Effects of Reservoir Installation, San Juan-Chama Project Water, and Reservoir Operations on Streamflow and Water Quality in the Rio Chama and Rio Grande, Northern and Central New Mexico, 1938-2000

By Jeff B. Langman and Scott K. Anderholm

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CONVERSION FACTORS, ABBREVIATIONS, AND DATUM

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon/day (gal/day)	3.785	liter/day (L/day)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
milligram per liter (mg/L)	1.0	part per million (ppm)

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

Temperature in degrees Fahrenheit (°F) or degrees Celsius (°C) may be converted as follows:

$$°C = (°F - 32) / 1.8$$

$$°F = (1.8 \times °C) + 32$$

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Abstract

The coordinated operation of Heron, El Vado, and Abiquiu Dams on the Rio Chama and Cochiti Dam on the Rio Grande and the importation of Colorado River Basin water by the San Juan-Chama Project have altered streamflow and water quality of the Rio Chama and Rio Grande in northern and central New Mexico. The coordinated retention of streamflow in the four reservoirs increased median streamflows, decreased extreme flows, and decreased periods of small streamflow; inflow of San Juan-Chama Project water increased overall streamflow in the Rio Chama and Rio Grande. These changes to streamflow decreased specific conductance and suspended-sediment concentration and increased pH in the Rio Chama and the Rio Grande.

Following construction of Heron and Cochiti Dams and integration of reservoir operations on the Rio Chama and the Rio Grande, the inflow of San Juan-Chama Project water and retention of snowmelt runoff influenced water quality. These influences varied by season because reservoir releases fluctuated according to downstream user needs and annual streamflow variation. The influences of San Juan-Chama Project water and retained snowmelt on water quality diminished with downstream flow as the Rio Grande was subjected to various natural and anthropogenic inflows. Because of the variability and type of seasonal influences, streamflow did not have a strong annual correlation with water quality in the Rio Chama or the Rio Grande.

Introduction

Streamflow and water quality in northern and central New Mexico are extremely important because of limited surface-water resources and a growing population. Construction and operation of reservoirs on the Rio Chama and Rio Grande and the importation of Colorado River Basin water by the San Juan-Chama Project (SJC Project) have likely altered streamflow and water quality of the Rio Chama and Rio Grande. These alterations could affect current (2004) and future uses of Rio Chama, Rio Grande, and SJC Project water.

The City of Albuquerque has implemented various initiatives under the Water Resources Management Strategy (City of Albuquerque, 1997) to ensure a sustainable water supply. The U.S. Geological Survey (USGS), in cooperation with the City of Albuquerque, investigated alterations and variations in streamflow and water quality in the Rio Chama and Rio Grande to better understand the effect of reservoir construction and operation and the introduction of SJC Project water.

The introduction of SJC Project water has the potential to alter water quality by introducing non-native water of different chemical composition. Additionally, the alteration of natural streamflow patterns may influence water quality by reducing normal seasonal variations such as those that occur during snowmelt runoff. It has been shown that operation of dams and impoundments can affect water quality through processes such as sediment retention, thermal stratification, increased evaporation, decomposition of retained organic material, and nitrogen supersaturation (U.S. Environmental Protection Agency, 1975). Such processes can occur because incoming water may be retained as reservoir storage for flood and sediment control, irrigation, recreation, or municipal supply.

Substantial alteration of Rio Grande streamflow and suspended sediment has been observed with construction and operation of Cochiti Dam. The magnitude of flood peaks has been reduced, suspended-sediment loads and bed material have diminished, and channel morphology has been altered downstream from the dam (Mussetter Engineering, Inc., 2002). Construction and operation of Elephant Butte Dam, south of the study area, also have altered Rio Grande streamflow and suspended-sediment concentration. The dam reduced peak flows, changed sediment transport, and altered stream geometry. The installation of the dam also allowed a substantial increase in agriculture along the Rio Grande because of increased availability of water for irrigation that resulted in an increase in irrigation-return flows with high salt content (Collier and others, 1996).

Purpose and Scope

This report describes the effects of reservoir installation, introduction of SJC Project water, and the coordination of reservoir operations on streamflow, specific conductance, pH, and suspended-sediment concentration of the Rio Chama and the Rio Grande in northern and central New Mexico. Data collected from 1938 to 2000 at Federal and State streamflow-gaging/

water-quality sites (sites) on the Rio Chama and the Rio Grande were analyzed to evaluate the effects of these influences.

Description of the Study Area

The study area includes the Rio Chama watershed from the Rio Chama near La Puente to the Rio Chama's inflow to the Rio Grande and the Rio Grande watershed from the Rio Grande at Taos Junction Bridge to the Rio Grande Floodway near Bernardo (fig. 1). Additionally, data for the Rio Grande near Del Norte in the headwaters of the Rio Grande in Colorado are included for climate and streamflow analysis. The surface-water monitoring network for this report is listed in table 1 and shown in figure 1. For this report, streamflow/water-quality sites are referred to by the study site name listed in table 1.

Physiography

The Continental Divide borders the study area to the west and the Sangre de Cristo, Sandia, and Manzano Mountains border it to the east (fig. 1). Elevations in the study area range from about 4,650 to 13,000 ft above NGVD29.

The Rio Grande is the main drainage in the study area, and the Rio Chama is its largest tributary in this area (fig. 1). The Rio Grande originates in the San Juan Mountains in south-central Colorado. The river flows through south-central Colorado and enters northern New Mexico through Sunshine Valley. The Rio Grande bisects New Mexico and exits the State near El Paso, Texas. The Rio Chama drains north-central New Mexico and discharges to the Rio Grande upstream from Española, New Mexico. Most surface-water inflow to the Rio Grande is derived from mountains adjacent to the Rio Grande upstream from Otowi (Ortiz and Lange, 1996).

The study area contains four large reservoirs—Heron Lake, El Vado Reservoir, Abiquiu Reservoir, and Cochiti Lake (fig. 1)—that have the potential to substantially alter streamflow and water quality. Heron Lake is located on Willow Creek (a tributary of the Rio Chama); El Vado and Abiquiu Reservoirs are located on the Rio Chama downstream from the Willow Creek inflow. Cochiti Lake is located on the Rio Grande at Cochiti Pueblo downstream from the Rio Chama inflow to the Rio Grande.

Climate

Climate in the study area is semiarid with substantial variation in precipitation from the lower valley areas to the mountains. This climate results in a highly variable streamflow regime. In the headwaters of the Rio Grande, annual precipitation can exceed 50 in., whereas other areas in the watershed may receive less than 6 in. (Ellis and others, 1993). Most surface water occurs as snowmelt runoff from March through June. Precipitation accumulations are largest during the summer monsoon season (July to September), and most of the precipitation during this season falls during July and August (Western Regional Climate Center, 2002a). Because of the brevity of summer thunderstorms and evapotranspiration (ET), precipitation during the monsoon season contributes less to daily-mean streamflow than snowmelt runoff.

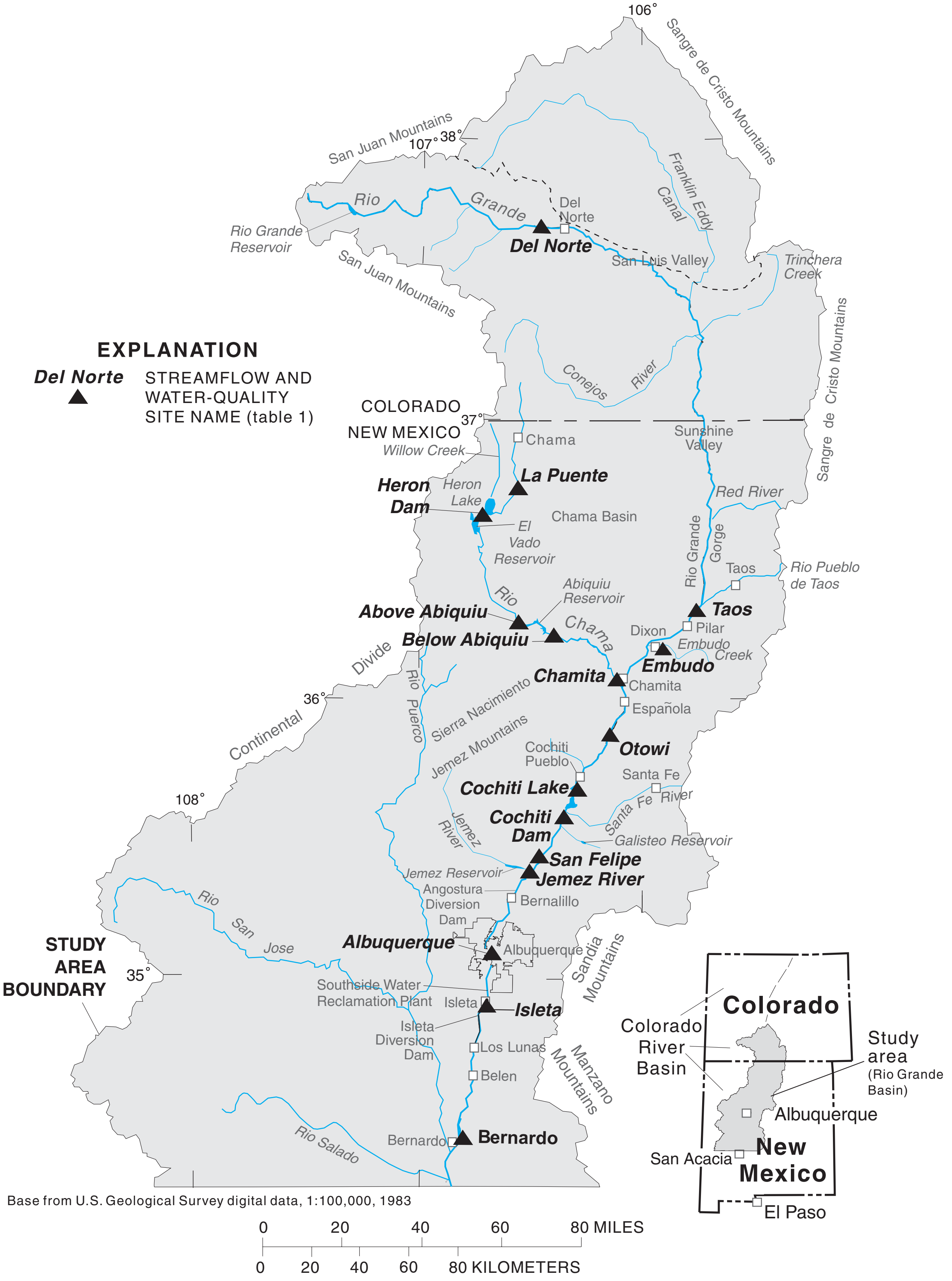
Legal Constraints on Streamflow

All annual streamflows of the Rio Chama and Rio Grande are accounted for by various compacts, treaties, and individual water rights. The interstate flow of the Rio Grande between Colorado, New Mexico, and Texas is governed by the Rio Grande Compact (Compact). Agreed upon in 1938, the Compact provides the framework for regulation of equitable apportionment of Rio Grande streamflow and permits each State to develop and use its water resources, provided each State meets its delivery obligations (Rio Grande Compact Commission, 1998). Table 2 shows applicable legislation and a brief description of the effect of each legislation on reservoirs in the study area.

The SJC Project was authorized by Congress in 1962 to divert streamflow from three tributaries of the San Juan River in southwestern Colorado in the Colorado River Basin into the Rio Chama in the Rio Grande Basin. Minimum instream flows are required for the three tributaries. Volumes larger than the minimum instream flows are available for diversion and storage in Heron Lake. Diversions cannot exceed 1,350,000 acre-ft for a 10-year moving average, and annual diversions cannot exceed 270,000 acre-ft.

Reservoirs

Heron Dam was completed in 1971 by the Bureau of Reclamation as part of the SJC Project. The SJC Project provides supplemental water supply to contractors such as the City of Albuquerque, the City of Santa Fe, and the Middle Rio Grande Conservancy District (MRGCD) (U.S. Army Corps of Engineers and others, 2000). The maximum capacity of Heron Lake is 401,300 acre-ft, and the firm yield is 96,200 acre-ft. Heron Lake is used solely for the storage and delivery of SJC Project water for municipal, domestic, industrial, recreational, irrigation, and fish and wildlife purposes (Bureau of Reclamation, 2002c). SJC Project water is not subject to the provisions of the Compact under which El Vado and Abiquiu Reservoirs and Cochiti Lake are operated. There is no carryover for SJC Project contractor allotment water in Heron Lake, so contractors must take delivery of their water by December 31 unless granted a waiver. Many contractors store SJC Project water in El Vado and Abiquiu Reservoirs.



Base from U.S. Geological Survey digital data, 1:100,000, 1983

Figure 1. Streamflow and water-quality sites in the Rio Grande study area.

Table 1. Selected information for streamflow/water-quality sites in the study area.

[USGS, U.S. Geological Survey; NAD27, North American Datum of 1927; mi^2, square miles; NGVD29, National Geodetic Vertical Datum of 1929; NA, not available]

USGS station number	USGS station name	Study site name (fig. 1)	Latitude and longitude (NAD27)	Location (county, hydrologic unit code)	Drainage area (mi^2)[1]	Datum (feet above NGVD29)	Daily-mean stream-flow record	Water-quality record
08284100	Rio Chama near La Puente	La Puente	36°39'45" 106°37'57"	Rio Arriba, 13020102	480	7,083	1955 - 2000	1974 - 2000
08284520	Willow Creek below Heron Dam	Heron Dam	36°39'56" 106°42'13"	Rio Arriba, 13020102	193	NA	1971 - 2000	None
08286500	Rio Chama above Abiquiu Reservoir	Above Abiquiu	36°19'06" 106°35'50"	Rio Arriba, 13020102	1,500	6,280	1961 - 2000	1962 - 1985
08287000	Rio Chama below Abiquiu Dam	Below Abiquiu	36°14'12" 106°24'59"	Rio Arriba, 13020102	2,047	6,040	1962 - 2000	1976 - 1985
08290000	Rio Chama near Chamita	Chamita	36°04'26" 106°06'40"	Rio Arriba, 13020102	3,044	5,654	1938 - 2000	1960 - 2000
08220000	Rio Grande near Del Norte	Del Norte	37°41'22" 106°27'38"	Rio Grande, 13010001	1,320	7,980	1938 - 2000	Not used
08276500	Rio Grande below Taos Junction Bridge	Taos	36°19'12" 105°45'14"	Taos, 13020101	6,790	6,050	1938 - 2000	1975 - 2000
08279000	Embudo Creek at Dixon	Embudo Creek	36°12'39" 105°54'47"	Rio Arriba, 13020101	305	5,859	1938 - 2000	Not used
08313000	Rio Grande at Otowi Bridge	Otowi	35°52'29" 106°08'30"	Santa Fe, 13020101	11,360	5,488	1938 - 2000	1959 - 2000
08317300	Cochiti Lake near Cochiti Pueblo	Cochiti Lake	35°37'01" 106°18'58"	Sandoval, 13020201	11,960	NA	Not used	1981 - 2000
08317400	Rio Grande below Cochiti Dam	Cochiti Dam	35°37'05" 106°19'24"	Sandoval, 13020201	11,960	5,226	1970 - 2000	1972 - 2000
08319000	Rio Grande at San Felipe	San Felipe	35°26'47" 106°26'24"	Sandoval, 13020201	13,160	5,116	1938 - 2000	1970 - 2000
08329000	Jemez River below Jemez Canyon Dam	Jemez River	35°23'24" 106°32'03"	Sandoval, 13020202	1,038	5,096	1943 - 2000	1966 - 2000
08330000	Rio Grande at Albuquerque	Albuquerque	35°05'21" 106°40'48"	Bernalillo, 13020203	14,500	4,946	1941 - 2000	1969 - 2000
08331000	Rio Grande at Isleta	Isleta	34°55'14" 106°40'44"	Bernalillo, 13020203	15,160	NA	Only sample flow[2]	1972 - 2000
08332010	Rio Grande Floodway near Bernardo	Bernardo	34°25'01" 106°48'00"	Socorro, 13020203	16,290	4,723	1938 - 2000	1946 - 2000

[1] Drainage area does not include noncontributing areas, closed basins, or out-of-basin areas associated with interbasin transfers.

[2] Streamflow determined only at the time of water-quality sample collection.

Constructed in 1935, El Vado is the oldest reservoir in the study area and stores native Rio Chama water and SJC Project water for irrigation, recreation, and flood and sediment control (U.S. Army Corps of Engineers, 1989). El Vado Reservoir is owned by the MRGCD and operated by the Bureau of Reclamation. The reservoir has a maximum storage of 180,000 acre-ft and typically contains about 40,000 acre-ft of SJC Project water (Bureau of Reclamation, 2002b). Native Rio Chama water is stored in El Vado Reservoir for inflows in excess of required outflows for MRGCD needs and other downstream rights including the Compact (Bureau of Land Management, 1992).

SJC Project water is not governed by the Compact and can be released to contractors at any time from storage in El Vado Reservoir (U.S. Army Corps of Engineers, 1989). Storage and release of native Rio Chama water, however, are governed by the Compact. Native Rio Chama water in El Vado Reservoir typically is stored during snowmelt runoff and subsequently released during the irrigation season (March 1 through November 1) (U.S. Army Corps of Engineers, 1989). During the irrigation season, native Rio Chama inflows as large as 100 ft^3/s are allowed to pass through the reservoir for downstream senior Rio Chama water-right holders.

In response to problems of poor drainage, flooding, and deterioration of agricultural land within central New Mexico, the U.S. Army Corps of Engineers (USACE) and Bureau of Reclamation cooperatively developed a comprehensive plan that included construction of Abiquiu Reservoir in 1963 (U.S. Army Corps of Engineers and others, 2000). Abiquiu Reservoir is owned and operated by the USACE for flood and sediment control and water supply and is the main flood-control structure on the Rio Chama. Abiquiu Reservoir has a maximum capacity of 1,535,300 acre-ft and a maximum storage capacity of 140,097 acre-ft for SJC Project water (U.S. Army Corps of Engineers, 2000). Abiquiu Reservoir is not capable of storing the entire 200,000 acre-ft of SJC Project water as authorized in 1981 by PL 97-140 (table 2) because of reduced storage capacity from sediment deposition and a lack of full storage easements on the margins of the reservoir (Bureau of Land Management, 1992).

All native Rio Chama inflows into Abiquiu Reservoir are allowed to pass through up to a discharge equal to the downstream channel capacity of 1,800 ft^3/s (U.S. Army Corps of Engineers, 2000). When inflows into the reservoir exceed downstream channel capacity, inflows are partly retained and generally released within a 24-hour period after the peak inflow, except during snowmelt runoff when water is stored for release during the irrigation season (U.S. Army Corps of Engineers, 2000). After July 1, when streamflow in the Rio Grande at Otowi Bridge (Otowi site) is less than 1,500 ft^3/s, no floodwater is released from Abiquiu Reservoir.

Congress authorized construction of Cochiti Dam in 1960 to provide flood and sediment control in the Rio Grande. A recreation pool of 1,200 surface acres was authorized for Cochiti Lake in 1964 (table 2) to be supplied with water from the SJC Project (U.S. Army Corps of Engineers, 1989). Cochiti Dam was completed in 1973 and is operated in conjunction with Galisteo, Jemez, and Abiquiu Reservoirs (fig. 1) for flood and sediment control (U.S. Army Corps of Engineers, 1999).

Native Rio Grande water is passed through Cochiti Lake unless retention is necessary for flood protection. SJC Project water can be stored prior to final release to downstream users (U.S. Army Corps of Engineers and others, 2000). Snowmelt runoff is stored in April and May; water is typically released in June and July and may extend into November for irrigation purposes. As with Abiquiu Reservoir, after July 1, when streamflow in the Rio Grande near Otowi Bridge is less than 1,500 ft^3/s, no floodwater is released from Cochiti Lake unless the reservoir has less than 212,000 acre-ft of summer flood storage (Bureau of Reclamation, 2002a). Cochiti Lake has a maximum capacity of 725,159 acre-ft.

The USACE allows about 5,000 acre-ft per year of SJC Project water to pass from Abiquiu Reservoir to Cochiti Lake to replace evaporative losses and protect fisheries. About one-third of this water is released in July, and the remaining water is delivered from November to February (Bureau of Reclamation, 2002c).

Tributaries

Within the study area, perennial tributaries to the Rio Grande, other than the Rio Chama, are few. Numerous intermittent and ephemeral drainages flow into the Rio Chama and Rio Grande in response to snowmelt or summer thunderstorms. Only Embudo Creek and the Jemez River (fig. 1) provide an annual-mean streamflow greater than 50 ft^3/s.

Embudo Creek has a drainage basin of 305 mi^2 at the streamflow gage located 0.5 mi upstream from the inflow of Embudo Creek to the Rio Grande. The annual-mean streamflow is 84.7 ft^3/s (1924 to 2000) (Ortiz and others, 2001). Because Embudo Creek flows unimpeded from its headwaters in the Sangre de Cristo Mountains to its inflow to the Rio Grande near Dixon (fig. 1) in a mostly undeveloped watershed, it is assumed that the streamflow and water quality of Embudo Creek have not changed substantially from 1938 to 2000.

The Jemez River drainage basin is 1,038 mi^2 at the Jemez River gage site (2.0 mi upstream from its inflow to the Rio Grande) and includes parts of the Jemez and Sierra Nacimiento Mountains (fig. 1). The annual-mean streamflow of the Jemez River, which may go dry during different periods of the year at its inflow to the Rio Grande, is 61.7 ft^3/s (1943 to 2000) at the Jemez River site; the largest recorded daily-mean streamflow is 3,640 ft^3/s (June 19, 1958) (Ortiz and others, 2001). The river enters the Rio Grande between the San Felipe and Albuquerque sites (fig. 1). Large flows typically occur in late March, April, and May during snowmelt runoff, and additional peak flows occur during the monsoon season. The Jemez Canyon Dam and Reservoir, completed in 1953, regulates flow for flood and sediment control (U.S. Army Corps of Engineers, 1989). The Jemez River drains an area that has geothermal activity and contains larger dissolved-solids concentrations and different mineral content than the Rio Grande (Trainer and others, 2000).

Irrigation Diversions and Inflows

Agricultural areas are located along the Rio Chama from Abiquiu Reservoir to the confluence with the Rio Grande and along the Rio Grande from Pilar to Otowi and from Cochiti Lake to Bernardo (fig. 1). These areas rely on diversions of Rio Chama and Rio Grande water for irrigation. The agricultural areas and irrigation systems along the Rio Chama and from Pilar to Otowi on the Rio Grande are small compared with agricultural areas and the irrigation system of the MRGCD.

