Prepared in cooperation with the Albuquerque–Bernalillo County Water Utility Authority

Water Quality, Streamflow Conditions, and Annual Flow-Duration Curves for Streams of the San Juan–Chama Project, Southern Colorado and Northern New Mexico, 1935–2010

Scientific Investigations Report 2013–5005
Revised May 2013

U.S. Department of the Interior
U.S. Geological Survey

Cover:

Left, Gage at Azotea Tunnel outlet near Chama, New Mexico, June 2, 2008.

Right, Gage at Azotea Tunnel outlet near Chama, New Mexico, September 23, 2008.

Water Quality, Streamflow Conditions, and Annual Flow-Duration Curves for Streams of the San Juan–Chama Project, Southern Colorado and Northern New Mexico, 1935–2010

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U.S. Department of the Interior
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Acknowledgments

The authors thank John Stomp and David Price of the Albuquerque–Bernalillo County Water Utility Authority for providing guidance and support for this investigation to improve understanding of the water resources available to the Albuquerque and Bernalillo County area.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)

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

$$°F=(1.8\times°C)+32$$

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

$$°C=(°F-32)/1.8$$

Unless otherwise noted, the datums used in this report for vertical coordinate information are referenced to the North American Vertical Datum of 1988 (NAVD 88).

Unless otherwise noted, the datums used in this report for horizontal coordinate information are referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations and Acronyms Used in This Report

Abbreviation or acronym	Full term
ABCWUA	Albuquerque–Bernalillo County Water Utility Authority
Ca	calcium
CDWR	Colorado Division of Water Resources
Cl	chloride
COV	coefficient of variation
CT	the ordinal day of the water year of the center of mass of annual discharge
DQF20	the ordinal day of the water year on which the 20th percentile of annual discharge occurred
DQF50	the ordinal day of the water year on which the 50th percentile of annual discharge occurred
ENSO	El Niño/Southern Oscillation
F	fluoride
HCO_3	bicarbonate
IQR	interquartile range
K	potassium
Mg	magnesium
MRGCD	Middle Rio Grande Conservancy District
Na	sodium
P.L.	Public Law
PDO	Pacific Decadal Oscillation
Q25	25th percentile
Q50	median or 50th percentile
Q75	75th percentile
Reclamation	Bureau of Reclamation
SJCP	San Juan–Chama Project
SNOTEL	SNOwpack TELemetry
SO_4	sulfate
SST	sea-surface temperature
ST	the ordinal day of the water year of the start of the spring pulse onset of the snowmelt runoff
USGS	U.S. Geological Survey

Water Quality, Streamflow Conditions, and Annual Flow-Duration Curves for Streams of the San Juan–Chama Project, Southern Colorado and Northern New Mexico

By Sarah E. Falk, Scott K. Anderholm, and Katya A. Hafich

Abstract

The Albuquerque–Bernalillo County Water Utility Authority supplements the municipal water supply for the Albuquerque metropolitan area, in central New Mexico, with water diverted from the Rio Grande. Water diverted from the Rio Grande for municipal use is derived from the San Juan–Chama Project, which delivers water from streams in the southern San Juan Mountains in the Colorado River Basin in southern Colorado to the Rio Chama watershed and the Rio Grande Basin in northern New Mexico. The U.S. Geological Survey, in cooperation with Albuquerque–Bernalillo County Water Utility Authority, has compiled historical streamflow and water-quality data and collected new water-quality data to characterize the water quality and streamflow conditions and annual flow variability, as characterized by annual flow-duration curves, of streams of the San Juan–Chama Project. Nonparametric statistical methods were applied to calculate annual and monthly summary statistics of streamflow, trends in streamflow conditions were evaluated with the Mann–Kendall trend test, and annual variation in streamflow conditions was evaluated with annual flow-duration curves.

The study area is located in northern New Mexico and southern Colorado and includes the Rio Blanco, Little Navajo River, and Navajo River, tributaries of the San Juan River in the Colorado River Basin located in the southern San Juan Mountains, and Willow Creek and Horse Lake Creek, tributaries of the Rio Chama in the Rio Grande Basin. The quality of water in the streams in the study area generally varied by watershed on the basis of the underlying geology and the volume and source of the streamflow. Water from the Rio Blanco and Little Navajo River watersheds, primarily underlain by volcanic deposits, volcaniclastic sediments and landslide deposits derived from these materials, was compositionally similar and had low specific-conductance values relative to the other streams in the study area. Water from the Navajo River, Horse Lake Creek, and Willow Creek watersheds, which are underlain mostly by Cretaceous-aged marine shale, was compositionally similar and had large concentrations of sulfate relative to the other streams in the study area, though the water from the Navajo River had lower specific-conductance values than did the water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek. Generally, surface-water quality varied with streamflow conditions throughout the year. Streamflow in spring and summer is generally a mixture of base flow (the component of streamflow derived from groundwater discharged to the stream channel) diluted with runoff from snowmelt and precipitation events, whereas streamflow in fall and winter is generally solely base flow. Major- and trace-element concentrations in the streams sampled were lower than U.S. Environmental Protection Agency primary and secondary drinking-water standards and New Mexico Environment Department surface-water standards for the streams.

In general, years with increased annual discharge, compared to years with decreased annual discharge, had a smaller percentage of discharge in March, a larger percentage of discharge in June, an interval of discharge derived from snowmelt runoff that occurred later in the year, and a larger discharge in June. Additionally, years with increased annual discharge generally had a longer duration of runoff, and the streamflow indicators occurred at dates later in the year than the years with less snowmelt runoff. Additionally, the seasonal distribution of streamflow was more strongly controlled by the change in the amount of annual discharge than by changes in streamflow over time.

The variation of streamflow conditions over time at one streamflow-gaging station in the study area, Navajo River at Banded Peak Ranch, was not significantly monotonic over the period of record with a Kendall's tau of 0.0426 and with a p-value of 0.5938 for 1937 to 2009 (a trend was considered statistically significant at a $p\text{-value} \leq 0.05$). There was a relation, however, such that annual discharge was generally lower than the median during a negative Pacific Decadal Oscillation interval and higher than the median during a positive Pacific Decadal Oscillation interval. Streamflow conditions at Navajo River at Banded Peak Ranch varied nonmonotonically over time and were likely a function of complex climate pattern interactions. Similarly, the monthly

distribution of streamflow varied nonmonotonically over time and was likely a function of complex climate pattern interactions that cause variation over time.

Study results indicated that the median of the sum of the streamflow available above the minimum monthly bypass requirement from Rio Blanco, Little Navajo River, and Navajo River was 126,240 acre-feet. The results also indicated that diversion of water for the San Juan–Chama Project has been possible for most months of most years.

Introduction

The Albuquerque–Bernalillo County Water Utility Authority (ABCWUA) supplements the municipal water supply for the Albuquerque metropolitan area, in central New Mexico, with water diverted from the Rio Grande. Water diverted from the Rio Grande is derived from the San Juan–Chama Project (SJCP) water contractors in southern Colorado and northern New Mexico, which delivers water from streams in the southern San Juan Mountains in the Colorado River Basin in southern Colorado to the Rio Chama watershed and the Rio Grande Basin in northern New Mexico. SJCP water is diverted from the upper tributaries of the San Juan River, in southern Colorado, across the Continental Divide to Heron Reservoir, in northern New Mexico, where it is routed to Albuquerque through the Rio Chama, in northern New Mexico, and the Rio Grande. Part of the diverted water is delivered to the City of Albuquerque. The distribution of surface water for municipal supply has raised questions about the water quality, including the concentrations of salinity, trace elements, and nutrients in water imported from the San Juan River watershed and the availability of water for diversion. Review of previous investigations of water quality in the Rio Chama watershed has indicated that there is limited information about the quality of SJCP water flowing into Heron Reservoir and about the quality of water stored in Heron Reservoir. Additionally, little is known about groundwater/surface-water interactions along the naturally occurring and constructed channels and tunnels used to convey water from the San Juan River watershed to Heron Reservoir and about the streamflow conditions on the streams from which the water is diverted. The U.S. Geological Survey (USGS), in cooperation with the ABCWUA, has compiled historical streamflow and water-quality data and collected new water-quality data to characterize the water-quality and streamflow conditions including the variability of annual flow of streams of the SJCP.

The SJCP delivers to the Rio Grande Basin water from the Colorado River Basin. The diverted water, approximately 96,200 acre-feet (acre-ft) annually, is divided among various entities that have contracts for the water, including two irrigation districts and numerous municipal, domestic, and industrial entities (generally referred to as SJCP contractors) (table 1). The SJCP infrastructure consists of diversion dams constructed in southern Colorado on the Rio Blanco, Navajo River, and Little Navajo River; a conduit and tunnel system; and Heron Dam. The conduit and tunnel system conveys the water approximately 26 miles (mi) across the Continental Divide and discharges it into Willow Creek above Heron Reservoir (figs. 1 and 2). Heron Dam, constructed on Willow Creek just upstream from the confluence with the Rio Chama, provides storage of water diverted from the San Juan River watershed and allows for controlled releases to SJCP contractors.

Table 1. List of the entities that have contracts for water from the San Juan–Chama Project and the amount of water contracted.

San Juan–Chama Project water contractors	Amount of water contracted (acre-feet)
Irrigation supply	
Middle Rio Grande Conservancy District	20,900
Pojoaque Valley Irrigation District	1,030
Municipal, domestic, and industrial	
City of Albuquerque	48,200
Jicarilla Apache	6,500
City and County of Santa Fe	5,605
County of Los Alamos	1,200
City of Espanola	1,000
Town of Belen	500
Village of Los Lunas	400
Village of Taos	400
Town of Bernalillo	400
Town of Red River	60
Twining Water and Sanitation District	15
Total	86,210
Cochiti Reservoir for fish and wildlife, pool reserve of 1,200 surface acres	5,000
Allocated, but uncontracted	4,990
Total	96,200

Purpose and Scope

This report, prepared in cooperation with the ABCWUA, describes the results of a study to characterize the water quality and streamflow conditions and annual flow variability, as characterized by annual flow-duration curves, of streams of the SJCP. The study area included the Rio Blanco and Little Navajo and Navajo Rivers in the San Juan River watershed upstream from the diversions on those streams and streams upstream from Heron Reservoir (figs. 1 and 2). Water-quality samples were collected in spring, summer, and fall of water years 2009 and 2010 (a water year is the 12-month period of October 1 through September 30 designated by the calendar year in which it ends), and existing water-quality and

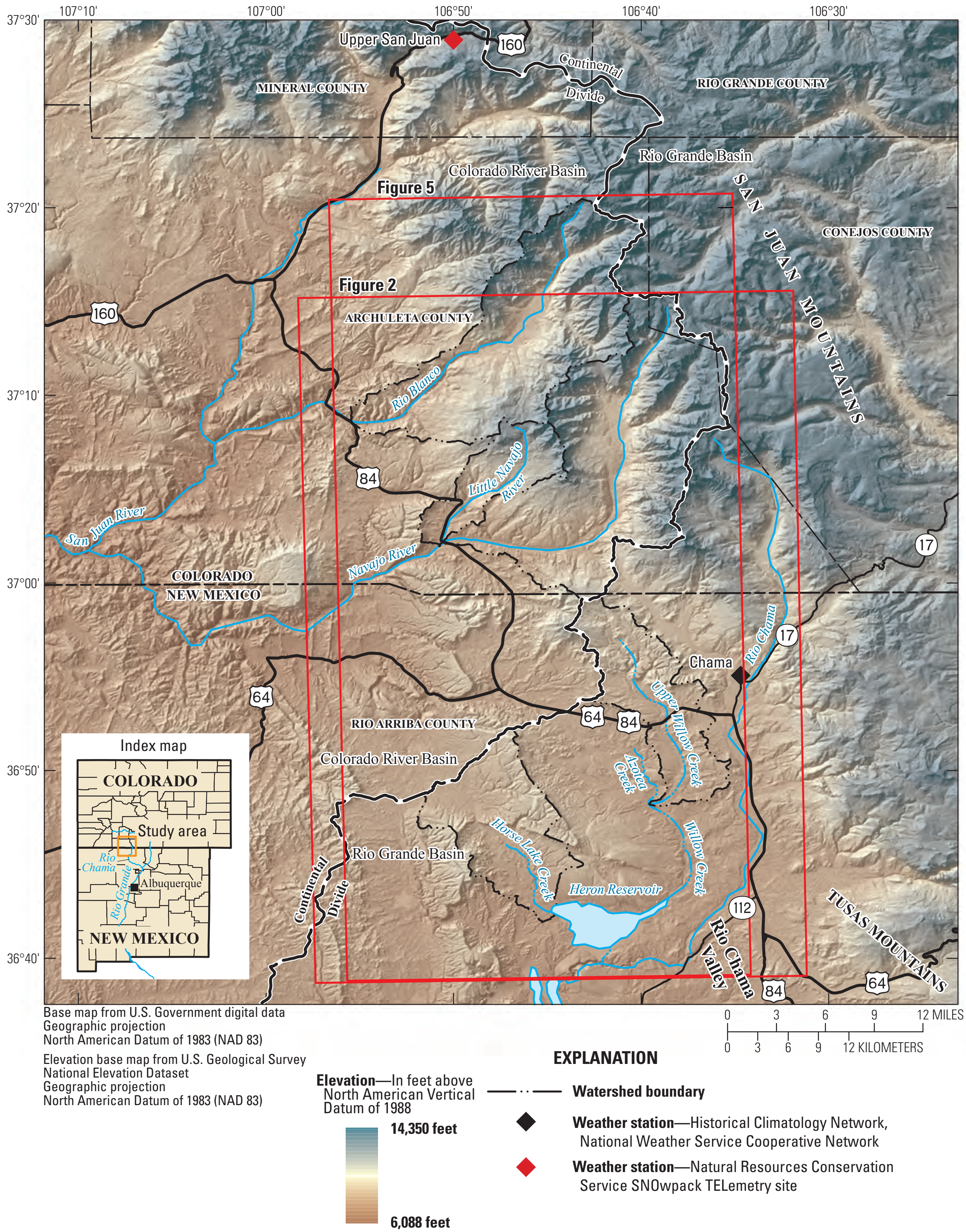
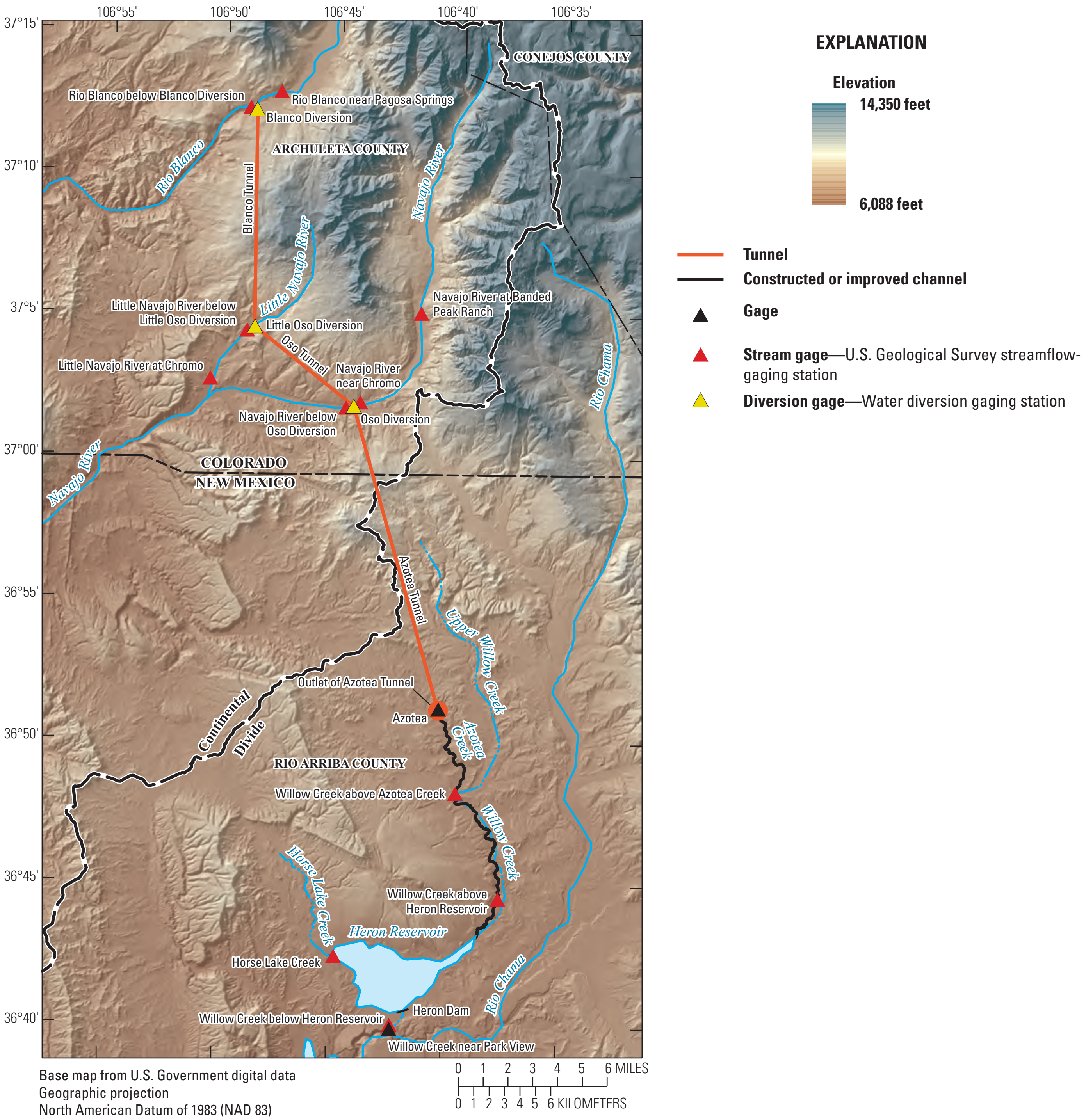


Figure 1. Location of the study area, hydrographic areas within the study area, selected geographic features, and climate stations, southern Colorado and northern New Mexico.



Base map from U.S. Government digital data
Geographic projection
North American Datum of 1983 (NAD 83)

Elevation base map from U.S. Geological Survey
National Elevation Dataset 10-meter digital
elevation model, 1/3 arc-second
Geographic projection
North American Datum of 1983 (NAD 83)

Figure 2. Schematic of the San Juan–Chama Project and location of streamflow-gaging stations and water-quality sampling sites in the study area, southern Colorado and northern New Mexico.

streamflow data from 1935 to 2010 were compiled. In this report, discharge is used for the volume rate of the flow of water because streamflow at several study sites is a combination of natural streamflow and diverted water, and streamflow is used when referring to flow conditions at a site.

Description of Study Area

The study area is located in the southern San Juan Mountains and Rio Chama Valley in northern New Mexico and southern Colorado (fig. 1). The southern San Juan Mountains, the southernmost extent of the Rocky Mountains, decline in elevation to the south into the Rio Chama Valley where they are bounded to the east by the Rio Chama (Atwood and Mather, 1932). The peaks of the southern San Juan Mountains form the Continental Divide, such that watersheds east of the peaks drain to the Rio Grande and watersheds west of the peaks drain to the Colorado River. Within the study area, the Rio Blanco, Little Navajo River, and Navajo River are located in the southern San Juan Mountains west of the Continental Divide and are tributaries of the San Juan River in the Colorado River Basin (fig. 1). Willow Creek and Horse Lake Creek are located in the Rio Chama Valley east of the Continental Divide and are tributaries of the Rio Chama in the Rio Grande Basin (fig. 1). The climates of the southern San Juan Mountains and the Rio Chama Valley differ because of variations in elevation.

Land-surface elevations of the watersheds of the three streams upstream from the SJCP diversions in the southern San Juan Mountains range from approximately 7,700 feet (ft) to 12,800 ft. The Upper San Juan SNOwpack TELemetry (SNOTEL) site (fig. 1 and table 2), located in the San Juan Mountains at an elevation of 10,200 ft, had an average annual precipitation of 53.9 inches for 1979–2009 and average annual average temperature of 33.4°F for 1986–2009 (Natural Resources Conservation Service, 2011). The annual average temperature for 1986–2009 ranged from 31.3°F to 37.6°F, and the annual precipitation for 1979–2009 ranged from 29.7 to 74.9 inches (figs. 3*A* and 3*B*). The months of May through October had average monthly temperatures greater than 32°F, and the months of November through April had average monthly temperatures of less than 32°F (fig. 3*C*). The majority of precipitation (71 percent) occurred from October through April, with 41 percent of precipitation from January to April, and 29 percent of precipitation occurred from May through September (fig. 3*D*).

Land-surface elevations in the Rio Chama Valley in the natural watershed of Heron Reservoir range from approximately 7,150 to 9,900 ft. The National Weather Service Cooperative Observer Program site located at Chama, N. Mex. (fig. 1 and table 2), located at an elevation of 7,850 ft, had average annual precipitation of 21.7 inches and average annual average temperature of 42.5°F for 1905–2009 (United States Historical Climatology Network, 2011). The annual average temperature at this site ranged from 39.5 to 47.3°F, and the annual precipitation ranged from 11.3 to 32.34 inches for 1905–2009 (fig. 4*A* and 4*B*). The months of April through November had average monthly temperatures greater than 32°F, and the months of December through March had average monthly temperatures less than 32°F (fig. 4*C*). Slightly more than half (56 percent) of the precipitation occurred from October through April, and 44 percent of precipitation occurred from May through September (fig. 4*D*).

The San Juan Mountains are composed of volcanic material deposited during the Middle Tertiary Period (Oligocene and Miocene; Lipman and others, 1970). Initial volcanic activity included deposition of lava and breccias, and later volcanic activity included deposition of explosive ash flows and tuffs and the formation of caldera complexes (Lipman and Steven, 1971). Later volcanic activity primarily extruded basalts that capped the older volcanics (Lipman and Steven, 1971). Cretaceous-aged bedrock units, including the Mancos Shale, Mesaverde Group, the Pictured Cliffs Sandstone, and the Lewis Shale, crop out along the western edge of the southern San Juan Mountains and along the canyons where the overlying volcanic rocks have been eroded (Bureau of Reclamation, 1955; Stoeser and others, 2007) (fig. 5). The Quaternary Period was marked by three intervals of glaciation that resulted in rapid erosion (Bureau of Reclamation, 1955) and deposition of terraces and glacial drift (Atwood and Mather, 1932).

The Rio Chama Valley is a shallow physiographic basin bounded on the west by anticlines that form the eastern edge of the San Juan Basin and bounded on the east by the Tusas Mountains (Muehlberger, 1967). Within the valley, the flat-lying floor runs northwest into Colorado. The surficial geology of the Rio Chama Valley in the vicinity of Heron Reservoir primarily is comprised of Mancos Shale with some outcropping of the Dakota Sandstone, especially along the northern edge of Heron Reservoir (fig. 5).

San Juan–Chama Project

The United States Congress authorized the initial stage of the SJCP in 1962 under Public Law (P.L.) 87–483 (An act to authorize the Secretary of the Interior to construct, operate, and maintain the Navajo Indian irrigation project and the initial stage of the San Juan–Chama project as participating projects of the Colorado River storage project, and for other purposes, Section 8, Public Law 87–483, June 13, 1962 [S.107] 76 Stat. 96), which allowed diversion of water from the Colorado River Basin to the Rio Grande Basin. Water that is diverted for the SJCP is a portion of the Colorado River water allocated to New Mexico by the Upper Colorado River Basin Compact. The authorization allowed for diversion of water from the Rio Blanco and Little Navajo and Navajo Rivers. Construction of the project started in 1964 and was completed in 1971. Water diversions into Heron Reservoir started in October 1970 (Allen, 2000).

Table 2. Climate stations, water-quality sampling sites, and streamflow-gaging stations used in analysis; abbreviated name used for the report; location information; period of record for streamflow data; period of record for water-quality samples; and number of samples with major-element analysis for stations in southern Colorado and northern New Mexico.

