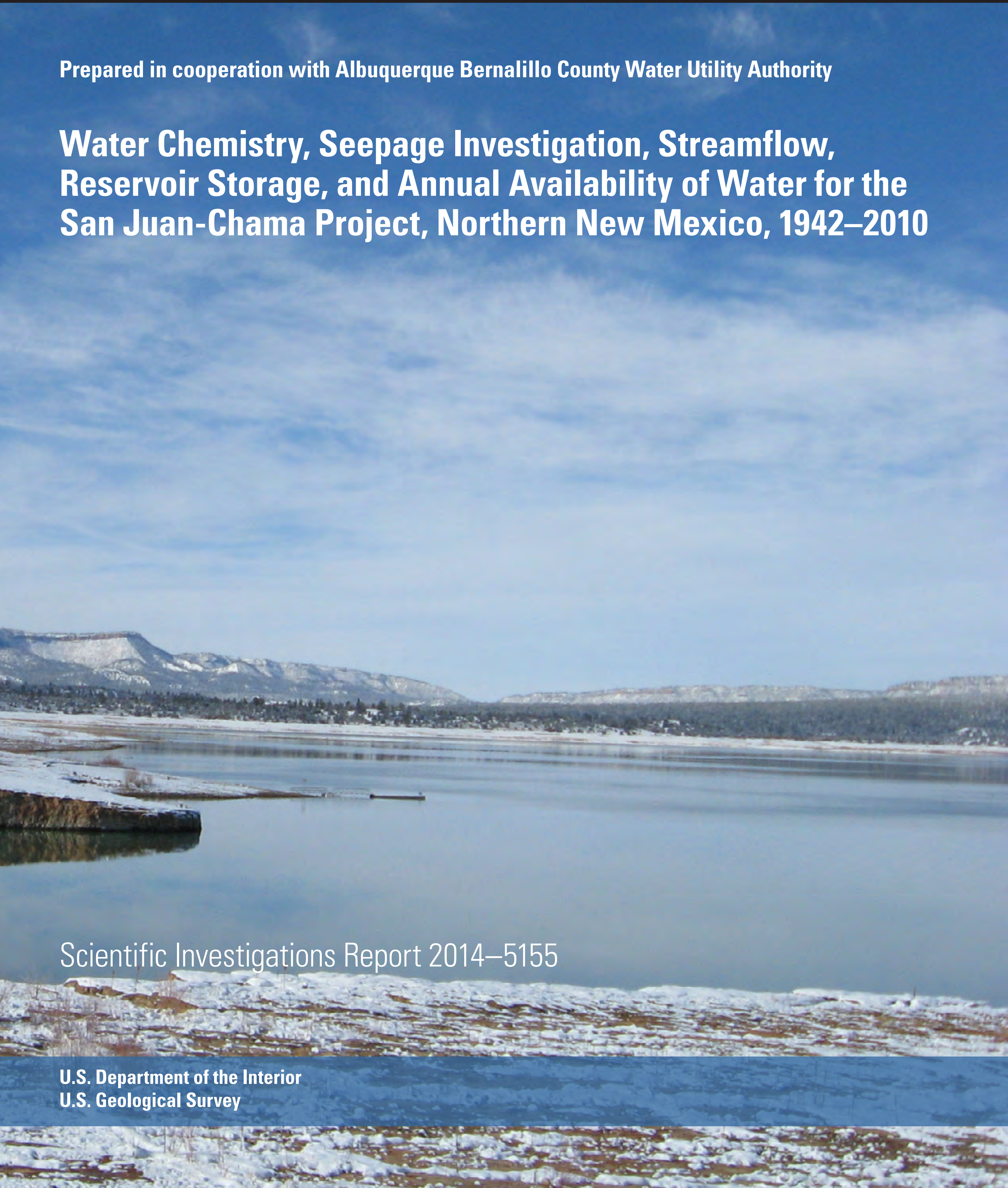
Prepared in cooperation with Albuquerque Bernalillo County Water Utility Authority

Water Chemistry, Seepage Investigation, Streamflow, Reservoir Storage, and Annual Availability of Water for the San Juan-Chama Project, Northern New Mexico, 1942–2010



Scientific Investigations Report 2014–5155

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

Front cover:

Background, Heron Reservoir looking west from the road over the dam, December 13, 2007. Photograph by Sarah E. McKean.

Water Chemistry, Seepage Investigation, Streamflow, Reservoir Storage, and Annual Availability of Water for the San Juan-Chama Project, Northern New Mexico, 1942–2010

By Sarah E. McKean and Scott K. Anderholm

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U.S. Department of the Interior
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SALLY JEWELL, Secretary

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^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)
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×°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 North American Datum of 1983 (NAD 83).

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 either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water Chemistry, Seepage Investigation, Streamflow, Reservoir Storage, and Annual Availability of Water for the San Juan-Chama Project, Northern New Mexico, 1942–2010

By Sarah E. McKean and Scott K. Anderholm

Abstract

The Albuquerque Bernalillo County Water Utility Authority supplements the municipal water supply for the Albuquerque metropolitan area, in central New Mexico, with surface water diverted from the Rio Grande. The U.S. Geological Survey, in cooperation with the Albuquerque Bernalillo County Water Utility Authority, undertook this study in which water-chemistry data and historical streamflow were compiled and new water-chemistry data were collected to characterize the water chemistry and streamflow of the San Juan-Chama Project (SJCP). Characterization of streamflow included analysis of the variability of annual streamflow and comparison of the theoretical amount of water that could have been diverted into the SJCP to the actual amount of water that was diverted for the SJCP. Additionally, a seepage investigation was conducted along the channel between Azotea Tunnel Outlet and the streamflow-gaging station at Willow Creek above Heron Reservoir to estimate the magnitude of the gain or loss in streamflow resulting from groundwater interaction over the approximately 10-mile reach.

Generally, surface-water chemistry varied with streamflow throughout the year. Streamflow ranged from high flow to low flow on the basis of the quantity of water diverted from the Rio Blanco, Little Navajo River, and Navajo River for the SJCP. Vertical profiles of the water temperature over the depth of the water column at Heron Reservoir indicated that the reservoir is seasonally stratified. The results from the seepage investigations indicated a small amount of loss of streamflow along the channel.

Annual variability in streamflow for the SJCP was an indication of the variation in the climate parameters that interact to contribute to streamflow in the Rio Blanco, Little Navajo River, Navajo River, and Willow Creek watersheds. For most years, streamflow at Azotea Tunnel Outlet started in March and continued for approximately 3 months until the middle of July. The majority of annual streamflow at Azotea Tunnel Outlet occurred from May through June, with a median duration of slightly longer than a month. Years with higher maximum daily streamflow generally are associated with higher annual streamflow than years with lower maximum daily streamflow.

The amount of water that can be diverted for the SJCP is controlled by the availability of streamflow and is limited by several factors including legal limits for diversion, limits from the SJCP infrastructure including the size of the diversion dams and tunnels, the capacity of Heron Reservoir, and operational constraints that limit when water can be diverted. The average annual streamflow at Azotea Tunnel Outlet was 94,710 acre-feet, and the annual streamflow at Azotea Tunnel Outlet was approximately 75 percent of the annual streamflow available for the SJCP. The average annual percentage of available streamflow not diverted for the SJCP was 14 percent because of structural limitations of the capacity of infrastructure, 1 percent because of limitations of the reservoir storage capacity, and 29 percent because of the limitations from operations. For most years, the annual available streamflow not diverted for unknown reasons exceeded the sum of the water not diverted because of structural, capacity, and operational limitations.

Introduction

The Albuquerque Bernalillo County Water Utility Authority (ABCWUA) supplements the municipal water supply for the Albuquerque metropolitan area, in central New Mexico, with surface water diverted from the Rio Grande. ABCWUA's allotment of surface water diverted from the Rio Grande is derived from the San Juan-Chama Project (SJCP), which delivers water from streams in the southern San Juan Mountains in the Colorado River Basin in southern Colorado to the Rio Chama in the Rio Grande Basin in northern New Mexico (fig. 1). 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

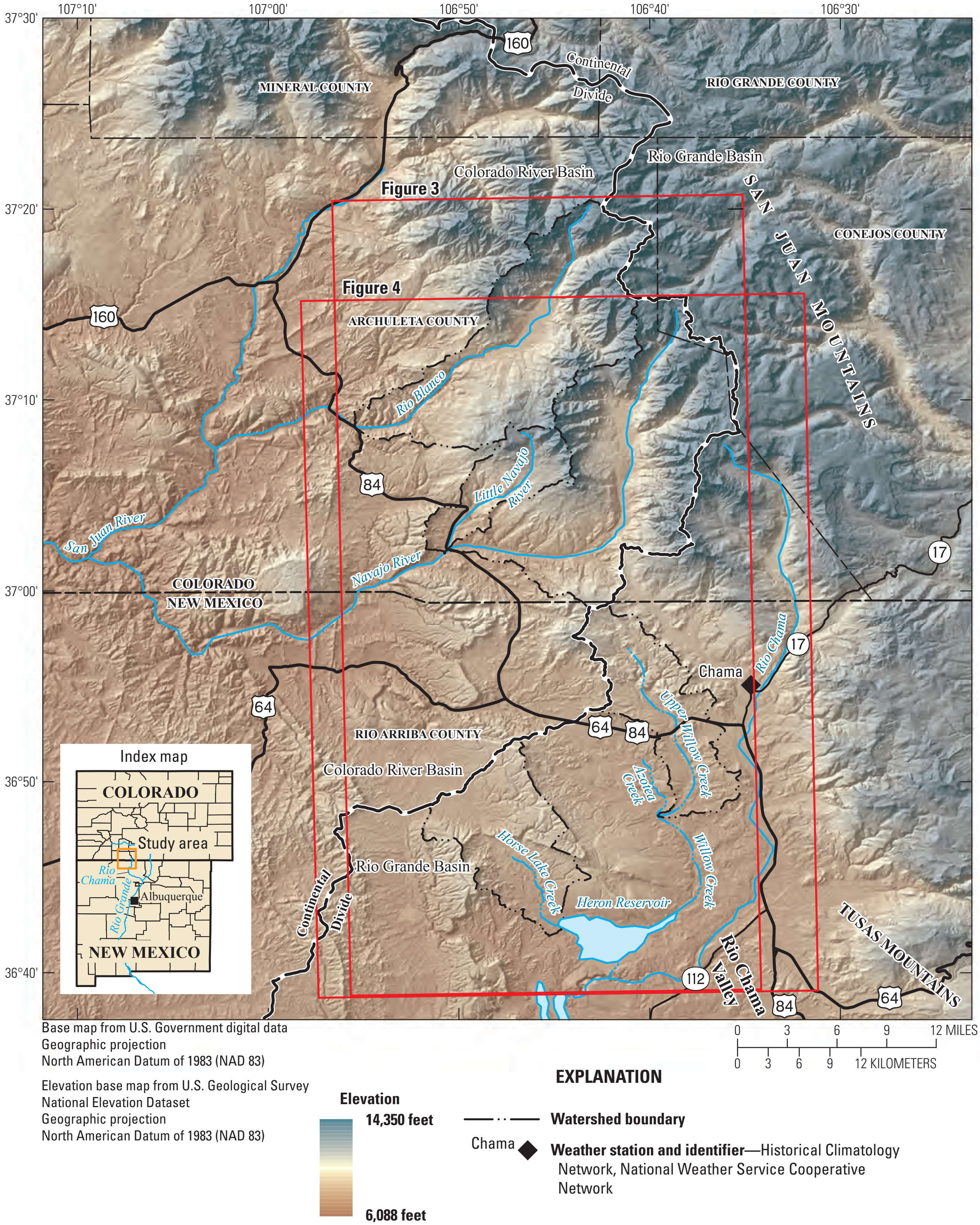


Figure 1. Location of the study area, hydrographic areas in the study area, selected geographic features, and climate stations, southern Colorado and northern New Mexico.

New Mexico. The water from Heron Reservoir is routed to Albuquerque through the Rio Chama, in northern New Mexico, and the Rio Grande. The distribution of surface water for municipal supply has increased interest in the water chemistry, including the concentrations of salinity, trace elements, and nutrients in water imported from the San Juan River watershed and the timing and availability of water for diversion.

Review of previous investigations has indicated that limited information exists about the chemistry of SJCP water flowing into and stored in Heron Reservoir. Additionally, little is known about groundwater/surface-water interactions along the approximately 11-mile (mi)-long channel used to convey water from Azotea Tunnel Outlet to Heron Reservoir (fig. 2). In an effort to provide more information about water chemistry and quantity, the U.S. Geological Survey (USGS), in cooperation with the ABCWUA, undertook this study in which water-chemistry data and historical streamflow were compiled and new water-chemistry data were collected to characterize the water chemistry and streamflow of the SJCP. Characterization of streamflow included analysis of the variability of annual streamflow and comparison of the theoretical amount of water that could have been diverted into the SJCP to the actual amount of water that was diverted for the SJCP. Additionally, a seepage investigation was conducted along the channel between Azotea Tunnel Outlet and the streamflow-gaging station (station) at Willow Creek above Heron Reservoir to estimate the magnitude of the gain or loss in streamflow resulting from groundwater interaction over the approximately 10-mi reach (fig. 2).

The SJCP water, approximately 96,200 acre-feet per year (acre-ft/yr), is divided among various entities that have contracts for the water, including irrigation districts and municipal, domestic, and industrial water users (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 mi across the Continental Divide and discharges it into Willow Creek above Heron Reservoir (figs. 1 and 2). Heron Reservoir and Heron Dam, constructed on Willow Creek just upstream from the confluence with the Rio Chama, provide storage of water diverted from the San Juan River watershed and allow for controlled releases to SJCP contractors and for downstream use including fish and wildlife and recreational purposes (Bureau of Reclamation, 2011a).

Purpose and Scope

This report describes the results of a study to characterize the water chemistry and streamflow including annual streamflow variability and availability of water from the SJCP including the channel between Azotea Tunnel Outlet and Heron Reservoir, Heron Reservoir, and the outflow from Heron Reservoir. This report also describes the results of seepage investigations conducted in August 2009 and June 2010 along the channel between Azotea Tunnel Outlet and the station at Willow Creek above Heron Reservoir. The study area included the Willow Creek watershed in northern New Mexico and the SJCP infrastructure from Azotea Tunnel Outlet to the station at Willow Creek below Heron Reservoir. Existing surface-water chemistry and streamflow data from 1943 to 2010 were compiled, and water-chemistry samples were collected in spring, summer, and fall of water years 2009 and 2010 (a water year is the 12-month period from October 1 through September 30 designated by the calendar year in which it ends). Vertical profiles of selected water-chemistry parameters were collected over the depth of the water column in Heron Reservoir coincident with sampling.

Description of Study Area

The study area is located in the Rio Chama Valley in northern New Mexico and southern Colorado (fig. 1). The southern San Juan Mountains are a southern subrange of the Rocky Mountains. In the study area, they 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; watersheds east of the divide drain to the Rio Grande, and watersheds west of the divide drain to the Colorado River. In the study area, Willow Creek, Azotea Creek, and Horse Lake Creek are located in the Rio Chama Valley east of the Continental Divide and are tributaries of the Rio Chama (fig. 1). The Rio Chama Valley is a shallow physiographic basin that is bounded on the west by anticlines that form the eastern edge of the San Juan Basin and the Tusas Mountains to the east (Muehlberger, 1967).

Land-surface elevations in the Rio Chama Valley in the Willow Creek watershed of Heron Reservoir range from approximately 6,088 to 9,900 feet (ft). The National Weather Service Cooperative Observer Program station 291664 located at Chama, N. Mex. (table 2 and fig. 1), at an elevation of 7,850 ft, indicated that average annual precipitation was 21.7 inches (in.) and average annual temperature was 42.5 degrees Fahrenheit (°F) during 1905–2009 (U.S. Historical Climatology Network, 2011). The annual average temperature at this station ranged from 39.5 to 47.3 °F, and the annual precipitation ranged from 11.3 to 32.34 in. for 1905–2009 (figs. 3*A* and 3*B*). Average monthly temperatures were greater than 32 °F in the months of April through November, and the average monthly temperatures were less than 32 °F in the months of December through March (fig. 3*C*). Slightly more than half (56 percent) of the monthly precipitation occurred from October through April, and 44 percent of monthly precipitation occurred from May through September (fig. 3*D*).

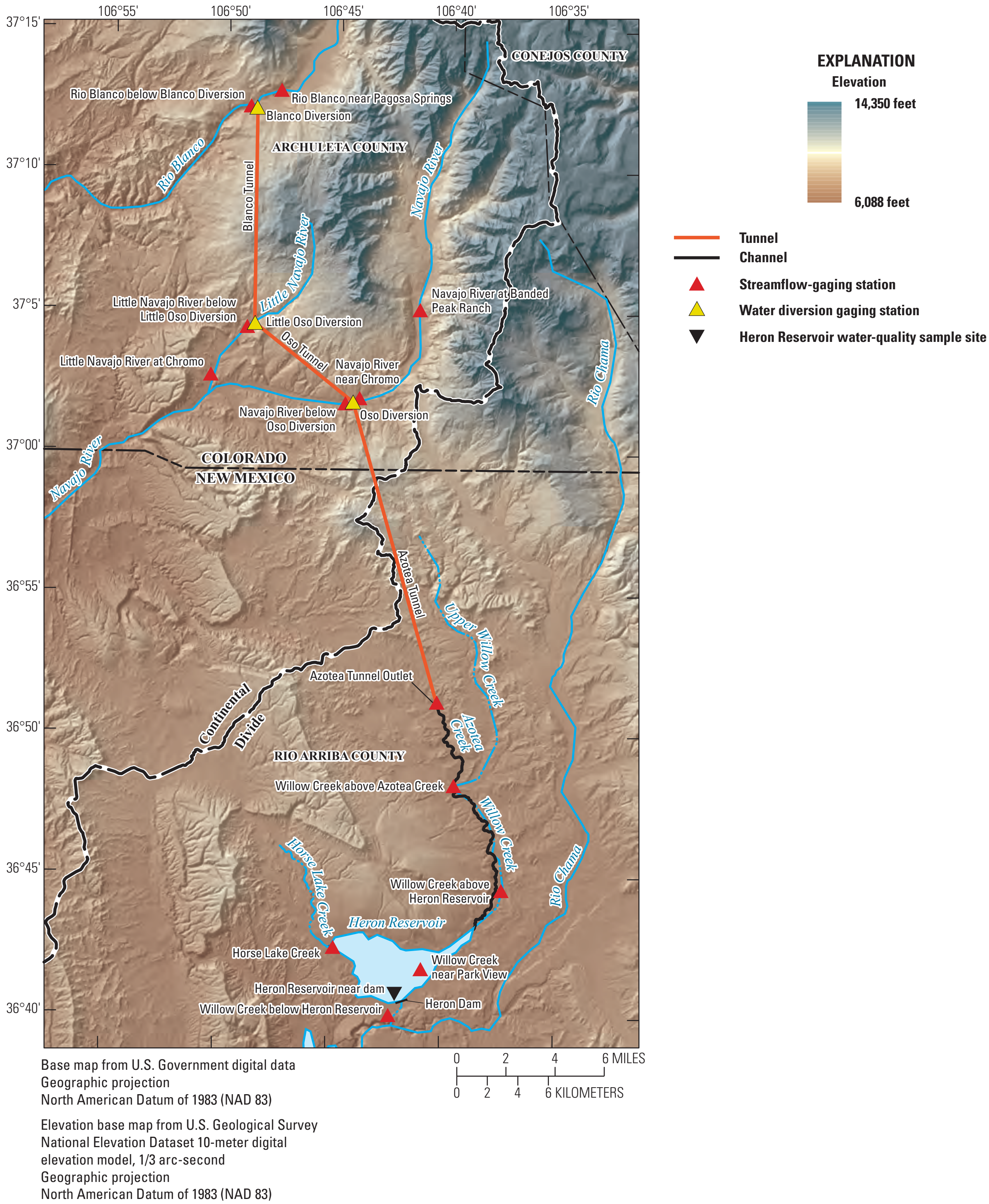


Figure 2. Schematic of the San Juan-Chama Project and location of stations in the study area, southern Colorado and northern New Mexico.

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

San Juan-Chama Project water contractors	Annual 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 (now the Albuquerque Bernalillo County Water Utility Authority)	48,200
Jicarilla Apache Nation	6,500
City and county of Santa Fe	5,605
Los Alamos County	1,200
City of Española	1,000
City of Belen	500
Village of Los Lunas	400
Village of Taos Ski Valley	400
Town of Bernalillo	400
Town of Red River	60
Twining Water and Sanitation District	15
Total	86,210
Cochiti Lake for fish and wildlife, pool reserve of 1,200 surface acres	5,000
Allocated but uncontracted	4,990
Total	96,200

The surficial geology near Heron Reservoir includes the Jurassic Morrison Formation, the Cretaceous Dakota Sandstone and Burro Canyon Formation, and the Cretaceous Mancos Shale (fig. 4). The Brushy Basin Member of the Morrison Formation is exposed in the gorge below Heron Dam (Owen, 2005) and at stream level downstream from the confluence of Willow Creek with Rio Chama (Lucas and others, 2005). The Morrison Formation is overlain by the Lower Cretaceous Burro Canyon Formation and the Upper Cretaceous Dakota Sandstone (Varney, 2005). Heron Dam is set in the Paguate Tongue of the Dakota Sandstone, which also forms the surficial exposures of the nearby southern shoreline (Owen, 2005). The Dakota Sandstone is composed of shallow and deepwater marine deposits including interbedded sandstone and carbonaceous shale and siltstone (Varney, 2005; Kelley, 2011). The Graneros Member of the Mancos Shale outcrops along most of the shore of Heron Reservoir, except along the southern and northeastern shoreline where the Paguate Sandstone Member of the Dakota Sandstone outcrops (Owen, 2005). The Mancos Shale is generally composed of sea-floor deposits of limy mud (Kelley, 2011).

The surficial geology along Willow Creek and the channel north of Heron Reservoir is mostly composed of Mancos Shale with outcroppings of Dakota Sandstone (fig. 4; Muehlberger, 1967; Green and Jones, 1997). Large outcrops of Dakota Sandstone and smaller outcrops of Dakota Sandstone overlain by the Graneros Shale Member of the Mancos Shale and the Greenhorn Limestone Member of the Mancos Shale occur along Willow Creek north of the confluence with the channel (Muehlberger and others, 1963). In addition, Quaternary alluvium and terrace deposits occur along upper Willow Creek and the channel (Muehlberger and others, 1963). Generally, Late Cretaceous-age to early Quaternary-age rocks have been eroded from this area (Kelley, 2011).

San Juan-Chama Project

The U.S. Congress initially authorized the SJCP in 1962 under Public Law (P.L.) 87-483, an act that authorized 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 a portion of the New Mexico allocation of water from the Colorado River Basin under the Upper Colorado River Compact to the Rio Grande Basin. Water diverted for the SJCP is stored in Heron Reservoir until the water is delivered on the basis of annual water contracts to the SJCP contractors downstream from Heron Reservoir (table 1). Generally, SJCP contractors cannot store water in Heron Reservoir from one year to the next and are obligated to schedule delivery of their full annual allotment of SJCP water by the end of the calendar year. Water from the Rio Grande Basin, which is any water from a source in the Rio Grande Basin, cannot be stored in Heron Reservoir; therefore, any Rio Grande water that flows into Heron Reservoir from the upstream watersheds must be accounted for and released. In P.L. 87-483, Congress stipulated that diversions from the San Juan River watershed be limited to a maximum of 1,350,000 acre-feet (acre-ft) of water in any 10 consecutive years and 270,000 acre-ft in a single year and that the reservoir is not allowed to spill. Additionally, diversions from the Rio Blanco and Navajo River are limited, such that streamflow in the rivers cannot be depleted below minimum monthly bypass requirements (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 in the 1964 Bureau of Reclamation (Reclamation) definite plan report (Bureau of Reclamation, 1964) and set by memorandum in 1977 (Bureau of Reclamation, 1986).

The SJCP infrastructure consists of three diversion dams (Blanco Diversion, Little Oso Diversion, and Oso Diversion), a tunnel and conduit system, and Heron Dam (schematic shown on fig. 2). The diversion dams were constructed on the Rio Blanco, Navajo River, and Little Navajo River in the southern San Juan Mountains (fig. 1). The tunnel system is gravity driven and includes siphons under the stream segments. The conduits connect the diversions to the tunnel system. The tunnel

Table 2. Descriptions of stations in the study area for the San Juan-Chama Project, northern New Mexico.