Table 2. Legislative history of authorization and operations for reservoirs in the Rio Grande study area.

[MRGCD, Middle Rio Grande Conservancy District; PL, Federal public law; SJC Project, San Juan-Chama Project]

Legislation	Date	Effect on reservoirs in the study area
MRGCD initiative	1935	Completion of El Vado Dam.
Rio Grande Compact	1938	Authorized water delivery obligations between Colorado, New Mexico, and Texas.
Flood Control Act (PL 80-858)	1948	Authorized comprehensive plan for improvement of Rio Grande Basin with a focus on flood control.
Upper Colorado River Basin Compact	1949	Set New Mexico's share of Upper Colorado river water at 11.25 percent.
Flood Control Act (PL 81-516)	1950	Authorized construction of Abiquiu Dam.
River and Harbor and Flood Control Act (PL 86-645)	1960	Set operating criteria for Abiquiu Dam and retention of floodwater during summer months for carryover storage under certain conditions. Authorized construction and operation parameters of Cochiti Dam.
PL 87-483	1962	Authorized SJC Project (including Heron Dam) that allows importing water from San Juan Basin of the Colorado River to the Rio Chama to supply specific municipal and irrigation users in the Rio Grande Basin. Set minimum instream-flow requirements for the Navajo and Little Navajo Rivers and Rio Blanco.
PL 88-293	1964	Authorized permanent pool in Cochiti Lake for recreation, fish, and wildlife.
City of Albuquerque Resolution	1974	Committed the City's allotment of SJC Project water to the establishment of an incidental recreational lake at Abiquiu Reservoir as a result of the annual storage.
Water Supply Storage (PL 97-140)	1981	Authorized the storage of as much as 200,000 acre-feet of SJC Project water in Abiquiu Reservoir.
PL 100-522	1988	Authorized the storage of as much as 200,000 acre-feet of Rio Grande Basin water in Abiquiu Reservoir instead of SJC Project water if space is available.
Wild and Scenic River Designations (PL 100-633)	1988	Designated three reaches of the Rio Chama upstream from Abiquiu Reservoir as wild and scenic river with recreational purposes.

Within the study area, the MRGCD provides irrigation water for agricultural purposes in a narrow band of land from Cochiti Lake to Bernardo (fig. 1). The MRGCD diverts water from the Rio Grande immediately downstream from Cochiti Dam, at the Angostura Diversion Dam about 5 mi north of Bernalillo, and at the Isleta Diversion Dam about one-half mi downstream from the Isleta site. The MRGCD provides water for flood irrigation by diverting water from the Rio Grande through a system of canals while directing return flows to the Rio Grande through drainage ditches and interior and riverside drains. The riverside drains also collect infiltrating water from the interior drains and canals and leakage from the Rio Grande to prevent waterlogging of agricultural areas (Kernodle and Scott, 1986). The riverside drains discharge to the Rio Grande at multiple locations in the study area.

Treated Wastewater and Urban Runoff

The City of Albuquerque operates the Southside Water Reclamation Plant, the largest wastewater-treatment facility in New Mexico, with a capacity to process 76 million gal/day (City of Albuquerque, 2002). Initially built in 1962, the plant was expanded periodically to increase treatment and receive all wastewater collected within the city limits. In 2001, continuous outflow at the Southside Water Reclamation Plant typically ranged from 80 to 90 ft^3/s. Within the study area, this treated wastewater is a larger daily-mean inflow to the Rio Grande than any other except the Rio Chama.

The City of Albuquerque has a large storm-water collection system that discharges to the Rio Grande. The largest conveyance channel collects storm-water runoff from more than 60 percent of the land area within the city limits. This channel typically has no measurable flow, but peak storm flows may exceed 4,000 ft^3/s for very brief periods of time (less than 1 hour) and can be substantially larger than flows in the Rio Grande during these events (Ortiz and others, 2001). Because of the episodic nature of storm-water runoff and the limitations of water-quality data, any influence on water quality from urban storm water is difficult to detect and is not discussed in this report.

Evapotranspiration

Evapotranspiration (sum of evaporation and transpiration, or ET) affects water quality by increasing constituent concentrations in water. Reservoirs in the study area provide substantial surface area for evaporation. Annual pan evaporation has averaged 51.72 in. for El Vado Reservoir (1923–2000), 63.72 in. for Abiquiu Reservoir (1957–2000), and 81.10 in. for Cochiti Lake (1975–2000) (Western Regional Climate Center, 2002b). ET from the Rio Chama and Rio Grande is substantial because of climate, reservoirs, and the broad channel areas and riparian corridor. The Action Committee of the Middle Rio Grande Water Assembly (1999) estimated that 75,000 to 195,000 acre-ft of water is lost to ET annually from the river channel and along the riparian corridor of the Rio Grande from Otowi to San Acacia (located about 13 mi south of Bernardo and outside the study area; fig. 1).

Ground-Water Inflows

The Rio Grande is hydraulically connected with the surrounding basin-fill aquifer system. The basin-fill aquifer is recharged along the mountain fronts, and ground water generally flows from the mountain areas toward the Rio Grande (Ellis and others, 1993; Anderholm and others, 1995).

Follansbee and Dean (1915) determined that the Rio Chama is likely a gaining stream from the town of Chama to the inflow to the Rio Grande. Various reaches of the Rio Chama showed seepage losses to ground water, but overall the river showed a 55-percent net gain of streamflow from ground-water inflows.

From Taos to Cochiti Lake (fig. 1), the Rio Grande is likely a gaining stream. Moore and Anderholm (2002) found an increase in streamflow greater than what could be attributed to the inflow from the Rio Chama, indicating other inflows in this area. The USGS did find a losing reach in this area during a seepage investigation in 2002 (Jack Veenhuis, U.S. Geological Survey, written commun., 2003), but also found that earlier seepage investigations in 1964 included this reach in a larger gaining reach (Jack Veenhuis, written commun., 2002).

From Cochiti Lake to Bernardo (fig. 1), the interaction of surface water and ground water becomes increasingly complex. In many areas of this reach, the water table outside the river corridor is below the river bottom (Kernodle and Scott, 1986; Kernodle and others, 1994). Within the river corridor, the effects of irrigation, drains, river leakage, and ET form complex interactions that make determining ground-water inflows difficult. The Rio Grande likely both gains and loses streamflow as a result of ground-water inflows and outflows through this reach. Veenhuis (2002) calculated a net loss of streamflow in the Albuquerque area during the winter months from 1996 to 2000, and Thorn (1995) calculated net losses in the Albuquerque area for all four seasons from 1989 to 1995. The Rio Grande is likely a losing stream overall from Cochiti Lake to San Acacia as determined by model simulations (McAda and Barroll, 2002).

Previous Water-Quality Studies

Water quality in the study area has been studied for various constituents over variable lengths of time. Nutrient, suspended-sediment, and pesticide concentrations and trends in the Rio Grande from 1972 to 1990 were analyzed by Anderholm and others (1995). Healy (1997) assessed dissolved solids, major constituents, nutrients, trace elements, and suspended-sediment concentrations from 1993 to 1995 for spatial variations and streamflow relations. Pesticides, volatile organic compounds, and nutrients in the Rio Grande from 1992 to 1995 were summarized by Levings and others (1998). Dissolved solids, nutrients, and suspended-sediment concentrations and loads in the Rio Grande from 1993 to 1995 were studied by Moore and Anderholm (2002). Miller and others (1997) presented trace-element and suspended-sediment data from 1994 for the upper Rio Grande in New Mexico. Trace-element concentrations and streamflow in the Rio Grande from 1994 to 1996 in the greater Albuquerque area were presented by Kelly and Taylor (1996) and Wilcox (1997). Passell and others (2004) evaluated hydrological and geochemical trends and patterns in the upper Rio Grande for streamflow and water-quality data collected from 1975 to 1999.

Methods of Analysis

Sources and Description of Data

This study was based on available data. Daily-mean streamflow data were collected from 1938 to 2000, and water-quality samples were collected at the selected sites during different time periods and at different frequencies from 1946 to 2000. Not all sites had sufficient sample populations of the selected constituents; thus, the data for these sites were not used for analysis. Site information and periods of record for available streamflow and water-quality data are shown in table 1.

Streamflow values used in this study are instream values that do not account for adjacent flow in drains, canals, and ditches. Flow in adjacent channels may return to the main channel upstream, downstream, or between sites used in this study for comparison of changes in the daily-mean streamflow. The total cross-sectional streamflow (instream flow plus flow in drains, canals, and ditches) is not used for comparison because the use of total cross-sectional streamflow would mask the effect of diversions and return flows on water quality, which is available only for instream flow.

Specific conductance, pH, and total suspended-sediment concentration (suspended-sediment concentration) have been the primary water-quality data collected at each site. Because of the large sample populations, these three water-quality constituents were used in conjunction with streamflow to determine changes in the Rio Chama and Rio Grande from 1938 to 2000. All data are stored in the USGS National Water Information System (NWIS) database.

Division of Data

Streamflow and water-quality data from 1938 to 2000 were divided into two periods: pre-December 1973 and post-December 1973. This division is based on the beginning of regulated streamflow in the Rio Grande at Cochiti Lake on December 1, 1973. Installation of Heron and Cochiti Dams began a period of new reservoir operation and reservoir operational integration on the Rio Chama and Rio Grande that was not present before 1973 when only El Vado and Abiquiu Reservoirs existed. With the installation of Heron and Cochiti Dams, reservoir operation at the existing dams changed as storage and release volumes increased (fig. 2). Although Heron Reservoir was in operation in 1971, the diversion, storage, and discharge of SJC Project water was not fully implemented until 1973.

Data Comparison

Summary statistics (minimum, 25th percentile, median, 75th percentile, and maximum values) provide an overview of streamflow and water-quality data for the pre- and post-December 1973 periods. The two periods were compared for monthly and overall period distributions using step-trend analysis that employed the two-tail Wilcoxon rank sum test and the Hodges-Lehmann estimator. The non-parametric Wilcoxon rank sum test was used to determine whether two sample populations came from the same population or whether they differed in central value (central location of sample population distribution). The test jointly ranks the sample populations, then compares the sum of the ranks for each population. The Hodges-Lehmann estimator was used to determine the direction of change (increase or decrease) in distributions (sample populations) and provide an estimate of the size of the change. The Hodges-Lehmann estimator is calculated by determining the median of all possible pair-wise differences between individual data points in each distribution. The estimator is insensitive to non-normal distribution characteristics such as skewness.

For this study, a statistical difference in distributions was based on a p-value $(1 - \alpha)$ less than or equal to 0.10 for all two-way tests (90-percent confidence interval). If the p-value was greater than 0.10, the comparison was considered to show no difference in distributions ("no difference" or "no significance"). If the p-value was greater than 0.05 and less than or equal to 0.10, an increase or decrease in distributions was considered "marginally significant." If the p-value was greater than 0.01 and less than or equal to 0.05, the change in distributions was considered "significant." If the p-value was less than or equal to 0.01, the change in distributions was considered "highly significant."

One-tail Wilcoxon rank sum tests were used for comparison of data distributions from two sites (upstream and downstream) during the same time period. Two-tail tests were first used to determine a difference in distributions, and one-tail tests were used to determine the direction (increase or decrease) of change. The Wilcoxon signed rank test was used for comparing upstream to downstream streamflow because of the logical pairing of daily mean values. A difference in distributions was considered significant if the one-tail test produced a p-value less than or equal to 0.05.

The LOESS smooth technique was used to analyze seasonal streamflow and water-quality variation. Data for each site were plotted by month and day without regard for year, and a LOESS (local) smooth technique was applied to produce a fit line of the data. LOESS fit lines use a locally weighted smoothing technique to provide a flexible fit line that responds to the individual data point and a few neighboring data points. A variable fit window with locally quadratic fitting was used to create the LOESS fit lines. The LOESS fit line represents long-term average seasonal constituent concentrations for the specified period. To show adequacy of fit, LOESS fit lines and the study period data are presented by constituent in the Supplemental Information section at the back of this report.

Kendall's tau correlation coefficient was used to present strength of correlation between streamflow and the individual water-quality constituents. Kendall's tau is a rank method (resistant to outliers) that measures the strength of the monotonic relation between two sample populations. The coefficient ranges from +1 (positive relation) to -1 (negative relation); values closer to ±1 indicate a stronger relation. A value of zero indicates no correlation. Generally, a coefficient equal to or greater than +0.7 or equal to or less than -0.7 indicates a strong correlation for Kendall's tau (Helsel and Hirsch, 1991).

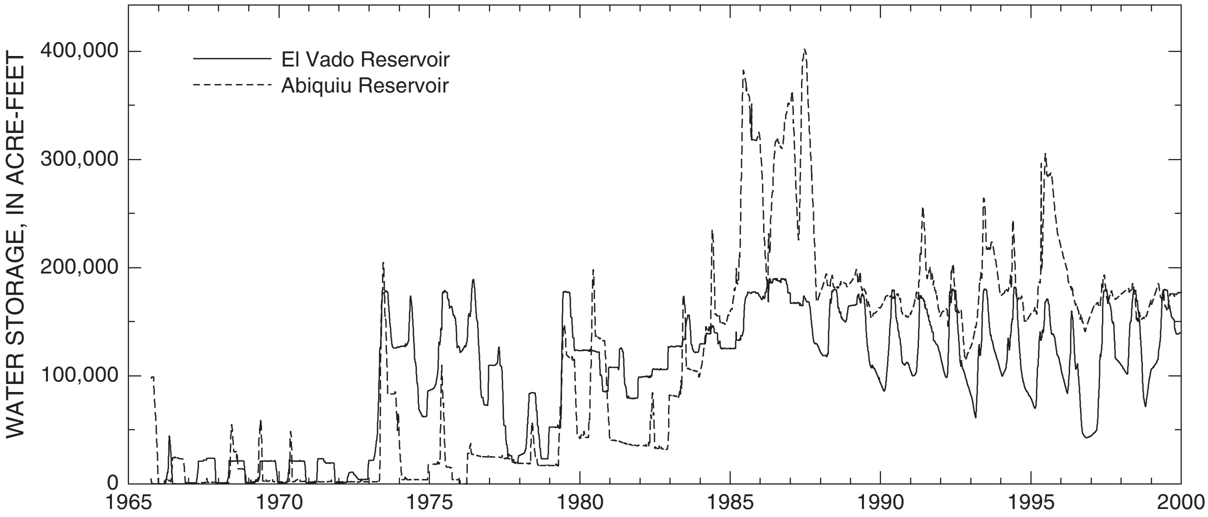


Figure 2. Water storage in El Vado and Abiquiu Reservoirs, 1965 to 2000.

Acknowledgments

The authors acknowledge the City of Albuquerque for the foresight and support to implement this study. In particular, the authors express their appreciation to John Stomp, City of Albuquerque Director of Water Resources, for his support of the study to better understand the State of New Mexico's water resources. The authors also thank Don Gallegos of the USACE for his insightful contribution to reservoir operations in northern and central New Mexico.

Effects of Reservoir Installation, San Juan-Chama Project Water, and Reservoir Operations on Streamflow and Water Quality

Potential Climate Bias

A concern when comparing streamflow and water-quality data between the pre- and post-December 1973 periods is the potential for a climate bias. If climate were the major influence in creating differences in streamflow between the two periods, the effect of reservoirs or the SJC Project could not be accurately evaluated. Streamflow at the La Puente and Del Norte sites was examined for differences between the pre- and post-December 1973 periods.

The Rio Chama near La Puente drains the headwaters of the Rio Chama in the southern San Juan Mountains upstream from any reservoirs or large diversions, and the Rio Grande near Del Norte drains the headwaters of the Rio Grande in the San Juan Mountains (fig. 1). Several small reservoirs are located on the Rio Grande and its tributaries upstream from Del Norte; however, there is little change in annual storage in these reservoirs (Rio Grande Compact Commission, 1998), and the reservoirs are considered to have insignificant storage capacity relative to the streamflow of the Rio Grande at this location.

There were only small differences in the distributions of daily-mean streamflow between the pre- and post-December 1973 periods for the sites of La Puente and Del Norte (fig. 3). With little difference in streamflow at the La Puente and Del Norte sites between the two periods, climate was assumed not to be a major influence. Most differences in streamflow in the pre- and post-December 1973 periods for sites downstream from the reservoirs can then be attributed to the effects of reservoir installation and operation and the SJC Project. A potential climate bias is further explored in the Streamflow section of this report.

Potential Sampling Bias

For valid comparison, water-quality samples must have been collected during streamflows that were representative of daily-mean streamflow distributions for the pre- and post-December 1973 periods. If sample-streamflow distributions were similar to daily-mean streamflow distributions for each of the pre- and post-December 1973 periods, then comparison of water-quality data for those two periods was assumed valid and not biased.

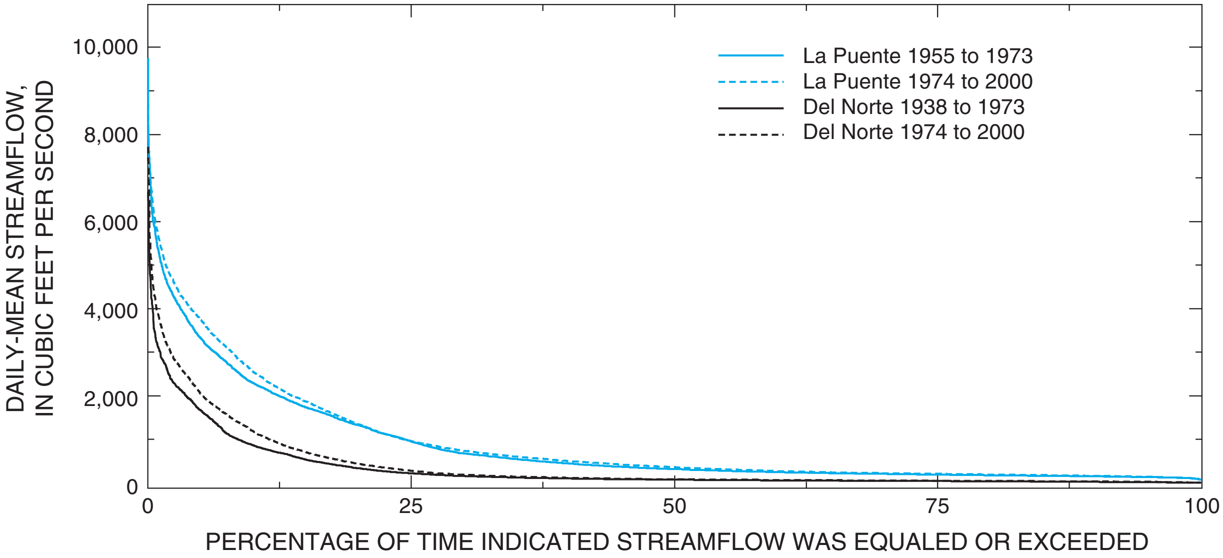


Figure 3. Duration plots of pre- and post-December 1973 daily-mean streamflow at Rio Chama site of La Puente and Rio Grande site of Del Norte.

Sample-streamflow distributions were similar to daily-mean streamflow distributions except at the San Felipe site and to a lesser extent at the Chamita, Albuquerque, and Bernardo sites during the pre-December 1973 period (figs. 4 and 5). The San Felipe pre-December 1973 sampling distribution lacked sufficient samples for comparison of pre- to post-December 1973 periods. The large (less than 25-percent frequency) pre-December 1973 streamflow samples from Chamita, Albuquerque, and Bernardo were overrepresented in the sample-streamflow distributions. However, the overall sample-streamflow distributions were generally similar to the daily-mean streamflow distribution. No sampling bias was apparent that would reduce the validity of the pre- to post-December 1973 comparison of streamflow and water-quality constituents at sites with sufficient sample populations in both periods.

Streamflow

Rio Chama

Installation and operation of the Rio Chama reservoirs and implementation of the SJC Project increased overall streamflow in the Rio Chama but decreased the largest streamflows downstream from the reservoirs. Streamflow at La Puente, upstream from the reservoirs, was slightly larger in post-December 1973 median and interquartile range, and streamflow at Above Abiquiu and Chamita, downstream from the reservoirs, was substantially larger in post-December 1973 medians and interquartile ranges (table 3). The maximum streamflow increased at La Puente and at Above Abiquiu, but the maximum streamflow decreased at Chamita.

