SUMMARY OF FLOW LOSS BETWEEN SELECTED CROSS SECTIONS ON THE RIO GRANDE IN AND NEAR ALBUQUERQUE, NEW MEXICO

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02-4131

Prepared in cooperation with the

CITY OF ALBUQUERQUE

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By Jack E. Veenhuis

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Albuquerque, New Mexico
2002

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	2.54	centimeter
foot	0.3048	meter
mile	1.609	kilometer
cubic foot per second	0.02832	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

The upper middle Rio Grande Basin, as defined by the U.S. Army Corps of Engineers, extends from the headwaters of the Rio Grande in southwestern Colorado to Fort Quitman, Texas. Most of the basin has a semiarid climate typical of the southwestern United States. This climate drives a highly variable streamflow regime that contributes to the complexity of water management in the basin. Currently, rapid population growth in the basin has resulted in increasing demands on the hydrologic system. Water management decisions have become increasingly complex because of the broad range of interests and issues. For these reasons, the U.S. Geological Survey, in cooperation with the City of Albuquerque, New Mexico, conducted paired flow measurements at two cross sections to determine cross-sectional loss in the Albuquerque reach of the Rio Grande.

This report statistically summarizes flow losses in the Albuquerque reach of the Rio Grande during the winter nonirrigation season from December 1996 to February 2000. The two previous flow-loss investigations are statistically summarized. Daily mean flow losses are calculated for the winter nonirrigation season using daily mean flows at three selected Rio Grande streamflow-gaging stations.

For the winter nonirrigation season cross-sectional measurements (1996-2000), an average of 210 cubic feet per second was returned to the river between the measurement sites, of which 165 cubic feet per second was intercepted by riverside drains along the 21.9-mile reach from the Rio Grande near Bernalillo to the Rio Grande at Rio Bravo Bridge streamflow-gaging stations. Total cross-sectional losses in this reach averaged about 90 cubic feet per second.

Regression equations were determined for estimating downstream total outflow from upstream total inflow for all three paired measurement studies. Regression equations relating the three daily mean flow recording stations also were determined. In each succeeding study, additional outside variables were controlled, which provided more accurate flow-loss measurements. Regression-equation losses between measurement cross sections ranged from 1.9 to 7.9 percent during the nonirrigation season and from about 5.9 to 6.4 percent during the irrigation season. Mean and median loss by reach length for all three daily mean flow stations and all three cross-sectional measurement reaches showed consistent flow loss per mile by season with allowance for nonideal river conditions for the initial measurement studies. Unsteady measurement conditions were reflected in the regression equation mean-square errors and ultimately in the change in daily mean discharge at the Rio Grande at Albuquerque gaging station during the measurement periods.

Introduction

The upper Rio Grande Basin, as defined by the U.S. Army Corps of Engineers, extends from the headwaters of the Rio Grande in south-central Colorado to Fort Quitman, Texas (fig. 1). Most of the basin has a semiarid climate typical of the southwestern United States. This climate drives a highly variable streamflow regime that contributes to the complexity of water management in the basin. Average annual precipitation ranges from about 7 to 15 inches over the upper and middle parts of the basin and exceeds 25 inches only in the high mountain areas.

Historically, water from the Rio Grande has been used primarily for crop irrigation. Currently, rapid population growth in the basin has resulted in increasing demands on the hydrologic system; thus, water management decisions have become increasingly complex. Riverflow losses and sources of ground-water recharge are becoming increasingly important. Flow-loss estimates in the Albuquerque reach of the Rio Grande are needed to help determine recharge to the Santa Fe Group aquifer system that Albuquerque depends on for its public water supply. This reach extends from south of Bernalillo to the Rio Bravo Bridge in the southern part of Albuquerque (fig. 2).

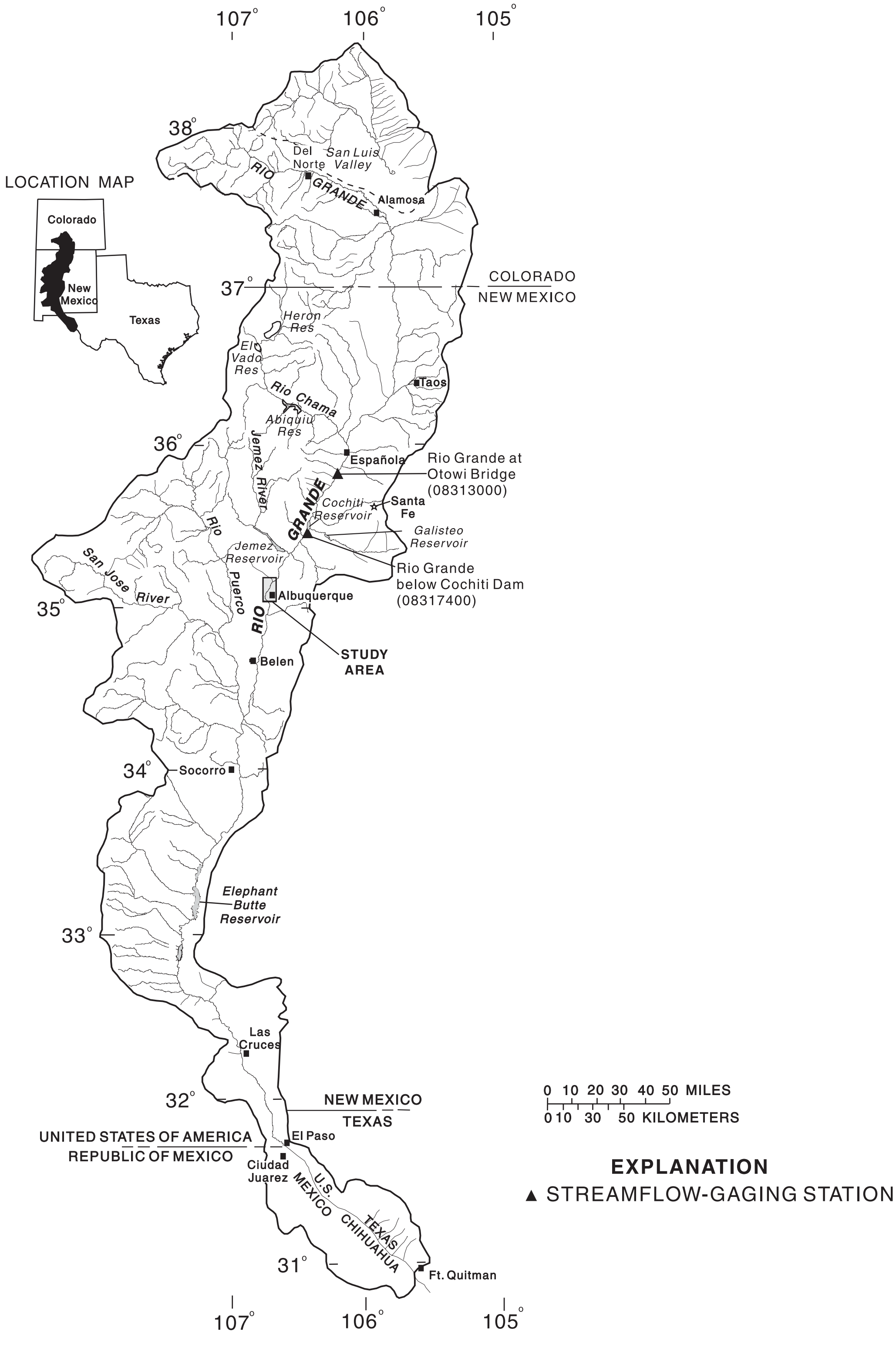
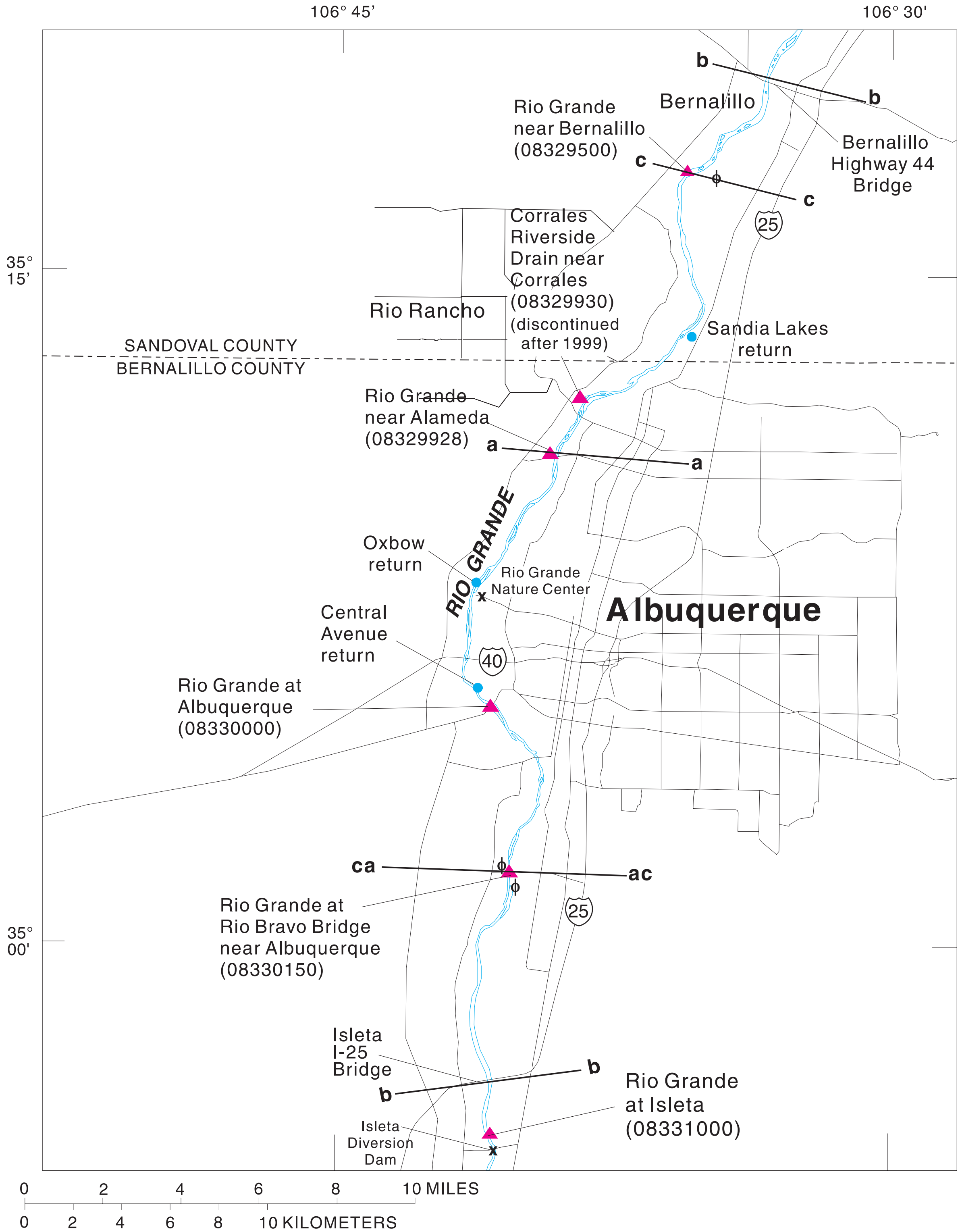


Figure 1. Study area and generalized extent of the Rio Grande drainage basin above Fort Quitman, Texas.



EXPLANATION

▲ STREAMFLOW-GAGING STATION
● RETURN-FLOW MEASUREMENT SITE
ϕ RIVERSIDE DRAIN

MEASUREMENT CROSS-SECTION LOCATIONS

a——a Monthly measurements, 1989-95 (Thorn, 1995)
b——b Weekly, August 1993 to February 1995 (Hansen, 1995)
c——c Winter nonirrigation season(current study, 1996-2000)
ca——ac Cross-section location for Thorne (1989-95) and the current study (1996-2000)

Figure 2. Streamflow-gaging stations, return-flow measurement sites, riverside drains, and cross-section locations on the Rio Grande.

For these reasons, the U.S. Geological Survey (USGS), in cooperation with the City of Albuquerque, conducted paired-flow measurements at two river cross sections to determine riverflow loss in the Albuquerque reach of the Rio Grande. Cross-sectional flow measurements were made along this reach at two streamflow-gaging stations: Rio Grande near Bernalillo (08329500) and Rio Grande at Rio Bravo Bridge (08330150). The measurements were conducted during four winter nonirrigation seasons from December 1996 to February 2000.

Purpose and Scope

This report presents the results of a flow-loss study in the Albuquerque reach of the Rio Grande during the winter nonirrigation season from December 1996 to February 2000 and compares these results with two previous flow-loss investigations. These two investigations were conducted on the Bernalillo to Isleta, New Mexico, reach of the Rio Grande. In addition, the quantity of water riverside drains intercept, the quantity of water that returns to the river, and stage differences between the riverside drains and the river were measured.

As a part of one of these flow-loss investigations, two streamflow-gaging stations were operated at the cross sections used in that study. The daily mean flow loss during the winter nonirrigation season was calculated between the daily mean flow at these two gaging stations and a long-term streamflow-gaging station in the middle of the measurement reach.

Hydrologic Setting

A discussion of flow characteristics of the Rio Grande and the storm-drain system is important for understanding the complex flow system in the Albuquerque area. The Rio Grande flow system in the Albuquerque reach consists of the river channel, irrigation canals, return-flow drains, and riverside drains (fig. 3). From March through October, part of the Rio Grande is diverted upstream from Bernalillo and flows through irrigation-supply canals to fields. Some of this flow returns to the river through return-flow drains and canals. In addition, riverside drains on either side of the river channel intercept channel-seepage water that prior to 1930 would have waterlogged adjacent fields that are substantially below the water level of the river. During November through February water is not diverted to canals, so the entire flow is conveyed by the river channel and riverside drains. These riverside drains intercept lateral seepage from both sides of the river and return this flow to the river at several locations.