[USGS, U.S. Geological Survey; CLIMATE, climate station; WC, water chemistry; SF, streamflow; STORAGE, volume of water in storage in reservoir; --, data not available; NWS Coop, National Weather Service Cooperative Observer Program; Reclamation, U.S. Bureau of Reclamation; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; NAD 27, North American Datum of 1927; CDWR, Colorado Division of Water Resources]

Site type	USGS site identifier	Site name	Site name for report
CLIMATE		Chama (Historical Climatology Network, National Weather Service Cooperative Network site 291664)	Chama
WC/SF	09343300	Rio Blanco below Blanco Diversion Dam near Pagosa Springs, Colo.	Rio Blanco below Blanco Diversion
WC/SF	09344400	Navajo River below Oso Diversion Dam near Chromo, Colo.	Navajo River below Oso Diversion
WC/SF	08284160	Azotea Tunnel Outlet near Chama, N. Mex.	Azotea Tunnel Outlet
WC	08284150	Willow Creek above Azotea Creek near Park View, N. Mex.	Willow Creek above Azotea Creek
WC/SF	08284200	Willow Creek above Heron Reservoir, near Los Ojos, N. Mex.	Willow Creek above Heron Reservoir
SF	08284300	Horse Lake Creek above Heron Reservoir, near Los Ojos, N. Mex.	Horse Lake Creek
WC/SF	08284500	Willow Creek near Park View, N. Mex.	Willow Creek near Park View
WC	364107106421710	Heron Reservoir near dam	Heron Reservoir
STORAGE	08284510	Heron Reservoir near Los Ojos, N. Mex.	Heron Reservoir storage
WC/SF	08284520	Willow Creek below Heron Dam, N. Mex.	Willow Creek below Heron Reservoir

Site name for report	Latitude	Longitude	Datum	Elevation	Datum
Chama	36° 55′ 00″	106° 35′ 00″	--	7,850	--
Rio Blanco below Blanco Diversion	37° 12′ 13″	106° 48′ 44″	NAD 83	7,858	NGVD 29
Navajo River below Oso Diversion	37° 01′ 49″	106° 44′ 14″	NAD 27	7,648	NGVD 29
Azotea Tunnel Outlet	36° 51′ 12″	106° 40′ 18″	NAD 27	7,520	NGVD 29
Willow Creek above Azotea Creek	36° 48′ 15″	106° 39′ 30″	NAD 27	7,404	NGVD 29
Willow Creek above Heron Reservoir	36° 44′ 33″	106° 37′ 34″	NAD 27	7,196	NGVD 29
Horse Lake Creek	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
Heron Reservoir	36° 41′ 07″	106° 42′ 17″	NAD 83	--	--
Heron Reservoir storage	36° 39′ 55.56″	106° 42′ 19.51″	NAD 83	--	--
Willow Creek below Heron Reservoir	36° 39′ 46″	106° 42′ 20″	NAD 83	6,935	NGVD 29

Site name for report	Parameters	Start of period of record	End of period of record	Data collection agency	Data reporting agency	Number of water-chemistry samples
Chama	Precipitation	1935	2010	NWS Coop	NWS Coop	
	Temperature	1935	2010	NWS Coop	NWS Coop	
Rio Blanco below Blanco Diversion	Discharge	1971	2010	CDWR	CDWR	
	Water chemistry	1973	2009	USGS	USGS	74
Navajo River below Oso Diversion	Discharge	1971	1971	CDWR	CDWR	
	Water chemistry	1971	2009	USGS	USGS	40
Azotea Tunnel Outlet	Discharge	1971	2010	Reclamation	USGS	
	Water chemistry	1974	2009	USGS	USGS	21
Willow Creek above Azotea Creek	Water chemistry			USGS	USGS	3
Willow Creek above Heron Reservoir	Discharge	1961	2010	USGS/Reclamation	USGS/Reclamation	
	Water qaulity	1973	2009	USGS	USGS	6
Horse Lake Creek	Discharge	1962	2009	USGS	USGS	
	Water chemistry	2008	2009	USGS	USGS	14
Willow Creek near Park View	Discharge	1942	1971	USGS	USGS	
	Water chemistry	1961	1965	USGS	USGS	76
Heron Reservoir	Water chemistry	2008	2009	USGS	USGS	4
Heron Reservoir storage	Discharge	1971	2010	Reclamation	USGS	
Willow Creek below Heron Reservoir	Discharge	1971	2008	Reclamation	USGS	
	Water chemistry	2007	2009	USGS	USGS	3

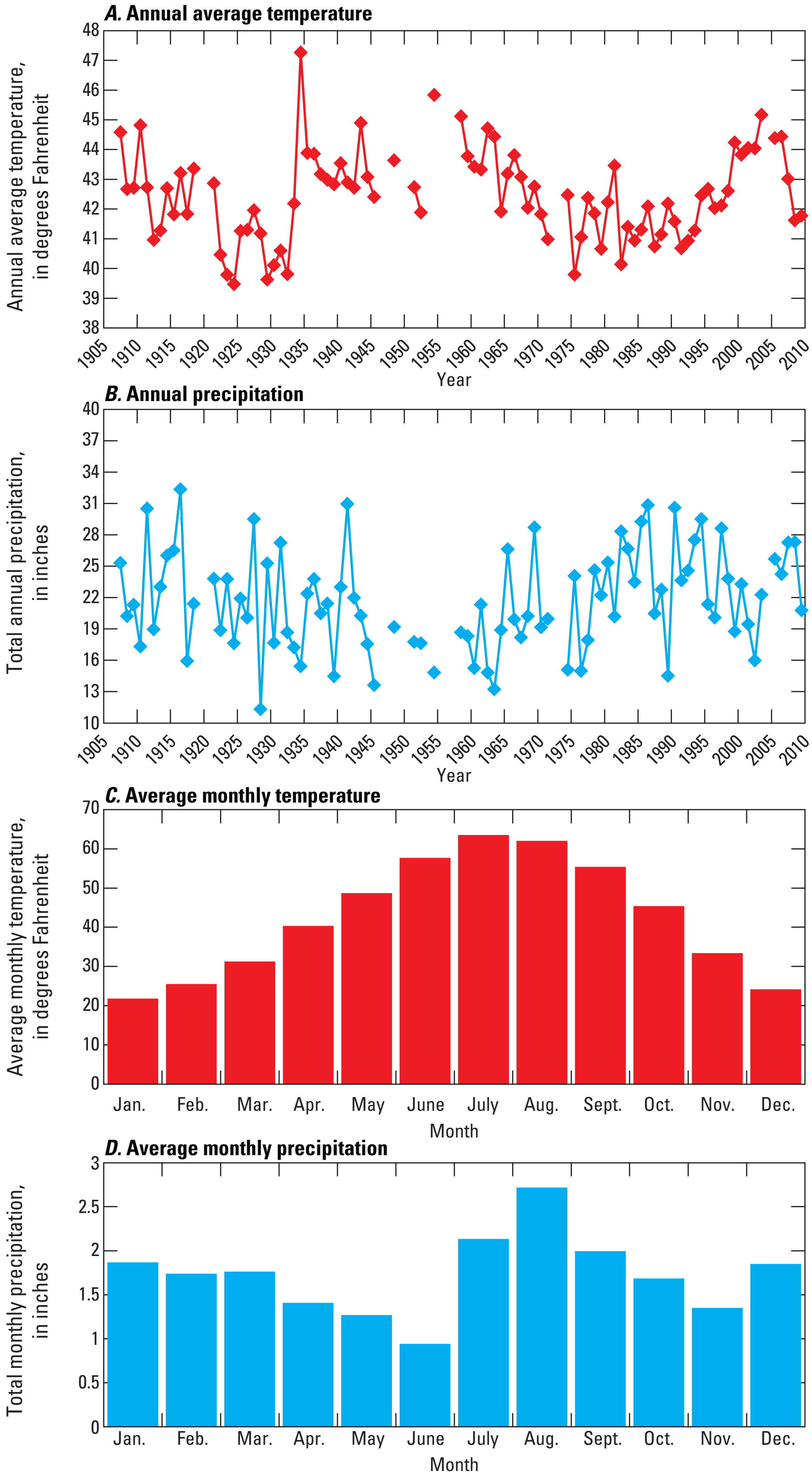
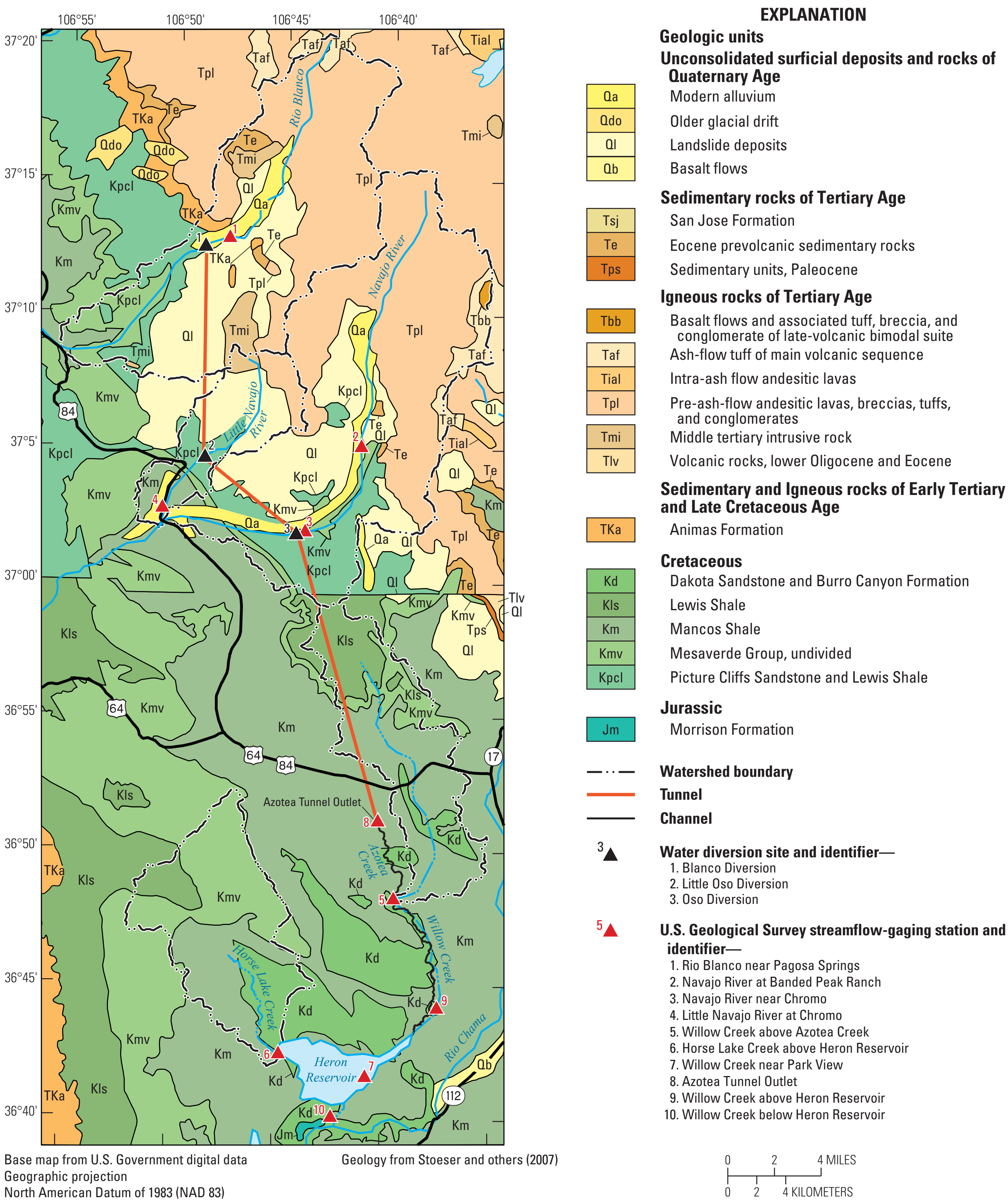


Figure 3. Temperature and precipitation data for climate station Chama (National Weather Service Cooperative Observer Program weather station), in the northern New Mexico part of the study area, 1905–2009. *A*, Annual average temperature. *B*, Annual precipitation. *C*, Average monthly temperature. *D*, Average monthly precipitation.



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

Geology from Stoeser and others (2007)

Figure 4. Surface geology of the study area, location of selected streamflow-gaging stations, and the boundary of selected watersheds, southern Colorado and northern New Mexico.

and conduit system conveys water across the Continental Divide and discharges into Azotea and Willow Creeks (fig. 2). Azotea Creek and sections of Willow Creek between Azotea Tunnel Outlet and Heron Dam were channelized to prevent erosion caused by increased streamflow within the channel from the water diverted for the SJCP (Cannon, 1969). Heron Dam, constructed on Willow Creek just upstream from its confluence with the Rio Chama, and Heron Reservoir provide storage of SJCP water and allow for controlled releases to SJCP contractors.

The capacity of the infrastructure limits the amount of water that can be diverted from the Rio Blanco, Little Navajo River, and Navajo River to Heron Reservoir. Water from the Rio Blanco is diverted at Blanco Diversion into the Blanco Tunnel, which has a capacity of 520 cubic feet per second (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 Azotea Creek in the Rio Grande Basin (Bureau of Reclamation, 2011a). Heron Dam is an earthfill structure that is 269 ft high (Bureau of Reclamation, 2011b). The reported reservoir capacity is 401,320 acre-ft (Bureau of Reclamation, 2011b); however, the storage capacity of Heron Reservoir has changed over time as the result of sediment accumulation. A bathymetry analysis of Heron Reservoir completed in 2010 calculated the total storage capacity of the reservoir as 428,355 acre-ft, with a surface area of 6,148 acres at a surface elevation of 7,190.8 ft (above the National American Vertical Datum of 1988 [NAVD 88]) and a normal storage capacity of 400,031 acre-ft at a surface elevation of 7,186.1 (above NAVD 88) (Ferrari, 2011). Ferrari (2011) also reported a reduction of storage capacity from sediment accumulation of 2,151 acre-ft from October 21, 1970, to July 2010. The dam outlet works, constructed on Willow Creek above the confluence with the Rio Chama, have a capacity of 4,160 ft^3/s (Bureau of Reclamation, 2011b).

Previous Studies

A review of previous investigations of water chemistry in the Rio Chama watershed indicated that limited information exists about the chemistry of SJCP water that flows into Heron Reservoir and the chemistry of water stored in Heron Reservoir. Additionally, little is known about groundwater/surface-water interactions along the channel used to convey water from the San Juan River watershed to Heron Reservoir. Although the New Mexico Environment Department (NMED) conducts studies of water quality throughout New Mexico, NMED does not include the Willow Creek watershed above Heron Reservoir in its cyclic total maximum daily load sampling (New Mexico Environment Department, 2003). Langman and Anderholm (2004) studied the effects of reservoir installation and operation and introduction of SJCP water into the Rio Grande Basin on the streamflow and water chemistry 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.

Reclamation prepared an update of the calculated yield of the SJCP in 1986. An operations model for the SJCP was developed by utilizing streamflow data, project infrastructure limitations, and estimates of scheduled water deliveries to determine the amount of water that could be diverted from the San Juan watershed and the amount of water available to be released from Heron Reservoir for the period from 1935 to 1984. The average amount of water diverted from the streams of the SJCP to Heron Reservoir was calculated to be 108,900 acre-ft/yr, and the firm yield (the maximum attainable yield without allowing shortages in supply) from Heron Reservoir was calculated to be 94,200 acre-ft/yr (Bureau of Reclamation, written commun., 1986). The report specified that in 1986 there were water contracts and commitments of 95,475 acre-ft/yr for the SJCP.

The firm yield estimate for Heron Reservoir was updated by Reclamation in 1999 to cover the interval from 1935 to 1997, including an additional 13 years of data from 1984 to 1997 (Bureau of Reclamation, 1999). The firm yield was defined as "the optimal amount of water that could be diverted from the three tributary streams… that would maintain regulated flows in the tributaries and meet the demands of the entities that had contracts for SJCP [sic] water without drying up the reservoir nor cause diverted water to be spilled from the reservoir″ (Bureau of Reclamation, 1999). The revised firm yield estimate was 96,500 acre-ft/yr; it was noted that this firm yield estimate was limited by flow conditions in 1978 and that the firm yield could not be increased without causing shortages in that year (Bureau of Reclamation, 1999). The average annual inflow to Heron Reservoir over the interval from 1935 to 1997 was 119,650 acre-ft (Bureau of Reclamation, 1999).

Methods of Analysis

Various methods were used to collect data for the study and to analyze the data. Water samples were collected to characterize the water chemistry. Discharge measurements were collected for the seepage investigation. Statistical methods were used for analysis of streamflow.

Water-Chemistry Data Collection

Water-chemistry data collected for this project were from 5 stations in the study area (table 2) and 2 stations in southern Colorado (Falk and others, 2013). Samples were collected from Azotea Tunnel Outlet, Willow Creek above Azotea Creek, Willow Creek above Heron Reservoir, Heron Reservoir, and Willow Creek below Heron Reservoir to characterize the chemistry of the diverted water. Samples were collected three times per year for 2 water years during low flow in October 2007 and November 2008 and during high flow (when SJCP water was diverted from the Rio Blanco, Little Navajo River, and Navajo River and streamflow is primarily composed of snowmelt runoff) in April and June of 2008 and May and June of 2009. Physical properties of the water (dissolved oxygen, pH, specific conductance, and temperature) were measured in the field. Samples were collected either as width-integrated samples if the water at the sampling station was not well mixed across the width of the section or as grab samples if the water at the sampling station was determined to be well mixed by observation of upstream conditions. The water at the sampling station was well mixed at stations that were downstream from flumes or the outlet works from the diversion dams that created turbulent flow. Samples from Heron Reservoir were collected with a Van Dorn water sampler, which is designed to collect a sample from a discrete depth interval. Samples were collected from a single depth interval if the reservoir was determined to be unstratified by observation of vertical profiles of physical parameters including temperature, specific conductance, and dissolved oxygen. If the reservoir was determined to be stratified, samples were collected from two depth intervals - a shallow sample collected above the thermocline and a deep sample collected below the thermocline. Samples collected from all stations were analyzed for major ions, alkalinity, trace elements, dissolved solids, and nutrients at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colo. The sample collected at Willow Creek below Heron Reservoir in August 2009 was also analyzed for a suite of organic compounds.

The methods used for the analysis of major ions, nutrients, and semivolatile compounds are outlined in Fishman (1993) and Patton and Kryskalla (2011). The methods used for the analysis of trace elements are outlined in Fishman and Friedman (1989), Garbarino (1999), and Garbarino and others (2006). The method for analysis of dissolved organic carbon is outlined in Brenton and Arnett (1993). The method for analysis of mercury is outlined in Garbarino and Damrau (2001). The methods used for analysis of volatile organic compounds are outlined in Connor and others (1998). The methods for organochlorine pesticides and gross polychlorinated biphenyls (PCBs) are outlined in Wershaw and others (1987). The methods for waste-indicator compounds are outlined in Zaugg and others (2006). The methods for human-health pharmaceuticals are outlined in Furlong and others (2008). Water-chemistry data obtained for this study were collected, processed, and preserved in accordance with established USGS methods as outlined in the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). The quality-assurance procedures employed in this study included the collection of two field blanks to assess potential contamination during sample collection, processing, transport, or analysis. No notable contamination was observed in the field blanks.

The USGS NWQL reports concentrations as quantitative, estimated, or censored (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 in the sample are censored and reported as less than (remark code "<") the LRL. Results for analyte concentrations that are below the LRL but greater than the LT-MDL are reported as estimated (remark code "E"). Analytes that were analyzed for but not detected were reported as "U," and analytes that were detected but not quantified were reported as "M."

This report also includes historical data available in the USGS National Water Information System database (U.S. Geological Survey, 2014). Historical water-chemistry data were checked for ion balance but were otherwise presumed to be correct. Unless stated otherwise, major-ion concentrations presented in this report refer to dissolved concentrations.

Results from particular water-chemistry samples were selected for evaluation because the samples were sequentially collected following a Lagrangian sampling scheme. Comparison of nutrient concentrations in water samples from Azotea Tunnel Outlet, Willow Creek above Azotea Creek, and Willow Creek above Heron Reservoir focused on the results from samples collected on May 5, 2009, and June 24, 2009. Evaluation of nutrient concentrations in water samples from Heron Reservoir focused on the results from samples collected in 2009. Analysis of nutrient concentrations in water samples from Willow Creek below Heron Reservoir focused on the results from samples collected in 2009 because these samples were closest in time to the samples collected on Heron Reservoir.

Surveys of water-chemistry along vertical profiles in Heron Reservoir were collected with a multimeter sonde instrumented with sensors for pH, specific conductance, dissolved oxygen, and temperature. The depth of the sonde was measured with a cloth tape attached along the length of the instrument cable, and measurements were collected at 5- to 10-ft intervals. Water-chemistry data obtained for this study with the sonde were collected in accordance with USGS methods described in the National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated).

Seepage Investigation

All discharge measurements collected during this study were made by using standard USGS discharge measurement protocols (Rantz, 1982a; Rantz, 1982b; and Nolan and Shields, 2000). Discharge measurements for the seepage investigation were collected with an acoustic Doppler current profile (ADCP) (Mueller and others, 2009) system mounted on a small trimaran or a temporary Parshall flume with a 2-in. throat. Discharge measurements were also collected from an artesian well and from a discontinued streamflow gage at Willow Creek above Azotea Creek by using the existing Parshall flume with a 2-ft throat. All measurement locations were selected to optimize favorable flow conditions including uniform cross-section and nonturbulent flow. Discharge measurements during the seepage investigation were conducted in downstream order, with the amount of time between measurements at the different stations estimated from stream velocity and the distance between the stations so that the same water was measured throughout the reach. Seepage investigations were conducted in June 2010 during high flow and in August 2009 during low flow. High flow was defined as the interval during which SJCP water was diverted from the Rio Blanco, Little Navajo River, and Navajo River and generally occurred from April to August. Low flow was defined as the interval during which SJCP water was not diverted to Azotea Tunnel. Streamflow at Azotea Tunnel Outlet generally decreased from July through October because the amount of water available for diversion for the SJCP declined. There was no streamflow at Azotea Tunnel Outlet from November to February because the gates on the SJCP diversion structures were closed for maintenance and safety reasons (V. Salazar, Manager of the Chama New Mexico Field Division, Bureau of Reclamation, oral commun., 2009). Analysis of streamflow at Azotea Tunnel Outlet for water year 2009 indicated that diversions ended by mid-August. The majority of streamflow at Willow Creek above Heron Reservoir is from Azotea Tunnel Outlet because there is little to no flow from tributaries between these two stations.

The gain or loss in streamflow resulting from interaction with groundwater can be calculated as the residual difference of all other gains and losses of streamflow in the reach (modified from Simonds and Sinclair, 2002) by using the following equation:

$$Qs = Qds - Qus - Qin - Qout \tag{1}$$

where

Qs is the net gain or loss in streamflow resulting from groundwater interaction in cubic feet per second;

Qds is streamflow measured at the downstream end of the reach in cubic feet per second;

Qus is streamflow measured at the upstream end of the reach in cubic feet per second;

Qin is the sum of inflows along in the reach such as inflow from tributaries or bank storage in cubic feet per second; and

Qout is the sum of outflows along the reach such as outflow to diversions and bank storage or evaporative losses from the water surface in cubic feet per second.

Streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir, primarily a function of the operation of the SJCP, is generally not steady. Over the interval of a day, streamflow at Azotea Tunnel Outlet is generally unsteady with a diurnal variation. Seasonally, streamflow at Azotea Tunnel Outlet is unsteady and varies daily such that streamflow is either increasing or decreasing without an interval of nearly constant flow (fig. 5*A*). Additionally, diversion of water for the SJCP generally occurs from early spring to early fall, and there is not an interval of natural base flow at Azotea Tunnel Outlet. Streamflow at Willow Creek above Heron Reservoir is primarily composed of water from Azotea Tunnel Outlet, with an additional small component of intermittent streamflow derived from the Willow Creek watershed; therefore, streamflow at Willow Creek above Heron Reservoir exhibits similar daily and seasonal variability in streamflow as streamflow at Azotea Tunnel Outlet.

Because of variable streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir, discharge measurements for the high-flow seepage investigation were collected over an interval of 8 hours (table 3). Data from the upstream and downstream stations were correlated to account for the water traveltime along the channel and the change in streamflow during the interval of measurement (fig. 5*B*). Adjustment for the water traveltime ensured that the same packet of water was being compared between the stations.

For the high-flow seepage investigation, discharge measurements were made at four stations with appreciable flow on June 24, 2010. Discharge measurements at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir were collected at 30-minute intervals over 7 hours (fig. 5*B*). Two ADCP systems were used to make concurrent measurements at the upstream and downstream stations. The ADCPs were connected to draglines spanning the stream width and were manually maneuvered across the stream. The two ADCP systems also were used to make concurrent measurements at the same stream section so that the measurements could be compared to determine the uncertainty between the two systems. The discharge measurements made with the two instruments were within the standard deviation (Helsel and Hirsch, 2002) of the repeated measurements; therefore, the discharge measurements made with the two instruments were not significantly different. The measured discharge was calculated as the average of multiple sequential discharge measurements (at least 3), and the uncertainty was calculated as 5 percent of the measurement. Because of the age and condition of the flume at the discontinued station at Willow

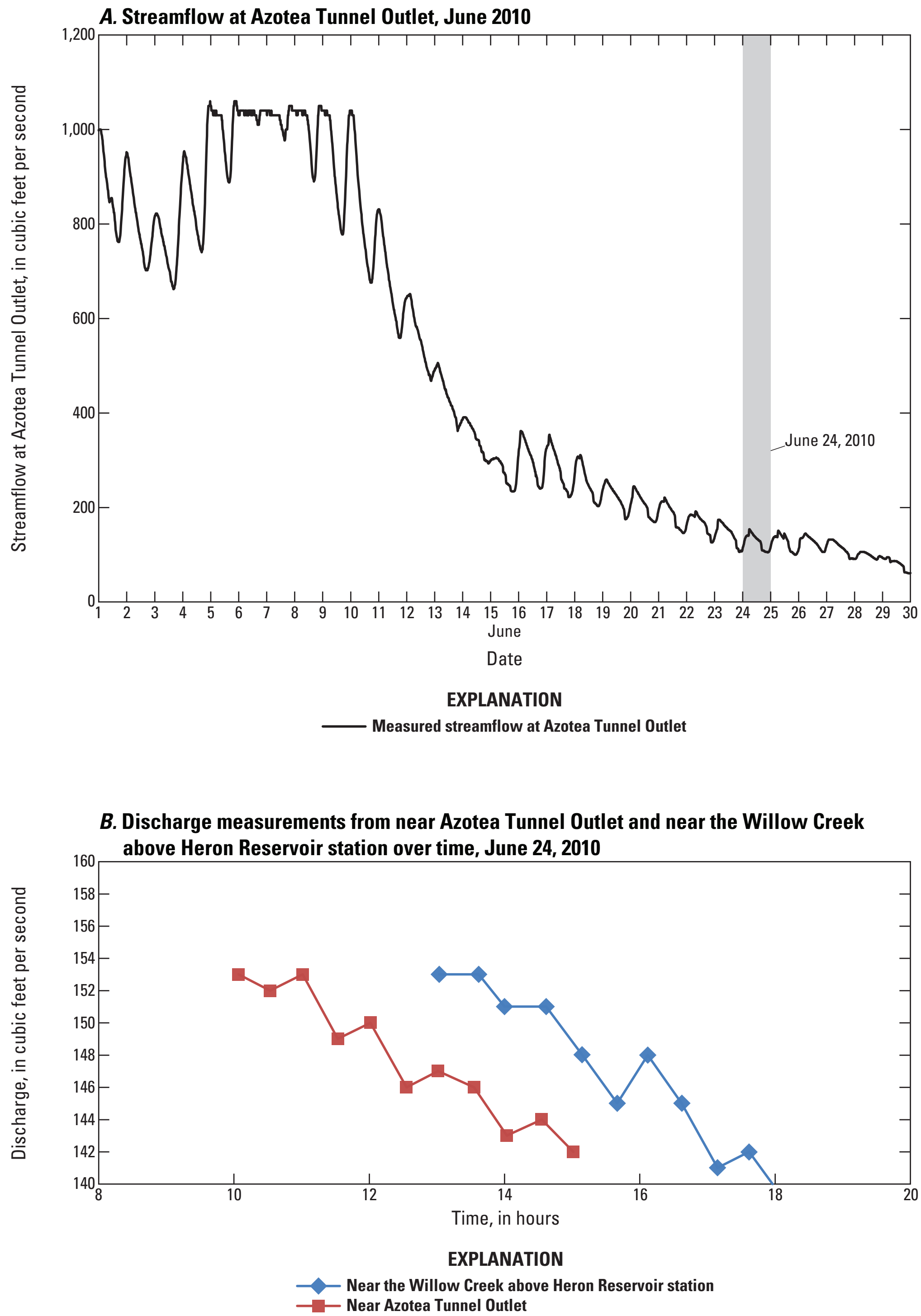


Figure 5. Streamflow measurements from Azotea Tunnel Outlet and the high-flow seepage investigation, northern New Mexico, June 2010. *A*, Streamflow at Azotea Tunnel Outlet, June 2010. *B*, Discharge measurements from near Azotea Tunnel Outlet and near the Willow Creek above Heron Reservoir station over time, June 24, 2010.

Table 3. Measurements from the high-flow seepage investigation at Azotea Tunnel Outlet, Willow Creek above Heron Reservoir, and Willow Creek above Azotea Creek and the calculated streamflow resulting from groundwater interaction and associated uncertainty, northern New Mexico, June 24, 2010.

[Measurement time, time of the discharge measurement; ft^3/s, cubic feet per second; --, no discharge at measurement location]

Pair	Azotea Tunnel Outlet		Willow Creek above Azotea Creek		Willow Creek above Heron Reservoir	
	Measurement time	Discharge (ft^3/s)	Measurement time	Discharge (ft^3/s)	Measurement time	Discharge (ft^3/s)
1	10:04	153	10:18	3.9	13:02	153
2	10:32	152	--	--	13:37	153
3	11:01	153	--	--	14:00	151
4	11:32	149	--	--	14:37	151
5	12:01	150	--	--	15:09	148
6	12:33	146	--	--	15:40	145
7	13:01	147	--	--	16:07	148
8	13:33	146	--	--	16:37	145
9	14:02	143	15:38	3.5	17:09	141
10	14:33	144	--	--	17:37	142
11	15:01	142	16:38	3.5	18:08	139

Creek above Azotea Creek, the accuracy was estimated to be greater than 10 percent, and the estimated uncertainty was plus or minus 0.5 ft^3/s at a measured discharge of 5 ft^3/s or less. Flow from an artesian well that flows into the channel was measured several times over the day and was determined to be less than 0.1 ft^3/s; thus, flow from the artesian well was not included in the calculations for the high-flow seepage investigation because it was 2 orders of magnitude less than the calculated streamflow and associated uncertainty. Streamflow at the discontinued station at Willow Creek above Azotea Creek was measured three times during the day. Evaporative losses were assumed to be minimal over the short distance between the measurement stations and the short interval of time over which measurements were collected. Accounting for evaporative losses would decrease a calculated gain of streamflow to the stream and increase a calculated loss of streamflow from the stream. Change in bank storage during the seepage investigation also was assumed to be minimal along the channel because the change in gage height at the upstream station was less than 1 ft, and the change in gage height at the downstream station was approximately 0.1 ft.