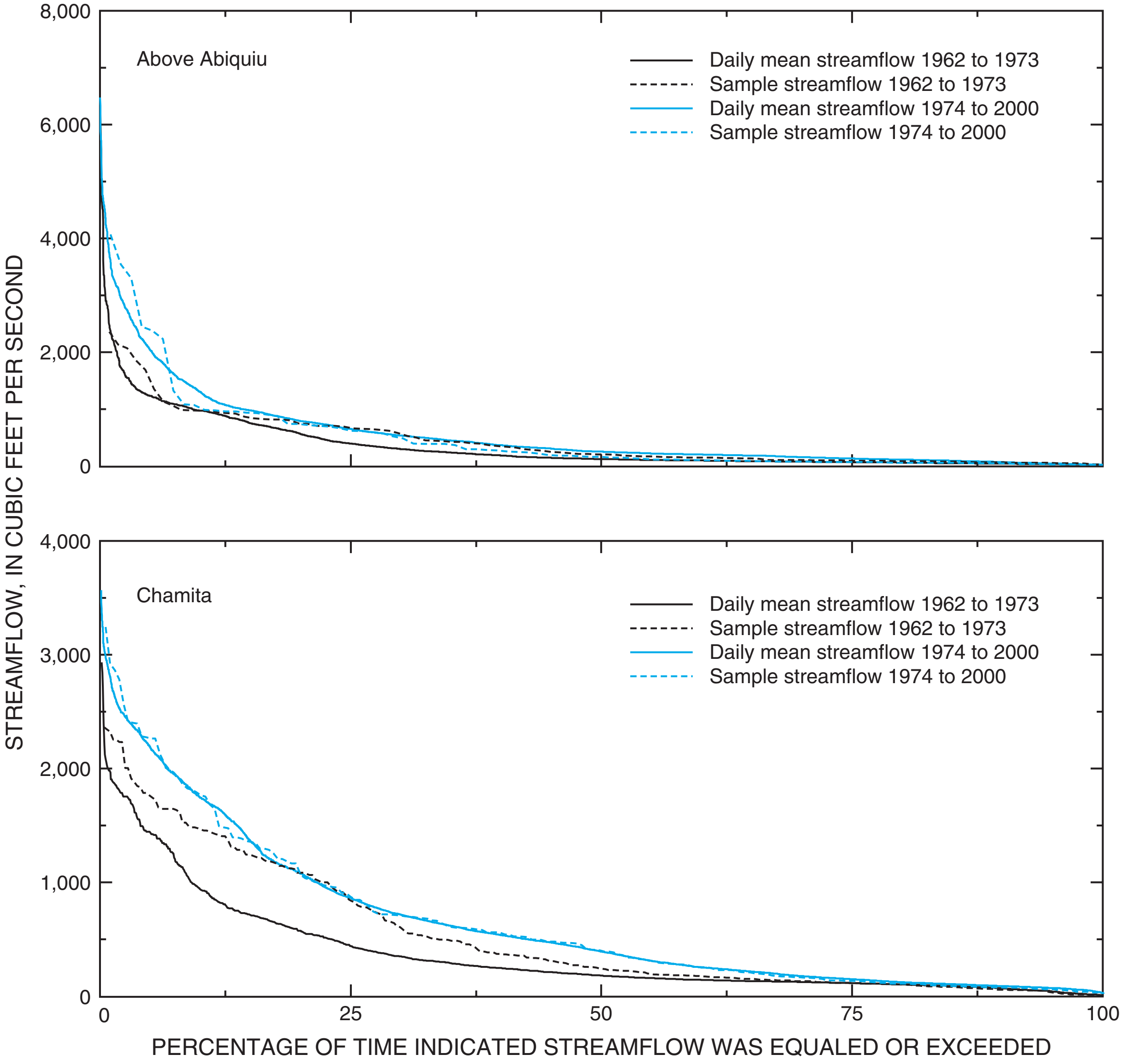


Figure 4. Duration plots of pre- and post-December 1973 daily-mean and sample streamflows for Rio Chama sites of Above Abiquiu and Chamita.

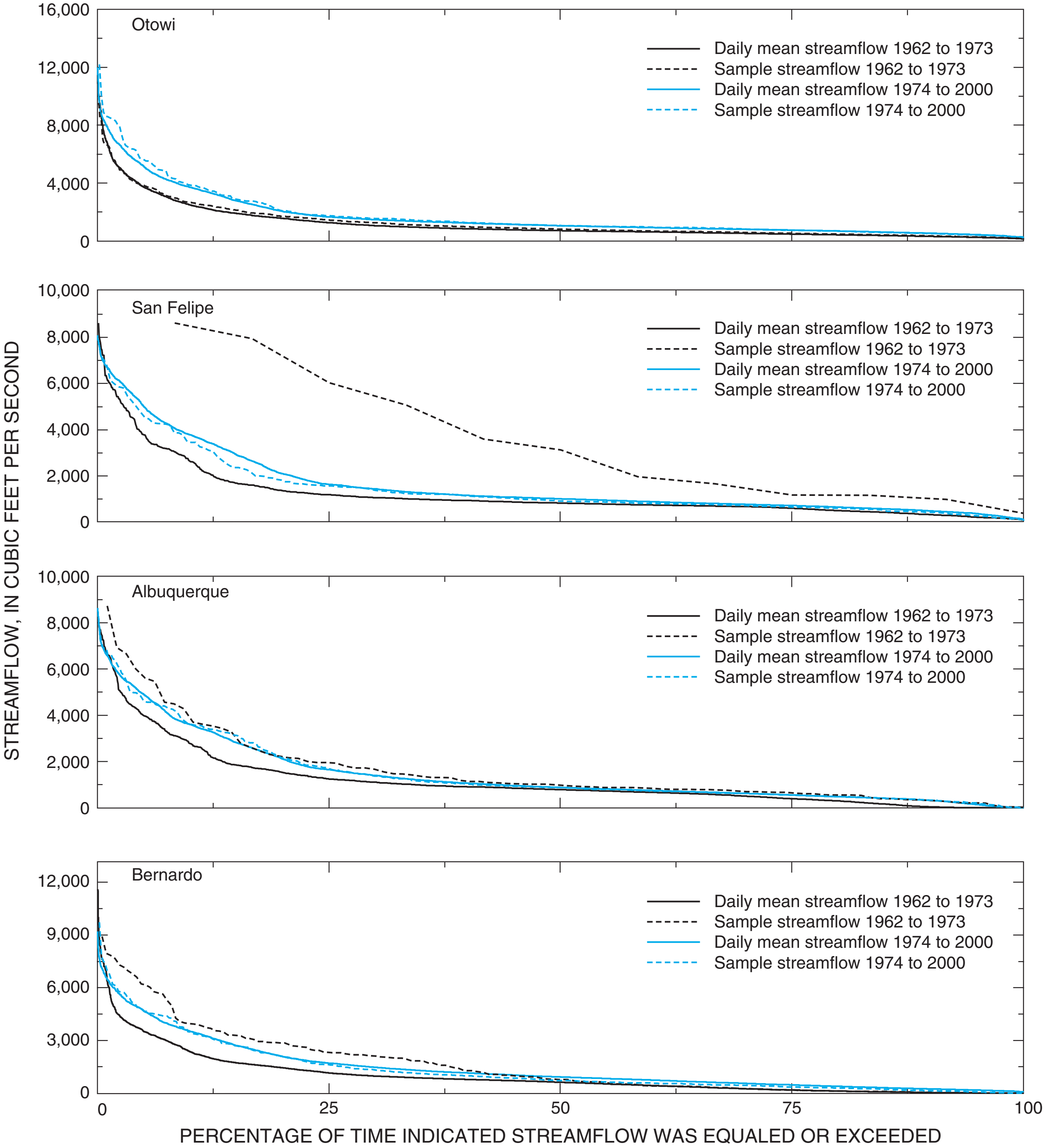


Figure 5. Duration plots of pre- and post-December 1973 daily-mean and sample streamflows for Rio Grande sites of Otowi, San Felipe, Albuquerque, and Bernardo.

Table 3. Pre- and post-December 1973 streamflow summary statistics for Rio Chama sites of La Puente, Above Abiquiu, and Chamita.

[ft^3/s, cubic feet per second; pre, pre-December 1973; post, post-December 1973]

Streamflow (ft^3/s)	La Puente pre	La Puente post	Above Abiquiu pre	Above Abiquiu post	Chamita pre	Chamita post
Minimum	4	4	8	19	0.5	17
25th percentile	45	51	69	131	63	142
Median	76	85	122	249	166	384
75th percentile	220	280	416	651	640	852
Maximum	6,690	7,720	6,180	6,480	8,760	3,567
Number of values	6,636	9,801	4,505	9,801	13,098	9,801

The annual-mean streamflow distributions for the Rio Chama increased from pre- to post-December 1973 for all sites affected by the reservoirs (fig. 6). The annual-mean streamflow distribution did not increase at the La Puente site. Increases in streamflow distributions at Above Abiquiu and Chamita were highly significant for all months except November at the Above Abiquiu site. For sites affected by the reservoirs, the largest monthly increases generally were during snowmelt runoff in March through July (fig. 6). Monthly increases at the La Puente site also were highly significant during snowmelt runoff, although smaller than those at Above Abiquiu and Chamita, indicating some climate influence.

Annual-mean streamflow distributions increased downstream in the Rio Chama in the post-December 1973 period (table 4), indicating likely surface- and ground-water inflows and the effect of the addition of SJC Project water. Because the median daily-mean streamflow of 384 ft^3/s at Chamita was equal to about 70 percent of the median daily-mean streamflow of 530 ft^3/s at Taos, the Rio Chama has a large influence on Rio Grande streamflow and water quality.

Post-December 1973 median daily-mean streamflow at La Puente was largest during snowmelt runoff from March through July with peak flows in May and small flows during all other months (fig. 7). Streamflow was less than 100 ft^3/s at the La Puente site from August through February. During the peak of snowmelt runoff, median daily-mean streamflow at La Puente was greater than 2,500 ft^3/s, larger than all other Rio Chama sites in the post-December 1973 period.

Storage of SJC Project water and snowmelt runoff in El Vado and Abiquiu Reservoirs affected downstream flow (fig. 7). El Vado Reservoir operations decreased streamflow in the Rio Chama from March to June (comparing the streamflow at Above Abiquiu to the streamflows at La Puente and Heron Dam) by storing part of the SJC Project water and snowmelt runoff. The reservoir increased streamflow in the Rio Chama from June to February as stored water was released. The maximum release from Abiquiu Dam was restricted to 1,800 ft^3/s because of downstream channel capacity. This restriction resulted in larger releases from Abiquiu Reservoir prior to and after the snowmelt runoff peak and during summer months than releases from El Vado Reservoir. Streamflow greater than 1,800 ft^3/s at the Chamita site during peak snowmelt runoff is attributable to tributary inflows between Abiquiu Reservoir and the Chamita site.

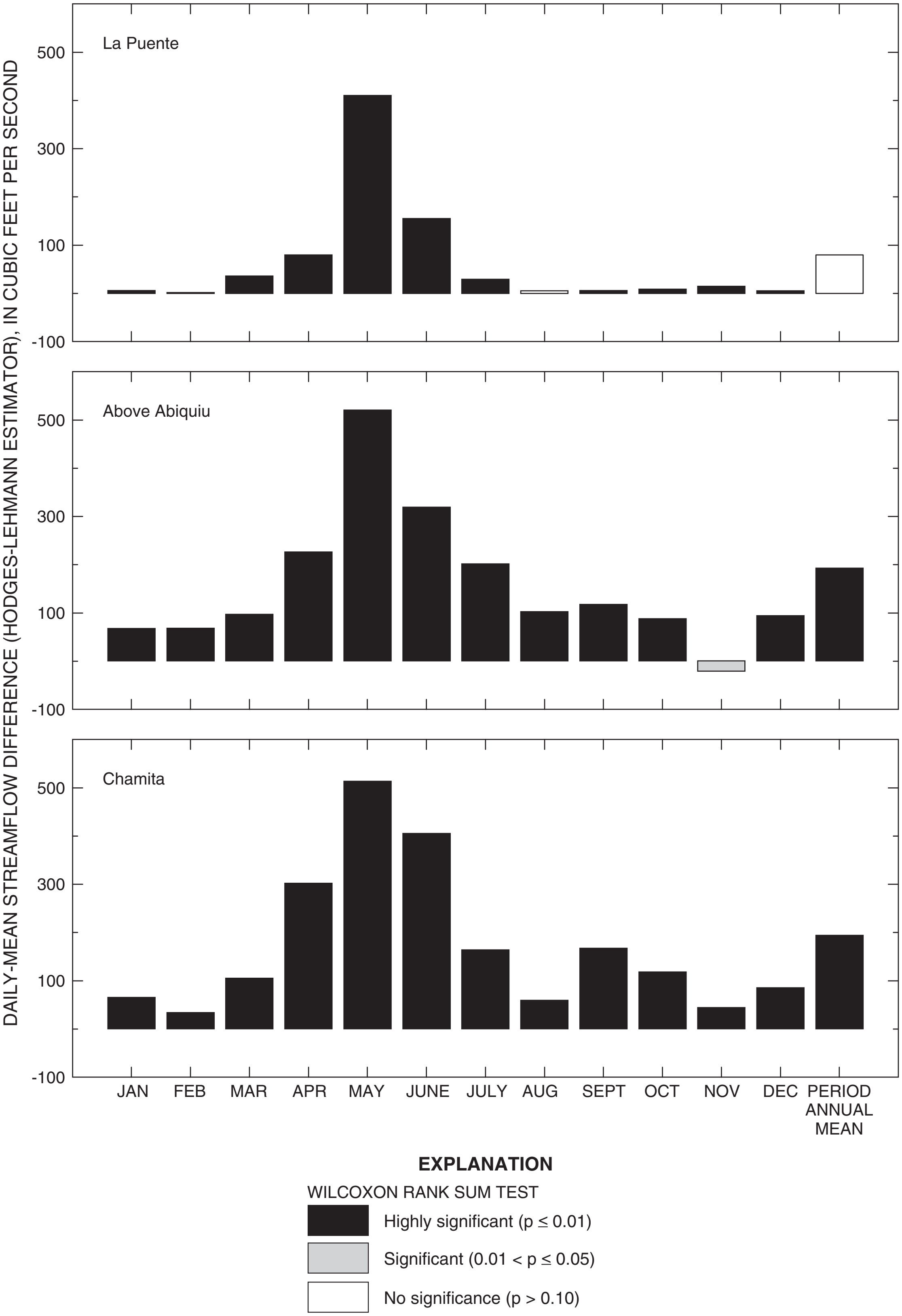


Figure 6. Monthly and period differences for pre- to post-December 1973 streamflow for Rio Chama sites of La Puente, Above Abiquiu, and Chamita.

Table 4. Annual-mean streamflow-distribution differences from upstream to downstream for Rio Chama sites of La Puente, Above Abiquiu, and Chamita and Rio Grande site of Taos for the post-December 1973 period.

[<, less than]

Wilcoxon signed rank test (one way)	La Puente to Above Abiquiu	Above Abiquiu to Chamita	Chamita compared with Taos
Difference in streamflow distributions	Increase	Increase	Increase
P-value	<0.001	<0.001	<0.001

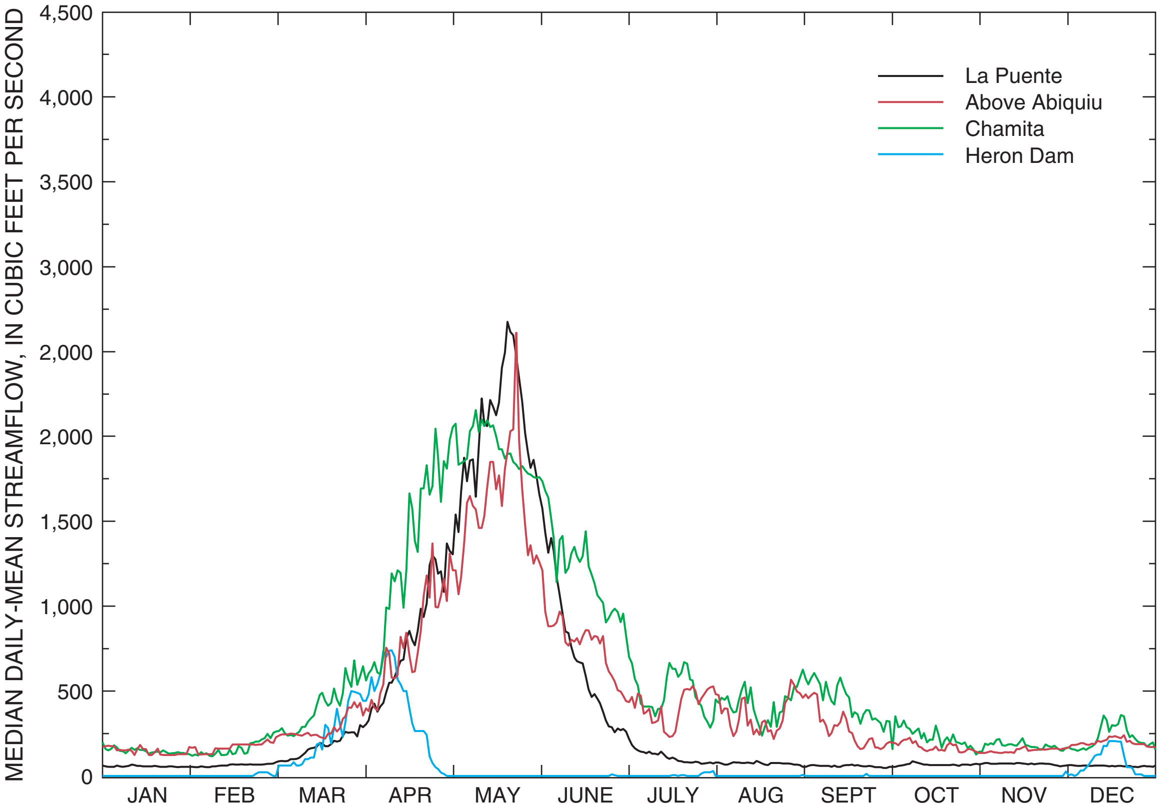


Figure 7. Post-December 1973 median daily-mean streamflow for Rio Chama sites of La Puente, Above Abiquiu, and Chamita and Rio Chama tributary site of Heron Dam.

Rio Grande

The operation of Rio Chama reservoirs, the Rio Grande reservoir of Cochiti Lake, and the addition of SJC Project water generally increased streamflow in the Rio Grande. Median streamflows and interquartile ranges increased and maximum streamflows decreased from pre- to post-December 1973 for all sites on the Rio Grande influenced by the reservoirs: Otowi, San Felipe, Albuquerque, and Bernardo (table 5). Minimum, median, and interquartile ranges in the post-1973 period were larger at the Taos site, upstream from the reservoirs, but these increases were smaller than increases at sites affected by the reservoirs.

Annual-mean streamflow distributions for the Rio Grande increased from pre- to post-December 1973 at all sites affected by the reservoirs and the SJC Project (fig. 8). There was no significant increase in annual-mean streamflow distributions at the Del Norte and Taos sites. Increases in streamflow distributions at the Rio Grande sites of Otowi, San Felipe, Albuquerque, and Bernardo were highly significant during all months except at San Felipe in November. The largest monthly increases were during snowmelt runoff in March through July. At the Del Norte and Taos sites, increases in streamflow were significant during snowmelt runoff, although much smaller than those at the sites downstream from the reservoirs, indicating some climate influence.

Median daily-mean streamflow of the Rio Grande increased by a factor of two from Taos to Otowi (from 530 to 1,050 ft^3/s), was similar between Otowi and San Felipe (1,050 to 1,020 ft^3/s), decreased from San Felipe to Albuquerque (1,020 to 874 ft^3/s), and increased from Albuquerque to Bernardo (874 to 920 ft^3/s) during the post-December 1973 period (table 5).

Changes in annual-mean streamflow distributions were similar to changes in median streamflow (table 6). However, streamflow distribution from Otowi to San Felipe decreased, and from Albuquerque to Bernardo did not change.

Much of the increase in streamflow from Taos to Otowi is due to the inflow of the Rio Chama, whereas the decrease between Otowi and San Felipe is a result of ET and the Cochiti Dam MRGCD diversion. The decrease in streamflow between San Felipe and Albuquerque is a result of ET and MRGCD diversions and possible ground-water losses. The lack of difference in streamflow between Albuquerque and Bernardo is likely a result of riverside drain inflows, ground-water inflows, and the Southside Water Reclamation Plant inflow balanced by ET and the Isleta MRGCD diversion.

Median daily-mean streamflow at all Rio Grande sites responded similarly to snowmelt runoff in the post-December 1973 period as streamflow increased in March and peaked in May (fig. 9). The largest median daily-mean peak streamflow was about 4,500 ft^3/s at the Otowi site. Rio Grande sites downstream from Otowi were moderated because of Cochiti Dam. Streamflows were less than 1,500 ft^3/s from July 1 to March 1 at all sites. Streamflows decreased abruptly after July 1 when floodwater releases from Abiquiu Reservoir and Cochiti Lake were halted.

Table 5. Pre- and post-December 1973 streamflow summary statistics for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, and Bernardo.

[ft^3/s, cubic feet per second; pre, pre-December 1973; post, post-December 1973]

Streamflow (ft^3/s)	Taos pre	Taos post	Otowi pre	Otowi post	San Felipe pre	San Felipe post	Albuquerque pre	Albuquerque post	Bernardo pre	Bernardo post
Minimum	159	171	106	195	54	67	0.1	0.1	0.1	72
25th percentile	300	351	510	740	507	724	240	549	154	472
Median	448	530	740	1,050	755	1,020	606	874	575	920
75th percentile	648	835	1,320	1,650	1,340	1,640	1,070	1,640	1,060	1,704
Maximum	9,730	8,120	22,000	12,000	21,300	8,095	20,600	8,650	19,600	9,208
Number of values	13,118	9,435	13,118	9,801	13,118	9,801	11,598	9,801	11,657	9,801

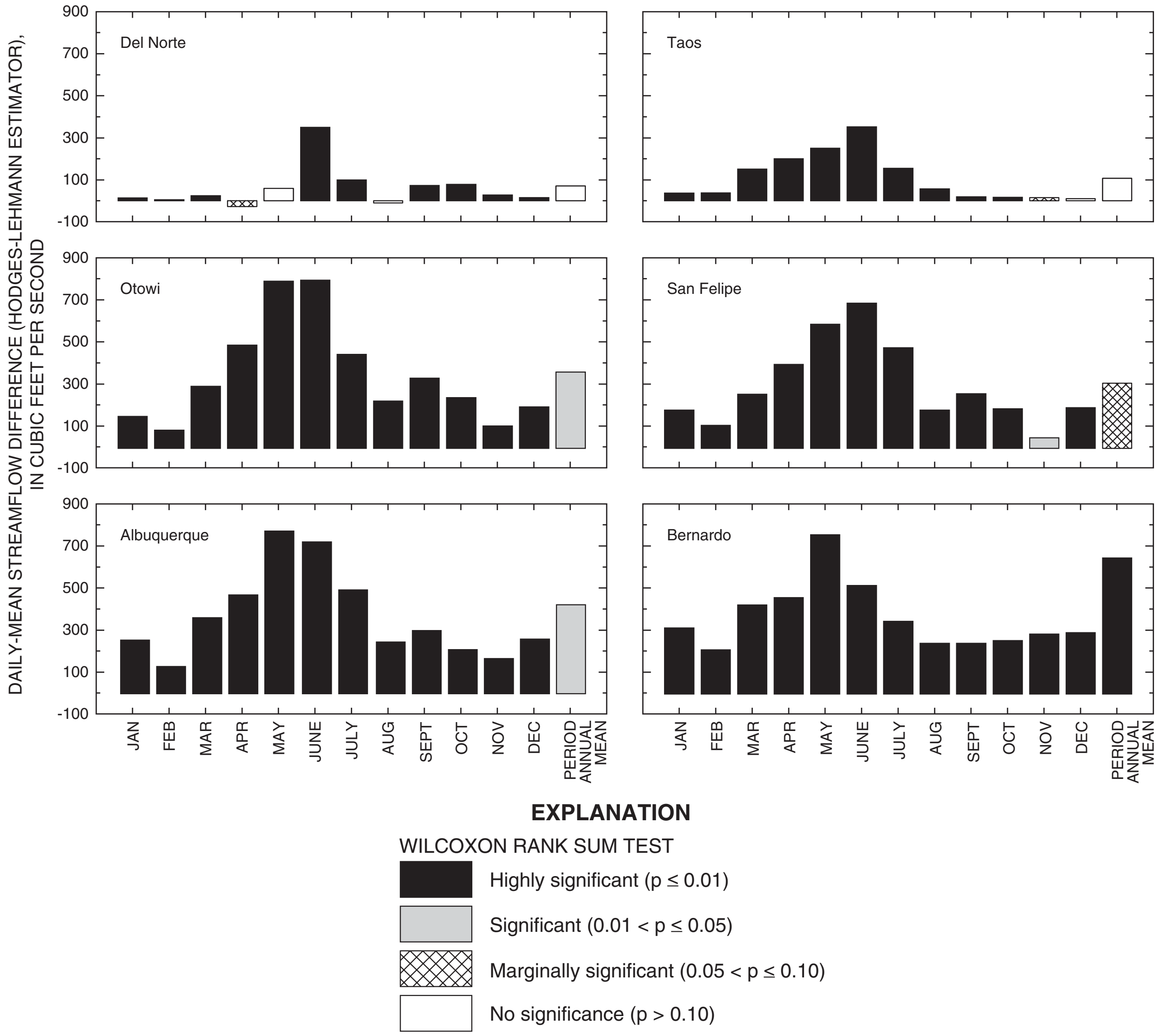


Figure 8. Monthly and period differences for pre- to post-December 1973 streamflow for Rio Grande sites of Del Norte, Taos, Otowi, San Felipe, Albuquerque, and Bernardo.

