir. Navajo Reservoir, on the San Juan River, began operation in 1963. Its capacity of 1,696,000 acre-feet is about 2.2 times the mean annual discharge of the San Juan River entering the reservoir. Each reservoir has changed the natural streamflow patterns at downstream sites.

Coal Mining and Its Possible Effects on Water Quality

By the 1960's, income from mineral production far exceeded that obtained from agriculture, which was the primary source of income until about 1945 (Sorensen, 1967). Metals mining constituted an initial stimulus for settlement of the northern part of the basin and continues to be economically important. By the mid-1940's, oil and gas production became part of the economy throughout the basin. In recent years, coal mining has become economically important, particularly in the west along the San Juan River where two large coal mines are operating (fig. 1). In the south along the Chaco River drainage, considerable controversy has been raised concerning proposed coal mining.

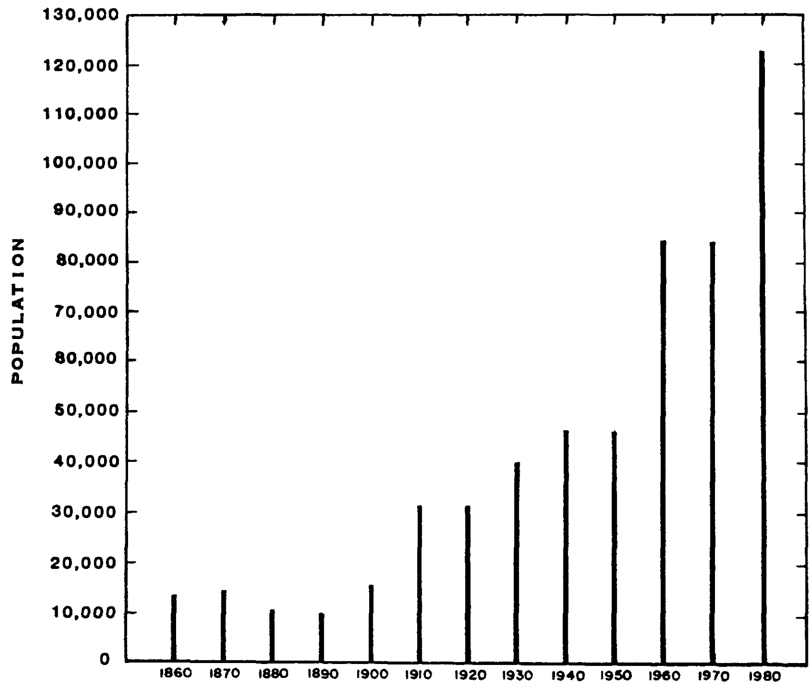


Figure 4.--Population, in 10-year intervals. Estimated from U.S. Census Bureau county-population records (U.S. Department of Commerce, 1860-1980).

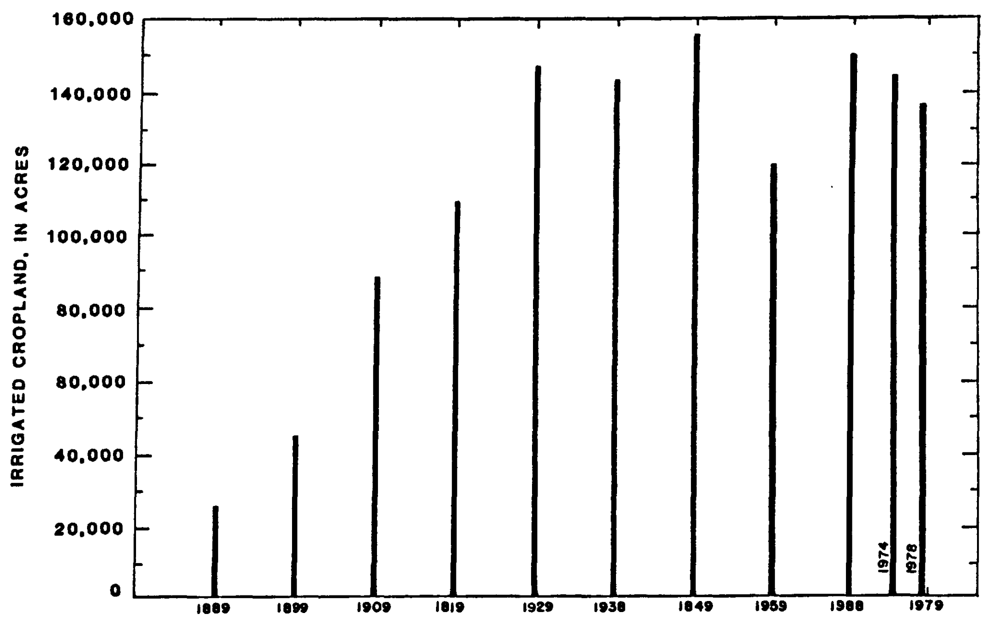


Figure 5.--Irrigated-cropland acreage. Estimated from U.S. Census Bureau records (U.S. Department of Commerce, 1860-1980).

These two coal mines along the San Juan River represent the first large-scale use of the area's coal in electrical generation. Both mines are associated with an electrical-power-generation facility. Navajo Mine and Four Corners Power Plant began mining operations and electrical-power generation in 1963. Additional power-generation units were added in 1964, 1969, and 1970. The Navajo Mine and Four Corners Power Plant are on the south side of the San Juan River (fig. 1). San Juan Mine and San Juan Power Plant began mining operations and power generation in 1973 on the north side of the San Juan River (fig. 1). Additional power-generation units were added in 1976 and 1979. Coal production of the mines increased from about 2 million tons in 1964 to about 10 million tons in 1979 (fig. 6).

Elements present in coal include a large percentage of carbon and smaller percentages of oxygen, hydrogen, nitrogen, and sulphur. Phosphorus, uranium, germanium, and several other elements also may be found. Traces of arsenic, cadmium, mercury, and selenium compounds usually are found upon combustion of coal (Masterton and Slowinski, 1973). Percentages of carbon, oxygen, and volatile matter vary with the degree of coalification. Whereas percentages of carbon increase with higher degrees of coalification, percentages of oxygen and volatile matter decrease. Hydrogen stays about the same.

Ash is the inorganic residue after coal has been burned. Ash is composed mostly of quartz, feldspar, and clay minerals, which include the oxides, silica dioxide (SiO_2), aluminum oxide (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na_2O), potassium oxide (K_2O), iron oxide (Fe_2O_3), and manganese oxide (MnO).

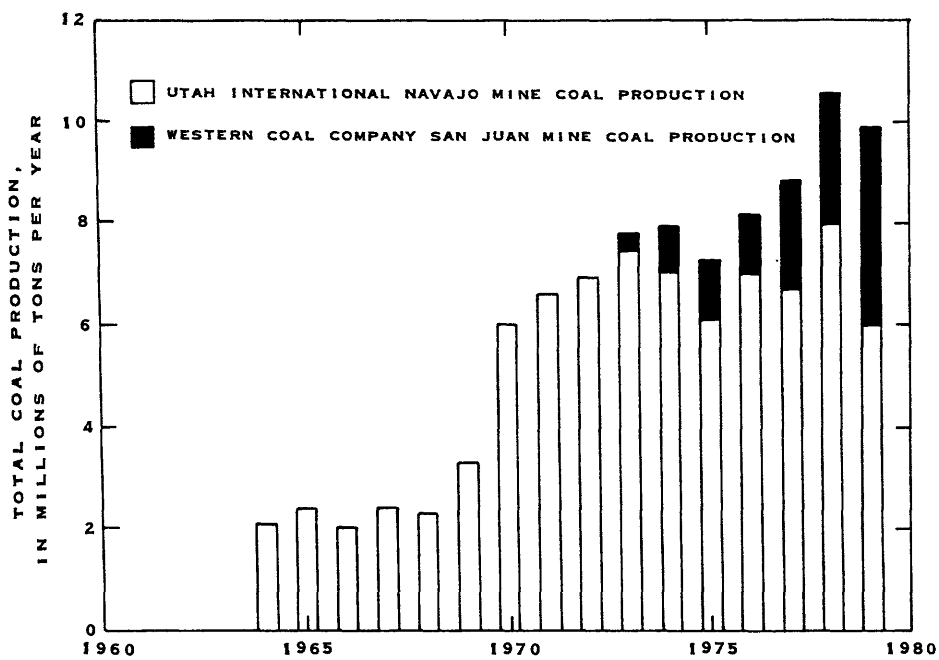


Figure 6.--Total coal production at Navajo and San Juan Mines (data from Nielson, 1963-79).

The Upper Cretaceous Fruitland Formation is the major source of coal production in the San Juan Basin. Both the Navajo Mine and the San Juan Mine produce coal from this formation. Coals in the Fruitland-Fruitland Field (fig. 7) are high volatile B and C bituminous coals; the sulphur content ranges from 0.68 to 1.01 percent and averages 0.86 percent (Beaumont, 1971). Shomaker (1971, p. 108) ranked the coal in the Navajo-Fruitland Field (fig. 7) as subbituminous; the sulphur content ranges from 0.3 to 3.3 percent and averages 0.8 percent.

Proximate, ultimate, and major and minor chemical analyses of 12 subbituminous coal samples and chemical analyses of 12 ash samples from the San Juan River region collected by the New Mexico Bureau of Mines and analyzed by the U.S. Bureau of Mines and the U.S. Geological Survey (Swanson and others, 1976) are summarized in tables 3 and 4. The 12 coal samples are ranked as subbituminous and have an average sulphur content, on an as-received basis, of 0.6 percent. Other analyses of the San Juan Basin coals and ash may be found in a report by Fassett and Hinds (1971). Even though the coals are considered to be low-sulfur coals (Shomaker, 1971), increased concentrations of sulfur and silica may be found in wastewater from coal slurries, ash ponds, and cooling towers.

During 1978-82, the U.S. Geological Survey collected and analyzed runoff samples from mine-reclamation plots (table 5). It is not known if the runoff reached any stream channels. Also included in table 5 are the mode concentrations for the 1974-81 water-year chemical analyses for the San Juan River at Shiprock. Comparing the runoff samples with the mode at the Shiprock station shows that the runoff generally had larger concentrations of sodium, potassium, sulfate, fluoride, larger specific conductance, and smaller pH. Potassium concentrations were consistently larger in all runoff samples.

Severson and Gough (1981) compared the chemical quality of topsoil and mine spoil from an area of the San Juan Mine that had been reclaimed. They reported that specific conductance, based on water-saturation extraction, and water-soluble concentrations of boron, calcium, chloride, and magnesium are three to five times as great in mine spoil as in topsoil. Shown and others (1981) stated that ground water in the replaced overburden would increase in specific conductance as a result of exposed soluble materials. This indicates that runoff and shallow ground water affected by leachate probably will have increased concentrations of the above constituents.

Soil-erodibility data were collected and used to predict sediment yield from coal-mining lands in northwestern New Mexico (Summer, 1981). A limited amount of data on soils disturbed by mining and then reclaimed indicates that mean erodibility indices on reclamation sites compare with smaller values in the moderate erodibility group of undisturbed soils. Summer's report states that sediment yield may decrease following mining because some steep slopes would be leveled and smoothed to a more horizontal gradient, covered with topsoil, and revegetated. Shown and others (1981) concurred with this analysis.

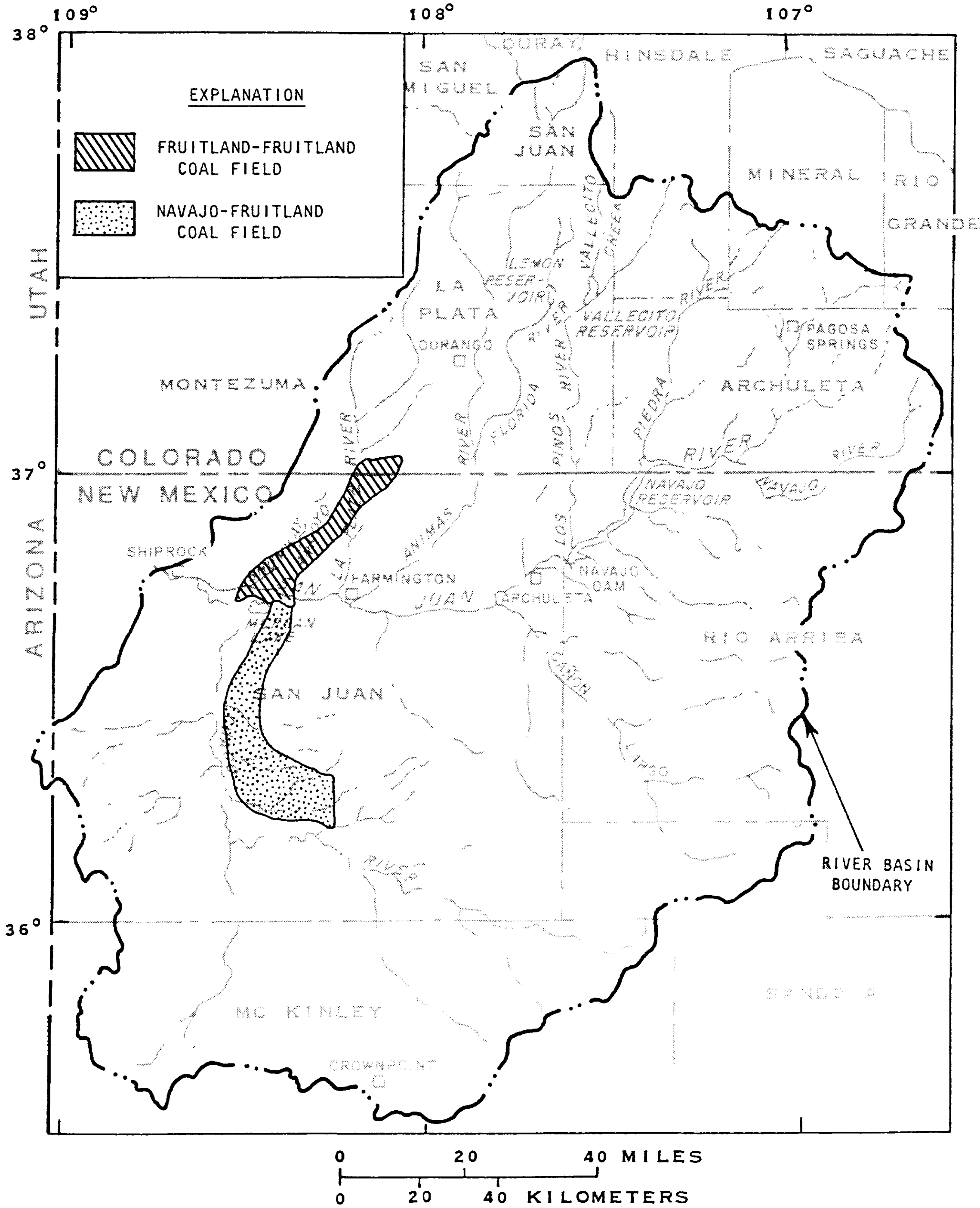


Figure 7.--Location of the Fruitland-Fruitland and Navajo-Fruitland coal fields.

Table 3. <u>Analytical summary of 12 coal samples from the San Juan River region, N. Mex., reported on an as-received, whole-coal basis</u>

[Data summarized from Swanson and others (1976). Original moisture content may be slightly more than shown because samples were collected and transported by plastic bags to avoid metal contamination. Major, minor, and trace-element values were calculated from analysis of ash. *, composite analysis of 11 of the 12 coal samples; < , less than]

Type of analysis	Constituent	Mean	Maximum	Minimum
Proximate*	Moisture in percent	8.6	11.5	4.8
	Volatile matter in percent	35.5	38.4	30.3
	Fixed carbon in percent	39.9	42.8	33.1
Ash in percent*		17.6	25.8	9.2
Ultimate*	Hydrogen in percent	5.0	5.6	4.6
	Carbon in percent	57.1	63.6	50.8
	Nitrogen in percent	1.2	1.4	1.1
	Oxygen in percent	18.4	21.1	15.1
	Sulfur in percent	.6	.9	.5
Energy in British thermal units*		10,000	11,180	8,820
Major, minor, and trace-element	Silica in percent	5.1	11	.86
	Aluminum in percent	2.4	3.9	.45
	Calcium in percent	.44	1.5	.18
	Magnesium in percent	.096	.158	.047
	Sodium in percent	.277	.664	.084
	Potassium in percent	.11	.32	.016
	Iron in percent	.60	1.2	.30
	Manganese in parts per million	28	82	7.2
	Titanium in percent	.11	.19	.042
	Phosphorus in parts per million	843	<1,600	<220
	Chlorine in percent	.039	<.075	<.010

Table 4. **Mean, maximum, and minimum values in percent for chemical assay of laboratory ash of 12 coal samples from the San Juan River region, N. Mex.**

[Data from Swanson and others (1976). Coals were ashed at 525 °Celsius; <, less than]

Constituent	Mean	Maximum	Minimum
Ash	19.5	37.5	5.1
Silica (SiO_2)	54	64	36
Aluminum oxides (Al_2O_3)	24	30	17
Calcium oxide (CaO)	3.8	11	1.3
Magnesium oxide (MgO)	.93	1.94	.65
Sodium oxide (Na_2O)	2.02	2.85	1.13
Potassium oxide (K_2O)	.60	1.0	.35
Iron oxide (III) (Fe_2O_3)	5.1	13	2.6
Manganese oxide (II) (MnO)	.021	.049	.005
Titanium dioxide (TiO_2)	1.0	1.4	.49
Phosphorus pentoxide (P_2O_5)	<1.0	<1.0	<1.0
Sulfur trioxide (SO_3)	4.0	14	1.3
Chloride (Cl)	<.20	<.20	<.20

Table 5. Results of chemical analyses of runoff samples from mine-reclamation plots and of streamflow samples at San Juan River at Shiprock, N. Mex.

[All chemical concentrations are in milligrams per liter. Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius; * indicates values represent sample mode]

Location	Date of sample	Calcium, dissolved	Sodium, dissolved	Magnesium, dissolved	Potassium, dissolved	Sulfate, dissolved	Chloride, dissolved	Fluoride, dissolved	Alkalinity (as $CaCO_3$)	Sodium adsorption ratio	pH	Specific conductance
San Juan Mine												
1974	07-12-82	40	29	7.1	18	7.0	13	0.3	220	1	6.9	460
reclamation	04-23-82	110	1,200	25	13	2,300	54	1.1	120	27	8.0	4,800
plot	10-02-81	39	47	6.7	22	8.0	15	.3	200	2	7.1	500
	02-13-79	31	9.8	2.9	17	13	9.8	.1	100	.5	-	-
1977	04-23-82	310	800	41	14	2,300	22	.5	90	11	7.0	4,580
graded pile	(upper stage)											
	04-23-82	36	86	3.9	9	160	4.9	.8	120	4	7.4	610
	(lower stage)											
	10-02-81	67	53	7.9	15	33	4.2	.5	270	2	6.9	625
	07-12-81	99	80	12	15	310	4.1	.4	210	2	6.7	965
	11-03-78	41	94	4.4	14	130	5.9	.5	210	4	7.0	640
	09-24-78	53	100	7.8	22	200	7.9	.5	210	3	7.4	940
Navajo Mine												
1973	04-23-82	31	10	4.5	9	17	2.5	.8	72	.5	7.5	275
reclamation	03-05-80	19	11	2.4	8	57	2.1	.2	3	.6	6.8	188
plot	02-13-79	38	23	6.9	-	-	-	-	38	.9	6.8	410
1976	02-13-79	13	100	.9	4	-	-	-	43	7	6.8	590
spoil pile	(upper stage)											
	02-13-79	18	210	1.6	6	43	39	.6	120	13	7.1	1,120
	(lower stage)											
1978	02-13-79	150	130	27	12	610	26	.8	74	3	6.0	1,330
reclamation	09-24-78	280	440	74	13	1,600	130	1.9	130	6	7.2	3,400
plot	09-24-78	300	500	92	15	1,900	210	2.4	100	7	7.3	3,600
San Juan River at Shiprock*	10-01-73 through 09-30-81	56	40	12	2.4	130	15	.3	110	1.2	8.0	550

In the San Juan River basin downstream from coal strip mines, potential impacts on surface-water quality could include: increased sedimentation due to surface runoff during the strip-mining process, but decreased sedimentation due to surface runoff after reclamation; increased specific conductance; increased dissolved-solids concentration; and increased concentration of dissolved potassium. The increases in specific conductance and dissolved-solids and dissolved-potassium concentrations could occur during times of storm runoff and in stream reaches affected by ground-water seepage.

EFFECTS OF COAL-MINE AND POWER-GENERATION OPERATIONS ON SURFACE-WATER QUALITY

Surface runoff from the San Juan Mine, effluent from the San Juan Power Plant facilities, and runoff from part of the Navajo Mine drain to the San Juan River. Runoff from most of the Navajo Mine and effluent from the Four Corners Power Plant facilities drain to the Chaco River (fig. 8).

Water-quality and streamflow data were collected by the U.S. Geological Survey at stations along the Chaco River (fig. 2) from 1975 through 1979. Data are sparse in the ephemeral reach of the Chaco River upstream from the Waterflow station (09367950 in figs. 2 and 8). Residents report that the reach below the power plant has become perennial since the power plant began operating. Self-monitoring data from the Four Corners Power Plant were collected from 1970 through 1979. Because water-quality data were not collected before the mine and power plant began operation, a pre-mine-and-power-plant versus post-mine-and-power-plant analysis could not be done. An upstream versus downstream analysis using graphical techniques was done. The amount of data upstream of the mine and power plant was insufficient to do statistical analyses. Piper diagrams and time-series plots were used in analyzing water quality along the Chaco River. Data along the Chaco River are not complicated by upstream effects such as reservoir operations and urbanization as is the case along the San Juan River main stem.

Numerous analytical techniques were applied to the water-quality and streamflow data collected at the gaging station at Shiprock. The data for Shiprock are more extensive than for the Chaco River system, and include samples collected periodically prior to the coal mining and power plants and daily samples for some constituents. Statistical analyses were made comparing pre-1963 data to post-1963 data to determine coal-mine and power-plant effects. Data from upstream stations were also analyzed to eliminate upstream cultural and natural effects, such as urbanization, changes in agricultural practices, and streamflow regulation by reservoirs.