For the low-flow seepage investigation, discharge measurements were made at six stations with measurable flow on August 19, 2009, through August 21, 2009, when streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir was extremely low. Streamflow resulting from groundwater interaction was determined for two reaches: Reach 1 covered the interval from a quarter mile downstream from Azotea Tunnel Outlet (referred to as “LF-Upstream”) to Willow Creek above the confluence with Willow Creek above Azotea Creek (referred to as “LF-Midpoint”), and Reach 2 covered the interval from LF-Midpoint to one-tenth of a mile upstream from Willow Creek above Heron Reservoir station (referred to as “LF-Downstream”). The discharge measurements for the low-flow seepage investigation included measurements collected with a 2-in. modified Parshall flume and measurement of the flow from an artesian well that flows into the channel. The estimated uncertainty for discharge measurements collected at the LF-Upstream and LF-Midpoint stations is 30 percent because of the extremely low streamflow quantity and poor channel conditions for the installation of the flume including a wide channel and sandy sediments. The estimated uncertainty for discharge measurements at the LF-Downstream station was 50 percent because of the extremely low streamflow quantity and poor channel conditions for installation of the flume that resulted in some portion of the streamflow bypassing the flume. The estimated uncertainty for the artesian well was 50 percent because the rate of flow was estimated by measuring the time required to fill a bucket, a method that lacks precision. It was assumed that evaporative losses were minimal over the short distance between the measurement stations; accounting for evaporative losses would decrease a computed gain to the stream system and increase a computed loss from the stream. It was also assumed that the change in bank storage was minimal along the channel because streamflow was steady during the investigation. Several measurements were made at the LF-Midpoint station over a 24-hour period to determine the variation in streamflow; measured discharge ranged from 0.03 to 0.02 ft^3/s (table 4).

Table 4. Low-flow seepage investigation results including the discharge measurements and associated uncertainty for Reach 1 from 1/4 mile downstream from the outlet of Azotea Tunnel to Willow Creek above the confluence with Willow Creek above Azotea Creek and Reach 2 from Willow Creek above the confluence with Willow Creek above Azotea Creek to 1/10 mile upstream from Willow Creek above Heron Reservoir station and the calculated streamflow resulting from groundwater interaction and associated uncertainty, northern New Mexico, August 19–21, 2009.

[ft^3/s, cubic feet per second; --, no discharge at measurement location]

Reach 1								
Willow Creek above the confluence with Willow Creek above Azotea Creek (LF-Midpoint)		1/4 mile downstream from Azotea Tunnel Outlet (LF-Upstream)		Artesian well		Gain or loss in streamflow resulting from groundwater interaction		Remark
Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	
0.03	0.02	0.02	0.01	0.04	0.02	-0.03	0.03	Maximum downstream discharge during interval
0.02	0.01	0.02	0.01	0.04	0.02	-0.04	0.02	Minimum downstream discharge during interval

Reach 2								
1/10 mile upstream from Willow Creek above Heron Reservoir station (LF-Downstream)		Willow Creek above the confluence with Willow Creek above Azotea Creek (LF-Midpoint)		Willow Creek above Azotea Creek		Gain or loss in streamflow resulting from groundwater interaction		Remark
Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	
0.08	0.04	0.03	0.02	--		0.05	0.04	Maximum upstream discharge during interval
0.08	0.04	0.02	0.01	--		0.06	0.04	Minimum upstream discharge during interval

Groundwater interaction for Reach 1 and Reach 2								
1/10 mile upstream from Willow Creek above Heron Reservoir station (LF-Downstream)		1/4 mile downstream from Azotea Tunnel Outlet (LF-Upstream)		Artesian well		Gain or loss in streamflow resulting from groundwater interaction		Remark
Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	Streamflow (ft^3/s)	Uncertainty (ft^3/s)	
0.08	0.04	0.02	0.01	0.04	0.02	0.02	0.05	Maximum downstream discharge during interval

Estimates of uncertainty for the seepage investigations include the uncertainty between the upstream and downstream measurement equipment and the uncertainty associated with each discharge measurement. The estimated uncertainty for the calculated streamflow resulting from groundwater/surface-water interactions was calculated by using the formula for the propagation of uncertainty for independent uncertainty (Taylor, 1997):

$$s = \sqrt{A^2 + B^2 + C^2} \quad (2)$$

where

s is the cumulative uncertainty for the calculated gain or loss in streamflow resulting from groundwater/surface-water interaction; and

A, B, and C are the estimated uncertainty for the individual discharge measurements.

For the high-flow seepage investigation, the estimated cumulative uncertainty was calculated as plus or minus 10 ft^3/s. For the low-flow seepage investigation, the estimated cumulative uncertainty ranged from 0.02 ft^3/s to 0.05 ft^3/s depending on the reach.

Analysis of Streamflow

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

Prior to 1971, the USGS collected streamflow data at stations on Willow Creek. Mean daily streamflow values for the stations at Willow Creek above Heron Reservoir near Los Ojos, N. Mex. (Willow Creek above Heron Reservoir), Willow Creek near Park View, N. Mex. (Willow Creek near Park View), and Horse Lake Creek above Heron Reservoir near Los Ojos, N. Mex. (Horse Lake Creek) (fig. 2) were calculated by following USGS streamflow measurement protocols described by Rantz (1982a, b). After 1971, streamflow data for Azotea Tunnel at Outlet near Chama, N. Mex. (Azotea Tunnel Outlet), Willow Creek above Heron Reservoir, and Willow Creek below Heron Dam, N. Mex. (Willow Creek below Heron Reservoir) were provided to the USGS by Reclamation as calculated mean daily streamflow. Stage data for Heron Reservoir near Los Ojos, N. Mex. (Heron Reservoir), were provided to the USGS by Reclamation as the daily observation at 2400 hours (midnight). The mean daily streamflow values and daily observations of reservoir stage for the stations reported to the USGS were retrieved from the USGS National Water Information System database (U.S. Geological Survey, 2014). Additional data used for computations in this report were retrieved from the CDWR online database (Colorado Division of Water Resources, 2011) and are detailed in Falk and others (2013).

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 at selected stations. Median annual streamflow was calculated for all stations on the basis of the calendar year for all years with complete records. Median monthly streamflow was calculated for each month with a complete record of streamflow.

Nonparametric statistical methods, including calculation of percentiles, were applied to describe streamflow. The 50th percentile annual streamflow duration (Q50, the median) is the volume of streamflow 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 streamflow for the period of record is less than or equal to the streamflow at the 75th percentile, and the 25th percentile (Q25) means that 25 percent of the annual streamflow for the period of record is less than or equal to the streamflow at the 25th percentile. The range of flows between the 25th and 75th percentiles, or interquartile range (IQR), represents 50 percent of the annual streamflow duration and indicates the distribution statistical dispersion of the data. Variation in streamflow can be characterized as the range of values 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 streamflow to determine the coefficient of variation (COV), which is a measure of the distribution of the annual streamflow.

Annual variation in streamflow 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 can be used to indicate future streamflow and 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 streamflow over the period of record from largest to smallest and calculating the exceedance probability by using the Weibull formula for calculating plotting positions (Helsel and Hirsch, 2002).

The length of time that water was diverted and the amount of water that was diverted each day were calculated with nonparametric statistical methods from daily streamflow data from Azotea Tunnel Outlet. The ordinal day of the year on which selected percentiles of annual flow occurred was determined for Azotea Tunnel Outlet. The selected percentiles included the first day of measurable streamflow at Azotea Tunnel Outlet, the ordinal day of the 25th percentile of annual streamflow, the ordinal day of the 75th percentile of annual streamflow, and the ordinal day of the 90th percentile of annual streamflow. The length of time that water was diverted to Azotea Tunnel Outlet was determined for two intervals:

(1) the duration for the IQR of annual streamflow, defined as the number of days between the ordinal day on which 25 percent of the annual streamflow occurred to the ordinal day on which 75 percent of the annual streamflow occurred, and (2) the duration for 90 percent of the annual streamflow, defined as the number of days between the start of streamflow and the ordinal day on which 90 percent of the annual streamflow occurred.

Trends in streamflow were evaluated with the Mann-Kendall trend test, a nonparametric rank-based method that determines if a parameter monotonically increases or decreases compared to another parameter (Helsel and Hirsch, 2002). Monotonic increases or decreases (trends) were considered statistically significant at a p-value less than or equal to 0.05. The p-value is “the probability of obtaining the calculated 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). The null hypothesis is “that there is no trend″ (Helsel and Hirsch, 2002, p. 324). 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 of 0.81 or greater. The sign of tau indicated whether the trend was negative or positive. These data were also tested for autocorrelation by regressing the lagged residuals of the variable over time for a significant trend, as described by Helsel and Hirsch (2002). All data included in the trend analysis were determined not to be significantly autocorrelated.

Water Chemistry

Water chemistry in the streams, channels, and reservoirs in the study area likely is influenced by the geology in the watersheds. The water chemistry, as represented by the ion composition, is a function of the source of the water, which is generally precipitation, and will evolve as a function of the mineral assemblages that are present in the rocks and ions already present in the water (Hem, 1989). The ion composition is affected by the mineral assemblage of the rocks and sediments with which the water comes into contact and the occurrence of biologic and biochemical processes (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) (Hem, 1989). The specific conductance typically is representative of the dissolved-solids concentration of the water (Hem, 1989). Water that is diverted to the SJCP from the Rio Blanco, Little Navajo River, and Navajo River likely is also influenced by the geology of these 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 generally is derived from the same storm systems (Ingersoll and others, 2008). As the precipitation makes contact with the ground, either as surface runoff or as infiltration into the subsurface, it is exposed to the geologic material in the watershed. Concentrations of dissolved solids and SO_4 in water in contact with Cretaceous-age marine shale generally increase along the groundwater flow path (Azimi-Zonooz and Duffy, 1993). Apodaca (1998) noted that the geochemical composition of water from the Mancos Shale near the study area is dominated by Ca and SO_4.

The chemistry of water in the study area varies by the geology along the flow path. A water type was determined for samples from Azotea Tunnel Outlet, Willow Creek above Azotea Creek, Willow Creek above Heron Reservoir, Heron Reservoir, and Willow Creek below Heron Reservoir on the basis of the concentrations of the major ions. Representative water compositions for each sample station were selected because the composition is typical of the chemical composition of all samples from the station and were plotted on a trilinear diagram along with the chemical composition of representative samples from Rio Blanco below Diversion, Navajo River below Diversion, and Horse Lake Creek (data from Falk and others, 2013) (fig. 6). 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 was predominant, the water was classified either as the two most common ions or as “mixed″ if the ions were present in nearly equal portions. Water from Azotea Tunnel Outlet was either HCO_3-Ca/Na/K type or HCO_3-Na/K type depending on flow. Water from Willow Creek above Azotea Creek was HCO_3/SO_4-Ca/Mg type, and water from Willow Creek above Heron Reservoir was either HCO_3-Ca/Na/K type or SO_4-Ca/Mg type depending on flow. Water from Heron Reservoir and Willow Creek below Heron Reservoir was HCO_3-Ca type for both high flow and low flow (fig. 6). Major- and trace-element concentrations in samples collected for this study were less than the U.S. Environmental Protection Agency’s primary and secondary drinking-water standards and less than the NMED surface-water standards for Heron Reservoir and perennial reaches of tributaries to the Rio Chama in the study area (U.S. Environmental Protection Agency, 2011; New Mexico Environment Department, 2011). All water-chemistry data are presented in appendix 1.

The specific conductance of water is proportional to dissolved-solids concentration in water (Hem, 1989). The specific conductance for all stations ranged from 71 to 1,060 microsiemens per centimeter (µS/cm) (fig. 7*A*). The largest range in values of specific conductance was in water from Azotea Tunnel Outlet, Willow Creek above Azotea Creek, and Willow Creek above Heron Reservoir. Water from

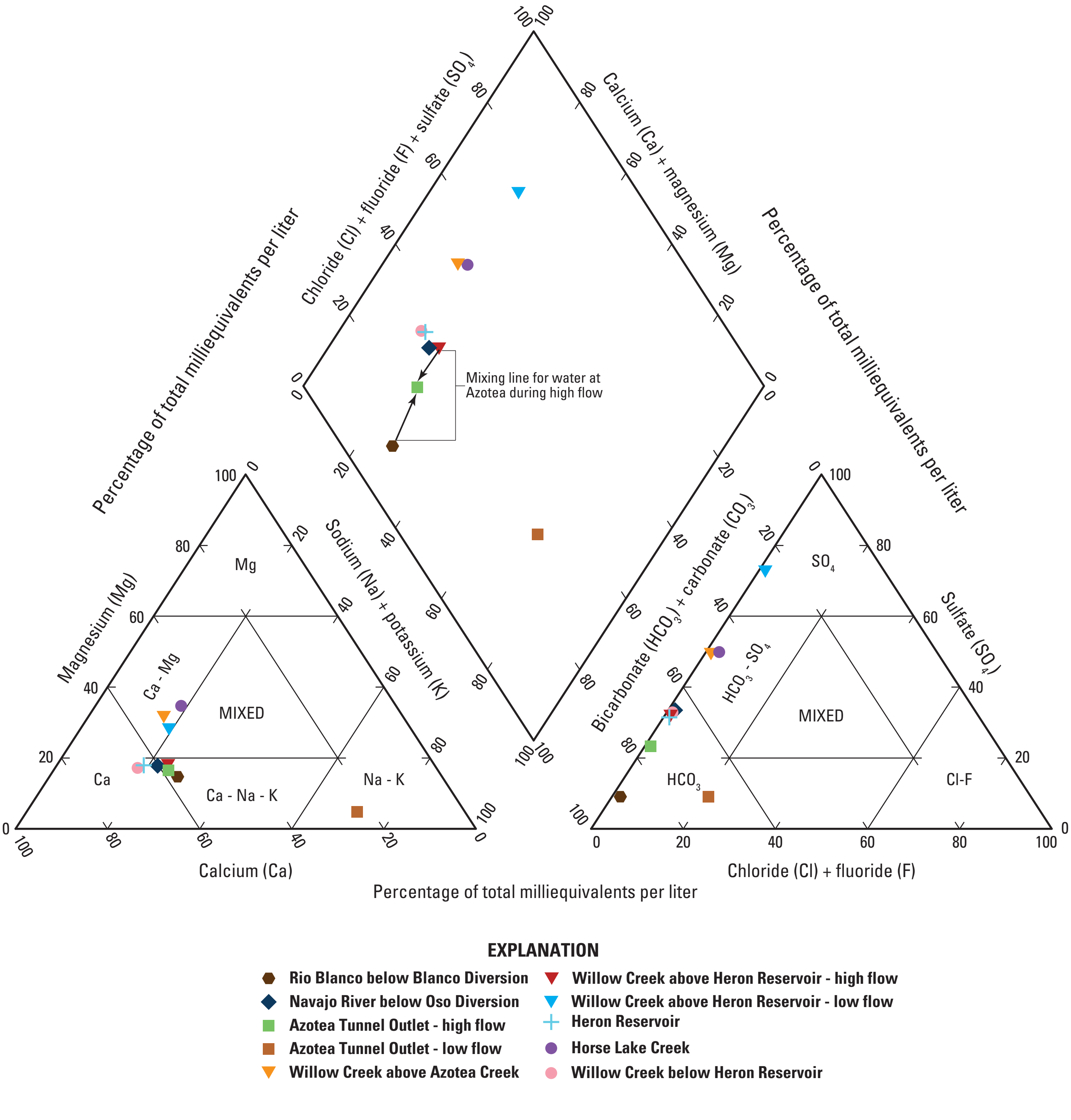


Figure 6. Representative water composition from selected stations in the study area, northern New Mexico and representative water composition from selected stations from Rio Blanco and Navajo River, southern Colorado.

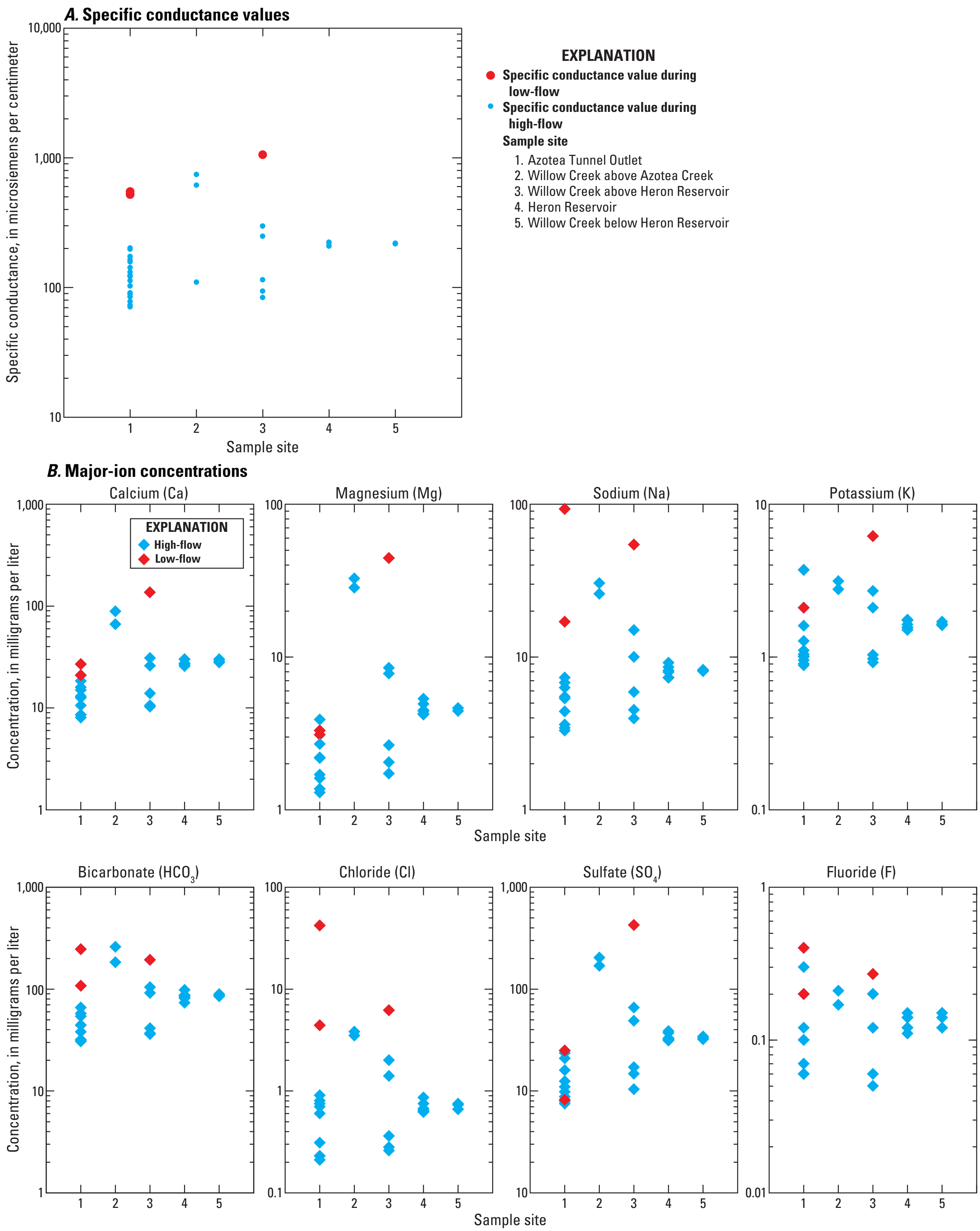


Figure 7. Variation of water-chemistry at selected sampling stations in the study area, northern New Mexico, 1973– 2009. *A*, Specific-conductance values. *B*, Major-ion concentrations.

Azotea Tunnel Outlet ranged from 71 to 551 µS/cm (fig. 7*A*), water from Willow Creek above Azotea Creek ranged from 110 to 746 µS/cm (fig. 7*A*), and water from Willow Creek above Heron Reservoir ranged from 84 to 1,060 µS/cm (fig. 7*A*). The specific conductance value of water from Heron Reservoir and Willow Creek below Heron Reservoir was approximately 210 µS/cm (fig. 7*A*).

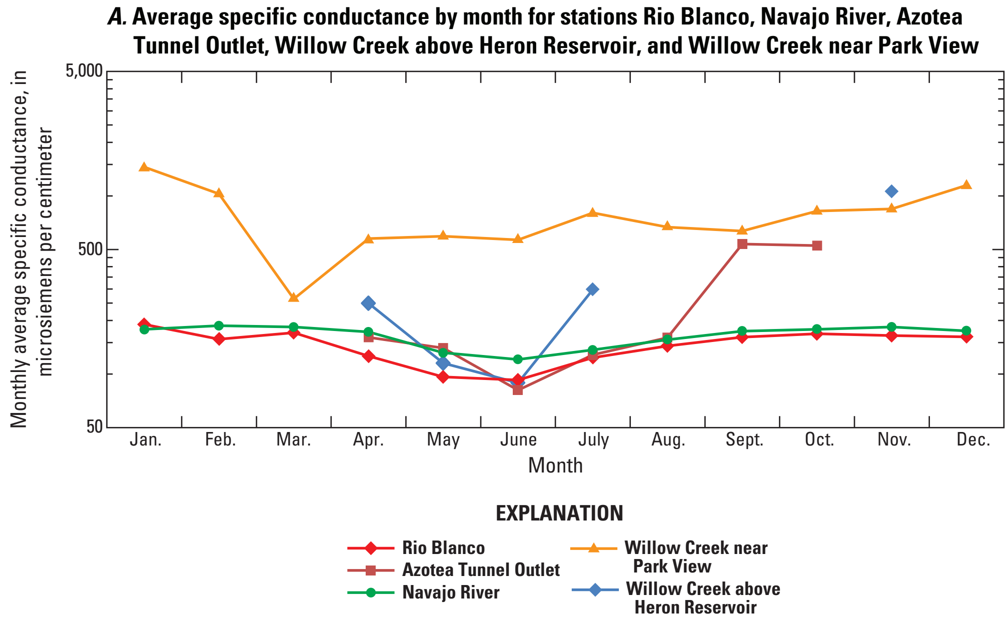
Azotea Tunnel Outlet and Willow Creek above Heron Reservoir

The chemistry of water from Azotea Tunnel Outlet and Willow Creek above Heron Reservoir varied with streamflow. Water at Azotea Tunnel Outlet during high flow was a mixture of water diverted from Rio Blanco, Little Navajo River, and Navajo River. The proportion of water derived from each stream varied on the basis of water availability and the legal, logistical, and structural limitations of the SJCP. Water at Azotea Tunnel Outlet during low flow was discharged at Azotea Tunnel Outlet after diversions for the SJCP were terminated and was generally a small volume typically less than 2 ft^3/s. The source of streamflow at Azotea Tunnel Outlet during low flow when water is not diverted from the SJCP is unknown; however, it likely originates in Azotea Tunnel. The majority of streamflow at Willow Creek above Heron Reservoir is from Azotea Tunnel Outlet because there is little to no flow from tributaries between these two stations. Water at Willow Creek above Heron Reservoir during high flow and low flow was a mixture of water from Azotea Tunnel Outlet and inflow from tributaries. Additional analyses of seasonal variation in streamflow are presented in later sections (see section "Variation and Trends in Streamflow for the San Juan-Chama Project").

During high flow, the specific conductance and ionic composition of water from Azotea Tunnel Outlet were similar to water from streams that contribute to the SJCP (figs. 7*A* and 8*A*). The variation in specific conductance of water from Azotea Tunnel Outlet was similar to water from Rio Blanco and Navajo River (fig. 8*A*). The ionic composition of water from Azotea Tunnel Outlet during high flow was similar to the composition of a mixture of water from Rio Blanco and Navajo River (Falk and others, 2013), such that the ionic composition of Azotea Tunnel Outlet fell on a line between the ionic composition of water from Rio Blanco and Navajo River (fig. 6). The similarity of the ionic composition of water from Azotea Tunnel Outlet to the ionic composition of a mixture of water from the Rio Blanco and Navajo River indicated that no substantial chemical changes or mixing with water from other sources occurred during transit through the SJCP infrastructure during high flow.

Water from Azotea Tunnel Outlet during low flow was compositionally different from water from streams that contribute to the SJCP and waters from the streams in the Willow Creek Basin including Horse Lake Creek and Willow Creek above Azotea Creek (fig. 6). Higher specific conductance values in water from Azotea Tunnel Outlet generally occurred during low flow than during high flow (figs. 7*A* and 8*B*). Concentrations of Ca, Na, HCO_3, and Cl were highest during low flow (fig. 7*B*). There was proportionately more Na, K, and Cl and proportionately less SO_4 and Mg in water from Azotea Tunnel Outlet during low flow than in water from any other station in the study area (fig. 6). Analysis of water-chemistry data from Azotea Tunnel Outlet during low flow suggests the existence of either another source of water other than the streams that contribute to the SJCP or the occurrence of a chemical process within Azotea Tunnel that changes the chemistry of the water. There is insufficient data to determine what that source of water might be or what chemical effect could occur; however, a possible source of water may be seepage of water along the 13-mi length of the concrete-lined Azotea Tunnel.