Table 6. Annual-mean streamflow-distribution differences from upstream to downstream for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo for the post-December 1973 period.

[<, less than]

Wilcoxon signed rank test (one way)	Taos to Otowi	Otowi to San Felipe	San Felipe to Albuquerque	Albuquerque to Bernardo
Difference in streamflow distributions	Increase	Decrease	Decrease	No difference
P-value	< 0.001	< 0.001	< 0.001	0.173

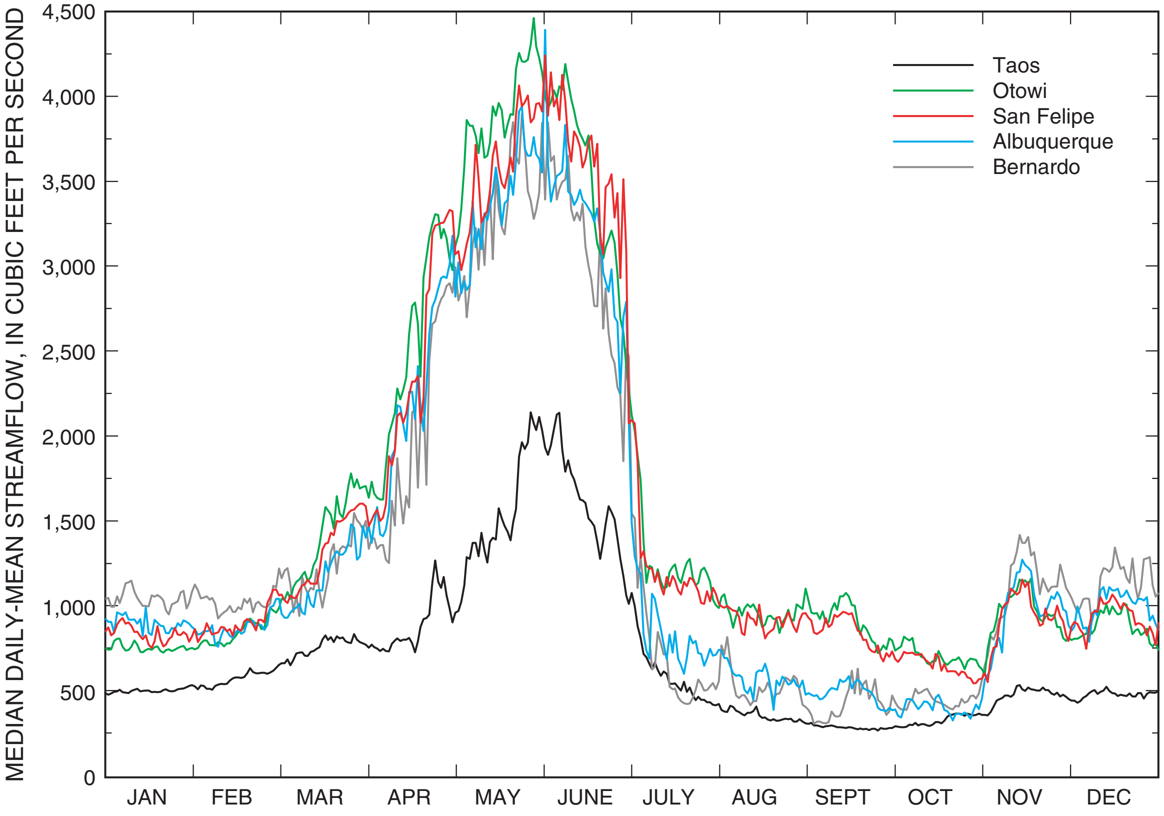


Figure 9. Post-December 1973 median daily-mean streamflow for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, and Bernardo.

Inflow from the Rio Chama to the Rio Grande was about 35 percent of Otowi's streamflow from October through February with only a small increase in December (fig. 9). Beginning in March, the Rio Chama carried snowmelt runoff and SJC Project water to the Rio Grande (about 50 percent of Otowi's streamflow) with a substantial reduction by July 1.

The trend for streamflow in the Rio Grande was similar to that observed in the Rio Chama near Chamita. The Otowi and San Felipe sites substantially increased in streamflow in March and decreased July 1 (fig. 9). Water was stored in Cochiti Lake mostly from March through May and released mostly in June, as shown by the difference between Otowi and San Felipe streamflows. MRGCD irrigation water from the Rio Grande was diverted from mid-May through the end of October, as shown by the difference in streamflows between the San Felipe and the Albuquerque and Bernardo sites. This trend was especially apparent on November 1 when streamflow at San Felipe, Albuquerque, and Bernardo increased as irrigation diversions stopped. Streamflow increased between Albuquerque and Bernardo from November 1 to mid-March and can be attributed to the Southside Water Reclamation Plant, riverside drain inflows, and potential ground-water inflows.

Specific Conductance

Rio Chama

Specific conductance at the Chamita site decreased in median value, interquartile range, and maximum value from the pre- to post-December 1973 period (table 7). Decreases in specific-conductance distribution at Chamita were highly significant from the pre- to post-December 1973 period and highly significant in January through March and July through December (fig. 10). Specific conductance did not change significantly in April and June, but an increase was highly significant in May. These significant decreases and increase exemplify the effect of reservoir operations as released SJC Project water and retained snowmelt decreased specific conductance in the Rio Chama throughout the year except when streamflow was retained during the snowmelt runoff.

Post-December 1973 specific conductance in the Rio Chama increased from La Puente to Chamita (table 8) and indicated that specific conductance in inflows of ground water, tributaries, and SJC Project water likely were larger than in native upper Rio Chama water (La Puente). Specific conductance of ground water and tributaries between La Puente and Chamita is unknown. Data retrieved from the U.S. Environmental Protection Agency STORET Legacy database for Heron Lake (table 9) indicated a median of 312 µS/cm, which was larger than the 190-µS/cm median for La Puente (table 7). The inflow of ground water and (or) tributaries to the Rio Chama between the La Puente and Chamita sites also likely increased specific conductance because the median specific conductance (353 µg/L) in water at the Chamita site was larger than that in Heron Lake.

Specific conductance increased downstream from Abiquiu Reservoir in the post-December 1973 period. The median specific conductance at the Above Abiquiu site was 357 µS/cm from 1976 to 1985. For the same period at the Below Abiquiu site, the median was 355 µS/cm. The median for the Chamita site from 1976 to 1985 was 440 µS/cm. The similar medians for Above Abiquiu and Below Abiquiu and the increase in median specific conductance from Below Abiquiu to Chamita indicate that most of the increase in specific conductance in the Rio Chama was likely a result of ground-water and tributary inflow downstream from Abiquiu Reservoir. Comparison of specific-conductance distributions for the Rio Chama (Chamita) and Rio Grande (Taos and Otowi) (table 8) indicates that specific conductance in the Rio Chama was larger than that in the Rio Grande and that the inflow of the Rio Chama was diluted with mixing of Rio Grande water.

Table 7. Pre- and post-December 1973 specific-conductance summary statistics for Rio Chama sites of La Puente and Chamita.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; pre-, pre-December 1973; post, post-December 1973; NA, not available]

Specific conductance (µS/cm)	La Puente pre	La Puente post	Chamita pre	Chamita post
Minimum	NA	46	132	176
25th percentile	NA	148	328	300
Median	NA	190	523	353
75th percentile	NA	230	676	473
Maximum	NA	375	1,000	864
Number of values	0	73	207	253

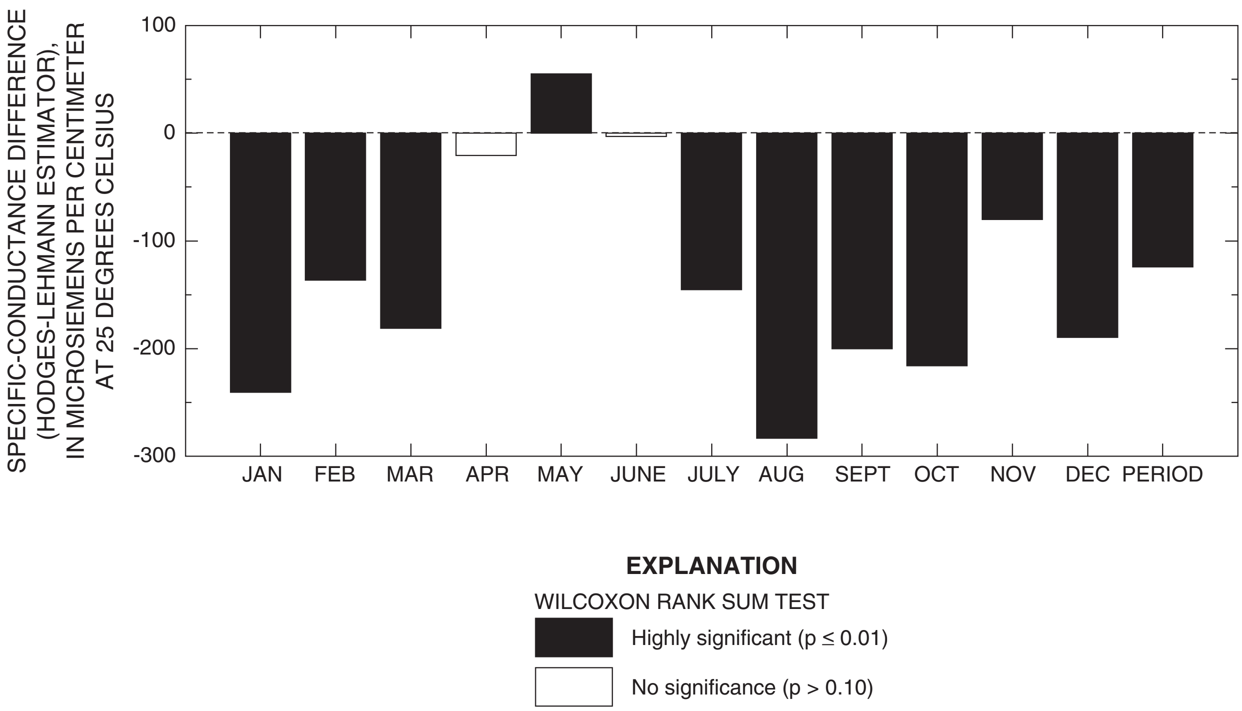


Figure 10. Monthly and period differences for pre- to post-December 1973 specific conductance for Rio Chama site of Chamita.

Table 8. Specific-conductance distribution differences from upstream to downstream for Rio Chama sites of La Puente and Chamita and Rio Grande sites of Taos and Otowi for the post-December 1973 period.

[<, less than]

Wilcoxon rank sum test (one way)	La Puente to Chamita	Chamita compared with Taos	Chamita compared with Otowi
Difference in specific-conductance distributions	Increase	Decrease	Decrease
P-value	< 0.001	< 0.001	< 0.001

Table 9. Heron Lake specific-conductance data.

[Retrieved from U.S. Environmental Protection Agency STORET Legacy Data Center; cond., conductance; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Constituent	8/26/87	Sample depth (feet)	5/14/91	Sample depth (feet)	8/14/91	Sample depth (feet)	10/29/91	Sample depth (feet)
Heron Lake: sample location is Heron deep, located near the dam								
Specific cond. (µS/cm)	305-352	0 - 108	325 - 347	0 - 148	286 - 328	0 - 148	293 - 326	0 - 148
Heron Lake: sample location is Heron shallow, located in the northeastern part of the reservoir								
Specific cond. (µS/cm)	305 - 305	0 - 29	308 - 342	0 - 49	274 - 306	0 - 56	292 - 292	0 - 52

Post-December 1973 specific conductance decreased at the La Puente and Chamita sites during the snowmelt runoff (fig. 11). Following the streamflow peak in May, specific conductance increased as streamflow decreased. Specific-conductance values were largest from January through March when ground-water and tributary inflows composed the majority of streamflow in the Rio Chama.

Rio Grande

Specific-conductance medians decreased from pre- to post-December 1973 for the Rio Grande sites of Otowi, Isleta, and Bernardo (table 10). Maximum specific conductance decreased at Otowi and Bernardo but slightly increased at Isleta. Specific-conductance distributions decreased significantly from the pre- to post-December 1973 period at Otowi and Bernardo (fig. 12). Specific-conductance distribution also significantly decreased between the two periods for the Isleta site (p-value less than 0.001), but data were insufficient for monthly comparisons of distributions. Specific-conductance distribution decreases at Otowi were significant or highly significant during all months except April. Decreases at Bernardo were marginally significant to highly significant during January, June, August, September, October, and December (fig. 12). The differences in magnitude and significance in pre- to post-December 1973 monthly decreases in specific conductance at Otowi and Bernardo show the lessening effect of the reservoirs further downstream as the Rio Grande was influenced by other inflows.

Specific conductance increased in the downstream direction in the Rio Grande during the post-December 1973 period (table 11). The increase in median specific conductance from Taos to Otowi (from 281 to 329 µS/cm) was likely a result of Rio Chama inflow (353 µS/cm at the Chamita site). The small median increase from the Otowi to San Felipe site (329 to 340 µS/cm) was likely a result of storage, mixing, and ET at Cochiti Lake and ET within the channel corridor.

The San Felipe to Albuquerque reach of the Rio Grande has the potential for substantial ET because of a broad, flat channel, but the reach also contains the inflow from the Jemez River. Inflow from the Jemez River is small compared with the Rio Grande. The larger specific conductance of the Jemez River (1,240-µS/cm median specific conductance and 4,700-µS/cm maximum specific conductance during the post-December 1973 period), however, may have increased median specific conductance in the Rio Grande from San Felipe to Albuquerque (from 340 to 368 µS/cm) in addition to increases caused by ET and irrigation-return flows.

The increase in median specific conductance from Albuquerque (368 µS/cm) to Isleta (425 µS/cm) and Bernardo (491 µS/cm) was likely a result of ET, treated wastewater inflow, and irrigation-return flows. Wilcox (1997) measured specific conductance ranging from 764 to 836 µS/cm (median of 816 µS/cm) for the City of Albuquerque's Southside Water Reclamation Plant and ranging from 398 to 486 µS/cm (median of 432 µS/cm) for the riverside drains in the Albuquerque area.

Seasonal variation of average specific conductance in the post-December 1973 period was similar for all sites on the Rio Grande (fig. 13). Specific conductance decreased with the beginning of snowmelt runoff in March, was smallest in May and June, and gradually increased throughout the summer months as releases from the reservoirs declined in volume. By September, specific-conductance values at all sites were similar to those prior to snowmelt runoff.

The larger specific conductance at Otowi compared with that at San Felipe from mid-June through July was likely a result of snowmelt runoff storage in Cochiti Lake. The difference in specific conductance between Otowi and San Felipe in March was small but began to increase in April as a greater amount of snowmelt runoff passed the Otowi site and part of this runoff was stored in Cochiti Lake (shown by the difference in streamflow at the Otowi and San Felipe sites). Streamflow at San Felipe was generally smaller than streamflow at Otowi during this period but was equal to or greater than streamflow at Otowi after mid-June with release of stored snowmelt runoff. With this shift in streamflow at San Felipe in mid-June, specific conductance at San Felipe decreased to concentrations smaller than those observed at Otowi as retained snowmelt was released from Cochiti Lake.

pH

Rio Chama

From the pre- to post-December 1973 period in water collected from the Rio Chama near Chamita (table 12), pH increased for all statistical values (minimum, 25th percentile, median, 75th percentile, and maximum). The increase in pH at the Chamita site was highly significant from the pre- to post-December 1973 period and highly significant in every month except December (significant) (fig. 14). The largest increases were in October and November, and the smallest increase was in July.

The post-December 1973 pH in the Rio Chama increased from La Puente to Chamita (table 13). The increase was likely a result of inflow of SJC Project water because pH was larger in Heron Lake (8.45 median pH, table 14) than pH at the La Puente site. Ground-water and tributary inflows between La Puente and Chamita also could increase pH, although no data were available for comparison.

For the post-December 1973 period, there was no difference in pH distributions at Chamita compared with the Taos and Otowi sites (table 13). This lack of difference indicates that the increase in pH in water at the Chamita site from the pre- to post-December 1973 period resulted in a pH in the Rio Chama that was similar to pH in the Rio Grande at Taos. Therefore, mixing of Rio Chama and Rio Grande water did not result in pH changes at Otowi.

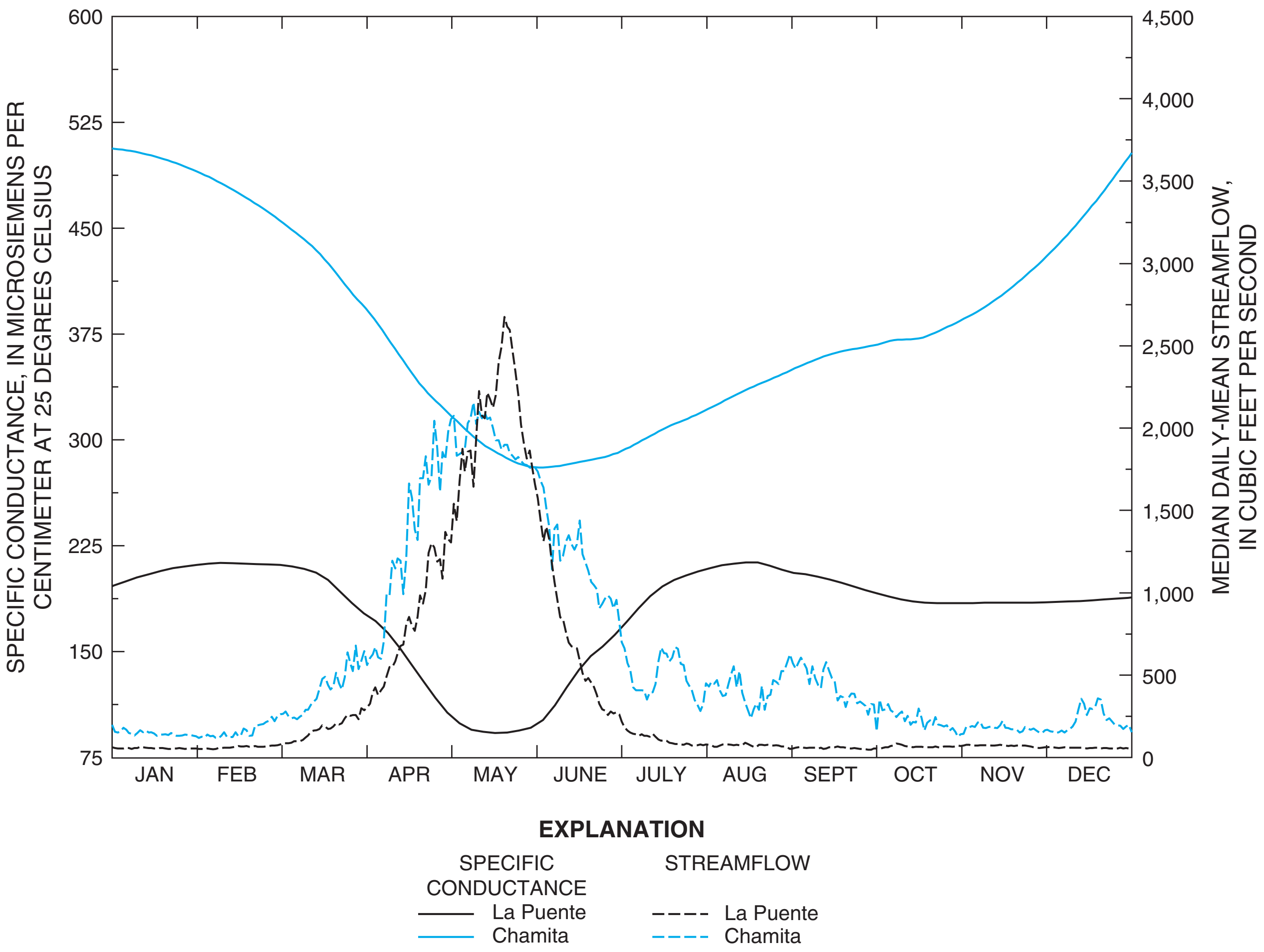


Figure 11. Post-December 1973 average (LOESS) specific conductance and median daily-mean streamflow for Rio Chama sites of La Puente and Chamita.

