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Traveltime of the Rio Grande in the Middle Rio Grande Basin, New Mexico, Water Years 2003–05

Scientific Investigations Report 2007–5292

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

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Conversion Factors

Multiply	By	To obtain
inch (in)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83).

Water year is the 12-month period of October 1 through September 30, designated by the calendar year in which it ends.

Traveltime of the Rio Grande in the Middle Rio Grande Basin, New Mexico, Water Years 2003–05

By Jeff B. Langman

Abstract

The quality of water in the Rio Grande is becoming increasingly important as more surface water is proposed for diversion from the river for potable and nonpotable uses. In cooperation with the Albuquerque Bernalillo County Water Utility Authority, the U.S. Geological Survey examined traveltime of the Rio Grande in the Middle Rio Grande Basin to evaluate the potential travel of a conservative solute entrained in the river's streamflow. A flow-pulse analysis was performed to determine traveltimes of a wide range of streamflows in the Rio Grande, to develop traveltime curves for estimating the possible traveltime of a conservative solute in the Rio Grande between Cochiti Dam and Albuquerque, and to evaluate streamflow velocities and dispersion and storage characteristics of the Rio Grande in the entire Middle Rio Grande Basin. A flow-pulse analysis was applied to 12 pulse events recorded during the 2003–05 water years for streamflow-gaging stations between Cochiti Dam and the city of San Acacia. Pulse streamflows ranged from 495 to 5,190 cubic feet per second (ft^3/s).

Three points of each pulse were tracked as the pulse passed a station—rising-limb leading edge, plateau leading edge, and plateau trailing edge. Most pulses indicated longer traveltimes for each successive point in the pulse. Dispersion and spreading of the pulses decreased with increased streamflow. Decreasing traveltimes were not always consistent with increasing streamflow, particularly for flows less than 1,750 ft^3/s, and the relation of traveltime and original pulse streamflow at Cochiti indicated a nonlinear component. Average streamflow velocities decreased by greater than 30 percent from San Felipe to San Acacia. The expected trend of increasing dispersion with downstream travel was not always visible because of other influences on streamflow. With downstream flow, distributions of the pulses became more skewed to the descending limbs, indicating possible short-term storage of a part of the pulses.

Introduction

The quality of water in the Rio Grande in New Mexico is becoming increasingly important as more surface water is being proposed for diversion from the river for potable and nonpotable uses. Historically, water from the Rio Grande in the Middle Rio Grande Basin was typically diverted for agriculture during part of the year, but with proposed diversions for municipal supply, a contaminant spill into the Rio Grande could have a substantial effect on use of the resource and health of the populace. In cooperation with the Albuquerque Bernalillo County Water Utility Authority (ABCWUA), the U.S. Geological Survey (USGS) examined traveltime of the Rio Grande in the Middle Rio Grande Basin to evaluate the potential travel of a conservative solute entrained in the river's streamflow (discharge or rate of flow). Traveltime refers to the time of movement of water and (or) waterborne solutes in a river from an upstream location to a downstream location under a given streamflow condition. In the event of contamination of water supplies, water-resource managers must decide when, and for how long, to suspend diversions. Knowledge of traveltime of the Rio Grande will allow water-resource managers to make informed decisions concerning the timing of diversions from the Rio Grande.

Purpose and Scope

The purpose of this report is to describe traveltimes of the Rio Grande in the Middle Rio Grande Basin during selected times of the year during water years 2003–05. A flow-pulse analysis was performed by using streamflow data from USGS streamflow-gaging stations (stations). Results were used to (1) determine traveltimes of a wide range of streamflows, (2) produce traveltime curves for estimating the potential traveltime of a conservative solute in the Rio Grande between any two points from Cochiti Dam to Albuquerque, and (3) evaluate streamflow velocities, dispersion, and storage characteristics in the entire Middle Rio Grande Basin (Cochiti Dam to San Acacia, about 115 river miles [mi]).

Description of the Study Area

The Middle Rio Grande Basin is the area within the Rio Grande Valley extending from Cochiti Lake to San Acacia (fig. 1). Rio Grande streamflow is released from Cochiti Dam and flows through the Cochiti, Santo Domingo, San Felipe, Santa Ana, and Sandia Pueblos prior to reaching the city of

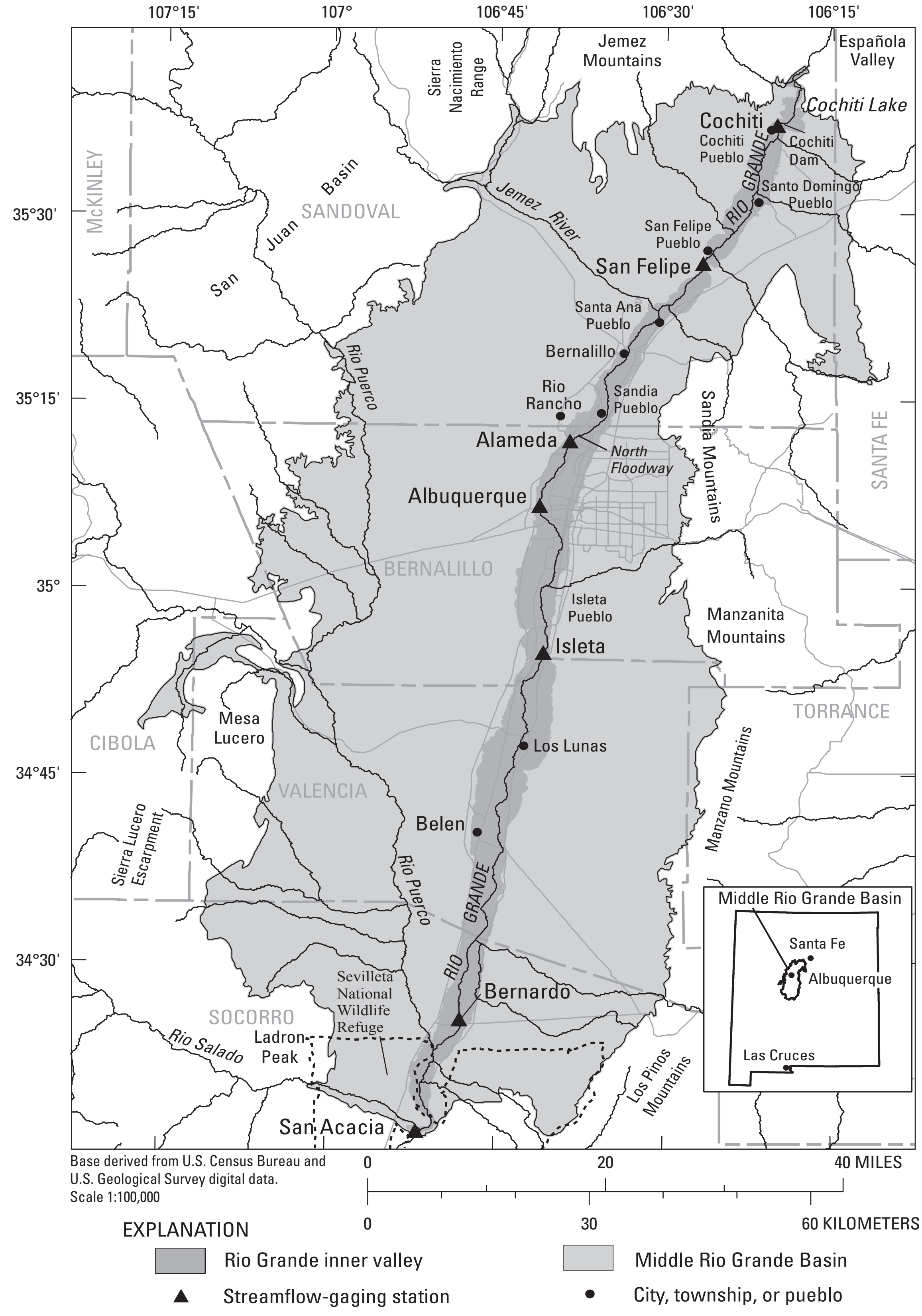

Figure 1. Middle Rio Grande Basin and the Rio Grande (modified from Bartolino and Cole, 2002).

Albuquerque. Downstream from Albuquerque, the Rio Grande flows through Isleta Pueblo, Los Lunas, Belen, Bernardo, and the Sevilleta National Wildlife Refuge before reaching San Acacia. Currently (2008), ground water is the principal source of water for municipal, domestic, commercial, and industrial uses in the basin, but water from the Rio Grande is the principal source of water for agriculture and imported water in the Rio Grande is being developed for municipal supply by the ABCWUA as part of the San Juan-Chama Drinking Water Project (Albuquerque Bernalillo County Water Utility Authority, 2007).

Physiography

The study area encompasses about 3,060 mi^2 and is bordered by the San Juan Basin and Sierra Lucero Escarpment to the west and the Sandia, Manzanita, Manzano, and Los Pinos Mountains to the east (fig. 1). Elevations in the study area range from about 4,500 feet (ft) to greater than 10,000 ft. The Middle Rio Grande Basin varies from 20 to 40 mi wide and is bisected by the Rio Grande and its alluvial flood plain (inner valley), which varies in width from 0.5 to 5 mi. The Rio Grande is the main drainage in the study area, and the Jemez River and Rio Puerco are the main tributaries. Between Cochiti Dam and San Acacia, the river declines in elevation about 575 ft over the 115 river mi (average gradient of 5 ft per mi). The Rio Grande in the study area is generally 200 to 300 ft in width, has a shifting sand substratum, and is braided with sandbars and islands (Lagasse, 1980).

Geology

The Middle Rio Grande Basin is part of a series of south-trending structural basins that compose the Rio Grande Valley (Kelley, 1977). The basin is constricted on the north and south by the convergence of eastern and western structural boundaries. The sedimentary fill of the basin is composed of the Neogene to Quaternary Santa Fe Group and Quaternary post-Santa Fe Group valley and basin-fill deposits. The upper part of the Santa Fe Group was deposited during the development of the ancestral Rio Grande and contains fluvial basin deposits as much as 1,500 ft thick (Hawley and Haase, 1992). The alluvium in the inner valley (current flood plain, fig. 1) consists of post-Santa Fe Group deposits from the most recent erosion and deposition sequence of the Rio Grande (Hawley and Haase, 1992). These channel and flood-plain deposits are as much as 120 ft thick.

Climate

Climate in the study area is mostly semiarid with substantial variation in precipitation from the lower valley areas to the mountains. Annual precipitation can exceed 40 inches in the mountains, whereas other areas in the watershed may receive less than 10 inches (Natural Resources Conservation Service, 1997). A majority of the annual precipitation typically occurs during the summer monsoon season (Western Regional Climate Center, 2002). Evapotranspiration from the Rio Grande riparian corridor is substantial because of the arid climate, reservoirs, broad channel areas, and larger riparian areas; mean annual evapotranspiration was estimated at about 155,000 acre-ft for the Rio Grande corridor from Cochiti Dam to San Acacia (S.S. Papadopulos and Associates, Inc., 2004).

Streamflow of the Rio Grande

The Rio Grande typically flows year-round within the Middle Rio Grande Basin, but selected reaches of the river may have no flow during summer or fall months. Statistical analysis of Rio Grande streamflow in the Middle Rio Grande Basin from 1974 to 1985 indicated that the river might be dry at Albuquerque, Bernardo, and San Acacia for short periods (Waltemeyer, 1989). Through the Middle Rio Grande Endangered Species Collaborative Program, the U.S. Bureau of Reclamation and U.S. Army Corps of Engineers (USACE) and their State and local partners have been working to reduce periods of no flow in the Rio Grande in the Middle Rio Grande Basin for protection of the endangered silvery minnow (*Hybognathus amarus*) (U.S. Fish and Wildlife Service, 2004).

Within the study area, Rio Grande streamflow is controlled by releases from Cochiti Dam. Congress authorized construction of the dam in 1960 (completed in 1973) to provide flood and sediment control in the Rio Grande. Snowmelt runoff is stored in Cochiti Lake in April and May and is typically released from June through September, and releases can extend through October for irrigation purposes. After July 1, when streamflow in the Rio Grande at Otowi Bridge, located about 26 mi upstream of Cochiti Dam, is less than 1,500 ft^3/second (s), no floodwater is released from Cochiti Lake unless the reservoir has less than 212,000 acre-ft of summer flood storage (Bureau of Reclamation, 2005). Since installation of Cochiti Dam, annual mean releases from Cochiti Lake have ranged from 1,360 to 2,360 ft^3/s, and the largest daily mean streamflow recorded was 8,290 ft^3/s (Byrd and others, 2005). Flood control requirements state that flow in the Rio Grande will be maintained at less than 7,000 ft^3/s as measured at the Rio Grande at Albuquerque station (Bureau of Reclamation, 2005).

The largest Rio Grande streamflows typically occur during the spring snowmelt, and the largest peaks typically occur during May (Langman and Anderholm, 2004; Langman and Nolan, 2005). Differences in streamflow volumes between stations increase from May and October because of irrigation diversions and return flows. Following the end of the irrigation season, streamflows increase, and differences in streamflow volumes between stations decrease (Langman and Anderholm, 2004; Langman and Nolan, 2005). The frequency of large streamflows in the Rio Grande has been reduced because of installation of Cochiti Dam (Langman and Anderholm, 2004), but large streamflows still occur as was evident during 2005 when the daily mean streamflow from Cochiti Dam peaked at nearly 7,000 ft^3/s in June and remained above 5,000 ft^3/s from May 12 to June 15 (U.S. Geological Survey, 2005).

Tributaries

Within the Middle Rio Grande Basin, perennial tributaries to the Rio Grande are few in number. Numerous intermittent and ephemeral drainages flow into the Rio Grande in response to snowmelt or summer thunderstorms, but only the Jemez River, Rio Puerco, and treated wastewater discharges typically provide intermittent or perennial inflow. The Jemez River has a drainage area of about 1,100 mi^2 that includes parts of the Jemez Mountains and the Sierra Nacimiento Range. The Jemez River, which may go dry during different periods of the year at its confluence with the Rio Grande, has an annual mean streamflow of 60.6 ft^3/s (1943 to 2004), and the largest recorded daily mean streamflow was 3,640 ft^3/s (June 19, 1958) (Byrd and others, 2005). Peak flows typically occur in late March, April, and May during snowmelt runoff with additional peak flows during the monsoon season (typically June through September). The Rio Puerco has a drainage area of about 7,350 mi^2 (1,130 mi^2 are noncontributing) and is the largest drainage contributing to the Rio Grande in the study area. The Rio Puerco originates in the San Juan Basin (fig. 1) and has a river length of about 110 mi. The Rio Puerco typically provides a small discharge to the Rio Grande (average annual mean streamflow was 40.2 ft^3/s from 1940 to 2004) but can provide substantial inflows during large storm events or during the spring snowmelt runoff (the largest recorded daily mean streamflow was 5,980 ft^3/s on May 5, 1941) (Byrd and others, 2005).

Treated wastewater is discharged directly to the Rio Grande from treatment plants in Bernalillo, Rio Rancho, Albuquerque, Los Lunas, and Belen (fig. 1). This water was originally withdrawn from the Middle Rio Grande Basin aquifer and can be classified as perennial tributary inflow to the Rio Grande. The ABCWUA Southside Water Reclamation Plant is the largest wastewater treatment plant in the study area, and from 1985 to 2000, discharge to the Rio Grande averaged 80.4 ft^3/s (U.S. Army Corps of Engineers, 2005). Individual discharges from all other treatment plants averaged less than 3 ft^3/s from 1985 to 2000 (U.S. Army Corps of Engineers, 2005). Storm runoff from urban areas contributes to the Rio Grande in the study area, but only the Albuquerque Metropolitan Arroyo Flood Control Authority has a large stormwater-collection system that discharges directly to the Rio Grande. The largest conveyance channel (North Floodway) collects stormwater runoff from nearly 88 mi^2 within Albuquerque's eastside (U.S. Geological Survey, 2006) and discharges stormwater runoff into the Rio Grande just upstream from the Alameda station. This channel typically has no measurable flow, but the recorded peak flow was 12,300 ft^3/s on August 14, 1980 (Byrd and others, 2005).

Ground-Water Inflows and Outflows

The Rio Grande is hydraulically connected with the basin-fill aquifer, which is composed of the saturated Santa Fe Group deposits (Kernodle and Scott, 1986). The basin-fill aquifer is recharged along the mountain fronts and from the Rio Grande and its tributaries, and recharge likely flows from the mountain areas towards the Rio Grande (Ellis and others, 1993; Anderholm and others, 1995). Ground water in the study area predominantly flows north to south with a greater east to west direction at the basin margins because of mountain-front recharge (Plummer and others, 2004). The effects of irrigation, drains, and river leakage form complex interactions that make it difficult to determine ground-water inflows and outflows to the river through the Middle Rio Grande Basin. The Rio Grande likely both gains and loses streamflow because of ground-water inflows and outflows through the Middle Rio Grande Basin. S.S. Papadopulos and Associates, Inc. (2004) determined that the Rio Grande from Cochiti Lake to the town of Bernardo typically loses water but does gain flow in winter months. The Rio Grande is likely a losing stream overall from Cochiti Lake to San Acacia, as was determined by model simulations (McAda and Barroll, 2002).