During high flow, small but distinct differences in ion composition and specific conductance existed in water from Willow Creek above Heron Reservoir compared to water from Azotea Tunnel Outlet. There was larger proportion of HCO_3 (fig. 6) and a slightly larger range of specific conductance values in water from Willow Creek above Heron Reservoir during high flow than in water from Azotea Tunnel Outlet (fig. 7*A*). Comparison of paired samples collected from Azotea Tunnel Outlet and Willow Creek above Heron Reservoir on the same day in 2008 and 2009 indicated that the concentrations of major ions, with the exception of F for all dates and alkalinity for May 2009, increased downstream, such that the concentrations of major ions were greater in water from Willow Creek above Heron Reservoir relative to water from Azotea Tunnel Outlet. Although the volume of surface-water inflows along the channel between Azotea Tunnel Outlet and Willow Creek above Heron Reservoir were generally small (approximately 2 orders of magnitude) relative to the volume of water in the channel, the dissolved-solids concentrations and major-ion concentrations of inflows derived from the Willow Creek watershed, such as Willow Creek above Azotea Creek, were generally much greater than concentrations at Willow Creek above Heron Reservoir (figs. 7*A* and 7*B*). There were increased concentrations of Mg and SO_4 in water sampled from the Willow Creek above Heron Reservoir relative to water from Azotea Tunnel Outlet (fig. 7*B*).The Willow Creek watershed is underlain mostly by the Mancos Shale (Cretaceous-age marine shale; fig. 4). It is likely that the dissolved-solids concentration of water at stations in the Willow Creek watershed was elevated relative to the dissolved-solids concentration in water from other watersheds not underlain by Mancos Shale (figs. 7*A* and 7*B*). During high flow, water at Willow Creek above Heron Reservoir was likely a mixture of water from Azotea Tunnel Outlet and a small volume of surface-water inflows from tributaries with large concentrations of dissolved solids such as Willow Creek above Azotea Creek. Simple mixing calculations indicated that small (less than 5 ft^3/s) volumes of water from Willow Creek above Azotea Creek could



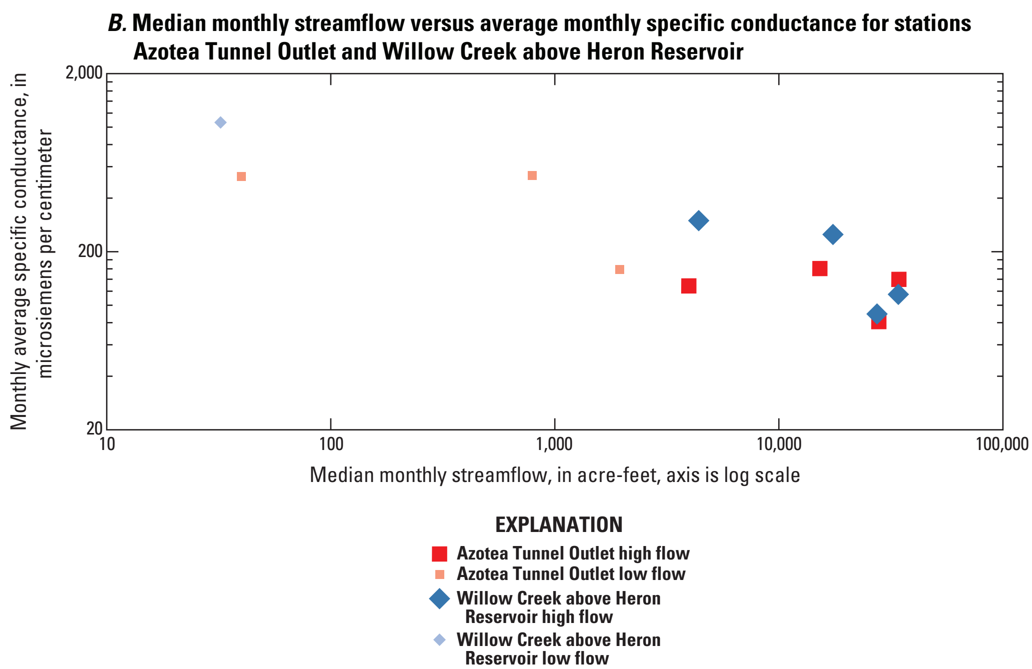


Figure 8. Monthly variation in specific-conductance values for selected stations and comparison of the variation of the average monthly specific conductance to the median monthly streamflow, with monthly streamflow categorized as high flow or low flow, for selected stations in the study area, northern New Mexico, 1973–2009. *A*, Average specific conductance by month for stations Rio Blanco, Navajo River, Azotea Tunnel Outlet, Willow Creek above Heron Reservoir, and Willow Creek near Park View. *B*, Median monthly streamflow as a function of monthly average specific conductance for stations Azotea Tunnel Outlet and Willow Creek above Heron Reservoir.

increase major-ion concentrations in water from Willow Creek above Heron Reservoir relative to water from Azotea Tunnel Outlet and could result in the difference in the ion composition observed between water from Azotea Tunnel Outlet and Willow Creek above Heron Reservoir.

Water from Willow Creek above Heron Reservoir during low flow was compositionally similar, with the exception of increased proportions of Cl and F and a decreased proportion of HCO_3, to water from streams in the Willow Creek Basin, including Horse Lake Creek and Willow Creek above Azotea Creek (fig. 6). Generally, the specific conductance was increased relative to high flow, and the concentrations of most major ions were highest during low flow (figs. 7*A* and 7*B*). During low flow, water at Willow Creek above Heron Reservoir was likely derived primarily from surface-water inflows from tributaries with large concentrations of dissolved solids such as Willow Creek above Azotea Creek and a small volume of water from Azotea Tunnel Outlet. The monthly variation in average specific conductance of water from Willow Creek near Park View is likely representative of water derived from the Willow Creek watershed (fig. 8*A*). Additionally, water at Willow Creek above Heron Reservoir was possibly affected by evaporative and chemical processes during transit from Azotea Tunnel Outlet that altered the proportion of ions, increasing Cl and decreasing HCO_3 concentrations relative to the concentrations of other ions.

In general, surface-water chemistry at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir varied throughout the year as a function of streamflow. Streamflow varied from high flow to low flow as the result of the quantity of water diverted from the Rio Blanco, Little Navajo River, and Navajo River for the SJCP. During high flow, the ionic composition of water from Azotea Tunnel Outlet was similar to the ionic composition of a mixture of water from Rio Blanco and Navajo River. Also, there were small but distinct differences in the ionic composition of water from Willow Creek above Heron Reservoir compared to water from Azotea Tunnel Outlet (fig. 6). Water at Willow Creek above Heron Reservoir was likely a mixture of water from Azotea Tunnel Outlet and a small volume of surface-water inflows from tributaries such as Willow Creek above Azotea Creek with large concentrations of dissolved solids. During low flow, the ionic composition of water from Azotea Tunnel Outlet was compositionally different from water from streams that contribute to the SJCP and waters from streams in the Willow Creek Basin; the source of the water is currently unknown. The ionic composition of water at Willow Creek above Heron Reservoir during low flow was compositionally similar to water from streams in the Willow Creek Basin and was primarily derived from tributary inflow to Willow Creek, with a minor contribution of flow from the SJCP. The increase in specific conductance and ion concentrations from Azotea Tunnel Outlet to Willow Creek above Heron Reservoir likely was a function of the tributary inflow along the channel including Willow Creek above Azotea Creek and physical and chemical processes affecting the water along the channel. The increase in specific conductance and ion concentrations is inversely proportional to streamflow, such that a smaller volume of streamflow would be more affected by tributary inflow and physical and chemical processes than a larger volume of streamflow.

An evaluation of nutrient concentrations in water samples from Azotea Tunnel Outlet, Willow Creek above Azotea Creek, and Willow Creek above Heron Reservoir focused on the results from samples collected on May 5, 2009, and June 24, 2009, because the three stations were sampled sequentially. Results from other samples are included in the analysis if needed but were not the focus of the analysis because the relation of water chemistry and streamflow causes variation in water chemistry at different flow conditions. The predominant form of total nitrogen reported at these stations was total ammonia plus organic nitrogen, the predominant form of dissolved nitrogen reported at these stations was ammonia plus organic nitrogen, and the predominant form of dissolved phosphorus was orthophosphate (table 5). The dissolved nitrogen component generally accounted for more than 50 percent of the total nitrogen, except for the June 2009 sampling at Willow Creek above Heron Reservoir in which the dissolved ammonia plus organic nitrogen component accounted for 34 percent of the total ammonia plus organic nitrogen. The dissolved phosphorus component generally accounted for less than 30 percent of the total phosphorus. Total organic carbon concentrations ranged from 3.3 to 11.8 milligrams per liter (table 5). In general, nutrient concentrations and organic carbon concentrations increased from Azotea Tunnel Outlet to Willow Creek above Heron Reservoir, likely because of higher concentrations of nutrients contributed by inflow of Willow Creek above Azotea Creek (table 5).

Heron Reservoir and Willow Creek below Heron Reservoir

The chemistry of water from Heron Reservoir and Willow Creek below Heron Reservoir are compositionally similar to the chemistry of water at Willow Creek above Heron Reservoir during high flow (fig. 6). In general, the concentration of major ions with the exception of K and Cl in water from Heron Reservoir and Willow Creek below Heron Reservoir was greater than the concentration of major ions in water from Azotea Tunnel Outlet during high flow. The specific conductance and concentration of major ions at Heron Reservoir and Willow Creek below Heron Reservoir are in the range of values for Willow Creek above Heron Reservoir during high flow (figs. 7*A* and 7*B*). The ionic composition and the concentration of major ions in samples from Heron Reservoir and Willow Creek below Heron Reservoir indicated that the chemistry of water for the SJCP is altered during transit along the channel from the Azotea Tunnel Outlet to Heron Reservoir, likely as a result of mixing with inflows along the channel.

Table 5. Selected water-chemistry data for Azotea Tunnel Outlet, Willow Creek above Azotea Creek, Willow Creek above Heron Reservoir, Heron Reservoir, and Willow Creek below Heron Reservoir, northern New Mexico, 2007–9.

[mg/L, milligrams per liter; <, less than; --, data not available; E, estimated value]

Station name	Date	Sampling depth	Total nitrogen, water, unfiltered	Total ammonia plus organic nitrogen, water, unfiltered	Total organic nitrogen, water, unfiltered	Ammonia plus organic nitrogen, water, filtered	Ammonia, water, filtered	Nitrate plus nitrite, water, filtered	Nitrate, water, filtered	Nitrite, water, filtered	Orthophosphate, water, filtered	Phosphorus, water, filtered	Total phosphorus, water, unfiltered	Total organic carbon, water, unfiltered
		feet	All concentrations reported as mg/L nitrogen								All concentrations reported as mg/L phosphorus			mg/L as carbon
Azotea Tunnel Outlet	5/5/2009	--	0.27	0.21	<0.21	0.12	<0.020	0.06	0.057	<0.002	0.028	0.025	0.094	4.5
Willow Creek above Azotea	5/5/2009	--	<0.90	0.86	<0.86	0.51	<0.020	<0.04	<0.040	<0.002	0.021	0.026	0.222	11.8
Willow Creek above Heron Reservoir	5/5/2009	--	0.28	0.23	<0.23	0.14	<0.020	0.05	0.051	<0.002	0.028	0.026	0.117	5.2
Azotea Tunnel Outlet	6/24/2009	--	<0.30	0.26	<0.26	0.13	<0.020	<0.04	<0.040	<0.002	0.026	0.032	0.098	3.3
Willow Creek above Azotea	6/24/2009	--	<0.77	0.73	<0.73	0.47	<0.020	<0.04	<0.040	<0.002	E0.008	0.011	0.109	10.7
Willow Creek above Heron Reservoir	6/24/2009	--	<0.33	0.29	<0.29	0.10	<0.020	<0.04	<0.040	<0.002	0.026	0.024	0.141	4.7
Heron Reservoir	4/8/2008	10	--	--	<0.16	--	<0.020	0.04	0.04	<0.002	0.01	--	0.03	2.9
Heron Reservoir	10/8/2008	11	--	--	<0.13	--	<0.020	<0.04	<0.040	<0.002	<0.008	--	0.009	3.3
Heron Reservoir	10/8/2008	75	--	--	<0.11	--	<0.020	0.11	0.107	<0.002	0.034	--	0.051	3.0
Heron Reservoir	5/6/2009	8	<0.37	0.33	<0.33	0.21	<0.020	<0.04	<0.040	<0.002	0.009	E0.006	0.024	3.3
Heron Reservoir	9/24/2009	12	<0.20	0.16	<0.16	0.14	<0.020	<0.04	<0.040	<0.002	E0.006	E0.004	0.015	2.9
Heron Reservoir	9/24/2009	70	0.26	0.16	<0.16	0.11	<0.020	0.09	0.092	<0.002	0.02	0.02	0.038	2.7
Willow Creek below Heron Reservoir	12/13/2007	--	--	--	<0.13	--	<0.020	0.05	E0.044	E0.001	0.013	--	0.03	2.7
Willow Creek below Heron Reservoir	11/17/2008	--	--	--	<0.17	--	<0.020	E0.03	E0.030	0.002	0.014	--	0.032	3.2
Willow Creek below Heron Reservoir	8/18/2009	--	0.26	0.17	<0.17	0.18	<0.020	0.09	0.09	<0.002	0.024	0.025	0.045	3.0

Vertical profiles of the water temperature over the depth of the water column collected in April 2008, October 2008, July 2009, August 2009, and September 2009 indicated that Heron Reservoir is thermally stratified in the summer and early fall and thermally mixed in early spring. Stratification of reservoirs occurs because of the variation of the density of water with temperature; the density of water increases as the temperature decreases to a maximum density at 4 degrees Celsius (°C), and water colder than 4 °C decreases in density (Nevers and Whitman, 2005). Stratification of reservoirs can occur in the summer as water that is near the surface is warmed relative to deeper water and in the winter as water that is near the surface is cooled and sinks downward (Nevers and Whitman, 2005). Because water colder than 4 °C is less dense than warmer water, stratification in the winter can result in the coldest water near the surface (Nevers and Whitman, 2005). Mixing of the stratified layers can occur from wind shear and during seasonal air temperature transitions that affect the temperature of water near the surface. The region between the upper warm zone and the lower cold zone is referred to as the "thermocline" and is generally defined as the region where the temperature changes at least 1 °C per meter (Graham and others, 2008).

Temperature-dependent density differences in a stratified water column can prevent mixing and can result in the formation of chemical variations between the layers. Typically, the dissolved-oxygen concentration of water in the deeper layer of a stratified reservoir will decrease, and the carbon dioxide and nutrient concentrations will increase because of the decomposition of organic material (Nevers and Whitman, 2005). Depending on the amount of organic material available for decomposition, the lower layers can become devoid of oxygen, or anoxic, and can be depleted enough to be insufficient to support aquatic life (Nevers and Whitman, 2005). Additionally, during summer stratification, the water near the surface can become depleted in oxygen because of decreased solubility of oxygen at increased temperatures, resulting in the highest oxygen concentrations at a middle zone where phytoplankton continues to produce oxygen (Nevers and Whitman, 2005). The inflow of water to a reservoir from upstream sources can mix with lower layers, increase oxygen concentrations at depth, and decrease stratification effects during the runoff season (Petts, 1986).

During turnover, when the stratified layers are mixed, the products of decomposition from the lower layer, including the increased concentrations of carbon dioxide and nutrients, are cycled into the upper layers, and the higher concentrations of dissolved oxygen in the upper layers are cycled into the lower layers (Nevers and Whitman, 2005). The chemistry of water released from reservoirs can be affected by the stratification of a reservoir if the dam outlet preferentially discharges water from a lower layer with decreased oxygen and increased carbon dioxide and nutrient concentrations.

Vertical profiles of the water temperature over the depth of the water column at Heron Reservoir indicated that the reservoir is seasonally stratified (fig. 9*A*). Heron Reservoir was not stratified in the spring of 2008 (April 2008); however, the reservoir was stratified in the summer (July and August 2009) and early fall of 2008 and 2009 (October 2008 and September 2009) (fig. 9*A*). Summer stratification of Heron Reservoir resulted in warmer water near the surface and cooler water at lower depths (fig. 9*A*). The top of the thermocline at Heron Reservoir increased in depth from approximately 25 ft below the water surface in July 2009 to approximately 45 ft below the water surface in October 2008 (fig. 9*B*). In 2008 and 2009, the temperature of the water surface increased through the spring from April to July and then decreased through late summer from July to October (fig. 9*A*). The seasonal shift in the temperature profile and the change in the depth of the thermocline suggest that the stratification of water in the reservoir transitions from unstratified to stratified through the summer, likely after the largest inflows of water from the SJCP have declined. It is likely that the reservoir turns over in the fall as the water near the surface cools in response to air temperatures and sinks; however, there are no data available to determine if the reservoir is thermally stratified in the winter.

Vertical profiles of the dissolved-oxygen concentration over the depth of the water column at Heron Reservoir indicated that the thermal stratification results in chemical stratification. The concentration of dissolved oxygen was nearly constant at all depths during the spring (fig. 9*B*); however, the concentration of dissolved oxygen varied with depth during the summer and fall (fig. 9*B*). The dissolved-oxygen concentration was greatest during the spring when the water temperature was lowest, which is consistent with increased oxygen solubility at lower water temperatures. When the reservoir was stratified, the dissolved-oxygen concentration was highest above and below the thermocline, and the lowest dissolved-oxygen concentration generally occurred at the top of the thermocline (fig. 9*B*). The dissolved-oxygen concentration in the reservoir below the thermocline declined through the summer with the lowest dissolved-oxygen concentrations in October.

Evaluation of nutrient concentrations in water samples from Heron Reservoir focused on the results from samples collected in 2009 because the samples collected on May 5 and June 24 were closest in time to the sample collection at Azotea Tunnel Outlet and Willow Creek. Results from other samples are included in the analysis if needed but were not the focus of the analysis because the relation of water chemistry and streamflow causes variation in water chemistry at different flow conditions. The predominant form of total nitrogen reported for Heron Reservoir was total ammonia plus organic nitrogen, the predominant form of dissolved nitrogen reported at these stations was ammonia plus organic nitrogen, and the predominant form of dissolved phosphorus was orthophosphate (table 5). The dissolved ammonia plus organic nitrogen component generally accounted for more than 50 percent of the total ammonia plus organic nitrogen. The dissolved phosphorus component of water from above the thermocline for May 2009 and September 2009 accounted for less than 30 percent of the total phosphorus; the dissolved

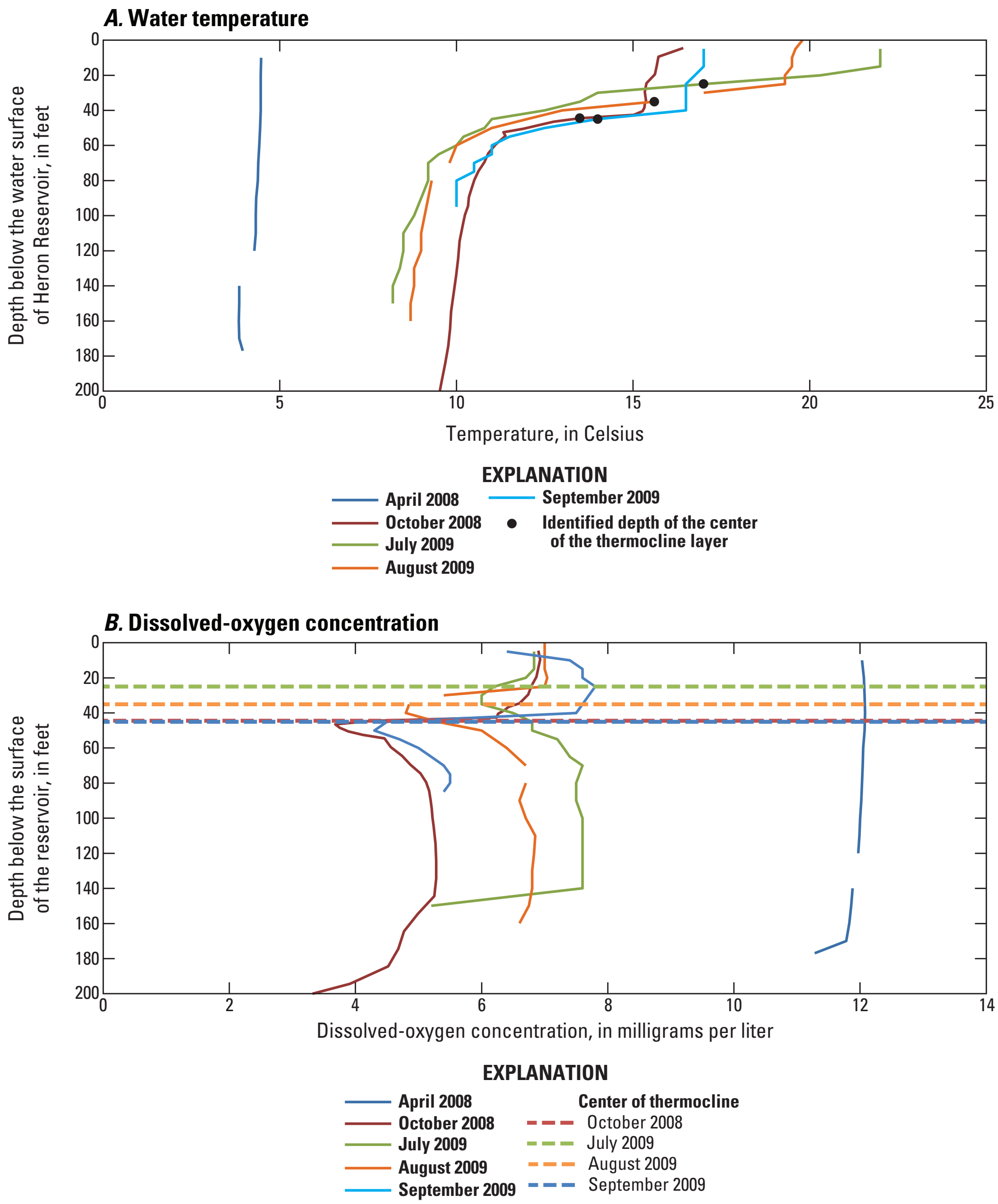


Figure 9. Vertical profiles of water chemistry parameters in Heron Reservoir, 2008–9. *A*, Water temperature. *B*, Dissolved-oxygen concentration.

phosphorus component of water from below the thermocline on September 2009 accounted for approximately 50 percent of the total phosphorus (table 5).

In general, nutrient concentrations and organic carbon concentrations varied above and below the thermocline if the reservoir was stratified. Nitrogen and phosphorus concentrations were equal or higher and organic carbon was slightly lower in samples from below the thermocline than in samples from above the thermocline (except for dissolved ammonia plus organic nitrogen in September 2009). It is likely that the variation in nutrient concentrations are the result of increased decomposition of organic material and less uptake of nutrients by algae below the thermocline. The concentration of dissolved solids and major ions did not vary substantially across the thermocline; there was a slightly higher concentration of dissolved solids in water from above the thermocline, which likely resulted from increased evaporation near the surface.

Analysis of nutrient concentrations in water samples from Willow Creek below Heron Reservoir focused on the results from samples collected in 2009 because these samples were closest in time to the samples collected on Heron Reservoir. Results from other samples are included in the analysis if needed but were not the focus of the analysis because the relation of water chemistry and streamflow causes variation in water chemistry at different flow conditions. The concentrations of nutrients in water from Willow Creek below Heron Reservoir were similar to concentrations of nutrients in water below the thermocline in Heron Reservoir (table 5). It is likely that water released from the dam is pulled from lower in the reservoir and that the water chemistry could be affected by nutrient cycling in the reservoir. The samples collected at Willow Creek below Heron Reservoir on August 18, 2009, included analysis of the water sample for volatile organic compounds, semivolatile organic compounds, organochlorine pesticides, polychlorinated biphenyl, wastewater indicator compounds, human-health pharmaceuticals, and mercury. The concentrations of these compounds were below the reporting level (reporting level varied by analyte) except for N,N-Diethyl-meta-toluamide (DEET), with an estimated concentration of 0.01 micrograms per liter in an unfiltered water sample.

Seepage Investigation

The gain or loss along the channel between Azotea Tunnel Outlet and the station at Willow Creek above Heron Reservoir was calculated for high flow and low flow. During high flow, there was a median calculated loss of 5±10 ft^3/s at a median streamflow of 148 ft^3/s, or an estimated loss of 3±7 percent for the reach of the channel between Azotea Tunnel Outlet and the Willow Creek above Heron Reservoir station. The results of a regression analysis (Helsel and Hirsch, 2002) of the total inflows to the reach (measured discharge near Azotea Tunnel Outlet and at Willow Creek above Azotea Creek) compared to the total outflow from the reach (measured discharge near the Willow Creek above Heron Reservoir station) also indicated an estimated loss of 3 percent, with a consistent trend of a loss for all the measurements (linear regression fit with a slope of 0.97 and a root mean square error of 1.6 ft^3/s; fig. 10). The results for the high seepage investigation indicated that a small but significant loss occurs along the reach between Azotea Tunnel Outlet and Willow Creek above Heron Reservoir.

During low flow, the estimated streamflow resulting from groundwater/surface-water interactions was calculated for Reach 1 and Reach 2 for a range of streamflow at the LF-Midpoint station. The calculated loss in streamflow for Reach 1 from the LF-Upstream station to the LF-Midpoint ranged from 0.03±0.03 ft^3/s to 0.04±0.02 ft^3/s, and the calculated gain in streamflow for Reach 2 from the LF-Midpoint to the LF-Downstream ranged from 0.05±0.04 ft^3/s to 0.06 ±0.04 ft^3/s (table 4). The estimated streamflow resulting from groundwater/surface-water interactions for the interval from the LF-Upstream station to the LF-Downstream station was 0.02±0.05 ft^3/s (table 4).

The results from the seepage investigations indicated a small amount of loss of streamflow along the channel. During high flow, the loss was estimated at 3 percent; however, the uncertainty in the measured streamflow measurements precludes an exact determination of the loss. During low flow, the estimated loss was extremely small, and the uncertainty generally was close to or exceeded the estimated loss. The possible loss of streamflow resulting from groundwater/surface-water interactions during low flow was not a significant volume compared to streamflow volumes during high flow.

Streamflow, Reservoir Storage, and Annual Availability of Water for the San Juan-Chama Project

Streamflow for stations in the SJCP were assessed with measured or estimated streamflow data. Streamflow statistics presented are for the period of record for each station; annual statistics are reported on the basis of calendar years (table 6).

The Azotea Tunnel Outlet station has been operated by Reclamation since 1970. The streamflow gage at Azotea Tunnel Outlet is a concrete flume in the tunnel structure. Median (50th percentile) annual streamflow from 1971 to 2010 was 89,290 acre-ft (table 6 and fig. 11*A*). Annual streamflow at Azotea Tunnel Outlet has been variable over the period of record. The annual streamflow was 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. Additionally, the range of values of annual streamflow that occurred most frequently, from 75,000 to 87,500 acre-ft, were below the median annual streamflow (fig. 11*A*). Streamflow at Azotea Tunnel Outlet is generally close to median annual streamflow with only two years less than 25,000 acre-ft (fig. 11*A*).

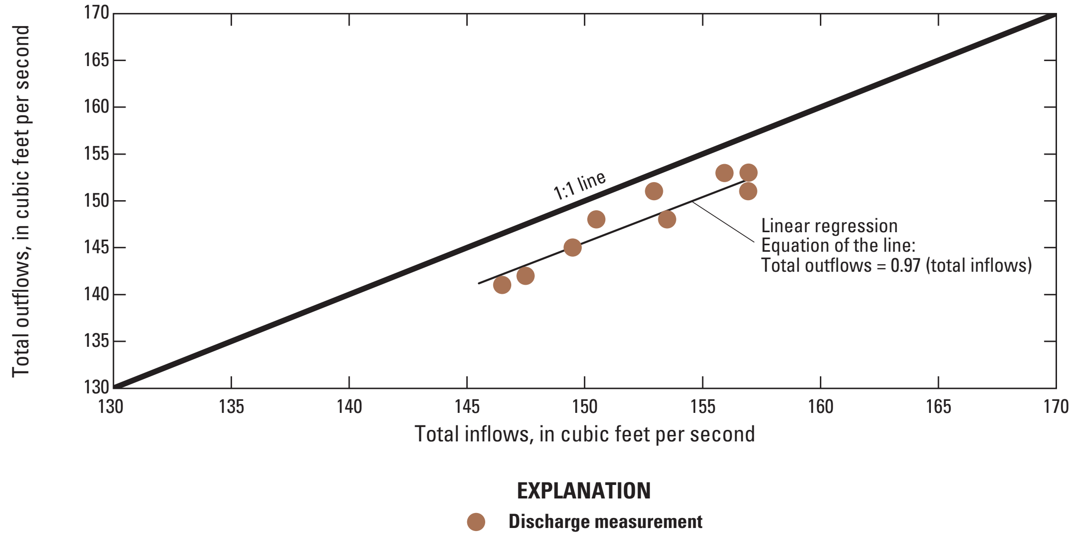


Figure 10. Comparison of the total inflows to the reach (measured discharge near Azotea Tunnel Outlet and at Willow Creek above Azotea Creek) and the total outflow from the reach (measured discharge near the Willow Creek above Heron Reservoir station) with fitted regression line.