Table 10. Pre- and post-December 1973 specific-conductance summary statistics for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; pre, pre-December 1973; post, post-December 1973; NA, not available]

Specific conductance (µS/cm)	Taos pre	Taos post	Otowi pre	Otowi post	San Felipe pre	San Felipe post	Albuquerque pre	Albuquerque post	Isleta pre	Isleta post	Bernardo pre	Bernardo post
Minimum	NA	144	200	165	NA	173	NA	192	245	220	289	224
25th percentile	NA	220	335	288	NA	303	NA	329	367	379	406	417
Median	NA	281	386	329	NA	340	NA	368	486	425	520	491
75th percentile	NA	329	442	370	NA	376	NA	425	580	470	644	575
Maximum	NA	550	1,310	628	NA	520	NA	570	690	720	1,940	865
Number of values	0	200	982	381	1	190	2	103	31	289	160	219

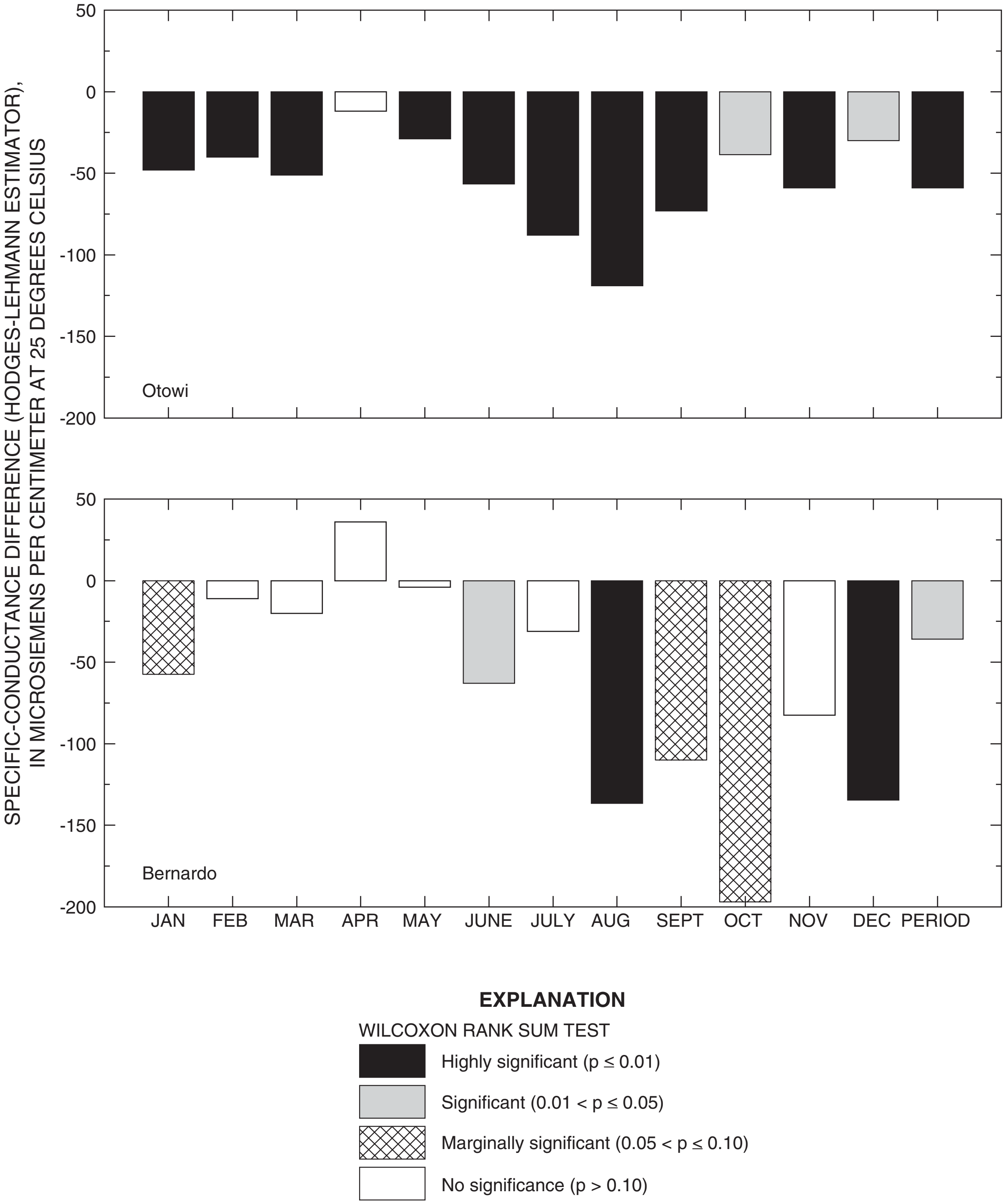


Figure 12. Monthly and period differences for pre- to post-December 1973 specific conductance for Rio Grande sites of Otowi and Bernardo.

Table 11. Specific-conductance distribution differences from upstream to downstream for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo for the post-December 1973 period.

[<, less than]

Wilcoxon rank sum test (one way)	Taos to Otowi	Otowi to San Felipe	San Felipe to Albuquerque	Albuquerque to Isleta	Isleta to Bernardo
Difference in specific-conductance distributions	Increase	Increase	Increase	Increase	Increase
P-value	< 0.001	0.015	< 0.001	< 0.001	< 0.001

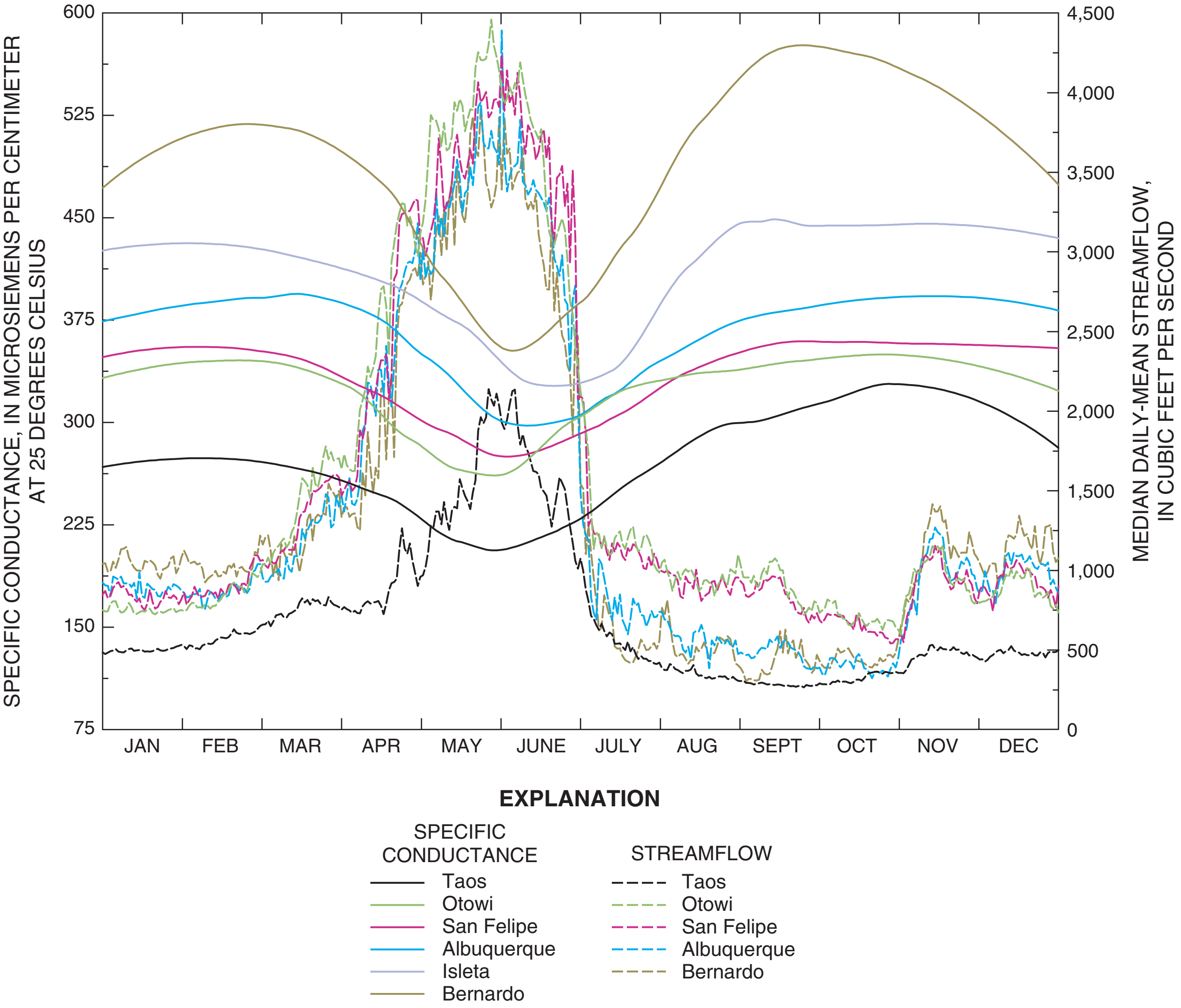


Figure 13. Post-December 1973 average (LOESS) specific conductance and median daily-mean streamflow for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

Table 12. Pre- and post-December 1973 pH summary statistics for Rio Chama sites of La Puente and Chamita.

[pre, pre-December 1973; post, post-December 1973; NA, not available]

pH (standard units)	La Puente pre	La Puente post	Chamita pre	Chamita post
Minimum	NA	6.3	6.9	7.5
25th percentile	NA	7.7	7.4	8
Median	NA	8.0	7.6	8.2
75th percentile	NA	8.2	7.8	8.4
Maximum	NA	8.8	8.5	8.8
Number of values	0	124	181	146

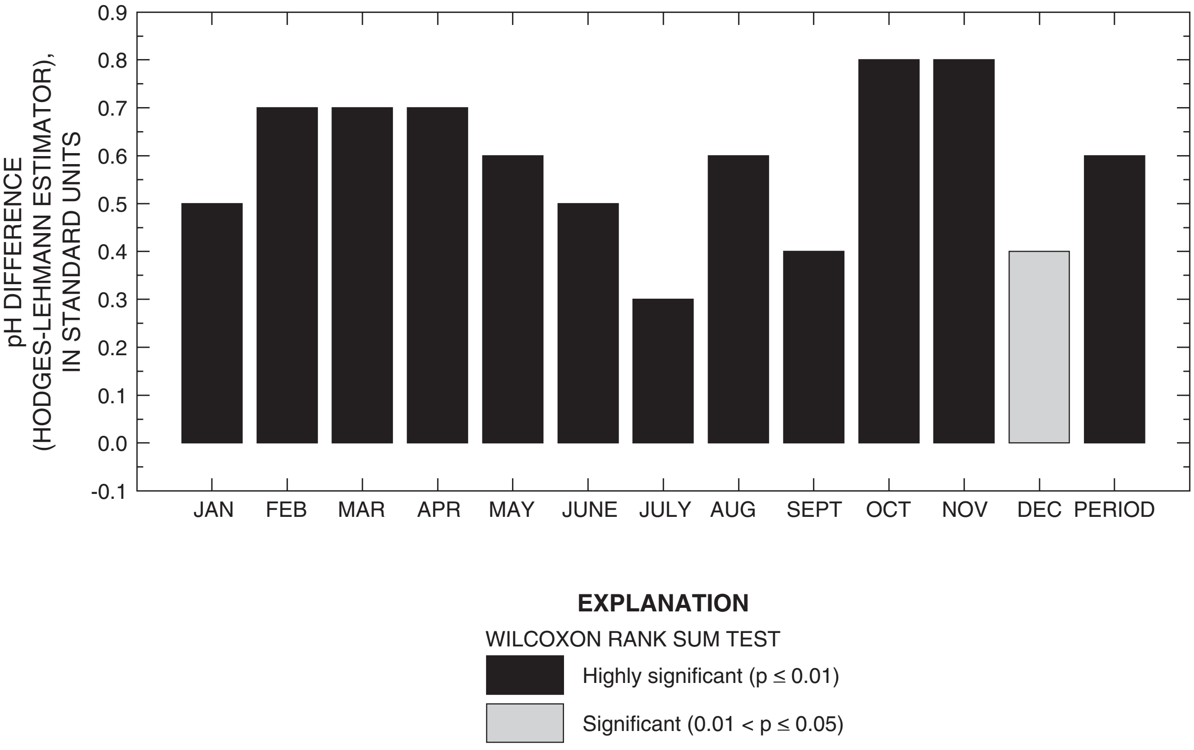


Figure 14. Monthly and period differences for pre- to post-December 1973 pH for Rio Chama site of Chamita.

Table 13. Distribution differences in pH from upstream to downstream for Rio Chama sites of La Puente and Chamita and Rio Grande sites of Taos and Otowi for the post-December 1973 period.

[<, less than]

Wilcoxon rank sum test (one way)	La Puente to Chamita	Chamita compared with Taos	Chamita compared with Otowi
Difference in pH distributions	Increase	No difference	No difference
P-value	< 0.001	0.463	0.145

Table 14. Heron Lake pH data.

[Retrieved from U.S. Environmental Protection Agency STORET Legacy Data Center; pH in standard units]

Constituent	8/26/87	Sample depth (feet)	5/14/91	Sample depth (feet)	8/14/91	Sample depth (feet)	10/29/91	Sample depth (feet)
Heron Lake: sample location is Heron deep, located near the dam								
pH	8.40	0	8.60	0	8.48	0	8.43	0
Heron Lake: sample location is Heron shallow, located in the northeastern part of the reservoir								
pH	8.30	0	8.65	0	8.47	0	8.38	0

In the post-December 1973 period, seasonal variations in pH at the La Puente and Chamita sites were not similar due to reservoir operations (fig. 15). The pH at La Puente was typically smaller than at Chamita except from June through August, and pH data for both sites indicate an inverse relation to streamflow. The pH in water from the La Puente site was smallest in early May just before the streamflow peak and largest in July following the end of snowmelt runoff. The values of pH in water at Chamita were smallest in June following the streamflow peak and largest in late October when reservoir releases were at a minimum.

The pH was typically smaller at the La Puente site than pH at the Chamita site except during summer months when pH at the La Puente site exceeded pH at the Chamita site from mid-June through mid-August (fig. 15). Following the peak of snowmelt runoff, biological productivity likely increased at the La Puente site as instream temperatures increased, thereby producing greater photosynthesis and an increase in pH. Biological productivity in a watershed continually changes with variable inputs of nutrients and energy, given natural seasonal variations (Black, 1996). With increased photosynthesis, pH increases as hydrogen-ion concentrations decrease as dissolved carbon dioxide decreases (Hem, 1989).

Following the pH peak at La Puente in July, pH decreased through August, remained stable in September, and decreased from October through December (fig. 15). The decrease in pH from mid-July through August is consistent with biological productivity as an influence on pH. Streamflow was stable during this period, indicating that ground-water and tributary inflows also were stable. Biological productivity may have peaked in July and decreased through August as a result of decreasing temperature (fig. 16). Following the decrease, pH remained relatively constant from late August through mid-October (fig. 15). The decrease in pH from mid-October through December was likely a result of another decrease in biological activity as water temperature further decreased (fig. 16).

The assumption of biological activity as an influence on pH in the Rio Chama is not as straightforward at the Chamita site. At this site, pH increased in late summer and fall as streamflow decreased to a minimum following summer reservoir releases and also decreased in early spring (fig. 15) as stream temperatures began to increase (fig. 16). The pH was largest when streamflow was smallest but did not correlate with the streamflow temperature peak as observed with the La Puente site (fig. 16). The retention and later release of snowmelt runoff from Abiquiu Reservoir appears to depress pH values at the Chamita site through the warm summer months. The shift in pH from the La Puente site to the Chamita site is likely a result of reservoir releases that controlled stream temperature, nutrient loads, and biological activity downstream from Abiquiu Dam.

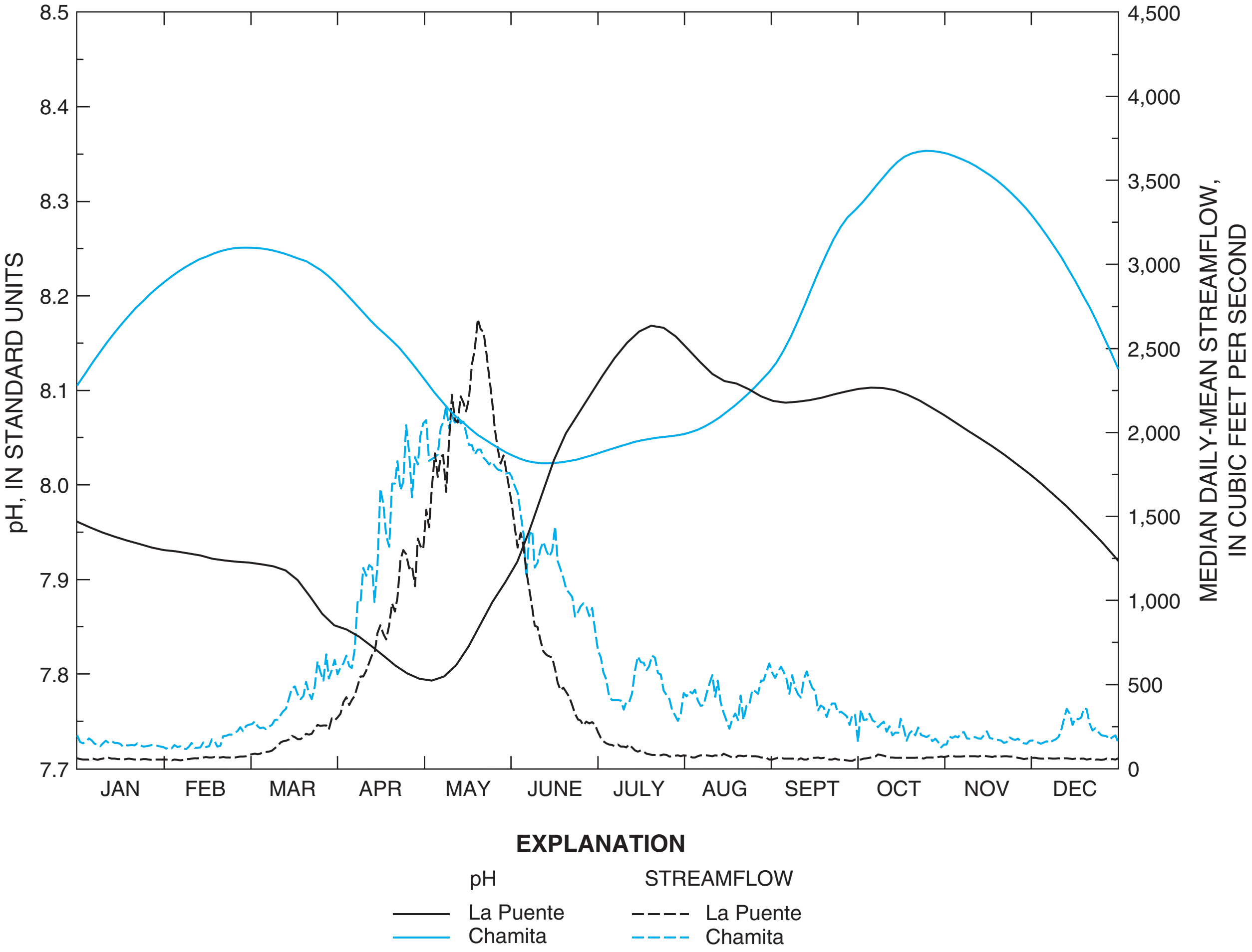


Figure 15. Post-December 1973 average (LOESS) pH and median daily-mean streamflow for Rio Chama sites of La Puente and Chamita.

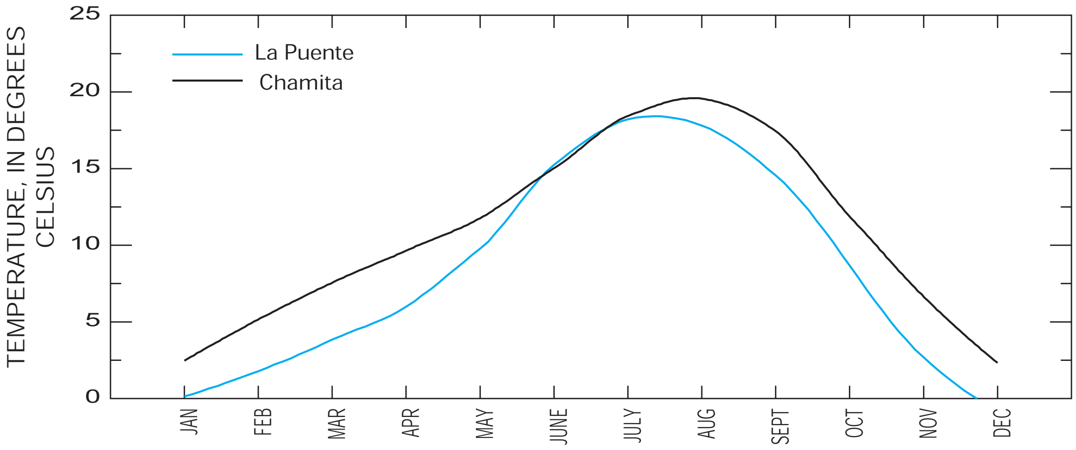


Figure 16. Post-December 1973 average (LOESS) water temperature for Rio Chama sites of La Puente and Chamita.

Rio Grande

For the Rio Grande sites downstream from the reservoirs, median pH was 7.7 or 7.8 during the pre-December 1973 period and ranged from 8.0 to 8.2 for the post-December 1973 period (table 15). The 25th and 75th percentile pH values increased at Otowi, Isleta, and Bernardo between the two periods. The pH at Otowi indicated a highly significant increase from pre- to post-December 1973 for all monthly distributions (fig. 17). Although the 25th percentile, median, and 75th percentile pH values all increased by 0.3 unit at the Isleta site (table 15), the overall pH distribution decreased from the pre- to post-December 1973 period (highly significant, p-value less than 0.001). The pH increase at Bernardo was highly significant from pre- to post-December 1973, but monthly distributions were a mixture of no significance to highly significant increases (fig. 17).

No downstream trend in pH was evident for the Rio Grande sites during the post-December 1973 period as was observed with specific conductance. The distributions of pH in the Rio Grande were similar for Taos and Otowi, decreased from Otowi to San Felipe, were similar for San Felipe and Albuquerque, decreased from Albuquerque to Isleta, and increased from Isleta to Bernardo (table 16). The decrease in pH from Otowi to San Felipe could have been a result of storage in Cochiti Lake. The pH at the Cochiti Lake site ranged from 7.2 to 9.0 with a median of 7.9, and pH at the Cochiti Dam site ranged from 7.8 to 8.3 with a median of 7.9. The median pH values for Cochiti Lake and Cochiti Dam were smaller than the Otowi site median pH of 8.2.