The annual variation of streamflow of the Rio Grande is characteristic of a river whose flow is mostly a result of snowmelt. Most of this runoff comes from snow that has fallen in the mountains of the upper Rio Chama Basin, the upper Rio Grande in the San Luis Valley in Colorado, and the upper Rio Grande in New Mexico (fig. 1). Snowmelt runoff is highest in May or early June and at its lowest in the fall and winter. In addition, summer monsoon thunderstorm runoff is superimposed on this streamflow regime. Gulf of Mexico moisture supplies about 40 percent of New Mexico precipitation in the form of summer thunderstorms (Scott Waltemeyer, U.S. Geological Survey, written commun., 2001). Most thunderstorms occur in July, August, and September and can result in local, intense rainfall and runoff. This highly localized runoff can add substantial flow to a much reduced riverflow near the end of summer when water use is at a maximum.

Cochiti, Galisteo, and Jemez Reservoirs (fig. 1), located upstream from Albuquerque, substantially influence riverflow downstream. These reservoirs control flood flows from about 90 percent of the contributing upstream drainage area. As a result, Rio Grande flow through Albuquerque is an attenuated version of a characteristic snowmelt streamflow cycle with an occasional superimposed summer thunderstorm inflow downstream from these three reservoirs. Except for the substantial reduction in the variation of flow in May and June, monthly flow distributions are quite similar to distributions prior to the construction of Cochiti Reservoir in 1973 (fig. 4). The annual peak flow recorded at the Rio Grande at Albuquerque gaging station (fig. 2), water years 1942-98, and the effect of Cochiti Reservoir on peak flow since 1973 are shown in figure 5.

At the Rio Grande at Albuquerque gaging station (fig. 2), riverside drains, irrigation canals, or laterals convey flow during the entire year. From November through February, riverside drains adjacent to both sides of the river and lower than the water surface of the Rio Grande collect river-water seepage and return it to the river downstream (fig. 3). From March through October, these drains also convey irrigation-return

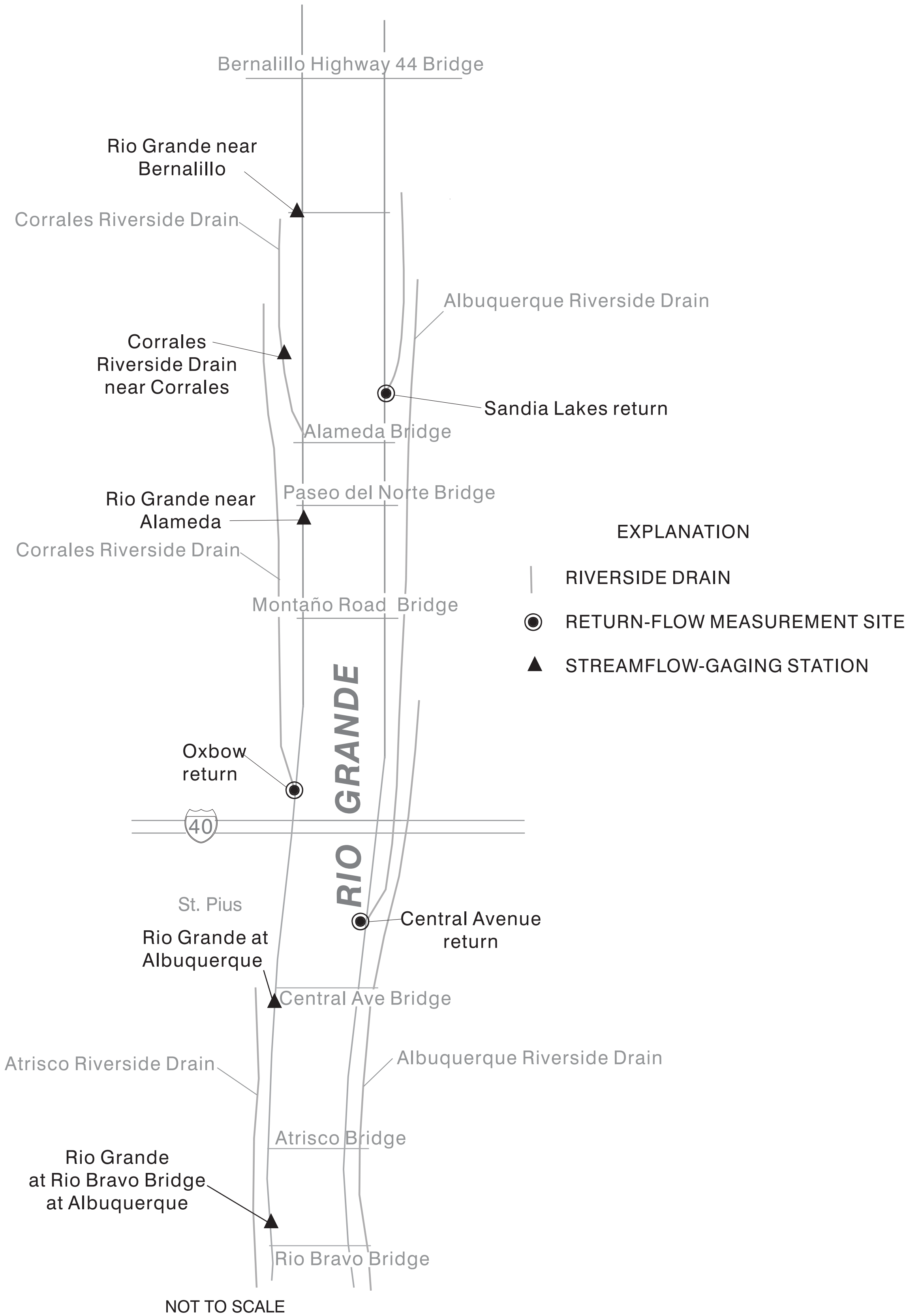


Figure 3. Locations of streamflow-gaging stations, riverside drains, and return-flow measurement sites along the Rio Grande in and near Albuquerque.

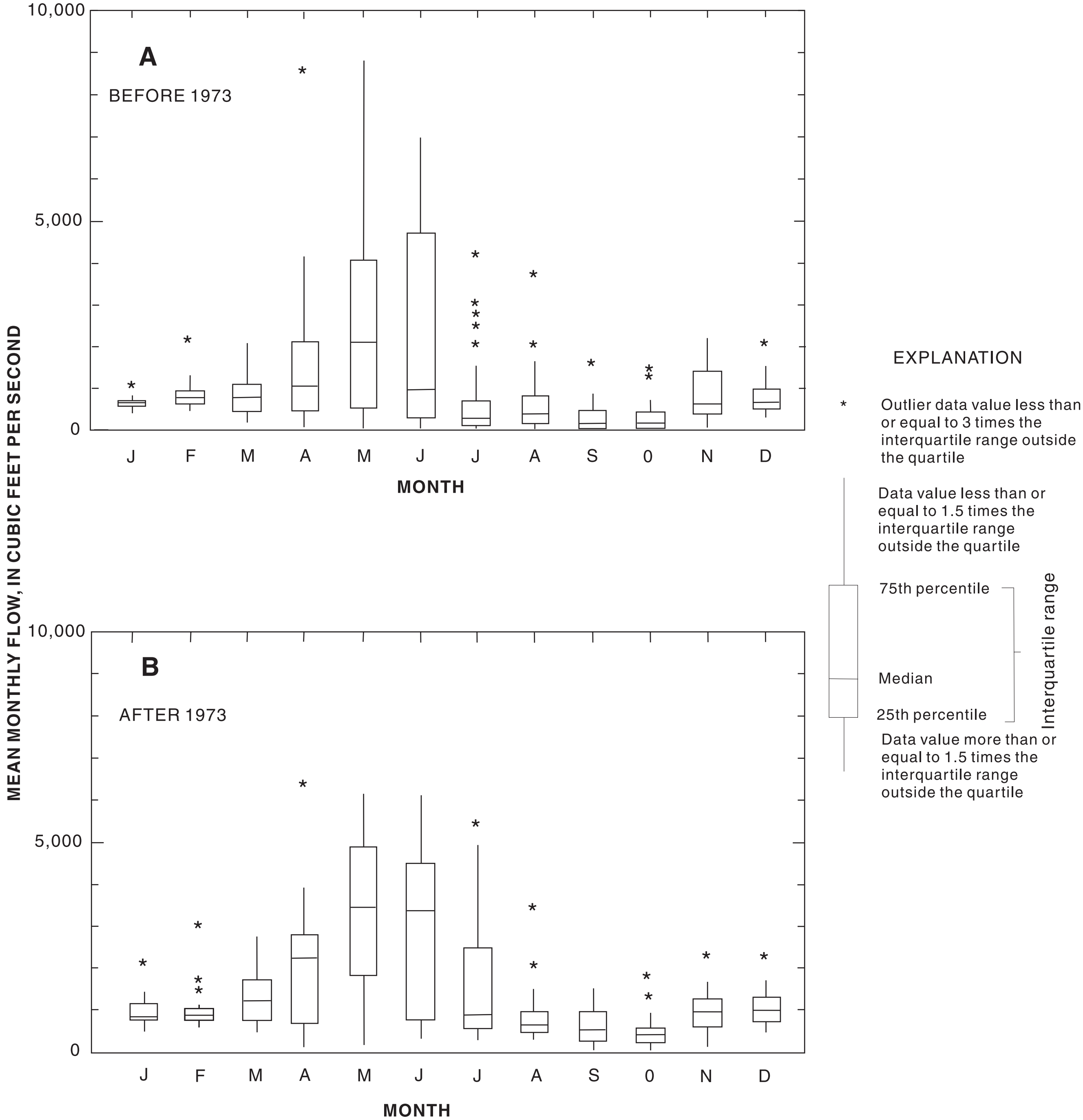


Figure 4. Monthly distribution of flow at the Rio Grande at Albuquerque (08330000) streamflow-gaging station before and after the construction of Cochiti Reservoir in 1973. Location of gaging station shown in figure 2.

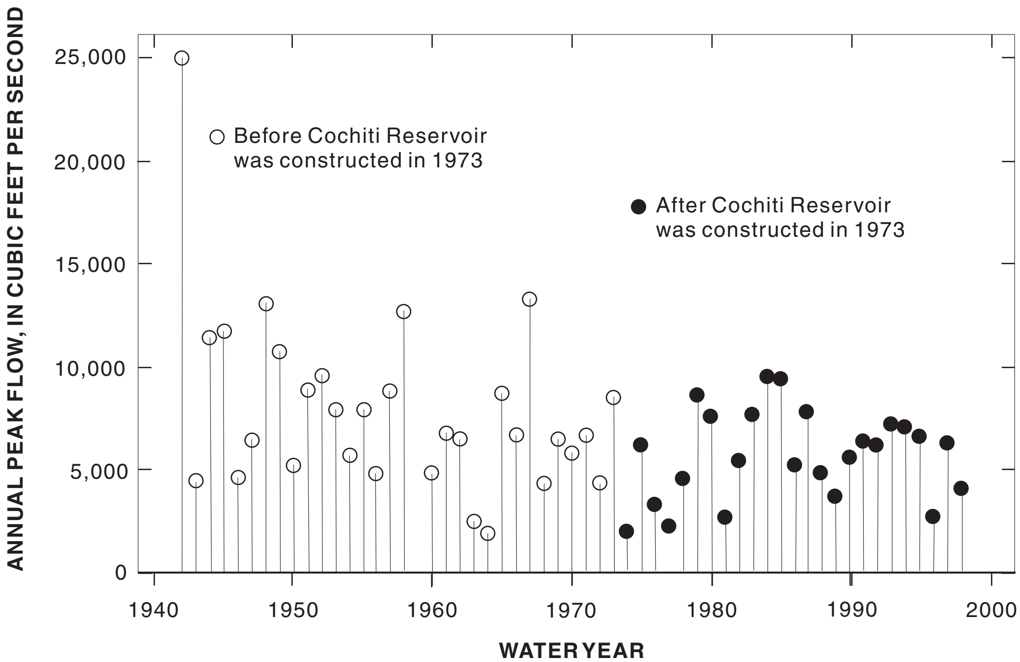


Figure 5. Annual maximum instantaneous peak flow at the Rio Grande at Albuquerque (08330000) streamflow-gaging station, 1942-98. Location of gaging station shown in figure 2.

flows as well as river-water seepage intercepted from the river. Flow in the drains averages about 14 percent of total annual flow of the river at this gaging station, but can range from a high of 36 percent of total cross-sectional flow in a dry year to as little as 5 percent of total flow in a wet year.

Flow is conveyed in irrigation canals about 8 months of the year. Riverside drains convey flow the entire year; drain flow during the nonirrigation season consists primarily of river-intercepted bed seepage that is returned to the river as drain-return flow. The change in the source of riverside drain water is visibly evident because flow during the nonirrigation months (November through February) is cold and clear due to its river seepage ground-water source. Flow in these riverside drains increases in the downstream direction. Because flow gradients in the drains are smaller than those in the river, the channel bottoms of the drains gradually rise until the water surface of the drain is higher than that of the river. At the point where the water surface of the drain becomes higher than that of the river, this intercepted seepage water is returned to the river. Where the water surface in a drain is equal to the water level of the river, a second drain at a lower elevation and outside the first drain begins intercepting river leakage. Increases in riverside-drain flow per mile vary depending on distance from the river to the drain, soil permeability, and riverside-drain elevation relative to the Rio Grande. Riverside-drain inflows and outflows measured from December 1996 to February 2000 are listed in table 1.

Previous Studies

Flow-loss studies conducted on the Rio Grande in Albuquerque include an intensive monthly flow-loss investigation by Thorn (1995) and a weekly flow-loss investigation by Hansen (1995). These studies are summarized below.

Thorn (1995) measured flow monthly from 1989 to 1995 at two cross sections established near two gaging stations: Rio Grande near Alameda (08329928) and Rio Grande at Rio Bravo Bridge near Albuquerque (08330150) (fig. 2). Sixty-one paired measurements were made at the two cross sections, 22 during the winter nonirrigation season and 39 during the summer irrigation season. Flow was measured in the morning at the upstream Alameda cross section and in the afternoon at the downstream Rio Bravo Bridge cross section in an attempt to measure the same water.