Table 6. Selected statistics for streamflow at selected streamflow-gaging stations in the study area, northern New Mexico.

[IQR, interquartile range]

	Azotea Tunnel Outlet	Willow Creek above Heron Reservoir	Willow Creek above Heron Reservoir	Horse Lake Creek	Willow Creek below Heron Reservoir	Willow Creek near Park View
Period of record included in the statistical analysis	1971–2010	1962–70	1971–2010	1963–2009	1971–2010	1943–69
Annual streamflow percentiles, in acre-feet						
10th percentile	47,520	2,460	51,442	6	49,730	1,750
25th percentile	62,920	4,430	66,436	37	72,600	2,700
50th percentile	89,290	5,710	102,570	185	95,540	9,170
75th percentile	117,580	11,100	125,824	679	118,220	15,120
90th percentile	144,930	14,680	161,530	969	127,960	20,480
IQR (75th percentile–25th percentile)	54,660	6,670	59,388	642	45,620	12,420
Coefficient of variation (IQR/50th percentile)	0.61	1.17	0.58	3.47	0.48	1.35

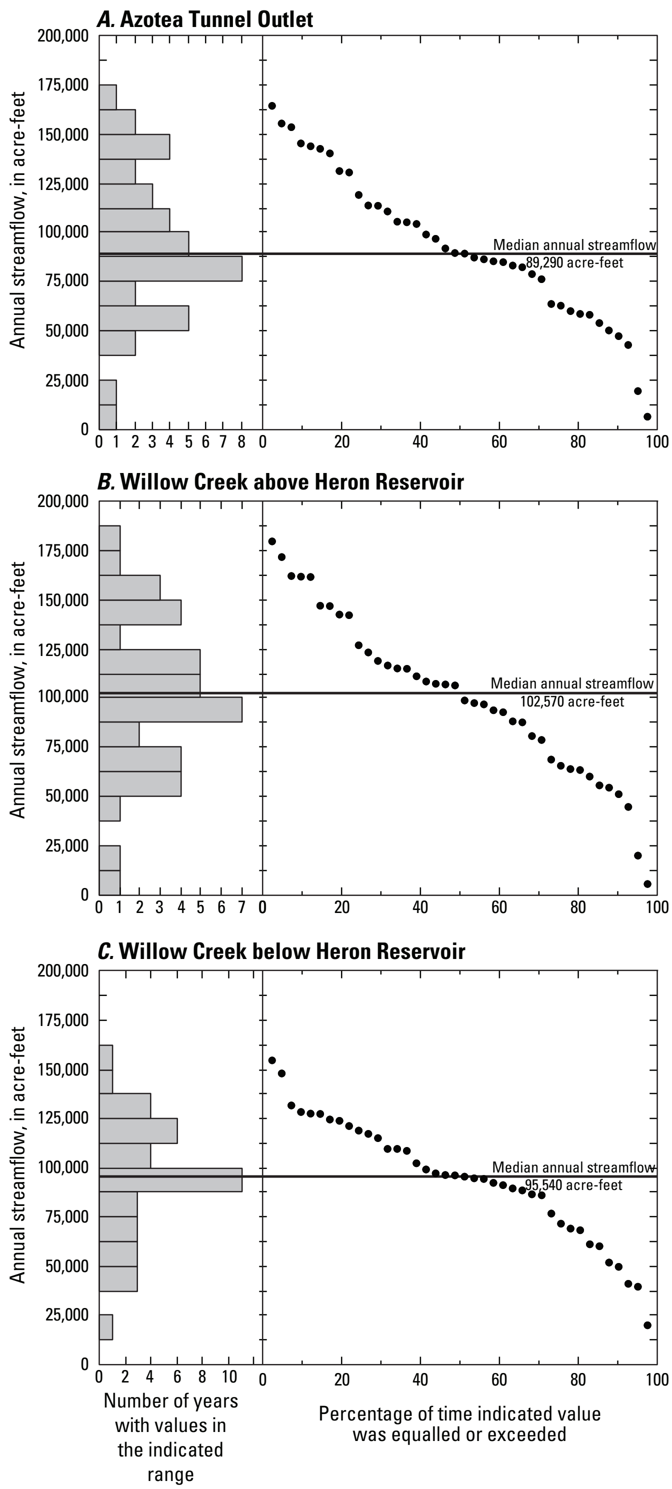


Figure 11. Distribution of annual streamflow, median annual streamflow, and annual flow-duration curves for selected streamflow-gaging stations in the study area, 1971–2010. *A*, Azotea Tunnel Outlet. *B*, Willow Creek above Heron Reservoir. *C*, Willow Creek below Heron Reservoir.

Streamflow on Willow Creek was measured at two stations: Willow Creek near Park View and Willow Creek above Heron Reservoir. The Willow Creek near Park View station was operated by the USGS from 1936 to 1971 (there was no winter record for 1936 through 1942) (table 2). The location of the station is detailed in Falk and others (2013). Median (50th percentile) annual streamflow from 1943 to 1969 at Willow Creek near Park View was 9,170 acre-ft (table 6).

Streamflow recorded at the Willow Creek above Heron Reservoir station for the period before the SJCP diversions (1962–70) is the natural streamflow on Willow Creek. Streamflow recorded at Willow Creek above Heron Reservoir for the period of the SJCP diversions (1971–2010) is the combined flow from Azotea Tunnel Outlet and the natural streamflow on Willow Creek. The station at Willow Creek above Heron Reservoir was operated by the USGS from 1962 to 1971 and has been operated by Reclamation since 1971. The location of the station is detailed in Falk and others (2013). Median (50th percentile) annual streamflow from 1962 to 1970 at Willow Creek above Heron Reservoir was 5,710 acre-ft (table 6), and median annual streamflow from 1971 to 2010 was 102,570 acre-ft (table 6 and fig. 11*B*). Because the majority of the streamflow at Willow Creek above Heron Reservoir is derived from the SJCP, the distribution of the annual streamflow is similar to Azotea Tunnel Outlet (fig. 11*B*). The COV for Willow Creek above Heron Reservoir decreased when diversions for the SJCP started and changed from 1.17 over the interval 1962–70 to 0.58 over the interval 1971–2010; this change indicates that annual variation in streamflow at Willow Creek above Heron Reservoir declined after the start of diversion of water for the SJCP.

The Horse Lake Creek station was operated by the USGS from 1962 to June 1971, by Reclamation from July 1971 to September 1998, and then again by the USGS since October 1998. The location of the station is detailed in Falk and others (2013). Median (50th percentile) annual streamflow over the period of record at Horse Lake Creek was 185 acre-ft (table 6). Seasonal and annual variations in streamflow for Horse Lake Creek are reported in Falk and others (2013).

Releases from Heron Reservoir are reported at the Willow Creek below Heron Reservoir gage. The streamflow at Willow Creek below Heron Reservoir has been reported by Reclamation and published by the USGS since 1971. Releases from Heron Reservoir were measured from 1971 to 2000 with mercury manometers located in the conduits of Heron Dam and were measured from 2000 to 2012 with rating tables for the radial gates (Jeff Albertson, Chama New Mexico Field Division, Bureau of Reclamation, oral commun., 2014). Median annual streamflow from 1971 to 2010 was 95,540 acre-ft (table 6 and fig. 11*C*). The annual volume of water released from Heron Reservoir includes SJCP water and Rio Grande water. Accounting for the Rio Grande water is required by the Rio Grande Compact and is reported annually by Reclamation to the Rio Grande Compact Commission. Accounting for the SJCP water diversions and deliveries and the Rio Grande water is calculated by using the Upper Rio Grande Water Operations Model (U.S. Army Corps of Engineers, 2013). The accounting for Rio Grande water is calculated by using several different methods. These methods include (1) mass balance equation for the reservoir, (2) the ratio inflow method that calculates the Rio Grande water as the difference between streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir with an adjustment of the resulting Rio Grande flow by a ratio factor to account for inflow below Willow Creek above Heron Reservoir, and (3) the net end-of-month gain method that is a variation of the mass balance equation (U.S. Army Corps of Engineers, 2005). The accounting for Rio Grande water also includes a method for estimating seepage from Heron Reservoir such that the seepage from Heron Reservoir is considered Rio Grande water for accounting purposes and the amount of Rio Grande water released from the reservoir is decreased by the amount of seepage (U.S. Army Corps of Engineers, 2005). The annual streamflow is asymmetrically distributed around the median, such that values greater than the median cover a smaller range than do values that are less than the median (fig. 11*A*); however, the range of values of annual streamflows that occurred most frequently, from 87,500 to 100,000 acre-ft, included the median streamflow.

The stage gage for Heron Reservoir is a water-stage recorder that has been operated by Reclamation since 1970. The stage data are recorded as an elevation of the water surface above mean sea level and are converted to storage capacity by using a capacity table that relates the elevation to storage contents in acre-feet. The volume of water in storage in Heron Reservoir on January 1 varied over time (fig. 12), generally depending on the inflow of water from upstream and the release of water for downstream uses.

The difference in the COV and the streamflow yield per square mile (Falk and others, 2013) for various streams in the study area showed that there was greater yield and less variability in annual streamflow in streams from large watersheds at high elevations than in streams from small watersheds at high elevations or streams at low-elevation watersheds. Falk and others (2013) concluded that the COVs for stations on the Rio Blanco and Navajo River, streams located at high elevation, were 0.61 or less and that the dispersion of the annual streamflow over the period of record was small relative to other streams in the study area. The study also concluded that the COVs for stations on Willow Creek and Horse Lake Creek, streams located at low elevation, were greater than 1 and that the dispersion of the annual streamflow over the period of record was large relative to other streams in the study area (Falk and others, 2013). The COVs for Azotea Tunnel Outlet, Willow Creek above Heron Reservoir (1971–2010), and Willow Creek below Heron Reservoir were 0.61 or less, and the COVs for Willow Creek near Park View, Willow Creek above Heron Reservoir (1962–70), and Horse Lake Creek were greater than 1 (table 6). The annual variability of streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir (1971–2010) is controlled by the variability in the high-elevation streams from which water is diverted for operation of the SJCP. Differences in air temperature and precipitation, generally related to changes in elevation, were likely the predominant cause of variation in streamflow yield among these stations.

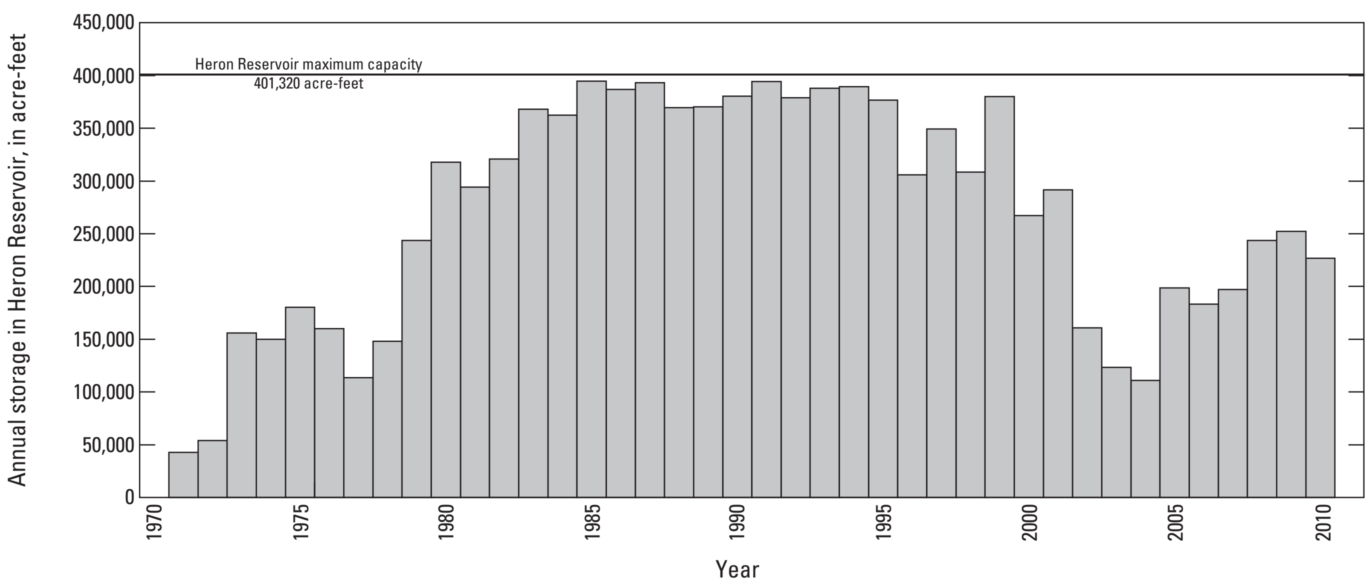


Figure 12. Annual storage in Heron Reservoir, in acre-feet, in northern New Mexico, 1970–2010.

Variation and Trends in Streamflow for the San Juan-Chama Project

Annual variability in streamflow for the SJCP was an indication of the variation in climate parameters that interact to contribute to streamflow in the Rio Blanco, Little Navajo River, Navajo River, and Willow Creek watersheds. For these watersheds, the variation in annual streamflow generally coincides with the timing of Pacific Decadal Oscillation (PDO) cycles, defined by using the North Pacific monthly sea-surface temperature anomaly (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). Annual streamflow for the SJCP has been lower during intervals when the PDO index is negative (correlated to drier conditions for the study area) than during intervals when the PDO index is positive (correlated to wetter conditions in the study area) (Falk and others, 2013). Annual streamflow at Azotea Tunnel Outlet ranged from 164,130 acre-ft (1979) to 6,360 acre-ft (2002) (fig. 13*A*), and annual streamflow at Willow Creek above Heron Reservoir ranged from 179,340 acre-ft (1979) to 5,540 acre-ft (2002) (fig. 13*A*).

The median monthly streamflow for Azotea Tunnel Outlet and Willow Creek above Heron Reservoir indicated that streamflow at these stations was typical of watersheds that are snowmelt-dominated systems, with the majority of streamflow occurring in April through June (fig. 13*B*). The median monthly streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir did not show the bimodal variation that is characteristic of streamflow for stations on Willow Creek and Horse Lake Creek above Heron Reservoir (Falk and others, 2013).

The volume of water diverted for the SJCP during a year depended on the length of time water was diverted and the amount of water that was diverted each day. The first day of measurable streamflow at Azotea Tunnel Outlet for the period of record started between day 60 (March 1) and day 105 (April 15) with a few exceptions. The start of streamflow was earlier than day 60 in 1972 and 1973 when the reservoir was filling and in 2007 and 2009, and streamflow started after day 105 in 1993 (fig. 14*A*). The start of streamflow at Azotea Tunnel Outlet has recently occurred earlier in the year than in previous years; since 1997, the start of streamflow at Azotea Tunnel Outlet occurred on day 80 (March 21) or earlier and in 2009 started on day 35 (February 4) (fig. 14*A*). Streamflow at Azotea Tunnel Outlet has decreased substantially over the period of record after day 198 (July 17), as determined by the 75th percentile of the ordinal day on which 90 percent of the annual streamflow occurred (table 7). The median duration of days for the IQR of annual streamflow was 37 days, and the median duration for 90 percent of the annual streamflow to occur was 99 days (table 7 and figs. 14*B* and 14*C*). For most years, streamflow at Azotea Tunnel Outlet started by March and continued for approximately 3 months until the middle of July. Streamflow that occurred at Azotea Tunnel Outlet after July generally accounted for a minor percentile of annual streamflow. The majority of annual streamflow at Azotea Tunnel Outlet generally occurred from May through June, with a median duration of slightly longer than a month. In general, larger annual streamflow was associated with a longer duration for the IQR but not with a longer duration for 90 percent of the annual streamflow (figs. 14*B* and 14*C*). Additionally, higher annual streamflow occurred in years with higher maximum daily streamflow (fig. 14*D*).

Trends in the seasonal distribution of streamflow at Azotea Tunnel Outlet over time can indicate changes in the timing of snowmelt runoff on the streams that are diverted for the SJCP and changes in the availability of water for diversion. The monthly percentage of annual streamflow and the monthly streamflow from March through October for 1971–2010 were tested for trends compared to time to determine if the amount of streamflow that occurred in these months changed over time. The monthly percentage of annual streamflow and the monthly streamflow for March through October for 1971–2010 was tested for trends compared to the volume of annual streamflow to determine if the volume of annual streamflow affected the monthly distribution of streamflow. Annual streamflow for 1971–2010 was tested for trends compared to time to determine if the volume of annual streamflow monotonically changed since 1971.

The amount of streamflow at Azotea Tunnel Outlet in April, May, and June has changed over time. Significant trends were detected for the monthly streamflow in April (weakly positive) and the monthly percentage of annual streamflow for May (weakly positive) and June (weakly negative) (table 8). These trends indicated that from 1971 to 2010, the amount of streamflow that occurred in April increased, the percentage of annual streamflow that occurred in May increased, and the percentage of annual streamflow that occurred in June decreased. These trends indicated that the streamflow at Azotea Tunnel Outlet has shifted to occur earlier in the year since 1971.

The amount of streamflow at Azotea Tunnel Outlet from April through August also is significantly correlated with annual streamflow. Significant trends for the monthly streamflow compared to annual streamflow at Azotea Tunnel Outlet were detected for April (weakly positive), May through July (strongly positive), and August (weakly positive) (table 8). Additionally, significant trends for the monthly percentage of annual streamflow compared to annual streamflow at Azotea Tunnel Outlet were detected for April (weakly negative), June (weakly positive), and July (moderately positive) (table 8). These trends indicated that more streamflow occurred from April through August for years with greater annual streamflow than during years with less annual streamflow.

Statistically significant trends for the monthly percentage of annual streamflow compared to annual streamflow were detected for April, June, and July (table 8). The significant trends for the monthly percentage of annual streamflow

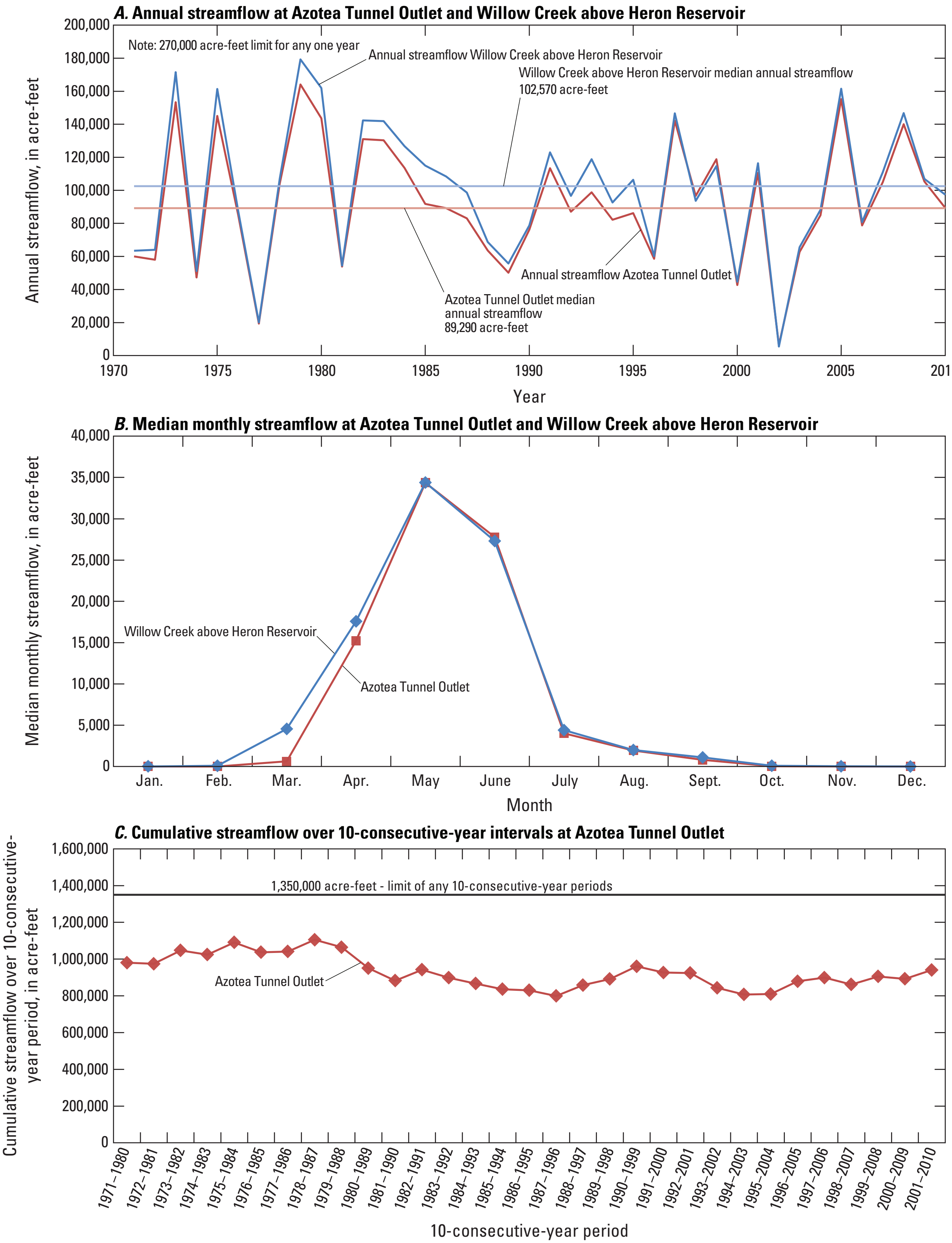


Figure 13. Annual and seasonal variation in streamflow at the streamflow-gaging stations Azotea Tunnel Outlet and Willow Creek above Heron Reservoir, in northern New Mexico, 1971–2010. *A*, Annual streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir. *B*, Median monthly streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir. *C*, Cumulative streamflow over 10-consecutive-year periods at Azotea Tunnel Outlet.

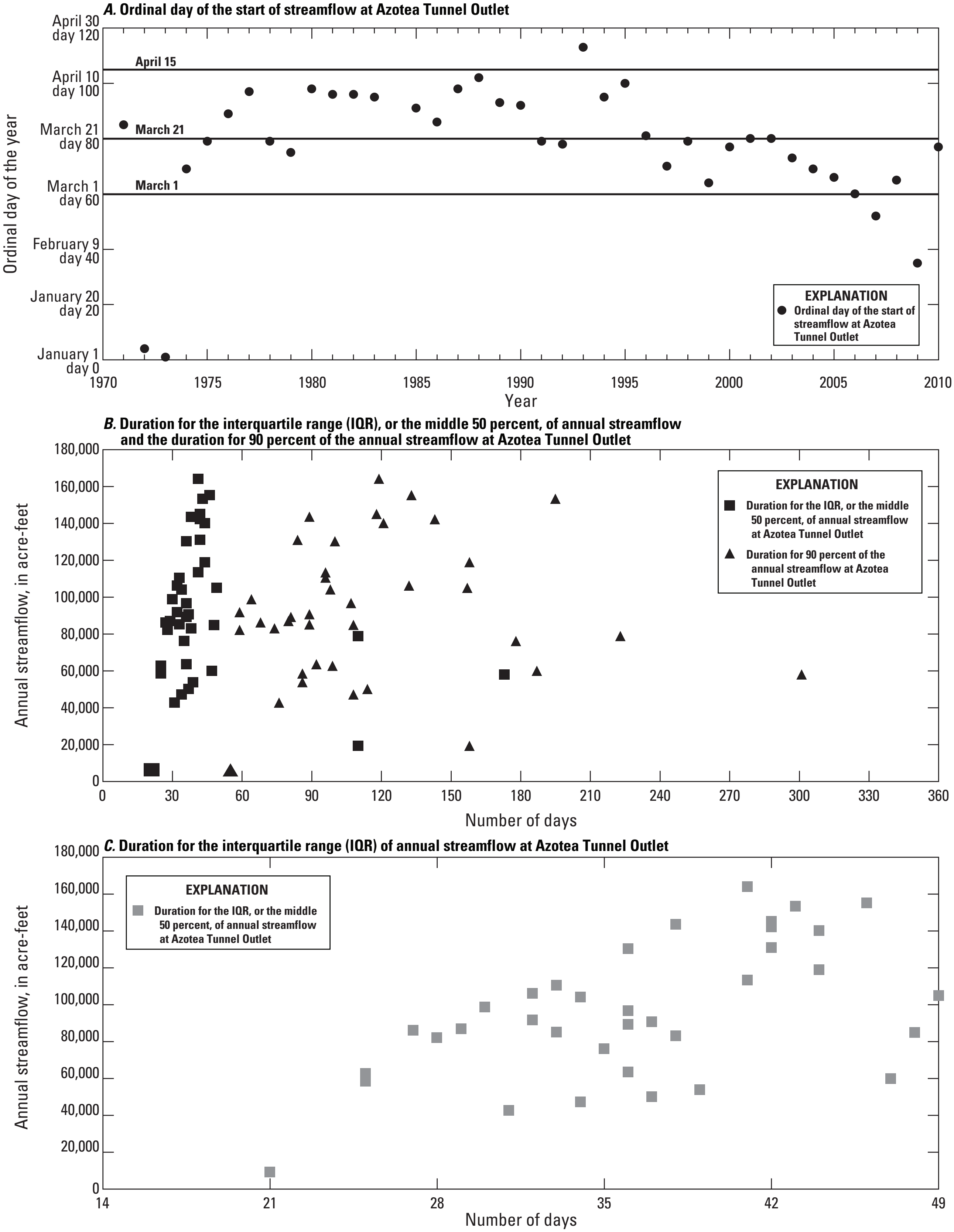


Figure 14. Variation in streamflow at the streamflow-gaging station Azotea Tunnel Outlet, northern New Mexico, 1970–2010. *A*, Ordinal day of the start of streamflow at Azotea Tunnel Outlet. *B*, Duration for the interquartile range, or the middle 50 percent, of annual streamflow and the duration for 90 percent of the annual streamflow at Azotea Tunnel Outlet Tunnel Outlet. *C*, Duration for the interquartile range of annual streamflow at Azotea Tunnel Outlet. *D*, Annual streamflow compared to the maximum daily streamflow at Azotea Tunnel Outlet.

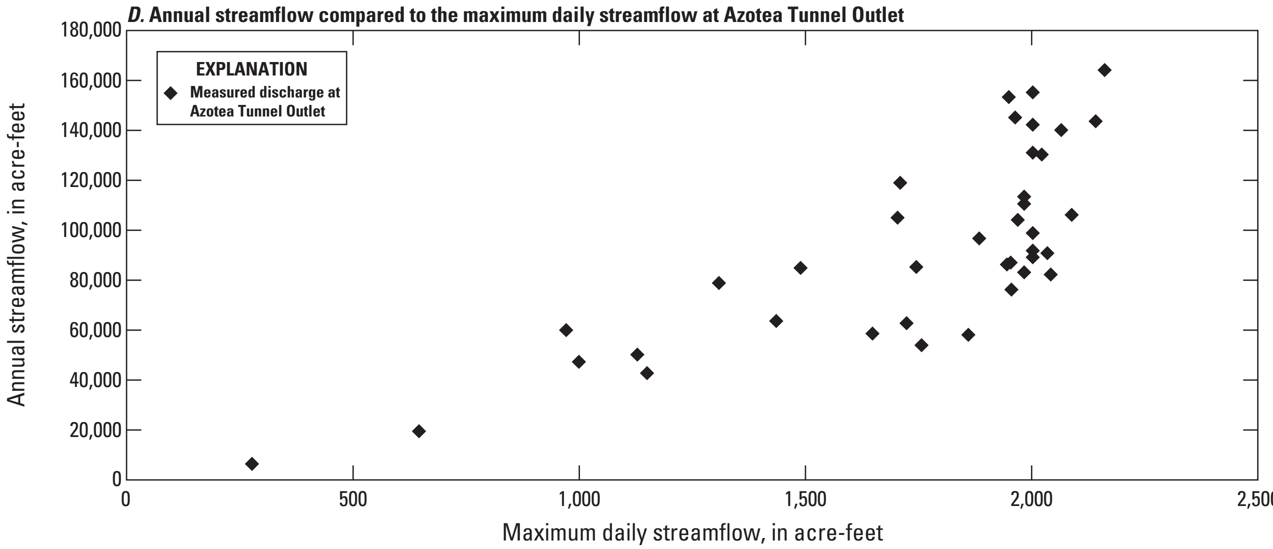


Figure 14. Variation in streamflow at the streamflow-gaging station Azotea Tunnel Outlet, northern New Mexico, 1970–2010. *A*, Ordinal day of the start of streamflow at Azotea Tunnel Outlet. *B*, Duration for the interquartile range, or the middle 50 percent, of annual streamflow and the duration for 90 percent of the annual streamflow at Azotea Tunnel Outlet Tunnel Outlet. *C*, Duration for the interquartile range of annual streamflow at Azotea Tunnel Outlet. *D*, Annual streamflow compared to the maximum daily streamflow at Azotea Tunnel Outlet.—Continued

Table 7. Selected statistics for characterization of streamflow at Azotea Tunnel Outlet, northern New Mexico, 1971–2010. Statistics include the ordinal day of the year on which selected percentiles of annual streamflow occurred and the number of days between selected percentiles.