Irrigation Diversions and Inflows

Agricultural sites in the study area rely on diversion of Rio Grande water for irrigation. The Middle Rio Grande Conservancy District (MRGCD) provides water for flood irrigation by diverting water from the Rio Grande and directing it into a system of canals while directing return flows to the Rio Grande through drainage ditches and interior and riverside drains. The riverside drains also collect water from the interior drains and canals and leakage from the Rio Grande to prevent the water table from rising outside of the riverside levees (Kernodle and Scott, 1986). Irrigation water diverted from the Rio Grande may return to the river as surface flow or as ground water discharged to the canals and drains.

Channel Geometry

The Rio Grande channel typically consists of a shifting sand substrate and a braided channel pattern. Because of increased anthropogenic influences, channel geometry currently undergoes less change from geomorphological processes than before installation of Cochiti Dam, irrigation diversions, and the levee system installed by the MRGCD and the USACE in the 1930s and 1940s (Mussetter Engineering, Inc., 2002); however, the predominantly sand channel still allows for the movement of the thalweg within the stream banks and the formation and migration of sandbars. Analysis of channel lateral mobility from 1918 to 1992 by Richard (2001) indicated that the Rio Grande was previously a wide, braided river that was laterally mobile but became a narrower, more stable channel with increased anthropogenic control. With a decreased sediment supply following installation of Cochiti Dam, bed sediment coarsened, and the channel degraded in the Middle Rio Grande Basin (Lagasse, 1980 and 1994; Richard, 2001).

Previous Studies

The Rio Grande through the city of Albuquerque was previously investigated for traveltime and reaeration characteristics. Waltemeyer (1994) determined that traveltime characteristics of the Rio Grande through Albuquerque were essentially the same for three methods used during the study—stream velocity, tracer dye, and tracer gas. The three methods indicated mean velocities of 1.06 to 1.13 mi per hour (h) (equivalent to 1.55 to 1.64 ft/s) at a flow of about 300 ft^3/s. Waltemeyer (1994) also performed a linear regression analysis of 22 streamflow values for the Rio Grande in Albuquerque that were recorded between 1985 and 1991 to derive a relation between streamflow and mean velocity. This equation was used to estimate traveltimes at various streamflows for multiple reaches of the Rio Grande within the city of Albuquerque.

The Rio Grande in the Middle Rio Grande Basin is currently (2008) being modeled for flood control and water accounting as part of the Upper Rio Grande Water Operations Model (URGWOM). This model is used to simulate water storage and delivery operations in the Rio Grande from its headwaters in Colorado to below Caballo Dam in southwest New Mexico (U.S. Army Corps of Engineers, 2005). As part of this model, streamflow traveltimes (lag times) have been estimated for reaches of the Rio Grande in the Middle Rio Grande Basin by using a wave-velocity method (Kleitz-Seddon or Seddon's law), where traveltime is based on a calculated wave velocity determined from streamflow and cross-sectional areas. This procedure assumes a station's cross section to be representative of the entire reach, and estimated traveltimes are based on application of the calculated wave velocity over the entire reach length (U.S. Army Corps of Engineers, 2005).

The study reach also was analyzed for streamflow velocity and sediment transport prior to the construction of Cochiti Dam. Streamflow velocities in the Rio Grande at San Felipe ranged from about 2 to 7 ft/s for discharges ranging from 360 to 9,700 ft^3/s (Culbertson and Dawdy, 1964), and velocities of the Rio Grande near Bernalillo were reported to range from about 3 to 8 ft/s for discharges ranging from 1,200 to 10,100 ft^3/s (Nordin, 1964). Streamflow velocities at the San Felipe station following installation of Cochiti Dam have ranged from about 1 to 7 ft/s during USGS streamflow measurements across a streamflow range of about 170 to 7,700 ft^3/s (U.S. Geological Survey, 2006).

Methods of Analysis

The method of analysis for this study is similar to the method used by Appel (1983) to estimate traveltimes of flood waves on the New River in West Virginia. Appel used a flow-pulse technique to produce traveltime curves that could be used to estimate the traveltime of a flood wave between any two points in the study area. For this study, traveltime curves were developed to estimate the potential traveltime of a conservative solute in the Rio Grande for any two points between Cochiti Dam and Albuquerque. Traveltime curves were developed through local-regression analysis of traveltime data for streamflow pulses. Additional points in the pulse shape and traveltime data for the entire Middle Rio Grande Basin also were examined to evaluate dispersion and storage characteristics of the Rio Grande that can affect traveltime.

An established method for determining traveltime characteristics of a river is the use of tracer dyes for tracking the movement of a solute particle as it is transported downstream (Kilpatrick and Wilson, 1989). Dyes are injected into a river to track movement of the streamflow because the dyes are transported with streamflow and behave in a similar manner as the water particles (Kilpatrick and Wilson, 1989). A flow-pulse analysis for traveltime determination uses existing streamflow data in which abrupt changes in a river's flow can indicate transport characteristics of a river over a wide range of flows. Flow-pulse analysis is applicable to dam-regulated rivers where abrupt changes in streamflow are visible at downstream stream-gaging stations. Given that a tracer (solute) was not tracked within the study reach, the traveltimes provided by the flow-pulse analysis are estimates for a conservative solute entrained in a selected streamflow. The flow-pulse analysis does not account for any solute behavior that would cause an entrained particle to travel differently than the streamflow mass.

Source and Description of Data

The study was based on available streamflow data from the USGS surface-water data collection program. Streamflow data from seven stations—Cochiti, San Felipe, Alameda, Albuquerque, Isleta, Bernardo, and San Acacia—on the Rio Grande in the Middle Rio Grande Basin were used for the flow-pulse analysis (table 1). Data consisted of continuous streamflow records (15-minute data) collected at each station for water years 2003–05, and pulse flow rates ranged from about 500 to 5,000 ft^3/s. This short period of record was selected to minimize potential temporal differences from geomorphological changes to the stream channel because of aggradation/degradation processes. The streamflow record of each station contains data for the in-stream flow of the Rio Grande at each location. Streamflow diverted by agricultural or municipal canals or other diversions that may be adjacent to the Rio Grande channel is not included in the record.

Table 1. Selected stream-gaging stations in the study area.

[USGS, U.S. Geological Survey; NAD 83, North American Datum 1983; mi^2, square miles; ft, feet; NAVD 88, North American Vertical Datum 1988; NA, not available]

USGS station number	Station name	Report station name (fig. 1)	Latitude and longitude (NAD 83)	Location (county, hydrologic unit code)	Drainage area (mi^2)[1]	Elevation (ft above NAVD 88)	Distance from Cochiti Dam (river miles)
08317400	Rio Grande below Cochiti Dam	Cochiti	35°37′04″ 106°19′28″	Sandoval, 13020201	12,000	5,229	0.1
08319000	Rio Grande at San Felipe	San Felipe	35°26′39″ 106°26′25″	Sandoval, 13020201	13,200	5,119	16.0
08329928	Rio Grande near Alameda	Alameda	35°10′54″ 106°39′22″	Bernalillo, 13020203	NA	[2]5,005	40.2
08330000	Rio Grande at Albuquerque	Albuquerque	35°05′21″ 106°40′49″	Bernalillo, 13020203	14,500	4,949	48.1
08330875	Rio Grande at Isleta Lakes near Isleta	Isleta	34°56′49″ 106°40′47″	Bernalillo, 13020203	15,100	4,873	59.2
08332010	Rio Grande Floodway near Bernardo	Bernardo	34°25′01″ 106°48′02″	Socorro, 13020203	16,300	4,725	100.3
08354900	Rio Grande Floodway at San Acacia	San Acacia	34°15′23″ 106°53′20″	Socorro, 13020203	23,800	4,657	115.4

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

[2] Elevation is an approximation from a handheld Global Positioning System unit. No official elevation has been established for this station.

Flow-Pulse Analysis

The flow-pulse analysis consisted of tracking streamflow pulses released from Cochiti Dam that were subsequently detected at downstream stations. Changes to flow releases from Cochiti Dam occur in steps (fig. 2), thereby providing defined pulses that can be tracked at existing stations. A flow pulse released from Cochiti Dam is initially recorded by the Cochiti station 700 ft downstream from the dam spillway. Data from this station were used as the initial point for traveltime determination, and this station was considered the “zero location.” Pulses selected for analysis consisted of prepulse, steady-state streamflow conditions of at least 1 day, followed by an abrupt rise in streamflow to a plateau stage substantially higher than the prepulse steady-state condition. The plateau stage would remain at a steady state for a minimum of 1 day, typically followed by a sharp decline in streamflow to a postpulse steady state with a similar flow rate to the prepulse condition. There are two parts of each pulse that were analyzed that likely have different velocities—the smaller initial streamflow of the rising limb (initial stage of the pulse) and the larger peak streamflow of the plateau stage. Examination of the traveltime of both parts is useful because of the operation of Cochiti Dam and the quick stage change in streamflow (fig. 2).

The different parts of a pulse were delineated by an increase or decrease in a streamflow record that was different from the “noise” in the record caused by turbulent flow or accuracy of the station equipment. The streamflow record was divided on the basis of three changes or points in the streamflow record—start of the pulse (rising-limb leading edge), transition from rising limb to steady pulse (plateau leading edge), and transition from the end of the pulse (plateau trailing edge) to a postpulse, steady-state flow (table 2 and fig. 3). The time for each point of a pulse to be detected at a station indicated the traveltime of that part of the pulse since its origin at Cochiti Dam. Centroids of the rising limb and plateau were calculated from these three points (table 2 and fig. 3). The transition from the plateau to falling limb was not analyzed because of problems identifying this point in the pulse shape.

Traveltime Curves

Average streamflow velocities (derived from traveltime and distance) of the leading edge and trailing edge of the pulse plateaus from Cochiti station to the Albuquerque station were used to develop traveltime curves for this reach of the study area. Local regression was used to determine the best-fit line for the velocity/streamflow relation. Local regression is a nonparametric technique that predicts a value at each point by fitting a weighted linear regression, where the weights decrease with distance from the point of interest (Helsel and Hirsch, 1991; Insightful Corporation, 2002). The window span controls the weighting interval and was individually adjusted for each relation (0.5 for leading edge and 1.6 for trailing edge) to minimize residuals while keeping the relation

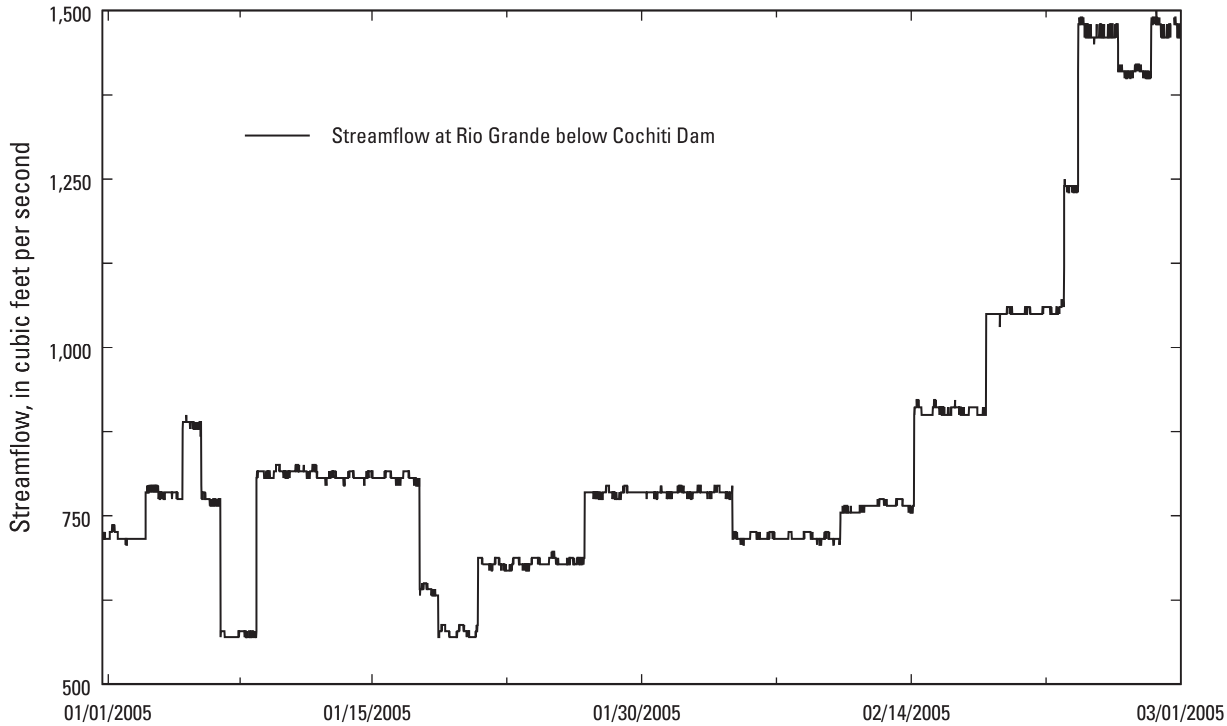

Figure 2. Example of pulse releases of streamflow from Cochiti Dam, January to March 2005.

Table 2. Pulse components for flow-pulse analysis.

Pulse component	Inflection point	Description
Rising limb	Leading edge	Start of increase from prepulse steady-state streamflow
	Centroid	Calculated (time) center of rising limb from leading edge of rising limb to trailing edge (plateau-leading edge). Rising limb was calculated by time because of the changing streamflow, which precluded calculation by volume
Plateau	Leading edge	Transition from rising limb to plateau stage of the pulse
	Centroid	Calculated center of plateau stage where half the plateau flow volume has passed and half the volume remains to pass the stream-gaging station
	Trailing edge	End of pulse event where streamflow begins a post-pulse steady state

positively correlated (increasing velocity with increasing streamflow). Plots of predicted versus actual values, residuals, and R^2 values (measure of the goodness of fit) were used to evaluate the fit of each model and the variability explained by the regression.

Dispersion and Short-Term Storage

The effects of dispersion (longitudinal) and short-term storage were analyzed to understand river characteristics and processes that could affect the traveltime of streamflow and entrained solutes. Dispersion and short-term storage act to spread the pulse distribution and to slow traveltime. Both influences can vary by reach and stage, and both are likely highly dynamic in the study area because of the shifting sand substrate. Advection is determined by streamflow velocity and causes transport of a solute because of the motion of the fluid (Huber, 1993). Advection does not alter the shape of a solute distribution if the velocity distribution is uniform vertically and from bank to bank. Retardation and spreading

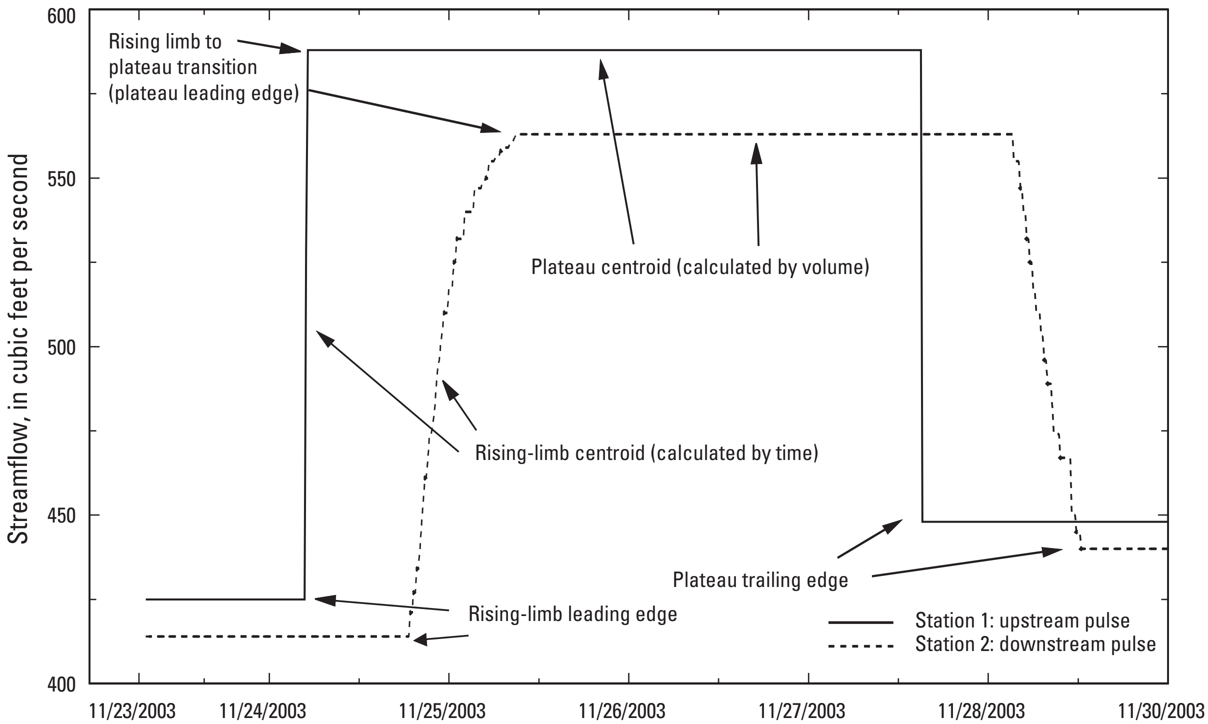

Figure 3. Components of flow-pulse analysis.

of a streamflow pulse are a result of dispersion and storage within the channel area. As defined for this study, dispersion includes all physical processes that would act on a pulse mass to disperse it and alter its travel within a stream channel, such as turbulent diffusion, mechanical dispersion, and differential advection. Additionally, dispersion is separated from short-term storage for this study in an attempt to identify discrete processes that act to slow streamflow.