[USGS, U.S. Geological Survey; CDWR, Colorado Division of Water Resources; CLIMATE, climate station; WQ, water quality; SF, streamflow; CO, Colorado; NM, New Mexico; NA, not available; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NAD 27, North American Datum of 1927; NRCS, Natural Resources Conservation Service; NWS Coop, National Weather Service Cooperative Observer Program; Reclamation, Bureau of Reclamation; URGWOM, Upper Rio Grande Water Operations Model]

Site type	USGS site identifier	CDWR site abbreviation	Site name	Site name for report
CLIMATE			Upper San Juan (Natural Resources Conservation Service SNOwpack TELemetry)	Upper San Juan
CLIMATE			Chama, New Mexico (Historical Climatology Network, National Weather Service Cooperative Network - site 291664)	Chama
WQ/SF	09343000		Rio Blanco near Pagosa Springs, CO	Rio Blanco near Pagosa Springs
SF		BLADIVCO	Blanco Diversion near Pagosa Springs	Blanco Diversion
WQ/SF	09343300	RIOBLACO	Rio Blanco below Blanco Diversion Dam near Pagosa	Rio Blanco below Blanco Diversion
SF		LOSODVCO	Little Oso Diversion near Chromo	Little Oso Diversion
WQ/SF	09345200 09345250	LITOSOCO	Little Navajo River below Little Oso Diversion Ditch	Little Navajo River below Little Oso Diversion
SF	09345500		Little Navajo River at Chromo, CO	Little Navajo River at Chromo
SF	09344000	NAVBANCO	Navajo River at Banded Peak Ranch near Chromo, CO	Navajo River at Banded Peak Ranch
WQ/SF	09344300		Navajo River above Chromo, CO	Navajo River above Chromo
SF		OSODIVCO	Oso Diversion near Chromo, CO	Oso Diversion
WQ/SF	09344400	NAVOSOCO	Navajo River below Oso Diversion Dam near Chromo, CO	Navajo River below Oso Diversion
WQ	08284150		Willow Creek above Azotea Creek near Park View, NM	Willow Creek above Azotea Creek
SF	08284160	AZOTUNNM	Azotea Tunnel at Outlet near Chama, NM	Azotea
SF	08284200		Willow Creek above Heron Reservoir, near Los Ojos, NM	Willow Creek above Heron Reservoir
WQ/SF	08284300		Horse Lake Creek above Heron Reservoir, near Los Ojos, NM	Horse Lake Creek above Heron Reservoir
WQ/SF	08284500		Willow Creek near Park View, NM	Willow Creek near Park View

Site name for report	Latitude	Longitude	Horizontal datum	Elevation (feet)	Elevation datum
Upper San Juan	37° 29'	106° 50'	NA	10,200	NA
Chama	36° 55' 00"	106° 35' 00"	NA	7,850	NA
Rio Blanco near Pagosa Springs	37° 12' 46"	106° 47' 38"	NAD 27	7,950	NGVD 29
Blanco Diversion	37° 12' 13"	106° 48' 44"	NAD 83	7,858	NGVD 29
Rio Blanco below Blanco Diversion Dam	37° 12' 13"	106° 48′ 44"	NAD 83	7,858	NGVD 29
Little Oso Diversion	37° 04' 38.3"	106° 48' 40.4"	NAD 83	7,756	NGVD 29
Little Navajo River below Little Oso	37° 04' 38.3"	106° 48' 40.4"	NAD 83	7,756	NGVD 29
Little Navajo River at Chromo	37° 02' 44"	106° 50' 33"	NAD 27	7,294	NGVD 29
Navajo River at Banded Peak Ranch	37° 05' 07"	106° 41' 20"	NAD 27	7,941	NGVD 29
Navajo River above Chromo	37° 01' 55"	106° 43' 56"	NAD 27	7,700	NGVD 29
Oso Diversion	37° 01' 49"	106° 44' 14"	NAD 27	7,648	NGVD 29
Navajo River below Oso Diversion Dam	37° 01' 49"	106° 44' 14"	NAD 27	7,648	NGVD 29
Willow Creek above Azotea Creek	36° 48' 15"	106° 39' 30"	NAD 27	7,404	NGVD 29
Azotea	36° 51' 12"	106° 40' 18"	NAD 27	7,520	NGVD 29
Willow Creek above Heron Reservoir	36° 44' 33"	106° 37' 34"	NAD 27	7,196	NGVD 29
Horse Lake Creek above Heron Reservoir	36° 42' 24.05"	106° 44' 44.14"	NAD 83	7,187	NGVD 29
Willow Creek near Park View	36° 40' 05"	106° 42' 15"	NAD 27	6,945	NGVD 29

Table 2. Climate stations, water-quality sampling sites, and streamflow-gaging stations used in analysis; abbreviated name used for the report; location information; period of record for streamflow data; period of record for water-quality samples; and number of samples with major-element analysis for stations in southern Colorado and northern New Mexico.—Continued

[USGS, U.S. Geological Survey; CDWR, Colorado Division of Water Resources; CLIMATE, climate station; WQ, water quality; SF, streamflow; CO, Colorado; NM, New Mexico; NA, not available; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NAD 27, North American Datum of 1927; NRCS, Natural Resources Conservation Service; NWS Coop, National Weather Service Cooperative Observer Program; Reclamation, Bureau of Reclamation; URGWOM, Upper Rio Grande Water Operations Model]

Site name for report	Parameters	Start of period of record	End of period of record	Data collection agency	Data reporting agency	Number of water-quality samples
Upper San Juan	Precipitation	1979	2010	NRCS	NRCS	
	Temperature	1986	2010	NRCS	NRCS	
Chama	Precipitation	1935	2010	NWS Coop	NWS Coop	
	Temperature	1935	2010	NWS Coop	NWS Coop	
Rio Blanco near Pagosa Springs	Discharge	1935	1971	USGS	USGS	
	Water quality	1958	1974	USGS	USGS	276
Blanco Diversion	Discharge	1993	2010	Reclamation	CDWR	
	Discharge	1974	1993	Reclamation	URGWOM	
Rio Blanco below Blanco Diversion Dam	Discharge	1971	2010	CDWR	CDWR	
	Water quality	1973	2009	USGS	USGS	74
Little Oso Diversion	Discharge	1993	2010	Reclamation	CDWR	
	Discharge	1974	1993	Reclamation	URGWOM	
Little Navajo River below Little Oso	Discharge	1996	2010	CDWR	CDWR	
	Water quality	2007	2009	USGS	USGS	13
Little Navajo River at Chromo	Discharge	1935	1952	USGS	USGS	
Navajo River at Banded Peak Ranch	Discharge	1935	2010	USGS/CDWR	CDWR	
Navajo River above Chromo	Discharge	1935	1970	USGS	USGS	
	Water quality	1959	1974	USGS	USGS	262
Oso Diversion	Discharge	1993	2010	Reclamation	CDWR	
	Discharge	1974	1993	Reclamation	URGWOM	
Navajo River below Oso Diversion Dam	Discharge	1971	2010	CDWR	CDWR	
	Water quality	1973	2009	USGS	USGS	40
Willow Creek above Azotea Creek	Discharge	1971	1973	USGS	USGS	
	Water quality	1973	2009	USGS	USGS	3
Azotea	Discharge	1971	2010	Reclamation	USGS/CDWR	
Willow Creek above Heron Reservoir	Discharge	1961	2010	BOR/USGS	BOR/USGS	
Horse Lake Creek above Heron Reservoir	Discharge	1962	2009	USGS	USGS	
	Water quality	1973	2009	USGS	USGS	5
Willow Creek near Park View	Discharge	1942	1971	USGS	USGS	
	Water quality	1961	1965	USGS	USGS	76

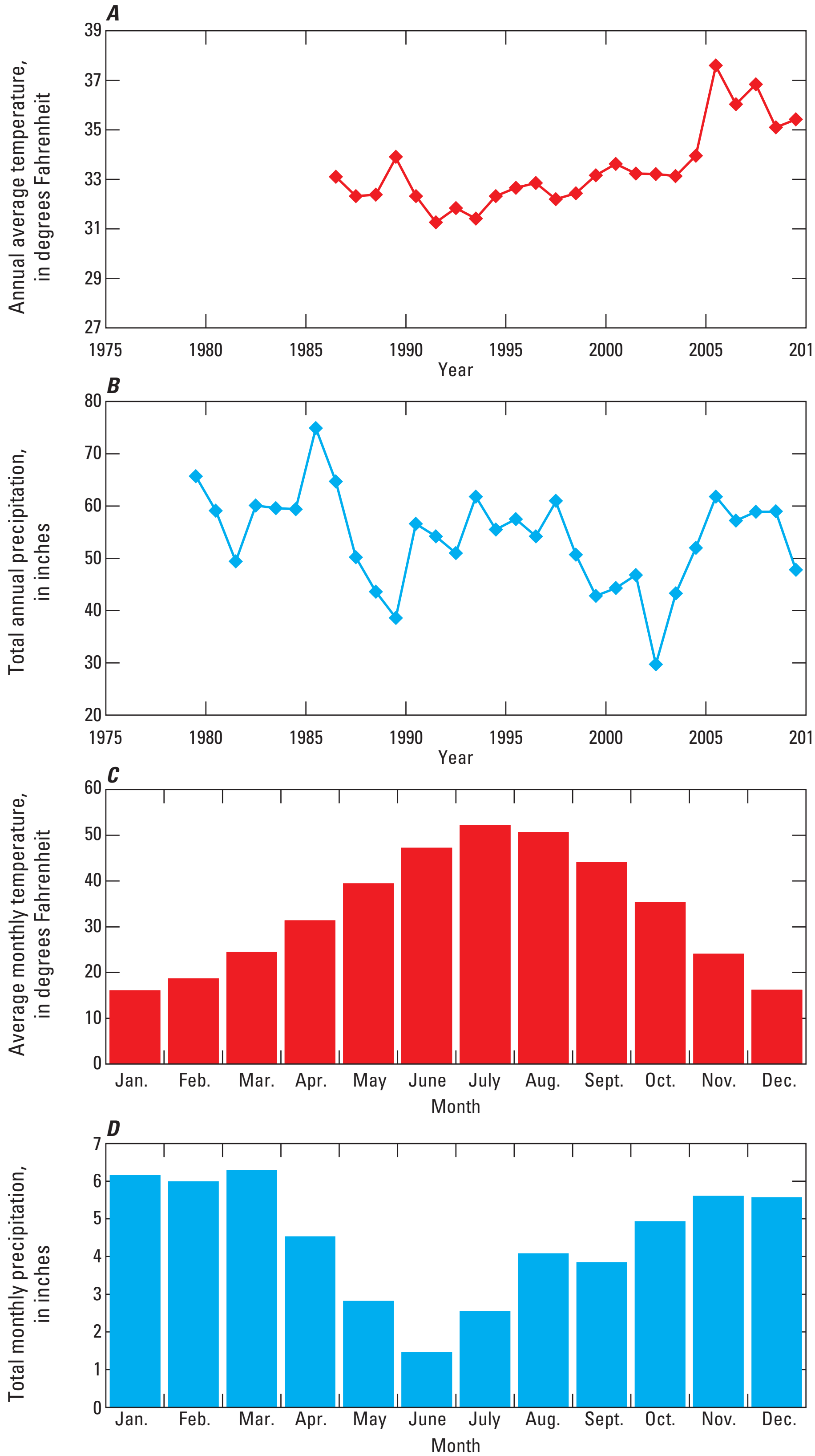


Figure 3. Temperature and precipitation data for climate station Upper San Juan (Natural Resources Conservation Service SNOwpack TELemetry site), in the southern Colorado portion of the study area. *A*, Annual average temperature, 1986–2009. *B*, Annual precipitation, 1979–2009. *C*, Average monthly temperature, 1986–2009. *D*, Average monthly precipitation, 1979–2009.

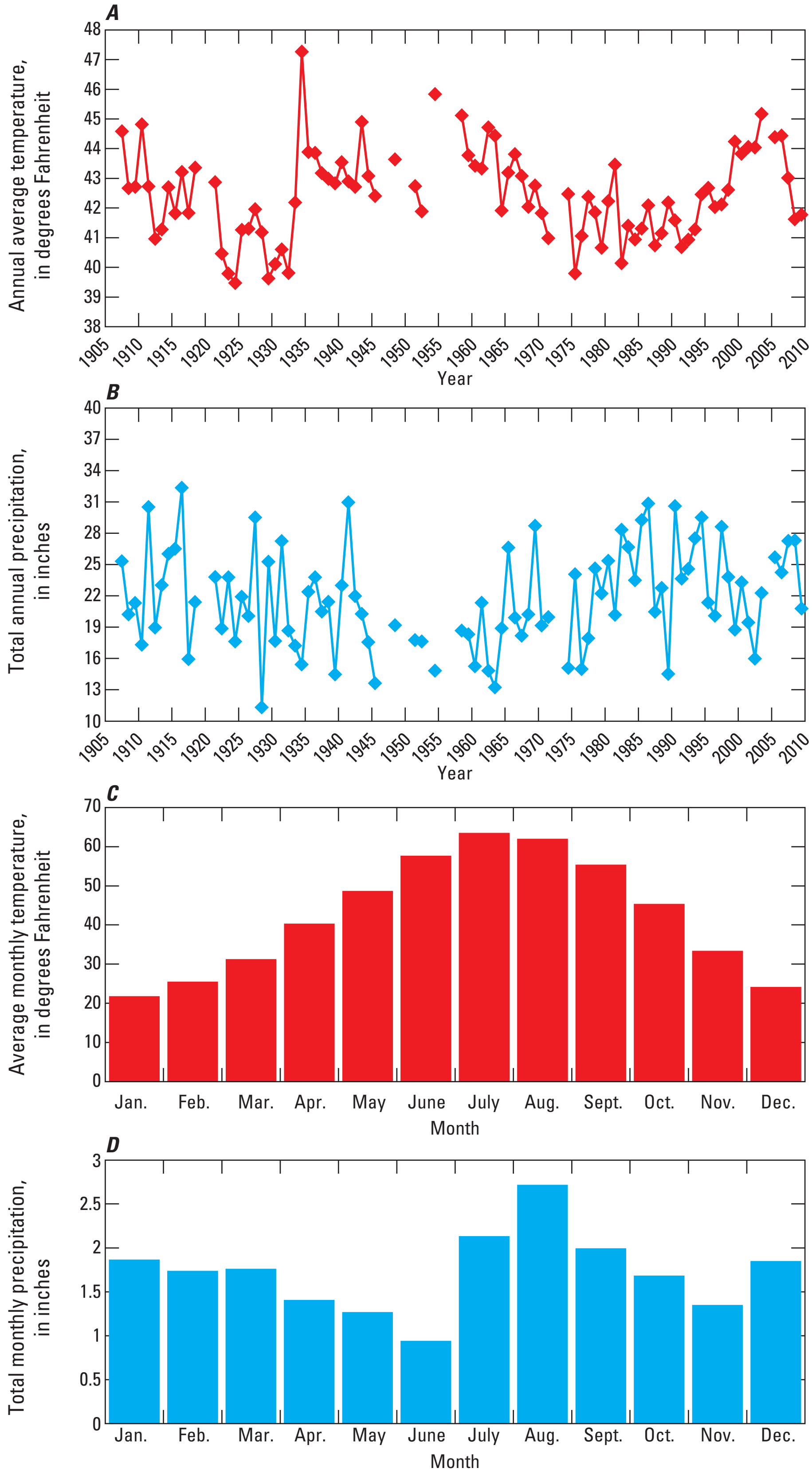
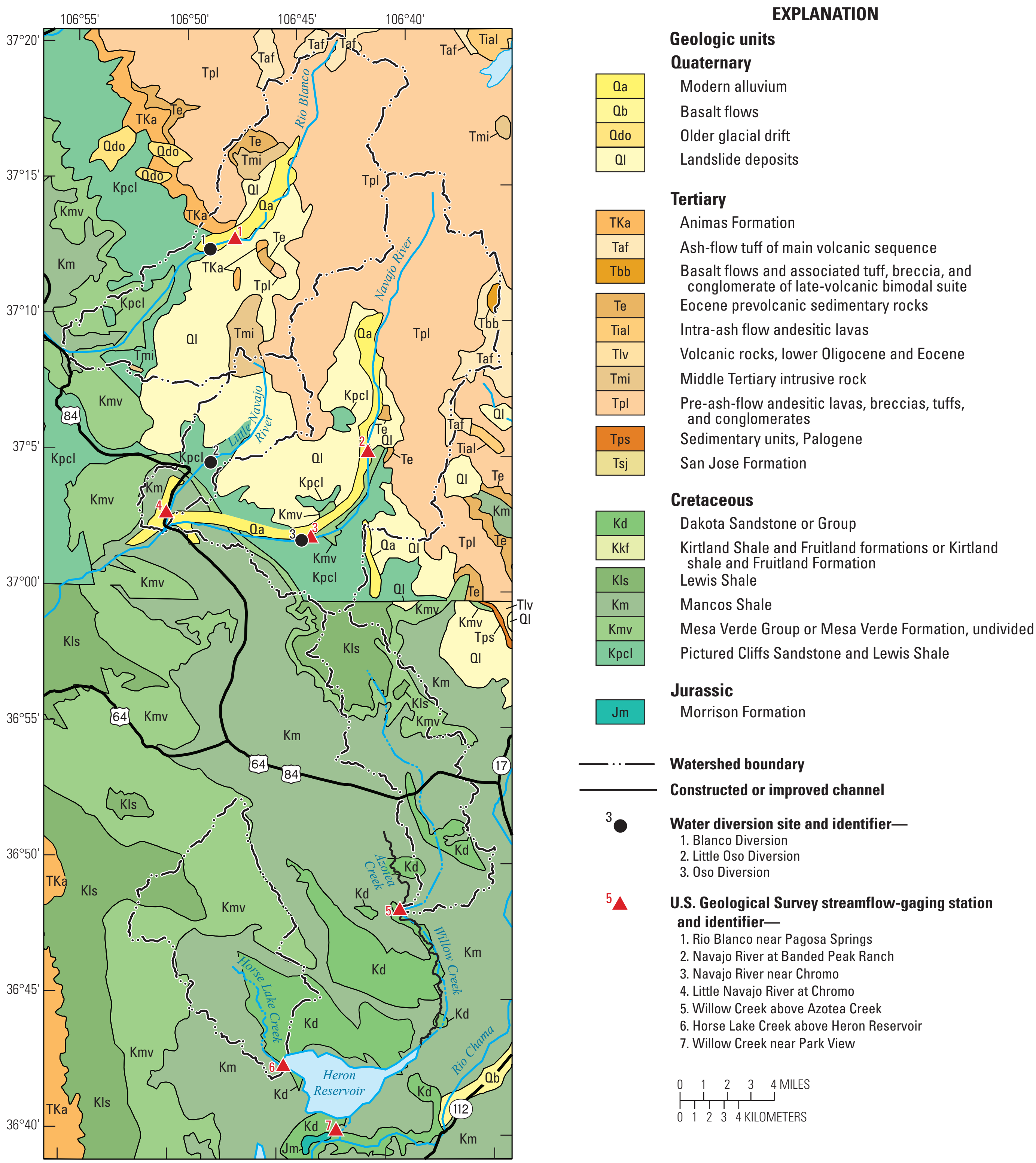


Figure 4. Temperature and precipitation data for climate station Chama (National Weather Service Cooperative Observer Program weather station), in the northern New Mexico portion of the study area, 1905–2009. *A*, Annual average temperature. *B*, Annual precipitation. *C*, Average monthly temperature. *D*, Average monthly precipitation.



Geologic data from U.S. Geological Survey digital data
Open-File Report 2005-1351, Version 1.2, December 2007
Geographic projection
North American Datum of 1983 (NAD 83)

Base map from U.S. Government digital data
Geographic projection
North American Datum of 1983 (NAD 83)

Figure 5. Surface geology of the study area, location of selected streamflow-gaging stations, and the boundary of selected watersheds, southern Colorado and northern New Mexico.

Water diverted for the SJCP is delivered to the SJCP contractors, on the basis of water contracts (table 1). Requirements for SJCP water are that it (1) must be used consumptively and beneficially in New Mexico, (2) must have a downstream destination, (3) must not harm native Rio Grande water (water that originates in the Rio Grande Basin), and (4) is not subject to the Rio Grande Compact (Bureau of Reclamation, 2010). SJCP contractors cannot store water in Heron Reservoir and are obligated to schedule delivery of their full allotment of SJCP water by the end of the calendar year. Any water remaining in storage in Heron Reservoir after the end of the year is relinquished to the general pool, although extensions can be granted by the U.S. Department of the Interior (Flanigan and Hass, 2008). Native water of the Rio Grande Basin, which is any water from a source within the Rio Grande Basin, cannot be stored in Heron Reservoir; therefore, any native Rio Grande water that flows into Heron Reservoir from the Willow Creek watershed must be accounted for and released. Native Rio Grande water is accounted for on a monthly basis by the Bureau of Reclamation (Reclamation).

Congress stipulated limitations on the amount of water that can be diverted. Diversions from the San Juan River watershed are limited to 1,350,000 acre-ft of water in any 10 consecutive years and 270,000 acre-ft in any 1 year (P.L. 87–483). Congress also stipulated that in years when shortages are anticipated "…prospective runoff shall be apportioned between the contractors diverting above those diverting at or below Navajo Reservoir in the proportion that the total normal diversion requirement of each group bears to the total of all normal diversion requirements" (P.L. 87–483).

The sum of annual diversions from the Rio Blanco and Navajo River are limited such that discharge in the rivers cannot be depleted below the minimum monthly bypass requirements (table 3) detailed in the report "San Juan–Chama Project, Colorado–New Mexico" (Bureau of Reclamation, 1955). The minimum monthly bypass requirements for the Little Navajo River were not set in P.L. 87–483 but were listed as 27 cubic feet per second (ft^3/s) for May through September in the 1964 Reclamation definite plan report (Bureau of Reclamation, 1964) and set by memorandum in 1977 as 27 ft^3/s for May through September and 4 ft^3/s for October through April (Bureau of Reclamation, 1986) (table 3).

The SJCP infrastructure consists of three diversion dams (Blanco Diversion, Little Oso Diversion, and Oso Diversion), a conduit and tunnel system, and Heron Dam (schematic shown on fig. 2). The diversion dams are constructed on the Rio Blanco, Navajo River, and Little Navajo River in the southern San Juan Mountains (fig. 2). The conduit and tunnel system conveys water across the Continental Divide and discharges into the constructed and improved channel of Azotea Creek (fig. 2). Heron Dam, constructed on Willow Creek just upstream from the confluence with the Rio Chama, provides storage of SJCP water and allows for controlled releases to SJCP contractors.

Table 3. San Juan–Chama Project minimum monthly bypass requirements for the Rio Blanco, Little Navajo River, and Navajo River, in the southern Colorado portion of the study area.

[$ft^3\ s^{-1}\ d^{-1}$, cubic feet per second per day; --, no minimum monthly bypass requirement]

	Rio Blanco		Little Navajo River		Navajo River	
	acre-feet	$ft^3\ s^{-1}\ d^{-1}$	acre-feet	$ft^3\ s^{-1}\ d^{-1}$	acre-feet	$ft^3\ s^{-1}\ d^{-1}$
Jan.	900	16	--	4	1,800	30
Feb.	800	15	--	4	1,900	35
Mar.	1,200	20	--	4	2,200	36
Apr.	1,200	21	--	4	2,200	38
May	2,400	40	1,600	27	5,300	87
June	1,200	21	1,600	27	3,300	56
July	1,200	20	1,600	27	3,300	54
Aug.	1,200	20	1,600	27	3,300	54
Sept.	1,200	21	1,600	27	3,300	56
Oct.	1,200	20	--	4	2,200	36
Nov.	1,200	21	--	4	2,200	38
Dec.	900	16	--	4	2,200	36

The capacity of the infrastructure limits the amount of water that can be diverted from the Rio Blanco, Little Navajo River, and Navajo River. Water from the Rio Blanco is diverted at Blanco Diversion into the Blanco Tunnel, which has a capacity of 520 ft^3/s and extends approximately 9 mi to the Little Navajo River (Bureau of Reclamation, 2011a). Water from the Blanco Tunnel is combined with water diverted from the Little Navajo River through the Little Oso Feeder Conduit (capacity of 150 ft^3/s; location not shown on fig. 2) into the Oso Tunnel (Bureau of Reclamation, 2011a). The Oso Tunnel has a capacity of 550 ft^3/s and extends approximately 5 mi to the Navajo River (Bureau of Reclamation, 2011a). Water from the Oso Tunnel is combined with water diverted from the Navajo River through the Oso Feeder Conduit (capacity of 650 ft^3/s; location not shown on fig. 2) into the Azotea Tunnel (Bureau of Reclamation, 2011a). Azotea Tunnel has a capacity of 950 ft^3/s and extends approximately 13 mi to the Azotea Creek in the Rio Grande Basin (Bureau of Reclamation, 2011a). Azotea Creek and sections of the Willow Creek between the outlet of Azotea Tunnel and the Heron Dam were channelized, including "re-alignment, installation of concrete drop structures, and riprap bank protection," to prevent erosion (Cannon, 1969). Heron Dam is an earthfill structure that is 269 ft high with a reservoir capacity of 401,320 acre-ft (Bureau of Reclamation, 2011b). The outlet works were constructed on Willow Creek above the confluence with the Rio Chama and have a capacity of 4,160 ft^3/s (Bureau of Reclamation, 2011b).

Previous Studies

Review of previous investigations of water quality in the Rio Chama watershed has indicated that there is limited information about the quality of SJCP water that flows into Heron Reservoir and about the quality of water stored in Heron Reservoir. Additionally, little is known about groundwater/surface-water interactions along the naturally occurring and constructed channels used to convey water from the San Juan River watershed to Heron Reservoir. Langman and Anderholm (2004) studied the effects of reservoir installation, operation, and introduction of SJCP water into the Rio Grande Basin on the streamflow and water quality of the Rio Chama and the Rio Grande in New Mexico. Langman and Anderholm (2004) reported a median specific-conductance value for water in Heron Reservoir of 312 microsiemens per centimeter (μS/cm) on the basis of four sampling events from 1987 and 1991. New Mexico Environment Department does not include the watershed above Heron Reservoir in its cyclic total maximum daily load sampling (New Mexico Environment Department, 2003).

An initial study of the SJCP was completed by Reclamation in 1955 as a plan for development submitted to secure congressional authorization for the project (Bureau of Reclamation, 1955). The study included a general description of the project area, proposed water allocations, a proposed development plan, estimated construction costs and allocation of construction costs, and estimated economic benefits. The initial report also included appendixes with reports on the geologic and hydrologic investigations that had been conducted (Appendix C–Geology and Appendix D–Hydrology).

Appendix D–Hydrology in the Reclamation plan for development (Bureau of Reclamation, 1955) included hydrologic investigations that were conducted on each tributary of the San Juan River that had a proposed project component. Studies in the plan for development included estimates of the annual volume of water available as runoff from each watershed, determination of the annual volume of water needed for the bypass requirements to satisfy prior water rights, evaporation rates for reservoirs, reported water-quality data, determination of diversion and reservoir capacities, estimated sedimentation rates, and flood frequency analysis. Appendix D–Hydrology also included the calculated annual volume of water available for diversion for 1928–51, which was computed as the annual volume of water available as runoff that exceeded the annual volume of water needed to meet the bypass requirement for prior water rights (Bureau of Reclamation, 1955). The average annual volume of water available as runoff for the Rio Blanco was 71,600 acre-ft (however, the average annual volume of water available as runoff for the Rio Blanco was calculated for this report from the listed annual discharges as 71,200 acre-ft), for the Little Navajo River was 9,300 acre-ft, and for the Navajo River was 88,200 acre-ft (Bureau of Reclamation, 1955) (table 4). For 1928–51, the average annual volume of water available for diversion from the Rio Blanco was 57,000 acre-ft, from the Little Navajo River was 6,700 acre-ft, and from the Navajo River was 57,900 acre-ft, with a combined average annual volume of water available for diversion of 121,600 acre-ft (Bureau of Reclamation, 1955) (table 4).

In 1963 the definite plan for the SJCP was prepared by Reclamation (a revised report was released in 1964; Bureau of Reclamation, 1964). The definite plan was designed to divert an average of 110,000 acre-ft of water annually. Hydrologic analysis of the amount of discharge that could be diverted was calculated from 1935 to 1957 and included data from the 1950s drought. For 1935–57, the average annual volume of water available for diversion was determined to be 110,500 acre-ft (Bureau of Reclamation, 1964). For 1935–57, it was estimated that the average annual demand for SJCP water was 103,600 acre-ft and that an average of 99,700 acre-ft of water could be supplied from Heron Reservoir to meet the SJCP demand (Bureau of Reclamation, 1964).

In 1981, Reclamation completed a report of model studies of design modifications to Blanco Diversion to reduce the flow of sediment into the diversion structures (Dodge, 1981). The report indicated that during high flows in 1974 sediment was deposited around the diversion dam and large cobbles were transported through the SJCP tunnels to the outlet of Azotea Tunnel. The report also detailed the problems dam operators encountered when they tried to sluice sediment and debris through the diversion structure. The report recommended modification of the dam to include a trap system that would reduce the amount of sediment diverted into the diversion tunnel.

Changes in the amount of streamflow derived from snowmelt runoff and the timing of the start and peak of the runoff could have implications for availability of water on the Rio Blanco, Little Navajo River, and Navajo River for diversion to the SJCP. Various studies have documented shifts in certain climatic parameters that could be an indication of changes in climate patterns that drive temperature and precipitation in the Western United States, such as annual precipitation, annual snowpack, annual discharge, the mass of streamflow attributable to snowmelt, and the timing of the start and peak of the runoff derived from snowmelt (snowmelt runoff). Selected studies of changes in the timing of the start and peak of the snowmelt runoff in the Western United States include Cayan and others (2001), Regonda and others (2005), Stewart and others (2005), Knowles and others (2006), Das and others (2009), Hidalgo and others (2009), and Clow (2010).

Several studies that compared timing of the start and peak of the snowmelt runoff in the Western United States indicate that the southern Rocky Mountain area can respond differently than do other areas. Several studies in the Western United States determined that trends of earlier start and peak of snowmelt runoff varied across the area and were distinct for the different regions within the Western United States. Regonda and others (2005) determined that changes in the start and peak of the snowmelt runoff were statistically significant in the Pacific Northwest but not statistically significant in the interior Western United States.