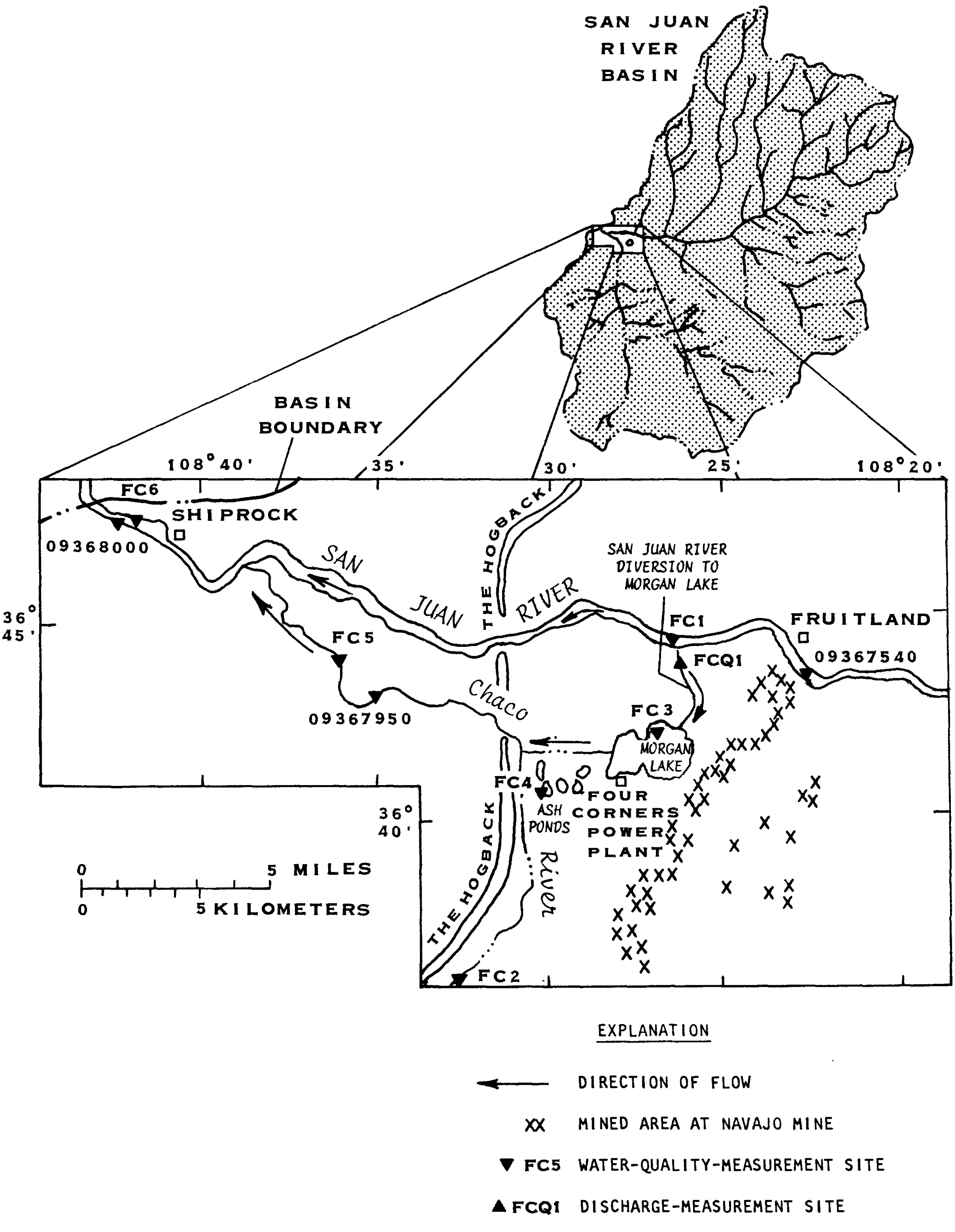


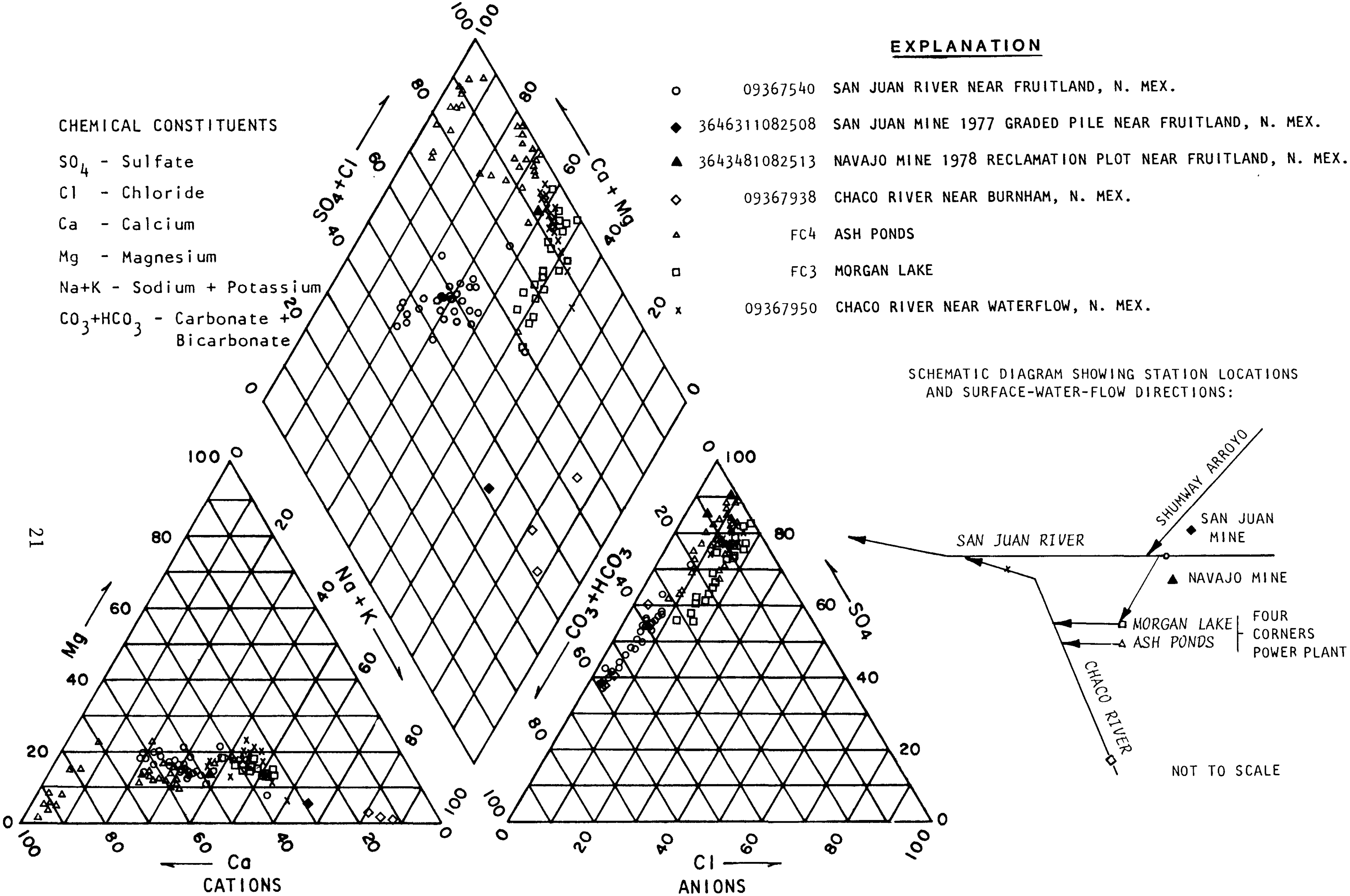
Figure 8.--Location of the Four Corners Power Plant and mined area at Navajo Mine.

Piper Diagram Analysis

Piper diagrams were used to illustrate U.S. Geological Survey and Four Corners Power Plant water-quality data from several surface-water sites to determine: (1) mixing of waters with different chemical composition; (2) relative changes in chemical-quality concentrations from upstream to downstream sites; and (3) relative water types when mixing of waters cannot be verified. Laboratory chemical analyses of the water samples had to have a cation-anion balance within 5 percent to be included in the Piper diagrams. Assuming all constituents remain in solution, when waters A and B mix, a plot of the mixture should fall within the straight line from A to B depending on relative concentrations of A and B waters and their proportionate volumes (Piper, 1944).

The Piper diagram (fig. 9), with plots from water of the Four Corners Power Plant facilities, San Juan Mine, Navajo Mine, and associated waters, is used to show the different relative chemical compositions of water in the Chaco drainage basin and the mixing effects of the San Juan River water with power-plant effluent. Period-of-record data were used for all sites. Chaco River near Burnham, N. Mex., contains sodium bicarbonate and sodium sulfate water. Chaco River near Waterflow contains sodium sulfate and calcium sulfate water. With the data available, mixing effects of Chaco River near Burnham, N. Mex., with the power-plant effluent cannot be shown because sampling dates of the upstream site, Chaco River near Burnham, N. Mex., do not coincide with those of the downstream site, Chaco River near Waterflow, N. Mex. Water from the San Juan River is diverted into Morgan Lake for use by the Four Corners Power Plant. The diverted water is altered at Morgan Lake and does not plot on the Piper diagram at the same location as water from the San Juan River near Fruitland. The Morgan Lake water is altered due to wastes from the power-plant facility producing sodium calcium sulfate water. Ash from the power plant is sluiced to ash ponds. After settling of ash, calcium sulfate water is released to the Chaco River. Water from the Chaco River near Waterflow likely is a mixture of natural upstream water, if there is flow, ash-pond effluent, and Morgan Lake discharge.

The Waterflow plots are between the ash-pond effluent and Morgan Lake plots (fig. 9). Morgan Lake contains large relative amounts of sodium, calcium, and sulfate and the ash ponds contain large relative amounts of calcium and sulfate producing sodium sulfate and calcium sulfate water at Waterflow. The power plant noticeably affects water quality of the Chaco River.



PERCENTAGE OF TOTAL IONS, IN MILLIEQUIVALENTS PER LITER

Figure 9.--Water-quality characteristics for the San Juan River, Four Corners Power Plant facilities, San Juan Mine, Navajo Mine, and Chaco River.

The mixing effects of the Animas, La Plata, and Chaco Rivers on the San Juan River are shown on the Piper diagram of the San Juan River and its tributaries (fig. 10). Seasonal low-flow data collected from October 1 through March 30 were used for all but the Chaco site; data for the entire year were used for the Chaco site. Low-flow data were used because they probably show the greatest impact from the Chaco River tributary. The diagram shows the water-quality data for the San Juan River from Archuleta, N. Mex., to Shiprock, N. Mex., trending toward the upper right part of the quadrilinear diagram. The water becomes relatively larger in dissolved-sodium and dissolved-sulfate concentrations and relatively smaller in dissolved-calcium and bicarbonate concentrations. The three tributaries contribute sulfate to the San Juan River. The Animas River contributes larger relative concentrations of dissolved calcium and La Plata and Chaco Rivers contribute larger relative concentrations of dissolved sulfate.

Piper diagrams of water quality before (pre-1963) and after (1963-79) mining began for the San Juan River at Farmington (upstream from mining) and at Shiprock (downstream from mining) are shown in figures 11 and 12, respectively. Due to lack of pre-mining data on the Chaco River and Shumway Arroyo, pre- versus post-mining Piper diagrams were not done for these sites. A slightly higher ratio of calcium and bicarbonate during 1963-79 than in 1962, which probably is caused by operation of the Navajo Reservoir, is shown in the Piper diagram of the San Juan River at Farmington. No noticeable difference between the two periods is indicated by the Piper diagram of the San Juan River at Shiprock.

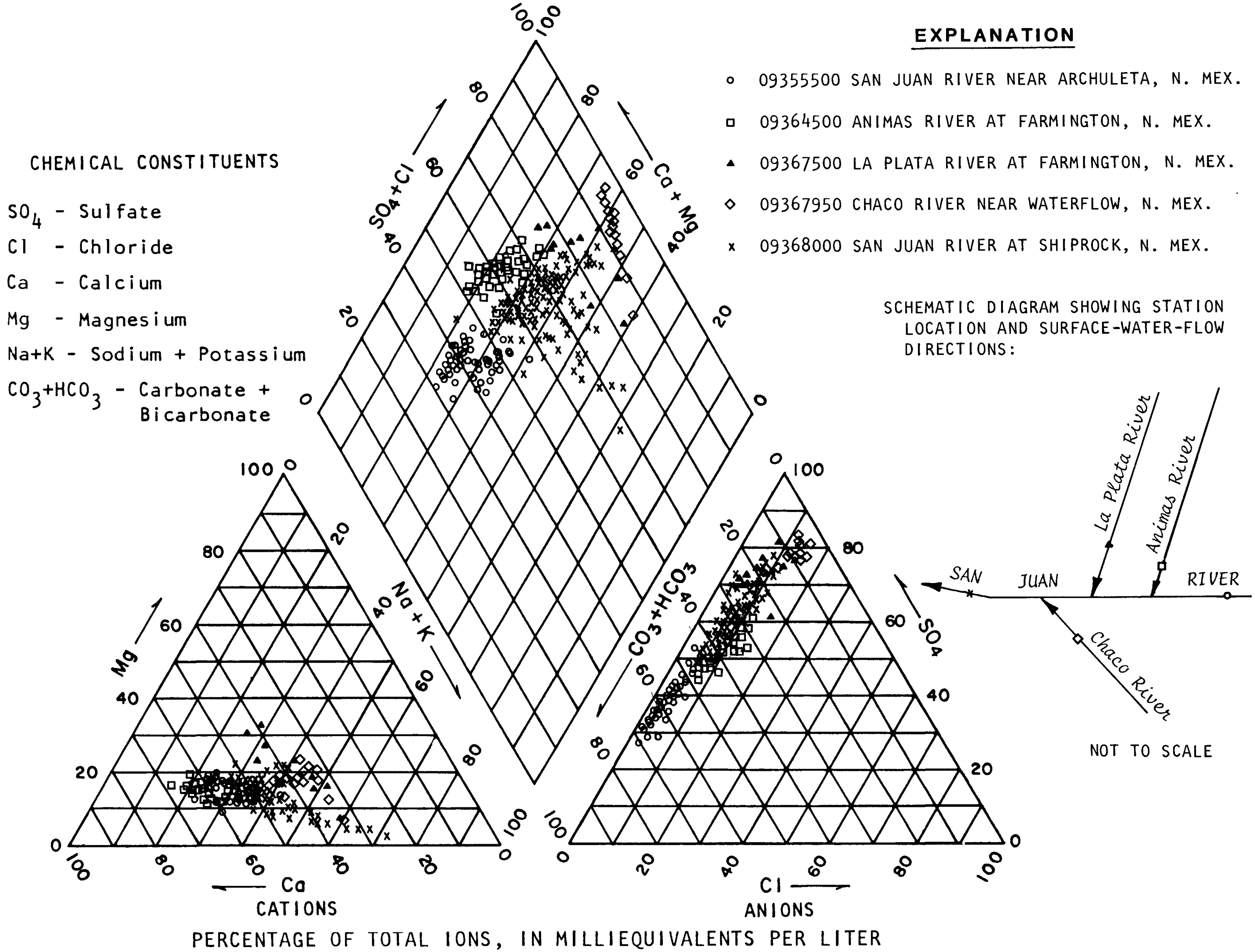


Figure 10.--Water-quality characteristics for the San Juan River and three tributaries (using low-flow data).

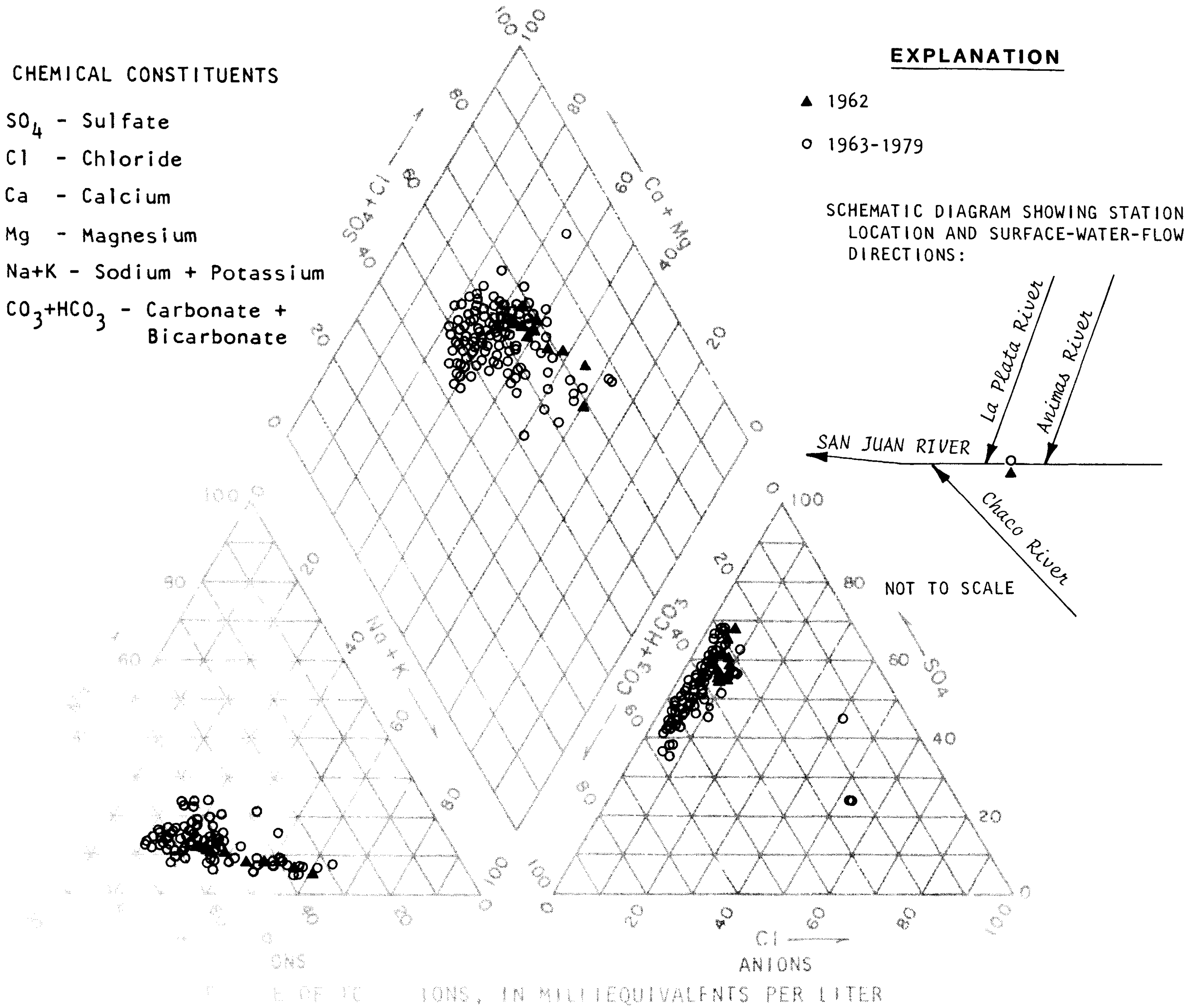


Figure 11.--Water-quality characteristics for the San Juan River at Farmington, N. Mex., before and after construction of the mine and reservoir (using low-flow data).

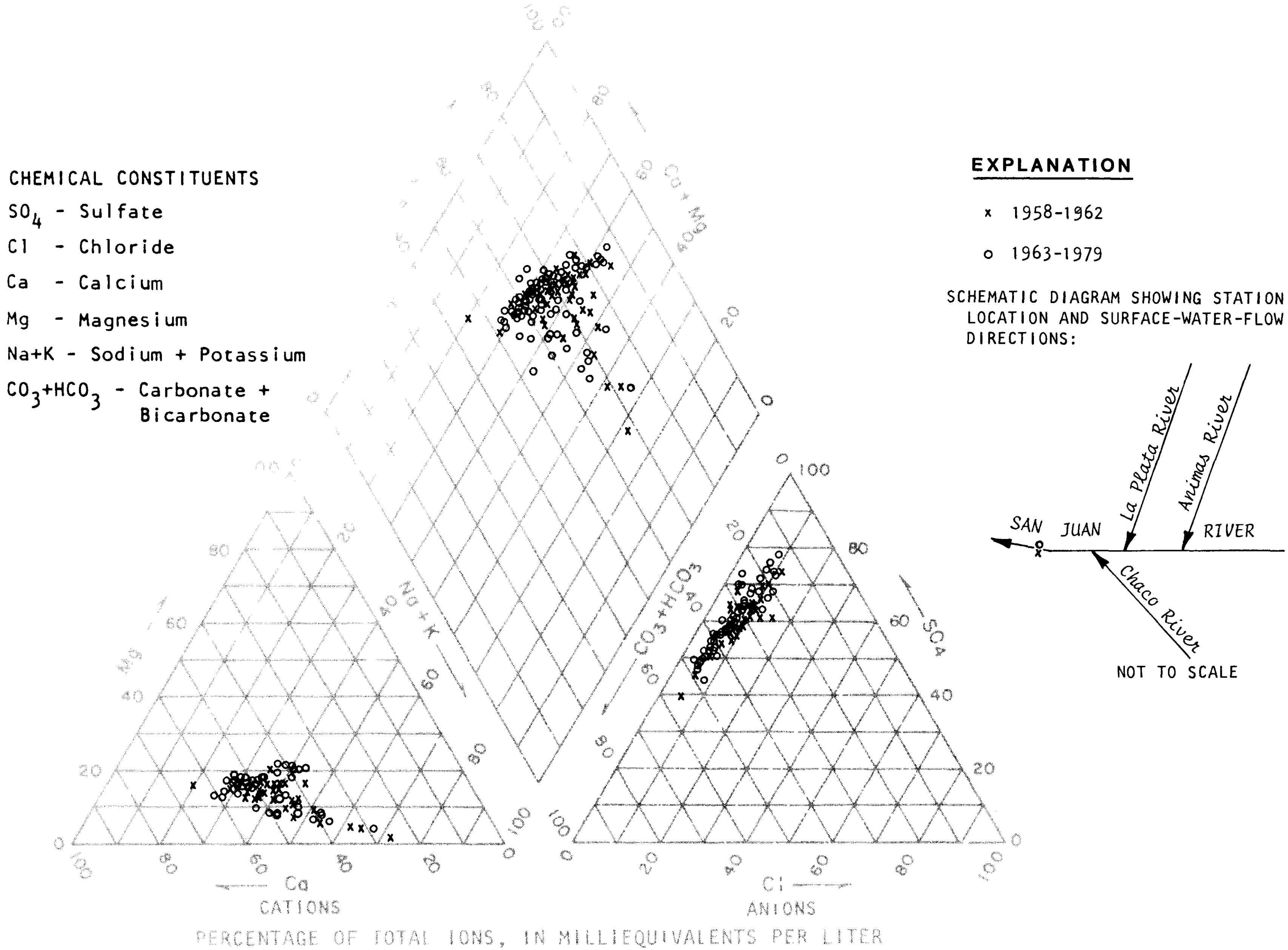


Figure 12.--Water-quality characteristics for the San Juan River at Shiprock, N. Mex., before and after construction of the mine and reservoir (using low-flow data).

Comparison of Time-Series Plots

Time-series plots are used to illustrate how data change over time. Time-series plots were examined for U.S. Geological Survey water-quality and streamflow data and Four Corners Power Plant water-quality and discharge data to determine if there are changes over time or between stations (figs. 13-19). U.S. Geological Survey streamflow data are monthly mean discharges that were calculated from mean daily discharges. The Four Corners Power Plant discharge and water-quality data are monthly means. Pre-mining and pre-power-plant data are not included in the Four Corners Power Plant data because the earliest observations were taken in 1971.

Time-series plots of specific conductance (fig. 13) and concentrations of dissolved calcium (fig. 14), dissolved magnesium (fig. 15), dissolved chloride (fig. 16), dissolved sulfate (fig. 17), and dissolved silica (fig. 18) were analyzed for Four Corners data collected at the San Juan River near Hogback (FC1), Morgan Lake (FC3), ash-pond effluent (FC4), Chaco River upstream of power plant (FC2), Chaco River downstream of power plant (FC5), and the San Juan River at Shiprock (FC6). (See fig. 8 for location of these stations.) Specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, and dissolved sulfate are larger at Morgan Lake than at the San Juan River at Hogback, whereas the concentration of silica is larger at the San Juan River at Hogback. Specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, dissolved sulfate, and dissolved silica are larger in the ash-pond effluent than at Hogback or Morgan Lake. An increase of specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, dissolved sulfate, and dissolved silica is apparent at the ash ponds after about January or February 1972. Although the data are sparse on the Chaco River upstream of the power plant, individual data points generally are higher for specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, and dissolved sulfate on the Chaco River downstream of the power plant than data points upstream. Concentrations of dissolved silica are about the same. A decreasing trend of specific conductance and dissolved-ion concentration is apparent on the time-series plots of the Chaco River downstream of the power plant. Specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, dissolved sulfate, and dissolved silica generally are about the same for the San Juan River at Hogback and at Shiprock.

The ash-pond effluent generally has the most concentrated power-plant wastes. Wastes from the power plant increase the specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, and dissolved sulfate in Morgan Lake. The chemical quality of effluent from Morgan Lake and the ash ponds has changed during the operation of the power plant. A decreasing trend in specific conductance and dissolved-ion concentration downstream from the power plant shows some correspondence with decreasing concentrations in Morgan Lake and the ash ponds. The Morgan Lake and ash-pond effluents from the power plant increase specific conductance and concentrations of dissolved calcium, dissolved magnesium, dissolved chloride, and dissolved sulfate downstream from the power plant. No effects of the power plant on water quality from the San Juan River at Shiprock were apparent.