If dispersion acted equally on the pulse volume, the rising and descending limbs would spread similarly, and the time to the pulse midpoint from the leading edge would be equal to the time from the pulse midpoint to the end of the pulse. If there is a short-term storage component because of channel geometry, the rising and descending limbs of the pulse may not spread equally. A storage component may consist of channel features such as secondary channels, bank storage, or depressions that are not part of the wetted channel at the initial flow level, but with an increase to larger flows, these features are included in the wetted channel. A short-term storage component would retain a portion of the pulse and discharge it to the main channel at some delayed time when the delayed volume would still be a part of the pulse. Short-term storage is different from a long-term storage component that would retain a portion of the pulse and the reintroduction of the volume to the river would occur after the pulse has passed and would not be visible in the hydrograph. To examine short-term storage, streamflow pulse distributions were evaluated for changes in skewness that would indicate a delay in part of the pulses compared to the overall pulse volumes. Skewness was calculated by using Fisher's measure of skewness:

$$m_f = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^f,$$

$$b = \frac{m_3}{m_2^{3/2}},$$

$$skewness = \frac{b\sqrt{n(n-1)}}{n-2}$$

m = moment, the subscript (f) indicates the specific moment about the mean (i.e., the second moment about the mean is the variance of the sample population);
n = size of the sample population;
$\bar{x}$ = mean value of the sample population;
b = coefficient of skewness.

Quality Control

As a streamflow pulse moves downstream, the sharp increase and decrease in flow degrades because of dispersion and short-term storage. The possible error of determining the time at which the streamflow changes begins to increase because of station “noise” and flattening of the inflection points. To reduce possible errors, the raw data were examined in conjunction with smoothed data (local regression was used with a variable window span that included cross-validation and a symmetric family assumption to reduce outlier distortion) to best fit the inflection points. Not all pulses were analyzed for each station or each part of the pulse because of incidences of apparent noise in the streamflow record that were sufficiently large to inhibit analysis of the data.

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The author acknowledges the ABCWUA for providing the support to implement this study. In particular, the author expresses appreciation to John Stomp, City of Albuquerque Water Resources Manager, Engineering and Planning, for his guidance and support of this study to better understand the State of New Mexico’s water resources.

Traveltime of the Rio Grande

The flow-pulse analysis was applied to selected pulses from the 2003–05 water years. Twelve pulses were analyzed for traveltime, and pulse streamflows ranged from 495 to 5,190 ft^3/s (steady-state plateau flow at the Cochiti station) (table 3). Seven pulses were analyzed for the traveltime of the rising-limb leading edge, rising-limb centroid, plateau leading edge, plateau centroid, and plateau trailing edge (full-pulse analysis). Five pulses were analyzed for rising-limb leading edge, rising-limb centroid, and plateau leading edge (plateau centroid and plateau trailing edge traveltimes were not available for these pulses because these pulses were part of “stair-step” increases that lacked descending limbs). Traveltimes for each inflection point on a pulse are presented as time since origin of that particular inflection point at the Cochiti station.

Most pulse events indicated longer traveltimes for each successive point in the pulse, which is an effect of dispersion and spreading of a pulse with downstream travel (figs. 4–15, tables SI-1 to SI-5, Supplemental Information). A large spreading occurred with pulse event 6 (fig. 9) between Isleta and Bernardo that is substantially different from all other pulse events. The cause of this large spreading is unknown, but it may be an effect of irrigation diversions and return flows. Pulse event 1 (fig. 4) also indicated more spreading than the other pulse events (except pulse event 6), but this spreading appears uniform from station to station. Spreading of the pulses typically decreased with increased streamflow except for the large spreading of pulse event 6. Pulse event 7 indicated no differences in traveltimes for the different points of the plateau, and traveltimes for parts of the plateau for pulse events 4 and 6 were similar and alternated in longest traveltime at different locations. Given different release times for the leading and trailing edges of the plateaus (time separation was 1–10 days for the various pulse events, table 3), these similar traveltimes of parts of the plateau may be a result of influences on a pulse—such as gains or losses—during travel through the basin that affected these points in the pulse differently.

Estimating Traveltime for Any Two Points Between Cochiti Dam and Albuquerque

Because San Juan-Chama Project water will be diverted from the Rio Grande by the ABCWUA (diversion will be located about 1,500 ft south of the Alameda gage), it is useful to provide a method to estimate the possible traveltime of a conservative solute spilled into the Rio Grande upstream from Albuquerque. The velocities of the leading edge and trailing edge of the pulse plateaus from the Cochiti station to the Albuquerque station (as determined by traveltimes between Cochiti and Albuquerque stations) were used to develop traveltime curves for this reach of the study area (figs. 16 and 17).

Local regression was used to best fit the variable relation of the leading and trailing edge velocities and the original pulse streamflow at Cochiti station. The predicted values of these two relations were used to determine possible traveltimes of Rio Grande streamflow between any two points for 5-, 10-, 25-, and 50-mi distances (figs. 16 and 17). The local regressions produced R^2 values of 0.94 and 0.75 for the leading and trailing edge velocities and residual standard errors of 0.13 and 0.34, respectively. The lesser fit of the local regression for the trailing edge relation was a result of a smaller sample size and greater variability of the data. A better fit of the model for the trailing edge data could have been achieved by decreasing the window span, but the relation would not have stayed positively correlated (increasing velocity with increasing streamflow). Because of the small sample size, a positive correlation was more appropriate for estimating potential traveltimes than creating a more complex model that explained a greater amount of the data variability.

The traveltime curves can be used to estimate the beginning and ending traveltimes of a well-mixed conservative solute plume in the Rio Grande for any two points between Cochiti and Albuquerque stations. The multiple curves represent possible travel distances between any two points in this reach of the Rio Grande. These figures provide no indication of concentration of a potential plume, and these traveltimes are only estimates of how long it might take a

Table 3. Pulse events at Rio Grande below Cochiti Dam selected for analysis of traveltime in the Middle Rio Grande Basin.

[ft^3/s, cubic feet per second; h, hours; >, greater than; NA, not available]

Pulse event	Beginning date/time[1]	Ending date/time[2]	Prepulse flow (ft^3/s)	Pulse plateau flow (ft^3/s)	Postpulse flow (ft^3/s)	Duration of steady state preceding pulse (days)[3]	Duration of rising limb (h)	Duration of pulse plateau and descending limb (h)
Full-pulse analysis								
1	Nov. 12, 2002, 0930	Nov 13, 2002, 0930	396	495	396	5	0.25	23.75
2	Jan. 2, 2004, 1030	Jan. 6, 2004, 0915	411	528	425	2	0.25	94.50
3	Nov. 24, 2003, 0945	Nov. 28, 2003, 0945	425	588	448	>7	0.25	95.75
4	Jan. 9, 2005, 1015	Jan. 18, 2005, 0845	570	816	641	2	0.25	214.25
5	Dec. 13, 2004, 1015	Dec. 23, 2004, 1100	944	1,060	678	6	0.25	240.25
6	May 14, 2003, 0900	May 16, 2003, 0845	716	1,440	1,030	8	0.75	46.00
7	May 12, 2004, 1000	May 16, 2004, 1330	3,010	3,350	2,740	3	0.25	99.25
Partial-pulse analysis [4]								
8	May 3, 2004, 1030	NA	1,250	1,850	NA	4	0.50	NA
9	May 4, 2004, 1100	NA	1,850	2,280	NA	1	0.50	NA
10	May 6, 2004, 1400	NA	2,280	2,740	NA	2	0.50	NA
11	May 7, 2004, 1330	NA	2,740	3,300	NA	1	0.25	NA
12	May 11, 2005, 0815	NA	4,010	5,190	NA	>5	0.25	NA

[1] Start of increased streamflow at the Cochiti station because of larger release from Cochiti Dam (rising-limb leading edge).

[2] Start of decreased streamflow at the Cochiti station because of smaller release from Cochiti Dam (plateau trailing edge).

[3] Time prior to pulse event during which flow release from Cochiti Dam remained at a steady state.

[4] Pulses were analyzed for rising-limb leading edge, rising-limb centroid, and plateau leading edge. Plateau centroid and plateau trailing edge traveltimes were not available for these pulses because these pulses were part of "stair-step" increases that lacked descending limbs.

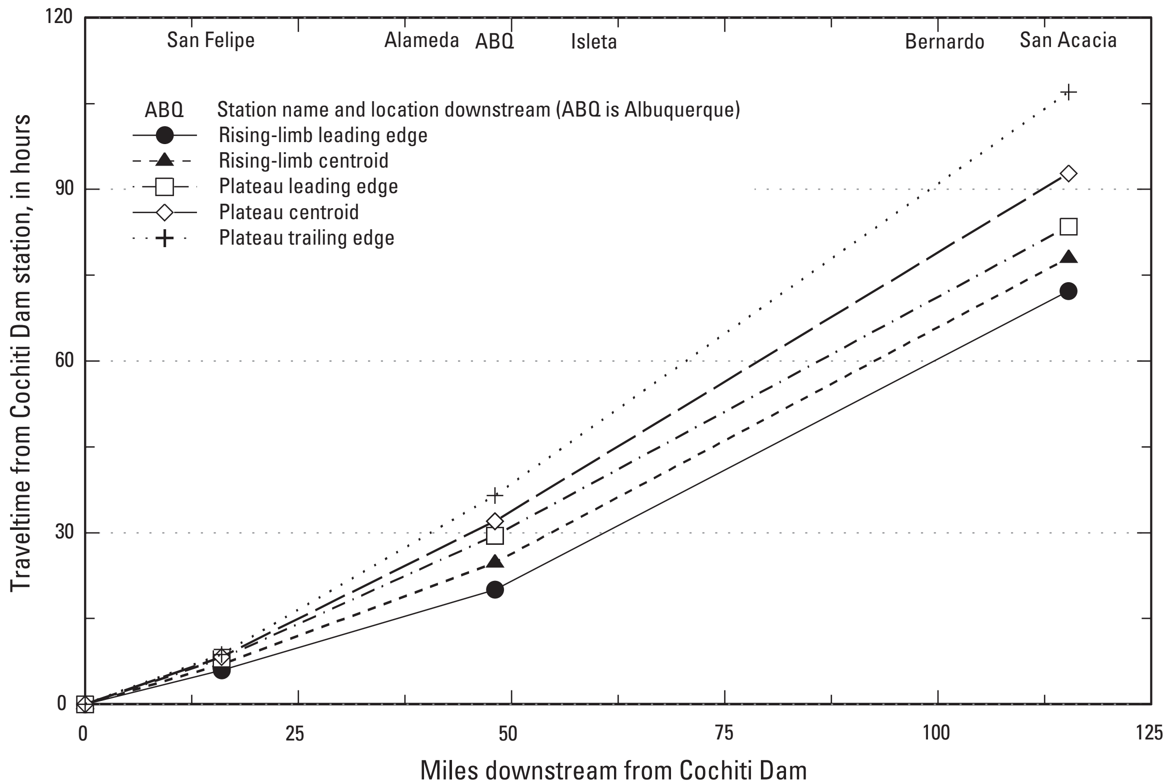

Figure 4. Traveltime of streamflow pulse event 1 (495 cubic feet per second) from Cochiti Dam to San Acacia, November 2002.

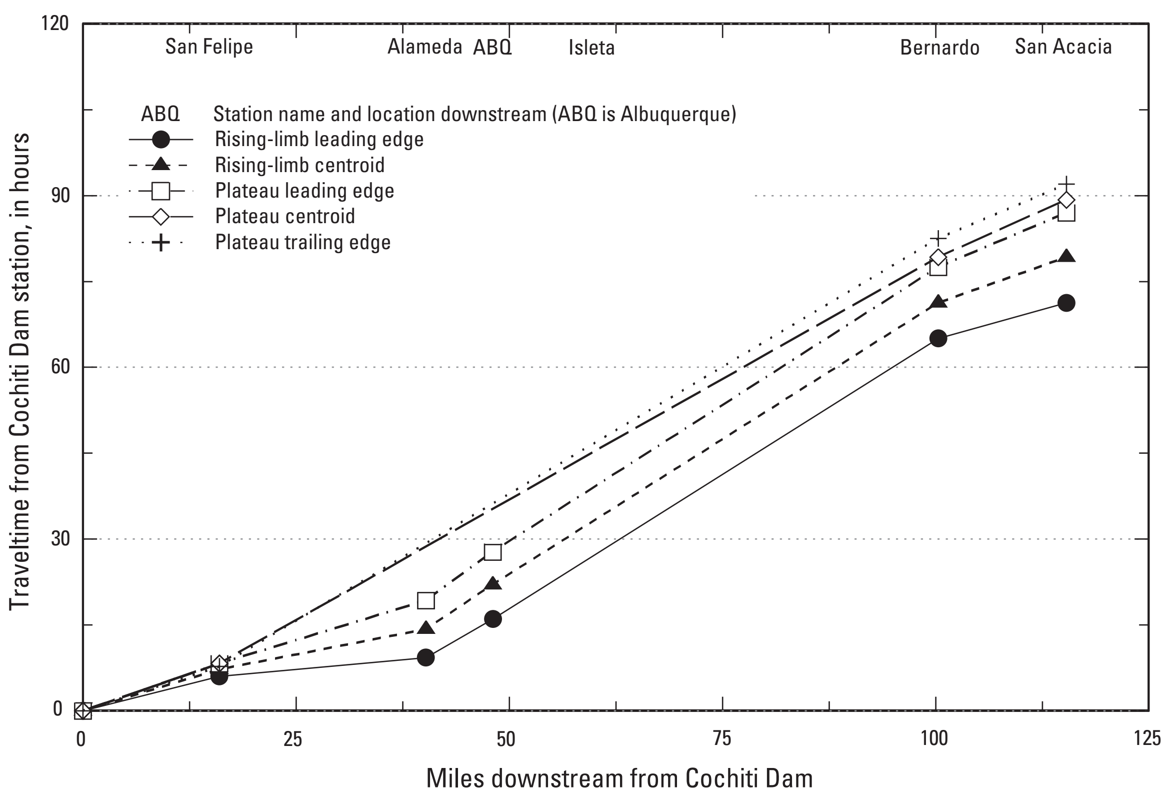

Figure 5. Traveltime of streamflow pulse event 2 (528 cubic feet per second) from Cochiti Dam to San Acacia, January 2004.

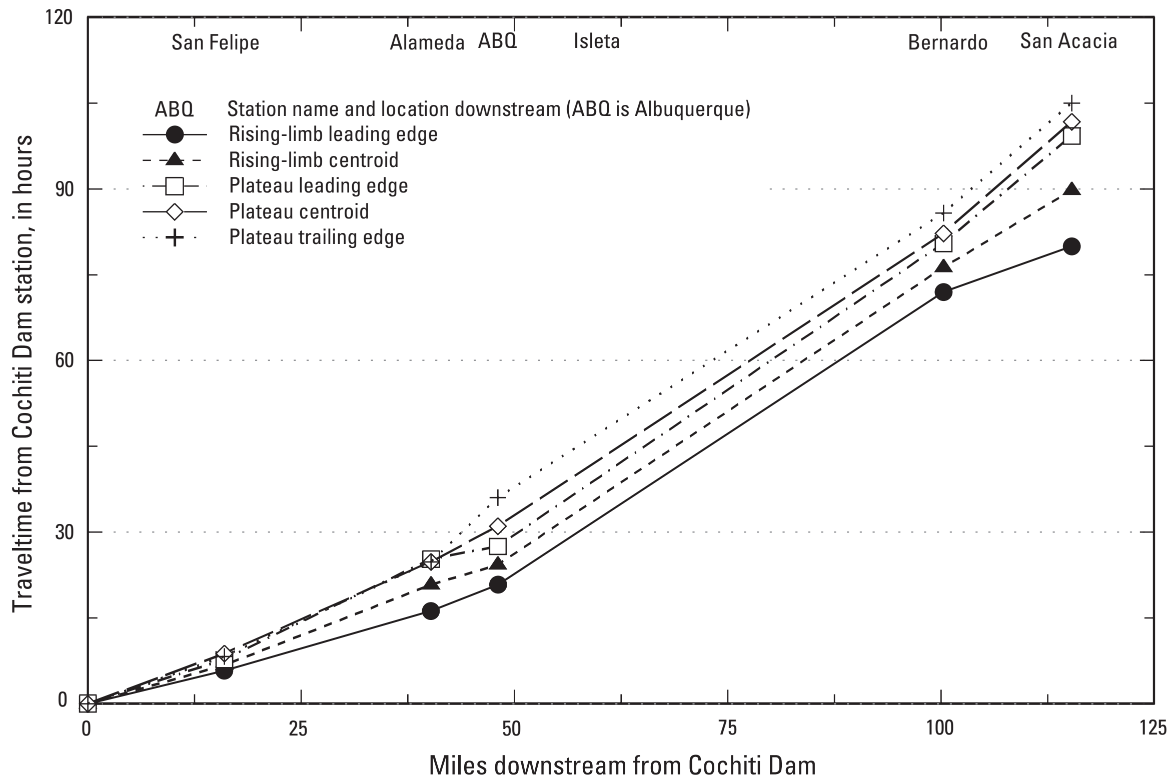

Figure 6. Traveltime of streamflow pulse event 3 (588 cubic feet per second) from Cochiti Dam to San Acacia, November 2003.