Table 1. Winter nonirrigation season (December through February) river and riverside drain flows, 1996-2000

[All flows in cubic feet per second. *, missing values]

			Rio Grande near Bernalillo cross section			Rio Grande at Rio Bravo Bridge cross section				
Year	**Month**	**Date(s) cross section measured**	**Three-measure-ment mean river inflow**	**Riverside drain inflow**	**Waste-water inflow**	**Three-measure-ment mean river outflow**	**Riverside drain outflow**	**Mass inflow**	**Mass outflow**	**Inflow minus outflow gain (-) or loss**
1996	Dec	3-4	610	66	2	597	41	678	638	40
1996	Dec	11-12	709	67	1	711	42	777	753	24
1996	Dec	17	757	66	2	*	*	825	*	*
1997	Jan	22-23	792	61	2	897	38	855	935	-80
1997	Jan	28-29	966	59	2	*	38	1,027	*	*
1997	Feb	4-5	789	63	2	843	37	854	880	-26
1997	Feb	11-12	819	70	2	767	36	891	803	88
1997	Feb	25-26	808	71	2	724	38	881	762	119
1997	Dec	17-18	1,060	114	3	1,070	42	1,177	1,112	65
1998	Jan	8-9	1,143	108	3	1,085	38	1,254	1,123	131
1998	Jan	14-15	1,033	105	3	1,003	40	1,141	1,043	98
1998	Jan	21-22	858	102	3	841	40	963	881	82
1998	Jan	28-29	876	105	3	990	37	984	1,027	-43
1998	Feb	11-12	979	99	3	924	38	1,081	962	119
1998	Feb	18-19	983	96	3	945	35	1,082	980	102
1998	Feb	25-26	948	99	3	846	34	1,050	880	170
1998	Dec	9-10	679	87	2	635	45	768	680	88
1998	Dec	16-17	760	87	2	720	44	849	764	85
1999	Jan	6-7	965	85	4	925	43	1,054	968	86
1999	Jan	13-14	925	80	4	825	40	1,009	865	144
1999	Jan	27-28	894	82	3	881	40	979	921	58
1999	Feb	3-4	812	81	3	742	39	896	781	115
1999	Feb	18-19	968	76	4	934	40	1,048	974	74
1999	Mar	1	570	78	2	772	40	*	*	*
2000	Feb	18-19	847	102	2	791	37	951	828	123

Measurements were made when storm-water inflows were not occurring and when riverflow appeared to be steady. No wastewater-treatment inflows enter between the two cross sections and no known surface-water inflows exist between the two sites. Cross-sectional flows measured from 1989 to 1995 ranged from approximately 22 to more than 5,900 cubic feet per second (ft^3/s) with a corresponding change in river stage of about 3.8 feet between the lowest and highest flows measured.

In the second study, the Bureau of Reclamation (BOR) (Hansen, 1995) made 69 weekly flow measurements between August 1993 and February 1995 at two cross sections: the Highway 44 Bridge north of Bernalillo and the Isleta I-25 Bridge north of the Rio Grande at Isleta gaging station (fig. 2). To determine streamflow loss, measurements were made at the upstream site in the afternoon and at the downstream site the next day. Twenty-five measurements were made during the winter nonirrigation season and 44 were made during the summer irrigation season. During this study, four wastewater inflows entered the river between the upstream and downstream cross sections. Major storm-water tributary inflows were documented, and reservoir-release changes were determined from streamflow records.

Methods

The Rio Grande near Alameda and the Rio Grande at Rio Bravo Bridge gaging stations (fig. 2) were operated as part of the Thorn (1995) flow-measurement investigation from March 1989 to September 1995 and from January 1991 to September 1995, respectively. The Rio Grande near Bernalillo gaging station was operated for stage during the current study (1996-2000). The Rio Grande at Albuquerque gaging station has been operated since October 1941 as part of other data collection efforts.

Waltemeyer (1994) conducted a study during the fall of 1991 to estimate travel time and reaeration for a reach of the Rio Grande extending from the Rio Grande Nature Center to the gaging station at the Isleta Diversion Dam. The study concluded that the streamflow velocity of the Rio Grande between the Rio Grande Nature Center and the Isleta Diversion Dam ranged from 1 to 2 miles per hour for discharges ranging from 250 to 1,500 ft^3/s. This range of velocities was used to estimate the time a parcel of water would travel from the upstream measurement site to the downstream measurement site.

During the winter nonirrigation season from December 1996 to February 2000 (current study), the USGS conducted a paired flow-measurement investigation. Twenty-five paired measurements of the river and riverside drains were made at two cross sections: the Rio Grande near Bernalillo and the Rio Grande at Rio Bravo Bridge gaging stations (fig. 2). Streamflow was measured at the upstream site in the afternoon and at the downstream site the next morning. Because these were winter season measurements, only the river and riverside drains at each cross section were measured. Minimal wastewater-return flows were recorded in this reach, and streamflow measurements were conducted when storm-water inflows were not occurring. The U.S. Army Corps of Engineers maintained constant releases from Cochiti and Jemez Reservoirs for 3 days prior to the measurements. As part of the flow-measurement procedure, air temperature and water temperature also were measured. To help avoid bias, most measurements were made by the same person or two people at the same time.

Riverside drain-return flow (where drain flow discharges to the river) was measured annually at four sites (fig. 2): Sandia Lakes return, Corrales Riverside Drain near Corrales gaging station, Oxbow return, and Central Avenue return (fig. 3). Return flow was presumed to be riverbed seepage. Return flows were added to the cross-sectional flow between cross sections to calculate total river-channel loss along this reach.

The difference between the elevation of the stage of the river and the elevation of the water surface of the riverside drain was measured once during flow measurements in February 2000. The gradient between the river and the riverside drain drives river leakage that is intercepted and returned to the river by the drains.

Acknowledgments

The author acknowledges personnel of the USGS Albuquerque Field Office for their help in making streamflow measurements. Also, the author acknowledges Reservoir Operations personnel at the U.S. Army Corps of Engineers for their cooperation in maintaining constant releases from Cochiti and Jemez Reservoirs during the current investigation.

FLOW LOSS IN AND NEAR ALBUQUERQUE

Principles of Flow-Loss Measurement

Measuring flow loss in the Rio Grande presents a somewhat difficult task. Rio Grande streamflow channels are constantly changing in response to daily, monthly, and annual variations in flow, sediment supply, and the formation of sand bars. All Rio Grande flow-measurement and gaging-station sites in and near Albuquerque are characterized by wide sand channels. The variations in channel depth necessitate frequent flow measurements to update stage-discharge relations because a large flow can easily change the stage as much as 2 feet for a given discharge. Thus, constant and episodic channel-bed changes result in changing stage-discharge relations and subsequently daily mean flows. Stage-discharge relations are a function of the rate of channel change and the length of time since the last measurement. Variations in channel depth during three successive measurements about 40 minutes apart at the Rio Grande near Bernalillo gaging-station cross section are shown in figure 6.

The following principles were used to make more accurate flow-loss measurements between two sites on the Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge gaging stations (fig. 2). (1) The stations were far enough apart that field personnel could measure the difference in daily mean flows considering the additional error inherent in the stage-discharge relation. (2) All cross-sectional flow was measured at both sites because there is usually transfer of flow between the conveyances that makes individual conveyance flow differences meaningless. (3) Cross-sectional flow was measured in the winter when there is less evapotranspiration and no routing of irrigation flow across the valley. (4) The error in measurement was reduced by measuring the river three successive times because of the constantly changing sand channel. (5) Cross-sectional flow was not measured during stormflow, and wastewater inflows were documented. (6) Reservoir releases were controlled so inflow to the reach was steady. (7) Travel time of the water was determined so that the same water was measured downstream.

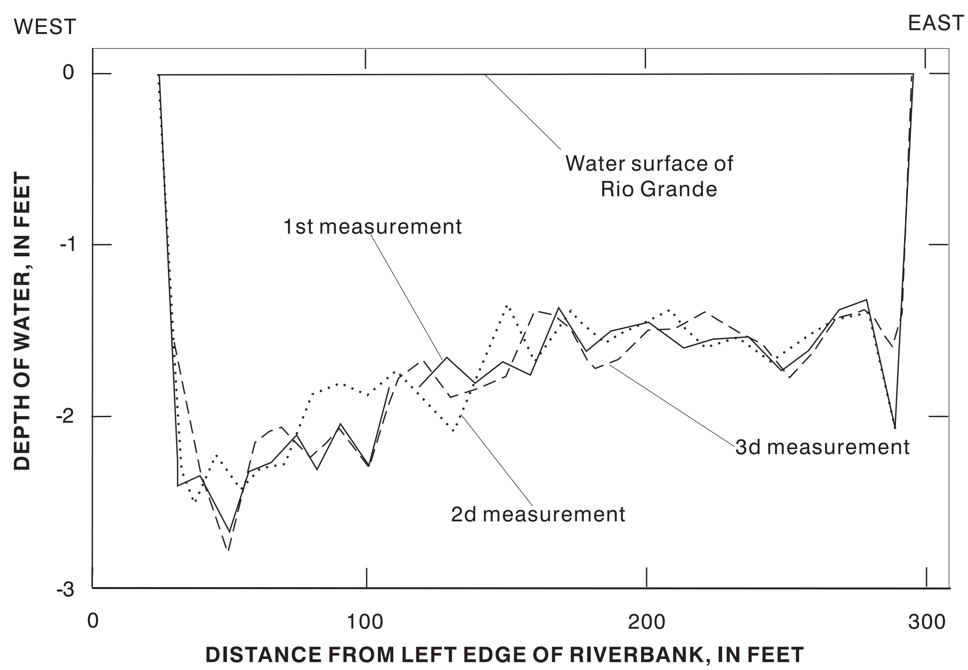


Figure 6. Cross section at the Rio Grande near Bernalillo (08329500) streamflow-gaging station showing variations in channel depth for three successive measurements made about 40 minutes apart as part of the current study (1996-2000). Location of cross section shown in figure 2. View is upstream.

The flow measurements in relation to stage of the Rio Grande near Alameda and Rio Grande at Rio Bravo Bridge gaging stations from 1989 to 1995 are shown in figure 7. Flow in the Rio Grande through Albuquerque can increase from about 22 to more than 5,900 ft^3/s with about a 3.8-foot increase in stage. For this short (12.9-mile) reach of the river (fig. 2), the difference in daily mean flow between the two gaging stations may be masked by errors in the stage-discharge rating at each site. These errors are a combination of error in the measurement of flow at each site and error caused by the changing relation between stage and discharge. Each measurement updates this relation, which then can be used to compute daily discharge. The computed daily discharge at each site depends on the recorded stages for the day and the applicable stage-discharge relation. Frequent discharge measurements were made to update the stage-discharge relation.

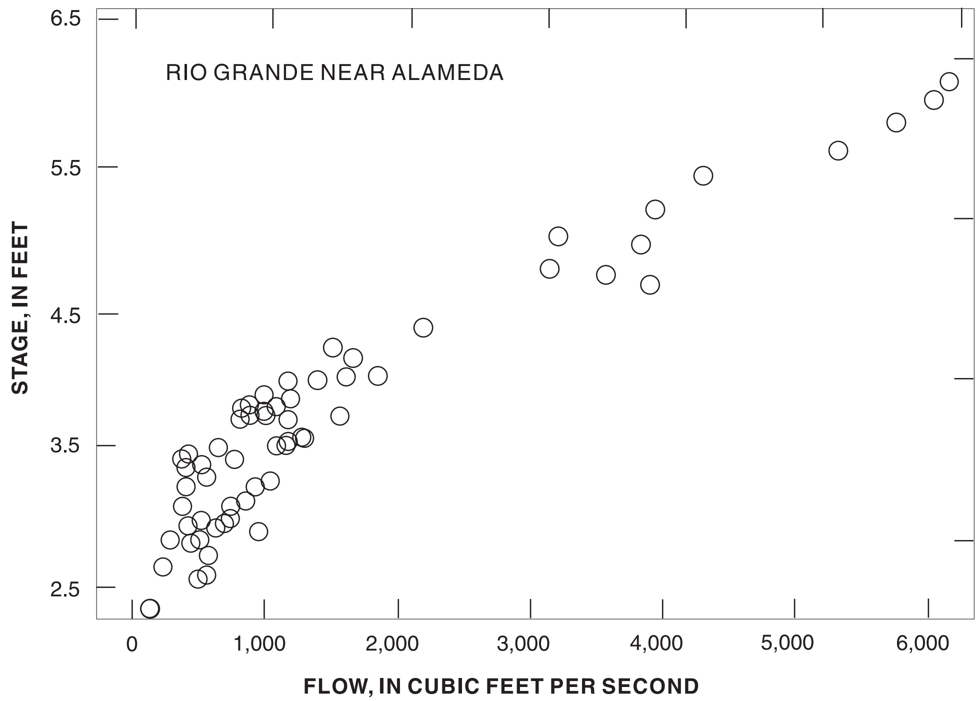
In the Albuquerque reach, flow seeps from the river to a riverside drain and is returned back to the river within a selected reach; thus, flow was measured in the channel and drains at each cross section to compare flow loss or gain between cross sections. Comparing all flow at one cross section to all flow at another cross section is the only meaningful way to make accurate flow-loss estimates.

In the current (1996-2000) study, flow measurements were restricted to the winter nonirrigation season (November through February) to help simplify and reduce variability of flow. This also eliminates travel-time differences for irrigation water that flows down a much longer path through the valley. Also, evapotranspiration during the summer can be substantial. Hansen (1985) estimated that summer evapotranspiration loss ranged from 8.6 to 54 ft^3/s for the 32-mile reach. In the current study, estimated evapotranspiration ranged from 2 to 4 ft^3/s of the cross-sectional loss, and transpiration was estimated to be negligible during the 4 winter months. Evaporation was estimated by multiplying the average monthly pan evaporation times the total water surface between the cross sections, the river, and riverside drains.

Three successive measurements were conducted on the river to reduce measurement error at both gaging stations. For these measurements, upstream river mean inflow ranged from 570 to 1,143 ft^3/s (table 1); riverside drain inflow at the Rio Grande near Bernalillo (one drain on the east side of the river) ranged from 59 to 114 ft^3/s. At the downstream gaging station (Rio Grande at Rio Bravo Bridge) river mean outflow ranged from 597 to 1,085 ft^3/s and riverside drain outflow ranged from 34 to 45 ft^3/s (table 1). Because flow in the river is about 8 to 10 times flow in the drains and the error is about the same percentage for the river and riverside drains, measuring the riverside drain three successive times was not necessary. The riverside drains also have a more stable channel bottom, so in effect measuring the river three successive times is the most efficient way to decrease the total inflow and outflow measurement error. The median of the average absolute difference between the three successive river measurements as a percentage of the three measurements was 3.1 at Rio Grande near Bernalillo and 3.1 at Rio Grande at Rio Bravo Bridge (fig. 8).