Table 4. Estimated availability of water for the San Juan–Chama Project including the annual volume of water available as runoff from each watershed, annual volume of water needed to meet the bypass requirement for prior water rights, and the calculated annual volume of water available for diversion from the Rio Blanco, Little Navajo River, and Navajo River, in the southern Colorado portion of the study area, 1928–51.

[Modified from tabulated data from the U.S. Bureau of Reclamation Plan for Development (1955), appendix D, tables D2-10 and D2-11, in thousand acre-feet]

Year	Annual volume of water available as runoff				Annual volume of water needed to meet the bypass requirement for prior water rights				Annual volume of water available for diversion			
	Rio Blanco	Little Navajo River	Navajo River	Total	Rio Blanco	Little Navajo River	Navajo River	Total	Rio Blanco	Little Navajo River	Navajo River	Total
1928	60.5	7.5	64.4	132.4	14.6	2.6	29.4	46.6	45.9	4.9	35	85.8
1929	103.5	12.2	119.8	235.5	14.1	3.9	30.4	48.4	89.4	8.3	89.4	187.1
1930	53.8	7.3	65.1	126.2	14.2	2.8	28	45	39.6	4.5	37.1	81.2
1931	45.1	5.7	53.9	104.7	13.8	2.5	30.5	46.8	31.3	3.2	23.4	57.9
1932	115.6	17.3	144	276.9	14.6	3.9	30.1	48.6	101	13.4	113.9	228.3
1933	51.2	5.5	60.1	116.8	14.1	3.2	29.9	47.2	37.1	2.3	30.2	69.6
1934	23.3	4.1	30.8	58.2	13.5	1.5	22.7	37.7	9.8	2.6	8.1	20.5
1935	126.4	13.7	130.3	270.4	14.5	4.1	31.7	50.3	111.9	9.6	98.6	220.1
1936	81.6	10.3	91.7	183.6	14.6	2.1	33.2	49.9	67	8.2	58.5	133.7
1937	102.2	14.7	118.9	235.8	14.5	2.8	31.4	48.7	87.7	11.9	87.5	187.1
1938	92.6	12.9	116.3	221.8	14	4	32.9	50.9	78.6	8.9	83.4	170.9
1939	48.4	6.7	68.1	123.2	14.2	1.9	29.2	45.3	34.2	4.8	38.9	77.9
1940	40	4.1	64.2	108.3	14.2	1.4	31	46.6	25.8	2.7	33.2	61.7
1941	144.4	28.5	184.7	357.6	14.6	5.2	33.2	53	129.8	23.3	151.5	304.6
1942	73.3	17.8	125.6	216.7	13.8	3.5	32.4	49.7	59.5	14.3	93.2	167
1943	50.9	6.1	74.9	131.9	14.5	1.7	29.8	46	36.4	4.4	45.1	85.9
1944	78.8	7.7	100.7	187.2	14.2	2.8	30.9	47.9	64.6	4.9	69.8	139.3
1945	83.7	10.1	97.6	191.4	14.3	2.6	30.7	47.6	69.4	7.5	66.9	143.8
1946	41.3	2.2	51.5	95	14.6	.2	31.2	46	26.7	2	20.3	49
1947	63.2	3.9	69.2	136.3	14.6	2.4	32.9	49.9	48.6	1.5	36.3	86.4
1948	65.1	8.7	85.4	159.2	13.7	2.7	30.4	46.8	51.4	6	55	112.4
1949	82.9	10.3	99	192.2	14.5	3.7	31.1	49.3	68.4	6.6	67.9	142.9
1950	44.5	3.3	55	102.8	13	.4	28	41.4	31.5	2.9	27	61.4
1951	36.7	2.5	46.7	85.9	13.3	1.2	26.7	41.2	23.4	1.3	20	44.7
Average	[1]71.2	9.3	88.2	168.8	14.2	2.6	30.3	47.1	57.0	6.7	57.9	121.6

[1]The average annual volume of water available from Rio Blanco was reported in appendix D table D2-10 (U.S. Bureau of Reclamation Plan for Development, 1955) as 71.6 thousand acre-feet. The average value reported here was calculated from the annual values.

Hidalgo and others (2009) reported that significant trends in the Columbia River Basin indicating the centers of mass of streamflow derived from snowmelt runoff were occurring earlier; however, the trends were not significant for the Colorado River Basin. Knowles and others (2006) examined historical changes in the ratio of rainfall and snowfall to total precipitation in the Western United States and concluded that, in areas of low to moderate elevation with moderate warming, precipitation had shifted from snowfall to rainfall driven by increased temperature. They noted, however, that sites in the southern Rocky Mountains had increased total winter precipitation and increased snowfall and concluded that more of the seasonal precipitation had shifted to colder months, resulting in mixed trends for the fraction of winter precipitation falling as snow (Knowles and others, 2006). Das and others (2009) concluded that climate trends such as warming, decreased ratio of snowfall to total precipitation, and increased winter runoff exceeded natural climate variability over significant areas of snow-dominated areas of the Western United States; however, in the southern Rocky Mountains, trends in warming and runoff from January through March did not exceed natural variability. Further analysis of climate variability in this area indicated that trends in annual runoff were within natural variability and that changes in runoff from January through March were likely the result from a shift in the timing of runoff and not from increased runoff (Das and others, 2009).

A recent study by Clow (2010) analyzed streamflow and snow-water equivalent data and compared trends between datasets and with precipitation and temperature trends for Colorado for 1978–2007. Clow (2010), following Moore and others (2007), used the day of each water year on which the 20th, 50th, and 80th percentile of flow had occurred to represent the beginning, middle, and end of snowmelt runoff. Clow (2010) used the regional Kendall test, which combines results from the Mann–Kendall trend test from individual sites to calculate trend slopes, to test for trends in snowmelt and streamflow timing and multiple linear regressions to determine the influence of precipitation and temperature. Results from the regional Kendall test trend analysis indicated significant trends for streamflow timing and snowmelt onset such that over time these events have occurred on dates that are earlier in the year than in previous years, winter temperatures have increased, and April snow-water equivalents have decreased (Clow, 2010). Multiple linear regression analysis indicated that trends in streamflow timing could be accounted for by changes in temperature and April snow-water equivalent (Clow, 2010).

In contrast to Clow and others (2010), Moore and others (2007) observed that measures of the timing of the streamflow derived from snowmelt runoff can produce stronger trends against the annual volume of discharge than time alone, such that "discharge is a stronger controlling variable than time" (p. 4). They proposed that changes in the volume of annual discharge can cause apparent shifts in the measures of streamflow timing because of changes in the streamflow pulse duration and volume. They concluded that "changes in runoff alone will affect any analyses of runoff timing, with high flows producing 'later' runoff and low flows producing 'earlier' runoff" (Moore and others, 2007, p. 4) (fig. 6) and suggested that "predicting future snowmelt runoff in the northern Rockies will require linking climate mechanisms controlling precipitation, rather than projecting response to simple linear increases in temperature" (p. 1).

Method of Analysis

The streamflow data compiled for this report were collected by the USGS, Colorado Division of Water Resources (CDWR), and Reclamation. Data either were requested from the collecting agency or were obtained from an agency-supported Web-accessible database. It was assumed that all data had been reviewed for accuracy and correctness, and no attempt was made to evaluate the quality of the data. Information for all streamflow-gaging stations is presented in table 2.

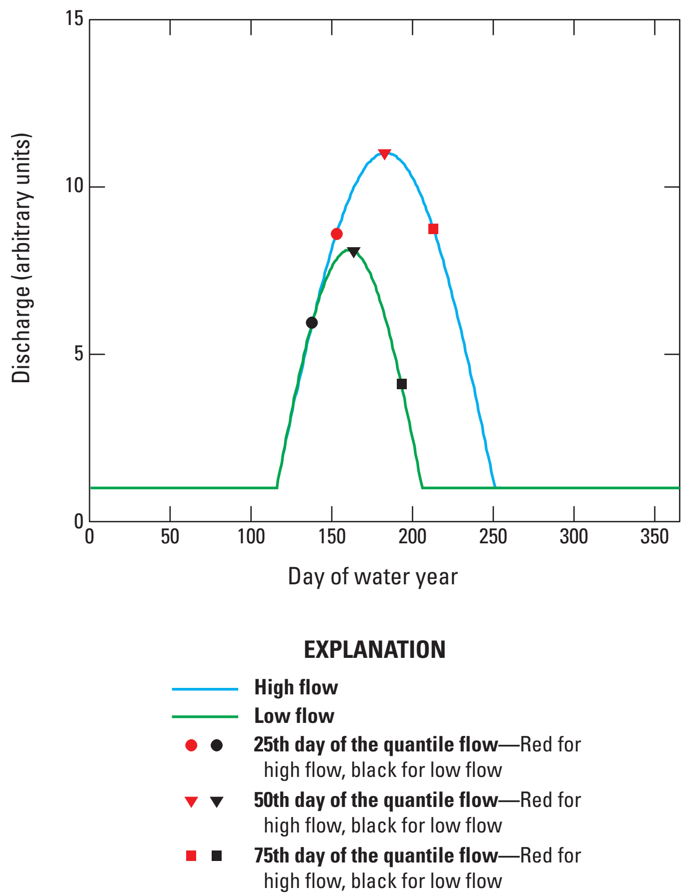


Figure 6. Conceptual model of streamflow for small volume of annual discharge (low flow) and large volume of annual discharge (high flow) with the same base flow. Modified with permission from Moore and others (2007).

All data in this report presented on an annual scale are compiled on the calendar year, except for the data for the indicators of the seasonal distribution of streamflow, which are compiled on the water year. The temporal period of the calendar year was primarily used so that the annual statistics could be easily compared to the legal limits of the SJCP. The temporal period of the water year, defined as the 12-month period of October 1 through September 30 designated by the calendar year in which it ends, was used for the indicators of the seasonal distribution of streamflow because the existing methods for calculating the various indicators are based on water year intervals.

The USGS collected streamflow data on the Rio Blanco, Little Navajo River, Navajo River, and Willow Creek prior to about 1970. Mean daily streamflow values for streamflow-gaging stations Rio Blanco near Pagosa Springs, Navajo River at Banded Peak Ranch (from 1935 to 1972), Navajo River above Chromo, Little Navajo River at Chromo, Willow Creek above Heron Reservoir (from 1961 to 1971), Willow Creek near Park View, and Horse Lake Creek above Heron Reservoir (fig. 2 and table 2) were calculated by following USGS streamflow measurement protocols described by Rantz (1982a and 1982b). Mean daily streamflow values for Navajo River at Banded Peak Ranch used in this report were retrieved from the USGS National Water Information System database (http://nwis.waterdata.usgs.gov/nwis/sw) for 1935–72; mean daily streamflow values for Navajo River at Banded Peak Ranch for 1972–95 were provided to the USGS by the CDWR and were reviewed by the USGS. Streamflow data for the streamflow-gaging stations Azotea (fig. 2 and table 2) for 1970–2010 and Willow Creek above Heron Reservoir for 1971–2010 were provided to the USGS by Reclamation as computed mean daily streamflow.

The CDWR currently (2011) operates the streamflow-gaging stations for streams in southern Colorado. Mean daily streamflow values for streamflow-gaging stations Rio Blanco below Blanco Diversion, Navajo River at Banded Peak Ranch (1995–2010), Navajo River below Oso Diversion, and Little Navajo River below Little Oso Diversion (fig. 2 and table 2) were retrieved from the CDWR Colorado's Decision Support Systems Web page (Colorado Division of Water Resources, 2011). Published mean daily streamflow data were downloaded for the beginning of the period of record to the end of water year 2009, and provisional mean daily streamflow data were downloaded for water year 2010 through the end of calendar year 2010. Mean daily streamflow at streamflow-gaging stations Rio Blanco below Blanco Diversion, Navajo River at Banded Peak Ranch (1972 to 2010), Navajo River below Oso Diversion, and Little Navajo River below Little Oso Diversion was calculated by following the State of Colorado Hydrographic Manual (McDonald, 2008).

Daily discharge data for 1974–93 for the streamflow-gaging stations Blanco Diversion, Oso Diversion, and Little Oso Diversion were compiled from the Upper Rio Grande Water Operations Model. Discharges for the diversions and the streamflow-gaging station at Azotea were calculated by Reclamation from the stage height and a theoretical rating for the flumes contained within each diversion dam and at the outlet of Azotea Tunnel.

Mean daily discharge values for streamflow-gaging stations Blanco Diversion, Little Oso Diversion, and Oso Diversion for 1993–2010 and Azotea for 1971 through 2010 (fig. 2 and table 2) also were retrieved from the CDWR Colorado's Decision Support Systems Web page. These data were provided by Reclamation. The daily discharge values were calculated on the basis of water stage measured by using floats and from theoretical ratings (Colorado Division of Water Resources, 2011).

It was necessary to calculate mean daily streamflow for Rio Blanco, Navajo River, and Little Navajo River above the diversions because the discharge measured at the streamflow gage is the amount of water bypassed by the SJCP and does not include water that is diverted by the diversion structures. The mean daily streamflow for each stream was calculated as the sum of the measured discharge below the dams and the diverted flow.

The measured discharges from the streamflow-gaging stations at the diversions were adjusted on the basis of the discharge measured at the streamflow gage at Azotea. On average, the measured discharge at Azotea is approximately 5 percent greater than the summed measured discharge of the three diversions (fig. 7). Reclamation noted in 1975 that comparisons of the sum of the discharge at the three diversions and the discharge at Azotea for 1971–75 showed an average gain of 3.9 percent, though it was noted that "…the actual amount diverted is not exactly known. As yet it has not been possible to check the rating of the flumes at the diversions" (Chief, Bureau of Reclamation, Water Operations Division, written commun., 1975). Though a cause for the calculated gain was not determined, it was indicated that sediment deposition in the flumes at Blanco Diversion, Little Oso Diversion, and Oso Diversion "could increase the approach velocity and result in a reduced stage within the flume" (Chief, Bureau of Reclamation, Water Operations Division, written commun., 1975).

For the computation of mean daily streamflow, it was assumed that gain or loss of significant volumes of water along the length of the tunnel is unlikely because Azotea Tunnel is a concrete-lined structure. The streamflow gages at the diversions and Azotea are constructed flumes with theoretical ratings. In 1975, Reclamation determined that the theoretical rating for Azotea was inaccurate at high flow, and the theoretical rating was adjusted by using discharge measurements (Chief, Bureau of Reclamation, Water Operations Division, written commun., 1975). At the time of this study, there was no information available to determine if the theoretical ratings for the flumes at the diversions have been verified. For this report it was assumed that the measured discharge at Azotea was more accurate than the measured discharge at the diversions, and therefore mean daily discharge measured at the diversions was adjusted to match the mean

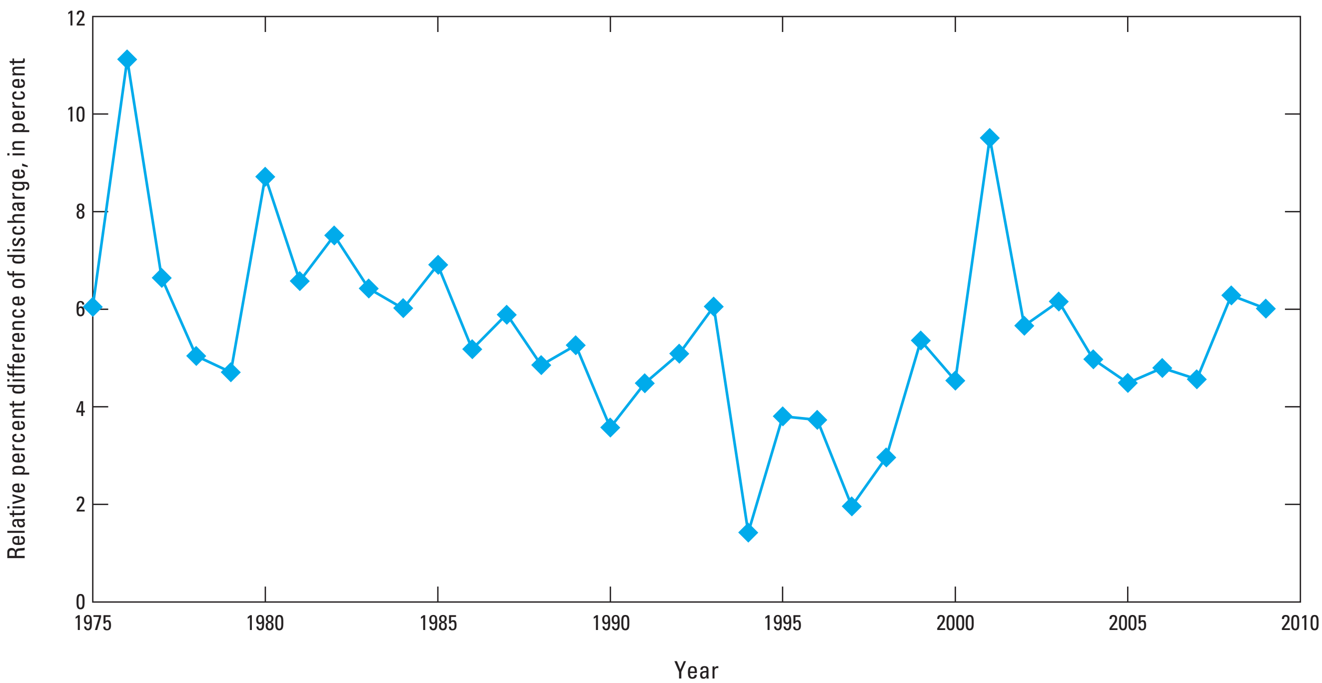


Figure 7. Relative percent difference of discharge between the discharge at the streamflow-gaging station at Azotea and the summed discharge of the streamflow-gaging stations at Blanco Diversion, Little Oso Diversion, and Oso Diversion, southern Colorado and northern New Mexico, 1975–2009.

daily discharge measured at Azotea. This assumption is consistent with previous estimates of streamflow for the Rio Blanco, Little Navajo River, and Navajo River by Reclamation (Bureau of Reclamation, 1986, 1999). The discharge values from the diversions were adjusted by calculating the difference between the combined daily discharge from the diversions and the daily discharge from Azotea. The difference was apportioned between the diversions on the basis of the proportional contribution to the total discharge. In general, the calculated daily mean streamflow for each stream was slightly greater than the measured discharge from the streamflow-gaging stations plus the measured diversion discharge (fig. 8).

Nonparametric statistical methods, which are dependent on the relative position of numerically ranked data (Helsel and Hirsch, 2002), were applied to calculate annual and monthly summary statistics for streamflow conditions at selected sites. Median annual discharge was computed for all sites on the basis of the calendar year for all years with complete records. Median monthly discharge for each month was computed for all sites for all months with complete records.

Trends in streamflow conditions were evaluated with the Mann–Kendall trend test, a nonparametric test to evaluate the significance of a monotonic trend over time (Helsel and Hirsh, 2002). The data were tested for autocorrelation by using the method detailed by Helsel and Hirsch (2002) to test for self-correlation, including testing the lagged residuals from regression of the variable over time for a significant trend. All data included in the trend analysis were determined to not be significantly autocorrelated.

Annual variation in streamflow conditions was evaluated with annual flow-duration curves. Flow-duration curves, or cumulative frequency curves, show the percentage of time that a specific streamflow is equaled or exceeded during a given period (Searcy, 1959). Flow-duration curves based on streamflow data that are representative of long-term flow conditions can be used as an indicator of future streamflow conditions and can be used to estimate the probability that a specific streamflow will be equaled or exceeded in the future (Searcy, 1959). Annual flow-duration curves were constructed for this report by ranking the annual discharge over the period of record from largest to smallest and computing the exceedance probability by using the Weibull formula for computing plotting positions (Helsel and Hirsch, 2002). A 50th percentile flow duration (Q50, also known as the median) is the flow exceeded 50 percent of the time over the period of record. The range between the 25th and 75th percentiles, or interquartile range (IQR), represents 50 percent of the flow duration and is an indication of the statistical dispersion of the data.

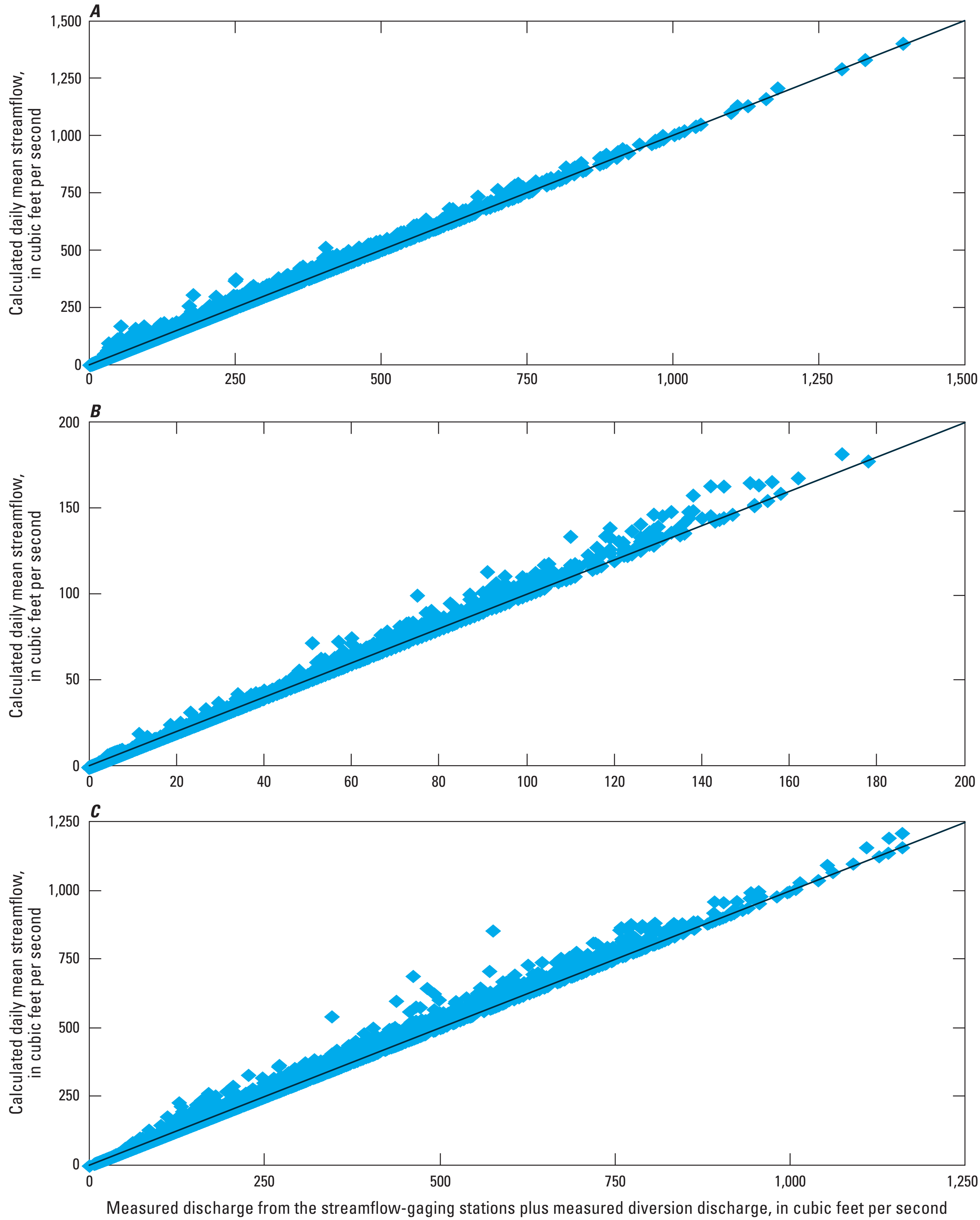


Figure 8. Calculated daily mean streamflow compared to the measured discharge from the streamflow-gaging stations plus the measured diversion discharge at the points of diversion on the Rio Blanco, Little Navajo River, and Navajo River, in the southern Colorado portion of the study area, 1974–2010. *A*, Rio Blanco below Blanco Diversion. *B*, Little Navajo River below Little Oso Diversion. *C*, Navajo River below Oso Diversion.

Water-quality samples, collected to characterize the quality of the diverted water, were collected from the Rio Blanco, Little Navajo River, and Navajo River near the diversions and from Azotea. Water-quality samples were collected three times a year for 2 water years—during base-flow conditions in October 2007 and November 2008 and during high-flow conditions (when streamflow is primarily composed of snowmelt runoff) in April 2008, June 2008, May 2009, and June 2009. Physical properties of the stream (dissolved oxygen, pH, specific conductance, and temperature) were measured. Samples were collected either as width-integrated samples if the water at the sampling location was not well mixed across the width of the section or as grab samples if the water at the sampling location was well mixed by upstream conditions. Water-quality samples collected from all stream sites were analyzed for major ions, alkalinity, trace elements, dissolved solids, and nutrients at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado. The methods used for the analysis of common ions and nutrients are outlined in Fishman (1993). The methods used for the analysis of trace elements are outlined in Garbarino and others (2006). Water-quality data obtained for this study were collected, processed, and preserved in accordance with established USGS methods as outlined in the National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). The field quality-control program included the collection of 2 field blank water samples to assess potential contamination during sample collection, processing, transport, or analysis. No significant contamination was measured in the field blanks. The USGS NWQL reports concentrations as quantitative, estimated, or censored, as described by Childress and others (1999). Results for analyte concentrations in a sample that are equal to or greater than the laboratory reporting level (LRL) are reported as quantitative values. The LRL is defined as two times the long-term method detection level (LT-MDL) where the LT-MDL is set to limit the occurrence of a false positive result in which an analyte is reported as a detection when it is not actually present. Results for analyte concentrations that are below the LT-MDL or not detected at all in the sample are censored and reported as less than (remark code of "<") the LRL. Results for analyte concentrations that are below the LRL but greater than the LT-MDL are reported as estimated (remark code "E").

Water Quality

Water-quality data presented in this report are from eight sites (table 2) and include historical data available in the USGS National Water Information System database (http://nwis.waterdata.usgs.gov/nwis/qw) and data from sampling conducted for this project. Unless stated otherwise, major-ion concentrations presented in this section refer to dissolved concentrations. Historical water-quality data for major ion concentrations were checked for ion balance but were otherwise presumed to be correct. Historical specific conductance data were evaluated and very small values reported for specific conductance, generally defined as values below 30 microsiemens per centimeter (µS/cm), were deemed to be unreasonable and were excluded from the current analysis. Major- and trace-element concentrations in samples from the streams were lower than U.S. Environmental Protection Agency primary and secondary drinking-water standards and New Mexico Environment Department surface-water standards for Heron Reservoir and for perennial reaches of tributaries to the Rio Chama in the study area (New Mexico Environment Department, 2011). All water-quality data are presented in appendix 1.