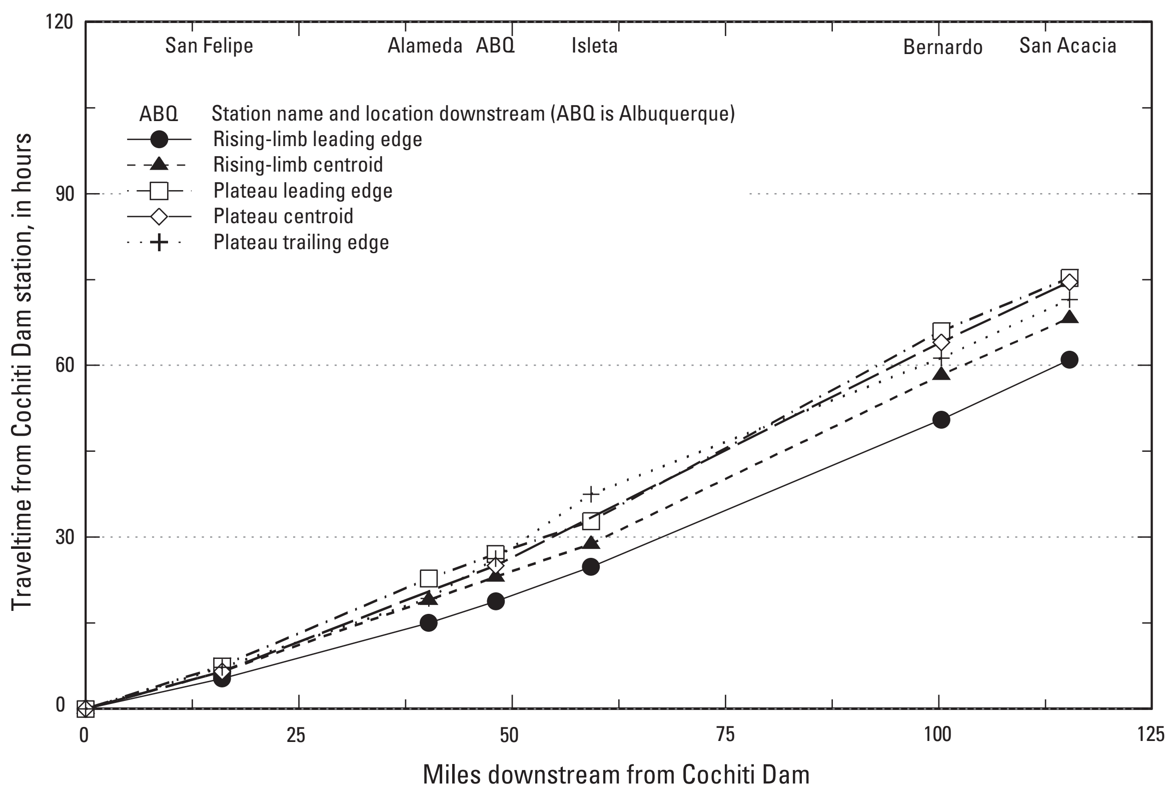

Figure 7. Traveltime of streamflow pulse event 4 (816 cubic feet per second) from Cochiti Dam to San Acacia, January 2005.

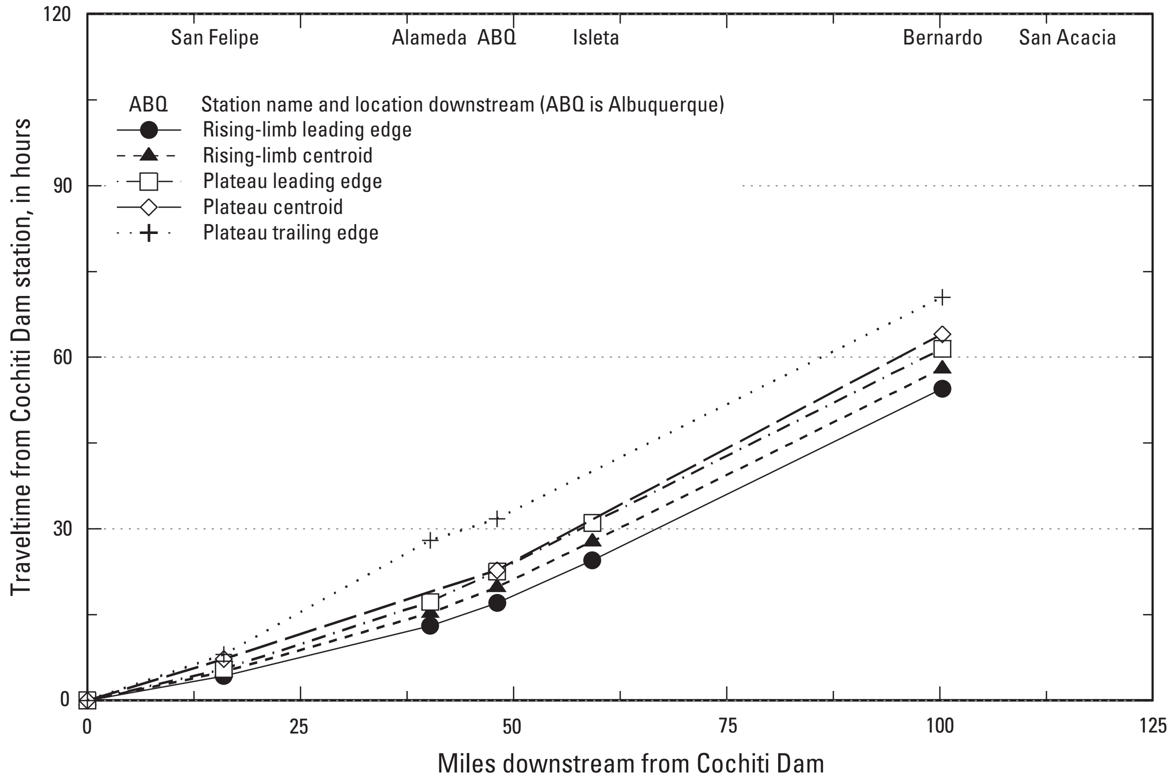

Figure 8. Traveltime of streamflow pulse event 5 (1,060 cubic feet per second) from Cochiti Dam to San Acacia, December 2004.

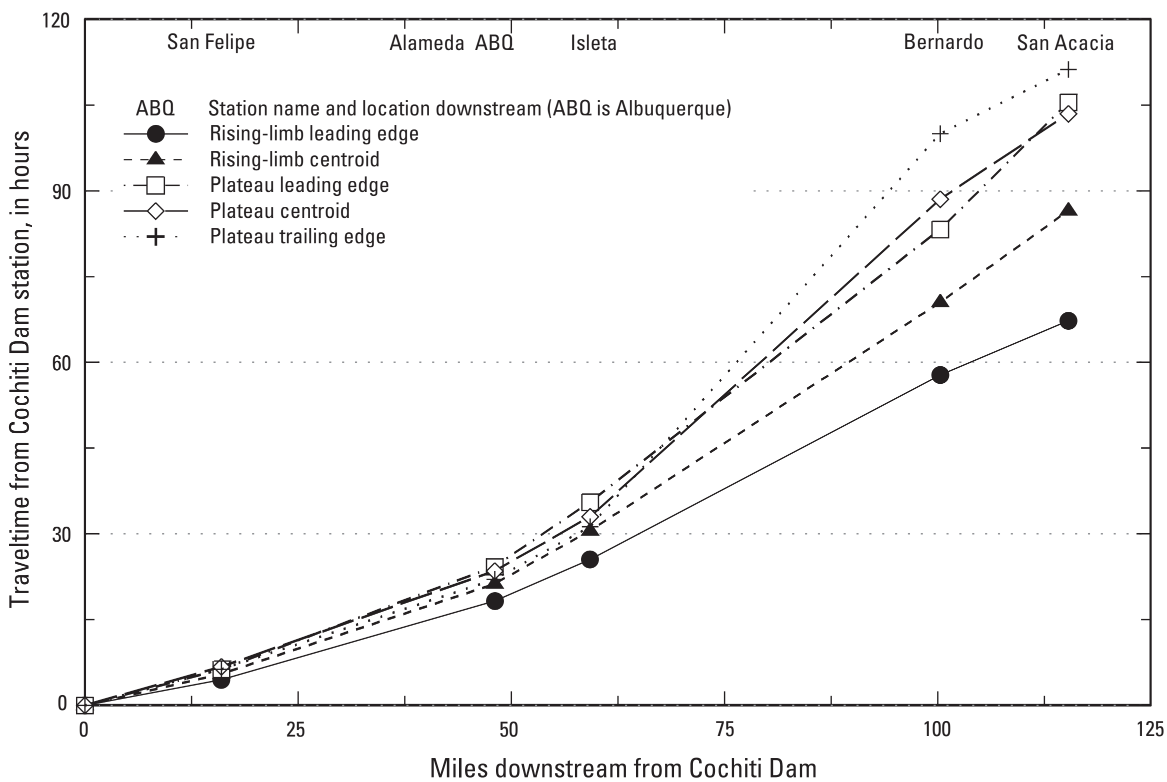

Figure 9. Traveltime of streamflow pulse event 6 (1,440 cubic feet per second) from Cochiti Dam to San Acacia, May 2003.

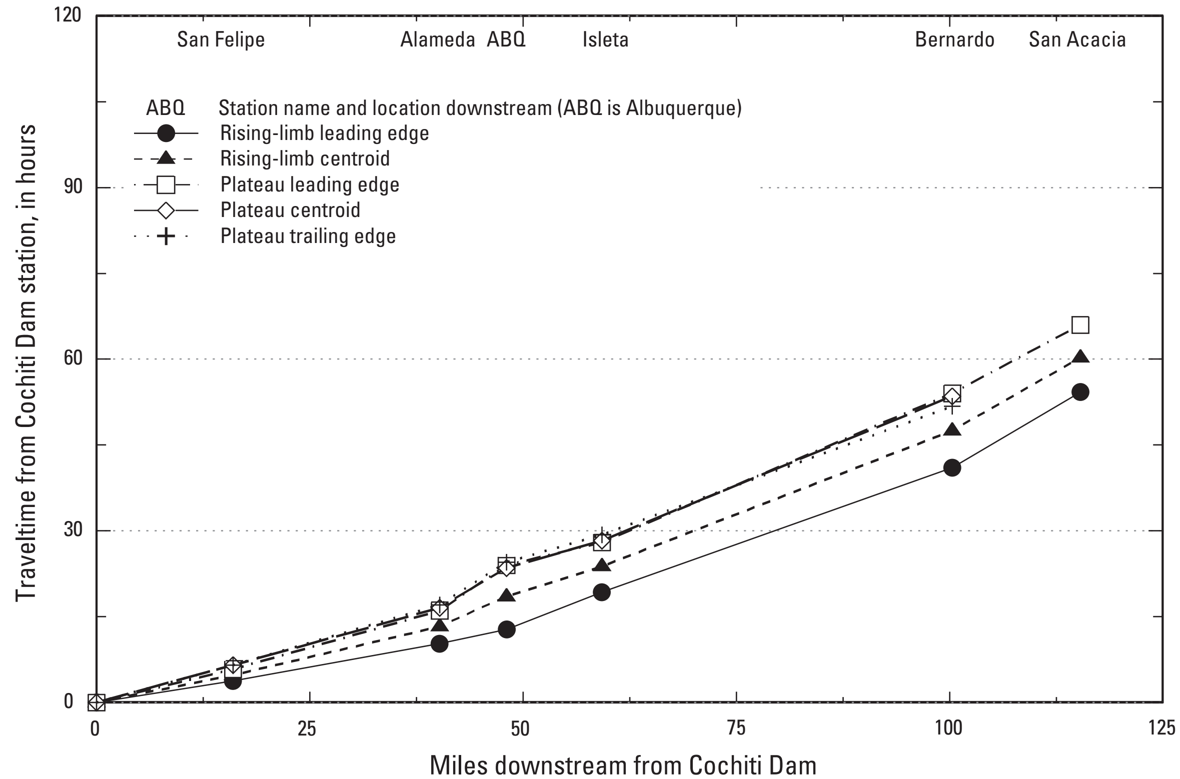

Figure 10. Traveltime of streamflow pulse event 7 (3,350 cubic feet per second) from Cochiti Dam to San Acacia, May 2004.

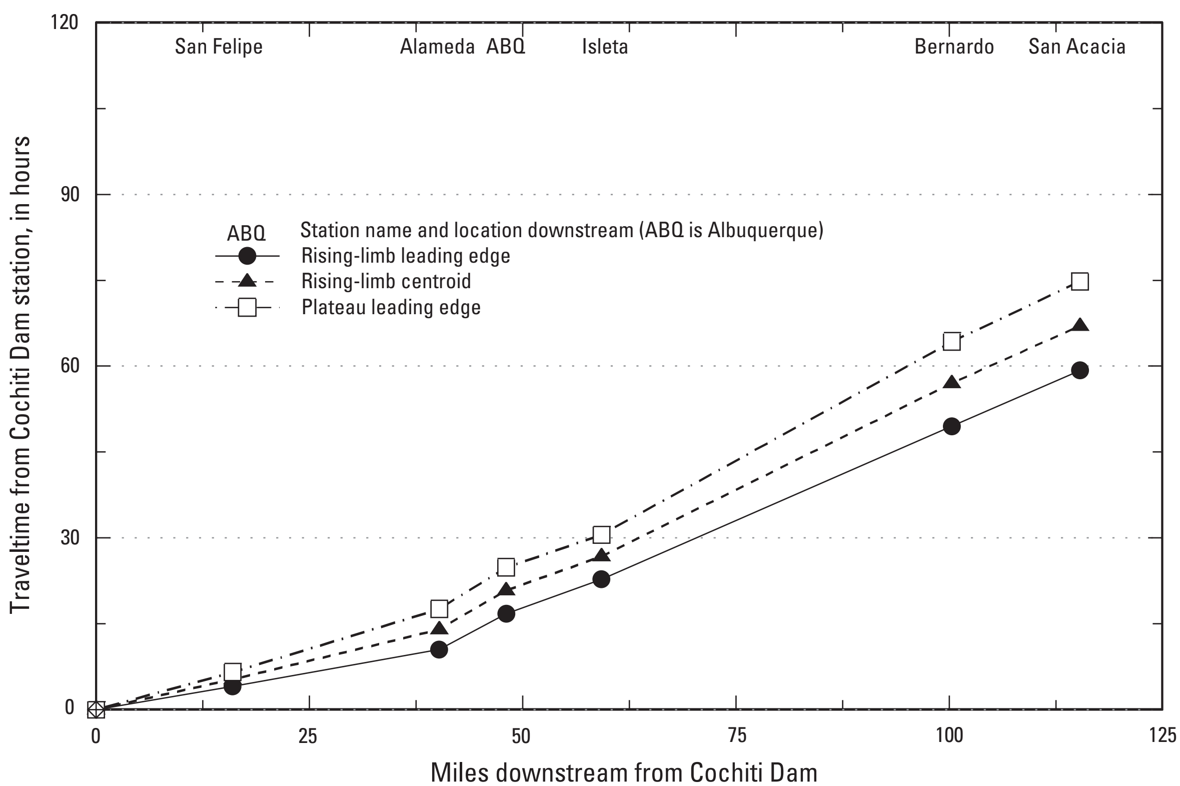

Figure 11. Traveltime of streamflow pulse event 8 (1,850 cubic feet per second) from Cochiti Dam to San Acacia, May 2004.

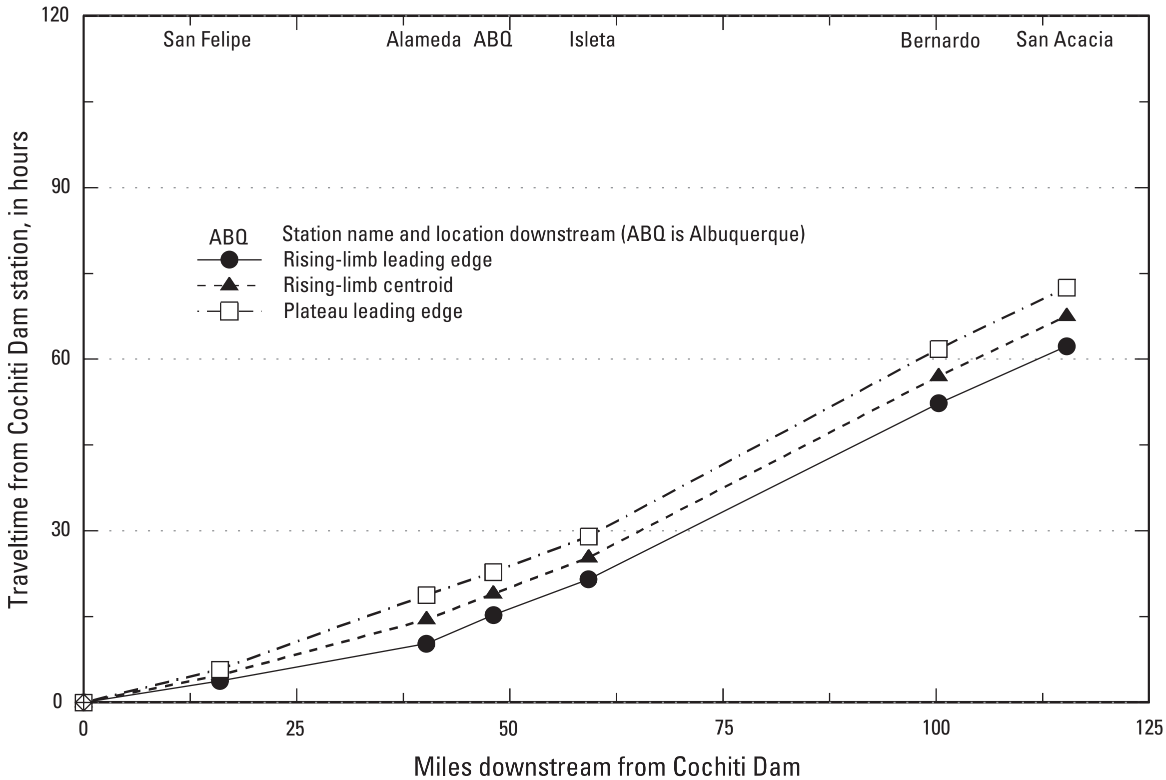

Figure 12. Traveltime of streamflow pulse event 9 (2,280 cubic feet per second) from Cochiti Dam to San Acacia, May 2004.