Stratification of Cochiti Lake may be causing smaller pH values near the bottom of the reservoir because of hypoxic or anoxic conditions. Under hypoxic conditions, pH may decrease as carbon dioxide increases with biological respiration (Black, 1996). In July 1999, June 2000, and September 2000, near the dam in Cochiti Lake, water-quality depth profiles showed dissolved-oxygen stratification (K. Bennett, U.S. Army Corps of Engineers, written commun., 2002). Additionally, Johnson and Barton (1980) found dissolved-oxygen stratification near the dam at Cochiti Lake during summer months and decreasing pH values with depth. Stratification occurred only during summer months, which likely limited the decrease in pH, and is the reason why median pH concentrations from Otowi to San Felipe decreased by only 0.1 standard unit (distribution decrease was significant; p-value of 0.01).

The decrease in pH from Albuquerque to Isleta (table 15) and the subsequent increase at Bernardo were probably an effect of the inflow from the City of Albuquerque's Southside Water Reclamation Plant between Albuquerque and Isleta and riverside drain inflows or ground-water additions between Isleta and Bernardo. Wilcox (1997) measured pH values ranging from 6.55 to 7.33 (median of 6.99) at the Southside Water Reclamation Plant from 1994 to 1996, which were smaller than the median pH value at the Albuquerque site. Wilcox (1997) also measured pH ranging from 7.33 to 8.37 (median of 7.84) for riverside drains in the Albuquerque area during the same period, yet these values do not indicate a possible increase in pH from riverside drain inflows between Isleta and Bernardo. The remaining potential sources of a larger pH inflow between Isleta and Bernardo could be additional downstream riverside drain inflows or possibly biological activity in this reach of the Rio Grande due to an increase in nutrients (Moore and Anderholm, 2002).

Table 15. Pre- and post-December 1973 pH summary statistics for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

[pre, pre-December 1973; post, post-December 1973; NA, not available]

pH (standard units)	Taos pre	Taos post	Otowi pre	Otowi post	San Felipe pre	San Felipe post	Albuquerque pre	Albuquerque post	Isleta pre	Isleta post	Bernardo pre	Bernardo post
Minimum	NA	7.1	6.8	6.6	NA	7.3	NA	6.8	6.7	6.6	7.1	6.8
25th percentile	NA	7.9	7.6	8.0	NA	7.9	NA	7.9	7.5	7.8	7.6	7.8
Median	NA	8.2	7.8	8.2	NA	8.1	NA	8.1	7.7	8.0	7.8	8.1
75th percentile	NA	8.4	8.0	8.3	NA	8.3	NA	8.2	7.8	8.1	7.9	8.4
Maximum	NA	8.9	9.2	8.9	NA	8.8	NA	8.7	8.4	8.5	8.5	9.5
Number of values	0	204	1,007	355	1	189	2	85	31	289	162	183

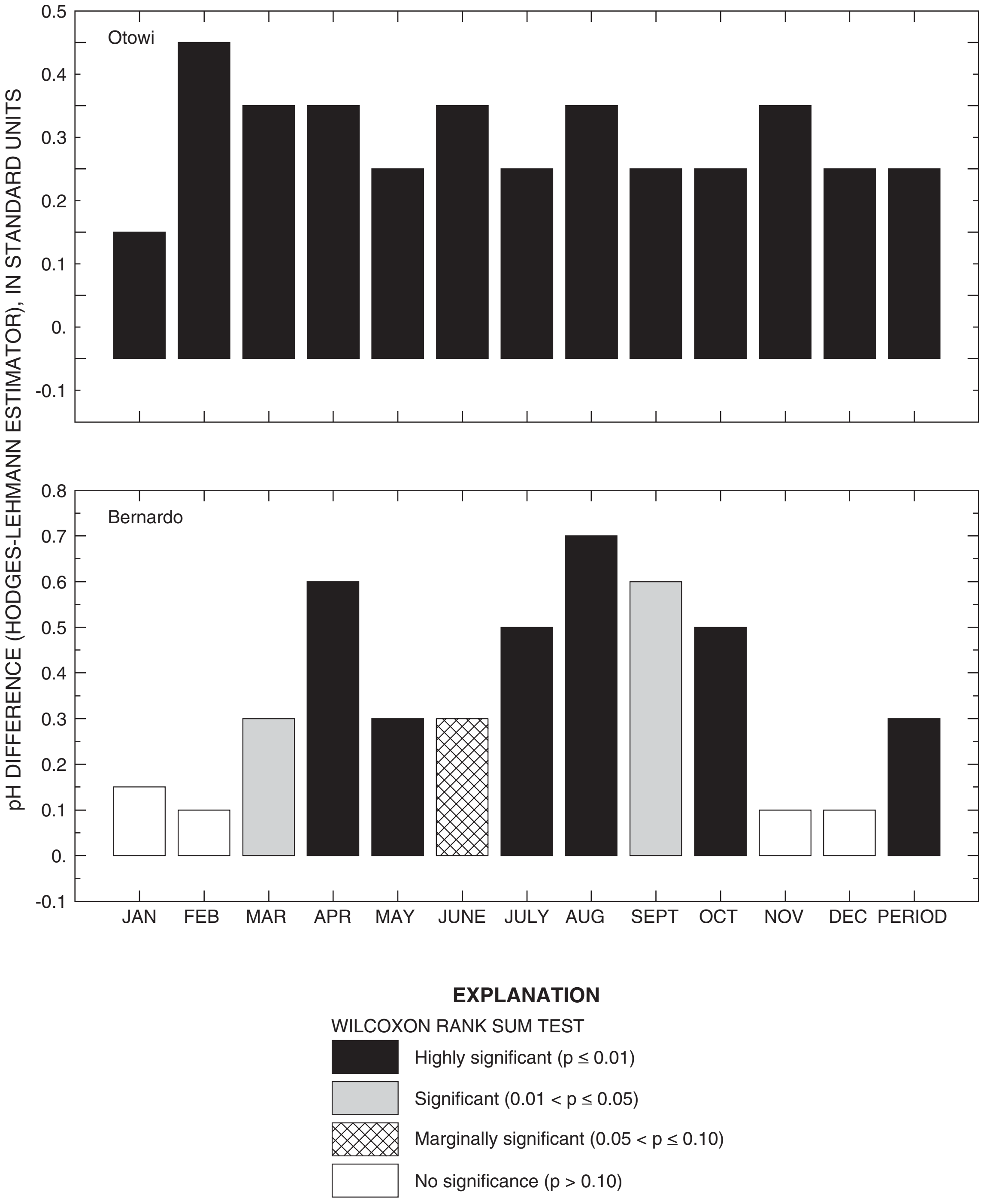


Figure 17. Monthly and period differences for pre- to post-December 1973 pH for Rio Grande sites of Otowi and Bernardo.

Table 16. Distribution differences in pH from upstream to downstream for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo for the post-December 1973 period.

[<, less than]

Wilcoxon rank sum test (one way)	Taos to Otowi	Otowi to San Felipe	San Felipe to Albuquerque	Albuquerque to Isleta	Isleta to Bernardo
Difference in pH distributions	No difference	Decrease	No difference	Decrease	Increase
P-value	0.230	0.010	0.070	0.001	< 0.001

A consistent seasonal pattern did not exist between sites on the Rio Grande for post-December 1973 pH except for decreases during snowmelt runoff (fig. 18). At all sites pH decreased slightly during snowmelt runoff, although at each site the timing of this decrease was different. The smallest and least variation in pH was at Isleta, likely a result of continuous Southside Water Reclamation Plant inflow. The pH at the Taos site indicated that pH in the Rio Grande upstream from inflow from the Rio Chama was smallest from January to July and largest from August to December; a similar trend was observed only at the Bernardo site.

The pH at the Otowi, San Felipe, and Albuquerque sites had little seasonal variability (fig. 18). At Otowi, pH values were larger than those at San Felipe except during May and June, the peak of snowmelt runoff. During snowmelt runoff, pH at Otowi decreased more than at the San Felipe site because the decrease in pH at San Felipe was moderated by mixing of inflow and water stored in Cochiti Lake. The difference in pH at Otowi and San Felipe generally increased throughout the summer months and into the fall, supporting the assertion that hypoxic or anoxic conditions in the reservoir were producing smaller pH values in the Rio Grande downstream from the reservoir. The decrease in pH between the San Felipe and Albuquerque sites from January through August was not due to inflow of the Jemez River. Median pH of the Jemez River in the post-December 1973 period was 8.2 (compared with 8.1 for San Felipe and Albuquerque), and a comparison of pH distributions for the San Felipe and Jemez River sites indicated larger pH for the Jemez River (p-value of 0.02).

The pH at the Bernardo site was more variable throughout the seasons compared with all other sites, and this variability likely resulted from riverside drain inflows and biological activity. The increase in pH beginning in June was likely a result of riverside drain inflows, and the large pH values at Bernardo during August and September were likely a biological effect from increased instream temperatures, smaller streamflow, and increased nutrients.

Suspended Sediment

Rio Chama

All suspended-sediment statistical values (minimum, 25th percentile, median, 75th percentile, and maximum) for the Rio Chama sites of Above Abiquiu and Chamita were smaller during the post-December 1973 period than during the pre-December 1973 period (table 17). Suspended-sediment concentrations at Above Abiquiu decreased highly significantly between the two periods, but monthly distributions ranged from no significance to highly significant (fig. 19). The decrease in suspended-sediment concentrations at the Chamita site was highly significant from the pre- to post-December 1973 period for all months except January (marginally significant) and July (marginally significant). The largest decreases in suspended-sediment concentrations between the two periods were in August at Chamita and in September at Above Abiquiu.

Suspended-sediment concentrations increased from La Puente to Above Abiquiu and from Above Abiquiu to Chamita in the post-December 1973 period (table 18). Additionally, suspended-sediment concentrations at Chamita were larger than at Taos and smaller than at Otowi. The difference in suspended-sediment concentration distributions between Chamita and the Rio Grande sites (table 18) indicates that the Rio Chama provided additional sediment to the Rio Grande but that Rio Chama inflow did not account for all the suspended-sediment concentration increase between Taos and Otowi.

During the post-December 1973 period, seasonal concentrations in suspended sediment in the Rio Chama peaked twice at Above Abiquiu and Chamita but only once at the La Puente site (fig. 20). Suspended-sediment concentration at La Puente peaked during snowmelt runoff in early May prior to the streamflow peak in mid-May. Additionally, suspended-sediment concentrations at La Puente were much smaller with little variation compared with those at the other sites. Suspended-sediment concentrations at the Above Abiquiu and Chamita sites peaked in April, more than 1 month before the snowmelt runoff peak. The peaks in suspended-sediment concentration prior to streamflow peaks indicate that the carrying capacity of streamflow exceeded the supply of available sediment during this time. The second peak at the Above Abiquiu and Chamita sites during the monsoon season was about 60 percent of the first peak (fig. 20).

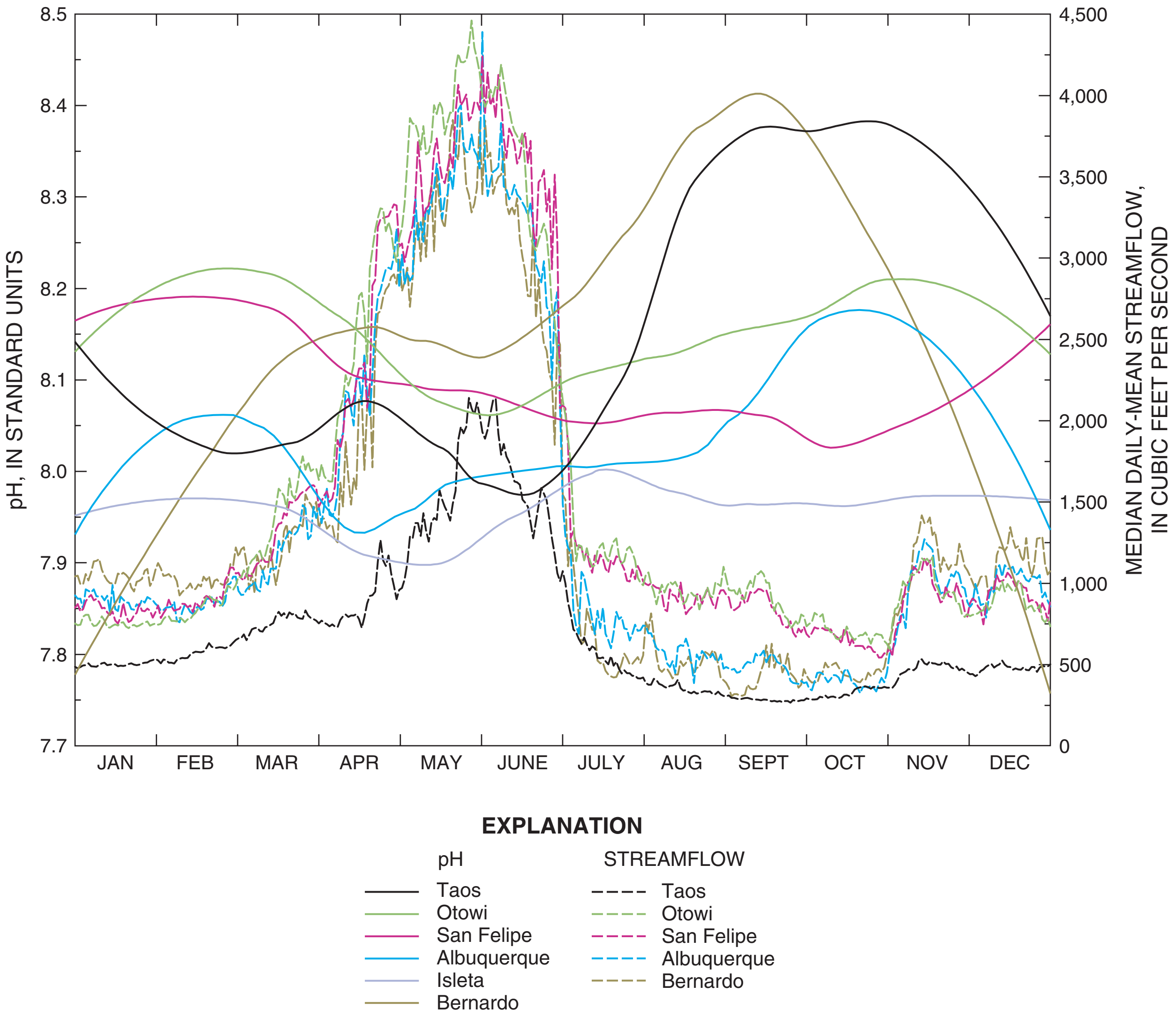


Figure 18. Post-December 1973 average (LOESS) pH and median daily-mean streamflow for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

Table 17. Pre- and post-December 1973 suspended-sediment summary statistics for Rio Chama sites of La Puente, Above Abiquiu, and Chamita.

[mg/L, milligrams per liter; pre, pre-December 1973; post, post-December 1973; NA, not available]

Suspended sediment (mg/L)	La Puente pre	La Puente post	Above Abiquiu pre	Above Abiquiu post	Chamita pre	Chamita post
Minimum	NA	1	50	4	100	21
25th percentile	NA	10	875	39	995	89
Median	NA	17	2,050	111	2,910	209
75th percentile	NA	39	7,768	367	6,665	658
Maximum	NA	703	70,800	14,300	47,500	14,500
Number of values	0	74	104	105	127	199

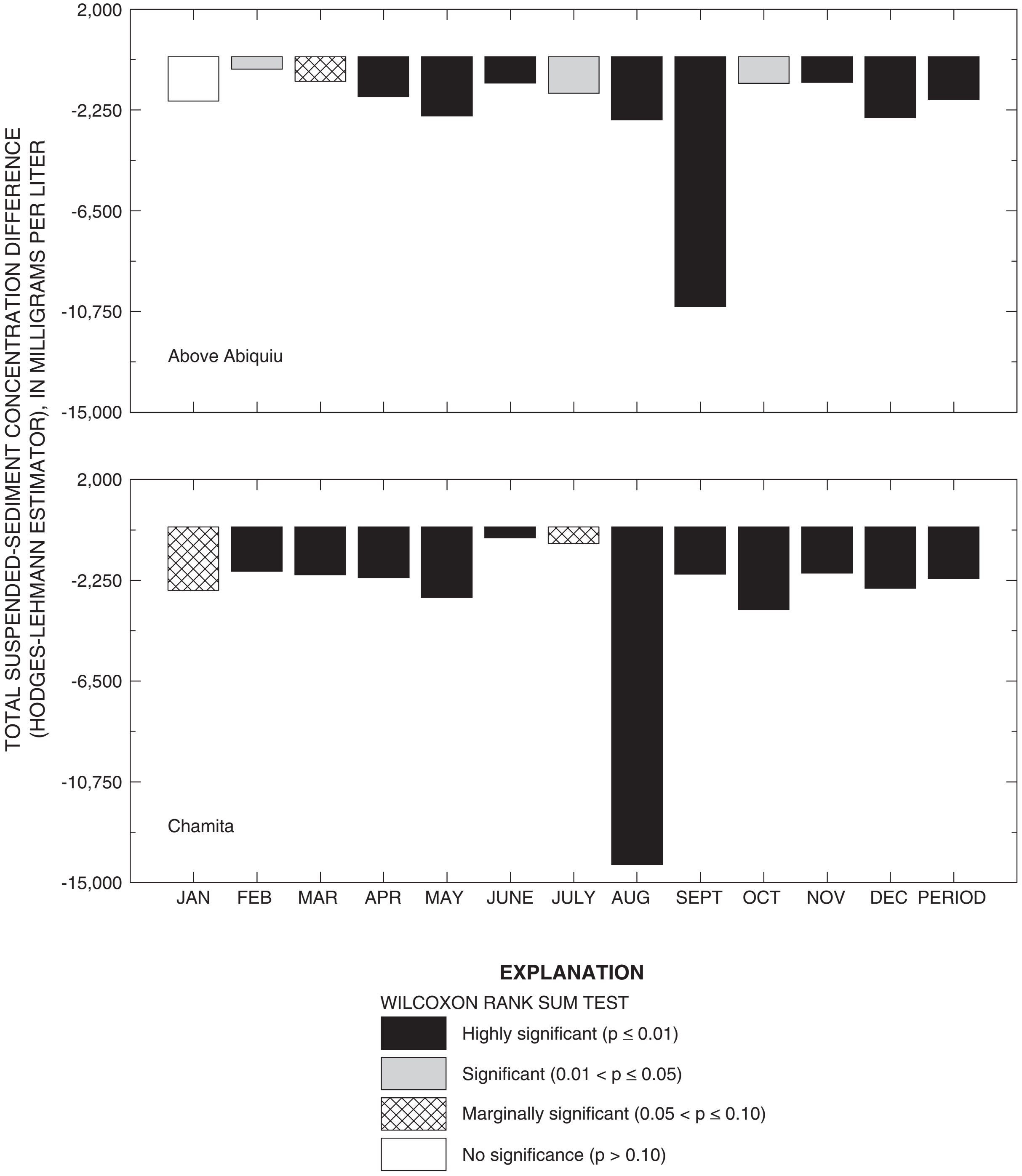


Figure 19. Monthly and period differences for pre- to post-December 1973 suspended-sediment concentration for Rio Chama sites of Above Abiquiu and Chamita.

Table 18. Suspended-sediment distribution differences from upstream to downstream for Rio Chama sites of La Puente, Above Abiquiu, and Chamita and Rio Grande sites of Taos and Otowi for the post-December 1973 period.

[<, less than]

Wilcoxon rank sum test (one way)	La Puente to Above Abiquiu	Above Abiquiu to Chamita	Chamita compared with Taos	Chamita compared with Otowi
Difference in suspended-sediment distributions	Increase	Increase	Decrease	Increase
P-value	< 0.001	< 0.001	< 0.001	< 0.001

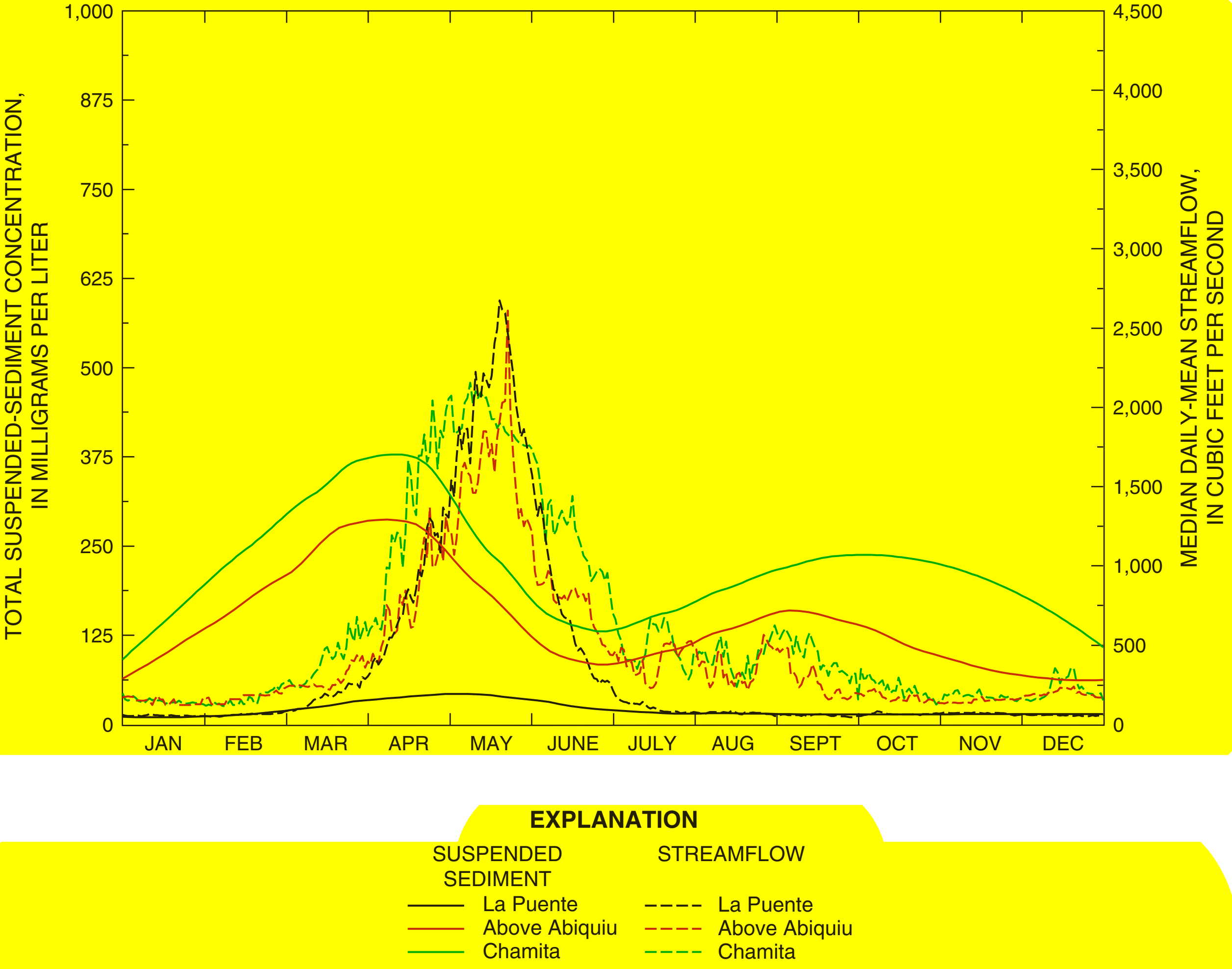


Figure 20. Post-December 1973 average (LOESS) suspended-sediment concentration and median daily-mean streamflow for Rio Chama sites of La Puente, Above Abiquiu, and Chamita.