For a more accurate flow-difference measurement, storm water, wastewater, or irrigation water should not enter the measurement reach. During the current study (1996-2000) two small documented wastewater flows entered the reach.

A constant release from Cochiti and Jemez Reservoirs (fig. 1) was necessary for accurate flow measurements. If flow is changing, the difference between two flow measurements may be due to nonsteady flow or interchange of water in bank storage. Daily flow of the Rio Grande in and near Albuquerque is primarily a result of releases from Cochiti Reservoir. Releases are varied to maintain a constant water-surface area in the reservoir. The Rio Grande at Otowi Bridge gaging station (fig. 1) records flows from watersheds that are about 80 percent unregulated. Thus, releases from Cochiti Reservoir are adjusted at least daily to match reservoir outflow to inflow. As a result, the median absolute change in daily mean flow for 2 consecutive days at the Rio Grande at Albuquerque gaging station is about 40 ft^3/s for the winter nonirrigation season and 69 ft^3/s for the summer irrigation season (fig. 9). Cochiti Reservoir releases for May 1999 illustrate the constant adjustment of outflow to inflow (fig. 10). The controlled releases from Jemez Reservoir and occasionally Galisteo Reservoir result in constantly changing flow in the Rio Grande. Changes in diversion, return flow during the 8-month irrigation season, and highly variable and localized storm inflow during the monsoonal season add to the variability of flow.



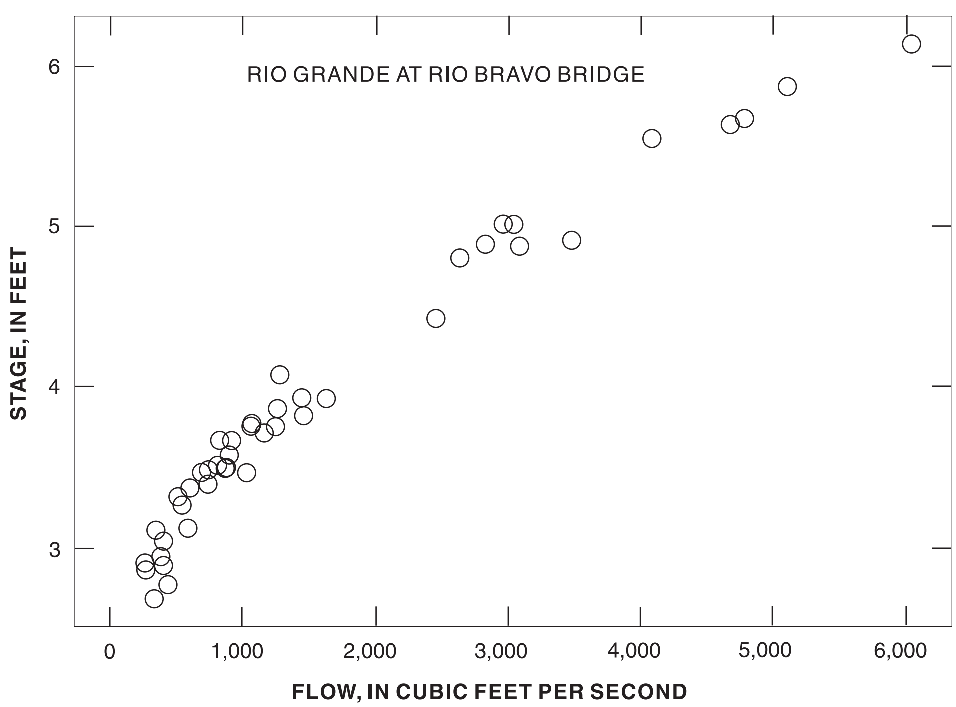


Figure 7. Stage-discharge relations at the Rio Grande near Alameda (08329928) and Rio Grande at Rio Bravo Bridge (08330150) streamflow-gaging stations, 1989-95. Location of gaging stations shown in figure 2.

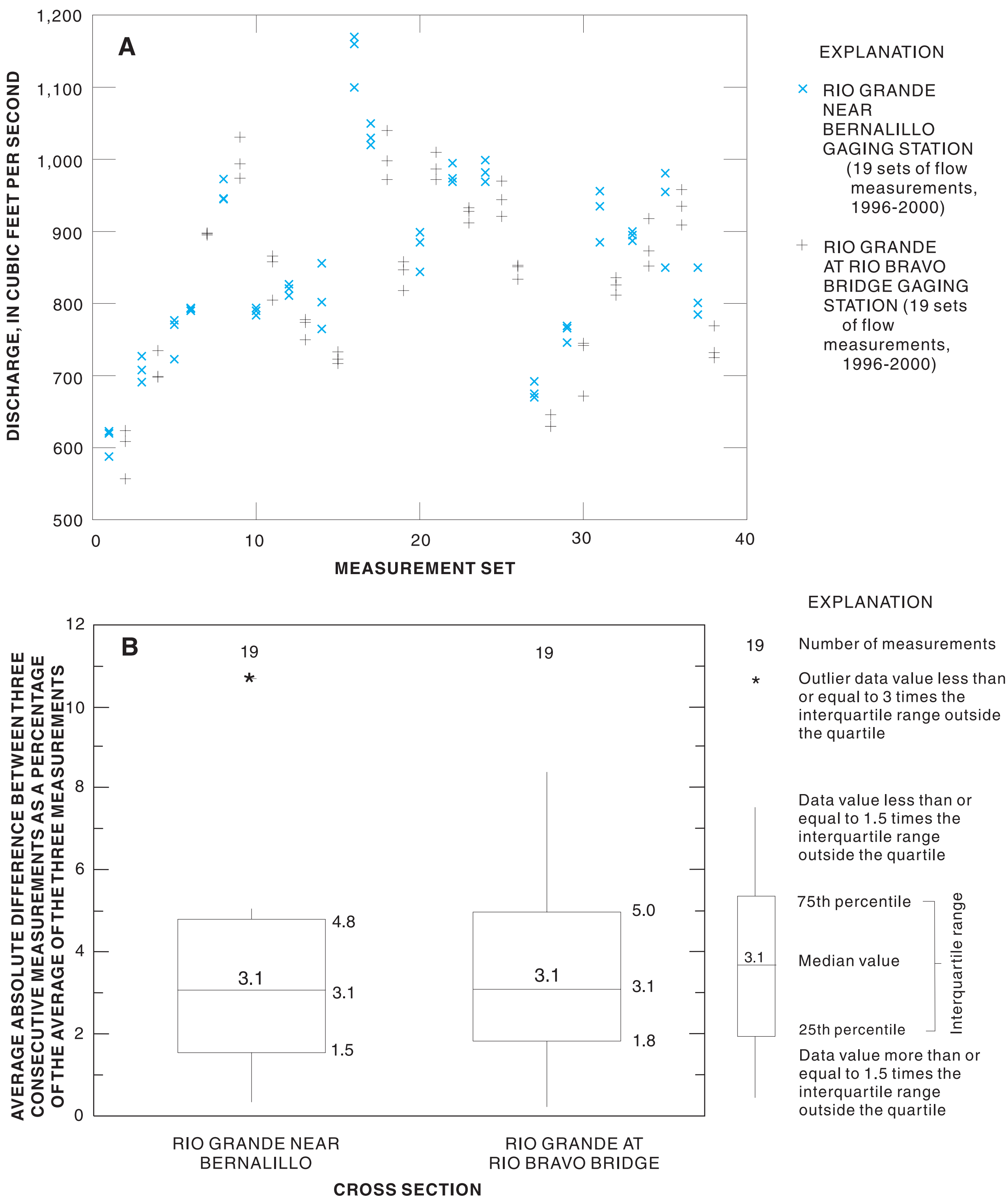


Figure 8. Discharge for and average absolute difference between three successive flow measurements at the Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge streamflow-gaging stations, 1996-2000. Location of gaging stations shown in figure 2.

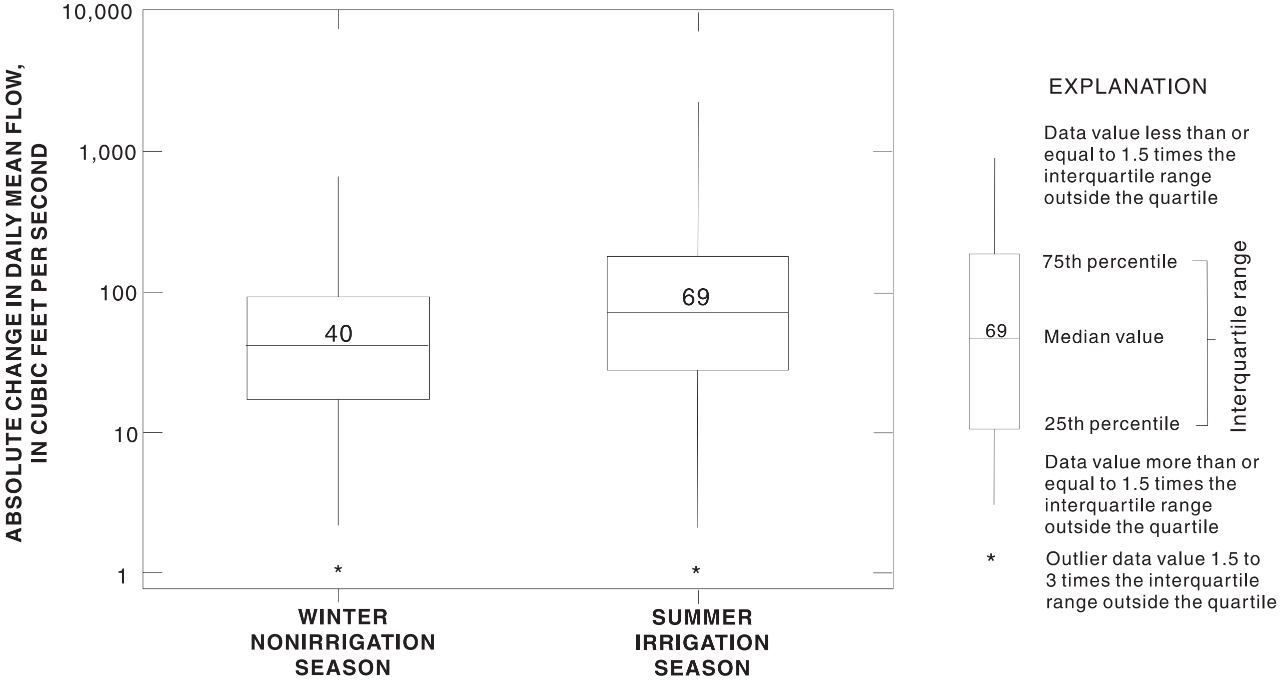


Figure 9. Absolute change in daily mean flow on 2 consecutive days at the Rio Grande at Albuquerque streamflow-gaging station during the winter nonirrigation and summer irrigation seasons, 1974-2000.

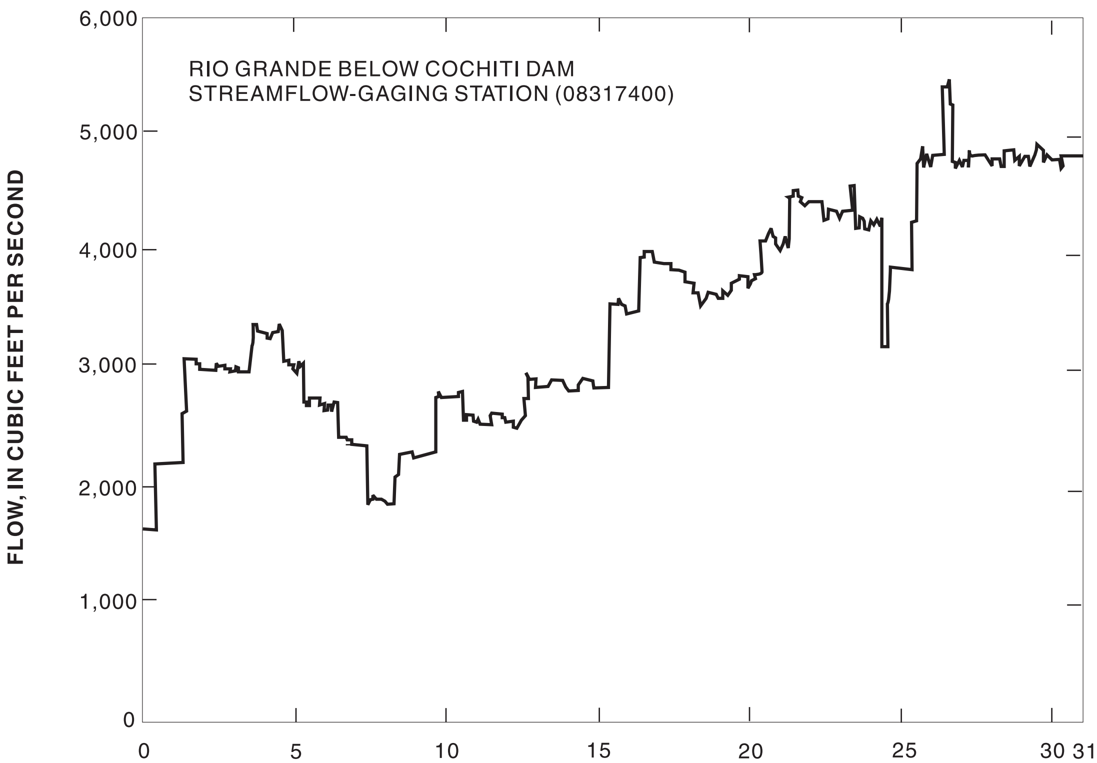


Figure 10. Cochiti Reservoir releases, May 1999. Location of gaging station shown in figure 1.

For the 1996-2000 study, flow in the Rio Grande was measured at the Rio Grande near Bernalillo cross section in the late afternoon and at the Rio Grande at Rio Bravo Bridge cross section the following morning. For the range of riverflows (table 1), the time between measurements was slightly longer than the travel time of water determined for this reach. This slight discrepancy has little effect on flow differences between two sites.