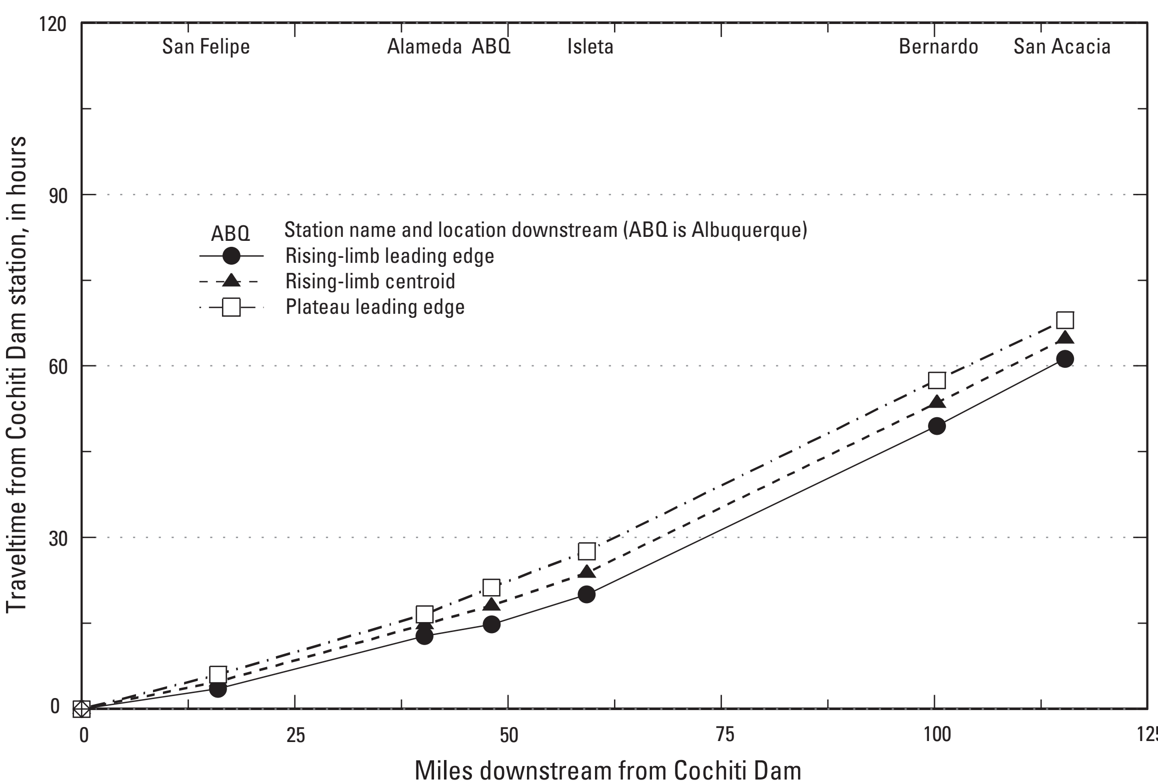

Figure 13. Traveltime of streamflow pulse event 10 (2,740 cubic feet per second) from Cochiti Dam to San Acacia, May 2004.

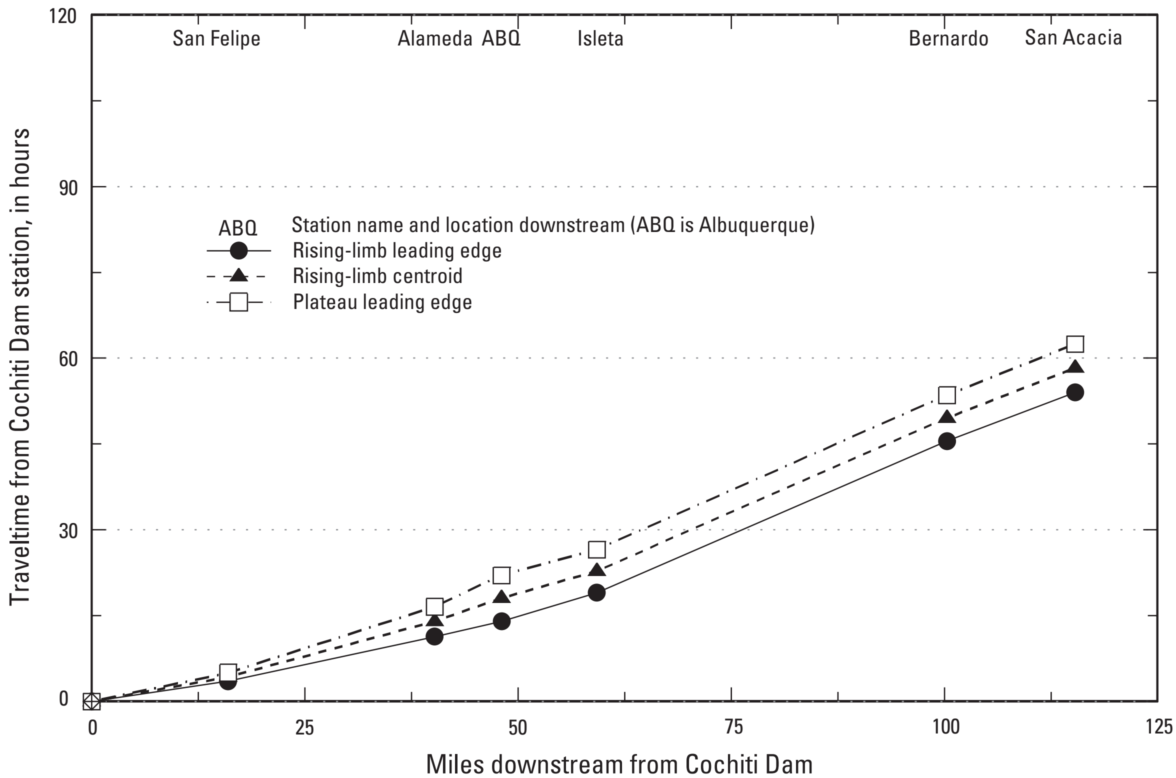

Figure 14. Traveltime of streamflow pulse event 11 (3,350 cubic feet per second) from Cochiti Dam to San Acacia, May 2004.

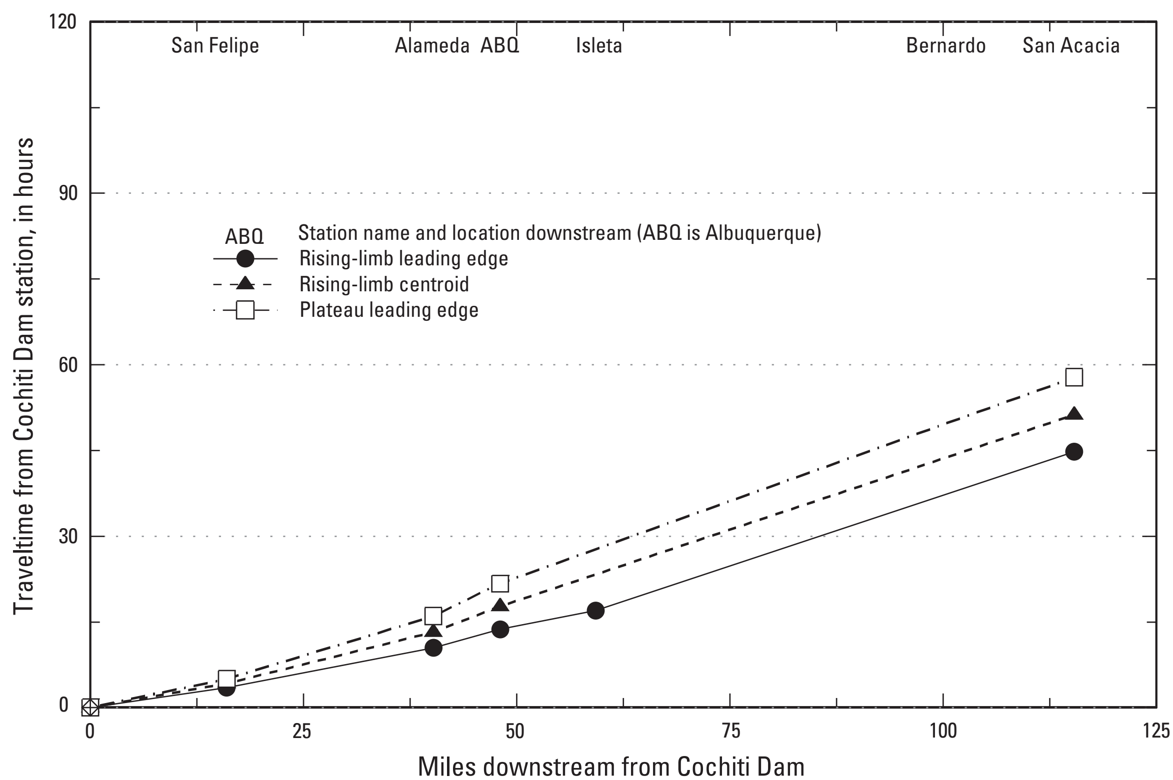

Figure 15. Traveltime of streamflow pulse event 12 (5,190 cubic feet per second) from Cochiti Dam to San Acacia, May 2005.

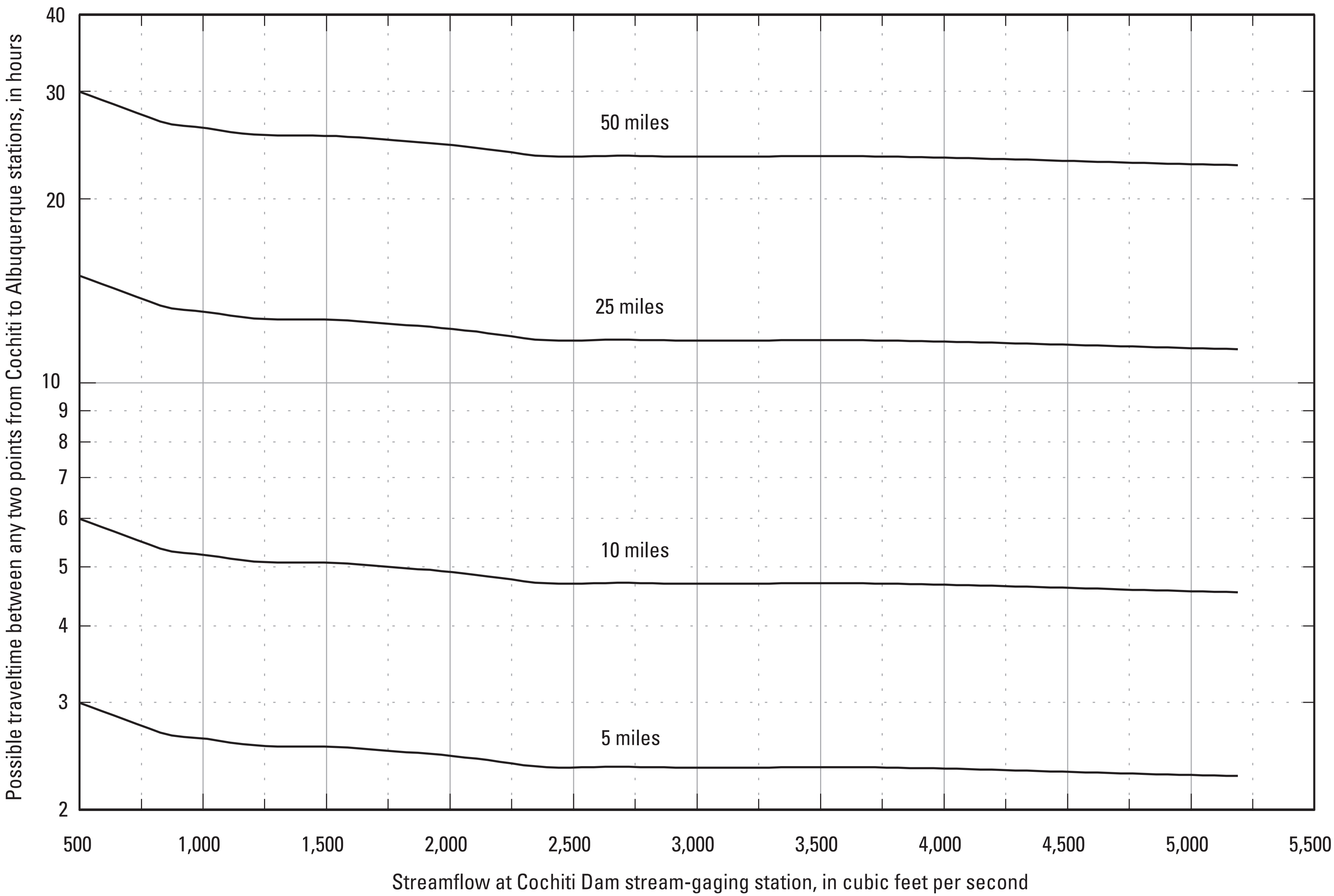

Figure 16. Traveltime curves for estimating leading-edge traveltime between any two points in the Rio Grande located between Cochiti and Albuquerque stream-gaging stations (derived from pulse plateau-leading-edge data).

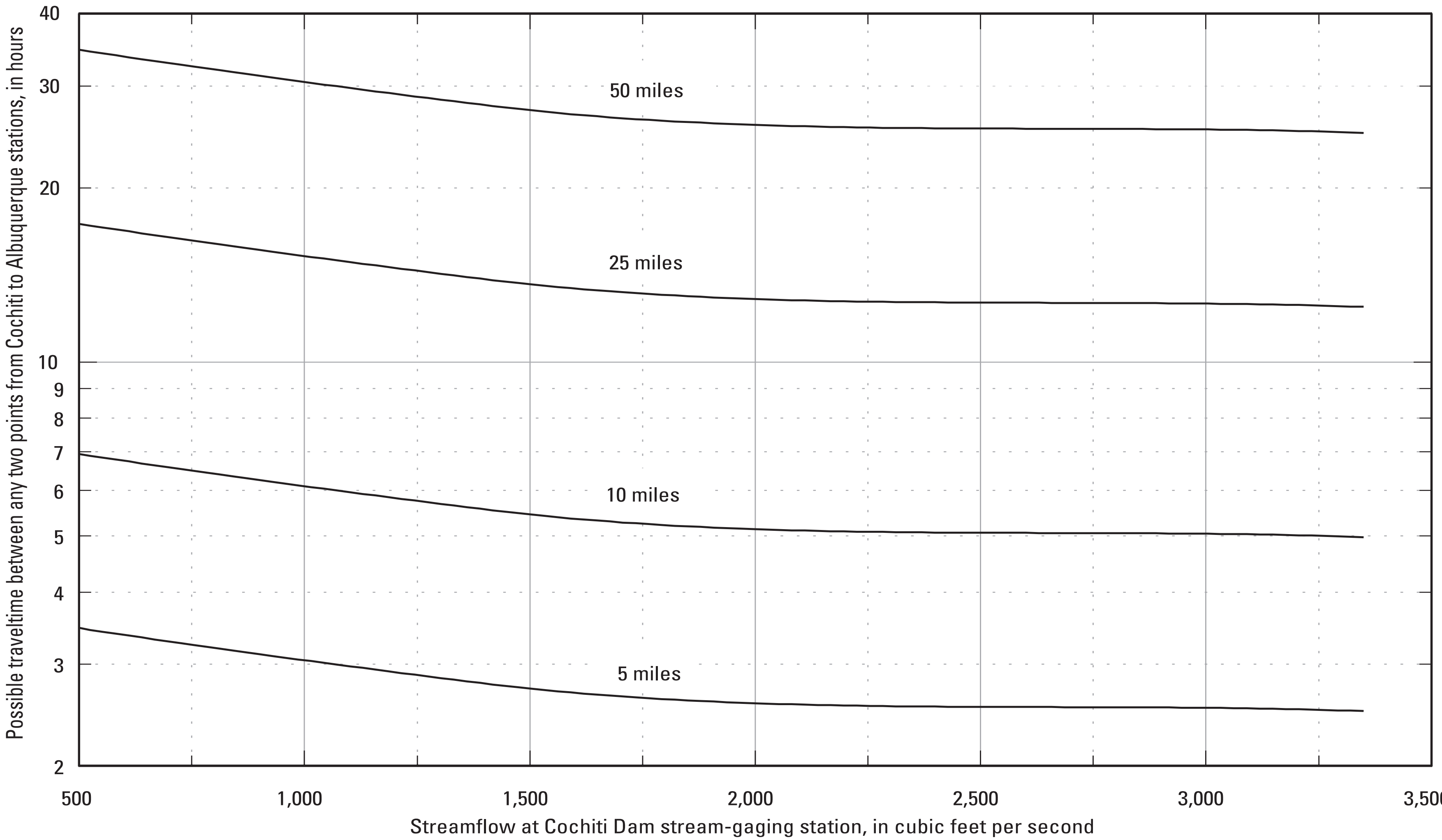

Figure 17. Traveltime curves for estimating trailing-edge traveltime between any two points in the Rio Grande located between Cochiti and Albuquerque stream-gaging stations (derived from pulse plateau-trailing-edge data).

solute to travel any given distance in the Rio Grande between Cochiti and Albuquerque stations. The variability of Rio Grande streamflow and channel characteristics in the Middle Rio Grande Basin can influence the traveltime of streamflow and a possible solute. The traveltime curves were developed from pulses during a recent period (2003–05 water years) to estimate traveltimes from existing channel conditions, but channel processes (aggradation, degradation, riparian growth, diversions) could alter future channel conditions and could affect traveltimes.