The ion composition of water is a function of the source of the water, generally precipitation, and is primarily controlled by evaporation and the mineral assemblage of the rocks and sediments with which the water comes into contact (Hem, 1989). The specific conductance, a measure of the ability of a fluid to conduct electrical current, increases as minerals from rocks and sediments dissolve into the water (Hem, 1989). Generally, the most abundant cations present in water are calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K), and the most abundant anions present in water are chloride (Cl), fluoride (F), bicarbonate (HCO_3), and sulfate (SO_4). The specific conductance typically is representative of the dissolved-solids concentration of the water (Hem, 1989). Water quality in the streams in the study area likely is influenced by the geologic conditions within the watersheds. The chemical composition of precipitation across the study area is likely to be equivalent because the topography across the region is similar and the precipitation is derived from the same storm system (Ingersoll and others, 2008). As the water, either as surface runoff or infiltration into the subsurface, is exposed to the geologic material in the watershed, the chemical composition and concentration of the dissolved solids will evolve as a function of the mineral assemblages that are present in the rocks and ions already present in the water. Water in contact with Cretaceous-aged marine shale generally has increased dissolved-solids concentrations and increased concentrations of SO_4 (Azimi–Zonooz and Duffy, 1993). Apodaca (1998) noted that the geochemical composition of water from the Mancos Shale near the study area is Ca-SO_4.

The quality of water in the study area varies by watershed. A water "type" was determined for each sample on the basis of the concentrations of the major ions. Representative water compositions for each sample location, selected because the composition is typical of the chemical composition of all samples from the location, were plotted on a trilinear diagram (fig. 9). The predominant composition, expressed in milliequivalents per liter (the concentration of the ion species expressed as the molar concentration normalized by the ionic charge; Hem, 1989), must be greater than 40 percent of the total. If no cation or anion is predominant, the water is classified either as the two most common ions or as

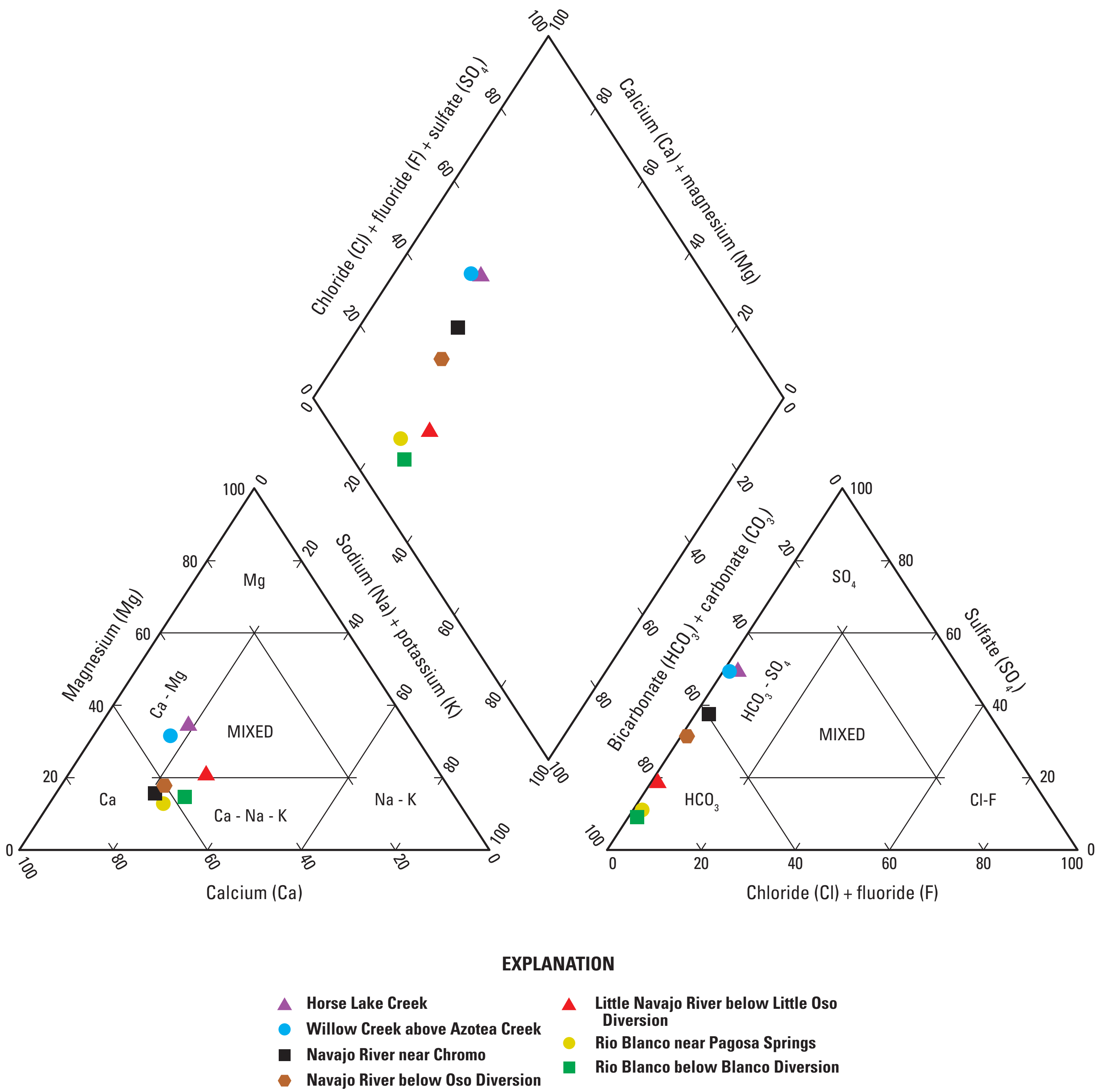


Figure 9. Trilinear diagram of representative water composition from selected water-quality sampling sites in the study area, southern Colorado and northern New Mexico.

mixed if the ions are present in nearly equal portions. Water from Rio Blanco below Blanco Diversion is HCO_3-Ca/Na/K type, water from Rio Blanco near Pagosa Springs is HCO_3-Ca type, and water from Little Navajo River below Little Oso Diversion is HCO_3-mixed cation type. Water from Navajo River above Chromo is HCO_3/SO_4-Ca type, and water from Navajo River below Oso Diversion is HCO_3-Ca type, though the samples from Navajo River below Oso Diversion are compositionally close to HCO_3/SO_4-Ca/Mg type. Water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek are HCO_3/SO_4-Ca/Mg type.

The concentration of dissolved solids and the major ions can be represented by specific conductance. Major-ion concentrations are available for only selected sites and samples. The specific conductance for all sites ranged from 62 to 2,970 microsiemens per centimeter (µS/cm) (fig. 10*A* and appendix 1). Water from Willow Creek near Park View generally had specific-conductance values that were greater than 300 µS/cm, and water from sites on the Rio Blanco, Little Navajo River, and Navajo River generally had specific-conductance values that were less than 250 µS/cm (fig. 10*A*). Water from Willow Creek above Azotea Creek and Horse Lake Creek above Heron Reservoir had greater concentrations of all major cations and all major anions except fluoride than did water from sites on the Rio Blanco, Little Navajo River, and Navajo River (fig. 10*B*). Water from sites on the Navajo River was compositionally shifted towards Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek (fig. 9), though water from sites on the Navajo River had much lower specific conductance than did water from the other streams (fig. 10*A*). Water from sites on the Navajo River had slightly lower concentrations of HCO_3 and slightly greater concentrations of SO_4 than did water from sites on the Rio Blanco and Little Navajo River and water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek (fig. 10*B*). Water from sites on the Navajo River also had increased concentrations of SO_4 relative to water from sites on the Rio Blanco and Little Navajo River (fig. 10*B*). The median specific conductance of water, representative of the total dissolved solids, from a comparable suite of samples from sites on the Navajo River was slightly greater (168 µS/cm) than the median specific conductance from sites on the Rio Blanco (134 µS/cm).

Upstream from the sampling locations, the Navajo River watershed is underlain by volcanic deposits and volcaniclastic sediments, such as landslide deposits and alluvium derived from volcanic material in the high elevations of the watershed and Cretaceous-aged marine shale and sandstone units in the low elevations (figs. 1 and 5). The Horse Lake Creek and Willow Creek watersheds are underlain mostly by Cretaceous-aged marine shale (fig. 5). It is likely that the water quality at sites in these watersheds was affected by Cretaceous-aged marine shale, such that water from these sites had increased dissolved-solids concentrations and increased concentrations of SO_4. The water from the Navajo River had high concentrations of dissolved-solids and SO_4 from contact with marine shale deposits, though the concentrations in the water at this site were lower than the concentrations in the water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek. Additionally, the high specific conductance of water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek likely was a function of the lower precipitation rates over the watersheds (as represented by the lower precipitation rate at Chama [fig. 4*B*] relative to the precipitation rate at Upper San Juan [fig. 3*B*]) and the resulting lower snowmelt runoff.

Water from the Rio Blanco and Little Navajo River watersheds was similar in chemical composition and generally had low specific conductance (figs. 9, 10*A*, and 10*B*). These watersheds are primarily underlain by volcanic deposits, volcaniclastic sediments and landslide deposits derived from these materials (fig. 5). The low dissolved-ion concentration, as indicated by the specific conductance, indicated either that these waters had been in contact with mineral assemblages that were less available for dissolution than the marine shale or that the residence time of the water in the watershed was shorter compared to other study watersheds and therefore less dissolution had occurred.

Generally, surface-water quality varied with streamflow conditions throughout the year. Base-flow conditions for mountain streams are generally observed from September through February, and high-flow conditions for mountain streams are generally observed from March to August. Intervals of base-flow conditions and high-flow conditions for low-elevation streams are more variable because of decreased snow accumulation and precipitation. Base-flow conditions generally are characterized by low streamflow that was derived from discharge of groundwater to the stream, and high-flow conditions are generally characterized by increased streamflow that was the result of snowmelt and precipitation events that generate direct runoff to the stream. The direct runoff generally does not infiltrate into the groundwater system, though the runoff can transit through the soil zone as it travels to the stream (Hem, 1989). Generally, water that has had less contact with geologic material will have low dissolved-solids concentrations; therefore, streamflow generated by direct runoff from snowmelt and precipitation events generally has lower dissolved-solids concentrations than does streamflow derived from groundwater (Hem, 1989).

For sites on the Rio Blanco, Little Navajo River, Navajo River, and Willow Creek, months with base-flow conditions were characterized by higher average specific-conductance values than those that occurred during months with high-flow conditions (figs. 11*A* and 11*B*). The lowest discharge and highest specific conductance occurred during months with base-flow conditions when streamflow was composed of water that had moved through the groundwater system and had been discharged to the stream channel (figs. 11*C* and 11*D*). The highest discharge and the lowest specific conductance occurred during months with high-flow conditions when streamflow was composed of water that was a mixture of base flow diluted with runoff from snowmelt and precipitation events.

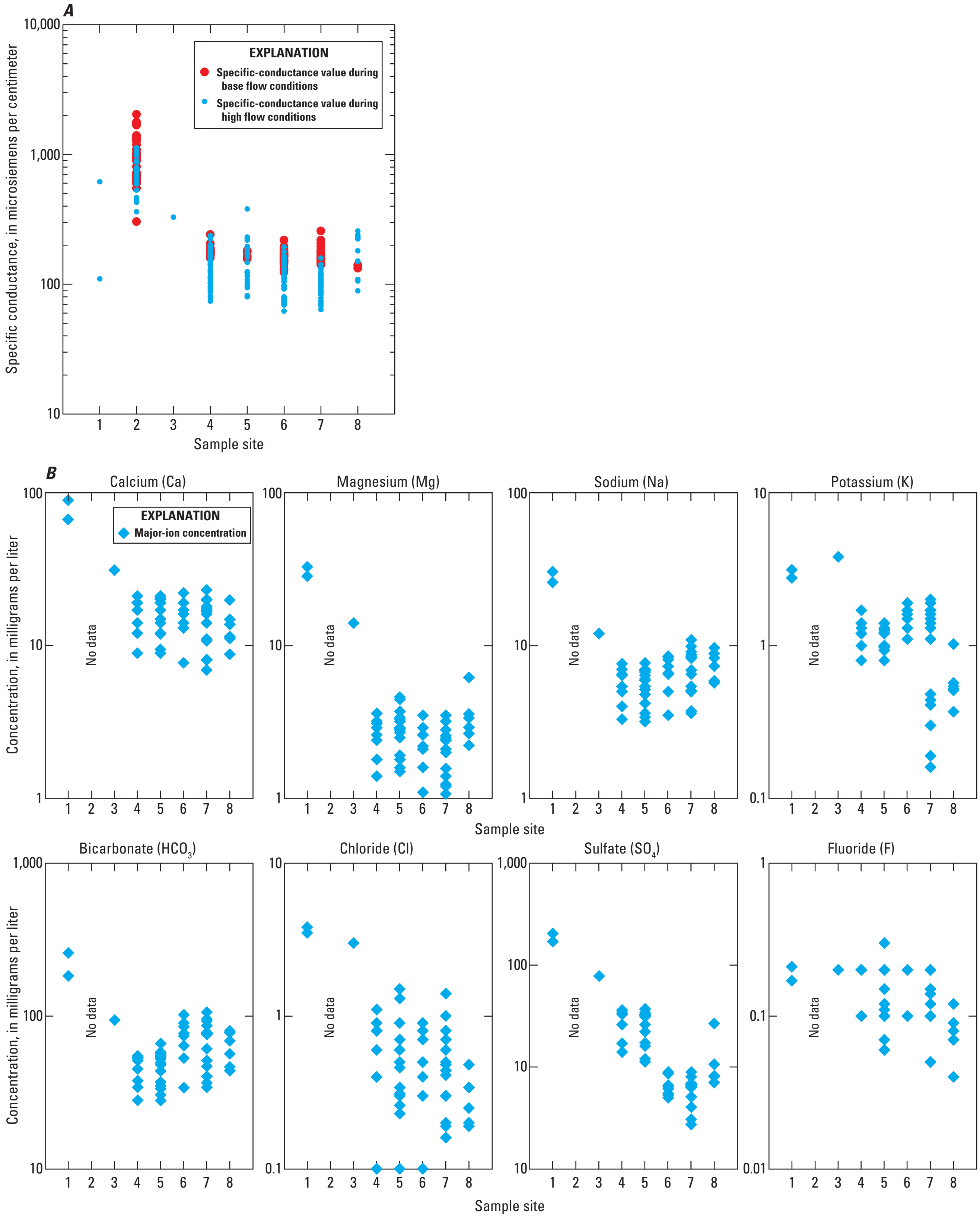


Figure 10. Variation of water-quality conditions at water-quality sampling sites in the study area, southern Colorado and northern New Mexico, 1958–2009. *A*, Specific-conductance values for selected sample sites. *B*, Major-ion concentrations for selected sample sites. Sample sites are (1) Willow Creek above Azotea Creek, (2) Willow Creek near Park View, (3) Horse Lake Creek above Heron Reservoir, (4) Navajo River above Chromo, (5) Navajo River below Oso Diversion, (6) Rio Blanco near Pagosa Springs, (7) Rio Blanco below Blanco Diversion, and (8) Little Navajo below Little Oso Diversion.

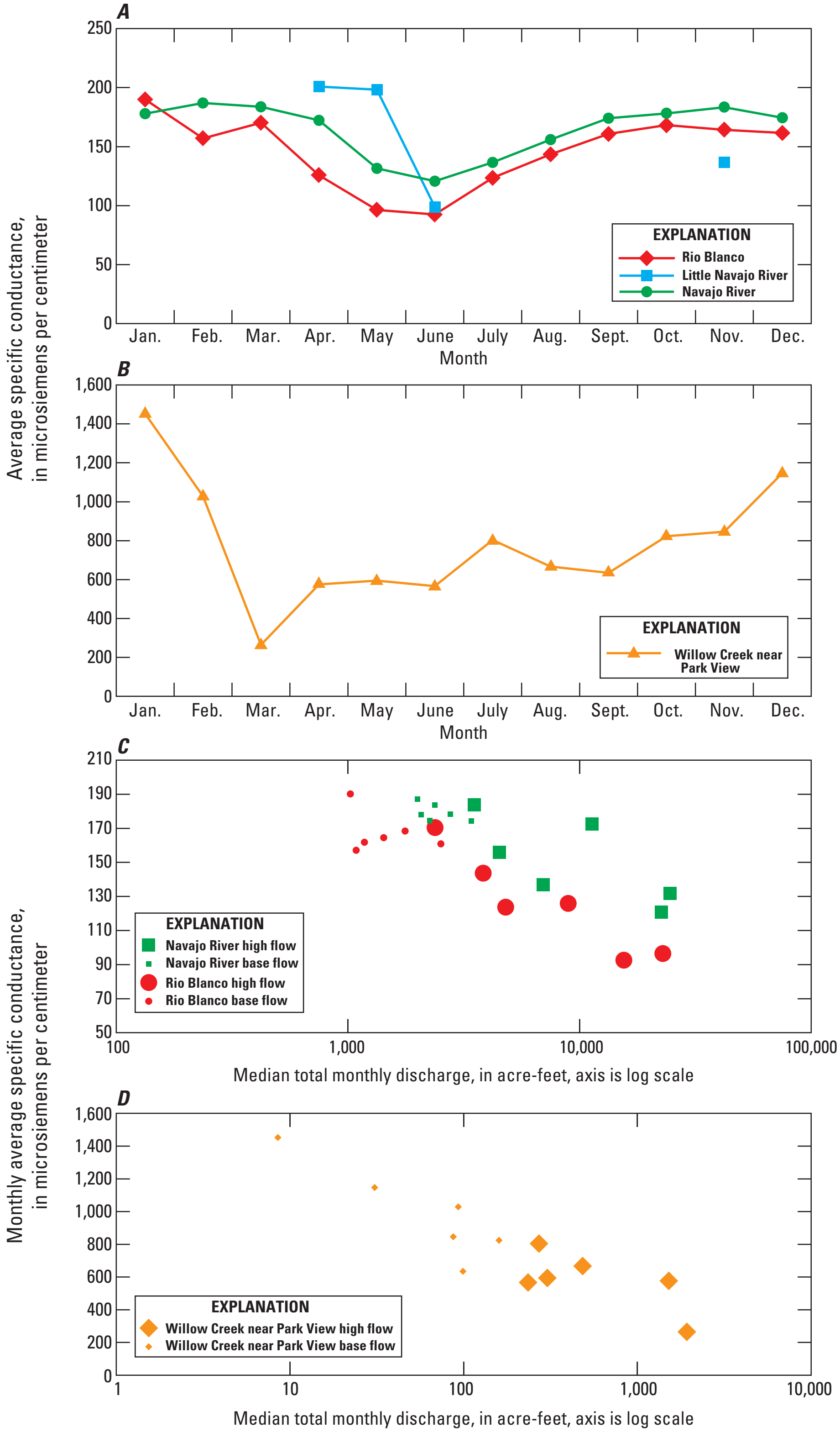


Figure 11. Monthly variation in specific-conductance values for selected water-quality sampling sites and comparison of the variation of the average monthly specific conductance to the median monthly discharge, with monthly discharge categorized as high-flow or base-flow conditions, for selected water-quality sampling sites in the study area, southern Colorado and northern New Mexico, 1958 to 2009. *A*, Average specific conductance by month for sites on the Rio Blanco, Little Navajo River, and Navajo River. *B*, Average specific conductance by month for sites on Willow Creek near Park View. *C*, Median monthly discharge versus average monthly specific conductance for sites on the Navajo River and Rio Blanco. *D*, Median monthly discharge versus average monthly specific conductance for Willow Creek near Park View.

For Willow Creek near Park View, the specific conductance was highly variable during high-flow conditions (range in discharge from approximately 1 ft^3/s to more than 900 ft^3/s) and ranged from 362 to 1,130 µS/cm (fig. 10*A*). Water from Willow Creek near Park View also had an inverse relation of average monthly specific conductance and median monthly discharge (fig. 11*D*). It was likely that streamflow in March through June was composed of water that was derived from snowmelt in the low-elevation watershed but that by July the snowpack had been completely melted and streamflow was base flow that was composed of groundwater discharge. In August, the increased streamflow resulted from runoff from increased precipitation from the summer monsoon, which diluted the base-flow component of streamflow and reduced the specific conductance.

For most sites, the predominant form of dissolved nitrogen was organic nitrogen. Dissolved ammonia plus organic nitrogen concentrations from all available data for all streams ranged from an estimated concentration of 0.07 to 0.51 milligrams per liter (mg/L) as nitrogen and a median concentration of 0.14 mg/L as nitrogen. Dissolved-ammonia concentrations were below the reporting limit of 0.02 mg/L as nitrogen for all samples except for the October 2008 sample from Navajo River (estimated concentration of 0.01 mg/L as nitrogen). Concentrations of dissolved nitrate plus nitrite were generally below the reporting limit of 0.04 mg/L as nitrogen for samples collected during base flow and all samples collected in June 2009; spring and summer runoff samples had dissolved nitrate plus nitrite concentrations ranging from 0.02 to 0.07 mg/L as nitrogen and a median concentration of 0.05 mg/L as nitrogen. The concentrations of dissolved nitrate plus nitrate were generally less than half the concentrations of dissolved ammonia plus organic nitrogen. Concentrations of total ammonia plus organic nitrogen ranged from 0.11 to 0.86 mg/L as nitrogen and had a median concentration of 0.24 mg/L as nitrogen. The concentrations of dissolved ammonia plus organic nitrogen were greater than 50 percent of the concentrations of total ammonia plus organic nitrogen.

Orthophosphate was the primary component of dissolved phosphorus. The concentration of dissolved orthophosphate ranged from 0.008 to 0.041 mg/L as phosphorus with a median concentration of 0.027 mg/L as phosphorus, and the concentration of dissolved phosphorus ranged from 0.011 to 0.058 mg/L as phosphorus with a median concentration of 0.026 mg/L as phosphorus. The dissolved-orthophosphate concentrations were generally greater than 80 percent of the dissolved-phosphorus concentrations. Total phosphorus concentrations ranged from 0.041 to 0.425 mg/L as phosphorus with a median concentration of 0.094 mg/L as phosphorus. Dissolved phosphorus was a minor component of total phosphorus. Total organic carbon concentrations ranged from 0.9 to 11.8 mg/L with a median concentration of 4.0 mg/L.

Streamflow Conditions and Annual Flow-Duration Curves

Streamflow conditions for streams in the SJCP were assessed by using measured or estimated streamflow data (table 2; streamflow conditions were not assessed for Blanco Diversion, Oso Diversion, Little Oso Diversion, or Azotea). Streamflow statistics presented are for the period of record for each station; annual statistics are reported on the basis of calendar years (table 5). Nonparametric statistical methods, including calculation of percentiles, were applied to describe streamflow. The 50th percentile annual discharge duration (Q50, the median) is the discharge exceeded 50 percent of the time over the period of record being analyzed. Similarly, the 75th percentile (Q75) means that 75 percent of the annual discharges for the period of record are less than or equal to the discharge at the 75th percentile, and the 25th percentile (Q25) means that 25 percent of the annual discharges for the period of record are less than or equal to the discharge at the 25th percentile. The range of flows between the 25th and 75th percentiles, or interquartile range (IQR), represents 50 percent of the annual discharge duration and is an indication of the statistical dispersion of the data. Variation in streamflow can be characterized as the range of values that occurs in the IQR: the larger the range of values in the IQR, the greater the variation in streamflow. The IQR can be compared between streams after normalizing the IQR to the median discharge to determine the coefficient of variation (COV), which is a measure of the dispersion of the annual discharge. The streamflow yield per square mile (mi^2), the amount of discharge per unit of contributing area in the watershed, was calculated as the median (Q50) annual discharge divided by the drainage area of the watershed above the streamflow gage.

Streamflow on the Rio Blanco was measured at two sites (the streamflow-gaging stations at Rio Blanco near Pagosa Springs and Rio Blanco below Blanco Diversion). The streamflow gage at Rio Blanco near Pagosa Springs was operated by the USGS from 1935 through 1971. The drainage area upstream from the streamflow gage is 58.0 mi^2 (table 5). In the 1930s, diversions for irrigation above the streamflow gage were noted in the station record (U.S. Geological Survey, 1937). In 1970 the station record noted that there were about 1,400 acres of irrigated land in the watershed upstream from the streamflow gage (U.S. Geological Survey, 1973a). Median (50th percentile) annual discharge over the period of record at Rio Blanco near Pagosa Springs was 58,150 acre-ft (table 5).

The streamflow gage at Rio Blanco below Blanco Diversion, hereafter referred to as “Rio Blanco - Combined,” has been operated by the CDWR since 1970. The streamflow gage measures flows bypassed by Blanco Diversion and does not include the volume of water that is diverted for the SJCP.

Table 5. Selected statistics for streamflow at selected streamflow-gaging stations in the study area, southern Colorado and northern New Mexico.

[IQR, interquartile range]

	Rio Blanco near Pagosa Springs	Rio Blanco - Combined	Navajo River at Banded Peak Ranch	Navajo River above Chromo	Navajo River - Combined	Little Navajo River at Chromo	Little Navajo River - Combined
Period of record included in the statistical analysis	1935–71	1975–2010	1937–2010	1936–37 and 1957–69	1975–2010	1936–51	1975–2010
Annual discharge percentiles, in acre-feet							
10th percentile	37,440	43,200	48,210	53,780	57,780	2,350	3,800
25th percentile	43,220	60,820	55,460	68,280	71,880	4,000	6,330
50th percentile (median)	58,150	74,620	74,800	84,670	93,020	8,170	8,620
75th percentile	73,850	95,340	101,370	109,760	122,300	12,310	13,360
90th percentile	92,970	104,810	116,950	126,530	138,850	21,030	16,410
IQR (75th–25th percentile)	30,630	34,520	45,910	41,480	50,420	8,310	7,030
Coefficient of variation (IQR/50th percentile)	0.53	0.46	0.61	0.49	0.54	1.02	0.82
Drainage area, in square miles	58.0	69.1	69.8	96.4	100.5	21.9	14.2
Streamflow yield per square mile, in acre-feet	1,003	1,080	1,072	878	926	373	607
Mean basin elevation, in feet	10,000	9,940	10,300	9,920	9,860	9,010	9,610

	Willow Creek near Park View	Willow Creek above Heron Reservoir	Horse Lake Creek above Heron Reservoir	Sum of Rio Blanco - Combined, Navajo River - Combined, and Little Navajo River - Combined
Period of record included in the statistical analysis	1943–69	1962–70	1963–2009	1975–2010
Annual discharge percentiles, in acre-feet				
10th percentile	1,750	2,460	6	105,370
25th percentile	2,700	4,430	37	137,350
50th percentile (median)	9,170	5,710	185	175,650
75th percentile	15,120	11,100	679	232,210
90th percentile	20,480	14,680	969	255,570
IQR (75th–25th percentile)	12,420	6,670	642	94,860
Coefficient of variation (IQR/50th percentile)	1.35	1.17	3.47	0.54
Drainage area, in square miles	193	112	45	183.8
Streamflow yield per square mile, in acre-feet	48	51	4	956

The drainage area upstream from the streamflow gage is 69.1 mi^2 (table 5). The streamflow gage is located on the left bank 250 ft downstream from the Blanco Diversion. Daily mean streamflow for Rio Blanco - Combined was calculated as the sum of the measured discharge from the streamflow gage at Rio Blanco below Blanco Diversion plus the measured diversion discharge at Blanco Diversion and was adjusted for the flow at Azotea (see Methods section for a complete description of the calculation of daily mean streamflow). The streamflow gage at Blanco Diversion is located within the dam structure and is a concrete flume. Discharge values for Blanco Diversion have been collected by Reclamation since 1971, though electronic data are available for only 1974 to the present. Median (50th percentile) annual discharge over the period of record for Rio Blanco - Combined was 74,620 acre-ft (fig. 12*A* and table 5). The annual discharge is nearly symmetric around the median (fig. 12*A*), the annual flow-duration curve for Rio Blanco - Combined is relatively linear, and the COV is small relative to other streams in the area (table 5), which are indications that annual streamflow conditions at Rio Blanco - Combined were generally close to the median and typically varied within a small range.