Hydrologic Characteristics of the Measurement Reach

Riverside drain flow during the summer irrigation season (March through October) at the Rio Grande near Bernalillo, Rio Grande near Alameda, Rio Grande at Albuquerque, and Rio Grande at Rio Bravo Bridge cross sections (fig. 2) is a combination of irrigation-return flow and river seepage that is intercepted by the riverside drains. River seepage constitutes total flow in drains during the nonirrigation season. From 1989 to 1995, riverside-drain flow ranged from 75 to 245 ft^3/s (Thorn, 1995) during the summer irrigation season at the Rio Grande near Alameda and Rio Grande at Rio Bravo Bridge cross sections.

During the winter nonirrigation season (November through February), flow in the single riverside drain east of the Rio Grande near Bernalillo cross section averaged about 10 percent of riverflow at that site. Drain flow at this cross section did not respond to every short-term change in river stage. Only long-term variation in riverflow was represented in the drain flow at this site, as would be expected for a predominantly river-seepage, gradient-controlled system. Flow in a drain at a given cross section during the nonirrigation season is a combination of the location of the cross section with respect to the location of the start of the drain and return-flow location and flow in the river at the cross section. Flow constantly increases from the beginning of a drain to where the drain returns flow to the river. Flows in the east- and west-riverside drains are highly correlated with each other during the nonirrigation season but do not immediately reflect rapidly changing riverflows. A large increase in riverflow does not produce a large increase in stage; increases in drain flow increase in proportion to increases in the difference between the river and the drain stage. Riverside drain flow at the Rio Grande at Albuquerque cross section (fig. 11) averages about 30 ft^3/s during the nonirrigation season because the cross section is only one-half mile downstream from the return flow above Central Avenue and about 1.5 miles from the start of that drain.

Two east riverside drain-return flows are between the Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge gaging stations: one located upstream from the Alameda Bridge near Sandia Lakes and one about one-half mile upstream from Central Avenue (fig. 12). The return flow at these two locations averaged 94.4 and 74.5 ft^3/s, respectively (table 2). The combined west riverside returns, Corrales Riverside Drain near the Alameda Bridge and Oxbow return north of Interstate 40, averaged 21.5 and 19.7 ft^3/s, respectively (table 2). Total east- and west-riverside-drain return flow between the Rio Grande near Bernalillo and the Rio Grande at Rio Bravo Bridge cross sections averaged about 210 ft^3/s. This flow represents the average rate of river seepage from November through February returned to the river after being intercepted by the drains. The total rate of inflow and outflow collected by drains in this 21.9-mile reach averaged about 165 ft^3/s (table 2).

Stage differences between the river and riverside drains at several locations between Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge are shown in figure 12. These differences ranged from -7.21 to +2.40 feet on the west side of the river and from -9.66 to +3.09 feet on the east side. Again the difference in water-surface elevation controls the interception of river-drained leakage and return flow to the river.

Water temperature also was measured when nonirrigation season cross-sectional flow was measured. Selected riverside-drain median water temperatures ranged from about 5 to 8 °C warmer than river water temperatures (fig. 13). This small difference supports the argument that water in the riverside drains is primarily river seepage intercepted by the drains.

Flow Relations between Measured and Gaged Cross Sections

Measurements at paired streamflow sites on the Rio Grande provide data that are highly correlated and not statistically independent, especially if the sites are in close proximity to one another. For daily discharge data computed at gaging stations and also for paired individual streamflow-measurement data, the downstream measurement statistically is highly dependent on the upstream measurement. For this reason, regression analysis of dependent downstream gaging-station data to independent upstream gaging-station data is an appropriate statistical technique.

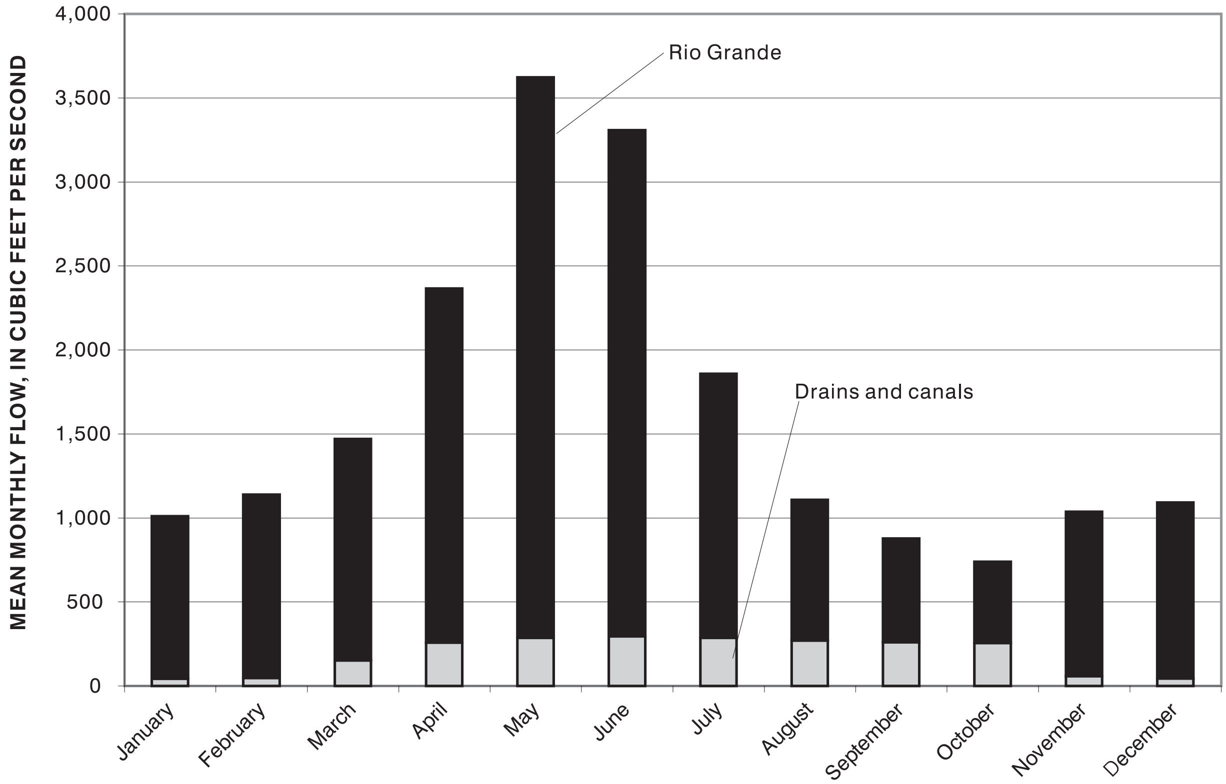


Figure 11. Mean monthly flow of the Rio Grande and riverside drains and canals at the Rio Grande at Albuquerque streamflow-gaging station (08330000), 1974-2000. Location of gaging station shown in figure 2.

Table 2. Winter nonirrigation season return flows measured between the Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge streamflow-gaging stations

[All flows in cubic feet per second. Location of gaging stations and return-flow sites shown in figure 3]

Date	Sandia Lakes return	Corrales Riverside Drain return	Oxbow return	Central Avenue return	Total returned in reach	Total collected by drains in reach
Feb 25, 1997, to Feb 26, 1997	79.2	20.7	19.0	75.9	195	161
Feb 27, 1997, to Feb 28, 1997	98.5	25.0	23.0	82.0	228	164
Mar 1, 1999	86.0	16.3	15.0	71.0	188	148
Feb 17, 2000, to Feb 18, 2000	114	23.9	21.9	69.0	229	186
Average	94.4	21.5	19.7	74.5	210	165

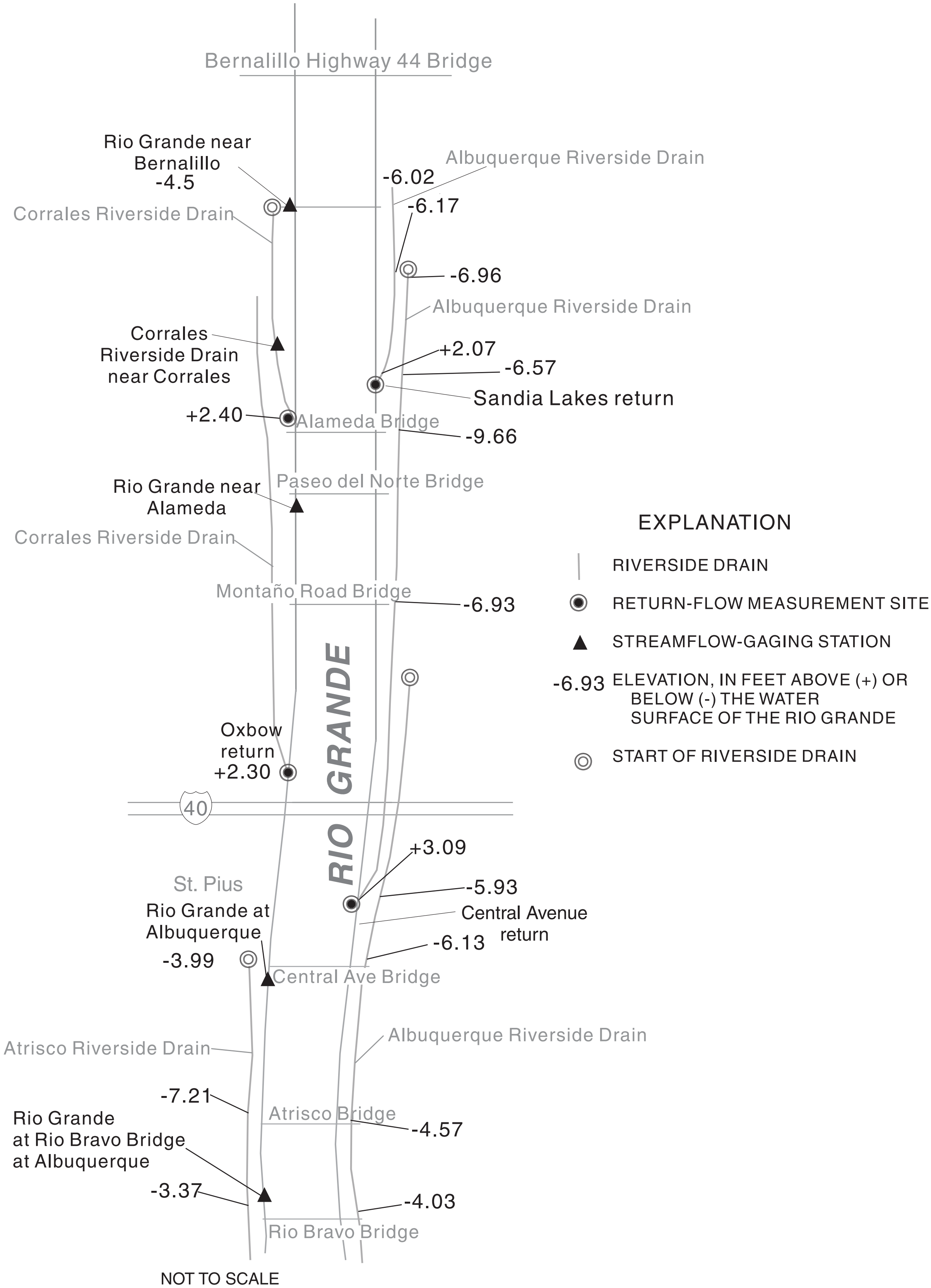


Figure 12. Stage differences of the Rio Grande and riverside drains at the Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge streamflow-gaging stations, February 18, 2000.

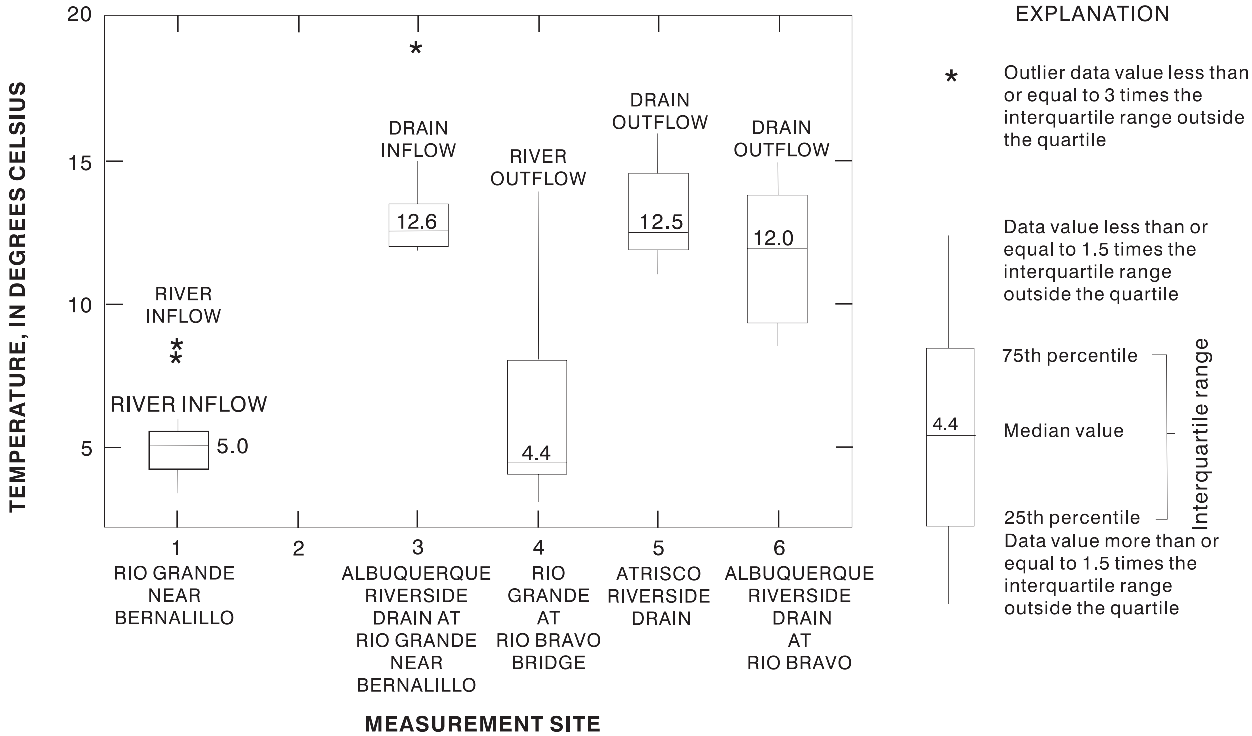


Figure 13. Water temperatures at two Rio Grande streamflow-gaging stations and selected riverside drain sites, 1996-2000. Location of sites shown in figure 12.