[Midspread of annual streamflow is defined as the number of days between the ordinal day on which 25 percent of the annual streamflow had occurred to the ordinal day on which 75 percent of the annual streamflow had occurred. Duration for 90 percent of the annual streamflow is defined as the number of days duration between the start of streamflow and the ordinal day on which 90 percent of the annual streamflow had occurred. IQR, interquartile range]

	First day of measureable streamflow	Ordinal day of 25th percentile of annual streamflow	Ordinal day of 75th percentile of annual streamflow	Ordinal day of 90th percentile of annual streamflow	Midspread of annual streamflow (IQR)	Duration for 90 percent of the annual streamflow
Ordinal day percentiles, in ordinal day of the year						
25th percentile	70	120	157	172	33	85
50th percentile (median)	79	125	164	180	37	99
75th percentile	94	133	174	198	43	133
IQR (75th percentile–25th percentile)	24	13	17	26	10	48

Table 8. Results of the Mann-Kendall trend test for monthly streamflow and the monthly percentage of annual streamflow for streamflow-gaging station Azotea Tunnel Outlet, in northern New Mexico, 1971–2010.

[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-value below the significance value of 0.05; --, not statistically significant]

	Trends in the time series of the monthly streamflow			Trends in the monthly streamflow compared to annual streamflow		
	Kendall's tau	p-value	Strength of correlation	Kendall's tau	p-value	Strength of correlation
March	0.1922	0.0920	--	0.1058	0.3535	--
April	**0.2282**	**0.0381**	**W**	**0.3231**	**0.0033**	**W**
May	0.1026	0.3513	--	**0.6179**	**<0.0001**	**S**
June	-0.1193	0.2785	--	**0.7094**	**<0.0001**	**S**
July	-0.0974	0.3759	--	**0.6590**	**<0.0001**	**S**
August	-0.0347	0.7530	--	**0.3610**	**0.0011**	**W**
September	0.0867	0.4341	--	0.2162	0.0512	--
October	-0.1286	0.2650	--	0.0029	0.9798	--

	Trends in the time series of the monthly percentage of annual streamflow			Trends in the monthly percentage of annual streamflow compared to annual streamflow		
	Kendall's tau	p-value	Strength of correlation	Kendall's tau	p-value	Strength of correlation
March	0.1902	0.0920	--	-0.0412	0.7149	--
April	0.1846	0.0934	--	**-0.3872**	**0.0004**	**W**
May	**0.2205**	**0.0451**	**W**	-0.1359	0.2168	--
June	**-0.2308**	**0.0360**	**W**	**0.3462**	**0.0017**	**W**
July	-0.1923	0.0805	--	**0.4410**	**<0.0001**	**M**
August	-0.0629	0.5680	--	0.1477	0.1802	--
September	0.0505	0.6489	--	0.0712	0.5208	--
October	-0.1316	0.2434	--	-0.0838	0.4579	--

were weakly negative for April, weakly positive for June, and moderately positive for July. The positive trends for the monthly percentage of annual streamflow in June and July indicated that increased annual streamflow was also correlated to proportionally more streamflow in these months than in other months (table 8). The relative amount of the streamflow increase in June and July was greater than the increase in other months, such that more of the increase in annual streamflow occurred in June and July. The weakly negative trend for the percentage of annual streamflow in April indicated that the proportion of streamflow in April decreased with increased annual streamflow.

The results from the Mann-Kendall trend test showed that there has not been a significant trend in the annual streamflow at Azotea Tunnel Outlet over time since 1971; however, the amount of streamflow during April has increased, the percentage of annual streamflow in May has increased, and the percentage of annual streamflow in June has decreased (table 8). These trends indicated that snowmelt may be occurring earlier in the year; however, the trends are only weakly correlated. Additionally, the trends in streamflow over time are not as strongly correlated as the trends in streamflow compared to annual streamflow.

The difference between the occurrence and the strength of significant trends between the time series of the seasonal distribution of streamflow and the seasonal streamflow compared to annual streamflow indicated that the seasonal distribution of streamflow was more strongly controlled by the change in the annual streamflow than by time. Similar results were obtained for the seasonal distribution of streamflow for Navajo River at Banded Peak Ranch, such that there was not a significant trend in the seasonal distribution of streamflow over time (Falk and others, 2013). The similarity of the trends for the streams of the SJCP and Azotea Tunnel Outlet indicates that the temporal changes in the seasonal distribution of annual streamflow for the streams of the SJCP are controlling the changes in streamflow at Azotea Tunnel Outlet. Additionally, Falk and others (2013) determined that increased annual streamflow for streams of the SJCP resulted in the snowmelt runoff occurring later in the year and that there was generally a longer duration of runoff.

Annual streamflow at Willow Creek below Heron Reservoir ranged from 19,880 to 154,180 acre-ft (figs. 11*C* and 15*A*). Annual streamflow at this station significantly increased from 1971 to 2010, with a Kendall's tau of 0.2846 and a p-value of 0.0097 that made it statistically significant. The average annual streamflow at Willow Creek below Heron Reservoir by decade was 70,320 acre-ft for 1970–79; 93,440 acre-ft for 1980–89; 104,490 acre-ft for 1990–99; and 105,690 acre-ft for 2000–10. Increased release of water from Heron Reservoir is likely related to changes in downstream use of the water.

The median monthly streamflow for Willow Creek below Heron Reservoir indicated that from 1971 to 2010 the largest streamflows generally occurred in March, April, and December and that smaller streamflows occurred in July, August, and September (fig. 15*B*). The timing of release of water from Heron Reservoir likely is related to the schedule of delivery for water by SJCP, such that more water is scheduled for delivery in the early spring and later summer. The large monthly streamflow at Willow Creek below Heron Reservoir in December is likely related to scheduled delivery of water remaining in storage prior to the end of the calendar year. Historically, the timing of large monthly releases from Heron Reservoir has varied, likely because of variations in downstream use and the total annual release. The majority of releases from Heron Reservoir during the 1970s and early 1980s occurred in December, and the majority of releases in the middle and late 1980s and 1990s occurred in March and April (fig. 15*C*). More recently in the 2000s, releases have been more evenly distributed through the year with some recent increases in releases in December (2007 and 2008) and September (2009 and 2010) (fig. 15*C*).

The annual variations in streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir are regulated by climate patterns such as the PDO that control the amount of precipitation in the watersheds that contribute to streamflow in the Rio Blanco, Little Navajo River, and Navajo River. Although there is not a significant monotonic trend in annual streamflow for streams that contribute to the SJCP over the period of record, annual streamflow has been lower during intervals when the PDO index is negative (indicating drier conditions) than during intervals when the PDO index is positive (indicating wetter conditions) (Falk and others, 2013). In general, streamflow at Azotea Tunnel Outlet will be lower during negative PDO index intervals and higher during positive PDO index intervals. The annual median of the PDO index, defined by following Falk and others (2013), has been negative since 2007 (fig. 16).

Changes in the seasonal distribution of streamflow for the Rio Blanco, Little Navajo River, and Navajo River could affect the amount of water diverted and the seasonal distribution of streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir. It is possible that a shortened duration for snowmelt runoff could result in higher daily streamflow than an equivalent snowmelt runoff with a longer duration. Higher daily streamflow could result in more days with streamflow volumes that exceed the capacity of the diversion structures and a reduction in the proportion of water that could be diverted for the SJCP. Less total annual snowmelt runoff will result in less total water available for diversion for the SJCP. Additionally, changes in the timing could affect the amount of streamflow available for diversions because the minimum bypass flow requirements for the Rio Blanco, Little Navajo River, and Navajo River vary by month. Determination of the possible effects of changes in the seasonal distribution of streamflow for the SJCP was beyond the scope of this report.

For the Rio Blanco, Little Navajo River, and Navajo River, longer duration of runoff generally occurred later in the year, a smaller percentage of streamflow generally occurred in March, and a larger percentage of streamflow and larger monthly streamflow generally occurred in June during years

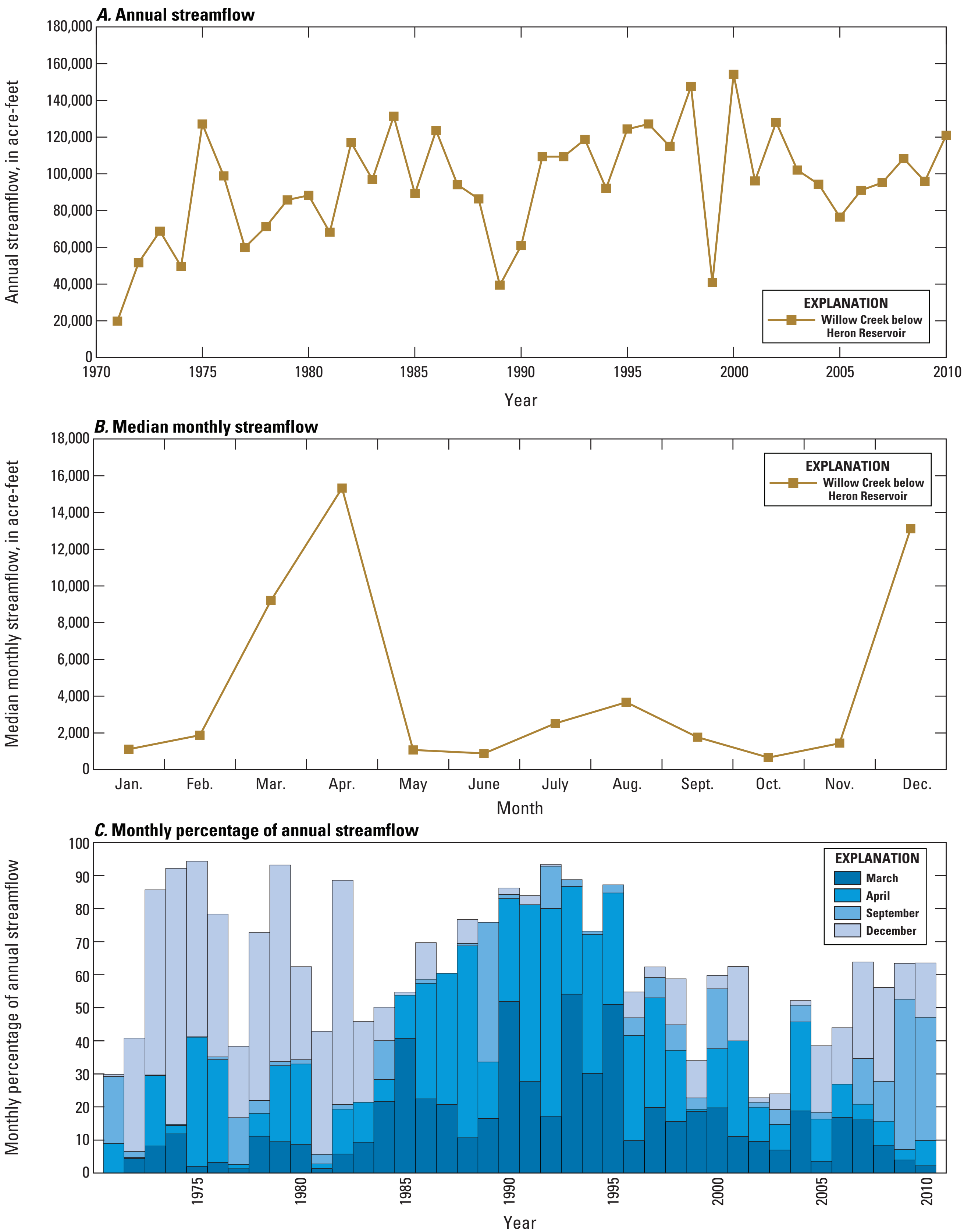


Figure 15. Annual and seasonal variation in streamflow at the streamflow-gaging station Willow Creek below Heron Reservoir, northern New Mexico, 1971–2010. *A*, Annual streamflow. *B*, Median monthly streamflow. *C*, Monthly percentage of annual streamflow for March, April, September, and December over the period of record.

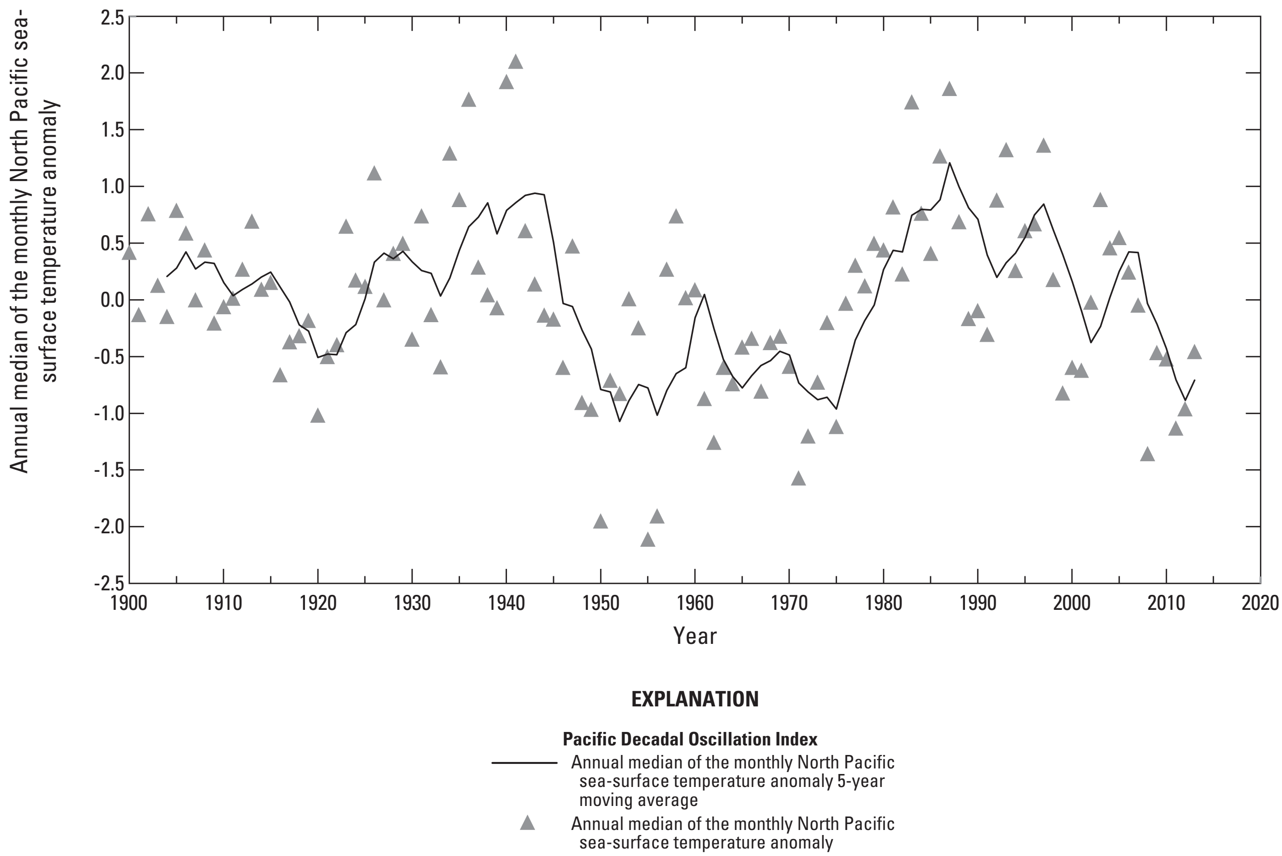


Figure 16. Pacific Decadal Oscillation index for 1900–2012, defined as the median annual monthly North Pacific sea-surface temperature anomaly with a 5-year moving average (data modified from Mantua and Hare, 2011).

with more annual streamflow (Falk and others, 2013). The majority of annual streamflow at Azotea Tunnel Outlet generally occurred from May through June with a median duration of slightly longer than a month. In general, a longer duration for the middle 50 percent of annual streamflow; a larger streamflow in May, June, and July; and a larger percentage of streamflow in June and July occurred during years with larger annual streamflow at Azotea Tunnel Outlet. Additionally, years with higher maximum daily streamflow were also years with higher annual streamflow. These results indicated that the timing and duration of streamflow at Azotea Tunnel Outlet occurred later and that higher daily streamflow occurred during years with more annual streamflow than during years with less annual streamflow.

The seasonal and annual streamflows at Willow Creek below Heron Reservoir are controlled by releases from Heron Reservoir to meet the demand from downstream users. Annual streamflow at Willow Creek below Heron Reservoir has increased over the period of record. Generally, streamflow at Willow Creek below Heron Reservoir was greatest during early spring with smaller flows in later summer; however, releases for recent years have been more evenly distributed through the year, with increases in releases in December and September.

Heron Reservoir Storage

For reservoir systems like Heron Reservoir, the seasonal and annual variations in the amount of water in storage in the reservoir are predominantly controlled by the volume of inflows and the demands for releases from the downstream water users. Storage in a reservoir will increase when the inflows exceed the outflows and seepage. For the analysis of change in reservoir storage, inflows to Heron Reservoir included gaged streamflows at Willow Creek above Heron Reservoir and Horse Lake Creek, ungaged streamflow and direct runoff into the reservoir, and precipitation onto the water surface. Outflows from Heron Reservoir included the gaged streamflow at Willow Creek below Heron Reservoir, evaporation from the water surface, and leakage from the reservoir. Leakage from Heron Reservoir was estimated in 1988 to "average between 2 and 3 cfs [cubic feet per second] at current storage levels" (Bureau of Reclamation, 1988) (2 ft^3/s for 1 year is equivalent to 1,448 acre-ft/yr). Average monthly pan evaporation rates for Heron Reservoir for 1975 to 2005 ranged from 3.6 to 8.5 in., with a maximum average monthly rate of 8.49 in. in June (table 9). The estimated annual evaporation from Heron Reservoir, calculated from the

Table 9. Average rates of precipitation and pan evaporation for Heron Resrvoir, northern New Mexico, 1975–2005 (modified from Whipple, 2007).

[--, data not available]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Pan evaporation, in inches	--	--	--	4.8	6.9	8.5	8.4	7.1	5.5	3.6	--	--
Precipitation, in inches	1.3	1.3	1.5	1.2	1.3	0.8	1.8	2.5	1.7	1.5	1.5	0.99

sum of the average monthly pan evaporation rates for April through October over the maximum surface area of 6,148 acres, was 22,940 acre-ft/yr. Average monthly precipitation rates for Heron Reservoir for 1975 to 2005 ranged from 0.8 to 2.5 in. (table 9). In general, the monthly average precipitation rates for 1975 to 2005 were slightly less than the monthly average precipitation rates for 1905 to 2009 (fig. 3). The estimated annual direct precipitation to Heron Reservoir, calculated from the sum of the average monthly precipitation rates for January through December for 1975–2005 over the maximum surface area of 6,148 acres, was 8,820 acre-ft/yr. For this analysis, the change in storage was calculated from the reported storage in Heron Reservoir.

The amount of water in storage at Heron Reservoir on January 1 of each year during the period 1970–2010 ranged from 42,630 acre-ft in 1971 to 394,800 acre-ft in 1985. For most years of the 1970s, the amount of water in storage increased annually (fig. 12). The reservoir was near capacity for most of the 1980s and 1990s (fig. 12). The amount of water in storage in the reservoir decreased from 2000 to 2004 and generally increased from 2005 to 2010 (fig. 12).

In general, the median monthly change in the volume of water in storage at Heron Reservoir was positive April through June and negative January through March and August through December (fig. 17). The largest median monthly increases in storage occurred in April, May, and June (fig. 17), the months when the largest median monthly streamflow occurred on Willow Creek above Heron Reservoir (fig. 13*B*). The largest individual monthly decreases in storage occurred in March, April, September, and December (fig. 17). Large decreases in storage in March, April, and December likely are associated with releases from Heron Reservoir for SJCP contractors, as measured at Willow Creek below Heron Reservoir (figs. 15*B* and 15*C*). The largest decreases in storage in June occurred in 1977, 2000, and 2002, when there was below average streamflow at Willow Creek above Heron Reservoir and above average streamflow at Willow Creek below Heron Reservoir. In general, storage changes at Heron Reservoir reflect the differences in streamflow at Willow Creek above Heron Reservoir and Willow Creek below Heron Reservoir.

Annual changes in the volume of water in storage at Heron Reservoir have ranged from a decrease in storage of 130,660 acre-ft in 2002 to an increase in storage of 102,200 acre-ft in 1973 (fig. 18*A*). Over the period of record, the change in storage fluctuated between an increase of 25,000 acre-ft and a decrease of 25,000 acre-ft (20 of the 40 years of record) (figs. 18*A* and 18*B*). Reservoir storage during years with near maximum reservoir capacity generally fluctuated over a small range because inflows for these years have nearly equaled outflow. Annual variation in reservoir storage has increased since 1995 (fig. 18*A*) and is likely affected by the variability in both inflows and outflows since 1995 (figs. 13*B* and 15*A*).

Seasonal and Annual Variation in Streamflow for Rio Grande Water

Rio Grande water (streamflow derived from water sources in the Rio Grande Basin) was measured on Willow Creek at two stations: (1) the station at Willow Creek near Park View for the period of record from 1942 to 1971 and (2) Willow Creek above Heron Reservoir for the period before the SJCP diversions from 1962 to 1970. Streamflow at Willow Creek near Park View exceeded the streamflow at Willow Creek above Heron Reservoir because the station at Willow Creek near Park View collected streamflow from a larger drainage area than did the Willow Creek above Heron Reservoir station (table 6); however, the streamflow at both gages followed the same annual trend from 1963 to 1970 (fig. 19*A*). The amount of Rio Grande water was also estimated at Willow Creek above Heron Reservoir for the period from 1971 to 2010 as the difference between measured streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir (streamflow at Willow Creek above Heron Reservoir minus streamflow at Azotea Tunnel Outlet). Rio Grande water, reported as measured streamflow or estimated streamflow, presented in this report was not calculated by following the methods used for the Rio Grande Compact, detailed in the Upper Rio Grande Water Operations Model (U.S. Army Corps

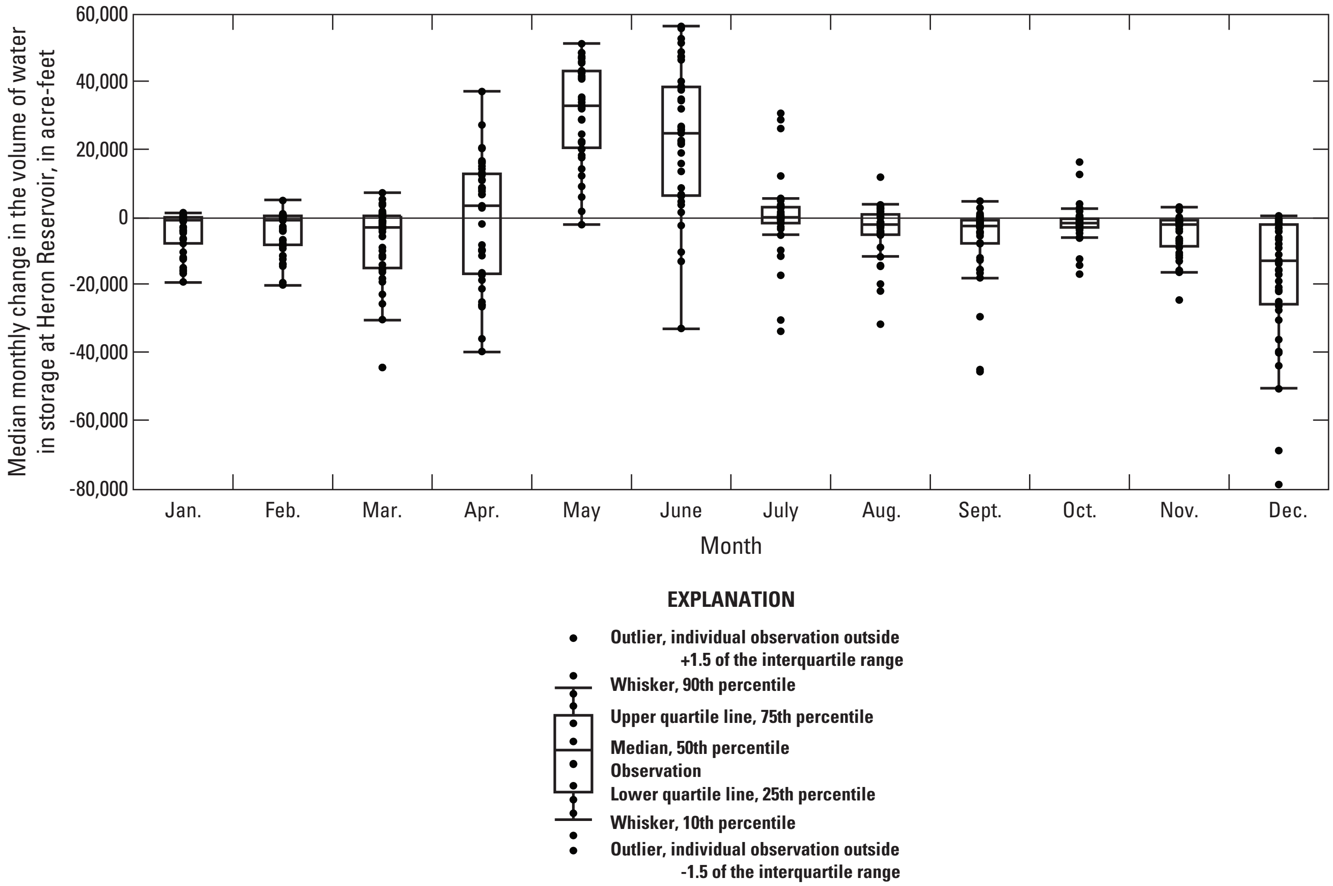


Figure 17. Median monthly change in the volume of water in storage at Heron Reservoir, northern New Mexico, 1970–2010.