Rio Grande

Median and 25th and 75th percentile values of suspended-sediment concentrations decreased from the pre- to post-December 1973 period for the Rio Grande sites of Otowi, San Felipe, Albuquerque, and Bernardo (table 19). The median decrease was largest at Bernardo and smallest at Otowi. Maximum concentrations decreased at all sites except San Felipe, which is likely a result of the small number of samples collected during the pre-December 1973 period. Decreases in suspended-sediment concentrations at the Otowi and Albuquerque sites were highly significant between the two periods and ranged from no significance to highly significant for the monthly distributions (fig. 21). Suspended-sediment concentrations decreased from the pre- to post-December 1973 period for San Felipe (highly significant) and Bernardo (highly significant).

Suspended-sediment concentrations for the Rio Grande alternately increased and decreased in the downstream direction in the post-December 1973 period (table 20). The effect of Cochiti Lake as a sediment control was evident with the decrease in concentrations between Otowi and San Felipe.

In the post-December 1973 period, the seasonal variation in Rio Grande suspended-sediment concentration (fig. 22) was a different pattern than what was observed in the Rio Chama. Suspended-sediment concentrations in the Rio Grande peaked only once (snowmelt runoff) at all sites except Otowi, which peaked twice. Concentrations were typically smallest at the Taos site. The largest suspended-sediment concentrations were at the Otowi site except during November through January when the concentrations were larger at the Bernardo site. Suspended-sediment concentrations at Otowi peaked early in May before the streamflow peak in mid-May and also peaked in August during the monsoon season. The two suspended-sediment concentration peaks at the Otowi site are likely a result of the Rio Chama, which also showed two peaks. Concentrations at the San Felipe site were similar to those at the Taos site, but two small increases in suspended sediment occurred in May and August at the San Felipe site.

Suspended-sediment concentrations were larger at the Albuquerque site during all months than concentrations at the San Felipe (upstream) and Isleta (downstream) sites (fig. 22). Concentrations did not increase at the Isleta site during snowmelt runoff or the monsoon season. Suspended-sediment concentrations increased from Isleta to Bernardo and increased at the Bernardo site during the snowmelt runoff, monsoon season, and in winter.

Table 19. Pre- and post-December 1973 suspended-sediment summary statistics for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

[mg/L, milligrams per liter; pre, pre-December 1973; post, post-December 1973; NA, not available]

Suspended sediment (mg/L)	Taos pre	Taos post	Otowi pre	Otowi post	San Felipe pre	San Felipe post	Albuquerque pre	Albuquerque post	Isleta pre	Isleta post	Bernardo pre	Bernardo post
Minimum	NA	4	40	14	565	5	77	9	NA	8	283	10
25th percentile	NA	19	746	228	1,705	35	1,235	169	NA	113	1,875	208
Median	NA	36	1,590	625	2,295	61	2,280	411	NA	193	3,260	461
75th percentile	NA	77	4,553	1,770	2,690	137	3,805	1,135	NA	510	5,955	965
Maximum	NA	24,700	163,000	45,300	2,990	14,300	76,600	45,800	NA	10,100	31,100	28,800
Number of values	0	131	140	352	12	181	96	479	0	214	59	412

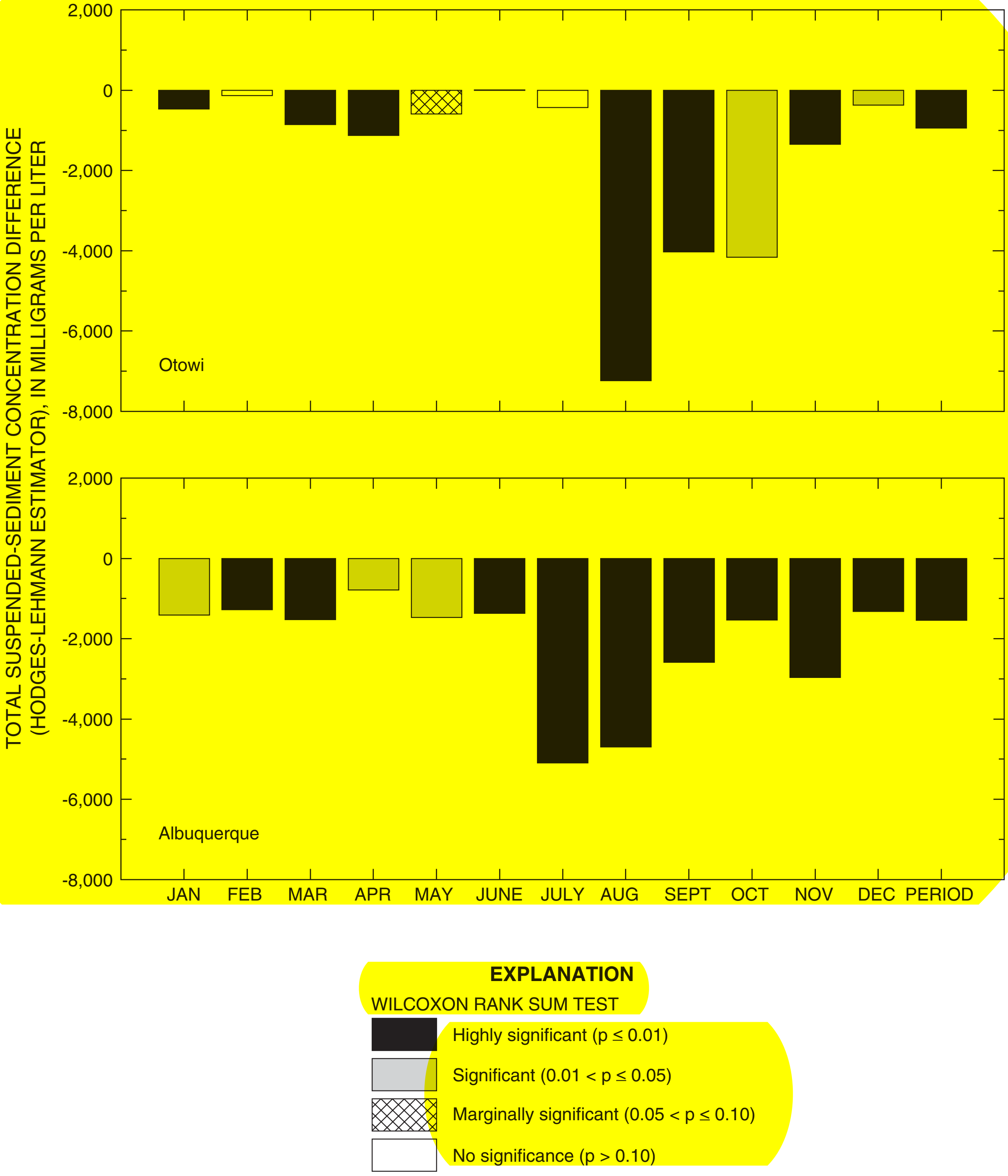


Figure 21. Monthly and period differences for pre- to post-December 1973 suspended-sediment concentration for Rio Grande sites of Otowi and Albuquerque.

Table 20. Suspended-sediment distribution differences from upstream to downstream for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo for the post-December 1973 period.

[<, less than]

Wilcoxon rank sum test (one way)	Taos to Otowi	Otowi to San Felipe	San Felipe to Albuquerque	Albuquerque to Isleta	Isleta to Bernardo
Difference in suspended-sediment distributions	Increase	Decrease	Increase	Decrease	Increase
P-value	<0.001	<0.001	<0.001	<0.001	<0.001

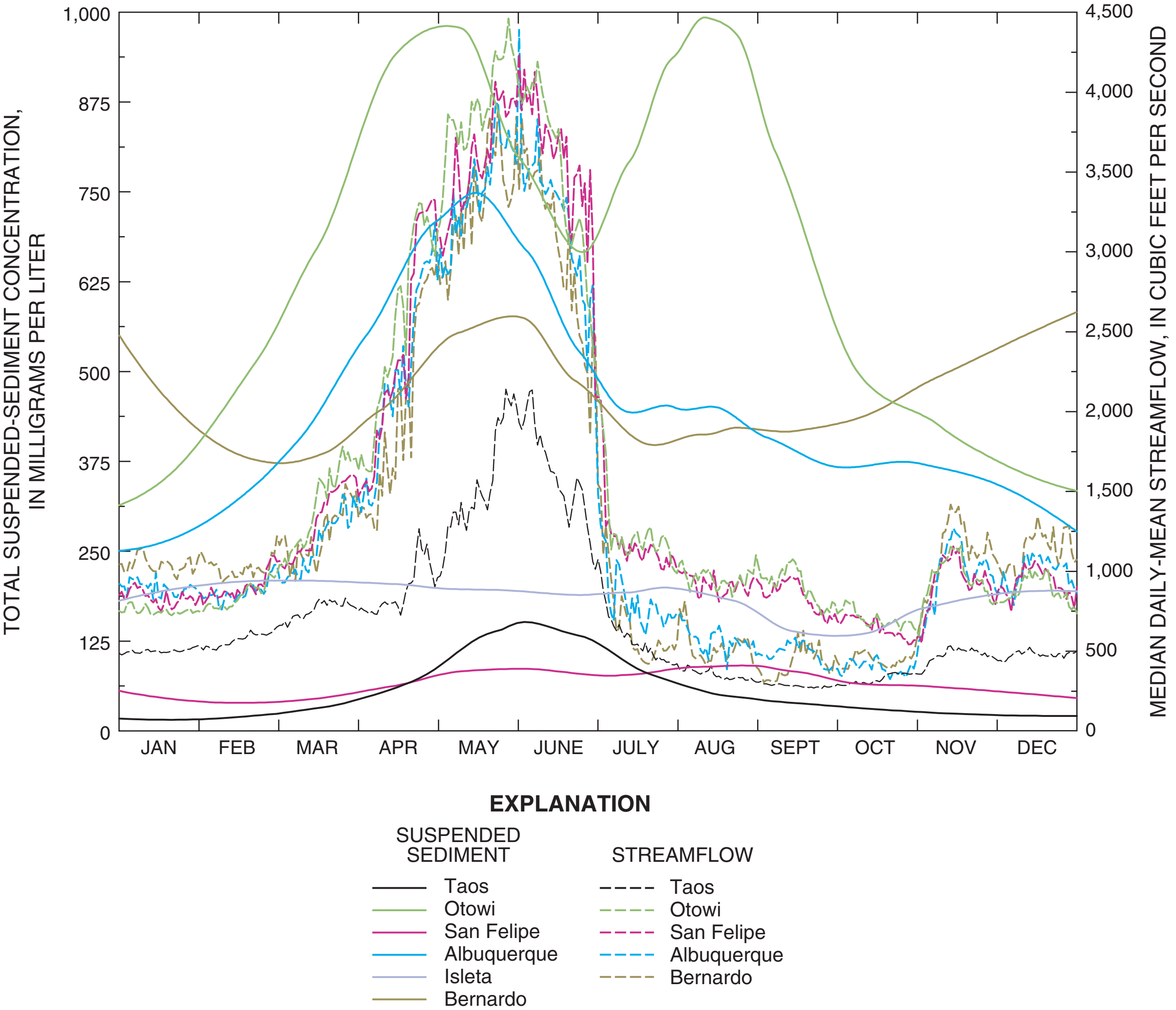


Figure 22. Post-December 1973 average (LOESS) suspended-sediment concentration and median daily-mean streamflow for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

Peaks of suspended-sediment concentrations during snowmelt runoff were most visible at sites that have instream sediment sources (unstable channel configurations that allow aggradation and degradation) and upstream tributary inflows. The smallest suspended-sediment concentrations through most of the seasons were at the Taos site because the site is located downstream from the Rio Grande Gorge (fig. 1), a stable channel area where the Rio Grande flows through a basalt canyon with few inflows. In contrast, the Otowi site is located in a narrow valley flood plain where the river has downcut into basin fill and the upstream reach receives multiple inflows of intermittent and ephemeral tributaries draining the river valley. Nordin and Beverage (1965) determined that the Rio Grande channel near Otowi increased in bed shear stress and bed-material size as streamflow increased. This increase in bed shear stress indicated scour and channel alteration with larger streamflows. Culbertson and Dawdy (1964) observed an accumulation of sediment in the Rio Grande between the confluence of the Rio Chama and the Otowi site.

The difference in suspended-sediment concentrations between the San Felipe and Albuquerque sites may have been a result of channel characteristics, bed material, and sediment-starved water discharged from Cochiti Lake. Lagasse (1980) found that cross-sectional profiles of the Rio Grande from Cochiti Lake to the San Felipe site did not substantially change from 1971 to 1980 (before and after installation of Cochiti Dam), but cross-sectional profiles of the Rio Grande from San Felipe to Albuquerque showed substantial alteration, indicating aggradation and degradation of the channel through this reach. Culbertson and Dawdy (1964) described the channel at the San Felipe site as stable with little evidence of aggradation and degradation.

Water discharged from Cochiti Lake was likely mostly sediment free, did not suspend much sediment prior to reaching the San Felipe site, then suspended sediment from San Felipe to Albuquerque where channel sediment was freely available. Suspended-sediment concentration also likely increased between San Felipe and Albuquerque because of inflows from tributaries.

The decrease in suspended-sediment concentration between the Albuquerque and Isleta sites was unusual because this reach of the river does not substantially change in morphology or gradient (Lagasse, 1980). This decrease may partly be a result of local channel geometry or local influences such as operation of the MRGCD Isleta Diversion Dam (fig. 1) or inflows of treated wastewater from the Southside Water Reclamation Plant (median of 24.5 mg/L; Wilcox, 1997) and riverside drains (median of 68.5 mg/L; Wilcox, 1997).

At the Bernardo site, suspended-sediment concentration increased with increasing streamflow during snowmelt runoff, but did not increase during the monsoon season (fig. 22). The lack of increase during the monsoon season is similar to the lack of increase in suspended-sediment concentration observed at the Albuquerque site during this period. Suspended-sediment concentrations at Bernardo increased when MRGCD diversions were halted (November to March), indicating that the smaller, wetted channel area and smaller streamflow during the diversions did not have sufficient instream sediment or velocity compared with the larger, wetted channel area during snowmelt runoff and when diversions were not occurring.

Minor increases in suspended-sediment concentration that did occur during the monsoon season were a result of intermittent and ephemeral streams contributing brief inflows to the Rio Grande. These inflows contribute little surface water to the Rio Grande (typically flow for 1 day or less in response to precipitation), but the inflows can have large concentrations of suspended sediment (Healy, 1997). Inflows from these streams can result in deposition of sediment in the Rio Grande channel that is subsequently resuspended and transported during larger Rio Grande streamflows. Nordin and Beverage (1965) described how tributary runoff during thunderstorms in the monsoon season caused sharp peaks in streamflow and suspended-sediment concentration in these intermittent and ephemeral streams.

Constituent Trends and Correlation

Temporal variations of streamflow, specific conductance, pH, and suspended-sediment concentration followed similar trends as the Rio Chama and Rio Grande responded to reservoir installation, SJC Project water, and reservoir operations. Streamflow and pH distributions increased and specific conductance and suspended-sediment distributions decreased at all sites from the pre- to the post-December 1973 period (fig. 23).

In the post-December 1973 period, the effects of reservoirs and SJC Project water created different overall and seasonal responses depending on proximity to certain reservoirs. Streamflow, specific conductance, and suspended-sediment concentration increased downstream in the Rio Chama and in the Rio Grande at Otowi (fig. 24) because of the introduction of SJC Project water and retention of snowmelt runoff in the Rio Chama reservoirs. The pH increased from Above Abiquiu to Chamita, but this increase did not affect the Rio Grande because no increase was observed from Taos to Otowi.

Effects of the reservoirs and SJC Project water were not as apparent in the Rio Grande as they were in the Rio Chama (fig. 24). Specific conductance increased downstream at all sites, but streamflow, pH, and suspended-sediment concentration indicated increases, decreases, and no change from site to site from Otowi to Bernardo. The alteration of streamflow and water quality in the Rio Grande as a result of the reservoirs and SJC Project water is demonstrated by the changes in these constituents from Otowi to San Felipe, but the effects of the reservoirs and SJC Project water are reduced or reversed because of additional influences on the Rio Grande downstream from San Felipe.

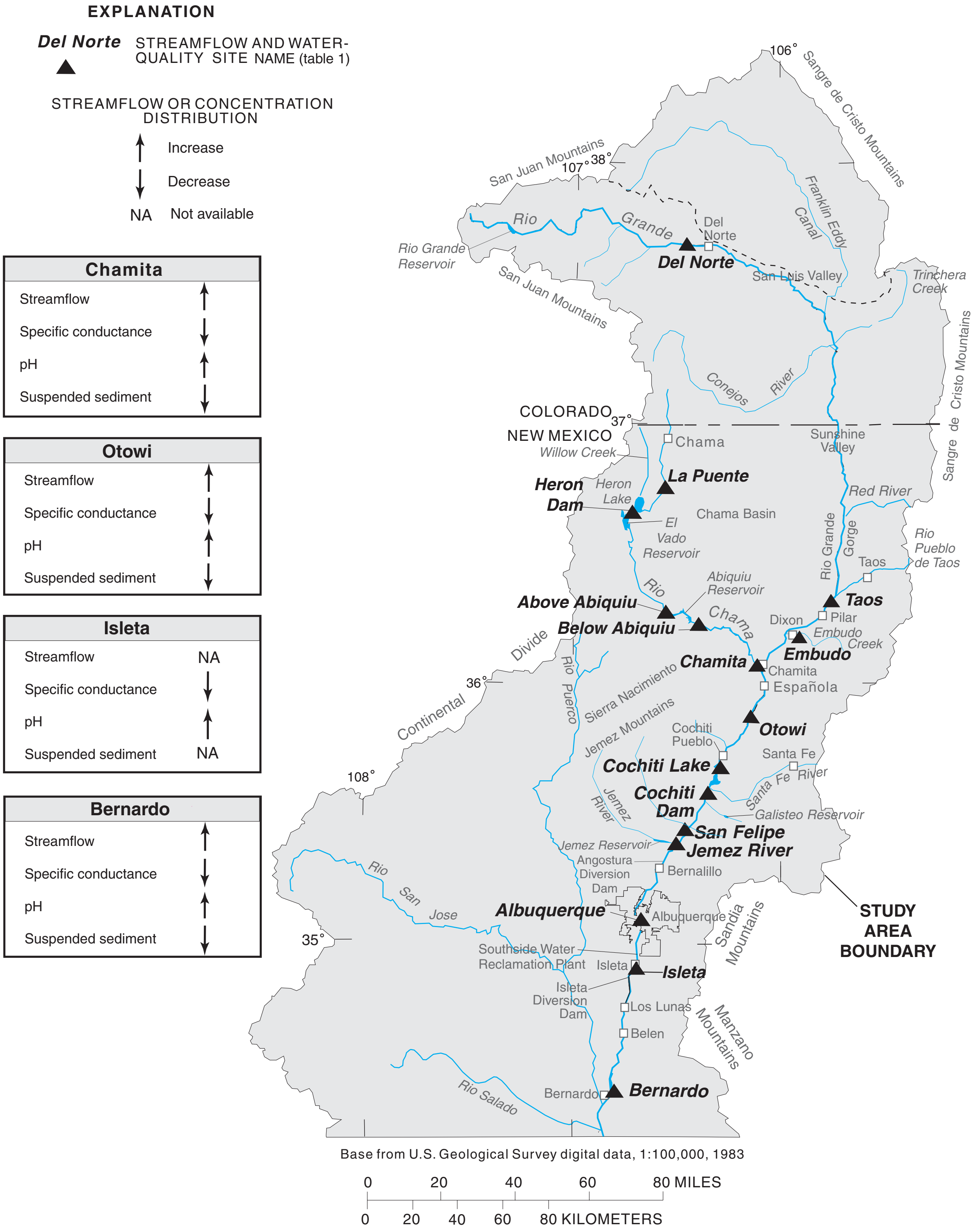


Figure 23. Pre- to post-December 1973 variations in streamflow, specific-conductance, pH, and suspended-sediment distributions in the Rio Grande study area.