Of additional concern is the traveltime of Rio Grande streamflow from the North Floodway Channel input and the ABCWUA diversion below Alameda Bridge, a distance of about 2.5 mi. The stream reach containing the North Floodway Channel input and the ABCWUA diversion is similar to the larger upgradient reach (no major changes in channel gradient or geometry). To focus more closely on the issue of traveltime from the North Floodway Channel input and the ABCWUA diversion, velocities derived from the pulse traveltimes between Cochiti and Albuquerque were used to develop additional traveltime curves specific to the 2.5 mi distance (fig. 18). The traveltime curves can be used to estimate the beginning and ending traveltimes of a well-mixed conservative solute plume in the Rio Grande that enters through the North Floodway Channel input and its likely arrival at the ABCWUA diversion. Overall, the likely traveltimes between these two points is relatively quick and ranges from 1.1 to 1.7 h.

Rio Grande Traveltime Characteristics

Traveltime of different parts of the pulse events indicates streamflow velocities, dispersion, and short-term storage of the Rio Grande. The shortest traveltimes for each pulse occurred with the leading edge of the rising limb. The rising limbs produced the largest velocities. A rising limb of a streamflow pulse benefits from a steeper hydraulic gradient and reduced inertia forces, allowing it to move more quickly than the steady-state flow of the pulse peak (Linsley and others, 1958). The difference in traveltime between the rising limb and plateau increased between San Felipe and San Acacia, although the percent difference decreased between the rising limb and plateau traveltimes (fig. 19). The increase in traveltime difference between the two parts of the pulse is likely a result of dispersion from streamflow interaction with the bed and bank of the channel that has a greater effect on the larger plateau flow. The decrease in percent difference is likely caused by a decrease in the difference in hydraulic gradients as the pulses flatten with downstream movement that reduces the contrast in velocities between the two parts of the pulse.

Increasing streamflows typically have larger velocities, but larger streamflows also encompass a greater amount of the stream channel and flood plain where increased dispersion and storage may occur. Mean streamflow velocities calculated from pulse traveltimes and distance between stations indicate that velocities were largest from Cochiti to San Felipe and San Felipe to Alameda (table 4). From Albuquerque to San Acacia, mean velocities were more variable with increases and decreases between stations dependent upon the pulse. Channel gradients are larger in the upper part of the basin compared to the middle and lower parts (Lagasse, 1980 and 1994; Mussetter Engineering, Inc., 2002), which can cause larger mean streamflow velocity.

The largest percent decreases in traveltime because of increasing streamflow occurred near the basin margins (San Felipe and San Acacia), and the smallest percent decreases were near Albuquerque (Albuquerque and Isleta stations) (fig. 20). These differences are likely a result of a changing channel morphology that increases and decreases differences in traveltime over the range of flow. Although the study area stations are not wholly representative of the channel shape of the river for that reach (from the upstream station to the following station), the relation of streamflow and channel width for each station provides an indication of channel configuration. From the streamflow/channel-width relation (fig. 21), the river channel is constricted near Cochiti Dam, San Felipe, and San Acacia, and channel width is the broadest in the middle of the basin near Albuquerque. Lagasse (1980 and 1994) and Mussetter Engineering, Inc. (2002) documented similar channel width trends through cross-sectional measurements.

Broader channel areas lessen the potential increase in velocity with increasing streamflow because of available in-channel area for braiding, meandering, and filling, which create longer flow paths and increase dispersion because of larger wetted perimeters that increase interaction with the channel substrate. A cross-sectional view of the variable channel bottom in the Rio Grande near Bernalillo is shown in figure 22. The effect of broad channel areas is reflected in the variability of traveltime for flows less than 1,750 ft^3/s (fig. 23). This larger variability of traveltime for smaller streamflows is likely a result of channel geometry. The availability of in-channel space for lateral movement of the river during smaller streamflows may allow the river to braid, meander, and shift before rising up the banks with increasing streamflow, or the river may choose an established channel with increasing streamflow. With multiple possible channels and flow patterns within the broader channel, smaller streamflows are likely to be more variable in traveltime.

Traveltime of streamflow at each station is inversely correlated to the originating pulse flow at Cochiti station (Pearson correlation coefficient ranging from -0.71 to -0.82 for plateau leading edge at all stations), but the relations appear to have a nonlinear component, particularly for smaller streamflows (fig. 23). A test of the linearity of the relation of traveltime (plateau leading edge) and streamflow at Cochiti station through least-squares regression indicates R^2 values ranging from 0.50 to 0.68. Explaining less than 70 percent of the data variability for all traveltime-Cochiti streamflow relations, a linear regression of the data is not a strong

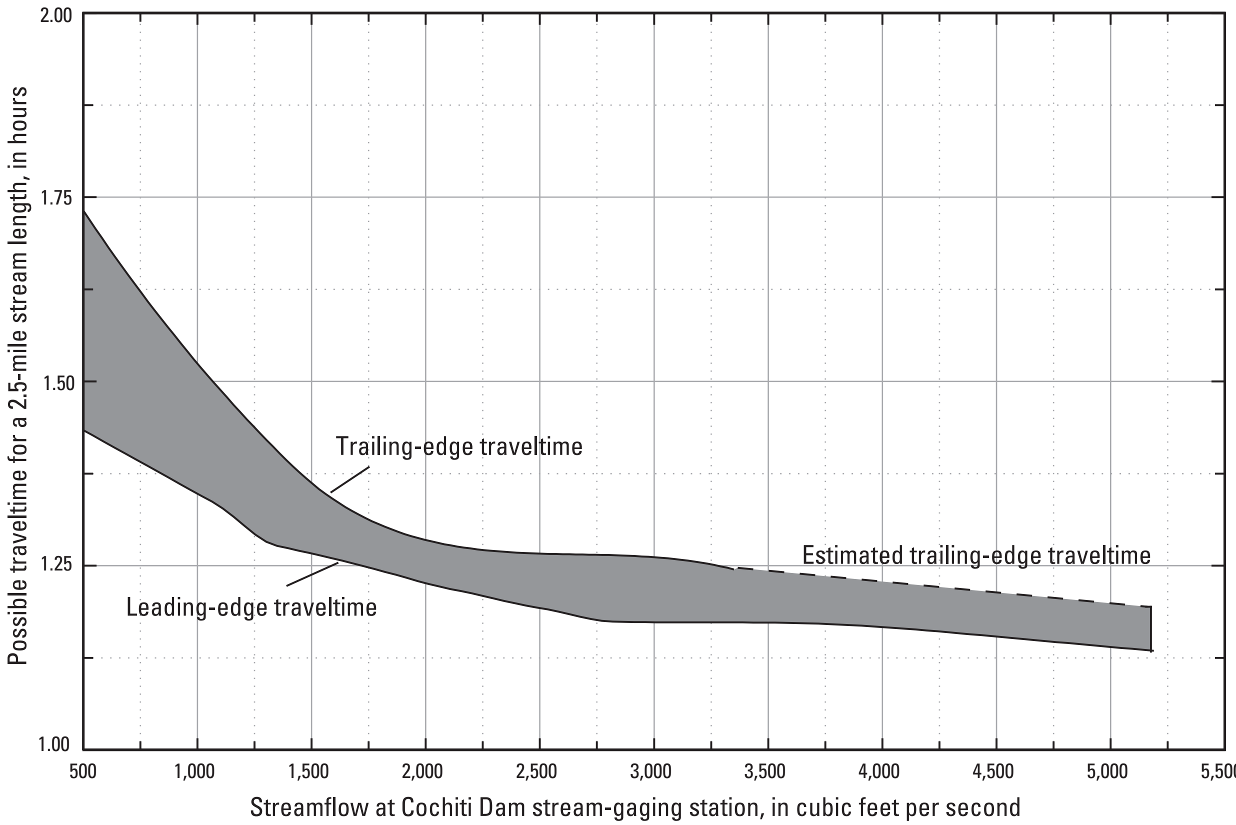

Figure 18. Traveltime curves for estimating leading-edge and trailing-edge traveltimes for a distance equal to the stream length of the Rio Grande between the North Floodway Channel input and the Albuquerque Bernalillo County Water Utility Authority-proposed diversion structure (derived from pulse leading-edge and plateau-trailing-edge data).

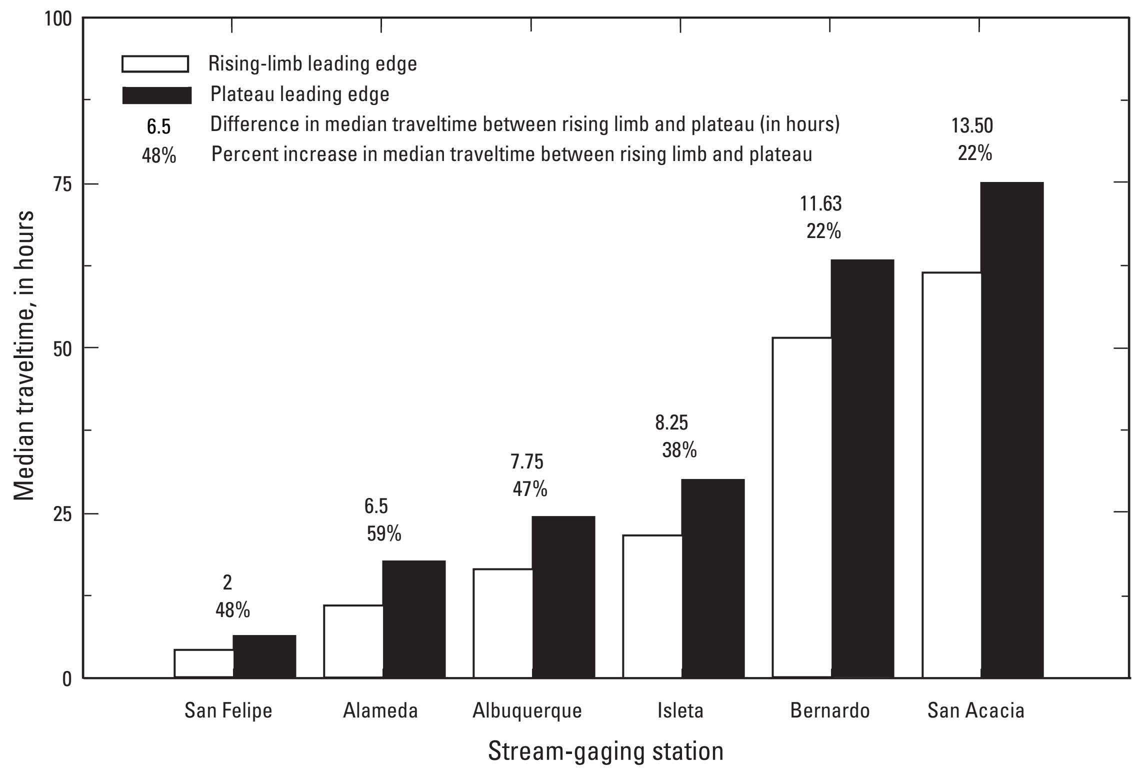

Figure 19. Median traveltimes for rising-limb leading edge and plateau leading edge of all pulse events.

Table 4. Streamflow velocities in feet per second at Rio Grande stations of San Felipe, Alameda, Albuquerque, Isleta, Bernardo, and San Acacia calculated by the traveltime of a pulse's plateau leading edge and the distance between stations.

[ft³/s; cubic feet per second; NA, not available; Std. dev., standard deviation]

Pulse	Pulse flow at Cochiti (ft³/s)	Streamflow velocities at stream-gaging stations (downstream order)					
		San Felipe[1]	Alameda	Albuquerque	Isleta	Bernardo	San Acacia
1	495	2.9	NA	2.2	NA	NA	1.8
2	528	2.8	3.2	1.3	NA	1.8	2.3
3	588	3.0	2.0	5.1	NA	1.4	1.2
4	816	3.1	2.3	2.7	2.9	1.8	2.4
5	1,060	4.2	3.0	2.2	1.9	2.0	NA
6	1,440	3.7	NA	2.6	1.5	1.3	1.0
7	3,350	4.1	3.5	1.4	4.1	2.3	1.8
8	1,250	3.6	3.2	1.6	2.9	1.8	2.1
9	1,850	4.1	2.7	2.9	2.6	1.8	2.1
10	2,280	3.9	3.4	2.4	2.6	2.0	2.1
11	2,740	4.7	3.1	2.1	3.6	2.2	2.5
12	4,010	4.7	3.2	2.0	NA	NA	2.7
Mean	1,701	3.7	3.0	2.4	2.8	1.8	2.0
Median	1,345	3.7	3.1	2.2	2.8	1.8	2.1
Std. dev.	1,169	0.65	0.47	0.98	0.85	0.32	0.53

[1] Velocity calculated from traveltime between Cochiti and San Felipe stations.

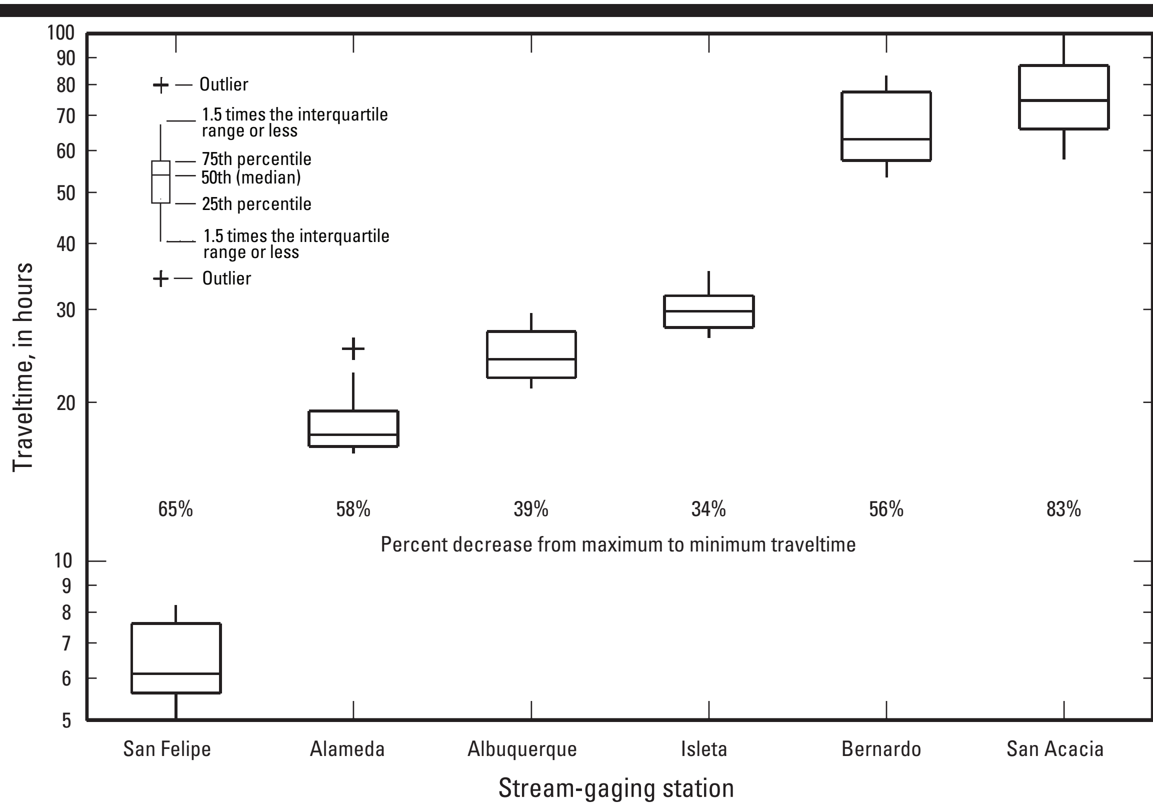

Figure 20. Streamflow pulse traveltime distributions (plateau leading edge) for Rio Grande stream-gaging stations of San Felipe, Alameda, Albuquerque, Isleta, Bernardo, and San Acacia.