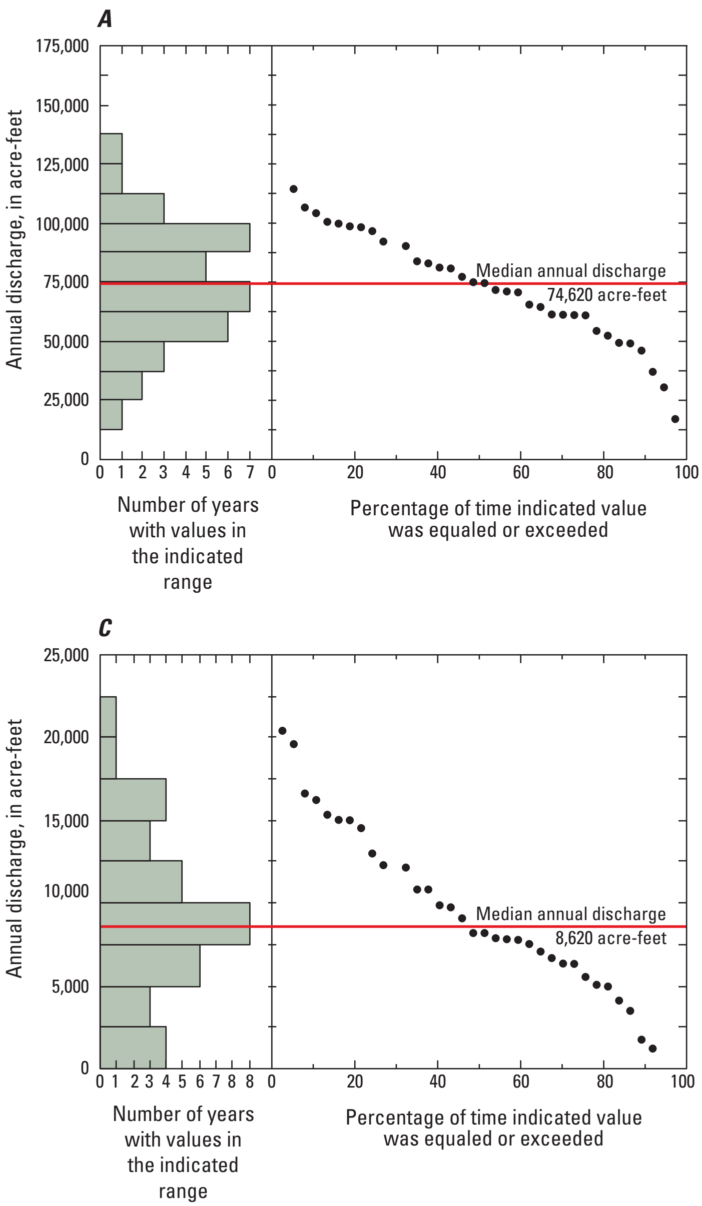


Figure 12. Distribution of annual discharge, median annual discharge, and annual flow-duration curves for selected for streamflow-gaging stations in the southern Colorado portion of the study area, 1975–2010. *A*, Rio Blanco - Combined. *B*, Navajo River - Combined. *C*, Little Navajo River - Combined.

Streamflow on the Navajo River was measured at three sites (the streamflow-gaging stations at Navajo River at Banded Peak Ranch, Navajo River above Chromo, and Navajo River below Oso Diversion). The streamflow gage at Navajo River at Banded Peak Ranch was operated by the USGS from 1936 to 1972 and has been operated by the CDWR since 1972. The drainage area upstream from the streamflow gage is 69.8 mi^2 (table 5). In 1945 the station record noted that there were no diversions upstream (U.S. Geological Survey, 1947a), and in 1995 the station record noted that there were diversions for irrigation of about 430 acres upstream from the station (Crowfoot and others, 1996). Median (50th percentile) annual discharge over the period of record at Navajo River at Banded Peak Ranch was 74,800 acre-ft (table 5).

The streamflow gage at Navajo River above Chromo was operated by the USGS from 1956 through 1970 (an earlier station, Navajo River near Chromo, was operated from 1935 through 1938 and was located 3.5 mi east of Chromo). The drainage area upstream from the streamflow gage is 96.4 mi^2 (table 5). In 1970, diversions for irrigation of about 1,000 acres upstream from the station were noted in the station record (U.S. Geological Survey, 1973a). The station record also indicated that the record was rated as good except for winter periods and periods of backwater from diversion, which was rated as poor (the rating of the accuracy attributed to streamflow records is indicated as 95 percent of the daily discharges being within ±5 percent, excellent; ±10 percent, good; ±15 percent, fair; and >15 percent, poor [Rantz,1982a and 1982b]). Median (50th percentile) annual discharge over the period of record at Navajo River above Chromo was 84,670 acre-ft (table 5).

The streamflow gage at Navajo River below Oso Diversion, hereafter referred to as "Navajo River - Combined," has been operated by the CDWR since 1970. This streamflow gage measures flows bypassed by Oso Diversion and does not include the volume of water that is diverted for the SJCP. The drainage area upstream from the streamflow gage is 100.5 mi^2 (table 5). The streamflow gage is located on the left bank 600 ft downstream from Oso Diversion. Daily mean streamflow for Navajo River - Combined was calculated as the sum of the measured discharge from the streamflow gage at Navajo River below Oso Diversion plus the measured diversion discharge at Oso Diversion and was adjusted for the flow at Azotea (see Methods section for a complete description of the calculation of daily streamflow). The streamflow gage at Oso Diversion is located within the dam structure and is a concrete flume. Discharge values for Oso Diversion have been collected by Reclamation since 1971, though electronic data are available for only 1974 to the present. Median (50th percentile) annual discharge over the period of record for Navajo River - Combined was 93,020 acre-ft (fig. 12*B* and table 5). The annual discharge is nearly symmetric around the median and almost equally distributed from 50,000 acre-ft to 150,000 acre-ft (fig. 12*B*), the annual flow-duration curve for Navajo River - Combined is relatively linear, and the COV is small relative to most of the other streams in the area (table 5), which are indications that the annual streamflow conditions at Navajo River - Combined were generally close to the median and typically varied within a small range.

Streamflow data on the Little Navajo River was measured at two sites (the streamflow-gaging stations at Little Navajo River at Chromo and Little Navajo River below Little Oso Diversion). The streamflow gage at Little Navajo River at Chromo was operated by the USGS from 1935 through 1952. The drainage area upstream of the streamflow gage is 21.9 mi^2 (table 5). In 1952, diversions for irrigation of about 650 acres upstream from the station were noted in the station record (U.S. Geological Survey, 1954). Median (50th percentile) annual discharge over the period of record at Little Navajo River at Chromo was 8,170 acre-ft (table 5).

The Little Navajo River below Little Oso Diversion streamflow gage, hereafter referred to as "Little Navajo River - Combined," has been operated by the CDWR since 1970. The streamflow gage measures flows bypassed by Little Oso Diversion and does not include the volume of water that is diverted for the SJCP. The drainage area upstream from the streamflow gage is 14.2 mi^2 (table 5). The streamflow gage is located on the right bank downstream from Little Oso Diversion. Daily mean streamflow for Little Navajo River - Combined was calculated as the sum of the measured discharge from the streamflow gage at Little Navajo River below Little Oso Diversion plus the measured diversion discharge at Little Oso Diversion and was adjusted for the flow at Azotea (see Methods section for a complete description of the calculation of daily streamflow). The streamflow gage at Little Oso Diversion is located within the dam structure and is a concrete flume. Discharge values for Little Oso Diversion have been collected by Reclamation since 1971, though electronic data are available for only 1974 to the present. Median (50th percentile) annual discharge over the period of record for the combined streamflow from Little Navajo River below Little Oso Diversion and Little Oso Diversion was 8,620 acre-ft (fig. 12*C* and table 5). The annual discharge is asymmetrically distributed around the median such that values greater than the median cover a larger range than do values that are less than the median (fig. 12*C*), the annual flow-duration curve for Little Navajo River - Combined is relatively linear, and the COV is greater than those for Rio Blanco - Combined and Navajo River - Combined (table 5), which are indications that the annual discharge from Little Navajo River - Combined was more variable than streamflow at sites on the Rio Blanco and Navajo River.

Streamflow on Willow Creek was measured at three sites (the streamflow-gaging stations at Willow Creek above Azotea Creek, Willow Creek near Park View, and Willow Creek above Heron Reservoir). The streamflow gage at Willow Creek above Azotea Creek was operated from 1971 through 1973. The drainage area upstream of the streamflow gage is 42 mi^2. Streamflow was measured from April 1971 to December 1972 and March to December 1973 by Reclamation, and the record represents natural runoff from the area (U.S. Geological Survey, 1973b). Median (50th percentile) annual discharge at

Willow Creek above Azotea Creek was not calculated because of the short interval of available data.

The streamflow gage at Willow Creek near Park View was operated by the USGS from 1936 to 1971 (1936 through 1942 had no winter record). The drainage area upstream from the streamflow gage is 193 mi^2 (table 5). From 1936 to 1966, the streamflow gage was located 0.3 mi downstream from Horse Lake Creek. The streamflow gage was relocated in 1966 to 0.7 mi downstream from Horse Lake Creek. The station record indicated that there were diversions for irrigation of about 300 acres upstream from the station (U.S. Geological Survey, 1947b). The station record also indicated that subsequent to 1965 the published record is a combination of Horse Lake Creek at its mouth and Willow Creek at a steel bridge that was pending construction (U.S. Geological Survey, 1971). Diversions from the Rio Blanco, Little Navajo River, and Navajo River to Azotea were made during November and December 1970 and added to the measured discharge. Median (50th percentile) annual discharge from 1943 to 1969 at Willow Creek near Park View was 9,170 acre-ft (table 5).

The streamflow gage at Willow Creek above Heron Reservoir was operated by the USGS from 1962 to 1971 and has been operated by Reclamation since 1971. The natural drainage area upstream from the streamflow gage is 112 mi^2. A concrete control structure was installed in June 1963. The streamflow gage was located on the right bank 7.5 mi upstream from Horse Lake Creek until 1971, when it was moved 900 ft upstream from the previous location (it is still located on the right bank) (U.S. Geological Survey, 1971). Streamflow recorded at Willow Creek above Heron Reservoir for the period before the SJCP diversions (1962–70) is the natural streamflow on Willow Creek. Median (50th percentile) annual discharge from 1962 to 1970 at Willow Creek above Heron Reservoir was 5,710 acre-ft (table 5).

The streamflow gage Horse Lake Creek above Heron Reservoir has been operated by the USGS since 1962. The drainage area upstream from the streamflow gage is 45 mi^2 (table 5). From 1962 to 1971, the streamflow gage was located on the left bank 8 mi downstream from Horse Lake. The streamflow gage was moved in 1971 to the right bank 3.7 mi northwest of Heron Dam, 7.8 mi downstream from Horse Lake. The station record indicated that there were diversions for stock tanks and irrigation of meadows above the site (Miller and Stiles, 2006). Median (50th percentile) annual discharge over the period of record at Horse Lake Creek above Heron Reservoir was 185 acre-ft (table 5).

The difference in the COV and the streamflow yield per square mile for various streams in the study area showed that streams from large watersheds at high elevations generally had greater annual discharge and less variability in annual discharge than did streams from small watersheds at high elevations and streams from low elevation watersheds. The COVs for sites on the Rio Blanco and Navajo River were 0.61 or less and indicated that the dispersion of the annual discharge over the period of record was small relative to other streams in the study area (table 5). The annual discharge for sites on the Rio Blanco and Navajo River generally occurred within a smaller range of values that were closer to the median than the other streams in the study area and more consistently had annual discharge that was close to the median annual discharge. The COVs for sites on the Little Navajo River, Horse Lake Creek, and Willow Creek were greater than 0.80 and the analysis of COVs indicated greater dispersion in the annual discharge over the period of record (table 5). The COVs for sites on Willow Creek, Horse Lake Creek, and Little Navajo River at Chromo were greater than 1, and the analysis of COVs indicated that the range in discharge from the 25th percentile to the 75th percentile exceeded the median flow and that the normalized variability of discharge around the median was larger than for other streams in the study area. The streamflow yield per square mile for sites on the Rio Blanco and Navajo River ranged from 878 to 1,080 acre-feet, the streamflow yields per square mile for sites on the Little Navajo River were 373 and 607 acre-ft, and the streamflow yields per square mile for Horse Lake Creek above Heron Reservoir and sites on Willow Creek ranged from 4 to 51 acre-ft (table 5). The Rio Blanco and Navajo River, high-elevation streams with large watersheds, have the greatest amount of discharge and the least annual variability in discharge relative to the other streams.

The streamflow measured on Willow Creek prior to diversions from the SJCP and on Horse Lake Creek is the native streamflow of the Willow Creek watershed. Historically, the annual discharge on Willow Creek derived within the watershed has varied from slightly more than 1,000 acre-ft in 1951 to almost 35,000 acre-ft in 1958, and annual discharge on Horse Lake Creek has ranged from no flow in 2000–2 and in 2004 to approximately 3,360 acre-ft in 1985 (figs. 13*A* and 13*B*). The distribution of annual discharge for Willow Creek near Park View is nearly bimodal, with a cluster of values at the low range of annual discharge and a cluster of values greater than the median annual discharge (fig. 14). The maximum annual discharge is an outlier that is almost 15,000 acre-ft greater than the next highest annual discharge (fig. 14). The large range and distribution of annual discharge for Willow Creek near Park View indicated that the native discharge of the Willow Creek watershed was highly variable relative to discharge from high-elevation streams like the Rio Blanco and Navajo River.

Seasonal and Annual Variations in Streamflow Conditions

Seasonal variation in streamflow conditions can be used to determine the predominant precipitation sources of runoff. The median monthly discharges for Rio Blanco - Combined (fig. 15*A*), Little Navajo River - Combined (fig. 15*B*), Navajo River - Combined (fig. 15*C*), and Navajo River at Banded Peak Ranch (fig. 15*C*) indicated that these watersheds were

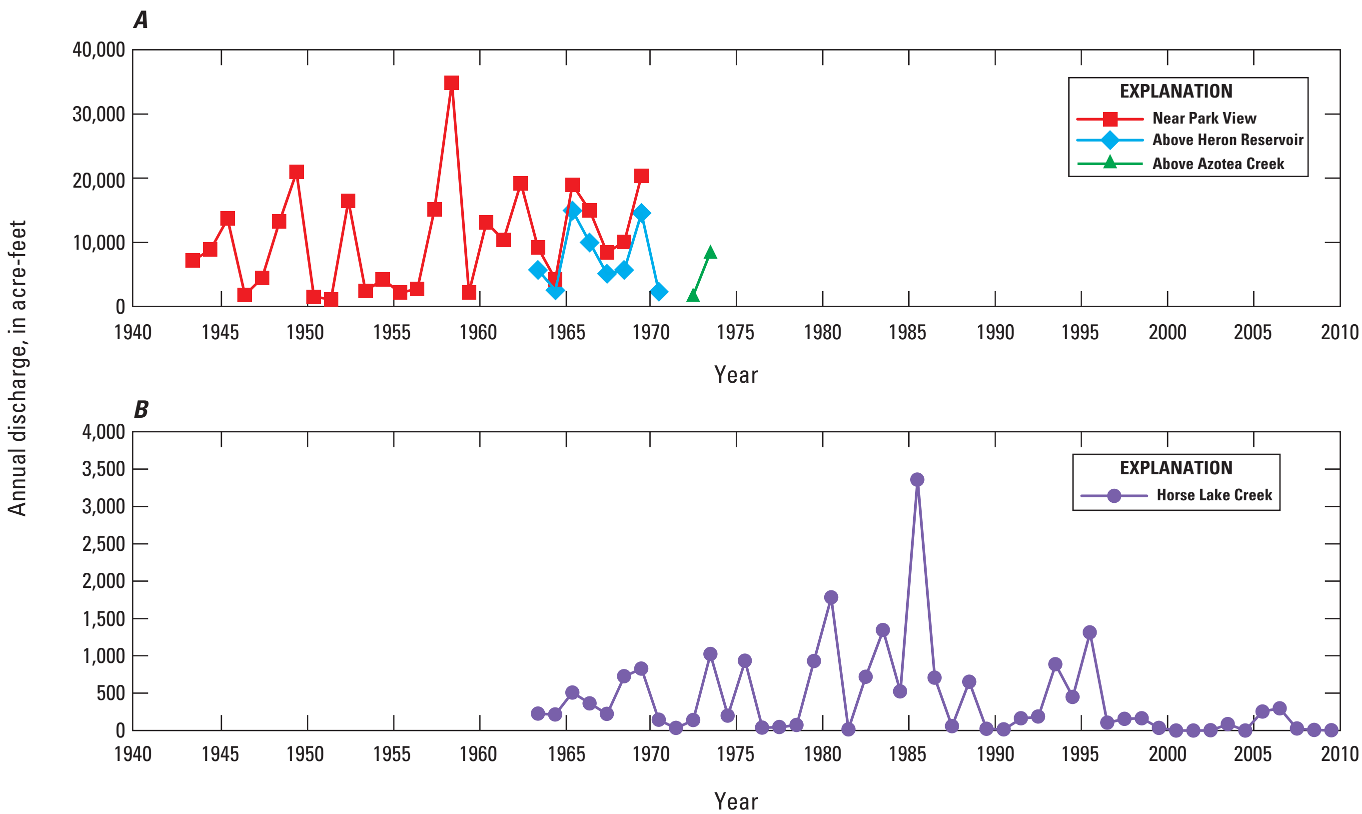


Figure 13. Annual discharge at streamflow-gaging stations in the northern New Mexico portion of the study area, 1943–2009. *A*, Streamflow-gaging stations on Willow Creek. *B*, Streamflow-gaging station on Horse Lake Creek.

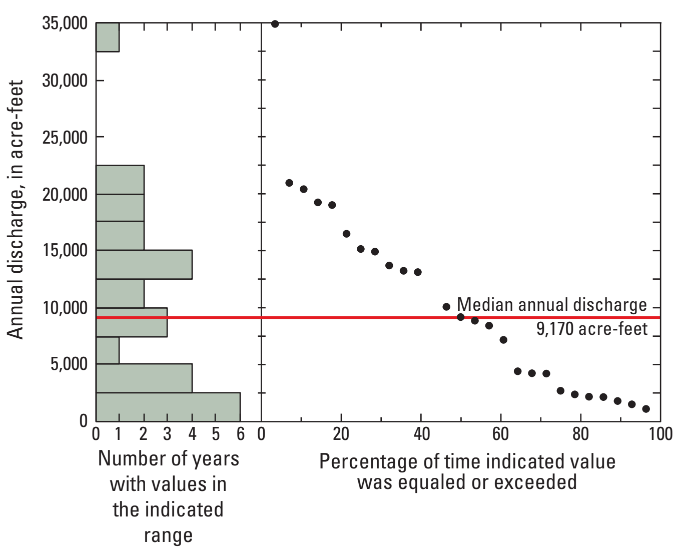


Figure 14. Distribution of annual discharge, median annual discharge, and annual flow-duration curves for the period of record for the streamflow-gaging station Willow Creek near Park View, in the northern New Mexico portion of the study area, 1943–69.

snowmelt-dominated systems with the majority of discharge occurring in April through June. Monsoonal rainfall occurring in July and August were likely to contribute to discharge; however, snowmelt runoff can also occur in early July, so it was not possible to determine the amount of discharge in July that resulted from monsoonal rainfall. Analysis of the median monthly discharge for sites on Willow Creek (fig. 15*D*) and Horse Lake Creek above Heron Reservoir (fig. 15*E*) indicated that the watersheds of these streams had multiple sources for streamflow including a large component in March and April that was likely derived from snowmelt runoff and a smaller, steady flow occurring through September with a peak in August that was likely the result of runoff from monsoonal rainfall. Differences in temperature and precipitation, generally related to changes in elevation, were likely the predominant cause of variation in streamflow conditions among these sites. The occurrence of peak discharge for Horse Lake Creek above Heron Reservoir and for sites on Willow Creek in March and April resulted from the early rise in temperature at the low elevations causing snowmelt runoff, and the low annual discharge and the low streamflow yield per square mile for these streams resulted from the low rates of annual precipitation at the low elevations.

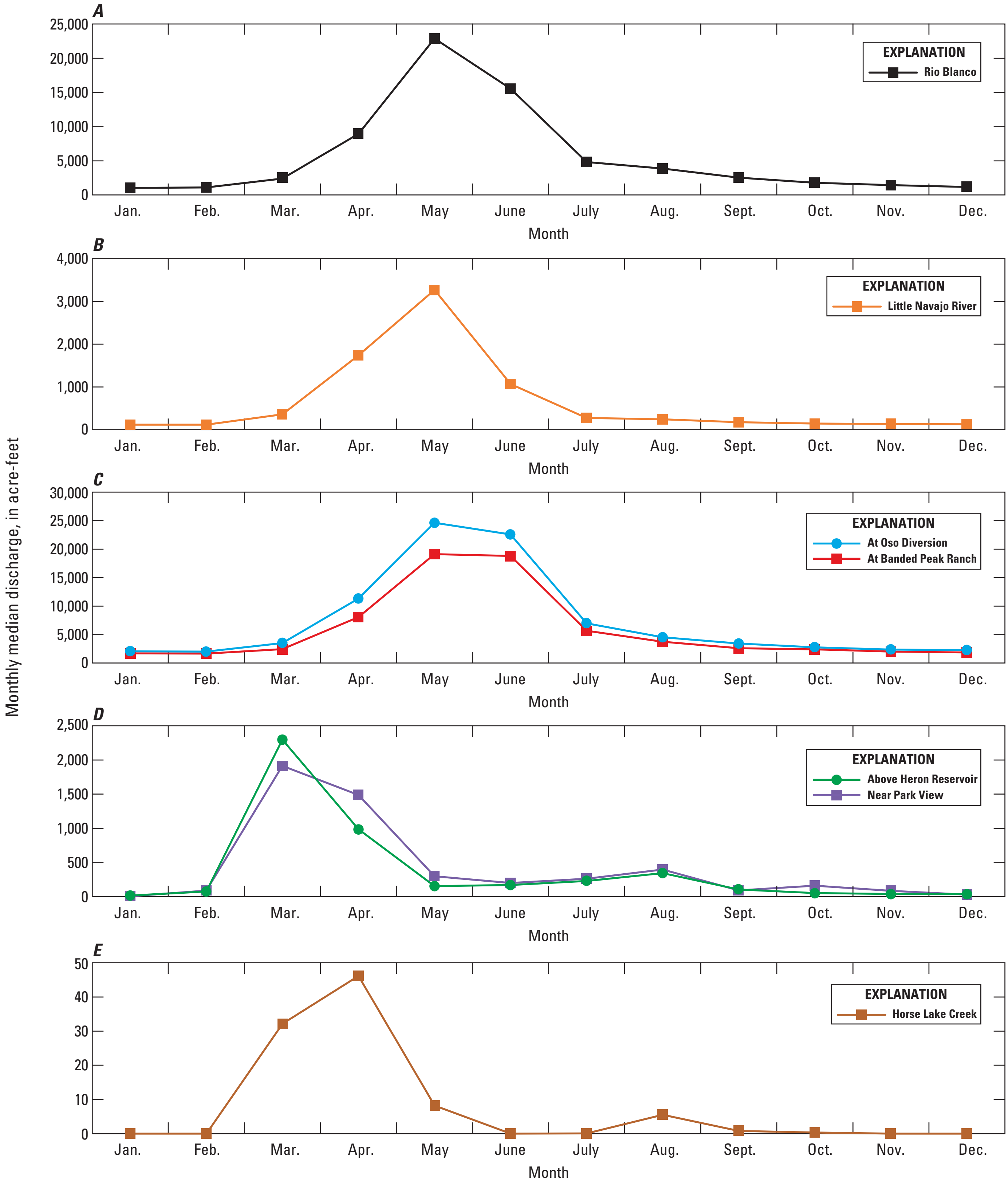


Figure 15. Median monthly discharge for selected for streamflow-gaging stations over the period of record in the study area, southern Colorado and northern New Mexico, 1943–2010. *A*, Rio Blanco - Combined. *B*, Little Navajo River - Combined. *C*, Navajo River - Combined and Navajo River at Banded Peak Ranch. *D*, Willow Creek above Heron Reservoir and Willow Creek near Park View. *E*, Horse Lake Creek above Heron Reservoir.

The streamflow record at Navajo River at Banded Peak Ranch is the longest continuous record available for the study area. The daily streamflow at Navajo River at Banded Peak Ranch is significantly statistically correlated to the streamflow records for Rio Blanco - Combined (Kendall's tau of 0.8202 with a p-value less than 0.0001), Little Navajo River - Combined (Kendall's tau of 0.6792 with a p-value less than 0.0001), and Navajo River - Combined (Kendall's tau of 0.8687 with a p-value less than 0.0001). The Navajo River at Banded Peak Ranch streamflow record was analyzed for long-term streamflow trends that are representative of streamflow conditions on the Rio Blanco and Navajo River.

Annual discharge at Navajo River at Banded Peak Ranch has ranged from 154,788 acre-ft per year (1941) to 24,119 acre-ft per year (2002; fig. 16). The 5-year moving average of the annual discharge (fig. 16) removes short-term fluctuations and shows intervals of time that have either greater than median flow or less than median flow. Annual variability in streamflow conditions is generally an indication of variation in the various climatic parameters that interact to contribute to streamflow, including precipitation and temperature. For snowmelt-dominated streams, streamflow is generally a function of winter precipitation and the timing of increasing spring temperatures (Stewart and others, 2005; Knowles and others, 2006). The annual discharge is slightly asymmetrically distributed around the median such that values greater than the median cover a slightly larger range than do values that are less than the median (fig. 17). The annual flow-duration curve is relatively linear; however, the slope of the low-discharge end is flattened, except for the 2 years with the lowest annual discharge. The flattened low-discharge end indicates that annual discharge during low-flow years is likely derived from base flow and is a function of the base-flow storage of the watershed (Searcy, 1959). The distribution of annual discharge and the flow-duration curve show that streamflow conditions at Navajo River at Banded Peak Ranch over the period of record were slightly skewed such that flows below the median were relatively close to the median, and flows above the median were more variable and covered a wider range of values (fig. 17).