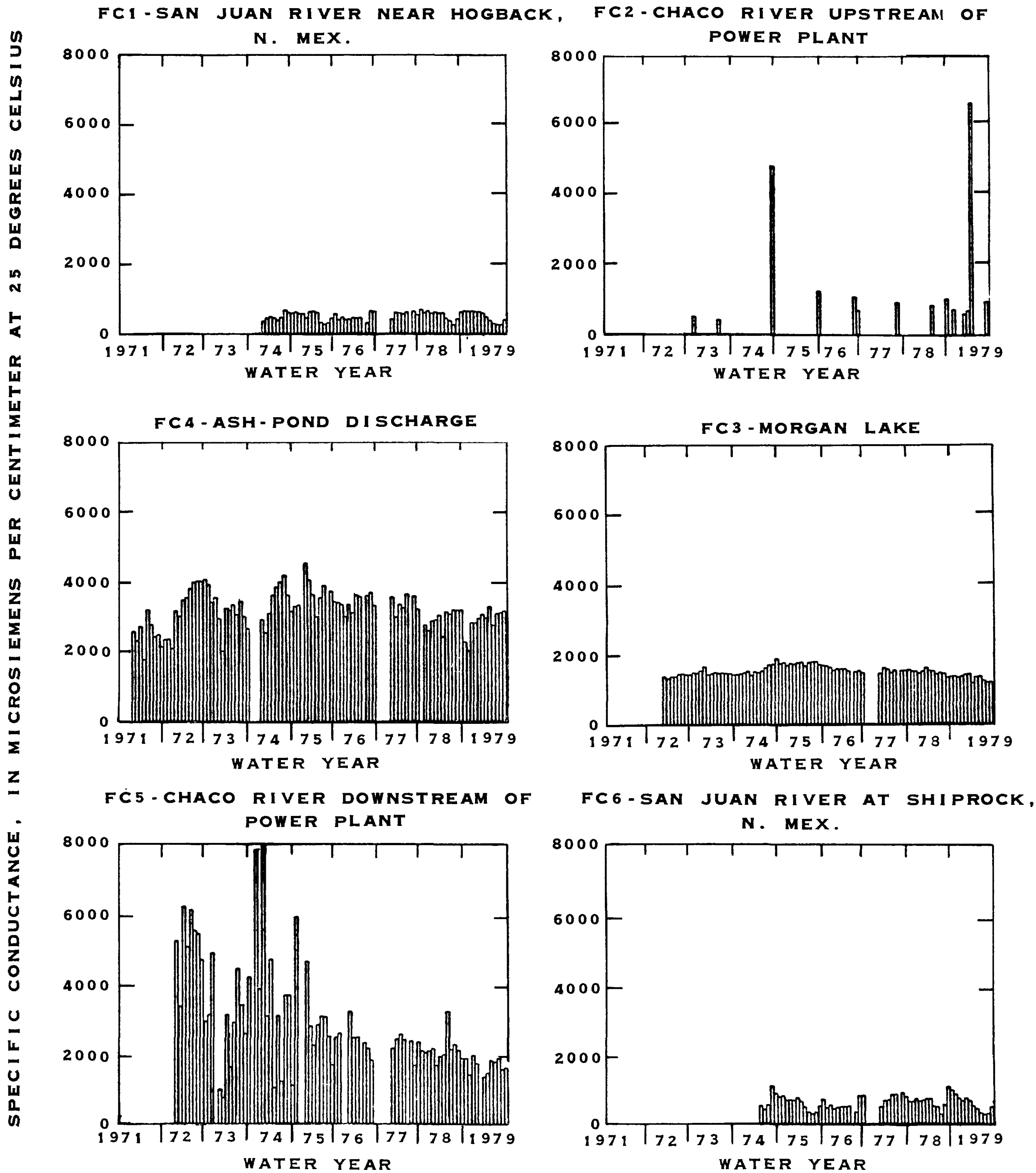


Figure 13.--Monthly means of specific conductance of water in the San Juan River, Four Corners Power Plant area, and Chaco River for water years 1971-79.

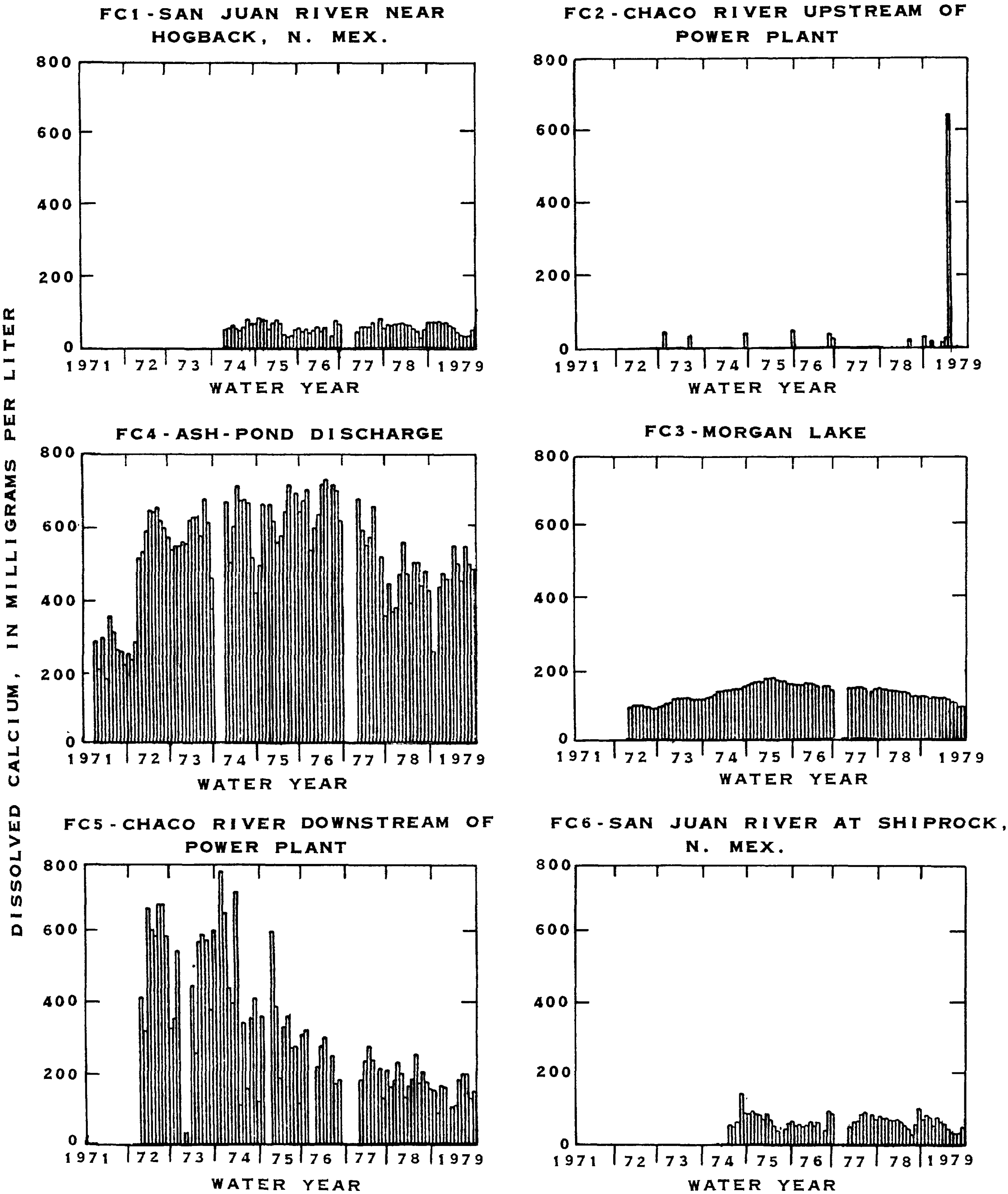


Figure 14.--Monthly means of dissolved-calcium concentration of water in the San Juan River, Four Corners Power Plant area, and Chaco River for water years 1971-79.

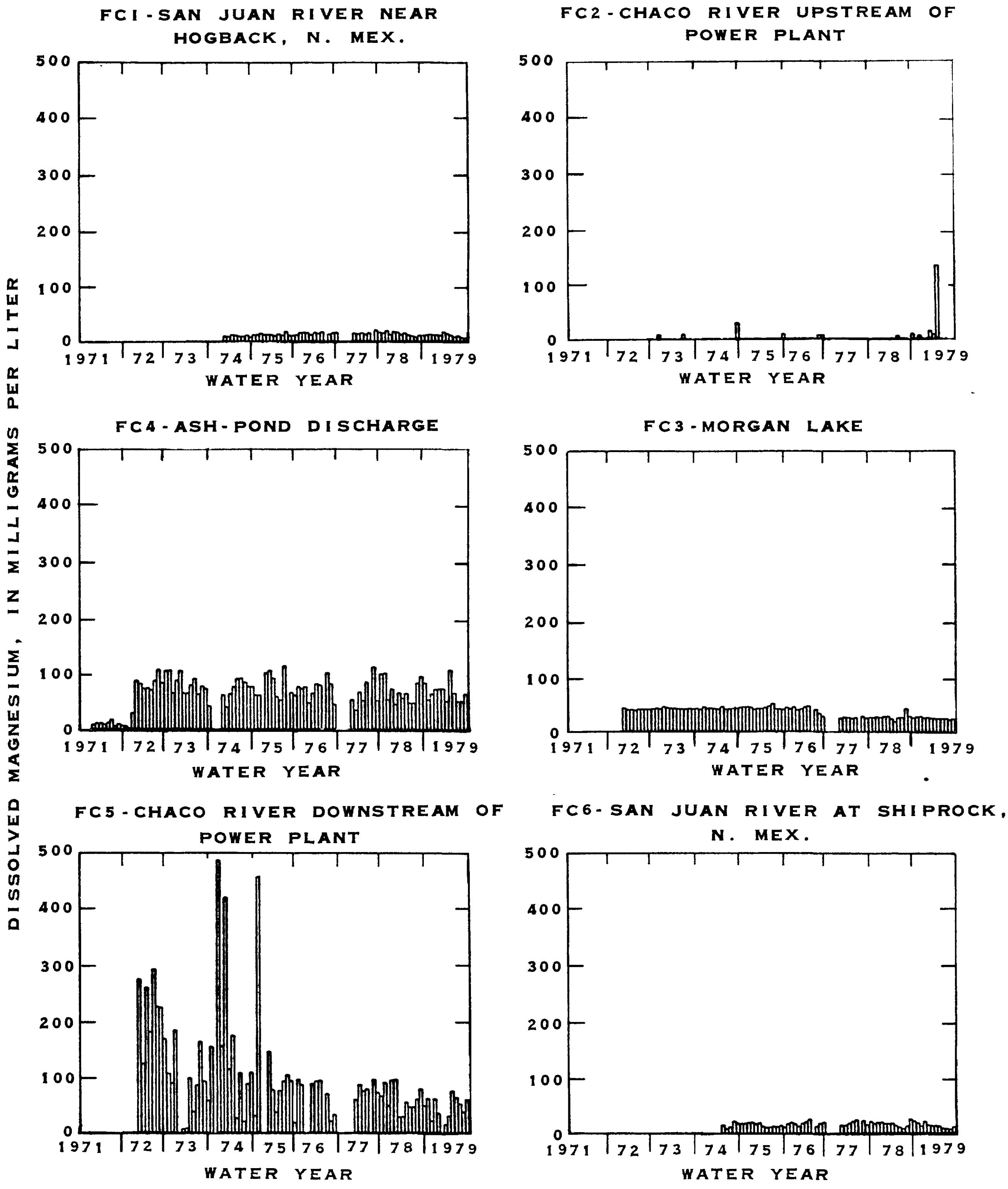


Figure 15.--Monthy means of dissolved-magnesium concentration of water in the San Juan River, Four Corners Power Plant area, and Chaco River for water years 1971-79.

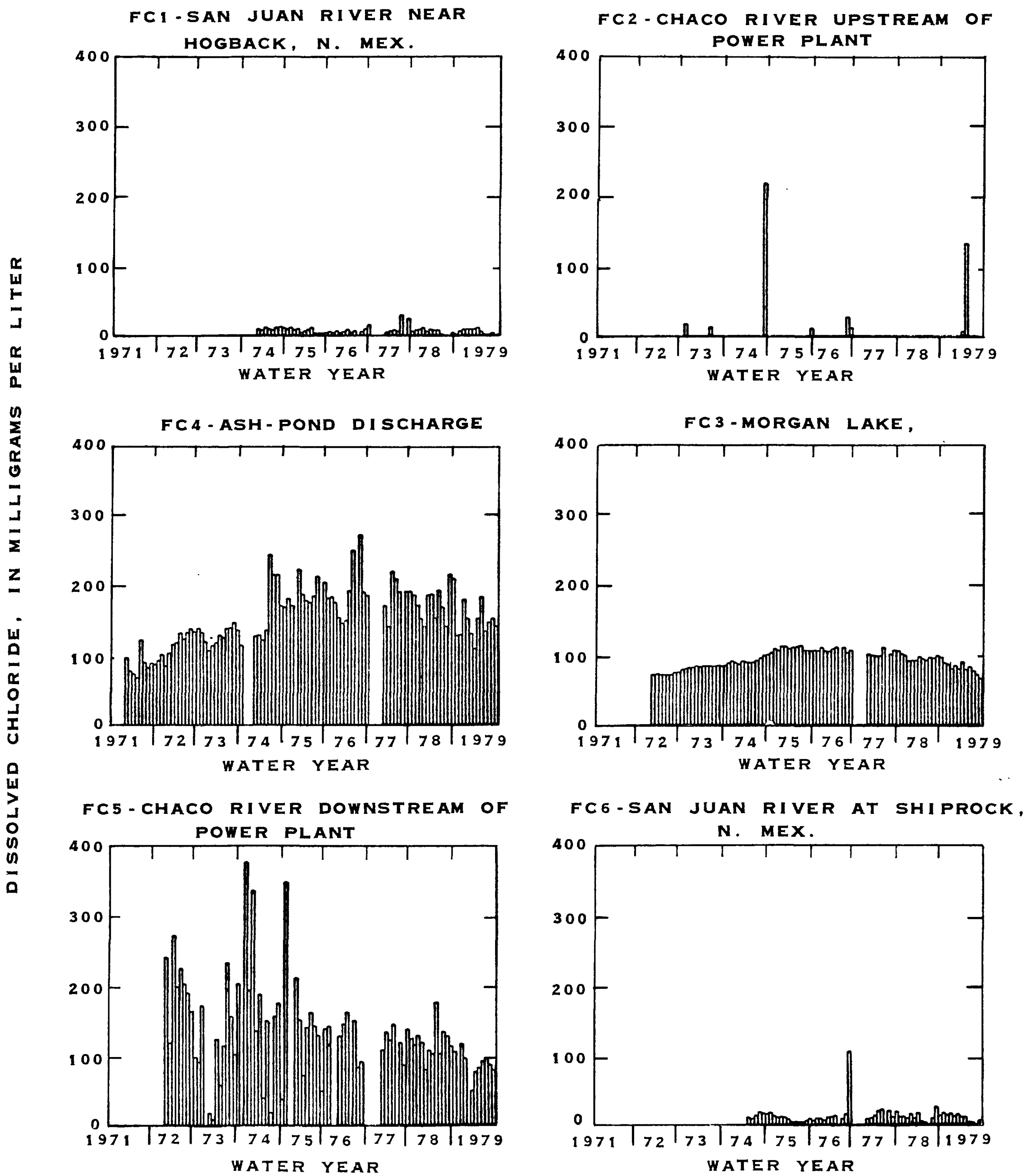


Figure 16.--Monthly means of dissolved-chloride concentration of water in the San Juan River, Four Corners Power Plant area, and Chaco River for water years 1971-79.

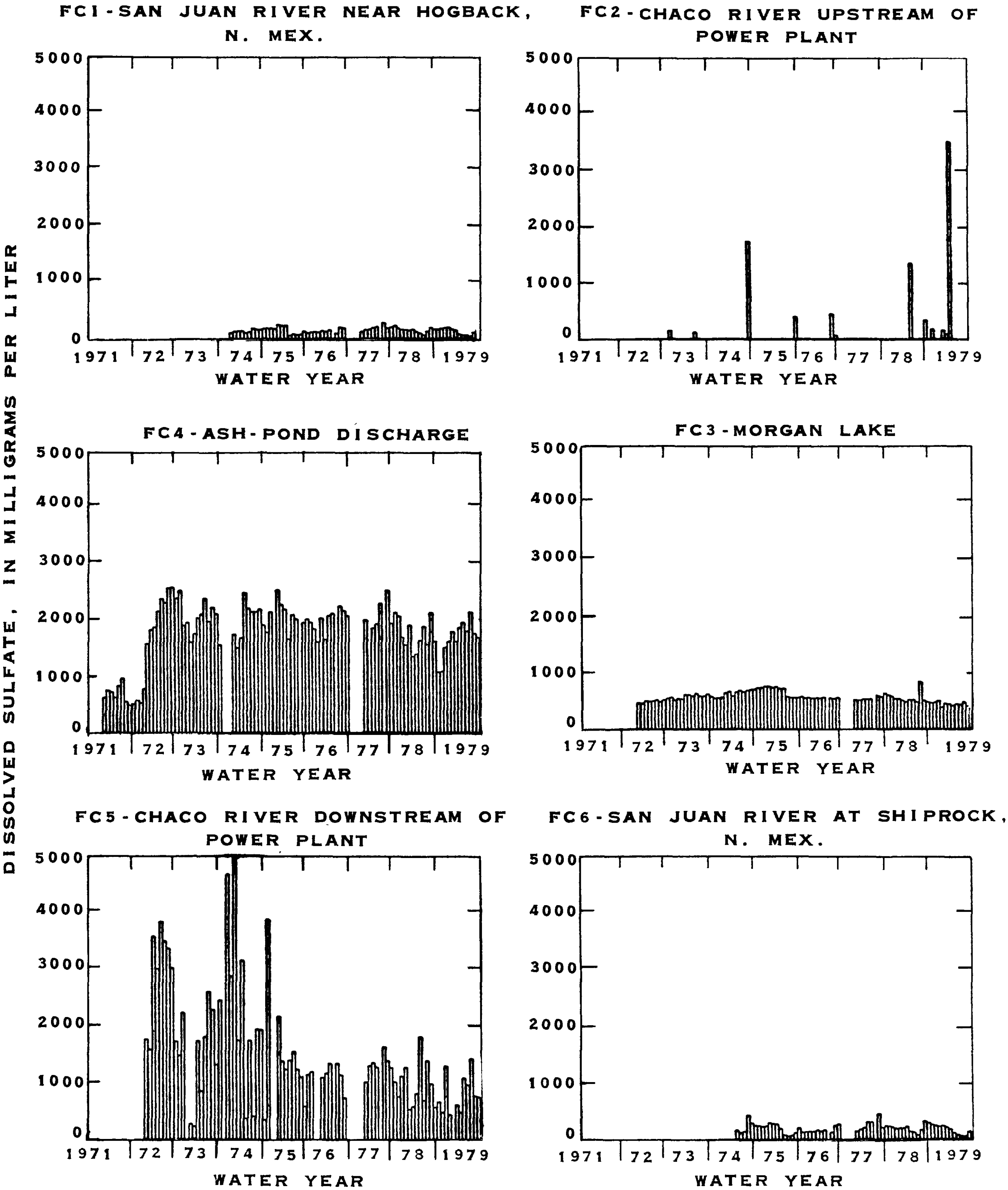


Figure 17.--Monthly means of dissolved-sulfate concentration of water in the San Juan River, Four Corners Power Plant area, and Chaco River for water years 1971-79.

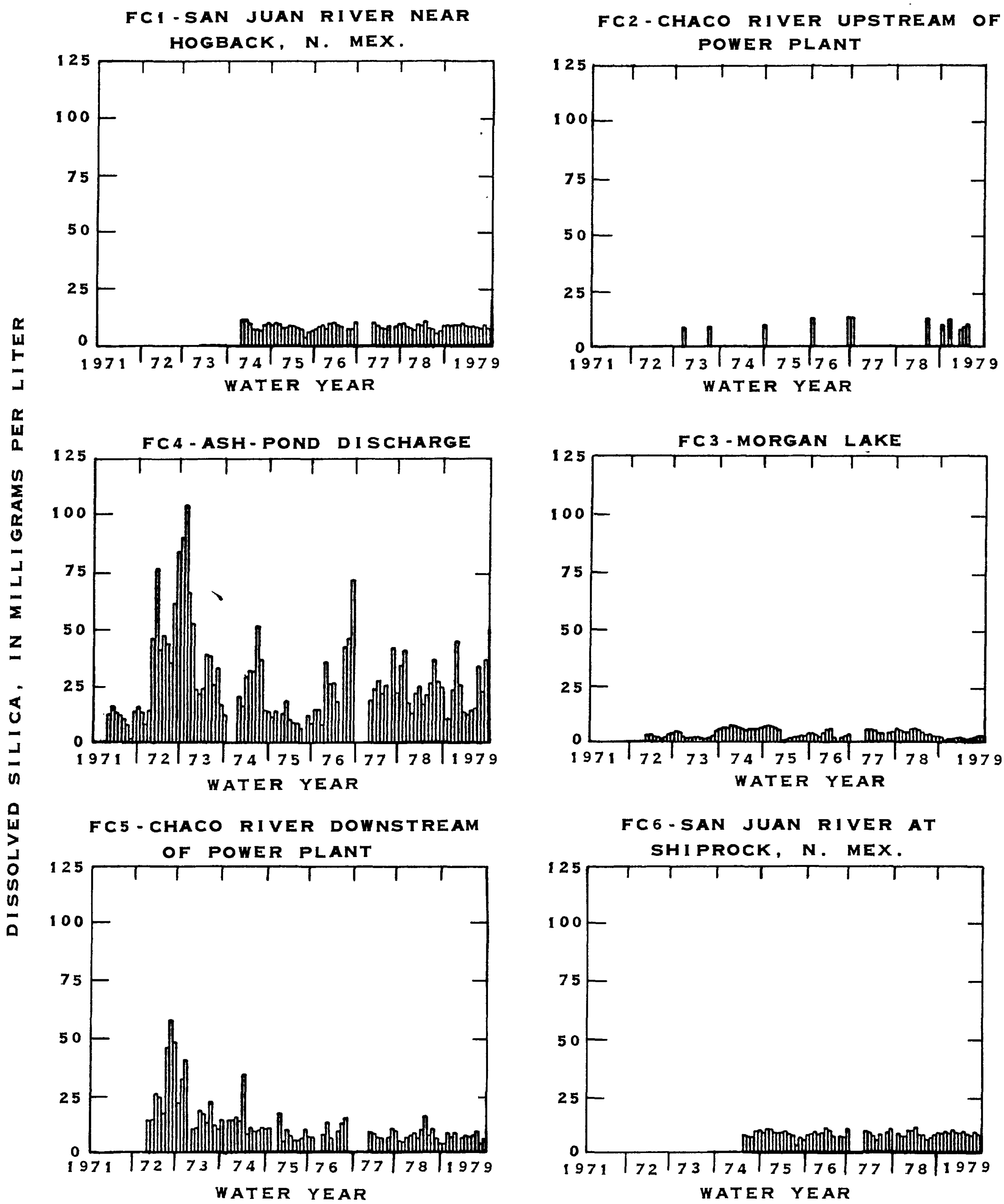


Figure 18.--Monthly means of dissolved-silica concentration of water in the San Juan River, Four Corners Power Plant area, and Chaco River for water years 1971-79.

Time-series plots of monthly mean discharges for the San Juan River diversion to Morgan Lake, Morgan Lake discharge to the Chaco River, ash-pond discharge to the Chaco River, Chaco River upstream of the Four Corners Power Plant (Chaco River near Burnham, N. Mex.), Chaco River downstream of the Four Corners Power Plant (Chaco River near Waterflow, N. Mex.), and the San Juan River at Shiprock are shown in figure 19. Four Corners discharge data were used to graph Morgan Lake discharge to the Chaco River and the ash-pond discharge to the Chaco River. U.S. Geological Survey streamflow data were used for the Chaco River upstream and downstream of the power plant and the San Juan River at Shiprock sites.

In comparing the discharge hydrographs, the following observations were made: (1) Discharge in the San Juan River is much greater than discharge through the Four Corners Power Plant facilities and the Chaco River (fig. 19), (2) discharge to the Chaco River from Morgan Lake is greater than from the ash ponds, and (3) the Chaco River downstream of the power plant generally has a greater discharge than upstream. The downstream discharge generally is power-plant discharge but there are some months when monthly mean discharge is slightly larger upstream of the power plant. Therefore, the effect of wastewater from the power plant may be noticeable on the small-discharge Chaco River but highly diluted on the large-discharge San Juan River.

Discharge and selected water-quality data for San Juan River at Pagosa Springs, Colo. (fig. 20), San Juan River near Archuleta, N. Mex. (fig. 21), and San Juan River at Shiprock, N. Mex. (fig. 22), were graphed in order to determine any changes caused by the operation of Navajo Reservoir. The amount of precipitation at Aztec Ruins National Monument is shown in figure 23.