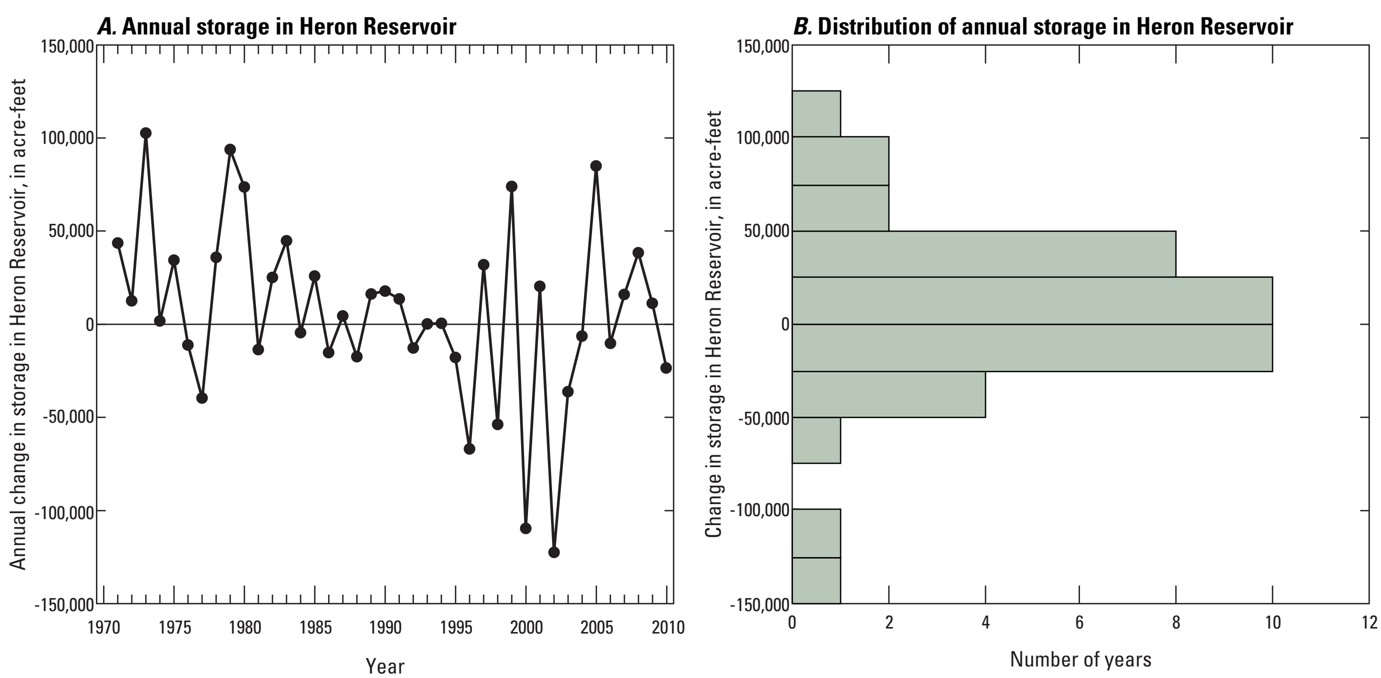
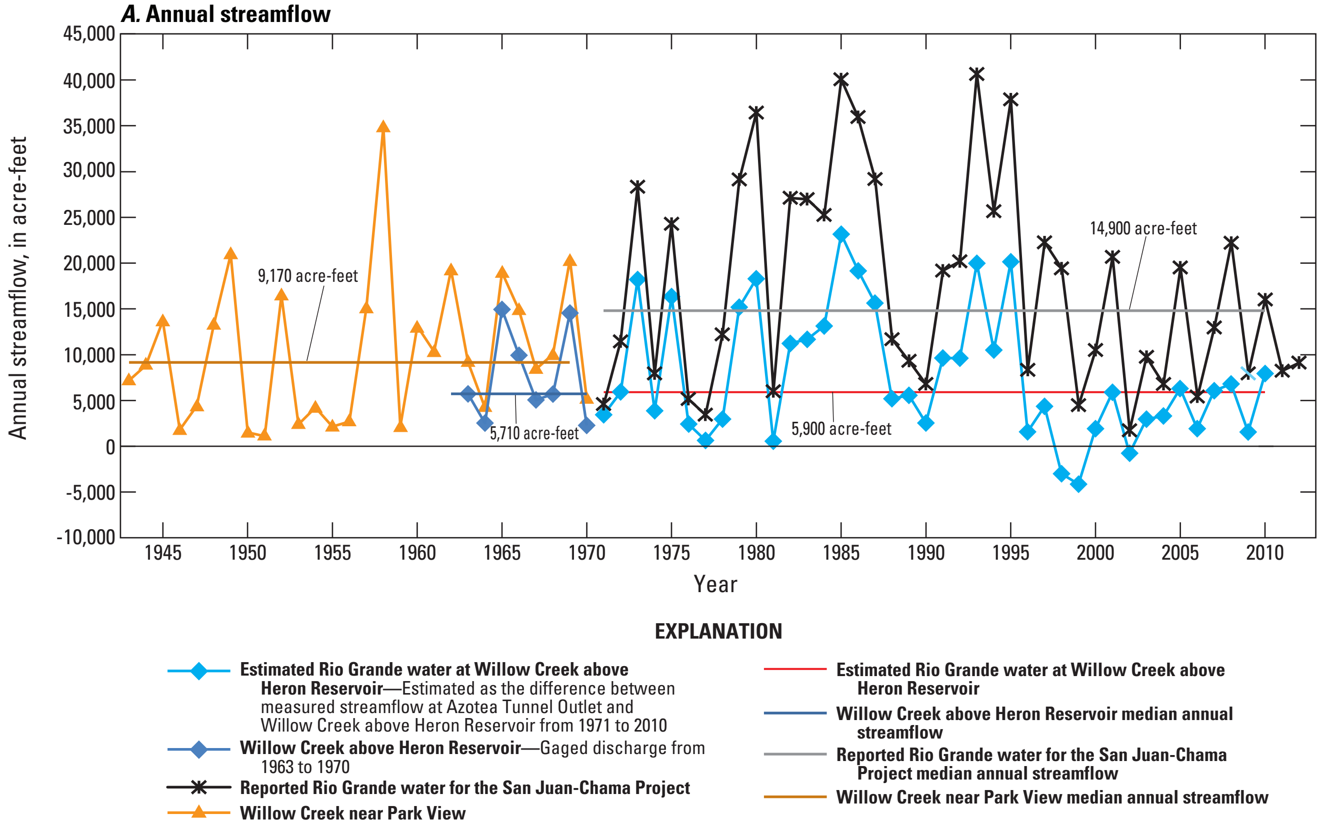


Figure 18. Annual variation in storage in Heron Reservoir, in northern New Mexico, 1970–2010. *A*, Annual storage in Heron Reservoir. *B*, Distribution of annual storage in Heron Reservoir.



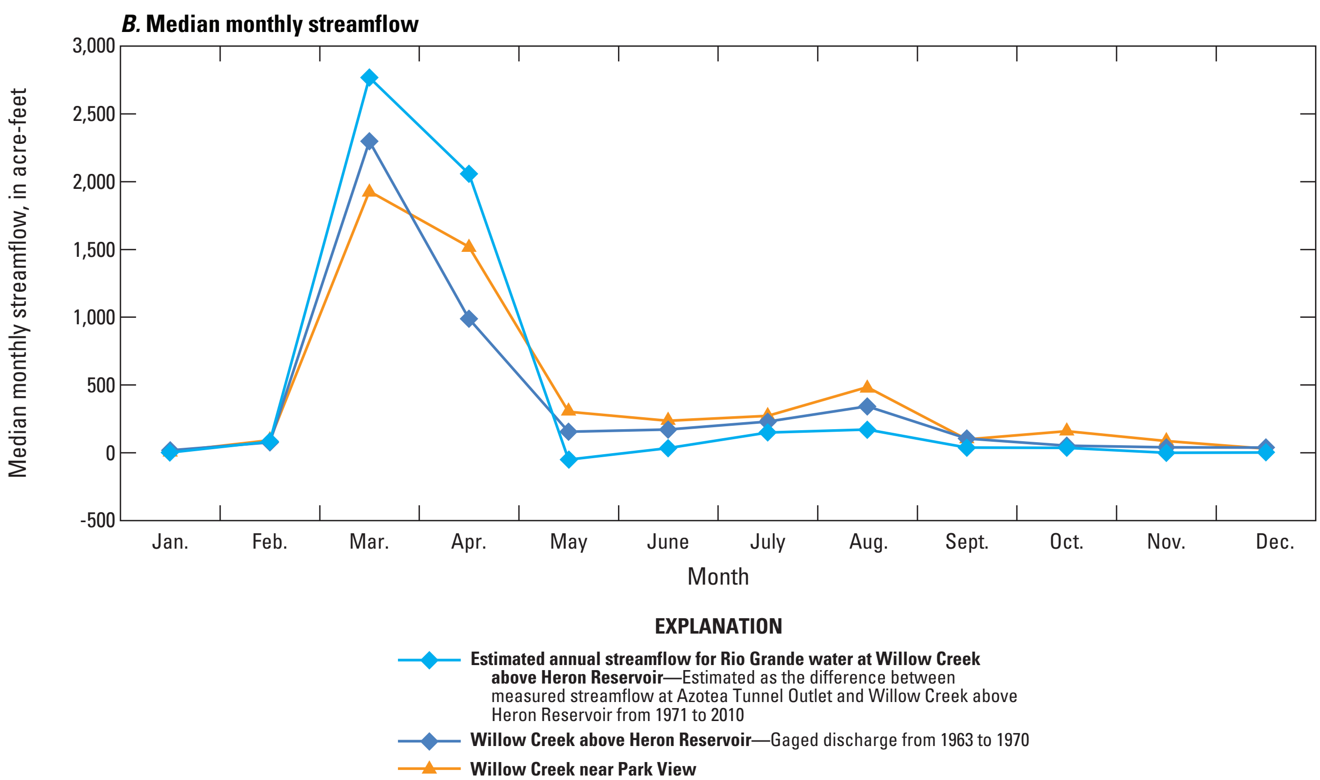


Figure 19. Annual and seasonal variation in Rio Grande streamflow at streamflow-gaging stations Willow Creek near Park View and Willow Creek above Heron Reservoir, 1942–2010. *A*, Annual streamflow. *B*, Median monthly streamflow.

of Engineers, 2005), but represents an estimate of the amount of Rio Grande water for the SJCP. The complex computational methods for calculating the Rio Grande water for the SJCP reported to the Rio Grande Compact Commission, shown in fig. 19*A* (N. Shafike, Interstate Stream Commission, written commun., 2014), are beyond the scope of this report.

Annual Rio Grande streamflow varied substantially over the period of record, and this variation was likely a function of climate including precipitation. The largest measured streamflow was 34,860 acre-ft on Willow Creek near Park View in 1958 (fig. 19*A*). Median annual streamflow from 1943 to 1969 at Willow Creek near Park View was 9,170 acre-ft (table 6). Median annual streamflow from 1963 to 1971 at Willow Creek above Heron Reservoir was 5,710 acre-ft (table 6). Median estimated annual streamflow for Rio Grande water at Willow Creek above Heron Reservoir from 1971 to 2010 was 5,900 acre-ft. Median reported Rio Grande water for the San Juan-Chama Project was 14,900 acre-ft (fig. 19*A*). The difference between measured streamflow at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir was less than zero acre-ft for 1998, 1999, and 2002 (fig. 19*A*). The estimated annual Rio Grande water at Willow Creek above Heron Reservoir from 1971 to 2010 varied over a range of approximately 500 to 20,000 acre-ft/yr until 1996. After 1996, the variability and magnitude of the estimated annual Rio Grande water changed noticeably; however, it was not possible to determine the cause from the available reported data for the stations (fig. 19*A*).

The median monthly Rio Grande streamflow indicated that snowmelt runoff in March and April was the main source of streamflow (fig. 19*B*). Monthly streamflow data for the two stations with measured streamflow and one station with estimated streamflow, all with different periods of record, showed a similar general trend throughout the year (fig. 19*B*). Approximately 70 percent of the annual streamflow occurred in March and April. Summer monsoon derived streamflow in July, August, and September comprised approximately 15 percent of the annual streamflow at these stations. From November to February when little to no water was diverted for the SJCP, most of the streamflow in Willow Creek was Rio Grande water.

Annual Availability of Water for the San Juan-Chama Project

Existing data have been used to compare the theoretical amount of water that could have been diverted for the SJCP to the actual amount of water that was diverted. The amount of water diverted from the streams is affected by a number of factors including legal, structural, capacity, and operational limitations. The effects of these factors on the amount of water available for diversion for the SJCP have been estimated by using historical streamflow data to sequentially determine the amount of water that could be diverted after accounting for the legal limitations (legally limited available streamflow), structural limitations (structurally limited available streamflow), capacity limitations (capacity-limited available streamflow), and operational limitations (operationally limited available streamflow). Evaluation of the effects of the factors that limit diversions could provide information to water management agencies to maximize the diversion of water for the SJCP and to assess possible changes to infrastructure or operating procedure.

The legal limitation that has the largest effect on the amount of streamflow available for diversion for the SJCP is the minimum monthly bypass requirements detailed by P.L. 87-483. Streamflow in the Rio Blanco, Little Navajo River, and Navajo River cannot be depleted below the minimum monthly bypass requirement for each stream. The minimum monthly bypass requirements vary for each stream by month, such that the required volume of streamflow maintained in each stream generally is larger March through September than October through February (Falk and others, 2013). In general, a daily minimum bypass requirement is determined by equally dividing the monthly requirement by the days of the month. The diversion gates at the Blanco Diversion Dam, Little Oso Diversion Dam, and Oso Diversion Dam are set every day or every few days to ensure the daily minimum bypass requirement for streamflow is satisfied (E. Wilcox, Chama New Mexico Field Division, Bureau of Reclamation, oral commun., 2009). Other legal limitations, including the maximum diversion in any 10 consecutive years and the annual maximum diversion, have not been exceeded since diversions started in 1971 (figs. 13*A* and 13*C*). An additional legal limitation for diversion of water is that water cannot be spilled from Heron Reservoir; however, this has not occurred because diversions have been reduced before the capacity was exceeded.

The legally limited available streamflow for the Rio Blanco, Little Navajo River, and Navajo River was calculated on the basis of the historical streamflow record for the period March 3, 1974, to December 31, 2010 (described in detail by Falk and others, 2013). The calculated daily streamflow above the minimum monthly bypass requirement was computed by subtracting the daily minimum bypass requirement from the daily streamflow for each stream. Daily calculations were not modified to ensure that the minimum monthly bypass was satisfied when daily streamflow was less than daily minimum bypass. The calculated daily legally limited available streamflow was aggregated to annual intervals to summarize the results. The legally limited available streamflow is greater than the actual water diverted because of the structural, capacity, and operational limitations.

The structural limitations that affect diversion of water for the SJCP include the capacity of the tunnels through which the diverted water is routed. The daily streamflow that can be diverted from Rio Blanco was limited by the capacity of Blanco Tunnel (520 ft^3/s), and the amount that can be diverted from Little Navajo River was limited by the capacity of Little Oso Feeder (150 ft^3/s). The combined amount of water that can be diverted from Rio Blanco and Little Navajo River was also limited by the capacity of Oso

Tunnel (550 ft^3/s). The daily streamflow that can be diverted from Navajo River was limited by the capacity of Oso Feeder (650 ft^3/s). The combined amount of water that can be diverted from Rio Blanco, Little Navajo River, and Navajo River was also limited to the capacity of Azotea Tunnel. The reported capacity of Azotea Tunnel is 950 ft^3/s; however, analysis of the daily streamflow data at Azotea Tunnel Outlet indicated that streamflow volumes of 1,050 ft^3/s were common. The daily structurally limited available streamflow was calculated by subtracting the amount of water that could not be diverted because of structural limitations from the legally limited available streamflow. The calculated daily structurally limited available streamflow was aggregated to annual intervals to summarize the results.

Comparison of the structurally limited available streamflow at Azotea Tunnel capacities of 950 ft^3/s and 1,050 ft^3/s indicated that the additional 100-ft^3/s capacity results in an average annual increase of 2,500 acre-ft of available streamflow with the largest increases in the 1970s and 1980s (fig. 20*A*). Additionally, most of the increases occurred in years with more than 90,000 acre-ft of streamflow available for diversion for the SJCP and escalated during years with more annual available streamflow for diversion for the SJCP (fig. 20*B*). These results indicated that operating the SJCP at a tunnel capacity of 1,050 ft^3/s could capture additional streamflow during years with average to above average streamflow. Historical streamflow at Azotea Tunnel Outlet exceeded 950 ft^3/s during years of large runoff; therefore, a maximum capacity of 1,050 ft^3/s for Azotea Tunnel was used to estimate the structurally limited available streamflow for the SJCP. Use of 1,050 ft^3/s for the capacity of Azotea Tunnel could result in an overestimation of the amount of water that could have been diverted for the SJCP during times that the reported limit of 950 ft^3/s was observed.

The storage capacity of Heron Reservoir is another limitation affecting the amount of water that can be diverted for the SJCP. The capacity-limited available streamflow is the amount of water that can be diverted for the SJCP, accounting for reductions in diversions to prevent exceeding the capacity of the reservoir. The reported storage in Heron Reservoir exceeded the maximum reported storage for several days over the period of record in the 1980s and 1990s to a maximum reported storage of 402,100 acre-ft. Management of reservoir operations, such as releases of water from storage during intervals when the reservoir was near maximum capacity, likely allows flexibility in the amount of inflows that can occur. Though analysis of streamflow and available storage in Heron Reservoir indicates that operation of the reservoir is more complicated, the simplifying assumption that the capacity-limited available streamflow could not exceed the reported capacity of Heron Reservoir was used for this report. In order to evaluate the effect of different storage capacities on the amount of streamflow that can be diverted for the SJCP, the capacity-limited available streamflow was calculated by using two different values: (1) the reported maximum storage capacity of 401,320 acre-ft and (2) a smaller storage capacity of 400,320 acre-ft. The smaller storage capacity provides an approximation of the effect that a change in the volume of storage in Heron Reservoir would have on the amount of water that could be diverted for the SJCP.

The capacity-limited available streamflow was calculated on a daily basis by subtracting water that could not be diverted because the reservoir capacity would be exceeded from the structurally limited available streamflow. A daily available storage in Heron Reservoir was calculated as the difference of the maximum reservoir storage capacity and the reported volume of water in storage in Heron Reservoir. If the daily available storage was greater than zero, the total daily structurally limited available streamflow was assumed to be divertible. The assumption that the storage capacity of the reservoir is decreased to 400,320 acre-ft will result in a maximum estimate of the amount of water not diverted and a minimum estimate for the capacity-limited available streamflow because it is likely that the reservoir was managed to allow inflow during intervals near capacity. The assumption that the maximum storage capacity of the reservoir is 401,320 acre-ft will result in a minimum estimate of the amount of water not diverted and a maximum estimate for the capacity-limited available streamflow. Outflow from Heron Reservoir was not explicitly incorporated into the estimate of the capacity-limited available streamflow; however, the use of the reported volume of water in storage for Heron Reservoir implicitly accounts for outflow. The calculated daily capacity limited available streamflow was aggregated to annual intervals to summarize the results.

Comparison of the capacity-limited available streamflow at the two reservoir storage capacities of 401,320 acre-ft and 400,320 acre-ft indicated that the difference of 1,000 acre-ft of storage capacity resulted in an average decrease of 7,700 acre-ft of available streamflow, with the largest decrease in the 1980s (fig. 20*A*). Decreased available streamflow resulting from a difference in the estimated maximum storage capacity occurred in years when more than 300,000 acre-ft of water was stored in Heron Reservoir, but not all years with more than 300,000 acre-ft of stored water were limited by reservoir capacity (fig. 20*B*). During the late 1980s, Heron Reservoir was near the maximum capacity; however, annual streamflow for these years was below average, and therefore the diversion of water for the SJCP was not limited by reservoir capacity. These results indicate that the limitation of the capacity of Heron Reservoir can substantially decrease the streamflow that can be diverted for the SJCP; however, this limitation only affected diversions in years with high annual available streamflow and near-capacity storage of water in the reservoir (fig. 20*C*). A capacity of 401,320 acre-ft for Heron Reservoir was used to estimate the capacity-limited available streamflow for the SJCP. Use of the 401,320-acre-ft capacity for Heron Reservoir could result in an overestimation of the amount of water that could have been diverted for the SJCP if the reservoir generally was managed to maintain some amount of volume of storage to provide a buffer for additional inflow.

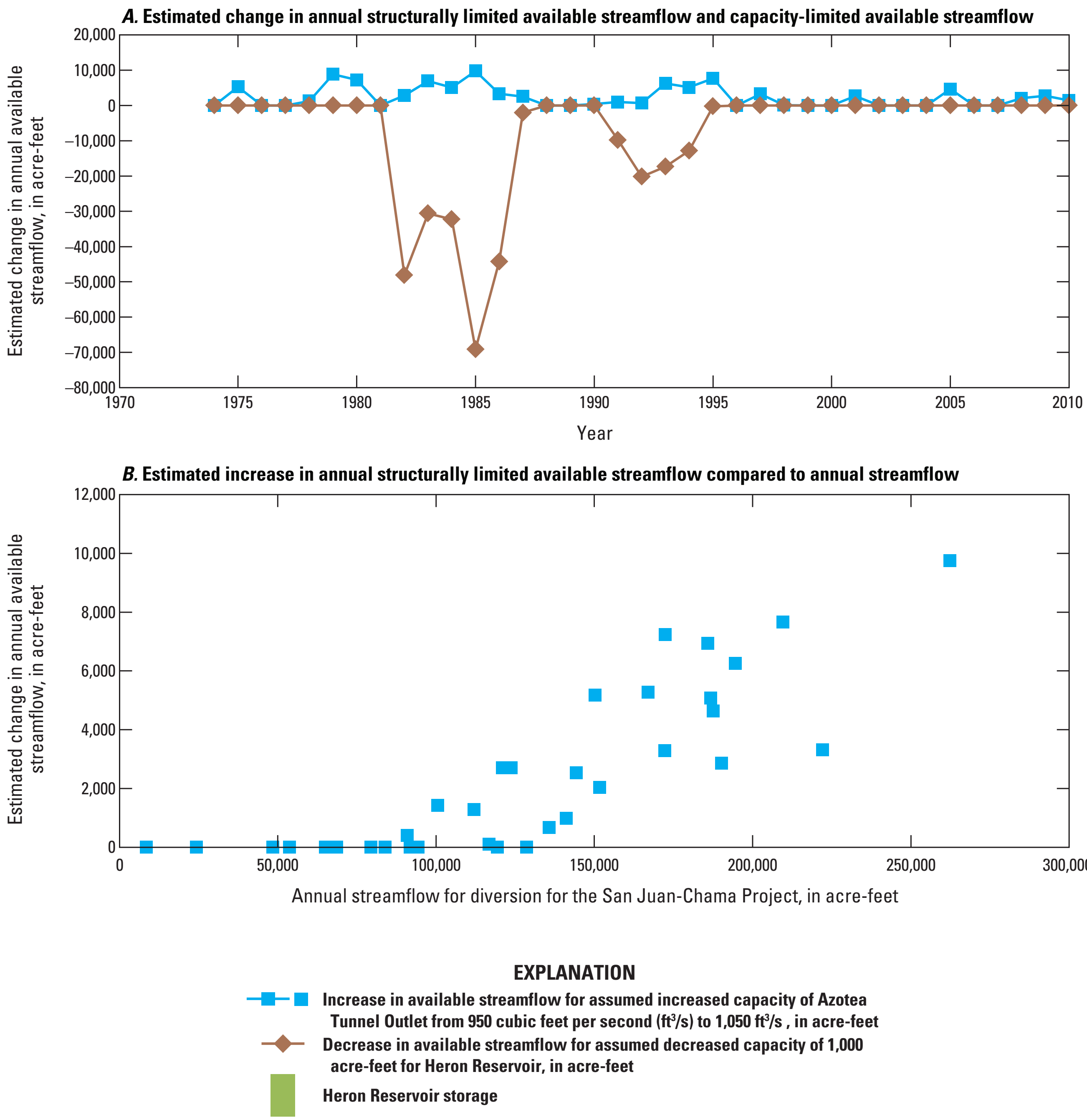


Figure 20. Change in the available streamflow for the San Juan-Chama Project from variation in the structural and capacity limitations. *A*, Comparison of the estimated increase in annual structurally limited available streamflow resulting from a larger estimated maximum capacity of Azotea Tunnel from 950 cubic feet per second (ft^3/s) to 1,050 ft^3/s and the estimated decrease in annual capacity-limited available streamflow resulting from a smaller estimated maximum capacity of Heron Reservoir from 401,320 acre-feet (acre-ft) to 400,320 acre-ft, 1974–2010. *B*, Comparison of the estimated increase in annual structurally limited available streamflow resulting from a larger estimated maximum capacity of Azotea Tunnel from 950 ft^3/s to 1,050 ft^3/s to annual streamflow measured at Azotea Tunnel Outlet. *C*, Comparison of the estimated decrease in annual capacity-limited available streamflow resulting from a smaller estimated maximum capacity of Heron Reservoir from 401,320 acre-ft to 400,320 acre-ft to annual streamflow measured at Azotea Tunnel Outlet, 1974–2010.

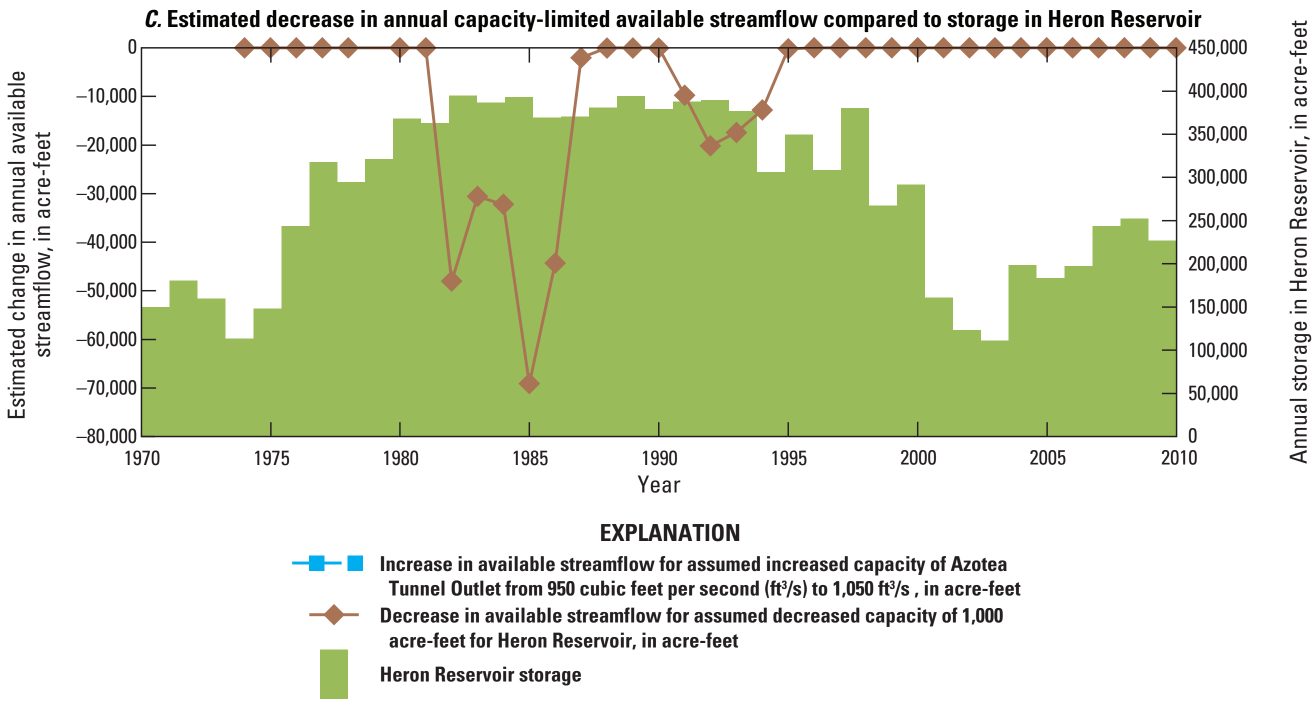


Figure 20. Change in the available streamflow for the San Juan-Chama Project from variation in the structural and capacity limitations. *A*, Comparison of the estimated increase in annual structurally limited available streamflow resulting from a larger estimated maximum capacity of Azotea Tunnel from 950 cubic feet per second (ft^3/s) to 1,050 ft^3/s and the estimated decrease in annual capacity-limited available streamflow resulting from a smaller estimated maximum capacity of Heron Reservoir from 401,320 acre-feet (acre-ft) to 400,320 acre-ft, 1974–2010. *B*, Comparison of the estimated increase in annual structurally limited available streamflow resulting from a larger estimated maximum capacity of Azotea Tunnel from 950 ft^3/s to 1,050 ft^3/s to annual streamflow measured at Azotea Tunnel Outlet. *C*, Comparison of the estimated decrease in annual capacity-limited available streamflow resulting from a smaller estimated maximum capacity of Heron Reservoir from 401,320 acre-ft to 400,320 acre-ft to annual streamflow measured at Azotea Tunnel Outlet, 1974–2010.—Continued

The amount of water that can be diverted for the SJCP is also limited by operational constraints as a result of the management of the SJCP. Historically, management of the SJCP included closure of the gates on the diversion structures on the Rio Blanco, Little Navajo River, and Navajo River from November to February for maintenance and safety reasons. The operationally limited available streamflow was calculated by determining which days recorded diversions of zero and subtracting the daily legally limited available streamflow from the daily capacity-limited available streamflow. If the operationally limited available streamflow was computed as less than zero, a value of zero was assumed. For each year, the day of the start of diversion of streamflow was determined as the first day on which flow occurred at Azotea Tunnel Outlet, and the day of the end of diversion of streamflow was determined as the day on which 99.9 percent of annual streamflow occurred. The calculated daily operationally limited available streamflow was aggregated to annual intervals to summarize the results.