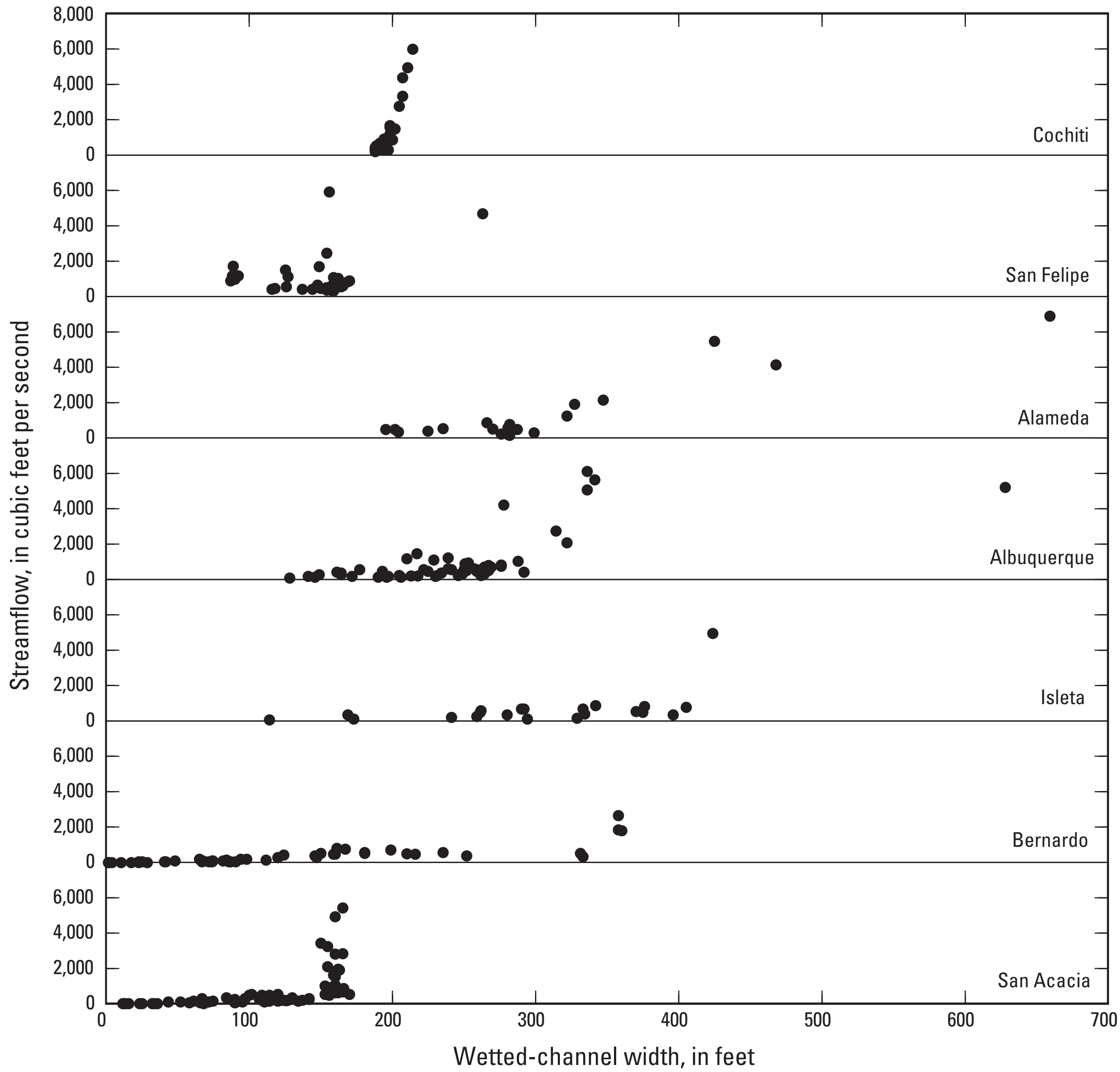

Figure 21. Streamflow and wetted-channel width for stream-gaging stations in the Middle Rio Grande Basin, water years 2003 to 2005.

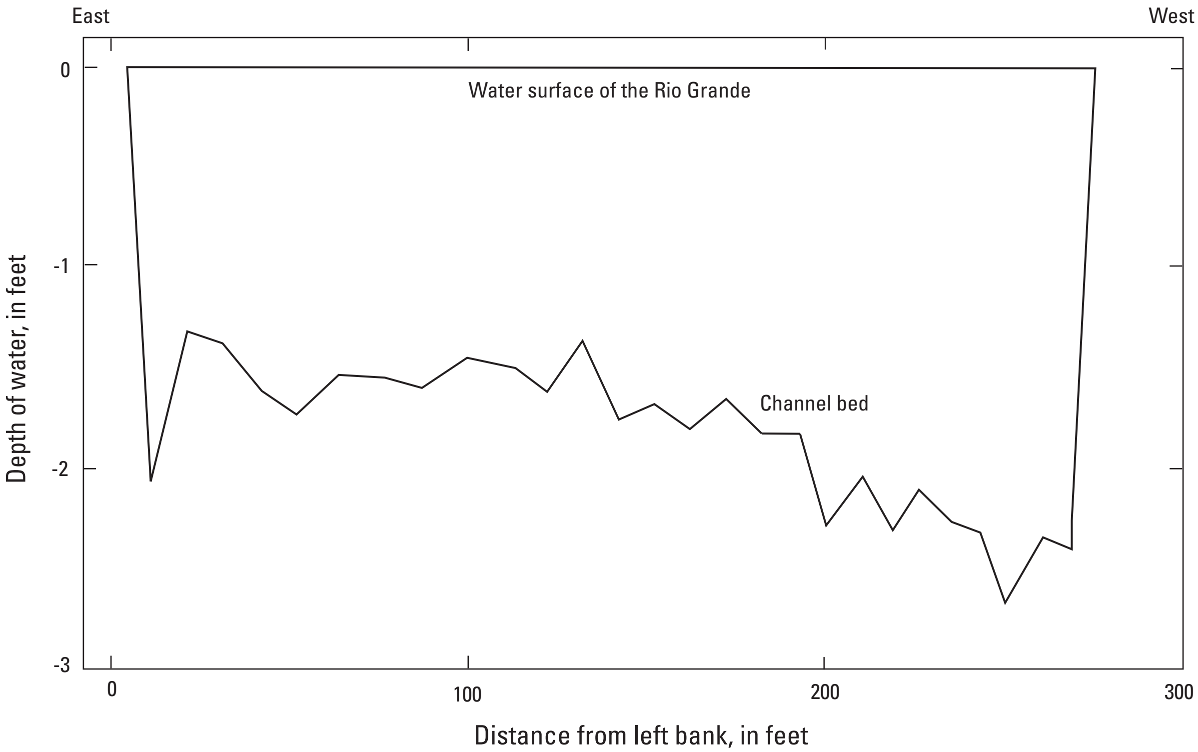

Figure 22. Cross-sectional measurement of the Rio Grande near Bernalillo (modified from Veenhuis, 2002).

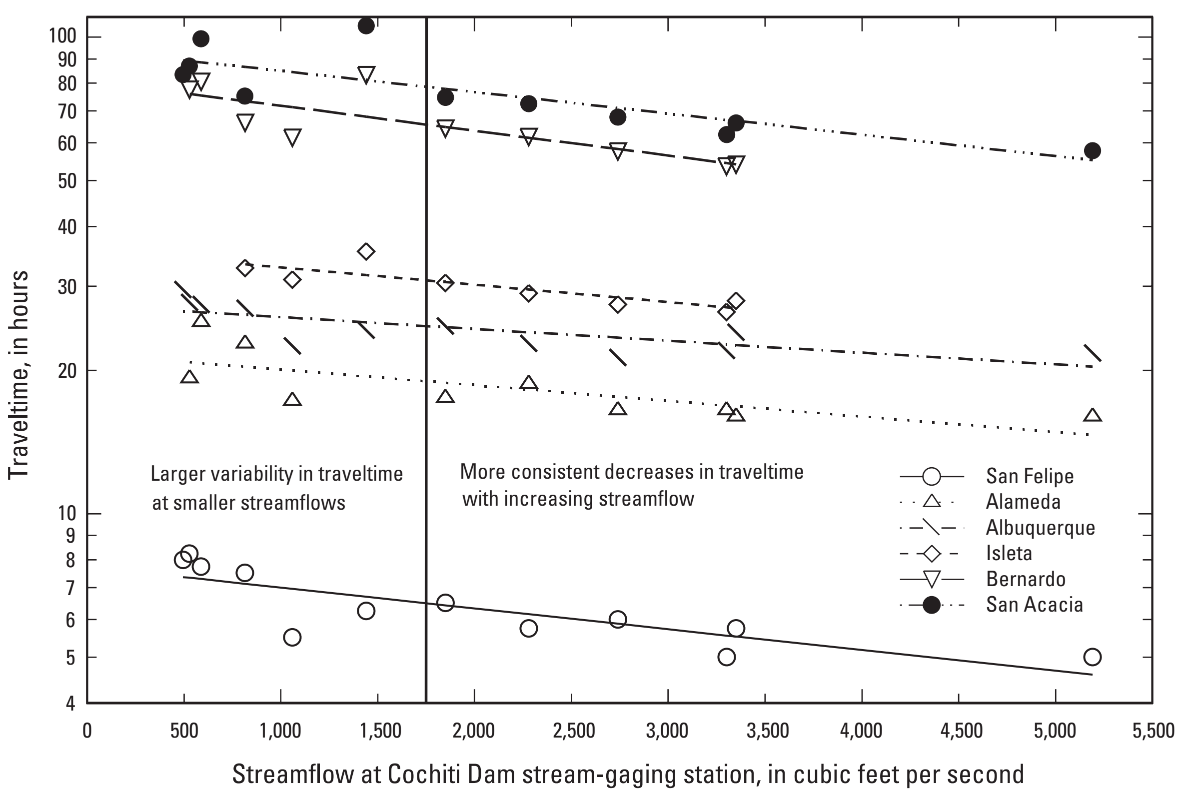

Figure 23. Traveltime for Rio Grande streamflow pulses (plateau leading edge) at the San Felipe, Alameda, Albuquerque, Isleta, Bernardo, and San Acacia stream-gaging stations.

predictor of traveltime in the Rio Grande. Local regression (nonlinear) was used for development of the traveltime curves and provides a more flexible model that can more accurately account for the shifting variability in the relation during different streamflows. A local regression relation for each station's traveltime of the plateau leading edge and the Cochiti pulse streamflow produced a range of R^2 values of 0.87–0.99 for a window span of 0.5 and a range of 0.62–0.81 for a window span of 1.0. The greater explanation of the data variability by local regression, particularly for a smaller window, indicates nonlinear components to the traveltime/streamflow relations.

Dispersion

Dispersion acts to slow and elongate a streamflow pulse through differences in vertical and transverse velocities caused by the water interacting with the channel substrate, which increases the time a pulse takes to pass a station (time of passage). A streamflow or solute pulse should continue to elongate and spread because of dispersion with increasing distance downstream. If there were no effect of dispersion on the streamflow pulse, the pulse volume remained steady, and the streamflow velocity did not change, then the time of passage would be the same at each station. The effect of dispersion for pulse event 1 is evident in the elongation and spreading of the pulse as it moved downstream (fig. 24). The pulse shape also indicates a changing pulse volume with downstream travel that was present with all pulses, and the pulse becomes skewed with downstream movement.

Pulse events 1 to 5 were recorded during late fall and winter months when streamflow in the Rio Grande is typically less affected by natural and anthropogenic influences because tributary inflows, irrigation diversions, and evapotranspiration are reduced. Fall and winter pulses generally increased in volume between Cochiti and San Felipe and between Bernardo and San Acacia (table 5). Spring pulses (pulse events 6 and 7) also increased in volume between Cochiti and San Felipe. Pulses increased in volume between San Felipe and Albuquerque at the smaller flows, but increases were not apparent at flows greater than 800 ft^3/s. Pulse volume decreased from Cochiti to Bernardo or San Acacia for the spring pulses because of irrigation diversions.

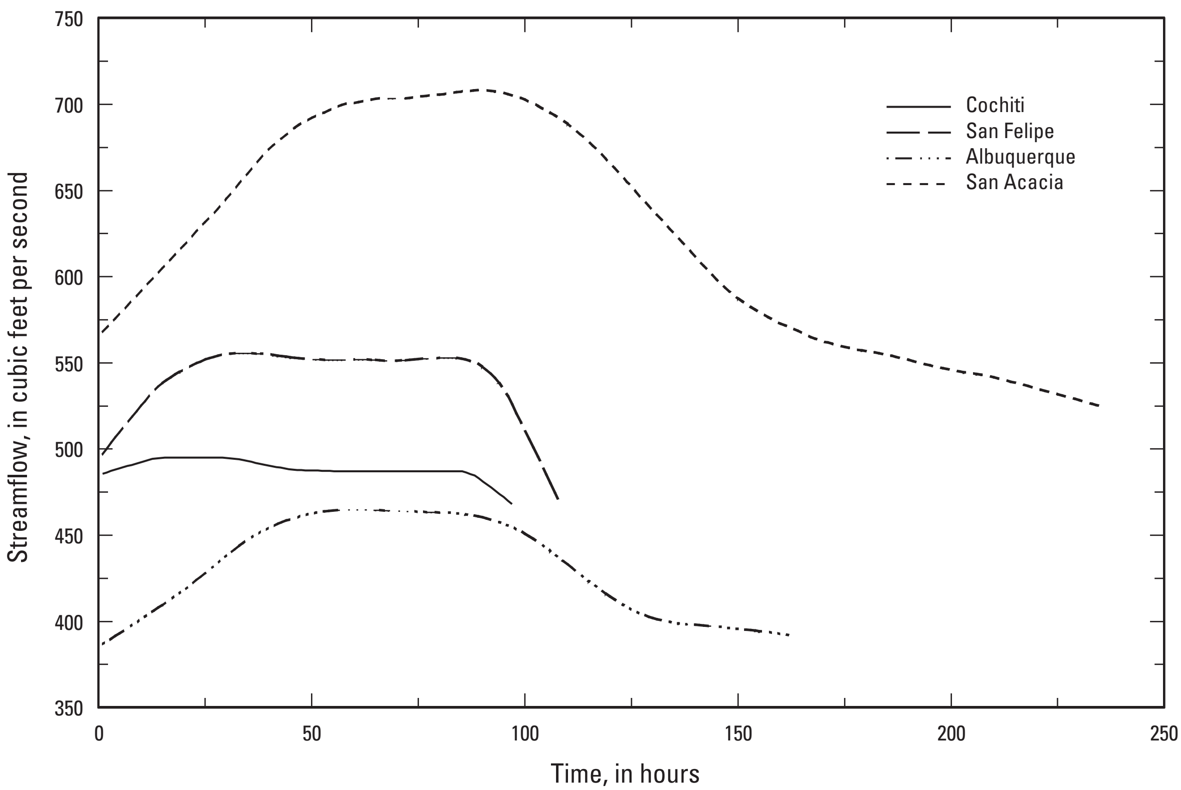

Figure 24. Streamflow trends (local regression) at the Rio Grande stream-gaging stations of Cochiti, San Felipe, Albuquerque, and San Acacia during pulse event 1.

Table 5. Percent change in pulse volume from Cochiti stream-gaging station to downstream stations of San Felipe, Albuquerque, Bernardo, and San Acacia.

[ft^3/s, cubic feet per second; acre-ft, acre-foot; percent, percent change in pulse volume from available upstream station; NA, not available]

Pulse event	Pulse flow at Cochiti (ft^3/s)	Pulse volume at Cochiti, acre-ft	Pulse volume change			
			San Felipe, percent	Albuquerque, percent	Bernardo, percent	San Acacia, percent
Fall and winter pulse events						
1	495	980	23.3	48.3	NA	[1]209.7
2	528	4,080	-0.1	NA	[2]20.2	29.8
3	588	4,500	7.3	16.0	26.4	36.2
4	816	15,670	4.1	-6.0	-8.2	-1.2
5	1,060	21,050	1.7	-1.1	-8.2	NA
Spring pulse events						
6	1,440	6,130	9.5	-13.9	-18.7	-27.2
7	3,350	27,430	3.9	2.7	-25.2	NA

[1] Percent change of pulse volume from Albuquerque to San Acacia station.

[2] Percent change of pulse volume from San Felipe to Bernardo station.

To examine the dispersive effect of the Rio Grande channel, the pulses were split into three groups—pulse events 1, 2, 3, and 4 (495 to 816 ft^3/s); pulse events 5, 8, and 9 (1,060 to 2,280 ft^3/s); and pulse events 7, 10, and 11 (2,740 to 3,350 ft^3/s)—and mean traveltimes were computed and converted to cubic feet per second from Cochiti to each downstream station (fig. 25). All three groups indicated decreases in average streamflow velocity of greater than 30 percent from San Felipe to San Acacia. The reduced slope and positive slope of the average velocity lines between Albuquerque and Isleta and between Bernardo and San Acacia indicate that the velocities increased between these stations and that the effect of dispersion was reduced.

A pulse's time of passage also can indicate the effect of dispersion and the variability of the effect that is due to streamflow level. The difference in time of passage (elongation of the pulse compared to the pulse at Cochiti station) is presented for all pulses except pulse event 6 (fig. 26). Pulse event 6 contained a large dispersion effect between Isleta and San Acacia that was not present with the other pulses and was considered an outlier. To reduce the effect of the changing pulse volume, the time of passage for each pulse was divided by the recovery ratio (pulse volume at Cochiti compared to the pulse volume at a downstream station) to normalize the data. Additionally, data for the Albuquerque station are not presented because of changes to the river channel that produce conflicting data from Alameda to Isleta. The transformed data provide a more representative presentation of the effect of dispersion and its downstream trend. The effect of dispersion was evident in the downstream direction, but there was not a consistent increase or decrease in dispersion with increasing or decreasing streamflow, and this lack of a dispersion trend with a change in streamflow was likely masked by changes in gradient and channel width (fig. 26).