The annual pattern of discharge for the upstream station, San Juan River at Pagosa Springs, Colo., is shown in figure 20. Snowmelt causes the large discharge May through July each year. The small discharges generally take place November through March when precipitation generally is in the form of snow. There does not appear to be any pattern to the data other than the yearly seasonal pattern.

Discharge of the San Juan River near Archuleta changed after 1963 (fig. 21). Extreme large and small discharges have moderated since 1963 in response to operation of the Navajo Reservoir. Daily water temperatures have also moderated since 1963, although the yearly, seasonal temperature pattern is still present. Seasonal fluctuations in specific conductance appear to be less dramatic after 1963. Before 1963, periods of large discharge (snowmelt runoff) corresponded with periods of small specific conductance and small discharge corresponded with large specific conductance. Suspended-sediment concentration and suspended-sediment load decreased to near zero after 1963.

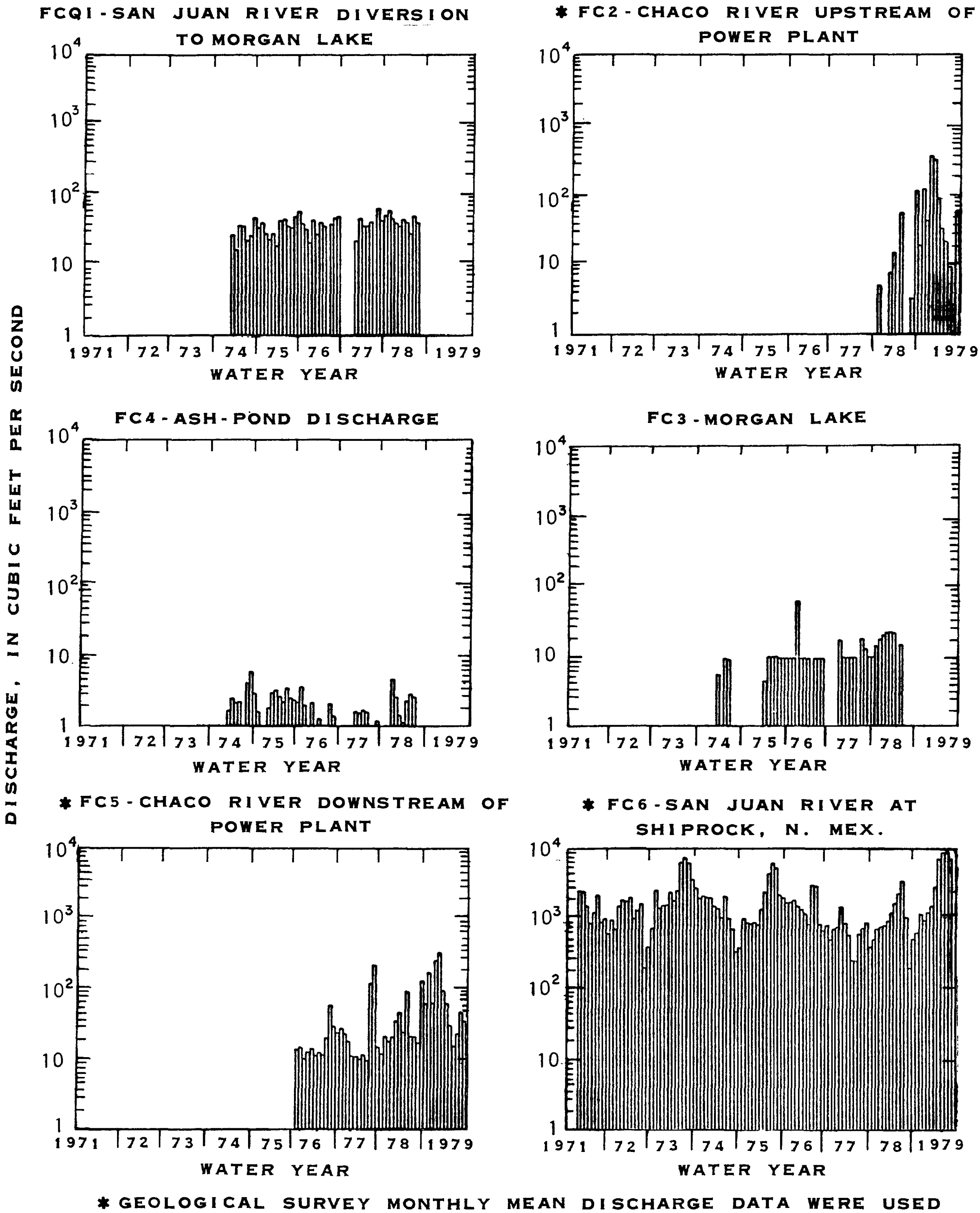


Figure 19.--Monthly mean discharge of the Four Corners Power Plant facilities and related sites for water years 1971-79.

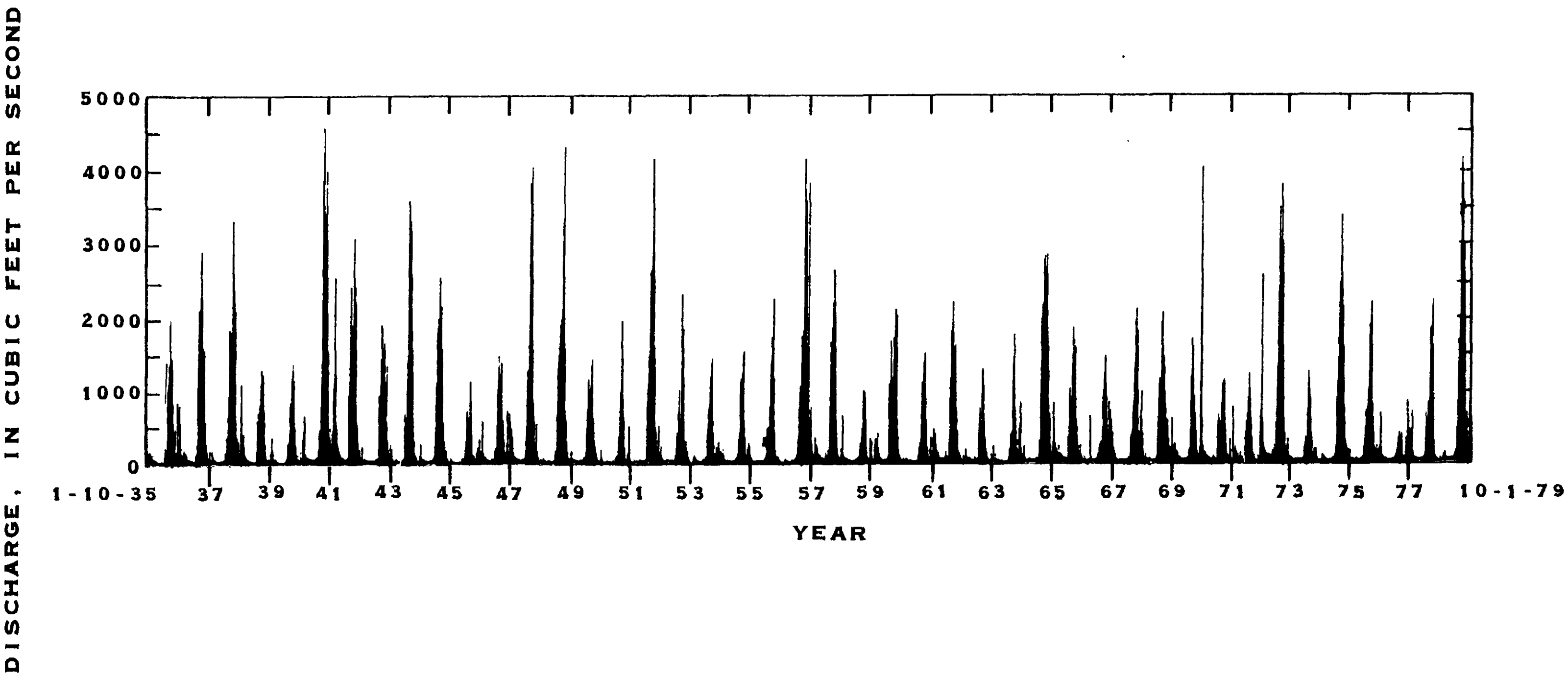
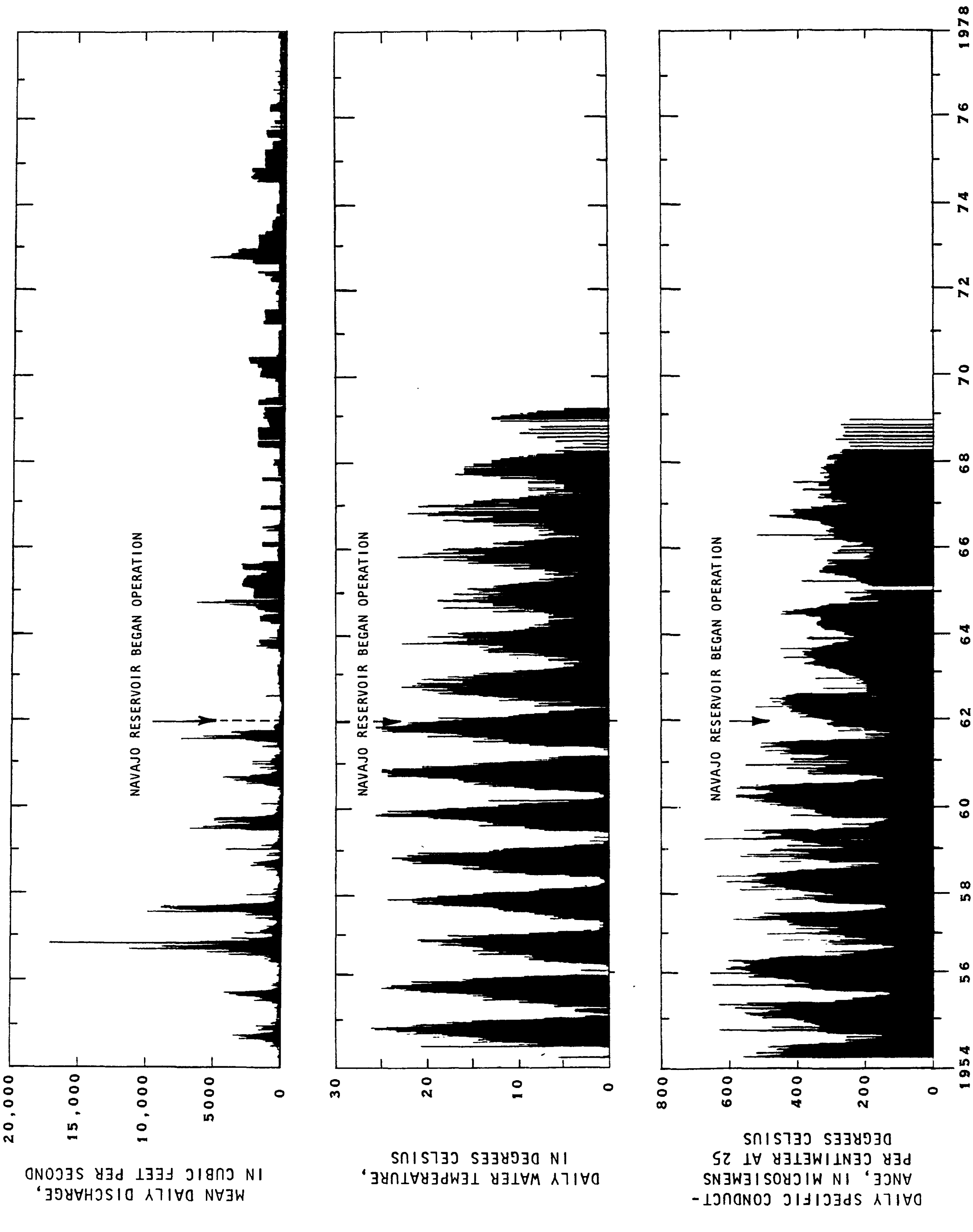


Figure 20.--Daily mean discharge for the period of record at San Juan River at Pagosa Springs, Colo.



MEAN DAILY DISCHARGE, IN CUBIC FEET PER SECOND
20,000
15,000
10,000
5000
0
DAILY WATER TEMPERATURE, IN DEGREES CELSIUS
30
20
10
0
DAILY SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS
800
600
400
200
0
NAVAJO RESERVOIR BEGAN OPERATION
NAVAJO RESERVOIR BEGAN OPERATION
NAVAJO RESERVOIR BEGAN OPERATION
1954
56
58
60
62
64
66
68
70
72
74
76
1978

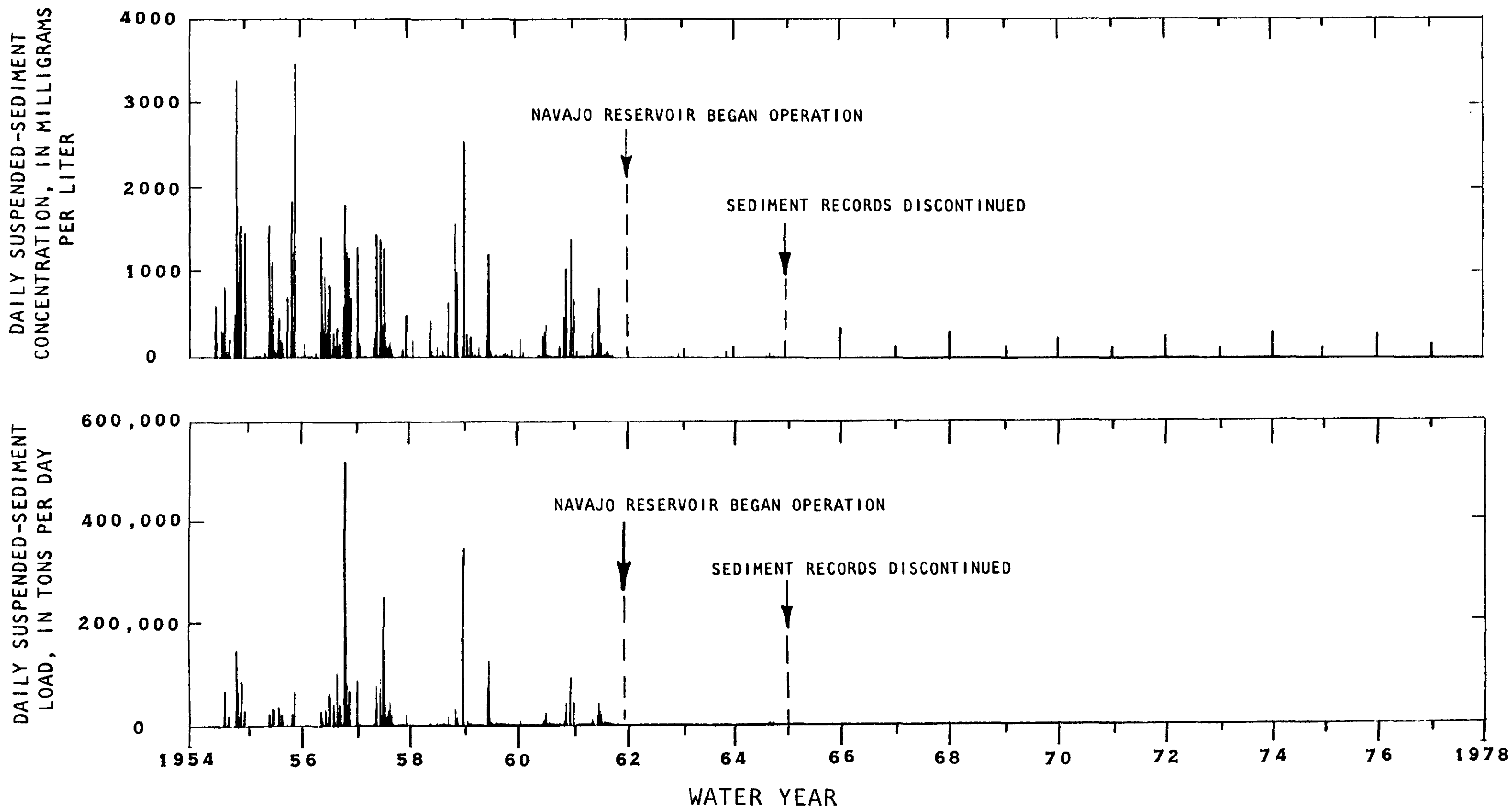
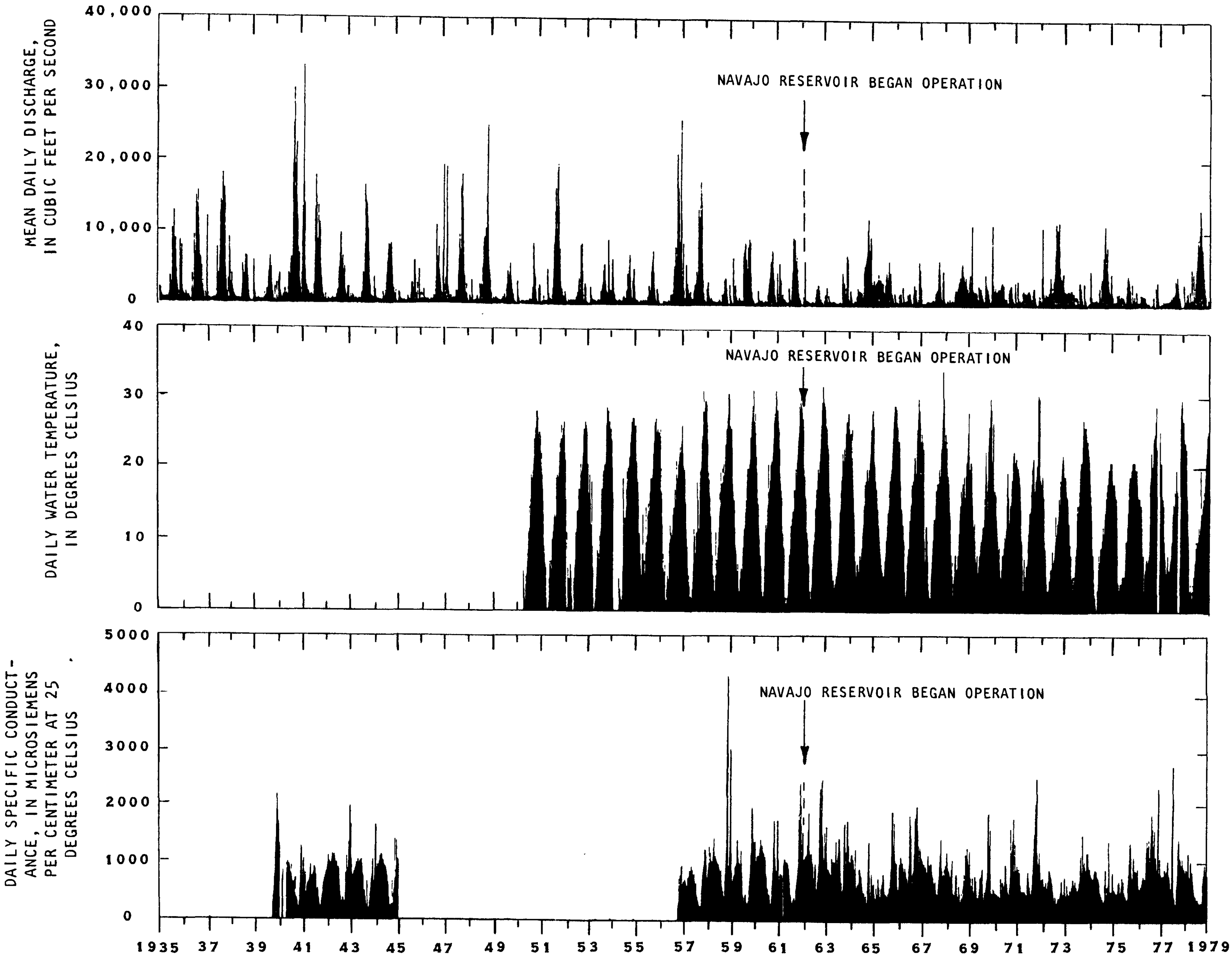


Figure 21.--Daily discharge, water temperature, specific conductance, suspended-sediment concentration, and suspended-sediment load for the period of record at San Juan River near Archuleta, N. Mex.


MEAN DAILY DISCHARGE, IN CUBIC FEET PER SECOND
40,000
30,000
20,000
10,000
0
NAVAJO RESERVOIR BEGAN OPERATION
DAILY WATER TEMPERATURE, IN DEGREES CELSIUS
40
30
20
10
0
NAVAJO RESERVOIR BEGAN OPERATION
DAILY SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS
5000
4000
3000
2000
1000
0
NAVAJO RESERVOIR BEGAN OPERATION
1935 37 39 41 43 45 47 49 51 53 55 57 59 61 63 65 67 69 71 73 75 77 1979

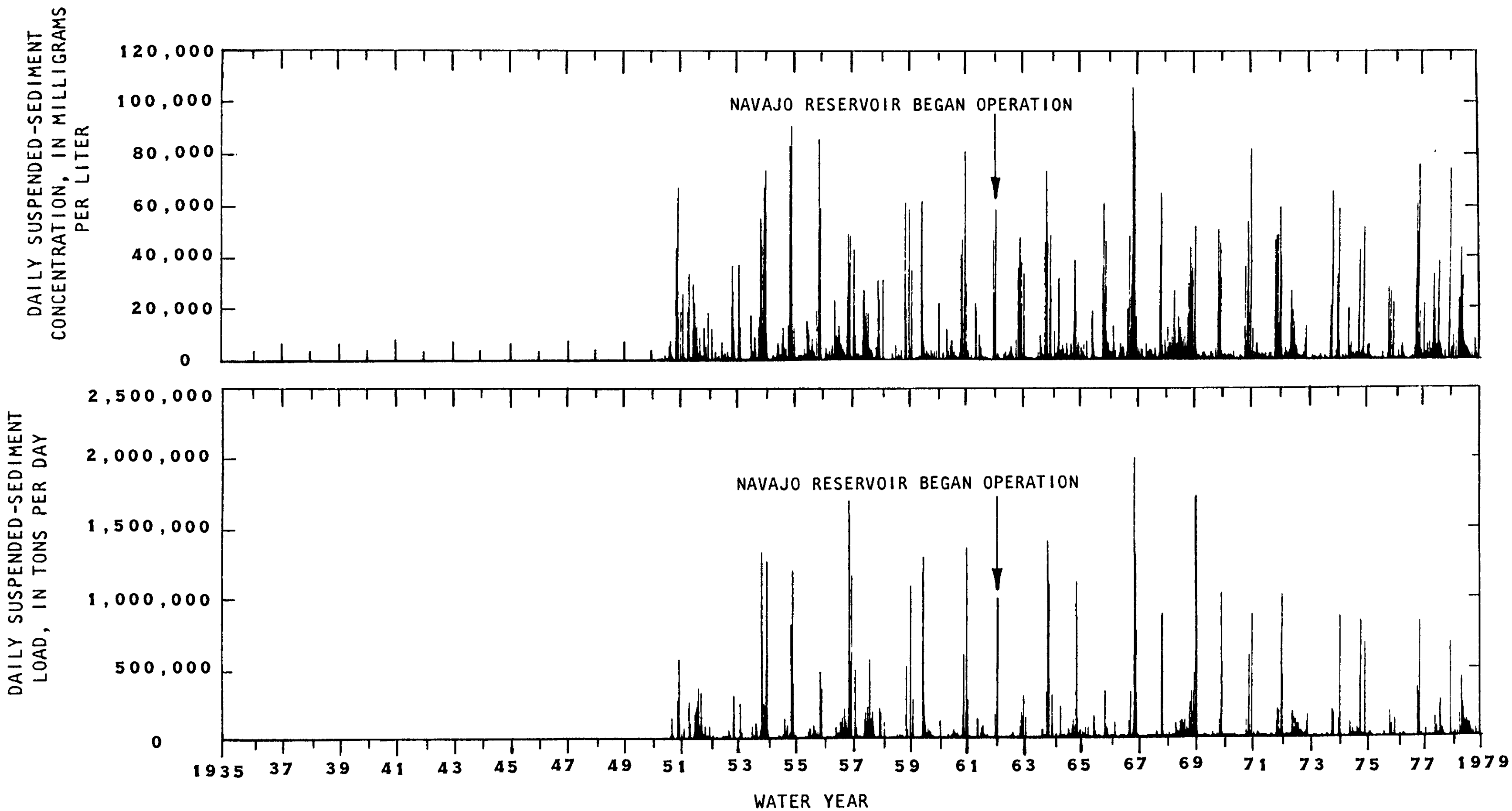


Figure 22.--Daily discharge, water temperature, specific conductance, suspended-sediment concentration, and suspended-sediment load for the period of record at San Juan River at Shiprock, N. Mex.