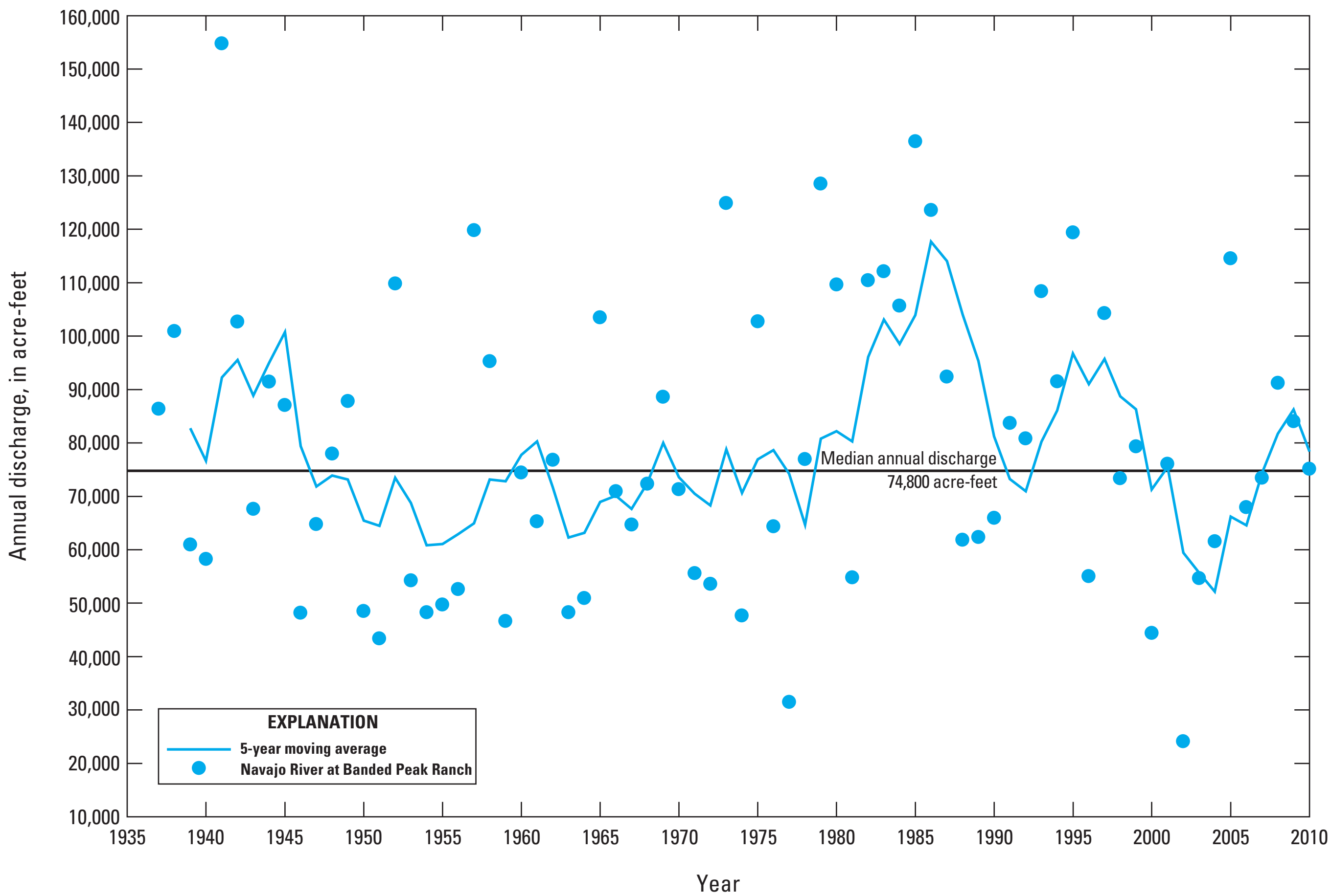


Figure 16. Annual discharge at streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, with a 5-year moving average and the median annual discharge for 1937–2010.

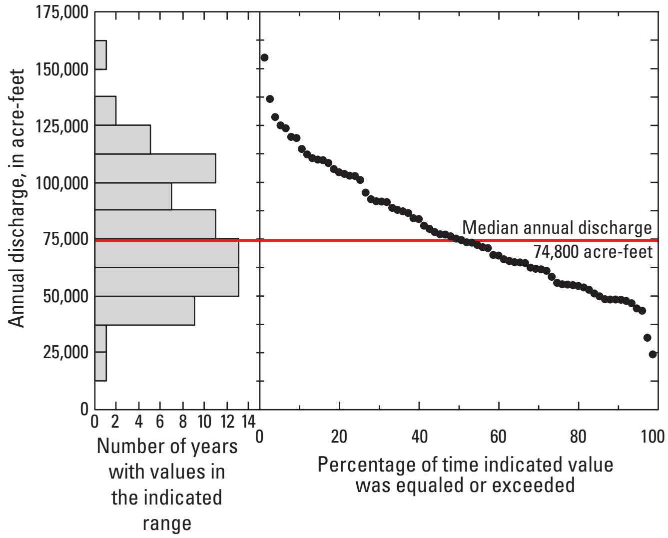


Figure 17. Distribution of annual discharge, median annual discharge, and annual flow-duration curves for the period of record for streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, 1937–2010.

In general, fluctuations in precipitation and temperature result from climate variations such as the Pacific Decadal Oscillation (PDO) and the El Niño/Southern Oscillation (ENSO). PDO climate cycles occur on 20- to 30-year intervals. The cycles are defined by the PDO index, defined as the "leading principal component of North Pacific monthly sea-surface temperature (SST) variability," and are indicated as negative or positive by the sign of the North Pacific monthly SST anomaly (fig. 18; values for the PDO index are modified from Mantua and Hare [2011]). The North Pacific monthly SST anomaly is defined as the difference between the observed North Pacific monthly SST and the mean North Pacific monthly SST. The North Pacific monthly SST anomaly is adjusted by the mean global monthly SST anomaly to remove variability from increases in the global SST (Mantua and Hare, 2002). A negative PDO index for an interval is associated with decreased precipitation in the Southwestern United States, and a positive PDO index for an interval is associated with increased precipitation in the Southwestern United States (Hanson and others, 2004). Mantua and Hare (2002) identified four intervals of the PDO index in the 20th century (fig. 18): a negative interval from 1890 to 1924 (not shown), a positive interval from 1925 to 1946 (beginning

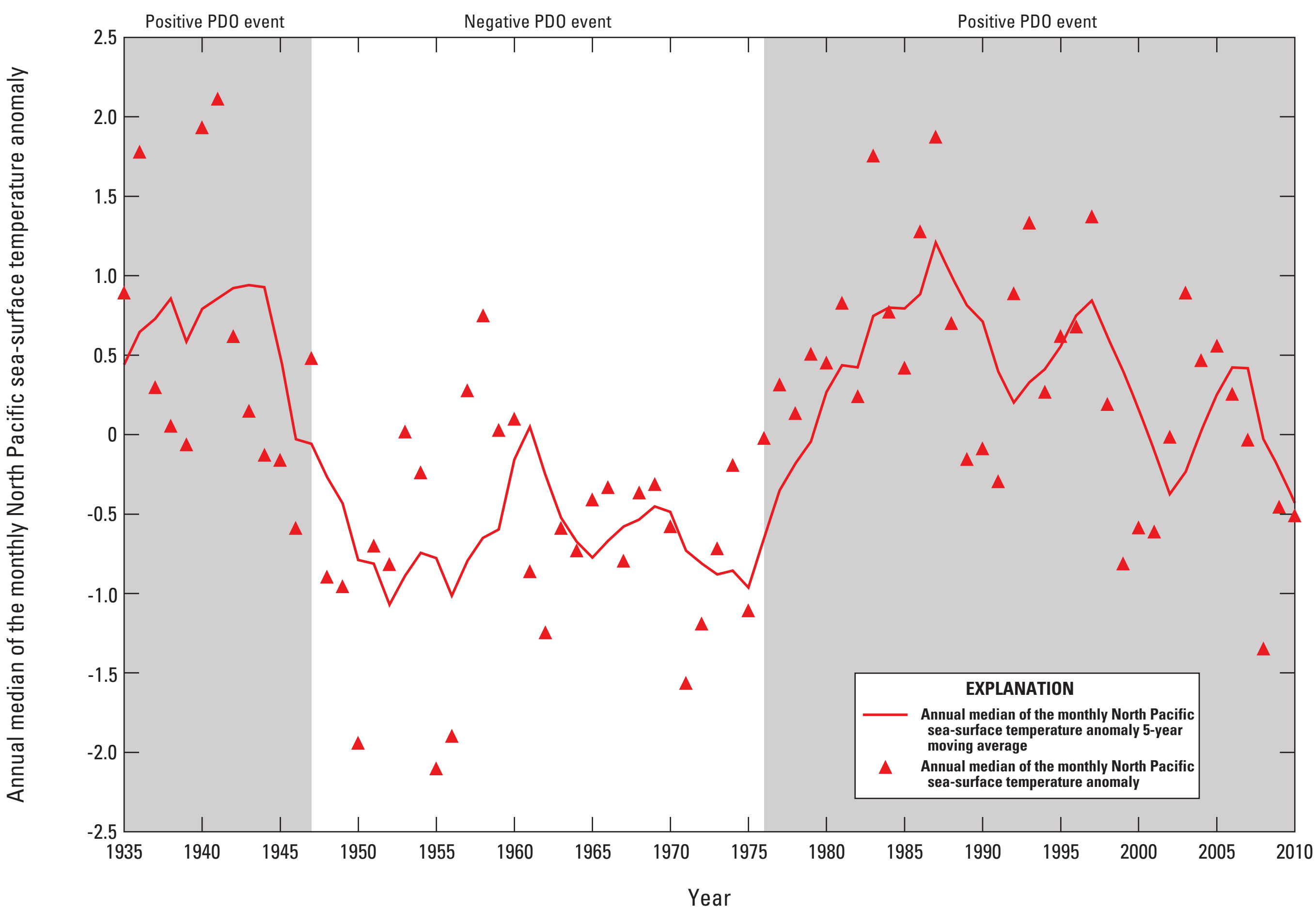


Figure 18. Median annual monthly North Pacific sea-surface temperature anomaly for 1935–2010, with a 5-year moving average, and the associated Pacific Decadal Oscillation (PDO) intervals (data modified from Mantua and Hare, 2011).

of interval not shown), a negative interval from 1947 to 1976, and a positive interval from 1977 to 1999. A possible change from positive to negative PDO index was identified as starting in 1999 (Minobe, 2000; Schmidt and Webb, 2001); however, more recent work has concluded that the climatic changes that occurred during 1999–2002 were not consistent with climatic changes that occurred during the 1976/1977 PDO index shift from negative to positive and that the PDO index was still positive in 2002 (Bond and others, 2003). For this report, the interval from 2000 to 2010 was included in the 1977–99 positive PDO interval.

In general, for Navajo River at Banded Peak Ranch, the annual discharge coincides with the timing of PDO cycles (fig. 19). For example, the negative PDO interval of 1947–76 coincides with an interval of annual discharge that is below the median (fig. 19). During positive PDO intervals during the period of record for Navajo River at Banded Peak Ranch (1937–46 and 1977–2010, fig. 20), the distribution of annual discharge is skewed higher than the median annual discharge for the period of record, and during the negative PDO interval, the distribution of annual discharge is skewed lower than the median annual discharge. Streams in the study area with data from more than one PDO interval generally have median annual discharge that is lower during the negative (drier) PDO intervals than during positive (wetter) PDO intervals (table 6).

ENSO variations, like PDO variations, reflect changes in the temperature of the Pacific Ocean that affect precipitation and temperature in North and South America (Dettinger and others, 2001). ENSO variations, each generally a 3- to 6-year cycle, are known as El Niño years when the eastern equatorial Pacific Ocean is unusually warm and as La Niña when the eastern equatorial Pacific Ocean is unusually cold (National Oceanic and Atmospheric Administration, 2011). El Niño years are associated with increased storm events and precipitation, warmer than normal land-surface temperatures, and increased streamflow in the southern part of the United States (Dettinger and others, 2001). Though ENSO climate variations significantly affect climatic parameters in the Southwestern United States, detailed analysis of the interdecadal variation in streamflow for the SJCP was not included in this report—there is increased complexity because of interactions between the interdecadal and decadal oscillations of the North Pacific with climate parameters over the Southwestern United States.

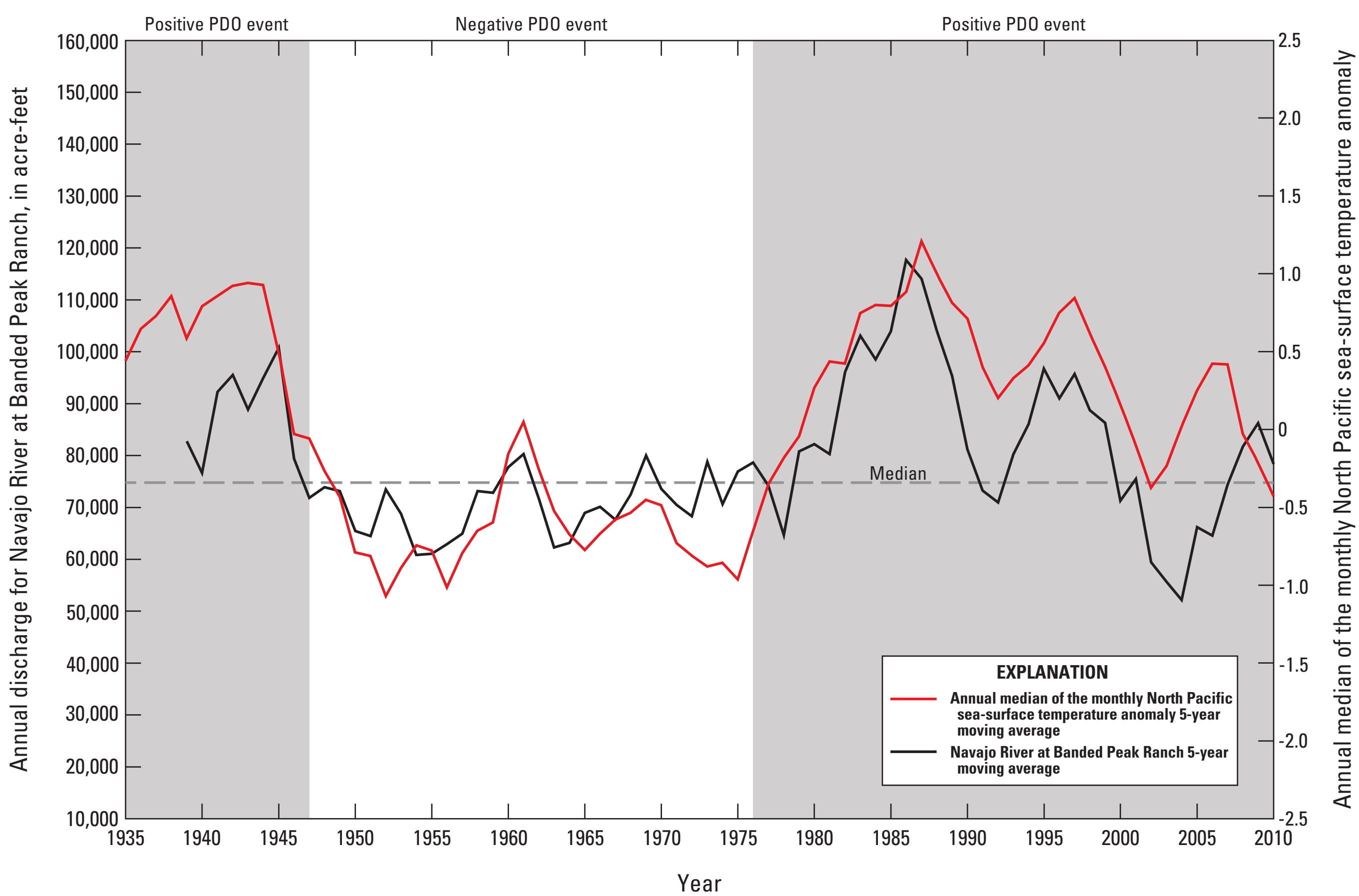


Figure 19. Five-year moving average of discharge for streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, 1937–2010, and the 5-year moving average of the median annual monthly North Pacific sea-surface temperature anomaly, 1935–2010.

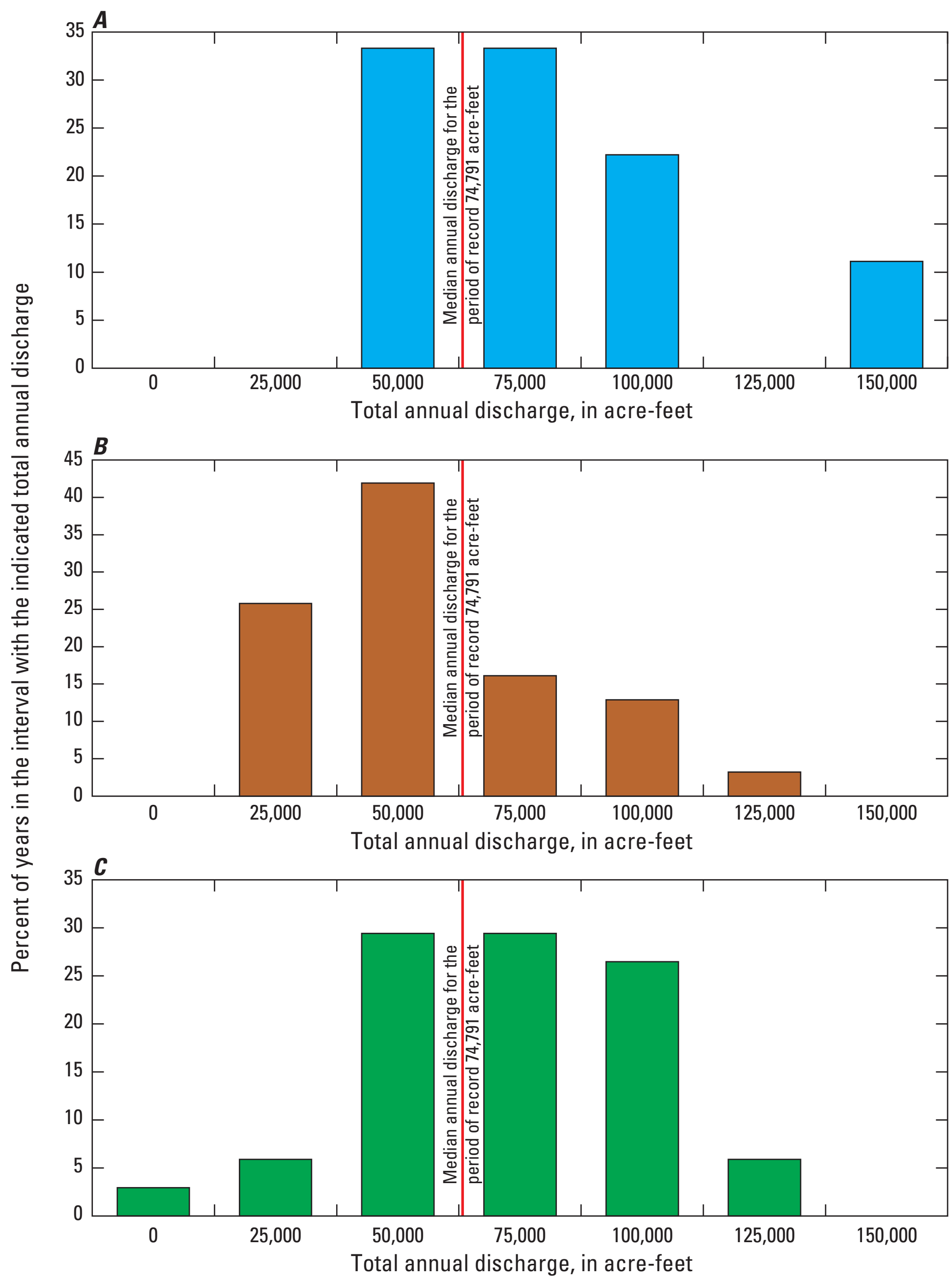


Figure 20. Distribution of annual discharge for streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, by Pacific Decadal Oscillation (PDO) interval. *A*, Positive PDO interval from 1935–46. *B*, Negative PDO interval from 1947–76. *C*, Positive PDO interval from 1977–2010.

Table 6. Average and median annual discharge for selected streams in the study area, southern Colorado and northern New Mexico, 1936–2010, during Pacific Decadal Oscillation intervals.

[In acre-feet]

	Navajo River above Chromo	Navajo River - Combined	Little Navajo River at Chromo	Little Navajo River - Combined	Rio Blanco near Pagosa Springs	Rio Blanco - Combined	Navajo River at Banded Peak Ranch	Willow Creek above Heron Reservoir	Willow Creek near Park View
1925–46 Pacific Decadal Oscillation positive interval									
Period of record			1936–46		1936–46		1937–46		1943–46
Median			9,980		70,400		86,740		8,000
Average			11,010		68,550		85,830		7,870
1947–76 Pacific Decadal Oscillation negative interval									
Period of record	1957–69		1947–51		1947–70		1947–76	1963–70	1947–69
Median	80,860		3,950		57,220		65,040	5,710	10,060
Average	84,750		5,720		58,250		71,160	7,600	10,870
1977–2010 Pacific Decadal Oscillation positive interval									
Period of record		1977–2010		1977–2010		1977–2010	1977–2010		
Median		93,010		8,620		74,620	80,080		
Average		95,650		9,830		74,930	83,390		

Trends in the Seasonal Distribution of Streamflow

Trends in the seasonal distribution of streamflow can indicate changes in the timing of snowmelt runoff. Previous work on the timing of snowmelt runoff in the Western United States has shown that over time runoff has recently occurred on dates that are earlier in the year than it occurred in previous years (for example, Cayan and others, 2001; Stewart and others, 2005; Clow, 2010). Additionally, Clow (2010) concluded that, for sites in Colorado, the duration of snowmelt runoff was increasing, perhaps in response to the relative increase of precipitation.

Changes in the seasonal distribution of streamflow could result in a change of the date of the streamflow peak, a change in the duration of the snowmelt runoff, or a combination of the changes. A shortened duration for a volume of runoff would result in a larger peak with higher daily discharge than a longer duration for the same volume of runoff, which would result in a smaller peak with lower daily discharge (fig. 21*A*). Changes in the timing and duration of streamflow for streams of the SJCP could affect the amount of water that could be diverted if the changes cause discharge amounts that are greater than the maximum capacities of the various diversion structures and tunnels of the SJCP.

Indicators of the seasonal distribution of streamflow (hereafter referred to as "streamflow indicators") for Navajo River at Banded Peak Ranch from 1937 to 2009 were tested for monotonic trends by using the Mann–Kendall trend test to determine if the seasonal distribution of streamflow of the SJCP had changed over time. The data tested for trends included the time series of the streamflow indicators, the streamflow indicators compared to the annual discharge, and the time series of the annual discharge. The streamflow indicators were tested for monotonic trends compared to the annual discharge to determine if the volume of annual discharge significantly affected the seasonal distribution of streamflow. Additionally, the annual discharge was tested for monotonic trends to determine if the volume of annual discharge had changed significantly over time. The time series of the streamflow indicators, the streamflow indicators compared to the annual discharge, and the time series of the annual discharge were tested for monotonic trends for the period of record and for the two PDO intervals with more than 15 years of data. The tested intervals were 1947–76 and 1977–2009.

The streamflow indicators that were tested included the ordinal day, or Julian day, of the water year of the center of mass of annual discharge (CT), the ordinal day of the water year of the start of the spring pulse onset of the snowmelt runoff (ST), the ordinal day of the water year on which the 20th and 50th percentiles of annual discharge occurred (DQF20 and DQF50, respectively), the monthly percentage of annual discharge in March and June, and the monthly discharge in March and June (fig. 21*B*). The

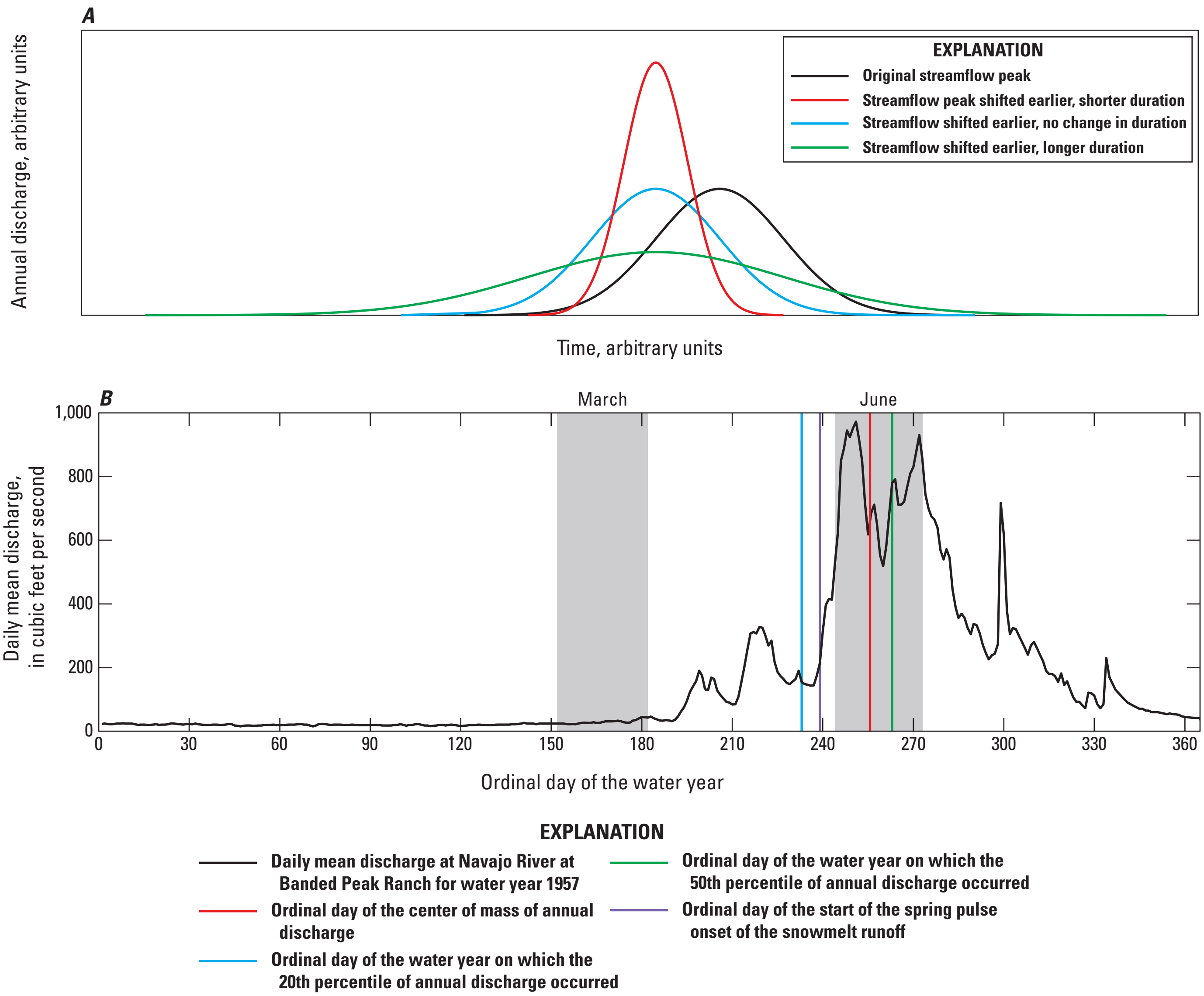


Figure 21. Effect of changes in the timing and duration of streamflow and example hydrograph showing indicators of the distribution of streamflow. *A*, Effect of changes in the timing and duration of the streamflow peak. *B*, Example of annual hydrograph of daily mean discharge from 1957 for Navajo River at Banded Peak Ranch and associated indicators of the seasonal distribution of streamflow.