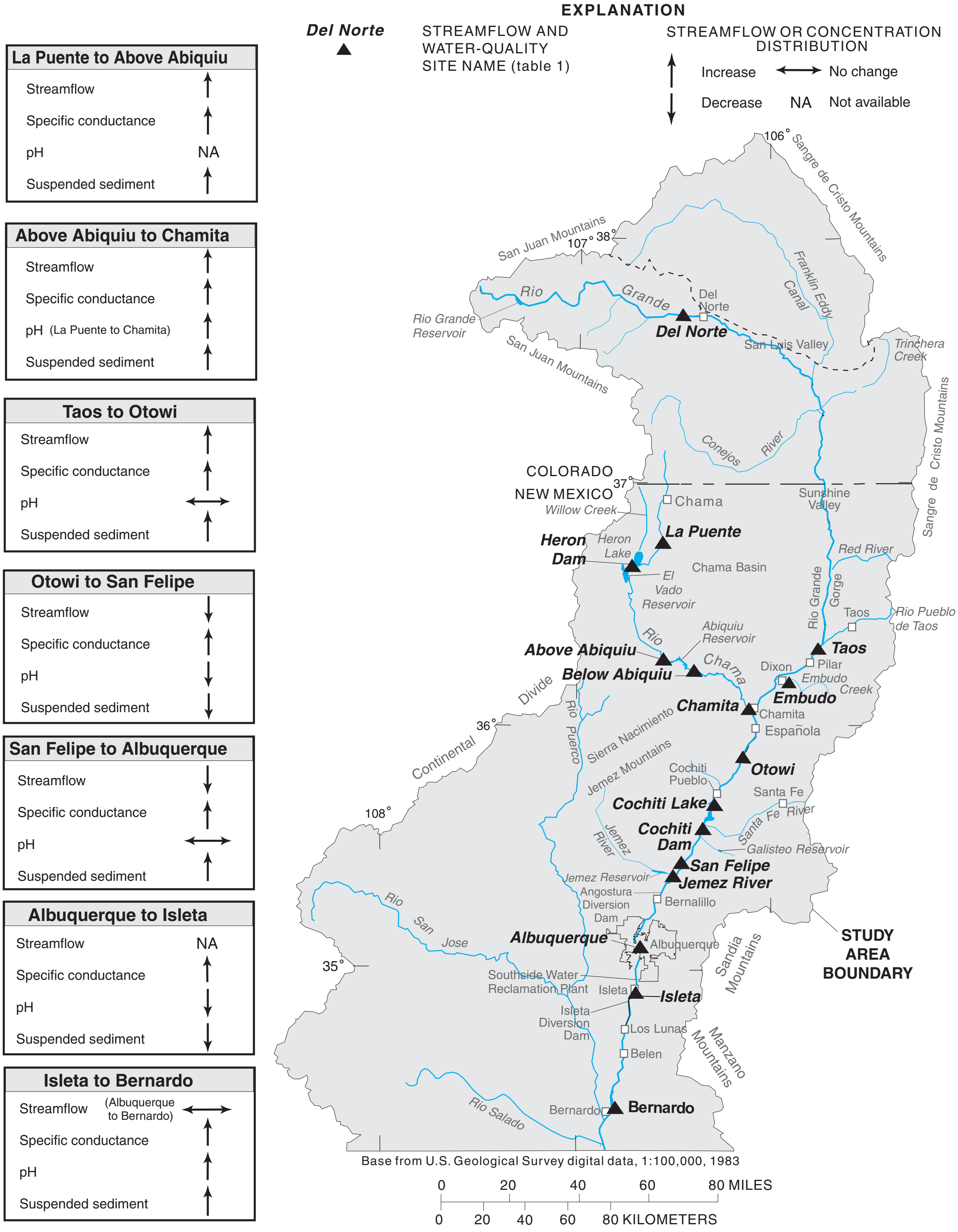


Figure 24. Post-December 1973 spatial variations in streamflow, specific-conductance, pH, and suspended-sediment distributions in the Rio Grande study area.

Rio Chama and Rio Grande streamflow indicated some correlation with water quality during certain seasons (figs. 11, 13, 15, 18, 20, and 22). Because of the variability and type of seasonal influences—snowmelt runoff, reservoir releases, monsoon precipitation, and irrigation diversions and return flows—streamflow and the water-quality constituents of specific conductance, pH, and suspended-sediment concentration in the Rio Chama and the Rio Grande did not demonstrate a strong annual correlation (table 21), although the small p-values associated with the correlation coefficients indicate that relations do exist between streamflow and water quality. Correlations might exist for specific seasonal periods; however, these periods of strong correlation likely vary by site and constituent.

Summary

Streamflow and water quality in northern and central New Mexico are extremely important because of limited surface-water resources and a growing population. Construction and operation of reservoirs on the Rio Chama and Rio Grande and the importation of Colorado River Basin water by the SJC Project can affect current (2004) and future uses of Rio Chama, Rio Grande, and SJC Project water. Prior to this study, the effect of the coordinated operation of Heron, El Vado, Abiquiu, and Cochiti Dams and the implementation of the SJC Project on streamflow and water quality in the Rio Chama and Rio Grande had not been fully documented. Evaluation of streamflow and water-quality data prior to and after the coordination of the dams and the implementation of SJC Project water indicated that streamflow patterns and water quality of the Rio Chama and the Rio Grande had been altered.

The combined effect of reservoir installation and operation and diversion of Colorado River Basin water into the Rio Grande Basin by the SJC Project was a decrease in extreme streamflows, an increase in median streamflows, and a decrease in periods of historically small streamflows. Inflow of SJC Project water increased annual streamflow volumes in the Rio Chama and Rio Grande, and reservoir storage increased median streamflows by retaining large flows and modifying reservoir releases to conform to channel capacities for flood protection. The SJC Project and Heron, El Vado, Abiquiu, and Cochiti Dams decreased streamflow variability and increased median streamflows in the study area. These changes to streamflow resulted in an overall decrease in specific conductance and suspended-sediment concentration and an increase in pH in the Rio Chama and the Rio Grande.

Following construction of Heron and Cochiti Dams and operational integration of the reservoirs on the Rio Chama and the Rio Grande, water quality was influenced by the inflow of Colorado River Basin water by the SJC Project, retention of snowmelt runoff, and to a lesser degree, by reservoir storage. The non-native water of the SJC Project was different from native Rio Chama and Rio Grande water. Retention of snowmelt runoff in the reservoirs influenced overall water quality in the Rio Chama and Rio Grande by distributing the normal dilution effect of snowmelt from the snowmelt runoff period to year-round. This dilution effect decreased downstream with influences such as the MRGCD and the City of Albuquerque’s Southside Water Reclamation Plant. Most changes in water quality attributable to the reservoirs were not evident in the Rio Grande at the Bernardo site.

The non-native water of the SJC Project and retained snowmelt provided a variable influence on water quality throughout the seasons because of managed releases from Heron Lake, El Vado Reservoir, Abiquiu Reservoir, and Cochiti Lake that fluctuated according to downstream user needs and reservoir inflows. The influence of SJC Project water and retained snowmelt on specific conductance, pH, and suspended-sediment concentration diminished with downstream flow as the Rio Grande was subjected to various natural and anthropogenic inflows. Cochiti Lake storage contributed to a small but identifiable influence on water quality because of hypoxic conditions in the reservoir during summer months. Because of the variability and type of seasonal influences, streamflow did not strongly correlate annually with water quality in the Rio Chama or the Rio Grande.

Table 21. Streamflow and water-quality correlation in the Rio Chama and Rio Grande during the post-December 1973 period.

[<, less than]

Streamflow correlation (Kendall’s tau)	Above Abiquiu	Chamita	Otowi	San Felipe	Albuquerque	Isleta	Bernardo
Specific conductance	-0.53	-0.57	-0.45	-0.49	-0.33	-0.58	-0.54
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
pH	NA	-0.14	-0.11	-0.06	-0.27	0.04	-0.14
p-value		0.025	0.004	0.243	0.000	0.306	0.004
Suspended sediment	0.26	0.14	0.19	0.23	0.22	0.32	0.15
p-value	0.000	0.004	0.000	0.000	0.000	0.000	0.000

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Supplemental Information

LOESS Fit Lines and Study Period Data

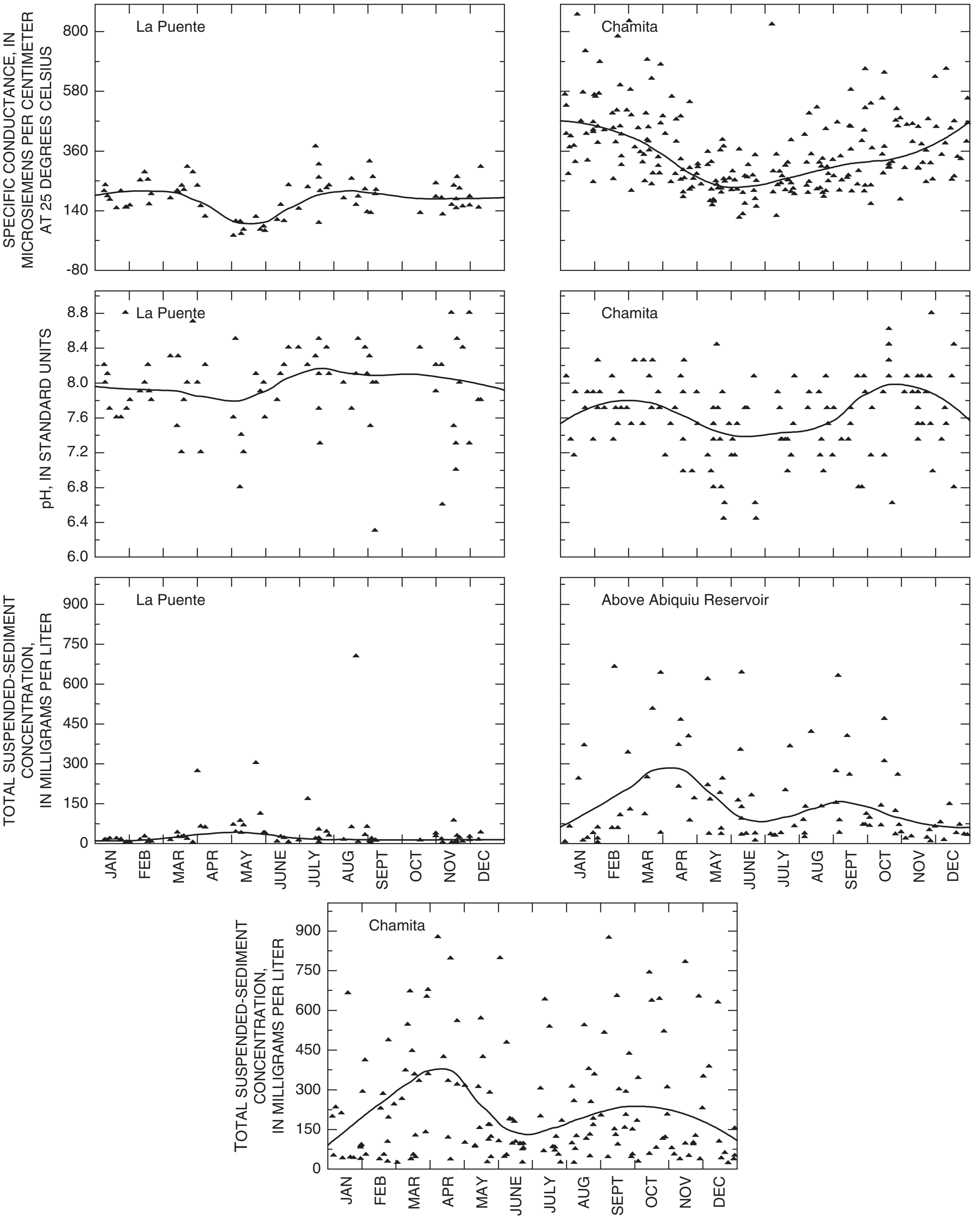

Figure S-1. LOESS fit lines and post-December 1973 data for specific conductance, pH, and total suspended sediment for composite annual year for Rio Chama sites of La Puente, Above Abiquiu, and Chamita.

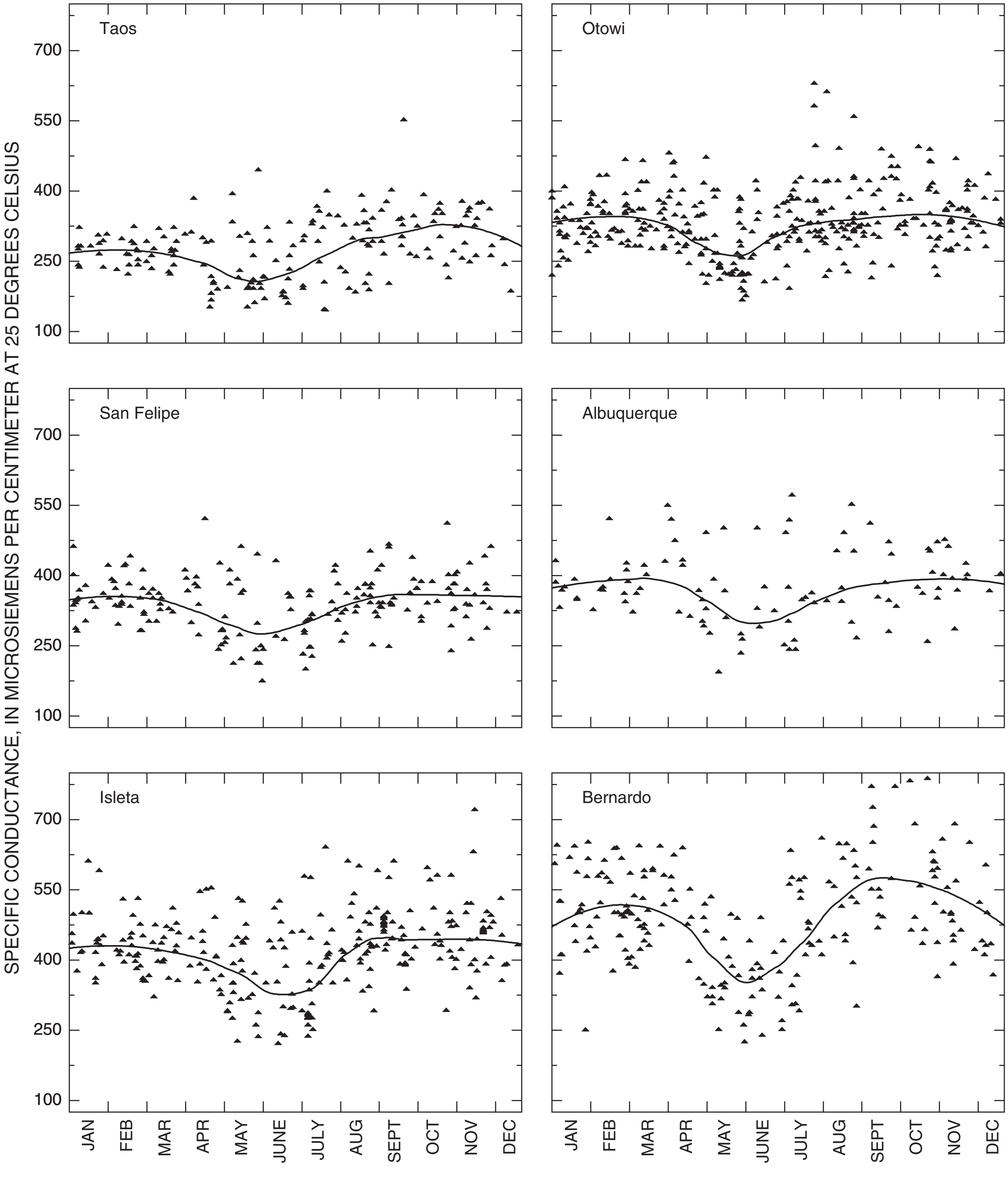

Figure S-2. LOESS fit lines and post-December 1973 data for specific conductance for composite annual year for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

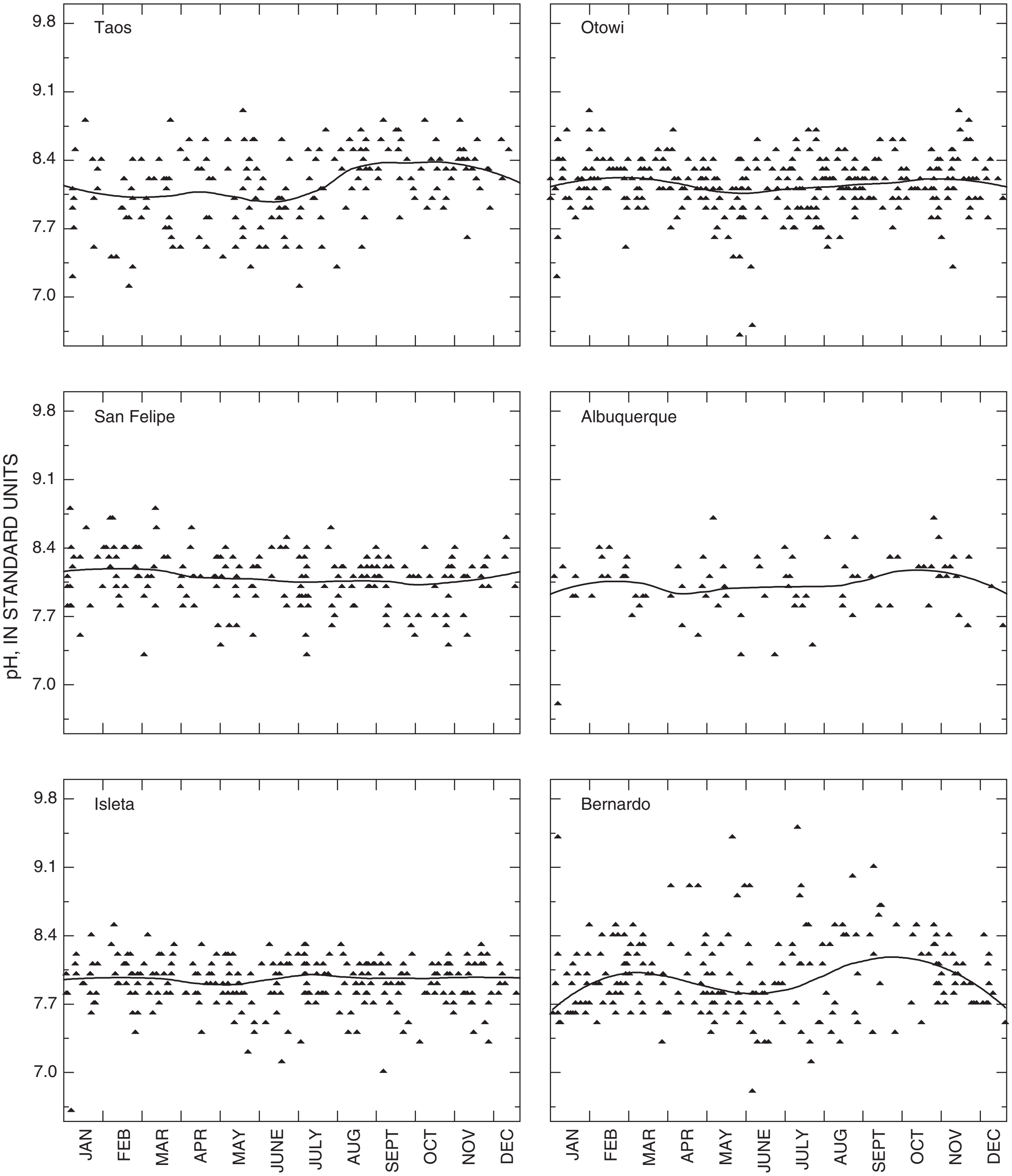

Figure S-3. LOESS fit lines and post-December 1973 data for pH for composite annual year for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.

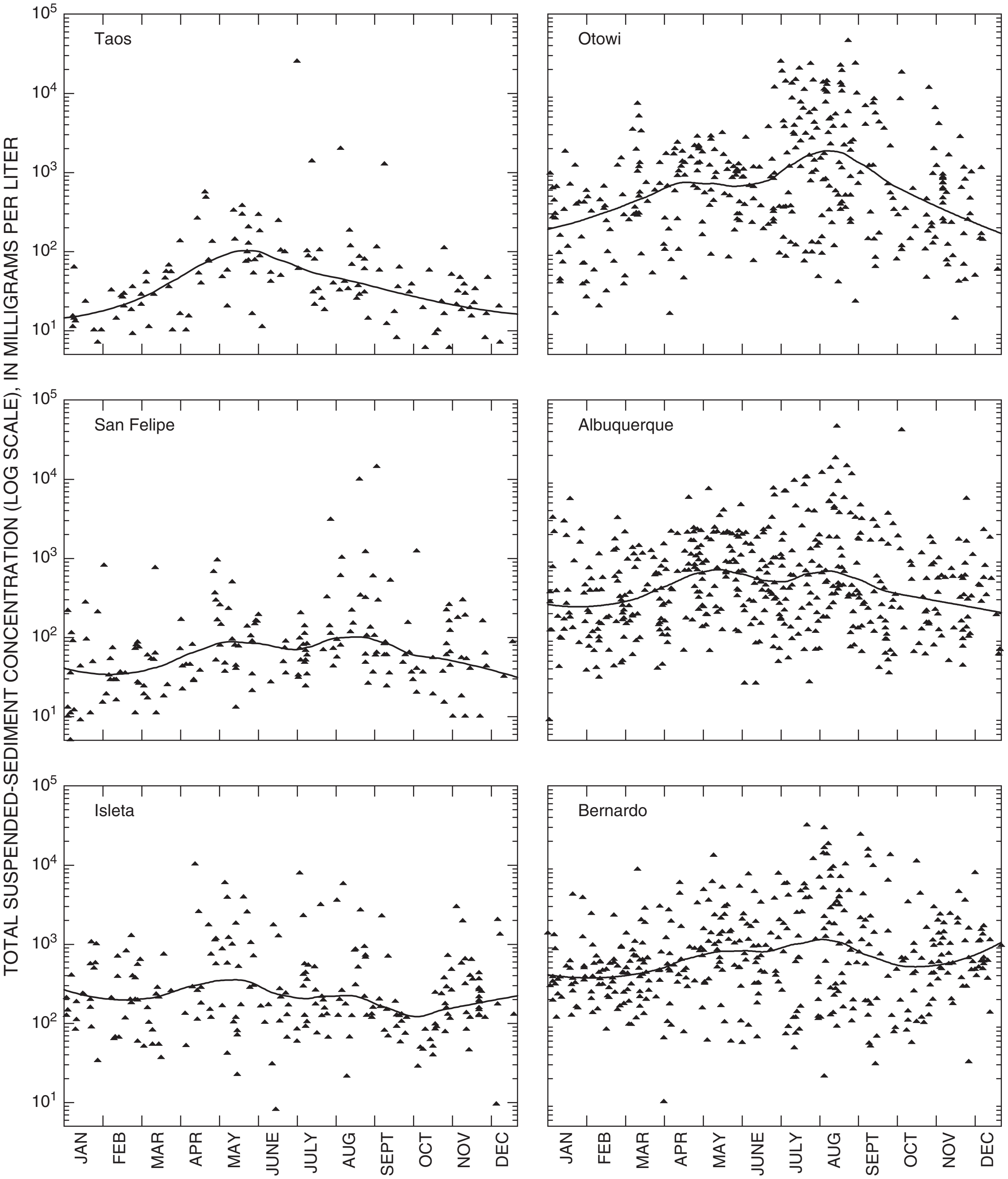

Figure S-4. LOESS fit lines and post-December 1973 data for total suspended sediment for composite annual year for Rio Grande sites of Taos, Otowi, San Felipe, Albuquerque, Isleta, and Bernardo.