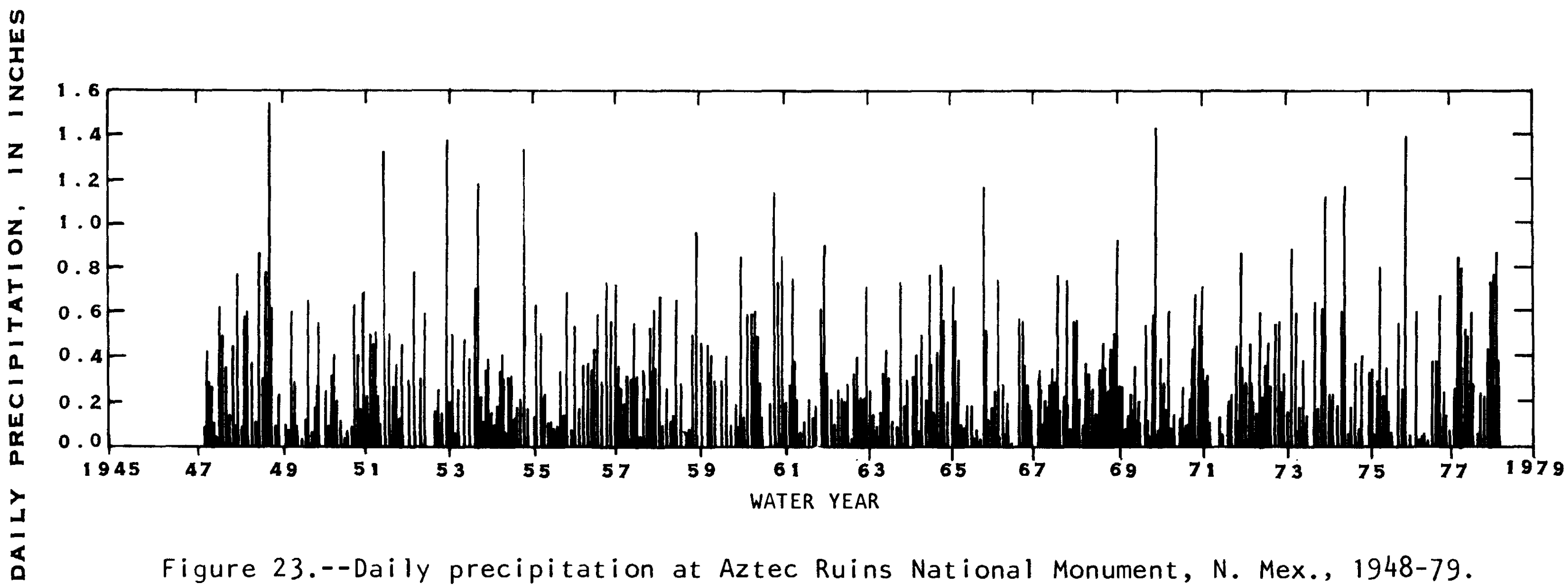


Figure 23.--Daily precipitation at Aztec Ruins National Monument, N. Mex., 1948-79.

Changes also are apparent in some daily plots for the San Juan River at Shiprock (fig. 22). These changes are not as distinct as at the upstream station (San Juan River near Archuleta, N. Mex.), but the same moderation of extreme values and disruption of the seasonal pattern in streamflow and specific conductance can be seen after 1963. These changes are believed to be caused by operation of Navajo Reservoir, though it is 83.6 river miles upstream. No distinct changes in patterns can be seen after 1963 for water temperature, suspended-sediment concentration, and suspended-sediment load. No changes or seasonal variation are apparent in the precipitation record for the nearby Aztec Ruins National Monument (fig. 23).

Comparison of Water-Quality and Streamflow Frequency Distributions

Variations in the shape of frequency distributions for pre- and post-1963 data exist because of differences in the characteristics of the data for those periods. In this case, the range of values measured for the pre-1963 period of record compared to the post-1963 period of record and the frequency (in percent) that each data value was observed (figs. 24-25) are shown in the frequency distribution. Frequency distributions are plotted for the actual numeric data values (raw data) and for their ranks (data values ordered from smallest to largest, and the value replaced by the order number). The distribution of ranks is particularly useful for streamflow data, sediment-concentration data, and sediment-load data. Unranked streamflow and sediment frequency distributions often are visually dominated by a few extreme values causing most of the observations to fall into a few bars of high frequency. Figure 25q is a good example. The majority of the observations are contained in one vertical bar of the frequency distribution. The frequency distribution of ranks overcomes this difficulty by spreading out data over a number of bars and allowing a good graphical comparison for detecting differences.

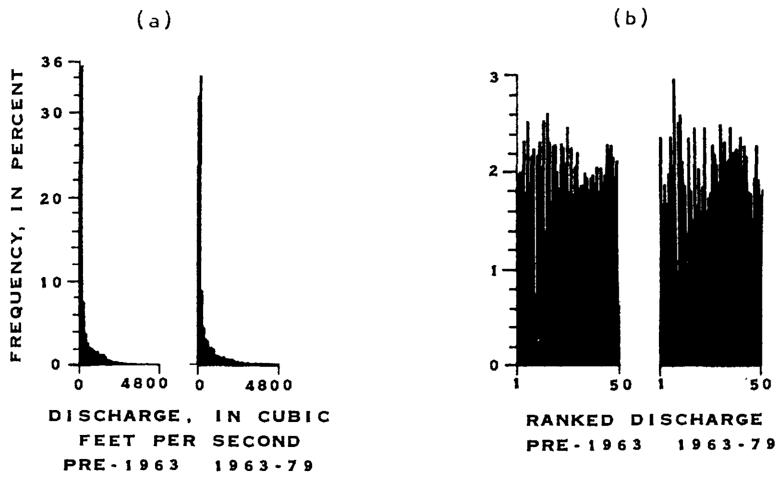
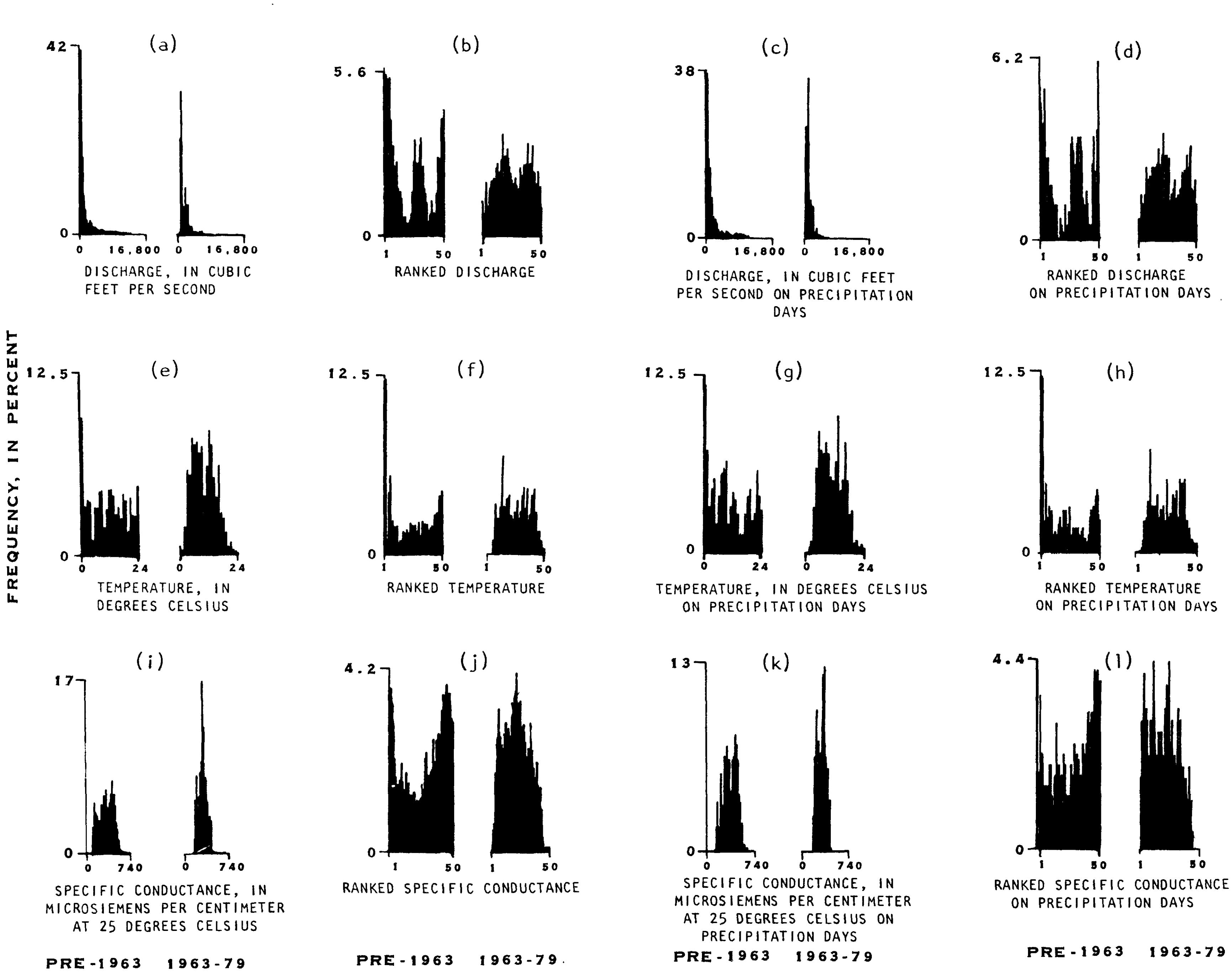


Figure 24.--Frequency distributions of daily and ranked-daily discharges from pre-1963 and 1963-79 water-year data for San Juan River at Pagosa Springs, Colo.


FREQUENCY, IN PERCENT
(a)
42
0
0
16,800
0
16,800
DISCHARGE, IN CUBIC FEET PER SECOND
(b)
5.6
0
1
50
1
50
RANKED DISCHARGE
(c)
38
0
0
16,800
0
16,800
DISCHARGE, IN CUBIC FEET PER SECOND ON PRECIPITATION DAYS
(d)
6.2
0
1
50
1
50
RANKED DISCHARGE ON PRECIPITATION DAYS
(e)
12.5
0
0
24
0
24
TEMPERATURE, IN DEGREES CELSIUS
(f)
12.5
0
1
50
1
50
RANKED TEMPERATURE
(g)
12.5
0
0
24
0
24
TEMPERATURE, IN DEGREES CELSIUS ON PRECIPITATION DAYS
(h)
12.5
0
1
50
1
50
RANKED TEMPERATURE ON PRECIPITATION DAYS
(i)
17
0
0
740
0
740
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS
PRE-1963 1963-79
(j)
4.2
0
1
50
1
50
RANKED SPECIFIC CONDUCTANCE
PRE-1963 1963-79
(k)
13
0
0
740
0
740
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS ON PRECIPITATION DAYS
PRE-1963 1963-79
(l)
4.4
0
1
50
1
50
RANKED SPECIFIC CONDUCTANCE ON PRECIPITATION DAYS
PRE-1963 1963-79

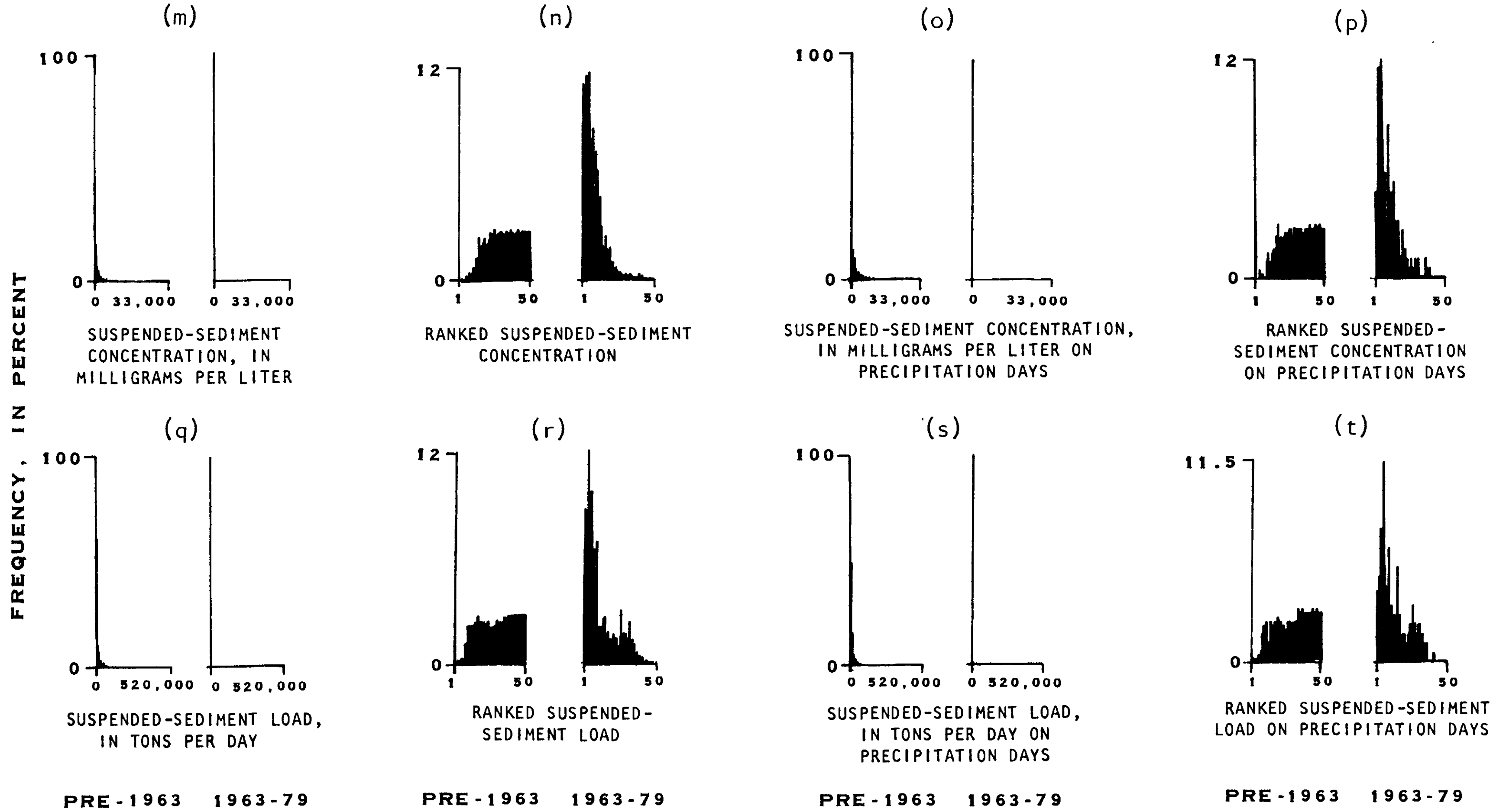


Figure 25.--Frequency distributions of daily and ranked-daily discharges and water quality for pre-1963 and 1963-79 water-year data for San Juan River near Archuleta, N. Mex.

Possible differences in the frequency distributions are: convex versus concave shapes (fig. 25j); bimodal versus trimodal shapes (fig. 25b); differences in the lengths of tails (fig. 25o); and differences in the height and width of the shapes (fig. 25i). The pre-1963 period contains the large and small extremes that are absent after 1963 (fig. 25i, j). In plot 25b, small, medium, and large discharge, characteristic of the pre-1963 period, is no longer characteristic after 1963. After 1963, the small and large extremes are absent and two discharges are characteristic, one larger than midrank discharges, and one smaller than midrank discharges. Even though both periods have predominantly small concentrations, those after 1963 are smaller than before (fig. 25o). Examining the distributions for San Juan River at Pagosa Springs, San Juan River near Archuleta, and San Juan River at Shiprock indicates that streamflow is unchanged after 1963 in the headwaters at the San Juan River at Pagosa Springs but that streamflow and other constituents are changed downstream of the Navajo Reservoir after 1963.

For the San Juan River near Archuleta, streamflow, temperature, specific conductance, suspended-sediment concentration, and suspended-sediment load all changed after 1963 (fig. 25a-t). These changes reflect the influence of Navajo Reservoir, which is 7.2 miles upstream from the measurement site. In general, the reservoir has: eliminated extreme small values, extreme large values, or both; decreased variability by lowering dispersion; and lowered the frequency-distribution mode.

For the San Juan River at Shiprock, streamflow, temperature, specific conductance, suspended-sediment concentration, and suspended-sediment load have all changed since 1963 (fig. 26a-t). These changes are very similar to changes for the San Juan River near Archuleta; therefore, changes after 1963 probably are due to the operation of Navajo Reservoir and not to the operation of coal mines.

If there is any significant amount of surface runoff from the coal mines, the coal-mine effects are easiest to detect on days when streamflow at Shiprock is affected by surface runoff. If precipitation occurred at the nearby Aztec Ruins National Monument station, it was judged that surface runoff from the coal-mined area could occur. Therefore, a new data set was created and tested for days when there was precipitation at the Aztec Ruins National Monument.

Some of the frequency distributions of ranks are different on precipitation days (fig. 26d, h, l, p, t) than on all days (fig. 26b, f, j, n, r). An examination of the ranked frequency distributions at Shiprock for suspended-sediment concentration and suspended-sediment load on precipitation days (fig. 26p, t) shows that the data are less frequently in the low-rank range and are more frequently in the five highest ranks after 1963. These changes may be due to some increase in sediment load from mining or from other changes in land use resulting from increased development around Farmington, N. Mex. Before 1963, the ranked daily specific conductance on precipitation days (fig. 26l) was variable. After 1963, the daily specific conductance on precipitation days ranged through the high and low ranks equally. This may be evidence that specific conductance is responding less to natural events such as precipitation and more to streamflow regulation by reservoirs, withdrawals and return flows by agriculture, and runoff and wastes from urban centers, mining, and manufacturing.

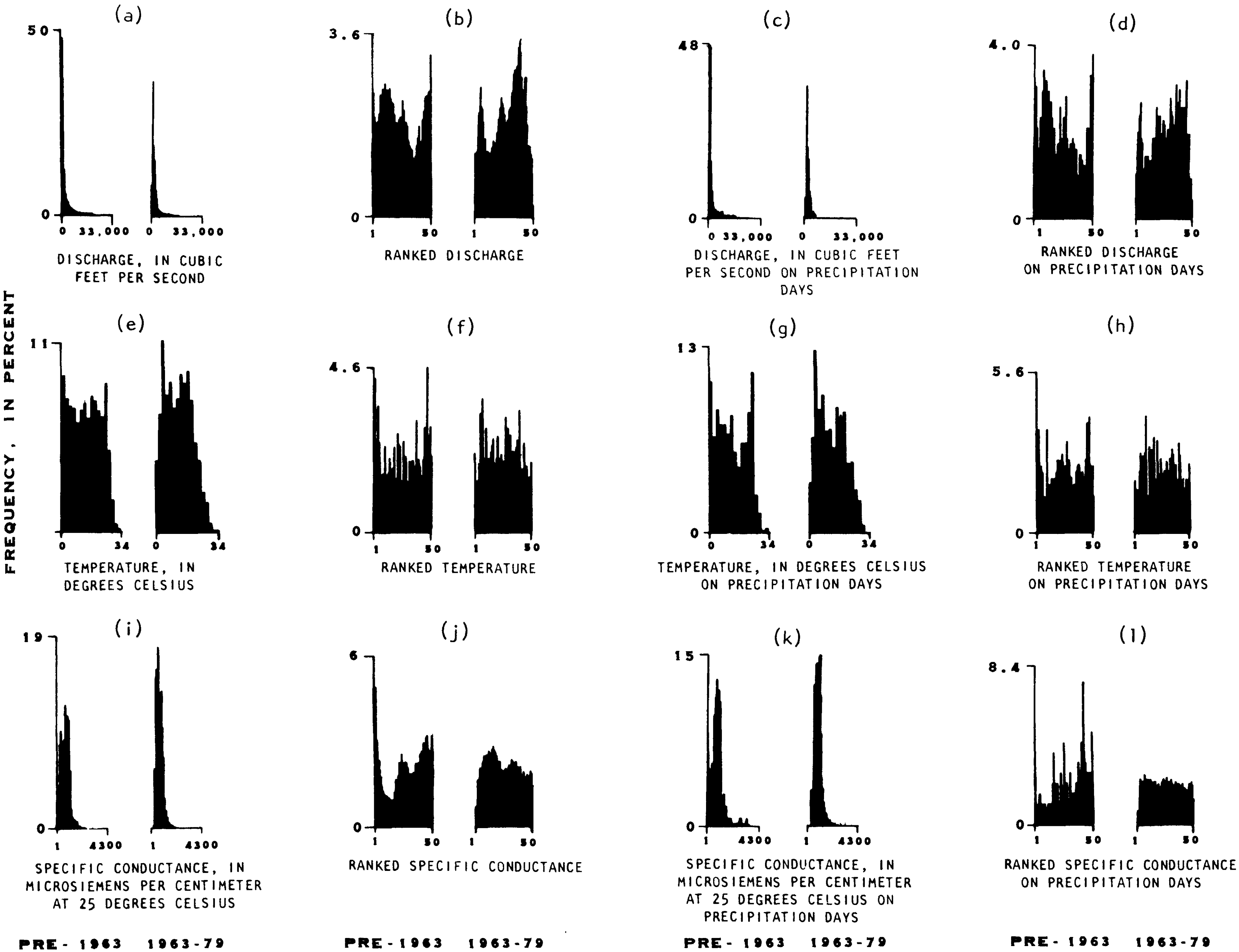
Frequency distributions on precipitation days at the upstream station, San Juan River near Archuleta (fig. 25d, h, l, p, t), do not show the same changes after 1963 as at the Shiprock station. The distributions generally are the same as on all days (fig. 25b, f, j, n, r) indicating that Navajo Reservoir has an overriding influence on surface runoff at this station. This implies that the changes at Shiprock are occurring between Archuleta and Shiprock, not upstream of Archuleta. Although changes in hydrologic data occurred after 1963, a direct relationship to coal mining is not indicated.

Comparison of Box-and-Whisker Plots

Another way of showing the distribution of water-quality and streamflow data is the box-and-whisker plot (Gerig, 1980). The box-and-whisker plot identifies the mean, median, the 25th percentile of the data, the 75th percentile of the data, adjacent values, and extreme values in the data set. The adjacent and extreme values are calculated as described by Tukey (1977, p. 39-48). Extreme values are subdivided into "outside" values and "far-out" values.

Box-and-whisker plots are shown side by side and at the same scale for comparison in figures 27-28. In order to obtain good resolution of the central values (25th through 75th percentiles), the base-10 logarithms of streamflow, suspended-sediment concentration, and suspended-sediment load were calculated and used for the vertical scale of the box-and-whisker plots. The main objective is to compare pre-1963 data with the post-1963 data.

Streamflow appears similar before and after 1963 for the San Juan River at Pagosa Springs (fig. 27). Extremes of discharge near Archuleta and at Shiprock decreased after 1963 (fig. 28a, b). The median discharge increased after 1963 near Archuleta. The mean for all days increased at Shiprock.