CT, defined by following Stewart and others (2005), was calculated from

$$CT = \frac{\Sigma\left(T_i Q_i\right)}{\Sigma Q_i}$$

where

T_i is the ordinal day of the water year, and
Q_i is the daily mean streamflow.

The ST, defined by following Cayan and others (2001), was calculated as the day of the minimum cumulative departure from the annual mean daily flow from day 101 to day 300 (equivalent to the ordinal days of the calendar year 9 to 208), which is "equivalent to finding the day after which most flows are greater than average" (Cayan and others, 2001, p. 402). The ordinal day of the water year of the 50th percentile of discharge, defined following Moore and others (2007) and Clow (2010), is the day on which the first half of the annual discharge has occurred, and the ordinal day of the water year of the 20th percentile of discharge is the day on which the first 20 percent of the annual discharge has occurred. Streamflow indicators were determined for all complete water years of streamflow record at Navajo River at Banded Peak Ranch; the streamflow indicators were determined for the water year because the existing methods for calculating the various indicators are based on water-year intervals.

The Mann–Kendall trend test is a nonparametric rank-based method that determines if a parameter monotonically increases or decreases over time (Helsel and Hirsch, 2002). Trends were considered statistically significant at a p-value ≤ 0.05. The p-value is “the probability of obtaining the computed test statistic, or one even less likely, when the null hypothesis is true… and the lower the p-value the stronger is the case against the null hypothesis” (Helsel and Hirsch, 2002, p. 108). Kendall’s tau “measures the strength of the monotonic relationship” (Helsel and Hirsh, 2002, p. 212) between two parameters. The strength of the monotonic relation was determined from the magnitude of tau and was classified as very weak for tau values less than 0.20, weak for tau values of 0.21–0.40, moderate for tau values of 0.41–0.60, strong for tau values of 0.61–0.80, and very strong for tau values greater than 0.81 (table 7). The sign of tau indicated whether the trend was negative or positive.

Time Series of the Indicators of the Seasonal Distribution of Streamflow

A significant trend for the time series of the streamflow indicators of CT, ST , DQF20, and DQF50 was detected only for DQF50 for 1977–2009 (table 7); the trend for CT for 1977–2009 was just above the significance level of $p \leq 0.05$ (table 7). Both of these trends were weakly negative. None of the intervals tested for the time series of annual discharge had a significant trend (table 7). The general lack of significant trends for the time series of the streamflow indicators shows that systemic changes in CT, DQF20, DQF50, and ST did not occur monotonically over the tested time periods. The departure of the streamflow indicators and annual discharge from the median for the period of record for Navajo River at Banded Peak Ranch shows that there were short intervals over which the indicators recurred earlier or later in the year and short intervals over which the annual discharge was recurrently greater than or less than the median; however, there were no overall trends for the periods of record that were tested (fig. 22).

Significant trends for the time series of the monthly percentage of annual discharge in March were detected for 1937–2009 and 1977–2009, and significant trends for the monthly discharge in March were detected for 1937–2009 and 1977–2009 (table 7). Significant trends for the time series of the monthly percentage of annual discharge in June were detected for 1977–2009, and significant trends for the monthly discharge in June were detected for 1977–2009 (table 7). The trends for March were weakly positive except for the very weakly positive trend for the percentage of discharge for 1937–2009. The trends for June were weakly negative (table 7). A positive trend for March indicated that the percentage of annual discharge that occurred in March increased over time, and a negative trend for June indicated that the percentage of annual discharge that occurred in June decreased over time. Departure of the monthly percentage of annual discharge in March and June from the median for the period of record for Navajo River at Banded Peak Ranch showed visual trends of increased discharge in March and decreased discharge in June over the period of record and particularly in the second half of the record (fig. 23). The results from the Mann–Kendall trend test for the time series of the streamflow indicators for discharge in March and June showed that the amount of discharge and the percentage of discharge that occurred in March increased over time and that the amount of discharge and the percentage of discharge that occurred in June has decreased since 1977 (table 7).

Indicators of the Seasonal Distribution of Streamflow Compared to Annual Discharge

Significant trends for the streamflow indicators compared to annual discharge were detected for all intervals except for the 1947–76 interval for ST (table 7); the trend for ST for the interval from 1947–76 was just above the significance level of $p \leq 0.05$ (table 7). The significant trends were moderately positive for all pairings except for the 1937–2009 interval for ST, which was weakly positive. Trends for the streamflow indicators compared to annual discharge indicated that as annual discharge increased the CT, DQF20, DQF50, and ST occurred at a later date in the year (fig. 24).

Significant trends for the monthly percentage of annual discharge in March and June and the discharge in June compared to annual discharge were detected for all intervals (table 7). The significant trends for the monthly percentage of annual discharge in March were moderately negative for 1937–2009 and 1977–2009 and strongly negative for 1947–76. The significant trends for the monthly percentage of annual discharge in June were moderately positive for all periods, and the significant trends for the discharge in June were strongly positive for all periods. A moderate negative trend for March indicated that the percentage of annual discharge that occurred in March decreased with increased discharge (fig. 25*A* and table 7), and the lack of a trend for the discharge in March indicated that discharge is unaffected by the amount of annual discharge (fig. 25*B* and table 7). During years with increased annual discharge, proportionally less discharge occurred in March than in other months. A moderately positive trend for the monthly percentage of annual discharge in June and a strong positive trend for the discharge in June indicated that increased annual discharge was correlated to increased discharge in June and that proportionally more discharge occurred in June than in other months during years with increased annual discharge (figs. 25*A* and 25*B* and table 7). The relative amount of the discharge increase in June was greater than the increase in other months, such that more of the increase in annual discharge occurred in June.

Table 7. Results of the Mann–Kendall trend test for the indicators of the seasonal distribution of streamflow for streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, selected intervals by water years during the period of record, 1937–2009.

[Strength of correlation: 0.00–0.20 very weak (VW), 0.21–0.40 weak (W), 0.41–0.60 moderate (M), 0.61–0.80 strong (S); bold, p-values below the significance value of 0.05; *, p-value is above the significance level of 0.05; --, not tested]

	Trends in the time series of the indicators of the seasonal distribution of streamflow			Trends in the indicators of the seasonal distribution of streamflow compared to annual discharge		
	Kendall's tau	p-value	Strength of correlation	Kendall's tau	p-value	Strength of correlation
Ordinal day of the water year of the center of mass of annual discharge (CT)						
1937–2009	-0.0662	0.4073		0.4224	**<0.0001**	**M**
1947–76	-0.0161	0.9006		0.4621	**0.0003**	**M**
1977–2009	-0.2311	0.0587*	**W**	0.4924	**<0.0001**	**M**
Ordinal day of the water year of the start of the spring pulse onset of the snowmelt-derived runoff (ST)						
1937–2009	-0.0062	0.9392		0.2975	**0.0002**	**W**
1947–76	0.1372	0.2916		0.2396	*0.0656	**W**
1977–2009	-0.1797	0.1447		0.4245	**0.0006**	**M**
Ordinal day of the water year on which the 20th percentile of annual discharge occurred (DQF20)						
1937–2009	-0.1179	0.1423		0.4891	**<0.0001**	**M**
1947–76	-0.0346	0.7889		0.5935	**<0.0001**	**M**
1977–2009	-0.2019	0.1002		0.5181	**<0.0001**	**M**
Ordinal day of the water year on which the 50th percentile of annual discharge occurred (DQF50)						
1937–2009	-0.0393	0.6268		0.4738	**<0.0001**	**M**
1947–76	0.0255	0.8442		0.4757	**0.0002**	**M**
1977–2009	-0.2896	**0.0191**	**W**	0.5389	**<0.0001**	**M**
Annual discharge, in acre-feet						
1937–2009	0.0426	0.5938		--	--	
1947–76	0.0621	0.6300		--	--	
1977–2009	-0.1705	0.1632		--	--	
Monthly percentage of annual discharge in March						
1937–2009	0.1667	**0.0370**	**VW**	-0.4909	**<0.0001**	**M**
1947–76	0.0069	0.9573		-0.6276	**<0.0001**	**S**
1977–2009	0.322	**0.0084**	**W**	-0.4394	**0.0003**	**M**
Monthly discharge in March						
1937–2009	0.2394	**0.0027**	**W**	0.0879	0.2713	
1947–76	0.1105	0.3917		-0.1519	0.2389	
1977–2009	0.2879	**0.0185**	**W**	0.2008	0.1005	
Monthly percentage of annual discharge in June						
1937–2009	-0.105	0.1887		0.4901	**<0.0001**	**M**
1947–76	-0.1218	0.3444		0.5126	**<0.0001**	**M**
1977–2009	-0.3144	**0.0101**	**W**	0.5606	**<0.0001**	**M**
Monthly discharge in June						
1937–2009	-0.0327	0.6821		0.7801	**<0.0001**	**S**
1947–76	-0.0023	0.9858		0.7885	**<0.0001**	**S**
1977–2009	-0.2917	**0.0170**	**W**	0.8030	**<0.0001**	**S**

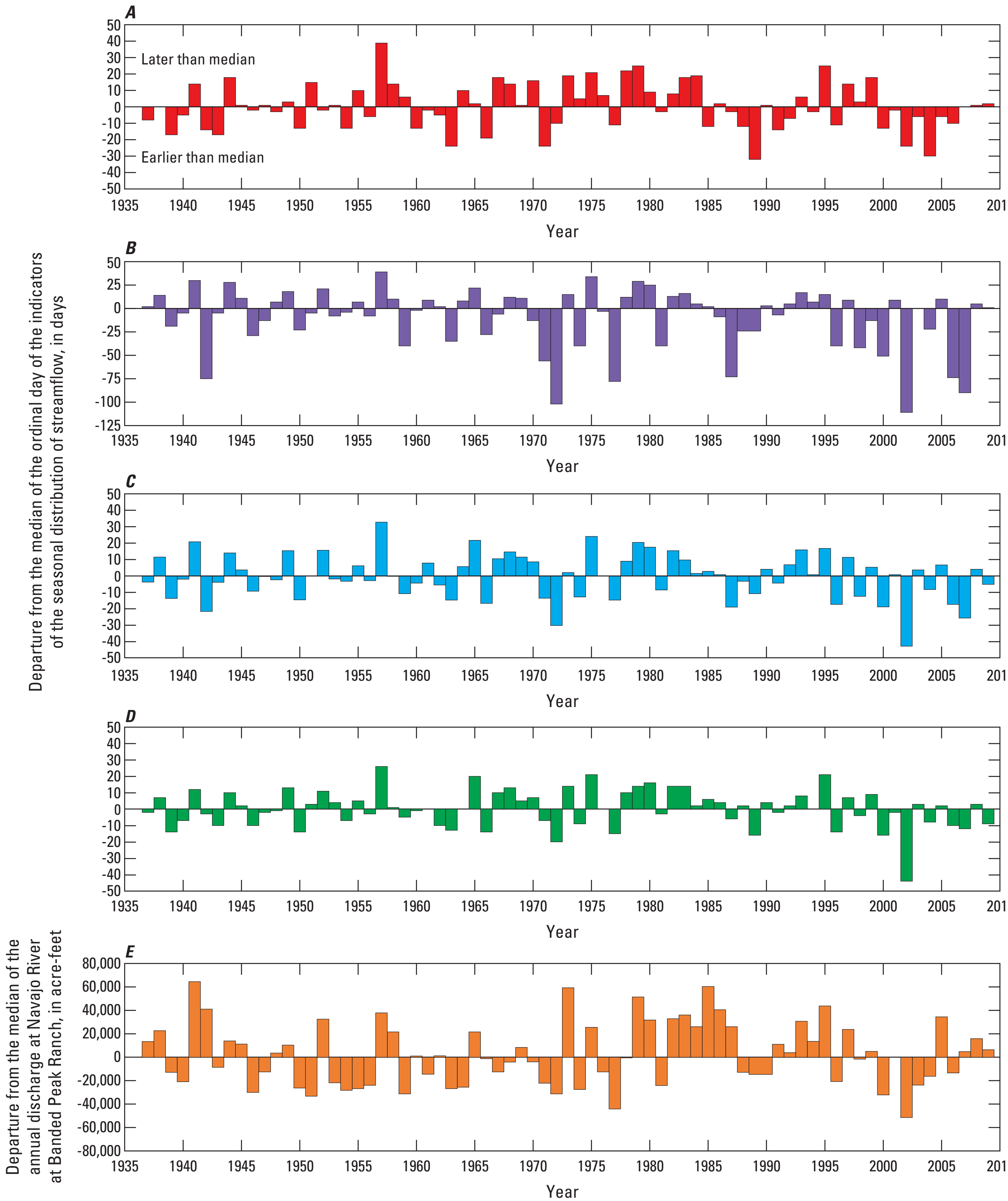


Figure 22. Departure from the median of the ordinal day of the indicators of the seasonal distribution of streamflow for streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, for the period of record, 1937–2009. *A*, Ordinal day of the water year of the start of the spring pulse onset of the snowmelt runoff. *B*, Ordinal day of the water year on which the 20th percentile of annual discharge occurred. *C*, Ordinal day of the water year of the center of mass of annual discharge. *D*, Ordinal day of the water year on which the 50th percentile of annual discharge occurred. *E*, Annual discharge by water year.

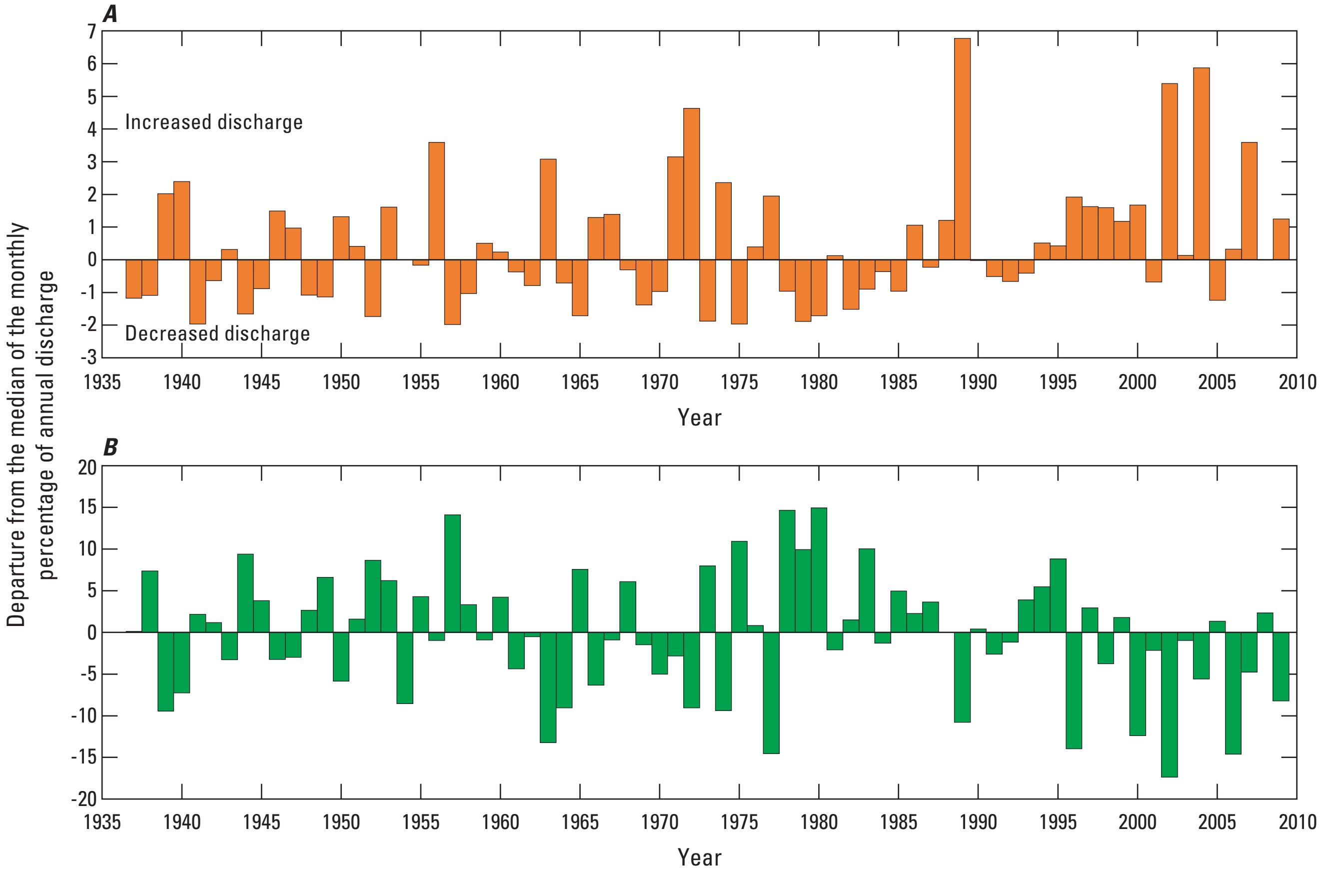


Figure 23. Departure from the median of the monthly percentage of annual discharge at streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, 1937–2009. *A*, March. *B*, June.

The difference between the occurrence and the strength of significant trends between the time series of the indicators of the seasonal distribution of streamflow and the indicators compared to annual discharge indicated that the seasonal distribution of streamflow was more strongly controlled by the change in the annual discharge than by changes in streamflow conditions over time. Moore and others (2007) observed that increased annual discharge could result in the ordinal day of the streamflow indicators of CT, ST, DQF20, and DQF50 occurring at later dates in the year. They proposed a conceptual model of streamflow conditions (fig. 6) for two flow conditions with the same base flow: high flow and low flow. Changes in annual discharge are the result of changes in snowmelt runoff; years with increased snowmelt will result in increased annual discharge. Moore and others (2007) showed that streamflow indicators are affected by changes in runoff with “higher flows producing ‘later’ runoff and lower flows producing ‘earlier’ runoff” (Moore, 2007, p. 4) because decreased snowmelt will generate less runoff for a shorter duration and increased snowmelt will generate more runoff for a longer duration. It is likely that trends in the monthly distribution of annual discharge are similarly affected by changes in the annual discharge.

In general, increased annual discharge resulted in the snowmelt runoff occurring later in the year on streams that are part of the SJCP. Years with more snowmelt runoff, likely from increased rates of precipitation and increased accumulation of snowpack, generally had a longer duration of runoff, and the streamflow indicators occurred at dates later in the year than the years with less snowmelt runoff. Years with increased annual discharge, as compared to years with decreased annual discharge, had a smaller percentage of discharge in March, a larger percentage of discharge in June, an interval of discharge derived from snowmelt runoff that occurred later in the year, and a larger discharge in June.

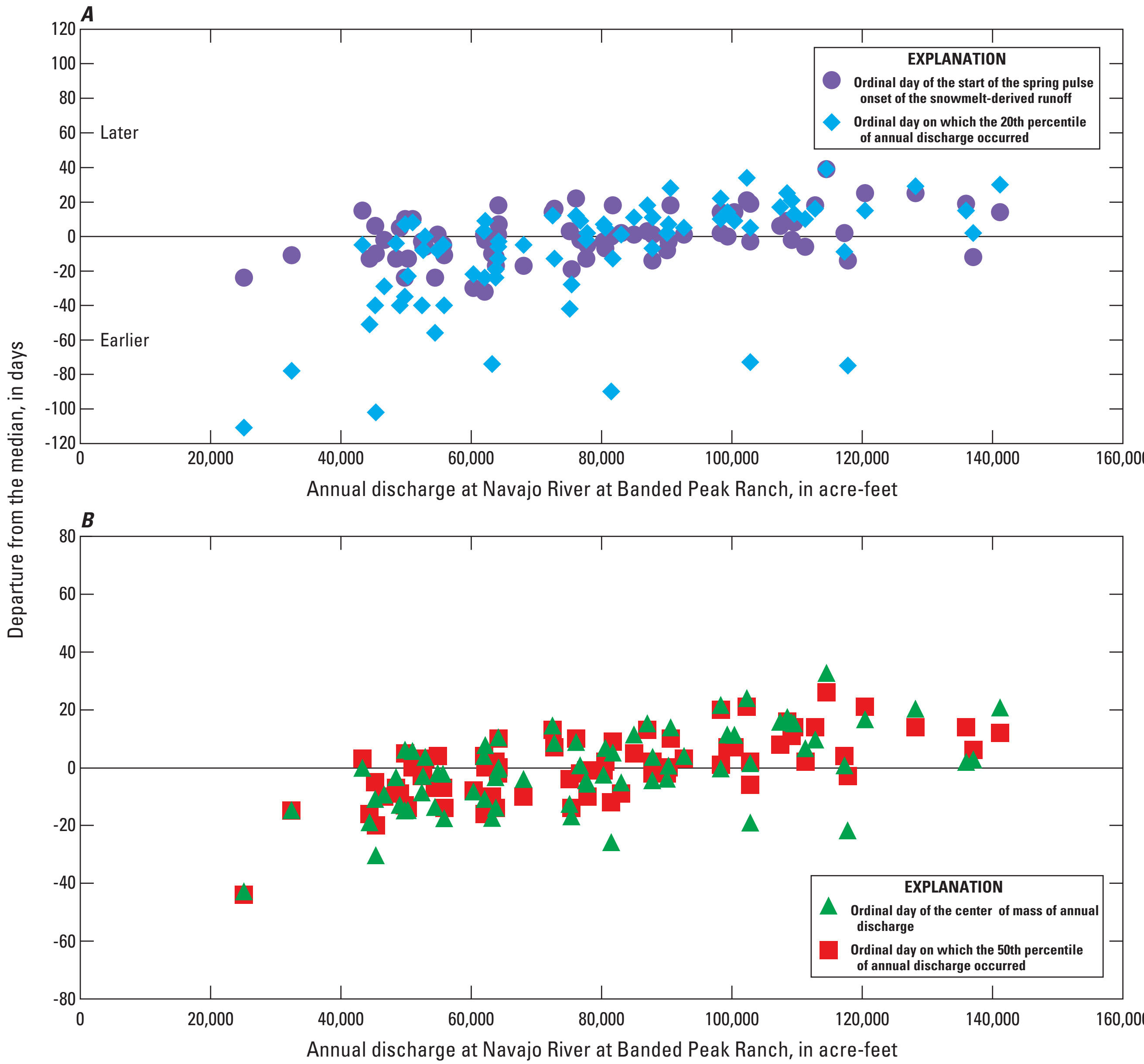


Figure 24. Variation of indicators of the seasonal distribution of streamflow compared to annual discharge at streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, 1937–2009. *A*, Departure from the median of the ordinal day of the water year of the start of the spring pulse onset of the snowmelt runoff and the ordinal day of the water year on which the 20th percentile of annual discharge occurred compared to annual discharge. *B*, Departure from the median of the ordinal day of the water year of the center of mass of annual discharge and the ordinal day of the water year on which the 50th percentile of annual discharge occurred compared to annual discharge.

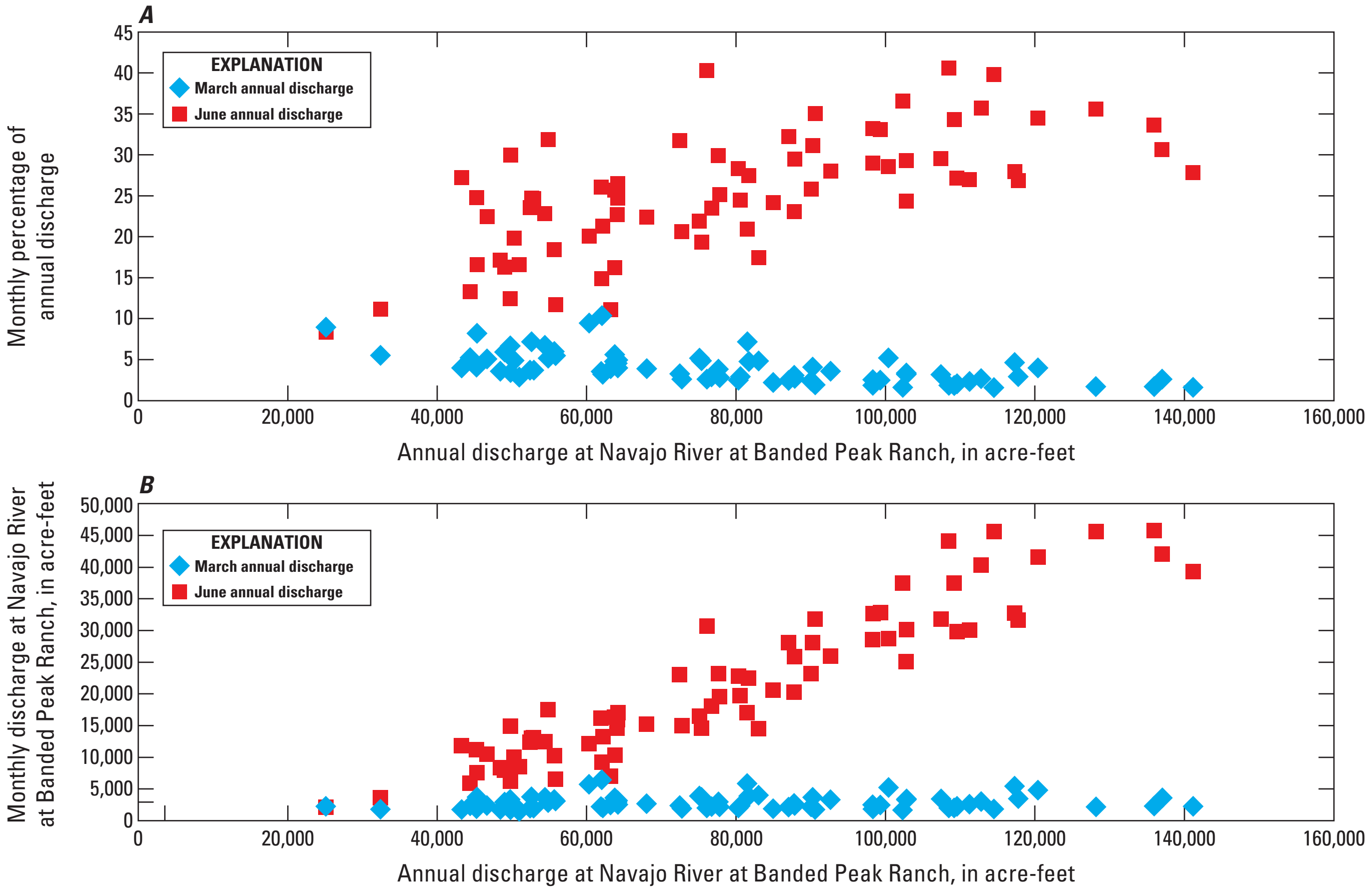


Figure 25. Variation of the monthly percentage of annual discharge in March and June and the monthly discharge in March and June compared to annual discharge at streamflow-gaging station Navajo River at Banded Peak Ranch, in the southern Colorado portion of the study area, 1937–2009. *A*, Monthly percentage of annual discharge in March and June compared to annual discharge. *B*, Monthly discharge in March and June compared to annual discharge.