For Hansen's (1995) and Thorn's (1995) studies, more accurate average flow losses could be calculated if flow measurements were removed from the analyses when unplanned inflow occurred or reservoir releases were changed. No measurements were removed prior to any of these statistical analyses.

Regression equations for estimated downstream total cross-sectional flow in relation to upstream total cross-sectional flow for selected gaging stations are listed in table 3. Daily mean flows at adjacent upstream and downstream gaging stations are generally highly correlated. The correlations and winter nonirrigation season regression equations for cross-sectional daily flow at selected gaging stations are listed in table 3A-B. When linear regression analysis is used between two paired sets of Rio Grande flows, whether the flows are measured or computed daily, the intercept term generally tends to not be significantly different from zero—that is, there is no constant loss but loss is directly related to upstream flow. The slope in the regression is statistically significant at a p-value less than 0.05. The slope also represents a ratio of daily flows or measurements at the downstream site in relation to those at the upstream site, or in effect, the part of the loss or gain that is directly related to flow.

Comparing total cross-sectional flow is the only valid flow comparison because the individual conveyances, such as riverside-drain return flows, are interconnected between the cross sections. Daily mean flows are highly correlated because the large number of days of flow minimizes the error caused by the changing stage-discharge relation at each gaging station. To compare total cross-sectional daily mean flows at the three cross sections, the estimated drain flow at each cross section was added to each daily mean recorded flow. The winter nonirrigation season cross-sectional daily-flow correlations and the distance between the cross sections are listed in table 3A-B. Also listed are the ratio of daily flow between the sites (the slope in regression analysis when the intercept is not significantly different from zero) and the average ratio of flow loss (1.00 minus the ratio of daily flow between the sites). The regression equation and mean-square error relating the total flow at the upstream and downstream sites also are listed in table 3A-B. Winter nonirrigation season daily mean flows, including the estimates for drain flow at each site, yield downstream to upstream ratios of daily discharge of 0.981 between the Rio Grande at Rio Bravo Bridge and Rio Grande at Albuquerque gaging stations, 0.949 between the Rio

Table 3. Regression equations for total downstream cross-sectional flow in relation to total upstream cross-sectional flow

(A) Regression equations for total cross-sectional daily mean flow at the three streamflow-gaging stations for the winter nonirrigation season, 1996-2000

Gaging-station name and reach distance (fig. 2)	Season and correlation coefficient (corr.)	Regression equation and mean-square error	Flow loss (in percent)	Range of total inflow (cubic feet per second)
Rio Grande at Rio Bravo Bridge (RGRB) to Rio Grande at Albuquerque (RGC) 4.9 miles	Winter Corr. = 0.932	RGRB = 0.981 RGC 8.6 percent	1.9	203 - 2,230
Rio Grande at Albuquerque (RGC) to Rio Grande near Alameda (RGA) 8.0 miles	Winter Corr. = 0.943	RGC = 0 .949 RGA 10.1 percent	5.1	217 - 1,830
Rio Grande at Rio Bravo Bridge (RGRB) to Rio Grande near Alameda (RGA) 12.9 miles	Winter Corr. = 0.879	RGRB = 0.930 RGA 12.5 percent	7.0	217 - 1,830

(B) Regression equations for total measured cross-sectional flow for three paired measurement studies for the winter nonirrigation and summer irrigation seasons, 1989-2000

Site or gaging station name and reach distance (fig. 2)	Season, number of measurements, and correlation coefficient (corr.)	Regression equation and mean-square error	Flow loss (in percent)	Range of total inflow (cubic feet per second)
Isleta I-25 Bridge (RGI) to Bernalillo Highway 44 Bridge (RGBB) 32 miles[1]	Summer 44 Corr. = 0 .991	RGI = 0 .936 RGBB 14.4 percent	6.4	800 - 7,040
	Winter 25 Corr. = 0.813	RGI = 0 .976 RGBB 12.5 percent	2.4	842 - 1,660
Rio Grande at Rio Bravo Bridge (RGRB) to Rio Grande near Alameda (RGA) 12.9 miles[2]	Summer 39 Corr. = 0.996	RGRB = 0.941 RGA 9.3 percent	5.9	321 - 6,310
	Winter 20 Corr. = 0.936	RGRB = 0.943 RGA 9.6 percent	5.7	344 - 1,680
Rio Grande at Rio Bravo Bridge (RGRB) to Rio Grande near Bernalillo (RGBG) 21.9 miles[3]	Winter 22 Corr. = 0.902	RGRB = 0.921 RGBG 6.5 percent	7.9	678 - 1,250

[1]Data from Hansen (1995)
[2]Data from Thorn (1995)
[3]Data from current study (1996-2000)

Grande at Albuquerque and Rio Grande near Alameda gaging stations, and 0.930 between the Rio Grande at Rio Bravo Bridge and Rio Grande near Alameda gaging stations (table 3A). The total cross-sectional daily flow regressions between the three gaging stations are shown in figure 14. Summer irrigation season daily flows were not compared because irrigation flow at each cross section could not be quantified.

Weekly cross-sectional flow was measured at the Isleta I-25 Bridge and the Bernalillo Highway 44 Bridge (fig. 2) by the BOR from August 1993 through February 1995 (Hansen, 1995) and is summarized by two regression equations in table 3B. Hansen used USGS-recorded storm inflows and City of Albuquerque and City of Rio Rancho recorded municipal daily wastewater inflows to account for inflow for measurements made during storms and dry weather. Storm-water flow was estimated using North Floodway and South Diversion Channel daily flows. The Rio Grande inner valley and west-side storm-water inflow to the Rio Grande was not quantified. Daily mean wastewater inflows were accounted for; the hourly variation of wastewater discharge was not. Reservoir releases were not held constant during measurement periods, which probably caused most of the variation in the differences in discharge measurements at the Isleta and Bernalillo sites. Cross-sectional measurements also included flow during the summer irrigation and winter nonirrigation seasons. Total measured outflow in relation to total measured inflow for this reach for the summer irrigation and winter nonirrigation seasons is shown in figure 15. The regression analysis ratios of downstream to upstream cross-sectional flow were 0.936 for the 44 summer measurements and 0.976 for the 25 winter measurements for this 32-mile reach (table 3B). These flow ratios apply for upstream cross-sectional total inflows ranging from 800 to 7,040 ft^3/s for the summer irrigation season and from 842 to 1,660 ft^3/s for the winter nonirrigation season. The mean-square error was 14.4 percent for the irrigation season and 12.5 percent for the nonirrigation season.

Cross-sectional flow measurements were made from 1989 to 1995 by the USGS (Thorn, 1995) at the Rio Grande at Rio Bravo Bridge and Rio Grande near Alameda gaging stations. Measurements were not made during storm-water inflow, and wastewater inflow did not enter the river in this reach of the Rio Grande. However, reservoir releases were not held constant. The ratios from regression analysis of downstream cross-sectional flow were 0.941 for 39 summer irrigation season measurements and 0.943 for 20 winter nonirrigation season measurements for this 12.9-mile reach (table 3B). Total measured outflow in relation to total measured inflow for this reach for the summer and winter seasons is shown in figure 16. Total cross-sectional upstream inflows ranged from 321 to 6,310 ft^3/s for the irrigation season and from 344 to 1,680 ft^3/s for the nonirrigation season (table 3B). The mean-square errors of 9.3 to 9.6 percent, respectively, were smaller than errors determined for the BOR study because there was greater control of some of the flow factors previously discussed.

Weekly cross-sectional flow was measured at the Rio Grande near Bernalillo, Rio Grande at Albuquerque, and Rio Grande at Rio Bravo Bridge gaging stations during the winter nonirrigation season (December through February) from 1996 to 2000 (current study). Reservoir releases were held constant except for two inadvertent releases. Flow loss could be more accurately estimated because flow was not measured during ice cover, during storms, or during the irrigation season, and evapotranspiration loss is much less in the winter. Two small wastewater-return flows from Rio Rancho near the Rio Grande near Bernalillo (upstream) gaging station were documented. The regression ratio of the Rio Grande at Rio Bravo Bridge (downstream) cross-sectional flow was 0.921 times the upstream cross-sectional flow for the 21.9-mile reach, and the mean-square error (6.5 percent) was much smaller than errors determined for Hansen (1995) and Thorn (1995) (table 3B) partly because the range of flow is much less. Cross-sectional inflow ranged from 678 to 1,250 ft^3/s for the regression equation. Total measured outflow in relation to total measured inflow for this reach for the winter nonirrigation season is shown in figure 17.

Flow Loss between Cross Sections and Daily Variation in Riverflow

For each succeeding paired cross-sectional flow-measurement study, additional information was obtained to help control outside variables that could affect more accurate flow-loss measurements in the Rio Grande. The usefulness of daily gaging-station measurements, the measurements' inherent accuracy, and the distance between gaging stations for meaningful flow differences also were determined. The regression equations estimating downstream from upstream cross-sectional flow had less error when more variables were controlled (table 3).

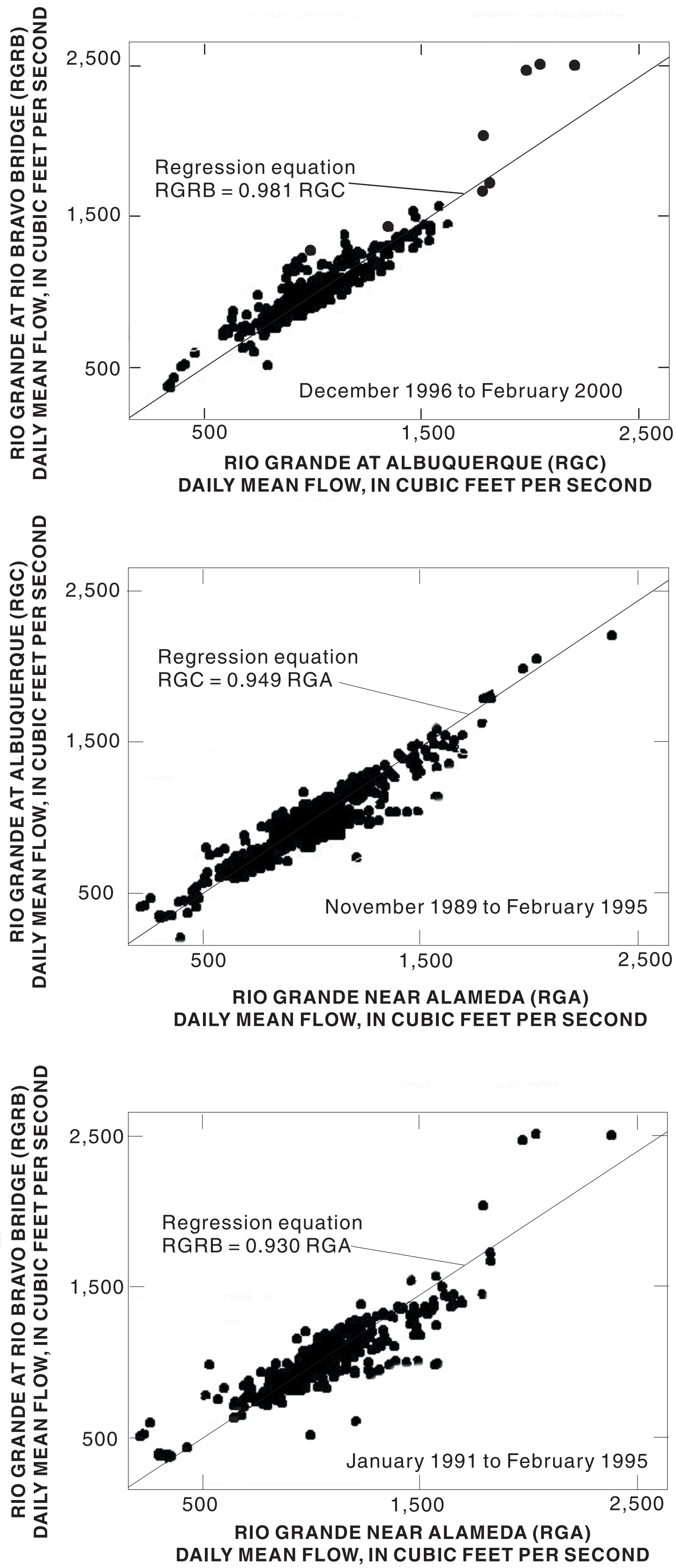


Figure 14. Comparison of total cross-sectional daily mean flow at selected streamflow-gaging stations for the winter nonirrigation season. Location of gaging stations shown in figure 2.