FREQUENCY, IN PERCENT
(a)
50
0
0 33,000 0 33,000
DISCHARGE, IN CUBIC FEET PER SECOND
(b)
3.6
0
1 50 1 50
RANKED DISCHARGE
(c)
48
0
0 33,000 0 33,000
DISCHARGE, IN CUBIC FEET PER SECOND ON PRECIPITATION DAYS
(d)
4.0
0
1 50 1 50
RANKED DISCHARGE ON PRECIPITATION DAYS
(e)
11
0 34 0 34
TEMPERATURE, IN DEGREES CELSIUS
(f)
4.6
0
1 50 1 50
RANKED TEMPERATURE
(g)
13
0
0 34 0 34
TEMPERATURE, IN DEGREES CELSIUS ON PRECIPITATION DAYS
(h)
5.6
0
1 50 1 50
RANKED TEMPERATURE ON PRECIPITATION DAYS
(i)
19
0
1 4300 1 4300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS
(j)
6
0
1 50 1 50
RANKED SPECIFIC CONDUCTANCE
(k)
15
0
1 4300 1 4300
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS ON PRECIPITATION DAYS
(l)
8.4
0
1 50 1 50
RANKED SPECIFIC CONDUCTANCE ON PRECIPITATION DAYS
PRE-1963 1963-79
PRE-1963 1963-79
PRE-1963 1963-79
PRE-1963 1963-79

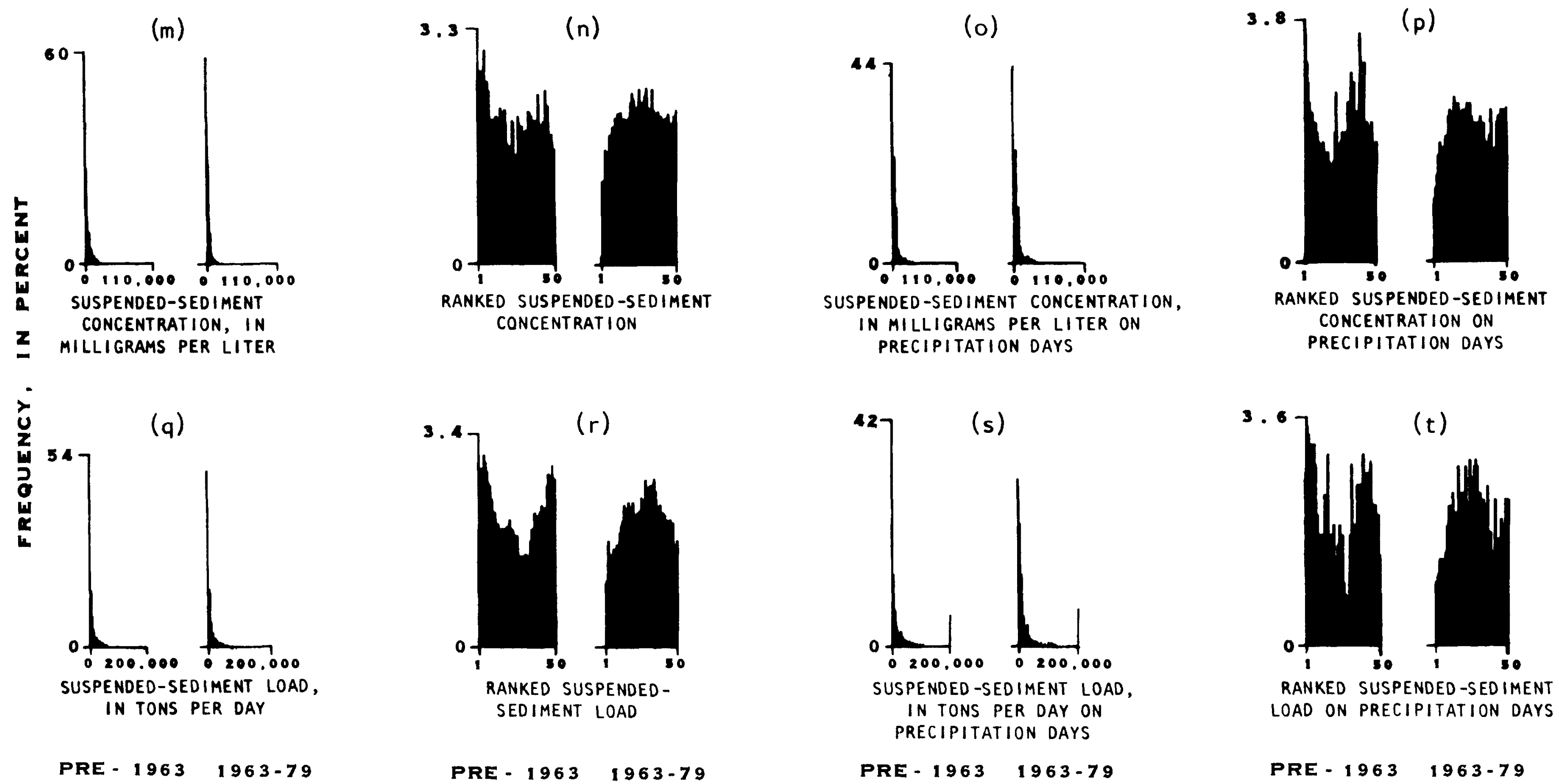


Figure 26.--Frequency distributions of daily and ranked-daily discharges and water quality from pre-1963 and 1963-79 water-year data for San Juan River at Shiprock, N. Mex.

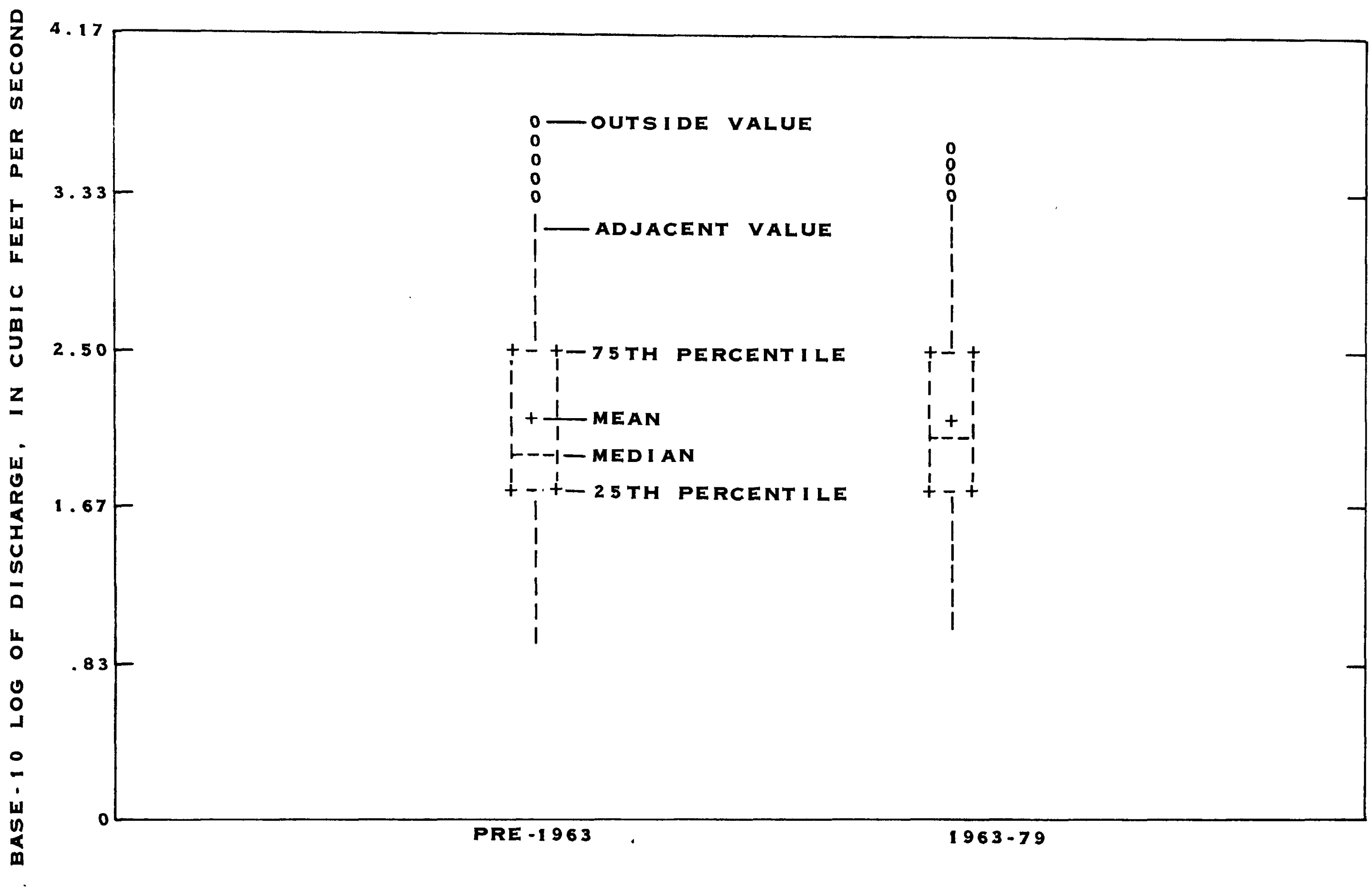
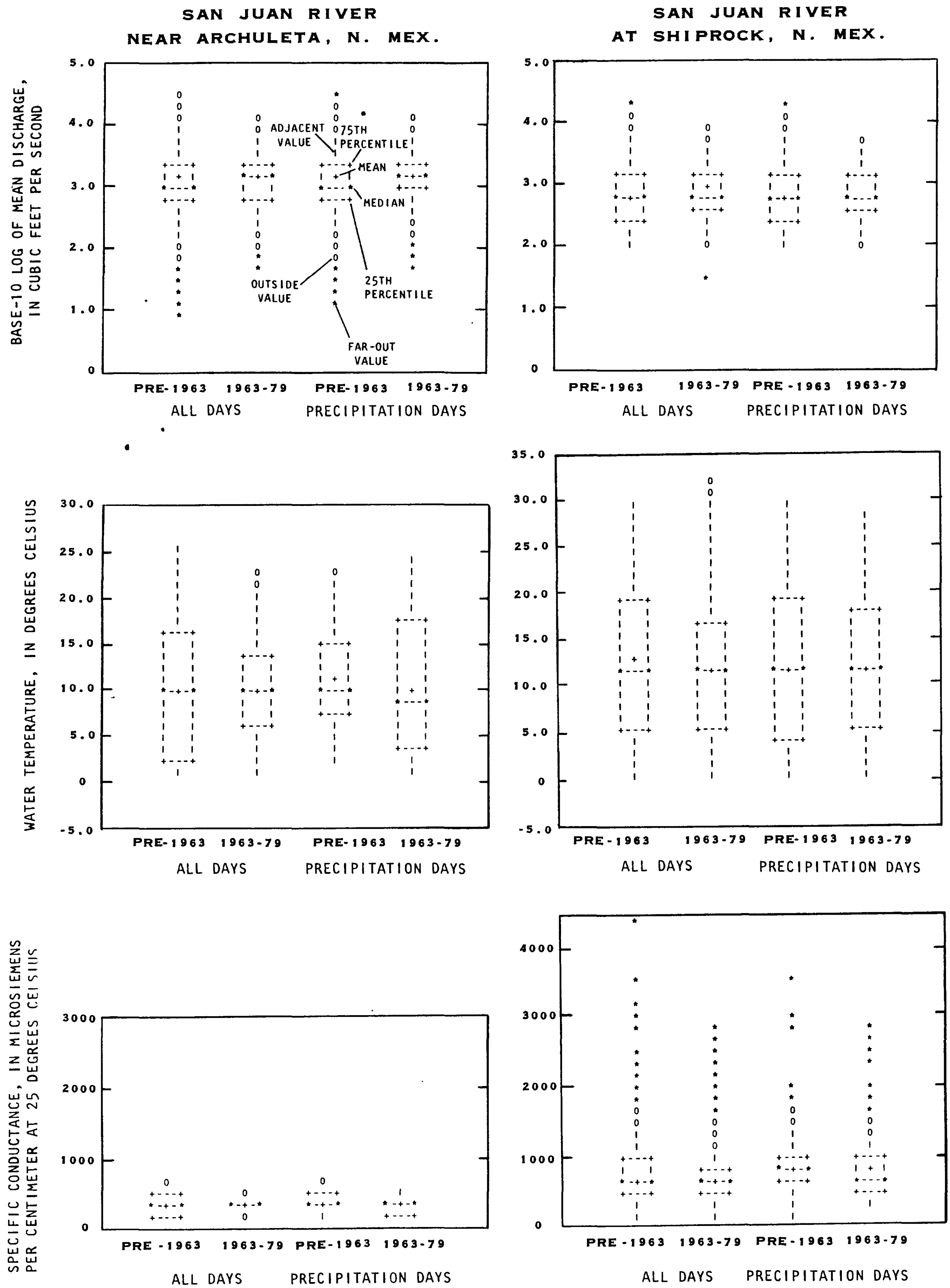


Figure 27.--Daily discharge at San Juan River at Pagosa Springs, Colo., for pre-1963 and 1963-79 water-year data.

At Shiprock and particularly near Archuleta, the box-and-whisker plots for specific conductance (fig. 28e, f), suspended-sediment concentration (fig. 28g, h), and suspended-sediment load (fig. 28i, j) generally are noticeably compressed and lower after 1963, compared to before 1963. The extreme values decrease as does the span of central values. These changes probably are caused by Navajo Reservoir.

Suspended-sediment concentration increased slightly during the post-1963 period on precipitation days at Shiprock (fig. 28h). Suspended-sediment-concentration central values increased by about 4,000 milligrams per liter although the position of the mean and median remained the same. Whether or not the increase is meaningful will be tested by statistical methods later. Specific-conductance central values and extreme values decreased.


SAN JUAN RIVER
NEAR ARCHULETA, N. MEX.
SAN JUAN RIVER
AT SHIPROCK, N. MEX.
BASE-10 LOG OF MEAN DISCHARGE, IN CUBIC FEET PER SECOND
5.0
4.0
3.0
2.0
1.0
0
ADJACENT VALUE
75TH PERCENTILE
MEAN
MEDIAN
OUTSIDE VALUE
25TH PERCENTILE
FAR-OUT VALUE
PRE-1963
1963-79
PRE-1963
1963-79
ALL DAYS
PRECIPITATION DAYS
WATER TEMPERATURE, IN DEGREES CELSIUS
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0
-5.0
SPECIFIC CONDUCTANCE, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS
4000
3000
2000
1000
0

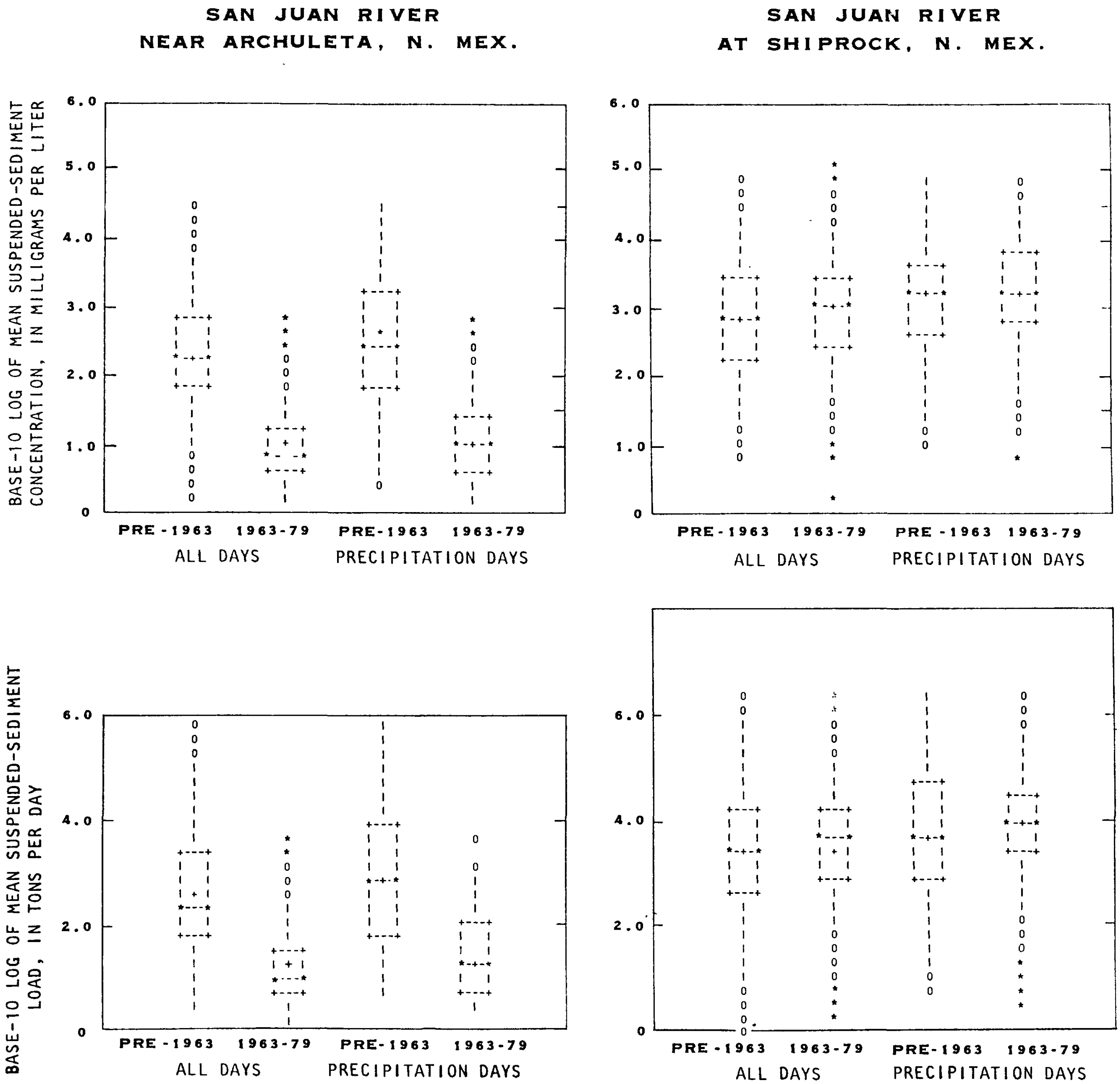


Figure 28.--Water quality and discharge for pre-1963 and 1963-79 water-year data at San Juan River near Archuleta, N. Mex., and San Juan River at Shiprock, N. Mex.

Results of Seasonal Kendall Test and Slope Estimator for Trend Magnitude

Analysis of water-quality data for monotonic trends (gradual changes) is complicated by non-normal distributions, seasonality, flow relatedness, missing values, and serial correlation. Daily streamflow and water-quality data were tested for normality by a modified version of the Kolmogorov-Smirnov D-statistic (Helwig and Council, 1979, p. 429). None of the data fit a normal distribution. Log transformations of the daily streamflow and water-quality data also did not fit a normal distribution. Seasonality is present in the data; there are missing values for some days (figs. 20-22).

The seasonal Kendall test and slope estimator for trend magnitude is a technique that deals effectively with the first four complications listed above (Hirsch and others, 1981). The serial correlation in daily water-quality and streamflow data was overcome by calculating and then testing the monthly median of the daily values. No adjustment for discharge relatedness was made in this application of the seasonal Kendall test.

The seasonal Kendall test and slope estimator for trend magnitude was applied to monthly water-quality data; monthly medians of daily streamflow and water-quality data; and monthly medians of daily streamflow and water-quality data on days when there was precipitation at the Aztec Ruins National Monument (referred to as precipitation days). The test was applied to data collected at the San Juan River near Archuleta station and the San Juan River at Shiprock station. The data were tested for the time prior to 1963 and 1963-79. Upstream trends were compared with downstream trends to separate the reservoir effects. Results are shown in table 6.

For the San Juan River near Archuleta prior to 1963 (table 6), there are decreasing trends in concentrations of dissolved solids and dissolved magnesium and increasing trends in concentrations of dissolved nitrate and in monthly medians of daily water temperature. In addition, there is a decreasing trend in monthly medians of daily suspended-sediment concentration on precipitation days prior to 1963. In comparison, for 1963-79, there are decreasing trends in concentrations of dissolved solids, dissolved sodium, and dissolved silica, and increasing trends in concentrations of dissolved magnesium and dissolved sulfate. In the monthly medians of daily data for 1963-79, there are increasing trends in discharge, suspended-sediment load, discharge on precipitation days, and suspended-sediment load on precipitation days, whereas there are decreasing trends in water temperature, specific conductance, and water temperature on precipitation days.

For the San Juan River at Shiprock, there are no trends in the monthly water-quality constituents prior to 1963 (table 6). There is a decreasing trend of 10 cubic feet per second per year in the monthly medians of daily discharge and an increasing trend of 0.14 degree Celsius per year in the monthly medians of daily water temperature on precipitation days. For 1963-79, specific conductance, and concentrations of dissolved solids, dissolved calcium, dissolved sodium, dissolved chloride, dissolved sulfate, dissolved silica, and dissolved-orthophosphate phosphorus have decreasing trends. In the monthly medians of daily data, there are decreasing trends in water temperature and specific conductance for both precipitation days and all days.

Table 6. Results of seasonal Kendall test and slope estimator for trend magnitude of water quality and streamflow for selected stations on the San Juan River

[ft^3/s, cubic feet per second; °C, degrees Celsius; mg/L, milligrams per liter]

Station name and number	Parameter tested	Data file	Pre-1963 water years: Number of observations	Pre-1963 water years: Seasonal Kendall test result	1963-79 water years: Number of observations	1963-79 water years: Seasonal Kendall test result
San Juan River at Pagosa Springs, Colo. 09342500	Streamflow	WATSTORE daily values	9,862	Trend of -0.9 ft^3/s per year	6,209	No trend
San Juan River near Archuleta, N. Mex. 09355500	Streamflow	WATSTORE daily values	2,861	No trend	6,209	Trend of +14 ft^3/s per year
	Water temperature		2,823	Trend of +0.2°C per year	2,283	Trend of -0.4°C per year
	Specific conductance		2,811	No trend	2,195	Trend of -14 microsiemens per year
	Suspended-sediment concentration		2,854	No trend	1,084	No trend
	Suspended-sediment load		2,860	No trend	1,096	Trend of +19 tons per day per year
	Streamflow on precipitation days	WATSTORE daily values and NOAA climatic records	430	No trend	956	Trend of +11 ft^3/s per year
	Water temperature on precipitation days		419	No trend	388	Trend of -0.4°C per year

Table 6. Results of seasonal Kendall test and slope estimator for trend magnitude of water quality and streamflow for selected stations on the San Juan River - Continued

Station name and number	Parameter tested	Data file	Pre-1963 water years: Number of observations	Pre-1963 water years: Seasonal Kendall test result	1963-79 water years: Number of observations	1963-79 water years: Seasonal Kendall test result
San Juan River near Archuleta, N. Mex. 09355500	Specific conductance on precipitation days	WATSTORE daily values and NOAA climatic records	420	No trend	373	No trend
	Suspended-sediment concentration on precipitation days		430	Trend of -31 mg/L per year	184	No trend
	Suspended-sediment load on precipitation days		430	No trend	184	Trend of +10 tons per day per year
	Specific conductance	WATSTORE water quality	282	No trend	287	No trend
	Dissolved solids		254	Trend of -2.4 mg/L per year	229	Trend of -2.0 mg/L per year
	Dissolved calcium		257	No trend	243	No trend
	Dissolved magnesium		255	Trend of -.24 mg/L per year	243	Trend of +.05 mg/L per year
	Dissolved sodium		254	No trend	231	Trend of -.23 mg/L per year
	Dissolved potassium		35	No trend	130	No trend
	Dissolved chloride		35	No trend	146	No trend
	Dissolved sulfate		35	No trend	143	Trend of +.6 mg/L per year

Table 6. Results of seasonal Kendall test and slope estimator for trend magnitude of water quality and streamflow for selected stations on the San Juan River - Continued

Station name and number	Parameter tested	Data file	Pre-1963 water years: Number of observations	Pre-1963 water years: Seasonal Kendall test result	1963-79 water years: Number of observations	1963-79 water years: Seasonal Kendall test result
San Juan River near Archuleta, N. Mex. 09355500	Dissolved fluoride	WATSTORE water quality	35	No trend	143	No trend
	Dissolved silica		35	No trend	143	Trend of -.29 mg/L per year
	Total nitrogen		0	-	73	No trend
	Dissolved nitrate nitrogen		23	Trend of +.17 mg/L per year	60	No trend
	Total phosphorus		0	-	88	No trend
	Dissolved-orthophosphate phosphorus		0	-	88	No trend
	Total organic carbon		0	-	36	No trend
	Dissolved cadmium		0	-	35	No trend
	Dissolved iron		31	No trend	131	No trend
	Dissolved manganese		1	-	24	No trend
San Juan River at Shiprock, N. Mex. 09368000	Streamflow	WATSTORE daily values	10,227	Trend of -10 ft^3/s per year	6,209	No trend
	Water temperature		3,641	No trend	6,059	Trend of -.13°C per year
	Specific conductance		3,103	No trend	6,127	Trend of -8.8 microsiemens per year
	Suspended-sediment concentration		4,270	No trend	6,209	No trend
	Suspended-sediment load		4,273	No trend	6,209	No trend