The effects of the variation in the structural and capacity limitations on the amount of water available for diversion for the SJCP was estimated by calculating the operationally limited available streamflow for four scenarios that span the structural and capacity limitations described previously. The four scenarios for operationally limited available streamflow included (1) Azotea Tunnel capacity of 950 ft^3/s and storage capacity of Heron Reservoir of 400,320 acre-ft, (2) Azotea Tunnel capacity of 1,050 ft^3/s and storage capacity of Heron Reservoir of 400,320 acre-ft, (3) Azotea Tunnel capacity of 950 ft^3/s and storage capacity of Heron Reservoir of 401,320 acre-ft, and (4) Azotea Tunnel capacity of 1,050 ft^3/s and storage capacity of Heron Reservoir of 401,320 acre-ft (fig. 21). Comparison of the scenarios indicated that the variations in the structural and capacity limitations primarily affected the available streamflow during the 1980s and early 1990s (fig. 21). Additionally, the variations in the structural and capacity limitations was minor compared to the amount of operationally limited available streamflow for the SJCP during recent years from 1999.

The calculations of the structurally limited available streamflow, capacity-limited available streamflow, and operationally limited available streamflow for the SJCP are

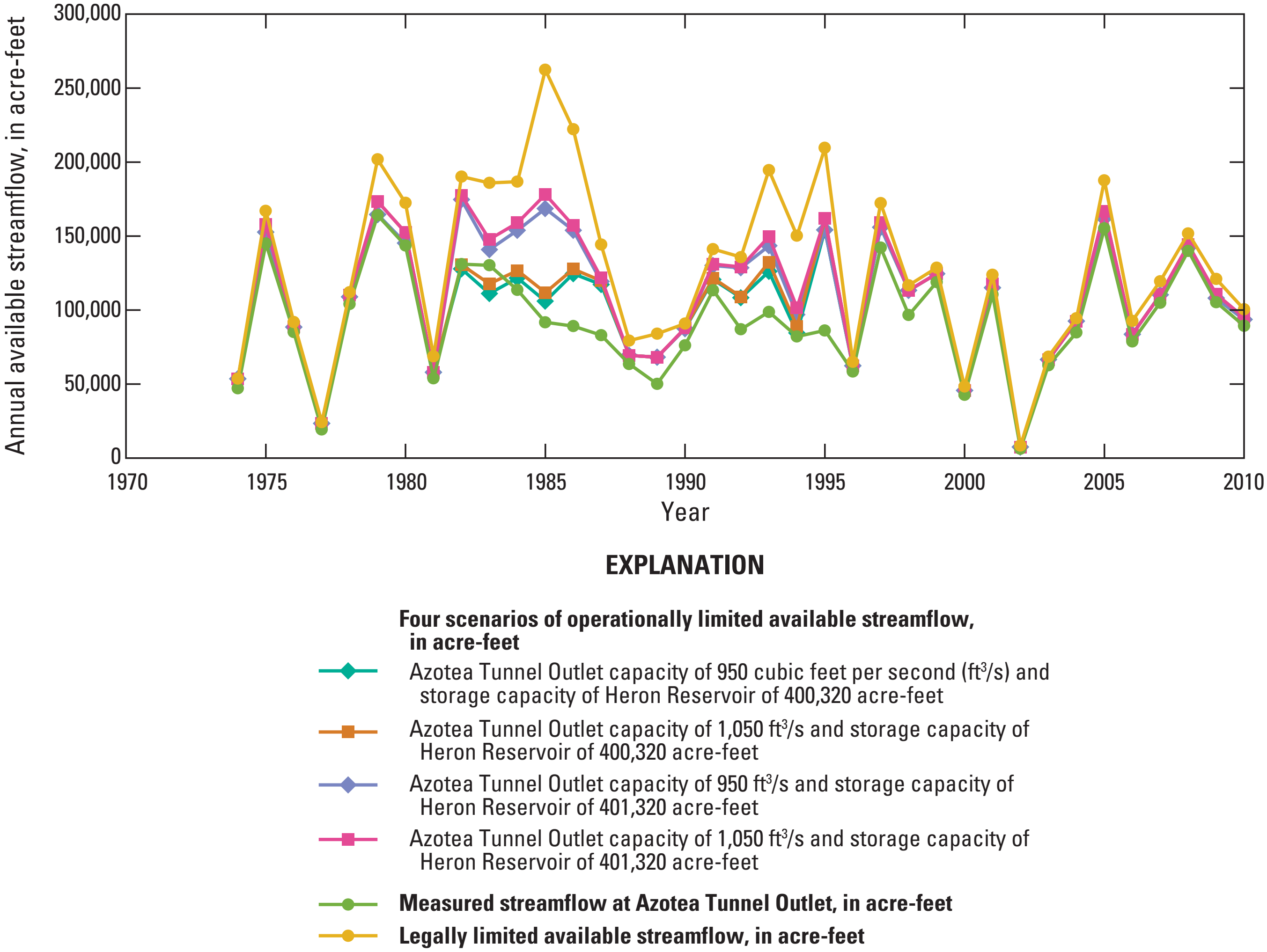


Figure 21. Operationally limited available streamflow for the San Juan-Chama Project for four scenarios of structural and capacity limitations, 1974–2010.

estimates and are subject to the limitations of the data and the simplifying assumptions that were made about management of the SJCP from 1971 to 2010. Consistent positive or negative errors in streamflow data would bias these estimates. Changes in operating procedures of the project would also affect the estimates of the structurally limited available streamflow and capacity-limited available streamflow. The estimated available streamflow is suitable for evaluating the significance of selected factors that affect the amount of water that can be diverted for the SJCP but is not suitable for accurate accounting of all factors that affect diversions for the SJCP. The estimated operationally limited available streamflow did not equal the actual diversion of streamflow measured at Azotea Tunnel Outlet, indicating that an amount of water was not diverted for reasons not accounted for in this analysis. Water is not diverted for many reasons, including higher bypass flows to ensure downstream requirements were met and times when ice or debris may block the intake structures such that flow cannot be diverted (C. Donnelly, Albuquerque Area Office, Bureau of Reclamation, written commun., 2013). Inclusion of additional reasons for decreased diversion of water for the SJCP was beyond the scope of this report (this volume of water is referred to as “available streamflow not diverted for unknown reasons”).

The annual availability of streamflow for the SJCP varied over the period from 1975 to 2010, which includes all years with complete record of daily flow (fig. 22). In general, variation in the estimate of streamflow availability for the different limitations was bounded by the variability in the streamflow for the SJCP (computed as the sum of the streamflow from Rio Blanco, Little Navajo River, and Navajo River) (fig. 22). The streamflow for the SJCP was less than the annual water contracted (95,475 acre-ft) during several years and was substantially reduced after accounting for

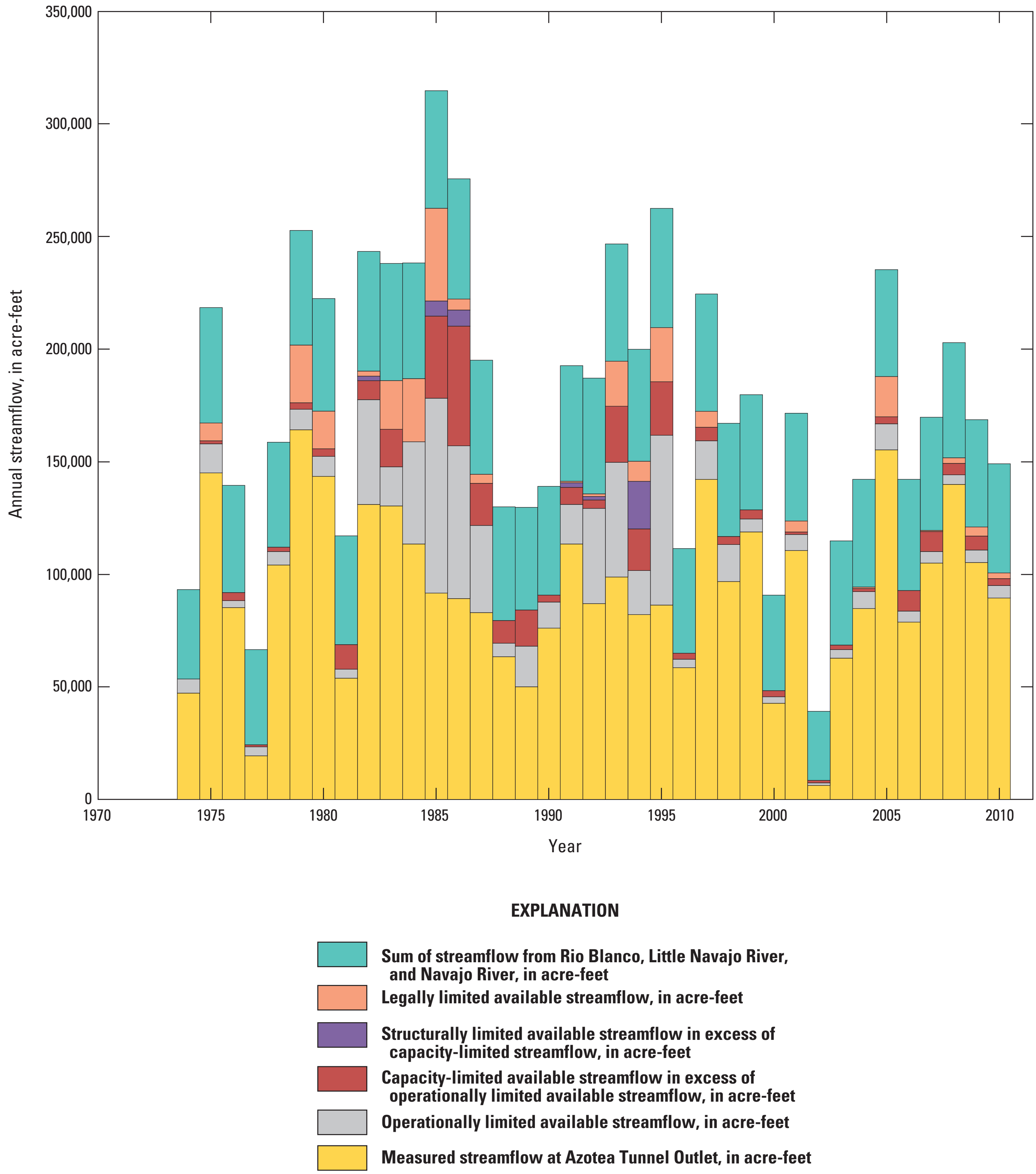


Figure 22. Annual available streamflow for the San Juan-Chama Project, 1975–2010, northern New Mexico.

the minimum monthly bypass requirement (legally limited available streamflow) (fig. 22). The reduction in available streamflow because of the structural limitations of the SJCP infrastructure (computed as the difference between legally limited streamflow available for diversion and the structurally limited available streamflow) was an annual average of 7,000 acre-ft (table 10). The capacity-limited available streamflow was the same as the structurally limited available streamflow for most years, except for a few years in the 1980s and 1990s when Heron Reservoir was near capacity. The annual average reduction in available streamflow because of operational limitations (computed as the difference between the capacity-limited available streamflow and the operationally limited available streamflow) was 9,000 acre-ft (table 10) and generally was larger in the 1980s and 1990s than the 1970s and 2000s (fig. 22).

The average annual legally limited available streamflow for the SJCP from 1975 to 2010 provided estimates of the expected amount of water available for diversion for the SJCP. The average annual legally limited available streamflow for the SJCP was 131,000 acre-ft, and the average annual streamflow at Azotea Tunnel Outlet was 94,710 acre-ft (table 10). On average, the annual streamflow at Azotea Tunnel Outlet was approximately 75 percent of the annual legally limited available streamflow for the SJCP. The annual streamflow not diverted for the SJCP, defined as the difference between the annual legally limited available streamflow for the SJCP and the measured annual streamflow at Azotea Tunnel Outlet, was an average of 35,000 acre-ft. The average annual percentage of available streamflow not diverted for the SJCP was 14 percent because of structural limitations of the capacity of infrastructure, 1 percent because of limitations of the reservoir storage capacity, and 29 percent because of the limitations from operations. For most years, the annual available streamflow not diverted for unknown reasons exceeded the sum of the water not diverted because of structural, capacity, and operational limitations (fig. 23). From 1975 to 2010, the average annual measured streamflow at Azotea Tunnel Outlet was 85 percent of the annual operationally limited available streamflow for that year (fig. 23). During the period from 2000 to 2010, the measured streamflow at Azotea Tunnel Outlet was an average of 93 percent of the estimated operationally limited available streamflow (fig. 23). The difference between the measured annual streamflow at Azotea Tunnel Outlet and the annual operationally limited available streamflow was greater at higher streamflow than at lower streamflow (fig. 24).

Table 10. Average annual available streamflow for selected limitations of the San Juan-Chama Project.

	Streamflow for the San Juan-Chama Project (the sum of the streamflow from Rio Blanco, Little Navajo River, and Navajo River)	Legally limited available streamflow (acre-feet)	Structurally limited available streamflow (acre-feet)	Capacity-limited available streamflow (acre-feet)	Operationally limited available streamflow (acre-feet)	Measured streamflow at Azotea Tunnel Outlet (acre-feet)
Average annual streamflow for 1975–2010, in acre-feet	180,000	131,000	124,000	123,000	114,000	94,710

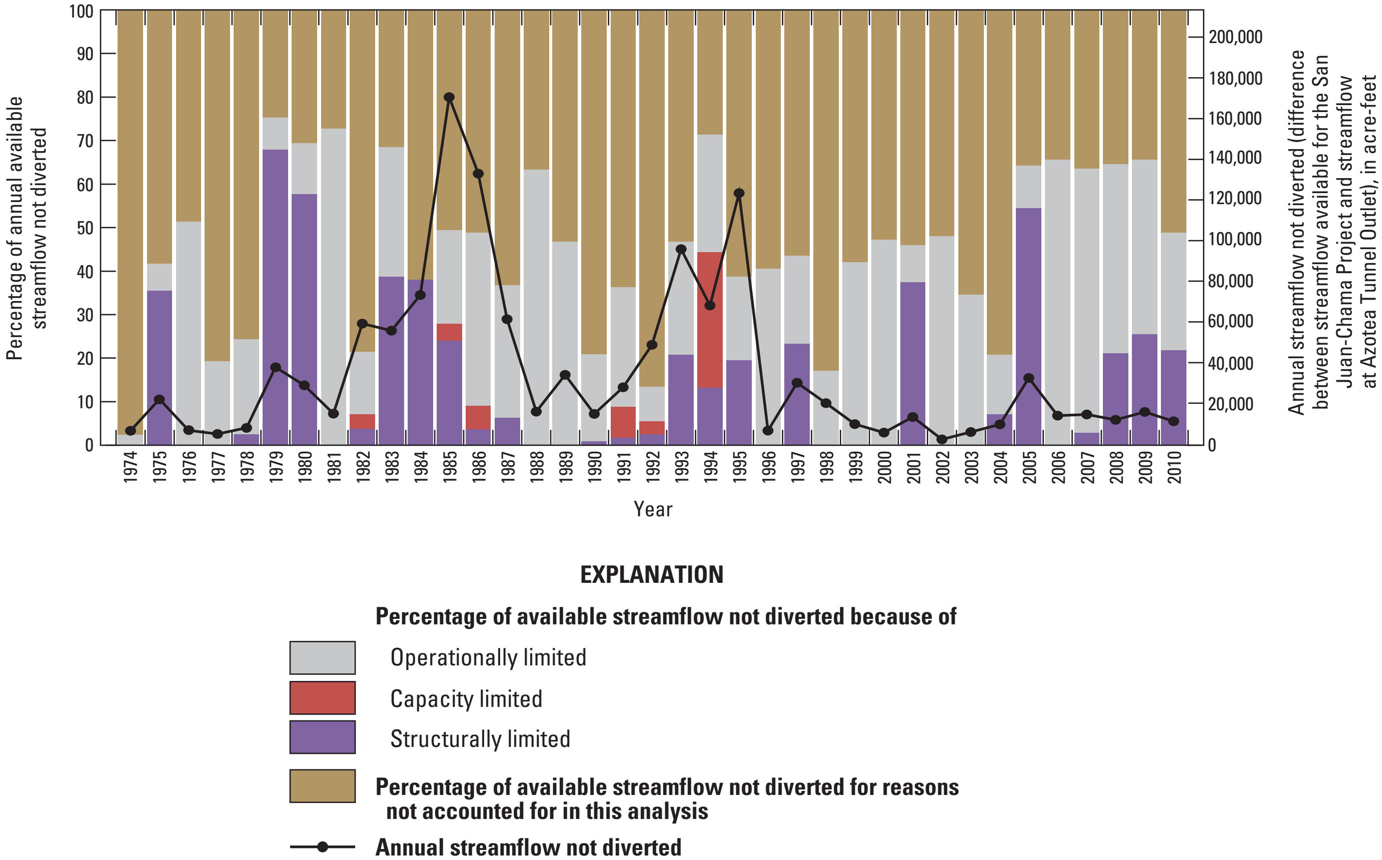


Figure 23. Percentage of annual available streamflow not diverted for the San Juan-Chama Project for structure, capacity, and operations limitations, percentage of annual streamflow not diverted for reasons not accounted for in this analysis, and the total annual streamflow not diverted for the San Juan-Chama Project, northern New Mexico, 1974–2010.

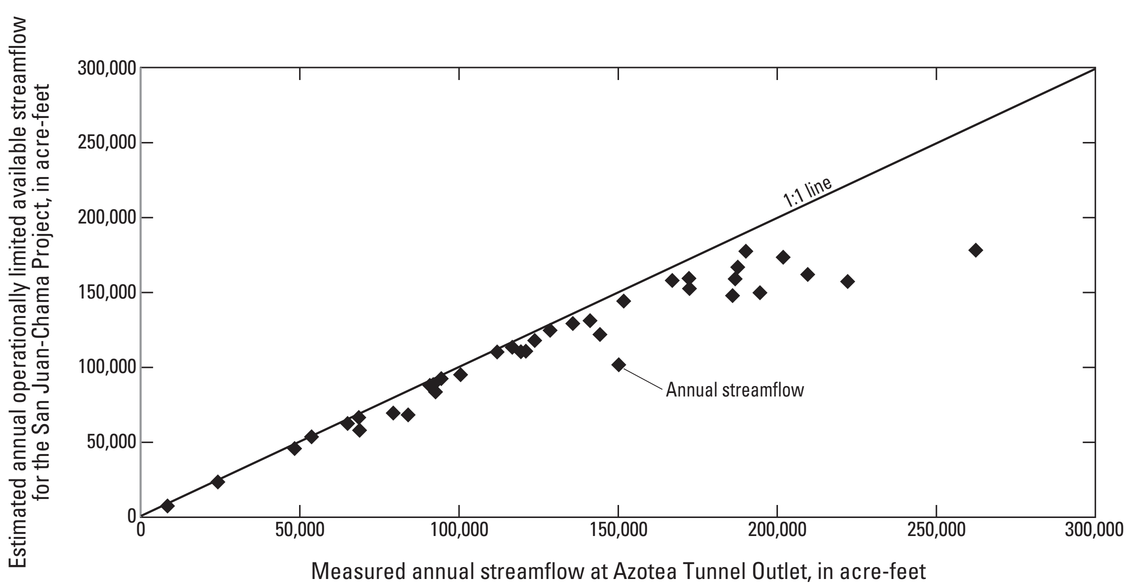


Figure 24. Measured annual streamflow at Azotea Tunnel Outlet compared to estimated annual operationally limited available streamflow for the San Juan-Chama Project, northern New Mexico, 1974–2010.

Summary

The Albuquerque Bernalillo County Water Utility Authority (ABCWUA) supplements the municipal water supply for the Albuquerque metropolitan area, in central New Mexico, with surface water diverted from the Rio Grande. ABCWUA's allotment of surface water diverted from the Rio Grande is derived from the San Juan-Chama Project (SJCP), which delivers water from streams in the southern San Juan Mountains in the Colorado River Basin in southern Colorado to the Rio Chama in the Rio Grande Basin in northern New Mexico. In an effort to provide more information about water chemistry and quantity, the U.S. Geological Survey (USGS), in cooperation with the ABCWUA, undertook this study in which historical streamflow and water-chemistry data were compiled, and new water-chemistry data were collected to characterize the water chemistry and streamflow of the SJCP. Characterization of streamflow included analysis of the variability of annual streamflow and comparison of the theoretical amount of water that could have been diverted into the SJCP to the actual amount of water that was diverted for the SJCP. Additionally, a seepage investigation was conducted along the channel between Azotea Tunnel Outlet and the streamflow-gaging station (station) at Willow Creek above Heron Reservoir to estimate the magnitude of the gain or loss in streamflow resulting from groundwater interaction over the approximately 10-mile reach.

In general, surface-water chemistry at Azotea Tunnel Outlet and Willow Creek above Heron Reservoir varied throughout the year as a function of streamflow. Streamflow varied from high flow to low flow on the basis of the quantity of water diverted from the Rio Blanco, Little Navajo River, and Navajo River for the SJCP. During high flow, the ionic composition of water from Azotea Tunnel Outlet was similar to the composition of a mixture of water from Rio Blanco and Navajo River, and there were small but distinct differences in ion composition and specific conductance in water from Willow Creek above Heron Reservoir compared to water from Azotea Tunnel Outlet. Vertical profiles of the water temperature over the depth of the water column collected in April 2008, October 2008, July 2009, August 2009, and September 2009 indicated that Heron Reservoir is thermally stratified in the early fall and thermally mixed in early spring. Vertical profiles of the dissolved-oxygen concentration over the depth of the water column at Heron Reservoir indicated that the thermal stratification results in chemical stratification. When the reservoir was stratified, the dissolved-oxygen concentration was highest above and below the thermocline, and the lowest dissolved-oxygen concentration generally occurred at the top of the thermocline. Major- and trace-element concentrations in samples collected for this study were less than the U.S. Environmental Protection Agency's primary and secondary drinking-water standards and less than the New Mexico Environment Department's surface-water standards for Heron Reservoir and perennial reaches of tributaries to the Rio Chama in the study area.

The results from the seepage investigations indicated a small amount of loss of streamflow along the channel. During high flow, the loss was estimated at 3 percent; however, the uncertainty in the measured streamflow measurements precludes an exact determination of the loss. During low flow, the estimated loss was extremely small, and the uncertainty generally was close to or exceeded the estimated loss. The possible loss of streamflow resulting from groundwater/surface-water interactions during low flow was not a significant volume compared to streamflow volumes during high flow.

Annual variability in streamflow for the SJCP was an indication of the variation in the climate parameters that interact to contribute to streamflow in the Rio Blanco, Little Navajo River, Navajo River, and Willow Creek watersheds. The median monthly streamflow for Azotea Tunnel Outlet and Willow Creek above Heron Reservoir indicated that streamflow at these stations was typical of watersheds that are snowmelt-dominated systems. For most years, streamflow at Azotea Tunnel Outlet started by March and continued for approximately 3 months until the middle of July. The majority of annual streamflow at Azotea Tunnel Outlet generally occurred from May through June, with a median duration of slightly longer than a month. Additionally, higher annual streamflow occurred in years with higher maximum daily streamflow. The results from the Mann-Kendall trend test showed that there was not a significant trend in the annual streamflow at Azotea Tunnel Outlet over time from 1971 to 2010. The difference between the occurrence and the strength of significant trends between the time series of the seasonal distribution of streamflow and the seasonal streamflow compared to annual streamflow indicated that the seasonal distribution of streamflow was more strongly controlled by the change in the annual streamflow than by time.

Historically, the timing of large monthly releases from Heron Reservoir has varied, likely because of variations in downstream use and the total annual release. The majority of releases from Heron Reservoir during the 1970s and early 1980s occurred in December, and the majority of releases in the middle and late 1980s and 1990s occurred in March and April. More recently in the 2000s, releases have been more evenly distributed through the year with some recent increases in releases in December (2007 and 2008) and September (2009 and 2010).

Rio Grande water (streamflow derived from water sources in the Rio Grande Basin) varied substantially over the period of record, and this variation was likely a function of climate including precipitation. The median monthly Rio Grande water indicated that snowmelt runoff in March and April was the main source of streamflow and accounted for approximately 70 percent of the annual streamflow. From November to February, when little to no water was diverted for the SJCP, most of the streamflow in Willow Creek was Rio Grande water.

The amount of water that can be diverted for the SJCP is controlled by the streamflow available for diversion and is limited by several factors including legal limitations for diversion, limitations from the SJCP infrastructure including the size of the diversion dams and tunnels, the capacity of Heron Reservoir, and operational constraints that limit when water can be diverted. Comparison of the structurally limited available streamflow at the two tunnel capacities of 950 cubic feet per second (ft^3/s) and 1,050 ft^3/s indicated that the additional 100 ft^3/s of capacity could capture additional streamflow during years with average to above average streamflow. Comparison of the capacity-limited available streamflow at the two reservoir storage capacities of 401,320 acre-feet (acre-ft) and 400,320 acre-ft indicated that the difference of 1,000 acre-ft of storage capacity can substantially decrease the amount of streamflow that can be diverted for the SJCP; however, the effect is constrained to years with high annual available streamflow and near-capacity storage of water in the reservoir.

The average annual streamflow at Azotea Tunnel Outlet was 94,710 acre-ft, and the annual streamflow at Azotea Tunnel Outlet was approximately 75 percent of the annual streamflow available for diversion for the SJCP. The average annual percentage of available streamflow not diverted for the SJCP was 14 percent because of structural limitations of the capacity of infrastructure, 1 percent because of limitations of the reservoir storage capacity, and 29 percent because of the limitations from operations.

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