The results from the Mann–Kendall trend test showed that there was not a significant trend in the time series of the annual discharge for any of the tested periods, which indicated that annual discharge was not monotonically increasing or decreasing over the tested periods, which included the period of record and the two PDO intervals with more than 15 years of data: 1947–76 and 1977–2009 (table 7). The monotonic correlations detected by the Mann–Kendall trend test are a measure of the association of two variables and whether one variable increases (a monotonically increasing correlation) or decreases (a monotonically decreasing correlation), linearly or nonlinearly, as the other variable increases (Helsel and Hirsch, 2002). Two variables can have a nonmonotonic relation in which the variables covary but the association changes between increasing and decreasing. The variation of annual discharge at Navajo River at Banded Peak Ranch was not significantly monotonic over the period of record or over the two PDO intervals; however, there was a relation such that annual discharge was generally lower than the median during a negative PDO interval and higher than the median during a positive PDO interval (figs. 19 and 20). Streamflow conditions at Navajo River at Banded Peak Ranch varied nonmonotonically over time and were likely a function of complex climate pattern interactions.

Nonmonotonic variations in climate patterns likely affect the monthly distribution of streamflow. The monotonic trends in the time series of the percentage of annual discharge in March for Navajo River at Banded Peak Ranch showed a very weak positive trend for the period 1937–2009, no significant trend for 1947–76, and a weak positive trend for 1977–2009 (table 7). The variation in the trends over time are an indication that the monthly distribution of streamflow, like the variation in annual streamflow, varied nonmonotonically over time and was likely a function of complex climate pattern interactions that caused variation over time.

Probability of Annual and Monthly Availability of Water

The availability of streamflow that can be diverted from the Rio Blanco, Little Navajo River, and Navajo River is a function of the daily discharge and the minimum monthly bypass requirement for each stream (generally applied equivalently to the days of the month). The amount of water that can be diverted for the SJCP is controlled by the availability of streamflow that can be diverted and is limited by structural and legal limitations (these legal limitations have not been exceeded in the period of record at Azotea) (fig. 26). The diversion of water for the SJCP also can be restricted by the capacity of Heron Reservoir, such that if the reservoir is near total capacity, additional water will not be diverted. Heron Reservoir was near the storage capacity of 401,320 acre-ft (Bureau of Reclamation, 2011a) during the 1980s and 1990s (fig. 27).

The combined annual streamflow available above the minimum monthly bypass requirement from Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined is an indication of the availability of water

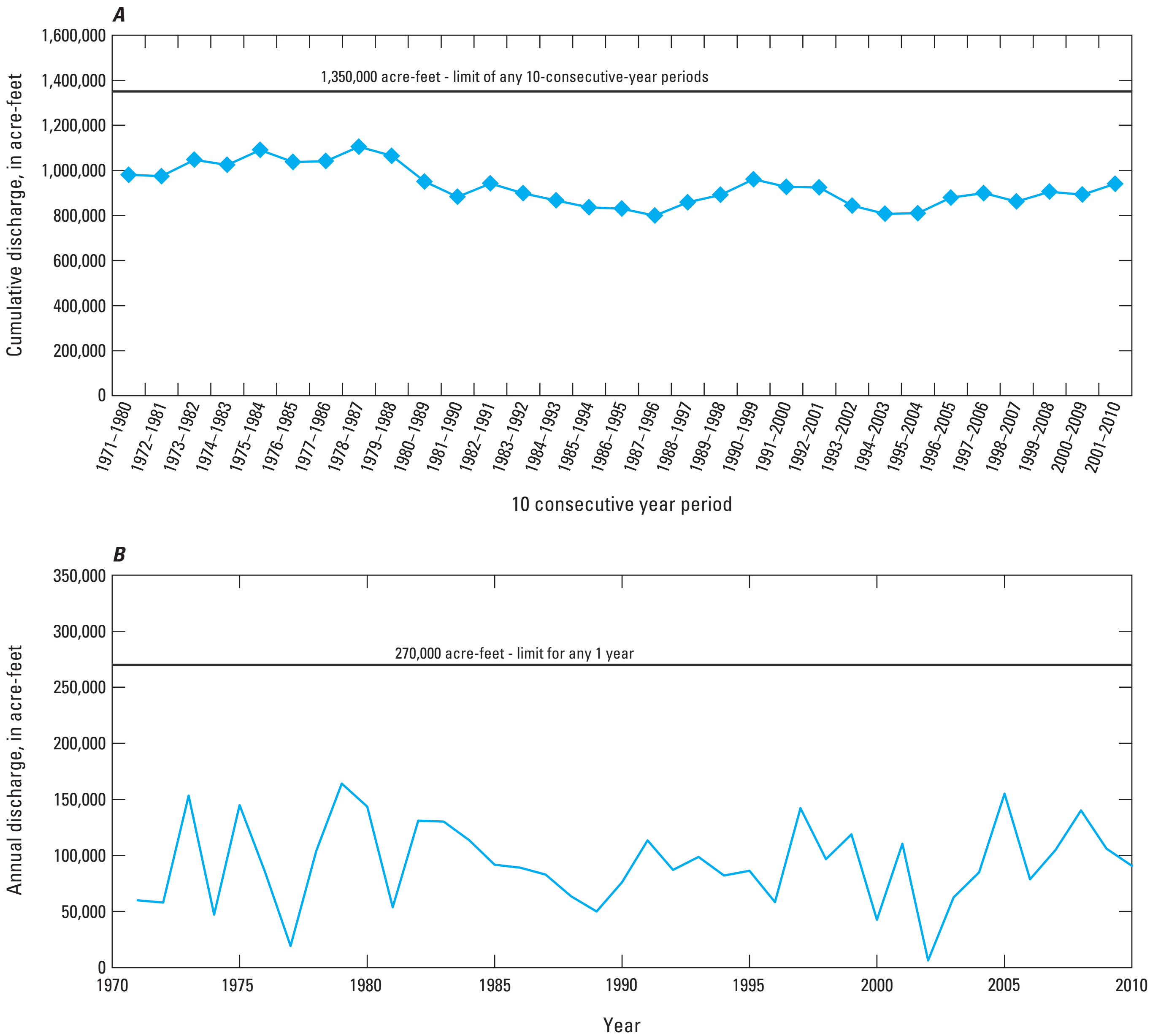


Figure 26. Discharge at the streamflow-gaging station Azotea, in the northern New Mexico portion of the study area, 1971–2010. *A*, Cumulative discharge over 10-consecutive-year periods. *B*, Annual discharge.

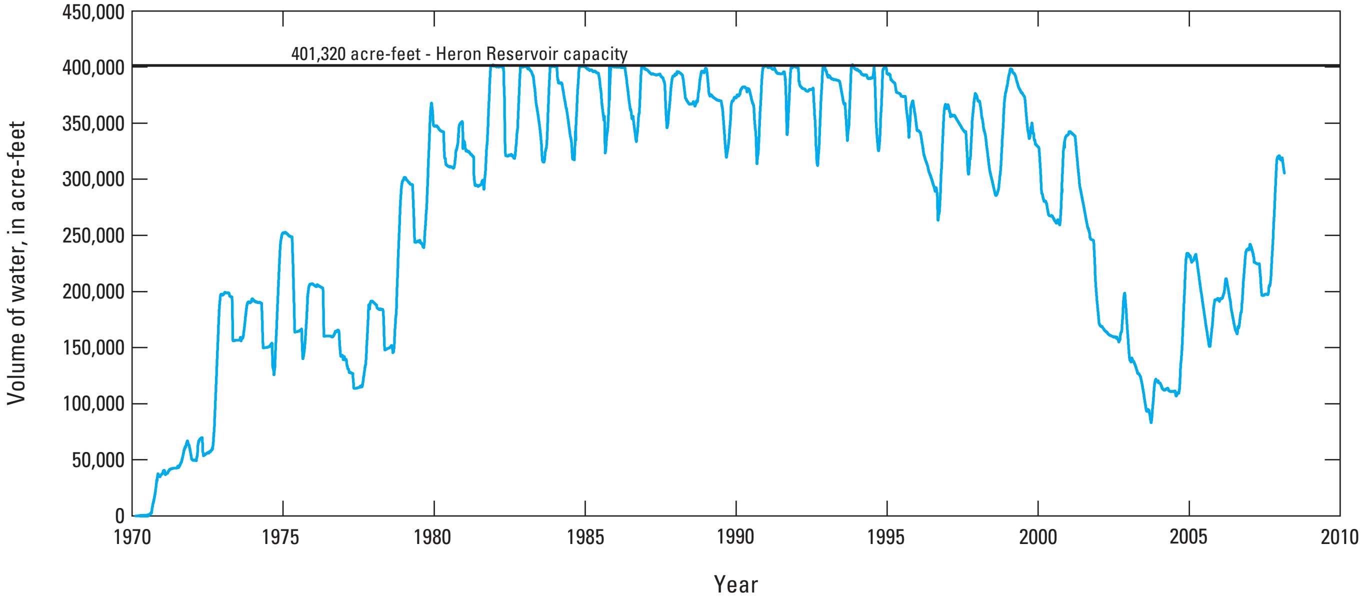


Figure 27. Volume of water in storage in Heron Reservoir, in the northern New Mexico portion of the study area, 1970–2009.

for the SJCP. Annual flow-duration curves, which show the percentage of time that a specific streamflow is equaled or exceeded during a given period, were constructed for the calculated streamflow above the minimum monthly bypass requirement. The median (50th percentile) annual discharge available above the minimum monthly bypass requirement from Rio Blanco - Combined was 60,150 acre-ft (fig. 28*A* and table 8), the median annual discharge available above the minimum monthly bypass requirement from Little Navajo River - Combined was 5,320 acre-ft (fig. 28*B* and table 8), and the median annual discharge available above the minimum monthly bypass requirement from Navajo River - Combined was 61,270 acre-ft (fig. 28*C* and table 8).

The calculated annual streamflow above the minimum monthly bypass requirement was computed by subtracting the minimum monthly bypass requirement for each day (determined by distributing the minimum monthly bypass requirement equally to every day of the month) from the daily discharge and summing the days with positive discharge. Days on which the discharge was below the minimum bypass requirement were set to 0 to prevent the accumulation of negative numbers from reducing the summed annual discharge. The median (50th percentile) of the sum of the streamflow available above the minimum monthly bypass requirement from Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined was 126,240 acre-ft (fig. 28*D* and table 8). The combined streamflow does not account for legal, logistical, and structural limits of the project.

The monthly streamflow available above the minimum monthly bypass requirement for Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined is an indication of the seasonal variability in the availability of water for the SJCP. The exceedance probability for monthly discharge (the probability that monthly discharge will exceed a particular volume) was determined from nonparametric statistics for monthly discharge for the period of record for each station. A high percentile indicates that the minimum monthly bypass requirement will be exceeded more often and, therefore, that water will be available for diversion. For March through July, the months in which the majority of water has been diverted, the discharge at Rio Blanco - Combined exceeded the minimum monthly bypass requirement at least 95 percent of the years (table 9). Monthly streamflow on Little Navajo - Combined exceeded the minimum monthly bypass requirement in May and June 79 percent and 40 percent of the years, respectively (table 9). There was no minimum monthly bypass requirement for Little Navajo River - Combined for March and April, and the streamflow has never exceeded the minimum monthly bypass requirement in July (table 9). The streamflow at Navajo River - Combined exceeded the minimum monthly bypass requirement in March 87 percent of the years, more than 95 percent of the years for April through June, and 89 percent of the years in July (table 9). These results indicate that diversion of water for the SJCP has been possible for most months of most years.

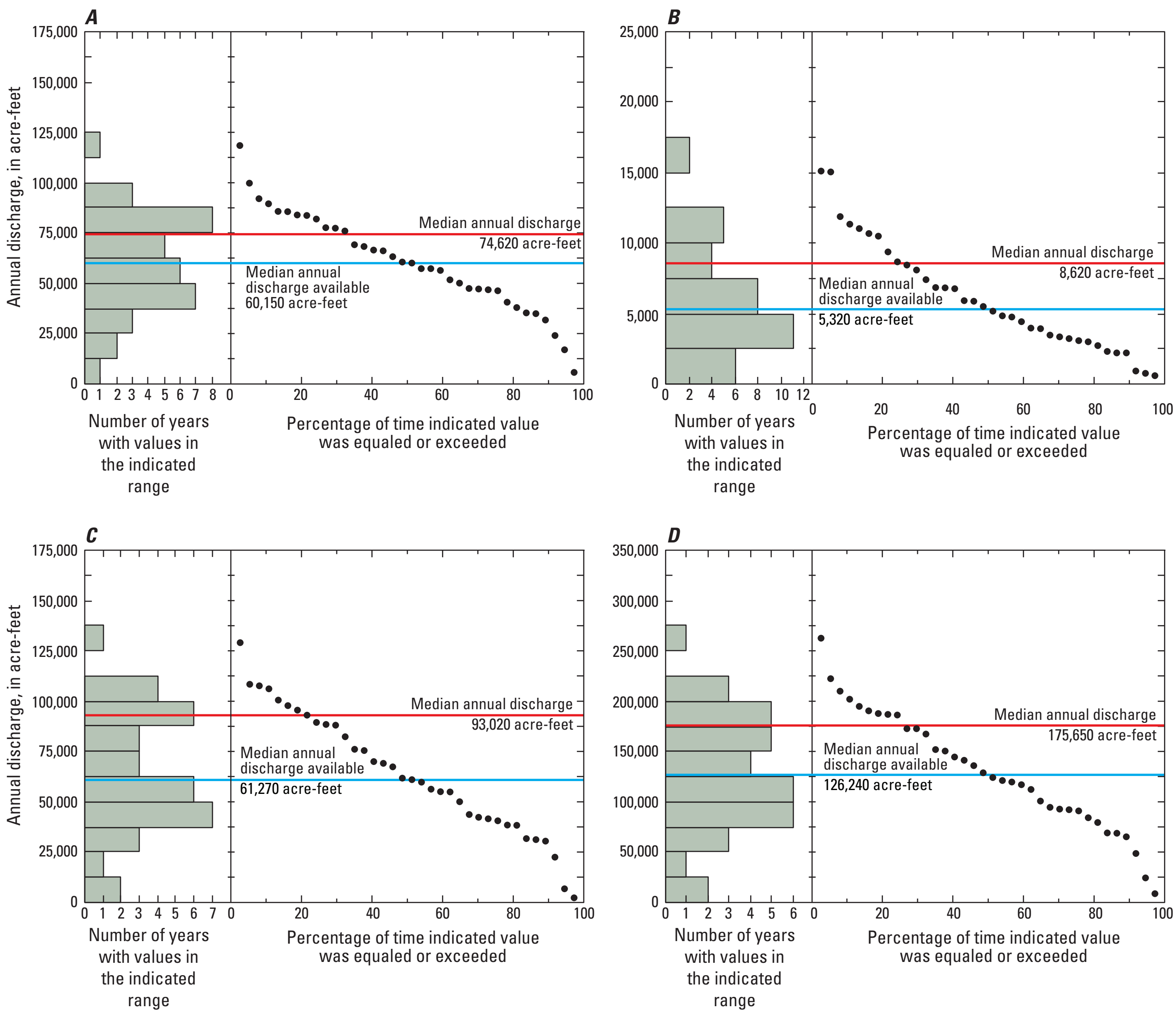


Figure 28. Distribution of annual discharge, median annual discharge, and annual flow-duration curves for the annual discharge above the minimum monthly bypass requirement of the San Juan–Chama Project and the median annual discharge for Rio Blanco - Combined, Little Navajo River - Combined, Navajo River - Combined, and the sum of streamflow for Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined above the minimum monthly bypass requirement, in the southern Colorado portion of the study area, 1975–2010. *A*, Rio Blanco - Combined. *B*, Little Navajo River - Combined. *C*, Navajo River - Combined. *D*, Sum of streamflow for Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined above the minimum monthly bypass requirement.

Table 8. Percentiles of annual discharge above the minimum monthly bypass requirement of the San Juan– Chama Project for Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined and the sum of streamflow for Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined, in the southern Colorado portion of the study area, 1975–2010.

[In acre-feet; IQR, interquartile range]

	Rio Blanco - Combined	Little Navajo River - Combined	Navajo River - Combined	Sum of Rio Blanco - Combined, Navajo River - Combined, and Little Navajo River - Combined
10th percentile	29,290	1,810	27,870	60,030
25th percentile	46,290	3,110	40,690	91,150
50th percentile	60,150	5,320	61,270	126,240
75th percentile	80,690	8,600	89,020	182,580
90th percentile	90,160	11,490	106,430	204,190
IQR (75–25)	34,400	5,490	48,330	91,430

Table 9. Median monthly discharge above the minimum monthly bypass requirement of the San Juan–Chama Project, the percentile of monthly discharge that exceeded the minimum monthly bypass requirement, and the discharge value at which the minimum monthly bypass requirement was exceeded for the calculated streamflow for Rio Blanco - Combined, Little Navajo River - Combined, Navajo River - Combined, in the southern Colorado portion of the study area, 1975–2010.

[In acre-feet]

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Rio Blanco - Combined	Minimum monthly bypass requirement	900	800	1,200	1,200	2,400	1,200	1,200	1,200	1,200	1,200	1,200	900
	Median monthly discharge	1,030	1,090	2,380	8,950	22,900	15,560	4,800	3,850	2,520	1,770	1,430	1,180
	Percentile of monthly discharge that exceeded the minimum monthly bypass requirement	70	78	95	99	99	99	97	97	89	91	78	85
	Discharge value at minimum exceedance percentile	910	808	1,220	4,210	4,030	1,720	1,230	1,210	1,300	1,220	1,200	905
Little Navajo River - Combined	Minimum monthly bypass requirement					1,600	1,600	1,600	1,600	1,600			
	Median monthly discharge	119	117	360	1,740	3,270	1,070	276	242	174	141	134	128
	Percentile of monthly discharge that exceeded the minimum monthly bypass requirement					79	40	0	0	0			
	Discharge value at minimum exceedance percentile					1,630	1,630	1,490	612	1,060			

Table 9. Median monthly discharge above the minimum monthly bypass requirement of the San Juan–Chama Project, the percentile of monthly discharge that exceeded the minimum monthly bypass requirement, and the discharge value at which the minimum monthly bypass requirement was exceeded for the calculated streamflow for Rio Blanco - Combined, Little Navajo River - Combined, Navajo River - Combined, in the southern Colorado portion of the study area, 1975–2010.—Continued

[In acre-feet]

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Navajo River - Combined	Minimum monthly bypass requirement	1,800	1,900	2,200	2,200	5,300	3,300	3,300	3,300	3,300	2,200	2,200	2,200
	Median monthly discharge	2,070	2,000	3,520	11,320	24,610	22,560	6,980	4,520	3,420	2,780	2,380	2,260
	Percentile of monthly discharge that exceeded the minimum monthly bypass requirement	81	63	87	99	98	97	89	71	56	86	69	52
	Discharge value at minimum exceedance percentile	1,800	1,940	2,200	3,970	5,980	3,880	3,580	3,330	3,310	2,210	2,210	2,210

Summary

The Albuquerque–Bernalillo County Water Utility Authority supplements the municipal water supply for the Albuquerque metropolitan area, in central New Mexico, with water diverted from the Rio Grande. Water diverted from the Rio Grande for municipal use is derived from the San Juan–Chama Project in southern Colorado and northern New Mexico, which delivers water from streams in the southern San Juan Mountains in the Colorado River Basin in southern Colorado to the Rio Chama watershed and the Rio Grande Basin in northern New Mexico. The U.S. Geological Survey, in cooperation with Albuquerque–Bernalillo County Water Utility Authority, has compiled historical streamflow and water-quality data and collected new water-quality data to characterize the water quality and streamflow conditions and annual flow variability, as characterized by annual flow-duration curves, of streams of the San Juan–Chama Project. The study area is located in northern New Mexico and southern Colorado and includes the Rio Blanco, Little Navajo River, and Navajo River, tributaries of the San Juan River in the Colorado River Basin located in the southern San Juan Mountains, and Willow Creek and Horse Lake Creek, tributaries of the Rio Chama in the Rio Grande Basin. Nonparametric statistical methods were applied to calculate annual and monthly summary statistics for streamflow conditions at selected sites, trends in streamflow conditions were evaluated with the Mann–Kendall trend test, and annual variation in streamflow conditions was evaluated with annual flow-duration curves.

The quality of water in the streams in the study area generally varied on the basis of the underlying geology and the volume and source of the streamflow. Water from the Rio Blanco and Little Navajo River watersheds, primarily underlain by volcanic deposits, volcaniclastic sediments and landslide deposits derived from these materials, was compositionally similar and had low specific-conductance values relative to the other streams in the study area. Water from the Navajo River, Horse Lake Creek, and Willow Creek watersheds, which are underlain mostly by Cretaceous-aged marine shale, was compositionally similar and had large concentrations of sulfate relative to the other streams in the study area, though the water from Navajo River had lower specific-conductance values than did the water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek. Additionally, the high specific-conductance of water from Horse Lake Creek above Heron Reservoir and Willow Creek above Azotea Creek likely were a function of the lower precipitation rates over these watersheds and the resulting lower amounts of snowmelt runoff relative to the precipitation rate and amount of snowmelt runoff from the Navajo River watershed. Major- and trace-element concentrations in the streams were lower than U.S. Environmental Protection Agency primary and secondary drinking water standards and New Mexico Environment Department surface-water standards for the streams.

Generally, surface-water quality varied with streamflow conditions throughout the year. Base-flow conditions for mountain streams are generally observed from September through February, and high-flow conditions for mountain streams are generally observed from March to August. For sites on the Rio Blanco, Little Navajo River, Navajo River, and Willow Creek months with base-flow conditions were characterized by higher average specific-conductance values than those that occurred during months with high-flow conditions. For sites on the Rio Blanco, Little Navajo River, and Navajo River, the highest discharge and the lowest specific conductance occurred during months with high-flow conditions when streamflow was composed of water that was a mixture of base flow diluted with runoff from snowmelt and precipitation events. For sites on Willow Creek, the specific conductance was highly variable during high-flow conditions when discharge was also highly variable and could be affected by variable snowmelt runoff and summer monsoon rainfall.

Streamflow in the study area varied on the basis of the size of the watershed above the streamflow gage and the elevation and precipitation rates of the watershed. The Rio Blanco and Navajo River, located in large mountain watersheds at high elevations, generally had annual discharge close to the median and that typically varied within a small range. The Little Navajo River, located in a small mountain watershed at a lower elevation than the other mountain watersheds, had highly variable annual discharge that varied over a large range. The Willow Creek and Horse Lake Creek watersheds, located at elevations lower than the mountain watersheds, had much greater variation in annual flow and considerably less streamflow yield per square mile than the annual variation and streamflow yield per square mile for the mountain watersheds.

Seasonal variation in streamflow for Rio Blanco - Combined, Little Navajo River - Combined, and Navajo River - Combined (the daily mean streamflow was calculated as the sum of the measured discharge from the streamflow gage plus the measured diversion discharge and was adjusted for the flow at Azotea) indicated that these watersheds are snowmelt-dominated with the majority of discharge occurring in April through June. The seasonal variation in streamflow for sites on Willow Creek and Horse Lake Creek indicated that these watersheds had multiple sources for streamflow including a large component in March and April that was likely derived from snowmelt runoff and a smaller, steady flow occurring through September with a peak in August that was likely the result of runoff from monsoonal rainfall. Differences in temperature and precipitation, generally related to changes in elevation, were likely the predominant cause of variation in streamflow condition among these sites.

Indicators of the seasonal distribution of streamflow ("streamflow indicators") for Navajo River at Banded Peak Ranch for 1937 to 2009 were tested for monotonic trends by using the Mann–Kendall trend test. Trends were considered statistically significant at a p-value ≤ 0.05. The general lack of significant trends for the time series of the streamflow indicators of the ordinal day of the water year of the center of mass of annual discharge (CT), the ordinal day of the water year of the start of the spring pulse onset of the snowmelt runoff (ST), and the ordinal day of the water year on which the 20th and 50th percentiles of annual discharge occurred (DQF20 and DQF50, respectively) indicated that systemic changes in streamflow conditions had not occurred monotonically over the tested time periods. Significant trends for the time series of the streamflow indicators for streamflow in March and June indicated that the amount of discharge and the percentage of discharge that occurred in March had increased over time and that the amount of discharge and the percentage of discharge that occurred in June had decreased since 1977. Trends for the streamflow indicators compared to annual discharge indicated that as annual discharge increased the CT, ST, DQF20, and DQF50 occurred at a later date in the year. Trends for the amount of discharge in March and June compared to annual discharge indicated that years with increased annual discharge had proportionally less discharge in March than in other months, increased discharge in June, and proportionally more discharge in June than in other months. The difference between the occurrence and the strength of significant trends between the time series of the indicators of the seasonal distribution of streamflow and the indicators compared to annual discharge indicated that the seasonal distribution of streamflow was more strongly controlled by the change in the annual discharge than by changes in streamflow over time.

In general, increased annual discharge resulted in the snowmelt runoff occurring later in the year on streams that are part of the SJCP. Years with more snowmelt runoff, likely from increased rates of precipitation and increased accumulation of snowpack, generally had a longer duration of runoff, and the streamflow indicators occurred at dates later in the year than the years with less snowmelt runoff. Years with increased annual discharge, compared to years with decreased annual discharge, had a smaller percentage of discharge in March, a larger percentage of discharge in June, an interval of discharge derived from snowmelt runoff that occurred later in the year, and a larger discharge in June.

The variation of annual discharge at Navajo River at Banded Peak Ranch was not significantly monotonic (a trend was considered statistically significant at a p-value ≤ 0.05) over the period of record or over the three Pacific Decadal Oscillation (PDO) cycles that occurred during the period of record. There was a relation, however, such that annual discharge was generally lower than the median during a negative PDO interval and higher than the median during a positive PDO interval. Streamflow conditions at Navajo River at Banded Peak Ranch varied nonmonotonically over time and were likely a function of complex climate pattern interactions. Similarly, the monthly distribution of streamflow varied nonmonotonically over time and was likely a function of complex climate pattern interactions that cause variation over time.

The availability of streamflow that can be diverted from the Rio Blanco, Little Navajo River, and Navajo River is a function of the daily discharge and the minimum monthly bypass requirement for each stream. The median annual discharge available above the minimum monthly bypass requirement from Rio Blanco - Combined was 60,150 acre-feet, from Little Navajo River - Combined was 5,320 acre-feet, and from Navajo River - Combined was 61,270 acre-feet. The median of the sum of the streamflow available above the minimum monthly bypass requirement from Rio Blanco - Combined, Little Navajo River - Combined, and Navajo

River - Combined was 126,240 acre-feet. The combined streamflow does not account for legal, logistical, and structural limits of the project. For March through July, the months in which the majority of water has been diverted, the discharge at Rio Blanco - Combined exceeded the minimum monthly bypass requirement at least 95 percent of the years. For March through July, the discharge at Navajo River - Combined exceeded the minimum monthly bypass requirement at least 87 percent of the years. Monthly streamflow from Little Navajo River - Combined exceeded the minimum monthly bypass requirement 79 percent of the years in May, 40 percent of the years in June, and 0 percent of the years in July. These results indicate that diversion of water for the SJCP has been possible for most months of most years.

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