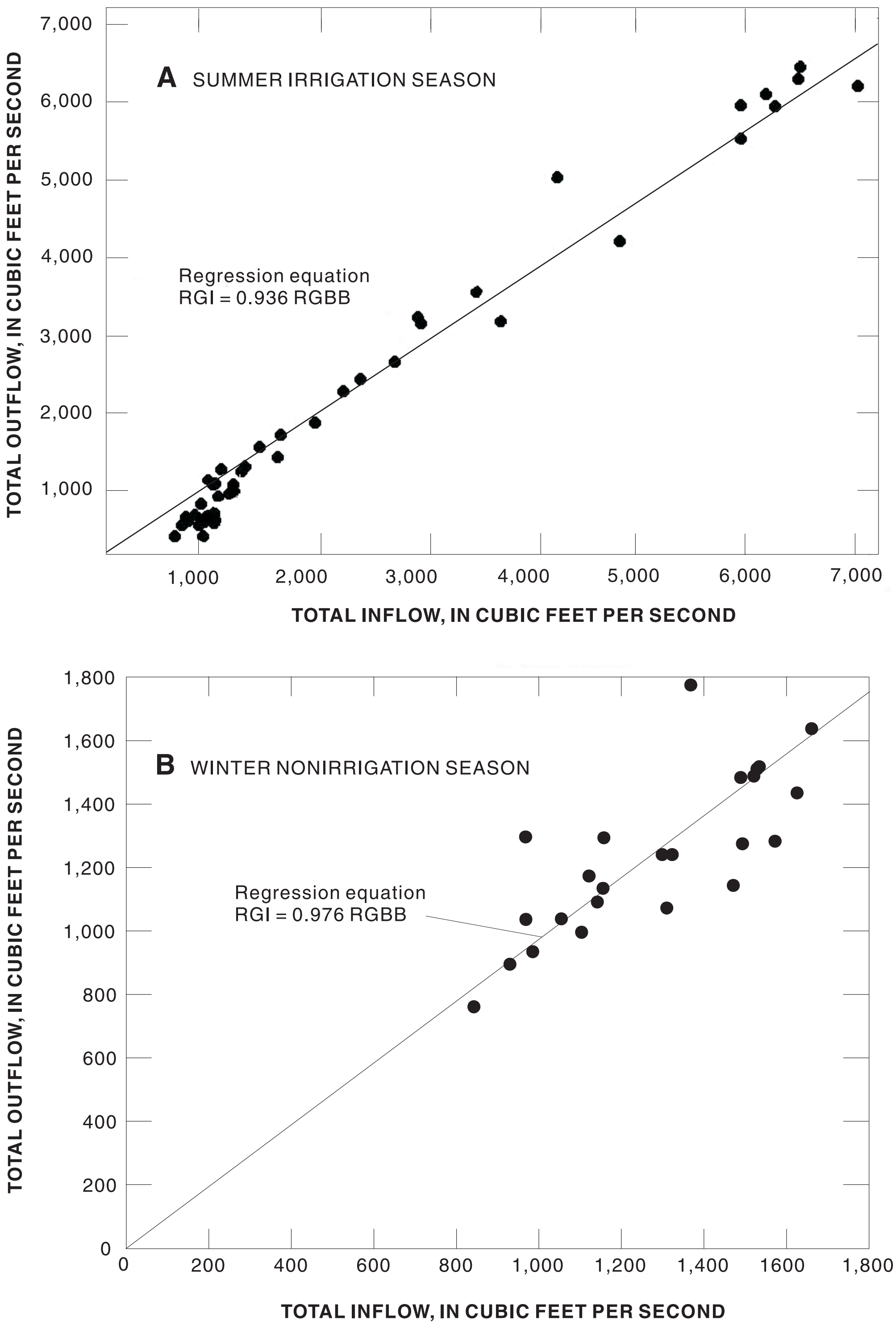


Figure 15. Total inflow and total outflow for the U.S. Geological Survey paired cross-sectional flow-measurement study (Hansen, 1995) from the Bernalillo Highway 44 Bridge (RGBB) to the Isleta I-25 Bridge (RGI) gaging stations for the summer and winter seasons, August 1993 through February 1995. Location of gaging stations shown in figure 2.

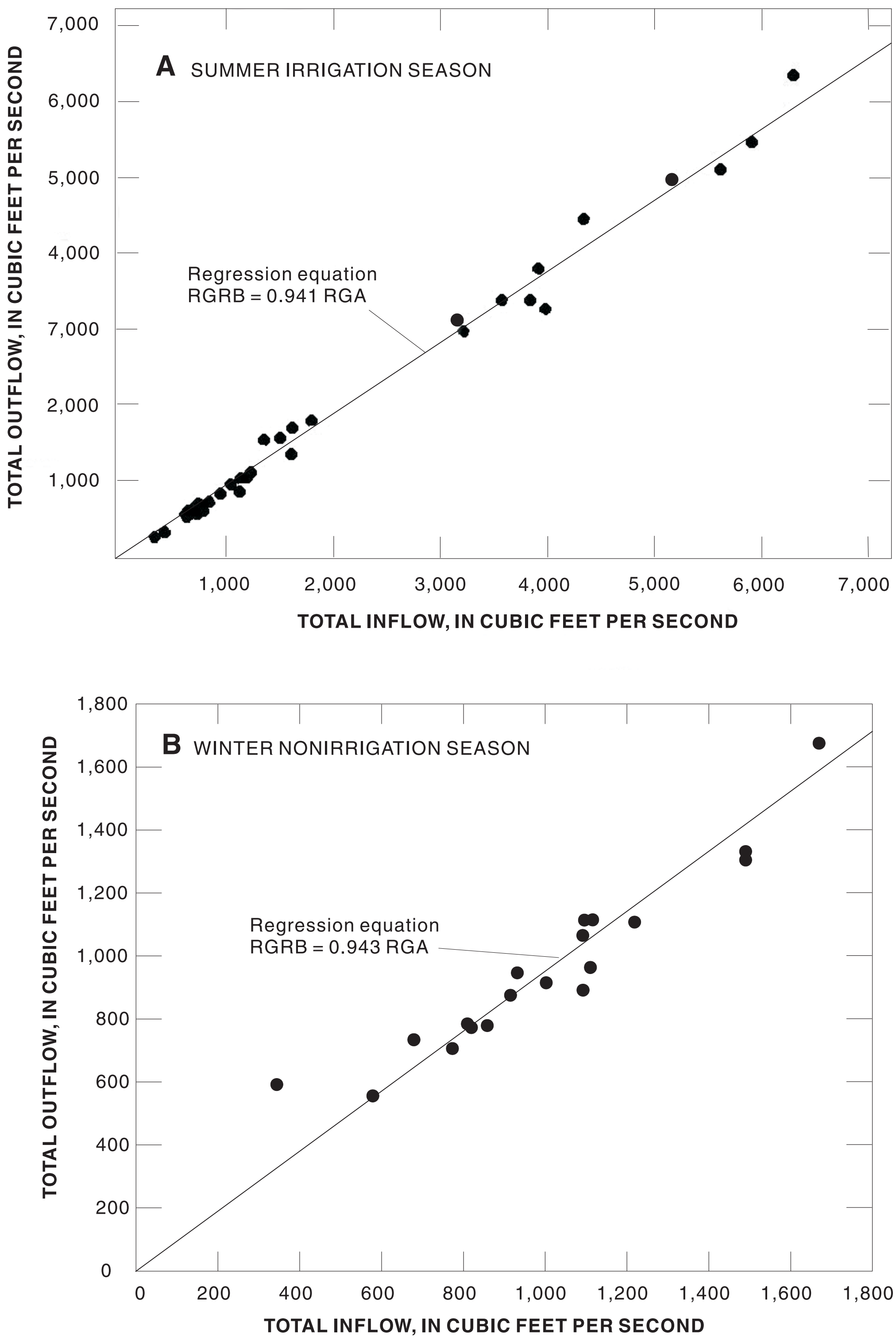


Figure 16. Total inflow and total outflow for the U.S. Geological Survey paired cross-sectional flow-measurement study (Thorn, 1995) from the Rio Grande near Alameda (RGA) to the Rio Grande at Rio Bravo Bridge gaging stations for the summer and winter seasons, 1989-95. Location of gaging stations shown in figure 2.

The increased accuracy of cross-sectional flow measurements also can be represented by the absolute daily mean change in flow at the Rio Grande at Albuquerque gaging station for 2 consecutive measurement days for the winter nonirrigation and summer irrigation seasons (fig. 18). The comparison of absolute change in riverflow represents reduction of the sources of flow variability and is probably the best indication of flow variability of the river during measurement days. Because flow changed between measurements during the first two studies, the loss calculated from the difference between upstream and downstream flow is not as accurate.

Another indication that provides an idea of flow loss between two sites is the differences in total flow between two cross sections regardless of any daily mean differences at adjacent gaging stations or measured cross-sectional differences at two sites. Paired losses calculated using this method, however, were extremely variable from measurement to measurement. Daily mean differences in flow represent all daily mean flow differences at the Rio Grande near Alameda, Rio Grande at Albuquerque, and Rio Grande at Rio Bravo Bridge gaging stations for the winter season compared to the distance between gaging stations (fig. 19). The differences between total inflow and total outflow between measurement cross sections for the summer irrigation and winter nonirrigation seasons are shown in figure 20 and listed in table 4.

The ratio of downstream total outflow to upstream inflow calculated from the slope of the regression equation subtracted from 1.00 represents the average flow loss as a portion of upstream flow of all the measurements. This technique uses all measurements to determine a flow-loss percentage, and this percentage can be used to estimate flow loss for a specific inflow discharge if it is within the range of measured inflows. These regression equation percent losses for summer irrigation and winter nonirrigation seasons in relation to distance between cross sections for all three flow-measurement studies are shown in figure 21. The median daily flow loss in relation to distance between cross sections is shown in figure 22. Both graphs show consistent flow loss per mile downstream and by season with allowance for nonideal river conditions for the initial measurement studies.

Flow loss for the current study (1996-2000) in relation to the change for 2 consecutive days of daily mean flow at the Rio Grande at Albuquerque gaging station is shown in figure 23. The individual paired measurement loss between the two cross sections (Rio Grande at Rio Bravo Bridge and Rio Grande near Bernalillo), for a steady-state river when the daily change is zero, is about 95 ft^3/s (fig. 23), which verifies the median loss of the paired measurements of 87.1 ft^3/s.

SUMMARY

The upper Rio Grande Basin, as defined by the U.S. Army Corps of Engineers, extends from the headwaters of the Rio Grande in southwestern Colorado to Fort Quitman, Texas. Most of the basin has a semiarid climate typical of the southwestern United States. This climate drives a highly variable streamflow regime that contributes to the complexity of water management in the basin. Currently, population growth in the basin has resulted in increasing demands on the hydrologic system. Water management decisions have become increasingly complex because of the broad range of interests and issues. For these reasons, the USGS, in cooperation with the City of Albuquerque, New Mexico, conducted paired flow measurements at two cross sections to determine cross-sectional loss in the Albuquerque reach of the Rio Grande.

Flow losses in the Albuquerque reach of the Rio Grande during the winter nonirrigation season from December 1996 to February 2000 and the two previous flow-loss investigations were statistically summarized. Daily mean flow losses are calculated during the winter nonirrigation season using daily mean flows at three selected Rio Grande streamflow-gaging stations.

During the winter nonirrigation season cross-sectional measurements (1996-2000), an average of 210 ft^3/s was returned to the river between the measurement sites, of which 165 ft^3/s was intercepted by riverside drains along the 21.9-mile reach from the Rio Grande near Bernalillo to the Rio Grande at Rio Bravo Bridge streamflow-gaging stations. The median total cross-sectional loss in this reach was 87.1 ft^3/s.

Regression equations were determined for estimating downstream total outflow from upstream total inflow for all three paired measurement studies. Regression equations relating the three daily mean flow gaging stations were determined. In each succeeding study, additional outside variables were controlled, which provided more accurate flow-loss measurements. Regression-equation losses between measurement cross sections ranged from 1.9 to 7.9 percent during the nonirrigation season and from about 5.9 to 6.4 percent during the irrigation season.

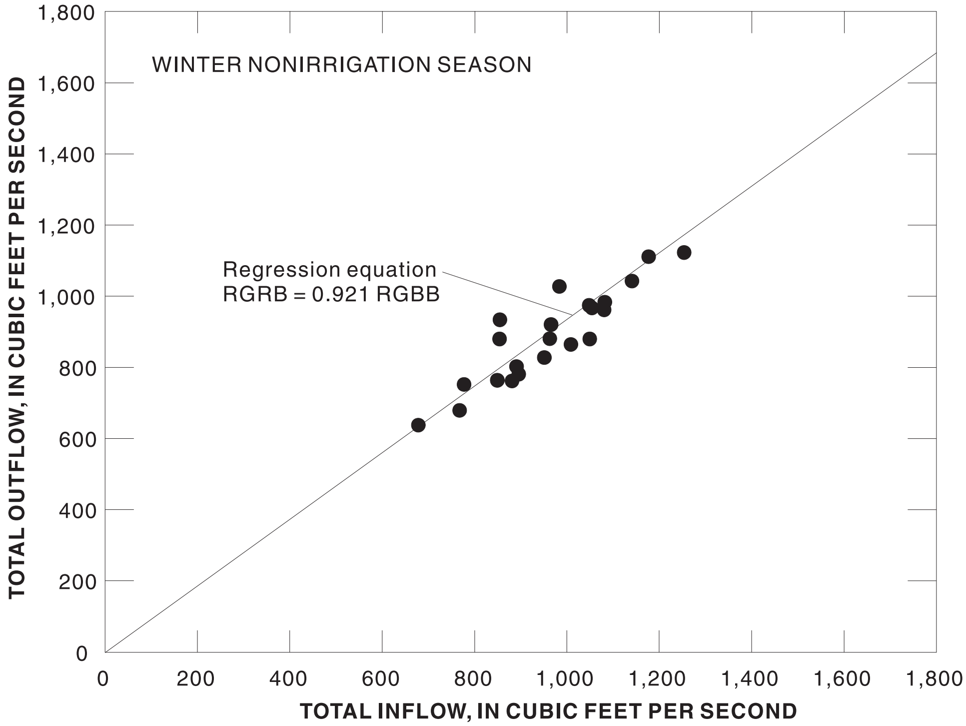


Figure 17. Total inflow and total outflow for the U.S. Geological Survey paired cross-sectional flow-measurement study (current study) from the Rio Grande near Bernalillo (RGBB) to the Rio Grande at Rio Bravo Bridge (RGRB) gaging stations for the winter season, December through February, 1996-2000. Location of gaging stations shown in figure 2.