Short-Term Storage

The possibility of a short-term storage component in the Rio Grande channel system could increase traveltime of a pulse and retain solutes in the system for longer durations compared to transport only affected by advection and dispersion. All pulses indicated a negative skewness that lessened with downstream flow (table 6). The initial negative skewness appears to be a function of a larger variation in pulse plateau streamflow near the rising limb of the pulse. All pulses indicated more variation in the plateau streamflow following the rising limb, which skews the distribution to this part of pulse. The slightly larger values of the plateau near the pulse rising limb are visible in the pulse event 1 trendline for the Cochiti station, which indicates a small decrease in the plateau flow near the midpoint of the plateau (fig. 24). The change to less negative or positive skewness with downstream flow indicates a greater lengthening of the descending limbs compared to the rising limbs of the pulses. This change in skewness is likely indicative of short-term storage because part of the pulse is being delayed, which extends the descending limb to a greater extent than the rising limb.

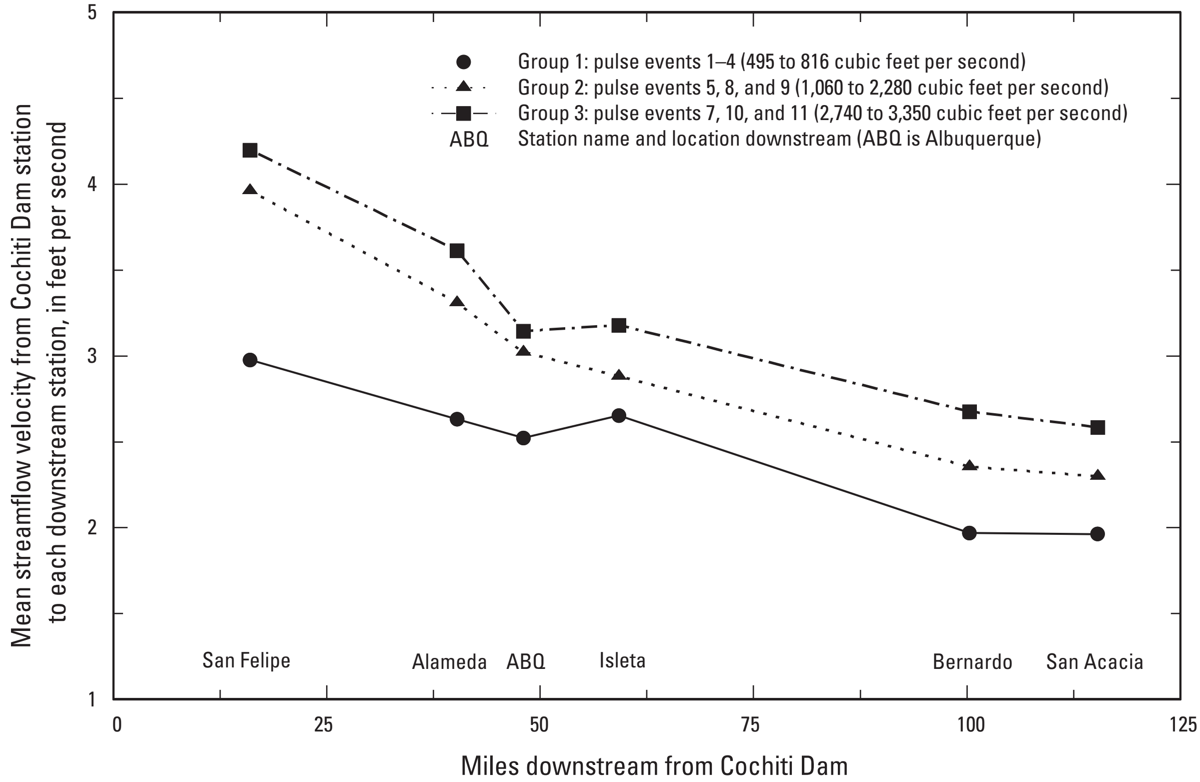

Figure 25. Mean streamflow velocity from Cochiti Dam to the downstream stream-gaging stations of San Felipe, Alameda, Albuquerque, Isleta, Bernardo, and San Acacia.

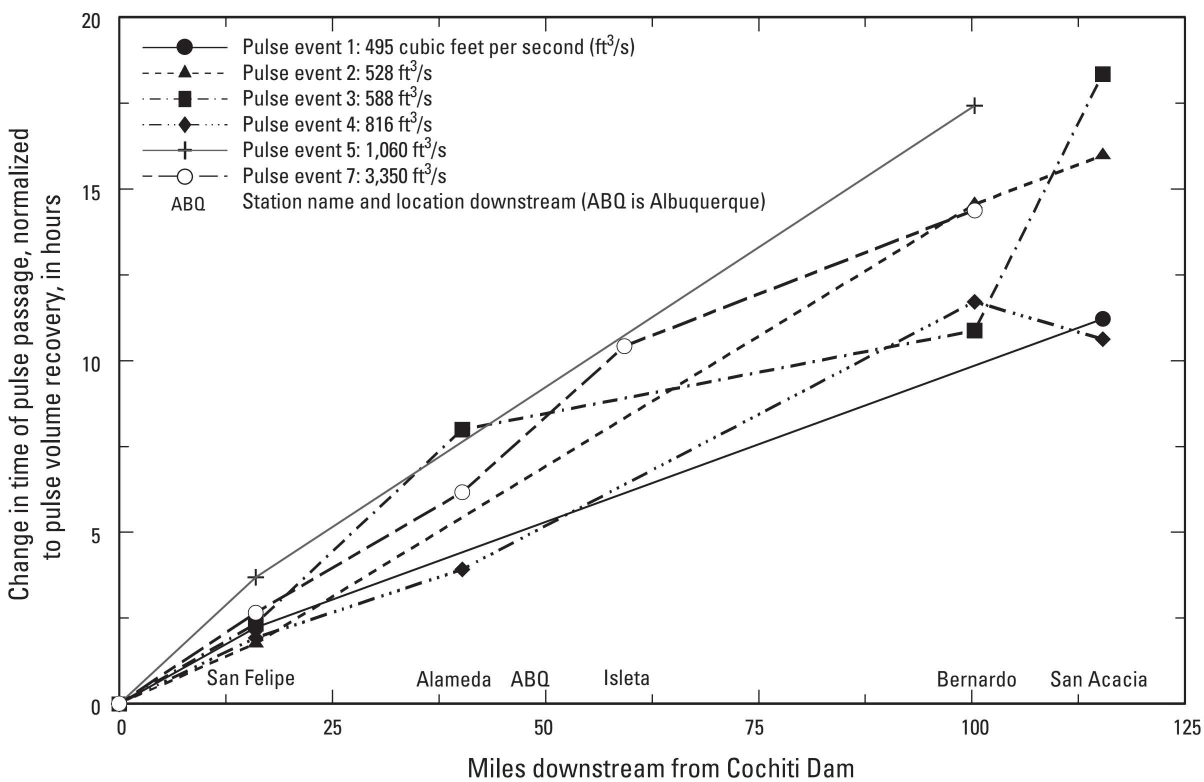

Figure 26. Time of passage for pulse events from Cochiti Dam normalized for changes in pulse volume for Rio Grande stream-gaging stations of San Felipe, Alameda, Albuquerque, Isleta, Bernardo, and San Acacia.

Table 6. Skewness of the pulse distributions.

[ft^3/s, cubic feet per second; skewness value indicates deviation of distribution from symmetry derived from Fisher's G; NA, not available]

Pulse event	Pulse flow (ft^3/s)	Cochiti	San Felipe	Alameda	Albuquerque	Isleta	Bernardo	San Acacia
1	495	-6.88	-1.87	NA	-0.11	NA	1.48	0.10
2	528	-4.05	-4.03	NA	NA	NA	-1.06	-1.17
3	588	-6.73	-3.50	-2.01	-1.57	NA	-1.35	-0.82
4	816	-12.24	-3.89	-1.28	-2.57	-2.50	-2.71	-2.13
5	1,060	-16.07	-5.98	-2.20	-3.25	NA	-3.15	NA
6	1,440	-2.49	-2.03	NA	-1.33	-1.10	-0.66	-0.32
7	3,350	-7.44	-3.22	-1.78	-1.98	-2.11	-0.90	NA

Summary

The quality of water in the Rio Grande is becoming increasingly important as more surface water is being proposed for diversion from the river for potable and nonpotable uses. Historically, water from the Rio Grande in the Middle Rio Grande Basin was typically diverted for agriculture, but with proposed diversions for municipal supply, a spill into the Rio Grande could have a substantial effect on use of the resource and health of the populace. In the event of contamination of water supplies, water-resource managers must decide when, and for how long, to suspend diversions; knowledge of traveltime characteristics of the Rio Grande will allow water-resource managers to make informed decisions concerning diversions from the Rio Grande.

A flow-pulse analysis was performed to determine traveltimes of a wide range of streamflows and produce traveltime curves to estimate the possible traveltime of a conservative solute in the Rio Grande for any two points between Cochiti Dam and Albuquerque. Additionally, traveltimes were used to evaluate streamflow velocities, dispersion, and storage characteristics in the entire Middle Rio Grande Basin. This study was based on available streamflow data from the USGS surface-water data collection program, and the flow-pulse analysis was applied to 12 pulses from the 2003–05 water years. Pulse streamflows ranged from 495 to 5,190 ft^3/s. Three points of each pulse were tracked as the pulse passed a station—rising-limb leading edge, plateau leading edge, and plateau trailing edge. Traveltime curves were developed through local-regression analysis of streamflow velocities determined from the traveltime of the leading and trailing edges of the pulse plateaus. Traveltime of the rising-limb leading edge, centroids of the rising limb and plateau, and the trailing edge of the plateau also were determined to examine the alteration of the pulse shape resulting from dispersion and storage characteristics.

Most pulses indicated longer traveltimes for each successive point in the pulse. The shortest traveltimes for each pulse occurred with the leading edge of the rising limb. Decreasing traveltimes were not always consistent with increasing streamflow, particularly for flows less than 1,750 ft^3/s, and the relation of traveltime and original pulse streamflow at Cochiti indicate a nonlinear component. Average streamflow velocities decreased by greater than 30 percent from San Felipe to San Acacia. The effect of dispersion was evident in the downstream direction, but there was not a consistent increase or decrease in dispersion with increasing or decreasing streamflow, and this lack of a dispersion trend with a change in streamflow was likely masked by changes in gradient and channel width. With downstream flow, distributions of the pulses became more skewed to the descending limbs. This greater lengthening of the descending limbs was likely a result of short-term storage that delayed a part of the pulses separate from the effect of dispersion.

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Supplemental Information

Table SI–1. Traveltime of rising-limb leading edge of pulse event from Cochiti Dam stream-gaging station.

[ft^3/s, cubic feet per second; NA, not available]

Pulse event (table 3)	Plateau flow at Cochiti Dam (ft^3/s)	Stream-gaging stations (downstream order)						
		Cochiti (hours)	San Felipe (hours)	Alameda (hours)	Albuquerque (hours)	Isleta (hours)	Bernardo (hours)	San Acacia (hours)
1	495	0.00	6.00	NA	20.00	NA	NA	72.25
2	528	0.00	6.00	9.25	16.00	NA	65.00	71.25
3	588	0.00	5.75	16.25	20.75	NA	72.00	80.00
4	816	0.00	5.25	15.00	18.75	24.75	50.50	61.00
5	1,060	0.00	4.25	13.00	17.00	24.50	54.50	NA
6	1,440	0.00	4.50	NA	18.25	25.50	57.75	67.25
7	3,350	0.00	3.75	10.25	12.75	19.25	41.00	54.25
8	1,850	0.00	4.00	10.50	16.75	22.75	49.50	59.25
9	2,280	0.00	3.75	10.25	15.25	21.50	52.25	62.25
10	2,740	0.00	3.50	12.75	14.75	20.00	49.50	61.25
11	3,300	0.00	3.50	11.25	14.00	19.00	45.50	54.00
12	5,190	0.00	3.50	10.50	13.75	17.00	NA	44.75

Table SI–2. Traveltime of rising-limb centroid of pulse event from Cochiti Dam stream-gaging station.

[ft^3/s, cubic feet per second; NA, not available]

Pulse event (table 3)	Plateau flow at Cochiti Dam (ft^3/s)	Stream-gaging stations (downstream order)						
		Cochiti (hours)	San Felipe (hours)	Alameda (hours)	Albuquerque (hours)	Isleta (hours)	Bernardo (hours)	San Acacia (hours)
1	495	0.00	7.00	NA	24.75	NA	NA	78.00
2	528	0.00	7.25	14.25	22.00	NA	71.25	79.25
3	588	0.00	6.75	20.75	24.25	NA	76.25	89.75
4	816	0.00	6.50	19.00	23.00	28.75	58.25	68.25
5	1,060	0.00	5.00	15.25	19.75	27.75	58.00	NA
6	1,440	0.00	5.50	NA	21.25	30.50	70.50	86.50
7	3,350	0.00	4.75	13.25	18.50	23.75	47.50	60.25
8	1,850	0.00	5.25	14.00	20.75	26.75	57.00	67.00
9	2,280	0.00	4.75	14.50	19.00	25.25	57.00	67.50
10	2,740	0.00	4.75	14.75	18.00	23.75	53.50	64.75
11	3,300	0.00	4.25	14.00	18.00	22.75	49.50	58.25
12	5,190	0.00	4.25	13.25	17.75	NA	NA	51.25

Table SI–3. Traveltime of plateau leading edge of pulse event from Cochiti Dam stream-gaging station.

[ft³/s, cubic feet per second; NA, not available]

Pulse event (table 3)	Plateau flow at Cochiti Dam (ft³/s)	Stream-gaging stations (downstream order)						
		Cochiti (hours)	San Felipe (hours)	Alameda (hours)	Albuquerque (hours)	Isleta (hours)	Bernardo (hours)	San Acacia (hours)
1	495	0.00	8.00	NA	29.50	NA	NA	83.50
2	528	0.00	8.25	19.25	27.75	NA	77.50	87.00
3	588	0.00	7.75	25.25	27.50	NA	80.50	99.25
4	816	0.00	7.50	22.75	27.00	32.75	66.00	75.25
5	1,060	0.00	5.50	17.25	22.50	31.00	61.50	NA
6	1,440	0.00	6.25	NA	24.25	35.50	83.25	105.50
7	3,350	0.00	5.75	16.00	24.00	28.00	54.00	66.00
8	1,850	0.00	6.50	17.50	24.75	30.50	64.25	74.75
9	2,280	0.00	5.75	18.75	22.75	29.00	61.75	72.50
10	2,740	0.00	6.00	16.50	21.25	27.50	57.50	68.00
11	3,300	0.00	5.00	16.50	22.00	26.50	53.50	62.50
12	5,190	0.00	5.00	16.00	21.75	NA	NA	57.75

Table SI–4. Traveltime of plateau centroid of pulse event from Cochiti Dam stream-gaging station.

[ft³/s, cubic feet per second; NA, not available]

Pulse event (table 3)	Plateau flow at Cochiti Dam (ft³/s)	Stream-gaging stations (downstream order)						
		Cochiti (hours)	San Felipe (hours)	Alameda (hours)	Albuquerque (hours)	Isleta (hours)	Bernardo (hours)	San Acacia (hours)
1	495	0.00	8.25	NA	32.00	NA	NA	92.75
2	528	0.00	8.25	NA	NA	NA	79.25	89.25
3	588	0.00	8.75	24.75	31.00	NA	82.25	101.75
4	816	0.00	6.50	NA	25.00	NA	64.00	74.50
5	1,060	0.00	7.25	NA	22.75	NA	64.00	NA
6	1,440	0.00	6.75	NA	23.50	33.00	88.50	103.50
7	3,350	0.00	6.50	16.50	23.50	28.25	53.50	NA
8	1,850	0.00	NA	NA	NA	NA	NA	NA
9	2,280	0.00	NA	NA	NA	NA	NA	NA
10	2,740	0.00	NA	NA	NA	NA	NA	NA
11	3,300	0.00	NA	NA	NA	NA	NA	NA
12	5,190	0.00	NA	NA	NA	NA	NA	NA

Table SI–5. Traveltime of trailing edge of pulse event from Cochiti Dam stream-gaging station.

[ft^3/s, cubic feet per second; NA, not available]

Pulse event (table 3)	Plateau flow at Cochiti Dam (ft^3/s)	Stream-gaging stations (downstream order)						
		Cochiti (hours)	San Felipe (hours)	Alameda (hours)	Albuquerque (hours)	Isleta (hours)	Bernardo (hours)	San Acacia (hours)
1	495	0.00	8.75	NA	36.50	NA	NA	107.00
2	528	0.00	7.75	NA	NA	NA	82.50	92.00
3	588	0.00	8.25	24.75	36.00	NA	85.75	105.00
4	816	0.00	7.25	19.25	26.25	37.50	61.25	71.50
5	1,060	0.00	8.00	28.00	31.75	NA	70.50	NA
6	1,440	0.00	6.25	NA	22.00	31.25	100.00	111.25
7	3,350	0.00	6.50	17.00	24.50	29.25	51.75	NA
8	1,850	0.00	NA	NA	NA	NA	NA	NA
9	2,280	0.00	NA	NA	NA	NA	NA	NA
10	2,740	0.00	NA	NA	NA	NA	NA	NA
11	3,300	0.00	NA	NA	NA	NA	NA	NA
12	5,190	0.00	NA	NA	NA	NA	NA	NA

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