Table 6. **Results of seasonal Kendall test and slope estimator for trend magnitude of water quality and streamflow for selected stations on the San Juan River - Continued**

Station name and number	Parameter tested	Data file	Pre-1963 water years: Number of observations	Pre-1963 water years: Seasonal Kendall test result	1963-79 water years: Number of observations	1963-79 water years: Seasonal Kendall test result
San Juan River at Shiprock, N. Mex. 09368000	Streamflow on precipitation days	WATSTORE daily values and NOAA climatic records	810	No trend	956	No trend
	Water temperature on precipitation days		475	Trend of +.14°C per year	931	Trend of -.12°C per year
	Specific conductance on precipitation days		190	No trend	947	Trend of -9.0 microsiemens per year
	Suspended-sediment concentration on precipitation days		626	No trend	956	No trend
	Suspended-sediment load on precipitation days		629	No trend	956	No trend
	Specific conductance	WATSTORE water quality	178	No trend	825	Trend of -9.4 microsiemens per year
	Dissolved solids		173	No trend	377	Trend of -6.1 mg/L per year
	Dissolved calcium		185	No trend	776	Trend of -1.0 mg/L per year
	Dissolved magnesium		184	No trend	776	No trend
	Dissolved sodium		184	No trend	620	Trend of -1.1 mg/L per year

Table 6. Results of seasonal Kendall test and slope estimator for trend magnitude of water quality and streamflow for selected stations on the San Juan River - Concluded

Station name and number	Parameter tested	Data file	Pre-1963 water years: Number of observations	Pre-1963 water years: Seasonal Kendall test result	1963-79 water years: Number of observations	1963-79 water years: Seasonal Kendall test result
San Juan River at Shiprock, N. Mex. 09368000	Dissolved potassium	WATSTORE water quality	7	No trend	387	No trend
	Dissolved chloride		177	No trend	773	Trend of -.17 mg/L per year
	Dissolved sulfate		177	No trend	772	Trend of -3.3 mg/L per year
	Dissolved fluoride		4	No trend	601	No trend
	Dissolved silica		183	No trend	771	Trend of -.20 mg/L per year
	Total nitrogen		0	-	94	No trend
	Dissolved nitrate nitrogen		7	No trend	127	No trend
	Total phosphorus		0	-	96	No trend
	Dissolved-ortho-phosphate phosphorus		0	-	154	Trend of -.00000001 mg/L per year
	Total organic carbon		0	-	54	No trend
	Dissolved cadmium		0	-	26	No trend
	Dissolved iron		4	No trend	175	No trend
	Dissolved lead		0	-	26	No trend
	Dissolved manganese		4	No trend	26	No trend

Several implications can be drawn from the trends: (1) Monotonic water-quality trends did not occur at the San Juan River at Shiprock station until after 1963; (2) streamflow at Shiprock decreased in the pre-1963 period, perhaps due to increased water use in the drainage basin; (3) prior to 1963, decreasing trends were found in sediment concentration and in concentrations of some constituents on precipitation days in the upper drainage basin (San Juan River near Archuleta station), perhaps due to less farming, to improved farm management, or to a decrease in ground-water base flow to streams; (4) decreasing trends in concentrations of some constituents are prominent after 1963 at both the Shiprock and Archuleta stations, although at Archuleta there are also some increasing trends; and (5) some post-1963 decreases at Archuleta correspond to the Shiprock decreases and may reflect changes due to reservoir operation. More decreasing trends occur at Shiprock than at Archuleta and no increasing trends occur at Shiprock, which indicates that changes are taking place in the basin between Archuleta and Shiprock.

Results of Wilcoxon Rank-Sum Test and SEASRS Procedure

Although the seasonal Kendall test is effective at detecting gradual monotonic trends, the test cannot detect abrupt step changes. Two additional tests were applied to the data to determine if a step change occurred in 1963. Both of these procedures assume that the data come from two populations, each of which has a constant mean. If there is a trend, either prior to 1963 or after 1963 (table 6), then it is not correct to apply either of these procedures.

The Wilcoxon rank-sum test (Helwig and Council, 1979) and the SEASRS procedure, a seasonally adjusted version of the Wilcoxon rank-sum test (Crawford and others, 1983), were applied to pre- and post-1963 precipitation (tables 7 and 8), streamflow, and water-quality data (tables 9 and 10). The Wilcoxon rank-sum test and the SEASRS procedure are nonparametric procedures that are effective in detecting differences in central values between two groups of data without assuming a normal distribution. No assumptions about how the data are spread around their location estimate are required. The SEASRS procedure computes a monthly median and then tests for a step increase or decrease, before versus after 1963, by individually comparing all Januarys, all Februarys, etc. The results by month are then combined into one yearly statistic that was evaluated at the 5-percent significance level. Both procedures fail to accurately detect differences for certain shaped distributions with unequal variances. If the only difference between periods is the lowering of dispersion, that is, if the extreme values at both ends are eliminated from one distribution and kept in another, the Wilcoxon rank-sum has little power to detect this difference (Lehmann, 1975, p. 32). This case was encountered in the hydrologic data of this report. (See figure 25j.)

Precipitation records were examined to answer the question, "Is there a significant change in pre-1963 versus post-1963 precipitation that would affect streamflow?" Daily precipitation data could not be tested directly because of their serial correlation. Instead, the total precipitation for each year of record was calculated and the annual mean prior to 1963 was tested against the annual mean after 1963. Monthly precipitation was used as input data to the SEASRS procedure.

The precipitation means for the pre- and post-1963 periods and results of hypothesis testing using the Wilcoxon rank-sum test and SEASRS procedure are shown in tables 7 and 8. In general, results show that pre-1963 precipitation is equal to post-1963 precipitation. Therefore, precipitation has not contributed to any changes in streamflow.

Streamflow and water-quality data from stations at Shiprock and near Archuleta were tested by the SEASRS procedure for days when there was precipitation at the nearby Aztec Ruins National Monument (table 9). Only those water-quality and streamflow data that did not have a trend detected by the seasonal Kendall test (table 6) were tested. A step decrease in specific conductance of 75 microsiemens occurred at the station near Archuleta. A step increase in streamflow of 188 cubic feet per second occurred at Shiprock. No change in sediment concentration or sediment load occurred.

Results of the SEASRS procedure applied to water-quality and streamflow data taken on all days are shown in table 10. Again, only those data that did not have a trend detected by the seasonal Kendall test (table 6) were tested. Suspended-sediment concentration had a step decrease of 142 milligrams per liter at Archuleta. Step decreases in concentrations of dissolved calcium, dissolved chloride, dissolved potassium, and dissolved fluoride occurred at the station near Archuleta. A step increase in suspended-sediment load of 601 tons per day at Shiprock was detected. No differences were detected in concentrations of dissolved magnesium, potassium, or fluoride.

Significant differences were detected at Archuleta that can be compared to Shiprock. These differences included a decrease in suspended-sediment concentration, decrease in dissolved-potassium concentration, and decrease in dissolved-fluoride concentration at Archuleta. All of these decreases were compensated for at the downstream Shiprock station because corresponding significant decreases were not detected there. The compensation in these parameters implies that coal-mining effects or other influences, such as urbanization, return flow from irrigated agriculture, or resuspension of suspended sediment in the water column were active between the two stations.

Table 7. Annual precipitation, in inches, prior to and after the beginning of the 1963 water year and results of hypothesis testing to determine if the two populations are significantly different

[Data from National Oceanic and Atmospheric Administration]

Station name	Parameter tested	Pre-1963 water years		1963-79 water years		Wilcoxon result (5-percent level of significance)
		Mean	Number of observations	Mean	Number of observations	
Star Lake, N. Mex.	Annual precipitation in inches	6.10	14	7.87	17	Samples are from the same population
Chaco Canyon National Monument, N. Mex.	Annual precipitation in inches	7.55	15	7.99	17	Samples are from the same population
Aztec Ruins National Monument, N. Mex.	Annual precipitation in inches	8.78	15	8.97	17	Samples are from the same population
Silverton, Colo.	Annual precipitation in inches	21.35	26	21.17	17	Samples are from the same population
Durango, Colo.	Annual precipitation in inches	18.34	26	18.36	17	Samples are from the same population
Pagosa Springs, Colo.	Annual precipitation in inches	17.90	23	18.49	17	Samples are from the same population

Table 8. **Monthly precipitation prior to and after the beginning of the 1963 water year and results of hypothesis testing to determine if the two populations are equal**

[Data from National Oceanic and Atmospheric Administration]

Station name	Parameter tested	Number of observations prior to beginning of 1963 water year	Number of observations during the water years 1963-79	SEASRS procedure result (5-percent level of significance)	Difference detected for pre-1963 period compared to 1963-79 period
Star Lake, N. Mex.	Monthly precipitation in inches	139	192	Locations of medians are equal	None
Chaco Canyon National Monument, N. Mex.	Monthly precipitation in inches	177	190	Locations of medians are equal	None
Aztec Ruins National Monument, N. Mex.	Monthly precipitation in inches	177	195	Locations of medians are equal	None
Silverton, Colo.	Monthly precipitation in inches	312	185	Locations of medians are equal	None
Durango, Colo.	Monthly precipitation in inches	315	206	Locations of medians are equal	None
Pagosa Springs, Colo.	Monthly precipitation in inches	278	204	Locations of medians are equal	None

Table 9. Median monthly streamflow and water quality on days when there was precipitation at Aztec Ruins National Monument prior to and after the beginning of the 1963 water year, and results of hypothesis testing using the SEASRS procedure to determine if the population medians are significantly different

Station name and number	Data file	Parameter tested	Number of observations for the pre-1963 water years	Number of observations for the 1963-79 water years	SEASRS procedure result (5-percent level of significance)	Difference detected for pre-1963 period compared to 1963-79 period
San Juan River near Archuleta, N. Mex. 09355500	WATSTORE daily values and NOAA climatic records	Streamflow on precipitation days	Could not be tested due to trend.			
		Water temperature on precipitation days	Could not be tested due to trend.			
		Specific conductance on precipitation days	420	373	Locations of medians are unequal	-75.25 microsiemens
		Suspended-sediment concentration on precipitation days	Could not be tested due to trend.			
		Suspended-sediment load on precipitation days	Could not be tested due to trend.			
San Juan River at Shiprock, N. Mex. 09368000	WATSTORE daily values and NOAA climatic records	Streamflow on precipitation days	810	956	Locations of medians are unequal	+188 cubic feet per second
		Water temperature on precipitation days	Could not be tested due to trend.			
		Specific conductance on precipitation days	Could not be tested due to trend.			
		Suspended-sediment concentration on precipitation days	626	956	Locations of medians are equal	
		Suspended-sediment load on precipitation days	629	956	Locations of medians are equal	

Table 10. Median monthly streamflow and water quality prior to and after the beginning of the 1963 water year, and results of hypothesis testing using the SEASRS procedure to determine if the two populations are significantly different

Station name and number	Data file	Parameter tested	Number of observations for the pre-1963 water years	Number of observations for the 1963-79 water years	SEASRS procedure result (5 percent level of significance)	Difference detected for pre-1963 period compared to 1963-79 period
San Juan River at Pagosa Springs, Colo. 09342500	WATSTORE daily values	Streamflow	Could not be tested due to trend.			
San Juan River near Archuleta, N. Mex. 09355500	WATSTORE daily values	Streamflow	Could not be tested due to trend.			
		Water temperature	Could not be tested due to trend.			
		Specific conductance	Could not be tested due to trend.			
		Suspended-sediment concentration	2,854	1,084	Locations of medians are unequal	-142 milligrams per liter
		Suspended-sediment load	Could not be tested due to trend.			
San Juan River at Shiprock, N. Mex. 09368000	WATSTORE daily values	Streamflow	Could not be tested due to trend.			
		Water temperature	Could not be tested due to trend.			
		Specific conductance	Could not be tested due to trend.			
		Suspended-sediment concentration	4,270	6,209	Locations of medians are equal	
		Suspended-sediment load	4,273	6,209	Locations of medians are unequal	+601 tons per day
San Juan River near Archuleta, N. Mex. 09355500	WATSTORE water quality	Dissolved sulfate	Could not be tested due to trend.			
		Dissolved calcium	257	243	Locations of medians are unequal	-8 milligrams per liter
		Dissolved silica	Could not be tested due to trend.			

Table 10. Median monthly streamflow and water quality prior to and after the beginning of the 1963 water year, and results of hypothesis testing using the SEASRS procedure to determine if the two populations are significantly different - Concluded

Station name and number	Data file	Parameter tested	Number of observations for the pre-1963 water years	Number of observations for the 1963-79 water years	SEASRS procedure result (5 percent level of significance)	Difference detected for pre-1963 period compared to 1963-79 period
San Juan River near Archuleta, N. Mex. 09355500	WATSTORE water quality	Dissolved chloride	35	146	Locations of medians are unequal	-2.7 milligrams per liter
		Dissolved magnesium	Could not be tested due to trend.			
		Dissolved potassium	35	130	Locations of medians are unequal	-1.0 milligram per liter
		Dissolved sodium	Could not be tested due to trend.			
		Dissolved fluoride	35	143	Locations of medians are unequal	-0.1 milligram per liter
		Dissolved solids	Could not be tested due to trend.			
		Specific conductance	282	287	Locations of medians are unequal	-76 microsiemens
San Juan River at Shiprock, N. Mex. 09368000	WATSTORE water quality	Dissolved sulfate	Could not be tested due to trend.			
		Dissolved calcium	Could not be tested due to trend.			
		Dissolved silica	Could not be tested due to trend.			
		Dissolved chloride	Could not be tested due to trend.			
		Dissolved magnesium	184	776	Locations of medians are equal	None
		Dissolved potassium	7	387	Locations of medians are equal	None
		Dissolved sodium	Could not be tested due to trend.			
		Dissolved fluoride	4	601	Locations of medians are equal	None
		Dissolved solids	Could not be tested due to trend.			

Analysis of Flow-Adjusted Specific Conductance

Specific conductance is often used to measure general water quality. Measured specific conductance was used as a means to detect changes in water quality over time.

Because power-plant and coal-mining activities are restricted to areas draining into the reach of the San Juan River between Shiprock and Farmington, the effects of those activities on water quality could appear as differences in specific conductance at Shiprock and Farmington. Changes over time could be related to changes caused by power-plant and coal-mining activities, agriculture, urbanization, and other natural and cultural activities.

Shortly after impoundment commenced at the Navajo Reservoir (June 1962), power-plant and coal-mining activities began (March 1963). Daily measurements of specific conductance on the San Juan River at Farmington were made from October 1962 to December 1979. Daily specific-conductance measurements were made from October 1957 to the present at Shiprock. Therefore, the period of record for this analysis is from October 1962 to December 1979.

Hypothesis Testing

One proposed hypothesis is that power-plant and coal-mining activities have changed the quality of water (increasing or decreasing specific conductance) at Shiprock from October 1962 to December 1979. During this period, coal-mining activities were increasing. One conclusion might be that power-plant and coal-mining activities did have a causal effect on water quality and an increase in these activities would have a corresponding effect on water quality at Shiprock with time. An evaluation to assess the possibility of a time trend for specific conductance was made using formal, nonparametric, statistical methods as well as graphical displays based on data-smoothing techniques.

Variations in specific conductance are very closely related to variations in discharge. In order to remove the influence of discharge on the analysis, flow-adjusted specific conductance was used instead of measured specific conductance.

The relationship between specific conductance and discharge can be approximated by the following equation:

$$SC(est) = b0 + (b1) f(Q) \qquad (1)$$

where SC(est) is the estimated specific conductance;
Q is discharge;
b0 and b1 are the fitted intercept and slope, respectively; and
f(Q) is some function of discharge.

Smith, Hirsch, and Slack (1982) used relationships of this form to obtain flow-adjusted concentrations of individual constituents.

A graphical examination of the relationships between measured specific conductance and various functions of discharge at Farmington and Shiprock showed that the inverse power transformation of discharge:

$$f(Q) = Q^{-3/8} \qquad (2)$$

was approximately linearly related to measured specific conductance (SC). The methods given by Mosteller and Tukey (1977, p. 79-115) were used to find this transformation of discharge. The relationship between specific conductance and the chosen transformation, f(Q), is shown for Farmington in figure 29 and for Shiprock in figure 30.

Linear regression was then used on the time series of measured specific conductance and discharge to obtain estimates of the slope and intercept (b1 and b0) for each station. By using the computed regression coefficients, time series of flow-adjusted specific conductance were computed for the Farmington and Shiprock stations:

$$FASCF = SC - SC(est) \quad \text{for Farmington} \qquad (3a)$$
$$FASCS = SC - SC(est) \quad \text{for Shiprock} \qquad (3b)$$

These resultant time series of flow-adjusted specific conductance represent deviations of actual specific-conductance measurements from the expected specific conductance based on discharge.

The difference of the flow-adjusted specific conductances between Shiprock and Farmington is:

$$DASC = FASCS - FASCF \qquad (4)$$

The DASC time series was computed only for days on which specific conductance and discharge were measured at both stations. The measure provided by the DASC time series ought to be independent of major effects on specific conductance upstream of Farmington. Therefore, the DASC series ought to be insensitive to effects on specific conductance introduced by such sources as Navajo Reservoir.

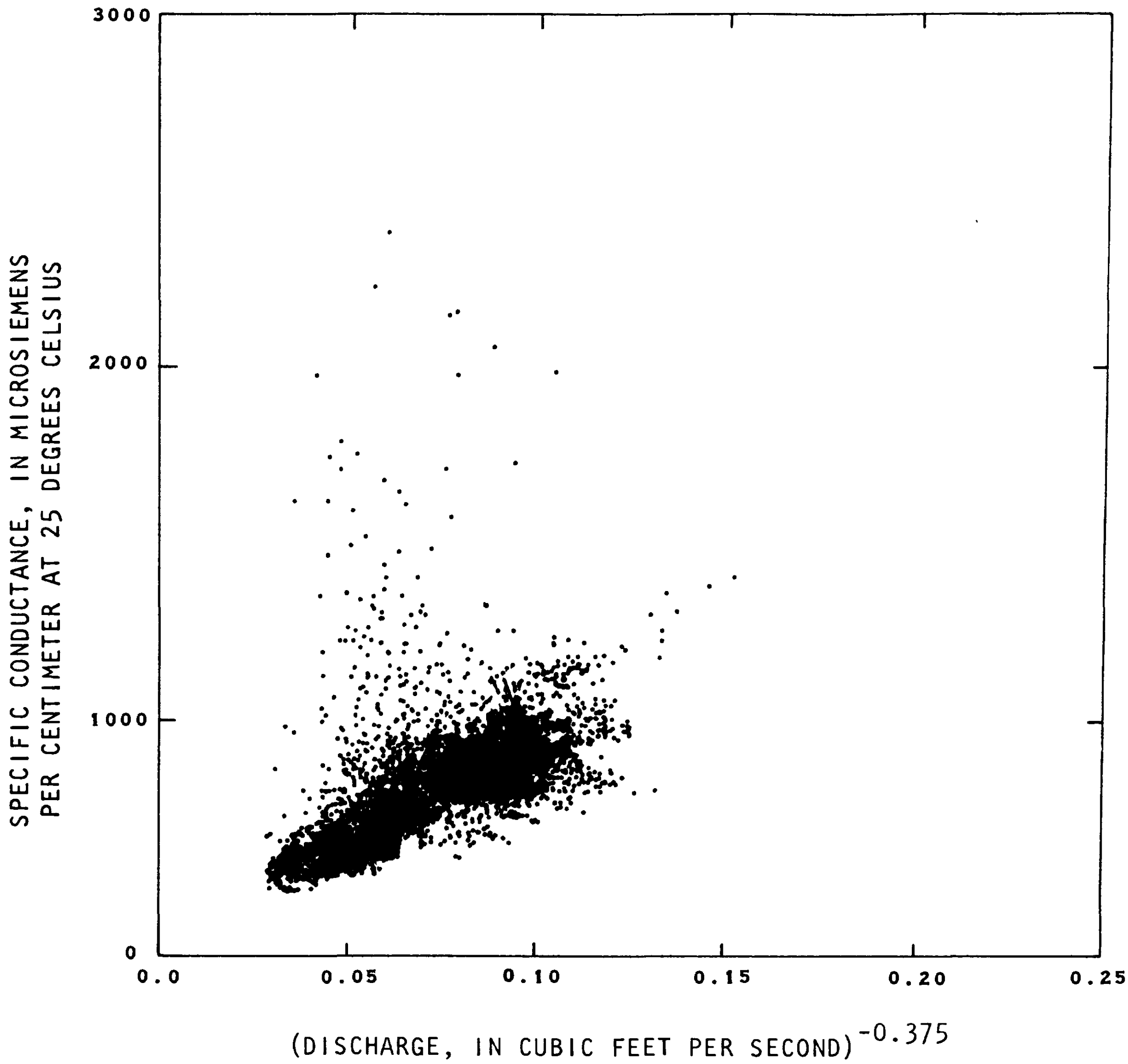


Figure 29.--Relationship between specific conductance and discharge$^{-0.375}$, San Juan River at Farmington, N. Mex.

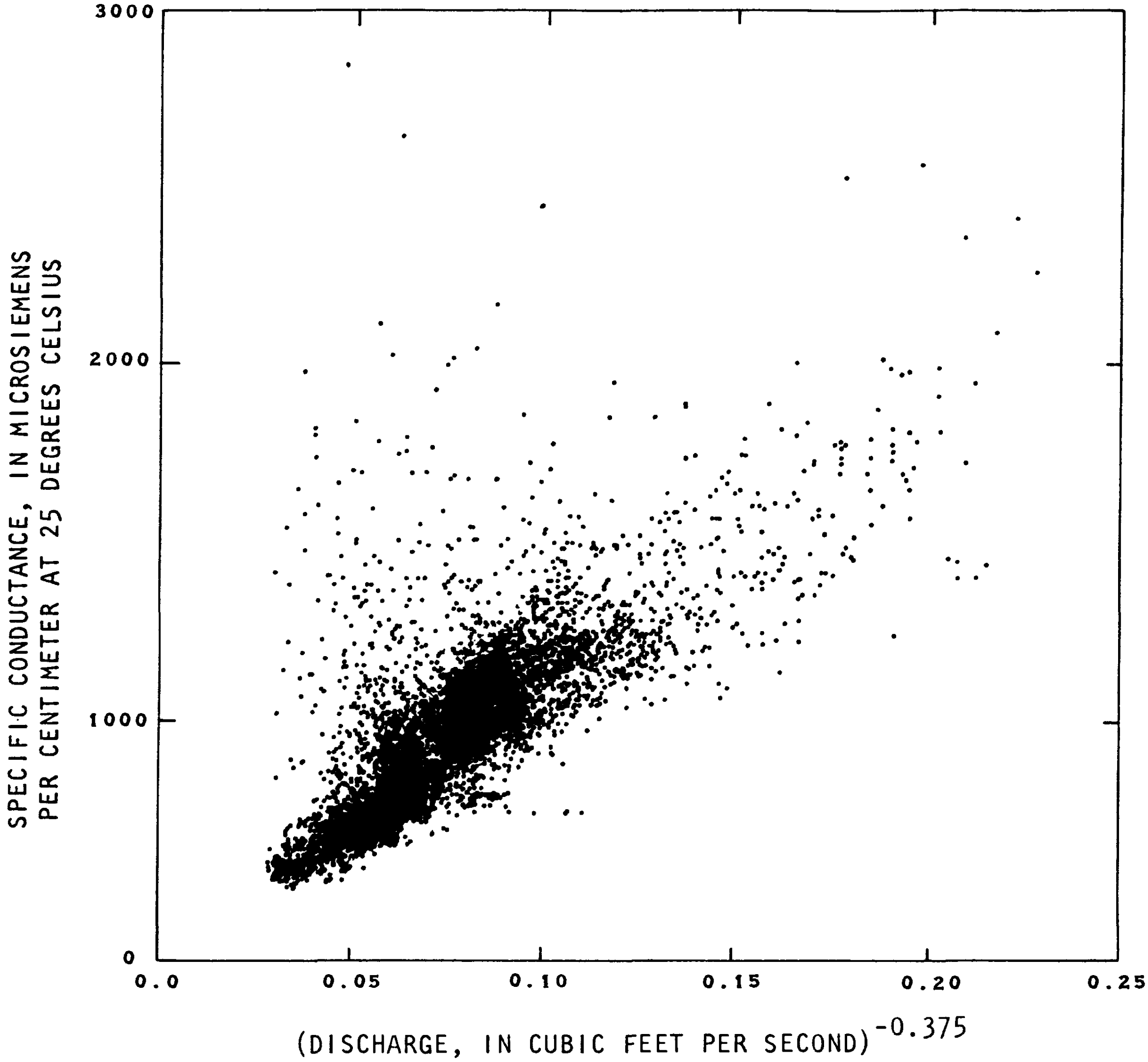


Figure 30.--Relationship between specific conductance and discharge$^{-0.375}$, San Juan River at Shiprock, N. Mex.

Unfortunately, the DASC time series is sensitive to aberrations related to sampling. Also, the DASC series would likely have serial correlation apart from that related to seasonality. Therefore, the DASC time series would not be appropriate to use as a basis for formal statistical testing.

The time series consisting of the median of each month's sequence of DASC's, denoted MDASC, was then constructed where:

$$MDASC(i) = \text{median}\ [DASC(i,j)] \qquad (5)$$

where i = month index (October 1962 = month 1, December 1979 = month 207); and
j = day index (j = 1,...., number of days in the ith month that both specific conductance and discharge were measured at Shiprock and Farmington).

Because of the averaging effect, this time series has much less variability than the daily series DASC. In addition, this time series probably would not have a serial-correlation component separate and distinct from that due to the presence of seasonality. The median was chosen as an estimator of location instead of the mean because of the median's resistance (lack of sensitivity) to extreme values.

The time series MDASC was formally tested for a monotonic trend over time. The hypothesis of randomness was tested against the alternative of either an increasing or decreasing trend in time (two-tailed test). First Mann's nonparametric test for trend was applied (Kendall, 1975). This test yielded a P value (probability value) of less than 0.0001 (table 11). For testing purposes, P values less than 0.05 were deemed significant. This significant P value along with the negative sign of the test statistic translated to a significant decreasing trend in time. Because the MDASC time series appeared to have a seasonal component, a related nonparametric test that was designed to be powerful in situations involving seasonality also was used (Hirsch and others, 1981). This test, denoted the "seasonal Kendall" test for trend, has as its basis a statistic that is composed of the sum of 12 individual statistics (one for each month of the year). This test also indicated a significant decreasing trend (table 11). These test results indicate that the characteristic difference in flow-adjusted specific conductance between Shiprock and Farmington, as measured by MDASC, has declined with time.

This conclusion presents a question as to whether the characteristic, flow-adjusted specific conductance, is decreasing at Shiprock, increasing at Farmington, or some combination of both. In an attempt to resolve this question, the following was considered.

Table 11. Probabilities that the given time series have no upward or downward trend as determined by Mann's test and the seasonal Kendall test for trend

[Probabilities have been computed using the normal approximation (without continuity correction) to the distributions of the respective test statistics. Also, the sign of each test statistic evaluated here was negative, thus implying decreasing trends in cases where the p-values were significant]

	Probability values	
Time series	Mann's test	Seasonal Kendall test
MDASC	0.0001	0.0001
MASCS	.0004	.0002
Q1ASCS	.0002	.0002
Q3ASCS	.0026	.0052
MASCF	.5130	.6664
Q1ASCF	.5178	.5654
Q3ASCF	.6820	.9840

Denote:

$$MASCS(i) = median\ [FASCS(i,j)] \quad (6)$$

where i = month index (October 1962 = month 1, December 1979 = month 207); and
j = day index (j = 1,..., number of days in the ith month that both specific conductance and discharge were measured at Shiprock);

and:

$$MASCF(i) = median\ [FASCF(i,j)] \quad (7)$$

where i = month index (October 1962 = month 1, December 1979 = month 207); and
j = day index (j = 1,..., number of days in the ith month that both specific conductance and discharge were measured at Farmington).

Using the same testing procedures that were used on the time series MDASC, MASCS and MASCF were separately evaluated for monotonic trends over time. The tests indicated a significant decreasing trend over time in the MASCS series and no detectable trend present in the MASCF series (table 11). These test results indicate decreasing specific conductance over time at Shiprock due to sources in the area draining into the reach of the San Juan River between Shiprock and Farmington.

The time series of monthly medians MASCF and MASCS represent a summary of the complete series FASCF and FASCS. In order to demonstrate the adequacy of the MASCF and MASCS series as indicators of the FASCF and FASCS series, trends of the 25th and 75th percentiles of the FASCF and FASCS series were investigated. The first and third quartiles of each month's sequence of flow-adjusted specific conductance at the Shiprock station were defined as:

$$Q1ASCS(i) = 25th\ percentile\ [FASCS(i,j)] \quad (8)$$

where i = month index (October 1962 = month 1, December 1979 = month 207); and
j = day index (j = 1,..., number of days in the ith month that both specific conductance and discharge were measured at Shiprock);

and

$$Q3ASCS(i) = 75th\ percentile\ [FASCF(i,j)] \quad (9)$$

where i = month index (October 1962 = month 1, December 1979 = month 207); and
j = day index (j = 1,..., number of days in the ith month that both specific conductance and discharge were measured at Shiprock).

Similarly, the Q1ASCF and Q3ASCF series were defined to be the related sequences derived from data collected at the Farmington station.

Both nonparametric testing procedures were again applied to the Q1ASCS, Q3ASCS, Q1ASCF, and Q3ASCF series (table 11). The tests on the first and third quartiles of the Shiprock series (FASCS) indicate a significant decreasing trend. The tests on the first and third quartiles of the Farmington series (FASCF) do not indicate any significant trend. The results of these tests agree with results obtained by using the monthly-median series.

Although the 25th, 50th (median), and 75th percentiles exhibit similar trends for each station, no statement concerning extreme values can be made. An extension of the trend analysis to more extreme monthly percentiles was not made because those percentiles have much less stability than do the central percentiles. By avoiding values outside the first and third quartiles, effects that could have occurred as regularly as seven to eight times (31 x .25 = 7.75) per month are ignored. Therefore, the analysis is sensitive only to effects on specific conductance that occur consistently.

Data Smoothing

In addition to the formal statistical testing procedures, a graphical presentation of various smooth representations of those time series studied can be useful. The first smoothed representation (fig. 31), denoted MDASC (smooth 1), is obtained by application of a nonlinear data-smoothing algorithm, "3RSSH, twice" (Velleman and Hoaglin, 1981), to the MDASC series. This smoothing algorithm operates on a time series much like an ideal low-pass filter. Such a filter removes spikes or valleys of short duration (high frequency) yet preserves the overall long-term (low-frequency) character of the series.

The second smooth (fig. 32), denoted MDASC (smooth 2), is obtained by applying a 13-month moving-average filter (Bloomfield, 1976) to the MDASC (smooth 1) series. The MDASC (smooth 2) series has been reduced in length by 12 (6 observations at each extreme) when compared to the MDASC (smooth 1) series. The salient feature of this filter is that it will completely remove a periodic component of the MDASC (smooth 1) series with a yearly cycle. The MDASC (smooth 2) series is an excellent descriptor of the overall long-term trend of the MDASC series.

The effects of the two smoothing operations on the MASCF, Q1ASCF, Q3ASCF and MASCS, Q1ASCS, Q3ASCS time series are shown in figures 33 and 34, respectively. Although a technical description of the transfer characteristics of the smoothers used is not appropriate here (for details see Bloomfield, 1976; and Velleman, 1980), notice how the three smooth series depicted in each of the figures follow the same general pattern in time. The patterns in the smooths represent real long-term structure present in their respective unsmoothed time series and are not merely a result of the smoothing operations. The patterns also provide evidence that the monthly median series (MASCF and MASCS) are good summary indicators of each month's sequence of flow-adjusted specific conductance.

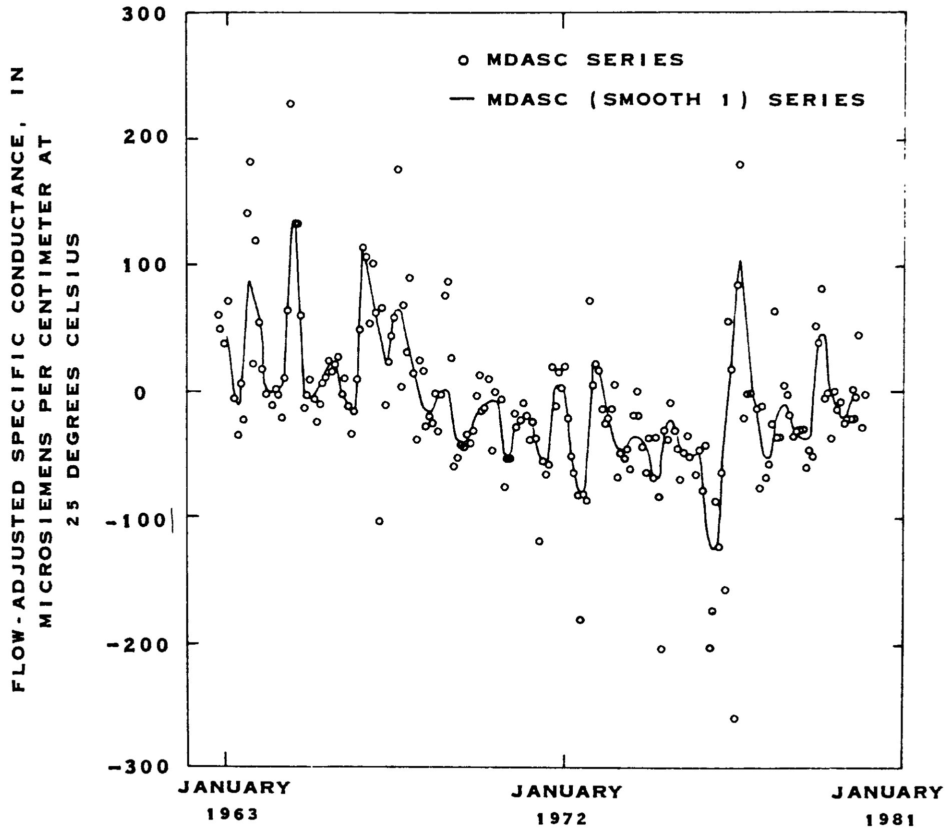


Figure 31.--MDASC (smooth 1) time series superimposed on the MDASC time series.

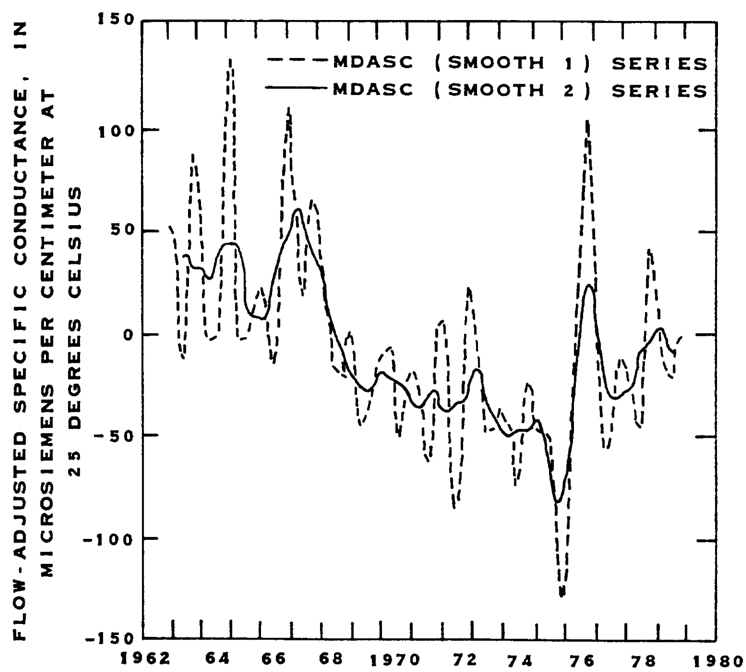


Figure 32.--The MDASC (smooth 2) time series superimposed on the MDASC (smooth 1) time series.

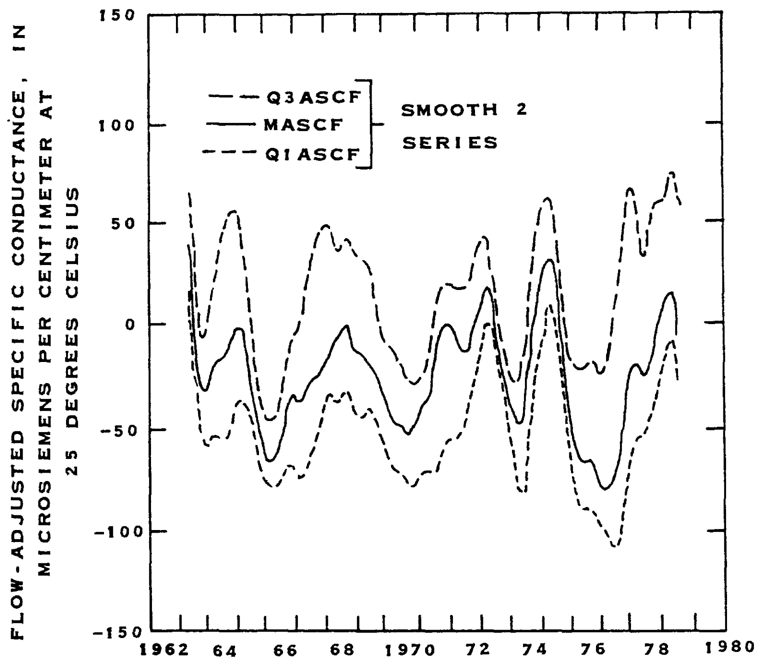


Figure 33.--Smoothed time series MASCF, Q1ASCF, and Q3ASCF derived from data collected at San Juan River at Farmington, N. Mex.

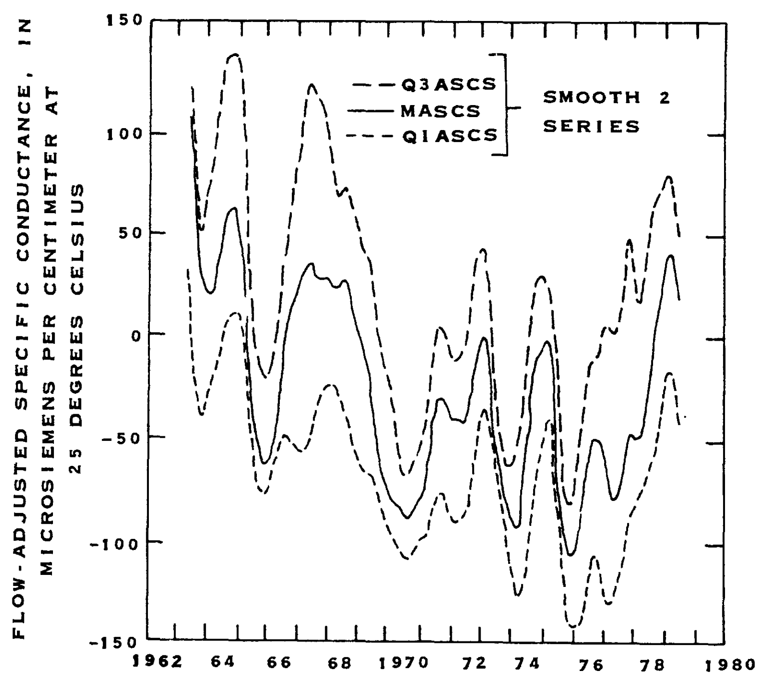


Figure 34.--Smoothed time series MASCS, Q1ASCS, and Q3ASCS derived from data collected at San Juan River at Shiprock, N. Mex.

The MDASC time series was found to have a decreasing monotonic trend in time by formal statistical testing. The decreasing nature of MDASC (smooth 2) is most evident in figure 32. By inspection of figure 32, one may doubt the presupposition of a monotonic trend. Because of the coincidence of a definite downturn in the MDASC time series (at least until 1974-75) and an increase in power-plant and coal-mining activities, there is no evidence to associate these activities with water-quality degradation, as shown by an increase in specific conductance. In fact, specific conductance decreased. Even if water quality had degraded during this period, a strong statement about causality could not be made because of the nature of the analysis. The analysis used is subject to many potential influential factors in the area drained by the reach of the San Juan River between Farmington and Shiprock. It is likely that many activities in this reach such as those related to agriculture and urbanization could have an effect on water quality. Finally, this analysis was not sensitive to activities such as weekly waste dumping that affects water quality (daily specific-conductance measurements) with a frequency of less than eight occurrences per month. Therefore, this analysis was capable only of resolving effects that were consistent from day to day.

COMPARISON OF ANALYTICAL TECHNIQUES

Subjective and objective methods were used to analyze data of this report. Subjective methods display data but require judgment of the analyst to determine if differences exist and, if so, whether the differences are significant. Objective methods do little to display data but calculate whether differences exist given a preselected significance level. Subjective methods allow human bias to enter into the analysis but promote better understanding of the data. Objective methods eliminate human bias but usually test only one data parameter, such as the mean, median, or sum. The best approach to data analysis is to combine subjective and objective methods.

Subjective analytical methods used were: (1) Piper diagram, (2) time-series plot, (3) frequency distribution, and (4) box-and-whisker plot. All of these methods were easily applied to the data. The frequency distribution and box-and-whisker plot are similar; the box-and-whisker plot may be preferred because it summarizes the frequency distribution and adds information about the mean. However, the intuitiveness of comparing shapes is appealing in the frequency distributions.

Objective analytical methods used were: (1) seasonal Kendall test, (2) Wilcoxon rank-sum test, and (3) SEASRS procedure. The seasonal Kendall test detects trends (gradual changes). The Wilcoxon rank-sum test and SEASRS procedure test for step (abrupt) increases or decreases in data and cannot be applied unless it has been shown that the data do not have any trend. These tests are nonparametric procedures and are favored unless the data are normally distributed. The Wilcoxon rank-sum test has little power when seasonal differences are present; the other two tests are effective in the presence of seasonality. Daily data are not useful as a test statistic because of serial correlation; yearly data often lose too much information unless the period of record is long. Monthly data are a good compromise. Because much of the hydrologic data contain extreme values, medians give a better indication of central tendency and typical value than do means.

The analysis of flow-adjusted, specific-conductance data with subsequent smoothing combines both subjective and objective analytical methods. This procedure was the best for eliminating upstream effects, thus reducing or eliminating the influence of the upstream Navajo Reservoir and subtle natural and cultural upstream effects.

For making substantive conclusions, hypothesis tests were used. Graphical (subjective) methods visually summarize the data and illustrate the proven results.

SUMMARY AND CONCLUSIONS

Graphical analysis of streamflow and water-quality data in the Chaco River basin indicates that changes in water quality were caused by power-generation activities. Limited data upstream from the power plant indicate that the Chaco River contains sodium bicarbonate and sodium sulfate waters. Downstream from the power plant, the Chaco River contains calcium sulfate and sodium sulfate waters. Larger specific conductance and larger concentrations of dissolved chloride, dissolved magnesium, dissolved calcium, dissolved sulfate, and dissolved silica are present in the Chaco River downstream from the power plant.

Because mining began in 1963, in the remainder of the San Juan River basin post-1963 changes in concentrations of dissolved solids, dissolved potassium, specific conductance, suspended-sediment concentration, and suspended-sediment load downstream from the surface coal mines were tested to determine if the mines were having an effect on surface water. None of the analytical methods used showed any increase in concentration of dissolved solids, dissolved potassium, or specific conductance downstream from the surface coal mines. In fact, dissolved-solids concentrations and specific conductance were shown to decrease by some analytical methods. The only evidence to suggest that surface coal mines may affect surface-water quality of the San Juan River is the difference between potassium-concentration trends at stations upstream and downstream from mining activity. A significant step decrease in pre-1963 versus 1963-79 dissolved-potassium concentration was detected at the San Juan River near Archuleta station. No corresponding significant decrease in dissolved-potassium concentration was detected at Shiprock (table 12). The indication is that dissolved potassium is being added to the San Juan River between Archuleta and Shiprock. The source of the dissolved potassium could be surface- and ground-water drainage from the surface-mined coal land, drainage from agricultural land, or industrial and municipal waste.

The central tendency of the suspended-sediment-load distribution increased since 1963 at Shiprock as shown by hypothesis tests using the SEASRS procedure. However, the SEASRS procedure also shows that streamflow increased on precipitation days after 1963. Since the suspended-sediment load is not independent of the streamflow (load = concentration x streamflow) and the SEASRS procedure indicates no significant difference in suspended-sediment concentration, the indicated increase probably is due to the increase in streamflow.

Therefore, it can be concluded that the small, ephemeral Chaco River basin shows changes in water quality due to effluent from the power-generation facilities. The discharge in the Chaco River is such a small percentage of the discharge (about 1.9 percent of the average annual runoff) at the downstream San Juan River at Shiprock station that the changes in water quality cannot be detected at the downstream site.

The influence of the Navajo Reservoir was separated from other effects. Daily streamflow, daily water temperature, and daily specific conductance were all moderated (loss of extreme values and seasonality disruption) at the San Juan River near Archuleta station, 7.2 river miles downstream from Navajo Dam. These constituents have become less variable because extreme low and high values were eliminated in the streamflow, specific-conductance, and water-temperature data after the reservoir began operation. Suspended-sediment concentration and suspended-sediment load dropped to near zero after the reservoir began operation. After 1963, changes in streamflow and specific conductance also are apparent at the San Juan River at Shiprock station even though the Navajo Reservoir is 83.6 river miles upstream.

It was not possible to identify any influence of the surface coal mines that was separable from that of urbanization, agriculture, and other cultural and natural changes with the available data. In order to determine the specific causes of changes in water quality it would be necessary to collect additional data at strategically located stations.

Table 12. Water-quality and streamflow differences and possible factors affecting the differences at upstream versus downstream stations along the San Juan River main stem

San Juan River at Pagosa Springs	San Juan River at Farmington	San Juan River near Archuleta	San Juan River at Shiprock	Possible factors affecting difference
Streamflow pattern is seasonal before 1963 and after 1963. No decrease in extreme values noticed.		A disruption in seasonality and elimination of extreme values for streamflow, water temperature, and specific conductance detected after 1963.	A disruption in seasonality and elimination of extreme values for streamflow and specific conductance detected after 1963.	Navajo Reservoir.
No significant trend in pre-1963 streamflow detected.		No significant trend in pre-1963 streamflow detected.	Significant decreasing trend in pre-1963 streamflow detected.	Increase in water use.
		Significant decreasing trend in pre-1963 suspended-sediment concentration on precipitation days detected.	No significant trend in pre-1963 suspended-sediment concentration on precipitation days detected.	1) Urbanization; 2) Agricultural lands; 3) Large sediment contribution from tributaries between Archuleta and Shiprock.
		Significant increasing trend in 1963-79 suspended-sediment load on precipitation days detected.	No significant trend in 1963-79 suspended-sediment load on precipitation days detected.	Large sediment contribution from tributaries between Archuleta and Shiprock.
		Significant step (abrupt) decrease in suspended-sediment concentration detected for 1963-79 compared to pre-1963.	No significant change in suspended-sediment concentration detected for 1963-79 compared to pre-1963.	1) Large aediment contribution from tributariea between Archuleta and Shiprock; 2) Coal, strip mining; 3) Urbanization; 4) Agricultural lands.
		Significant decreasing trend in pre-1963 dissolved solids and magnesium detected.	No significant trend in pre-1963 dissolved solids or magnesium detected.	1) Urbanization; 2) Agricultural lands.
		Significant increasing trend in 1963-79 dissolved-magnesium and sulfate concentrations detected.	No significant trend in 1963-79 dissolved magnesium and a significant decreasing trend in 1963-79 dissolved-sulfate concentration detected.	Decrease in minerals mining in Animas River headwaters.
		Significant step (abrupt) decrease in dissolved potassium and fluoride concentrations detected for 1963-79 compared to pre-1963.	No significant change in dissolved-potassium and dissolved-fluoride concentrations detected for 1963-79 compared to pre-1963.	1) Coal strip mines; 2) Agricultural lands; 3) Industrial and municipal waste.
	No significant trend in 1963-79 flow-adjusted specific conductance detected.		A significant decreasing trend in 1963-79 flow-adjusted specific conductance detected.	1) Change in ground-water seepage to surface streams.

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