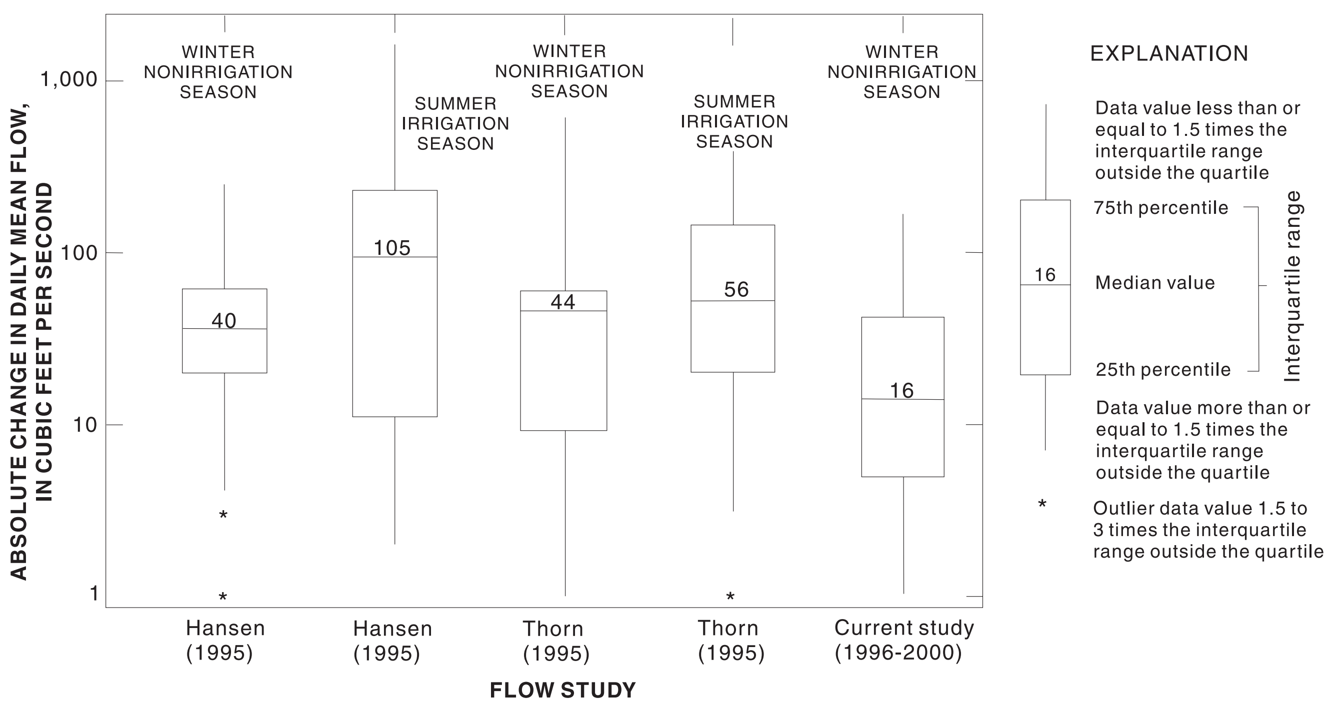


Figure 18. Absolute change in daily mean flow for 2 consecutive measurement days at the Rio Grande at Albuquerque streamflow-gaging station during the winter nonirrigation and summer irrigation seasons, 1989-2000. Location of gaging station shown in figure 2.

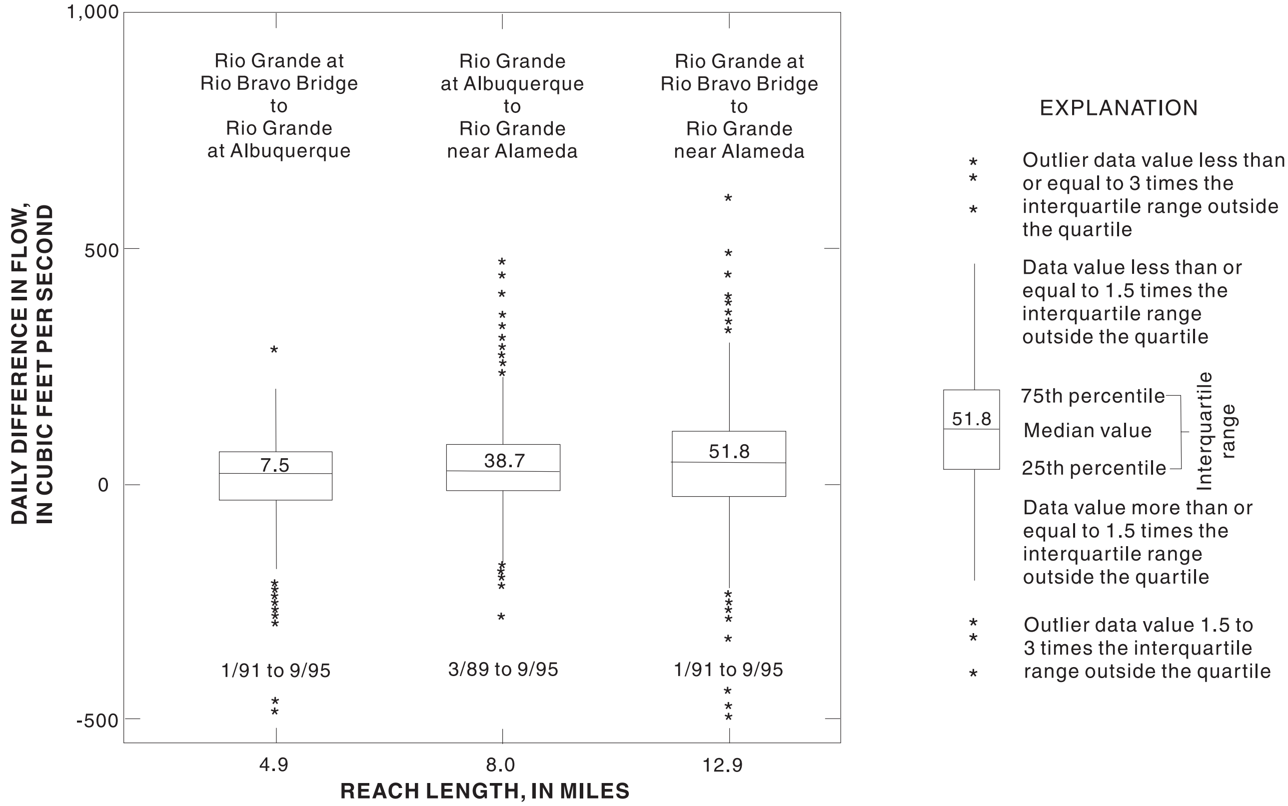


Figure 19. Daily differences in flow in relation to distance between selected streamflow-gaging stations for the winter nonirrigation season. Location of gaging stations shown in figure 2.

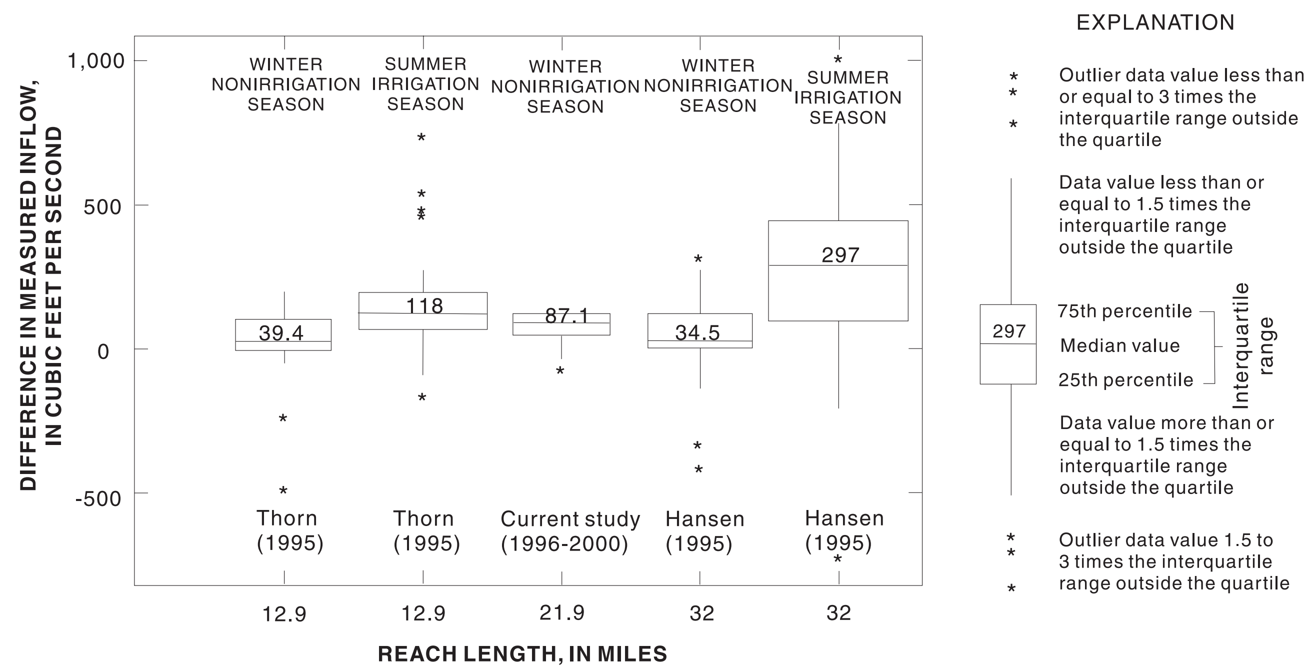


Figure 20. Difference in measured cross-sectional flow in relation to distance for the three paired flow-measurement studies. Location of cross sections shown in figure 2.

Table 4. Estimated flow loss between cross sections on the Rio Grande in and near Albuquerque

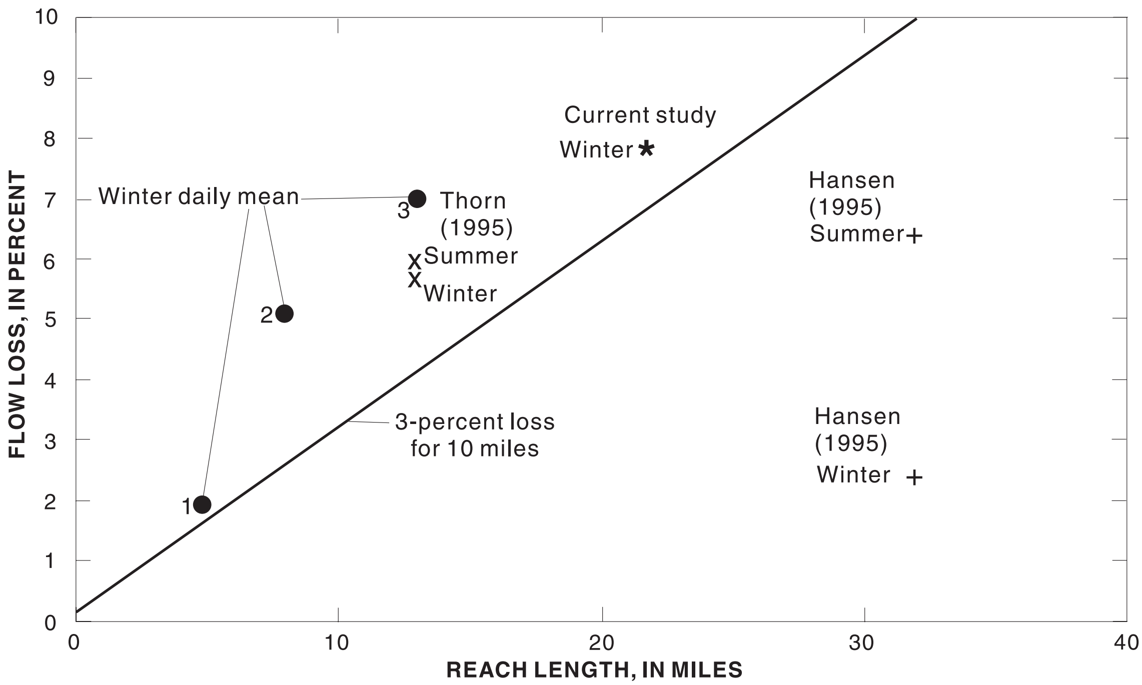
[ft^3/s, cubic feet per second]

(A) Estimated flow loss of the Rio Grande between the Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge streamflow-gaging stations, 1996-2000

Gaging-station name and reach distance (fig. 2)	Flow-loss regression (percent)	Daily mean loss (ft^3/s)
Rio Grande at Rio Bravo Bridge to Rio Grande at Albuquerque 4.9 miles	Winter only 1.9	Median 7.5
Rio Grande at Albuquerque to Rio Grande near Alameda 8.0 miles	Winter only 5.1	Median 38.7
Rio Grande at Rio Bravo Bridge to Rio Grande near Alameda 12.9 miles	Winter only 7.0	Median 51.8

(B) Estimated flow loss of the Rio Grande for three paired-measurement studies conducted from 1989 to 2000

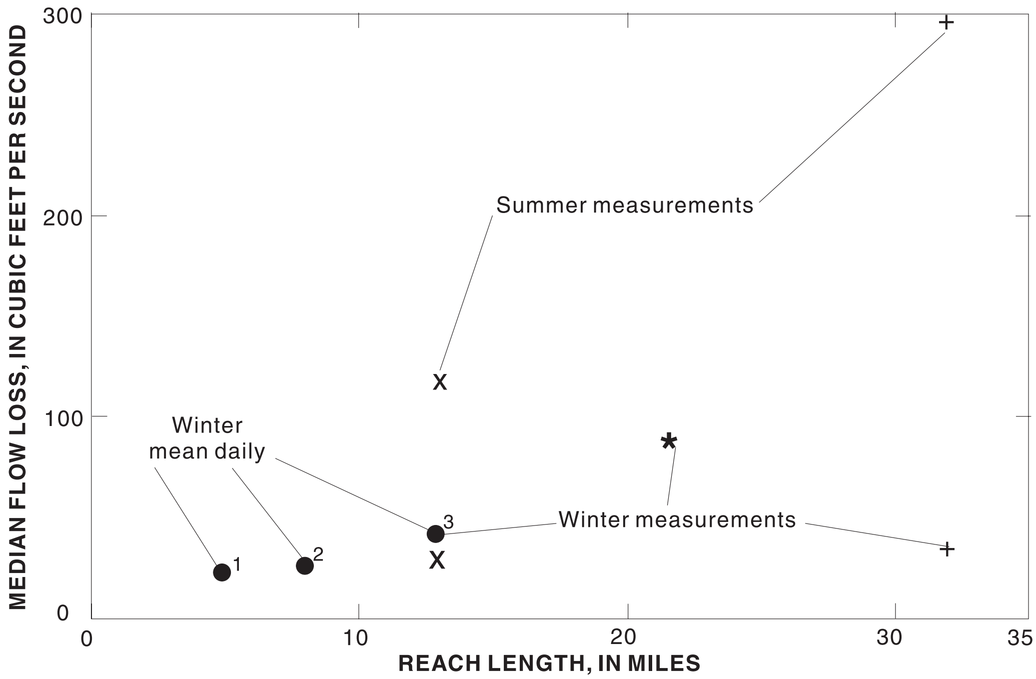
Site or gaging-station name and reach distance (fig. 2)	Season and number of measurements	Regression equation flow loss (percent)	Individual measurement losses (ft^3/s)
Isleta I-25 Bridge to Bernalillo Highway 44 Bridge 32 miles	Summer 44	6.4	Median 297
	Winter 25	2.4	Median 34.5
Rio Grande at Rio Bravo Bridge to Rio Grande near Alameda 12.9 miles	Summer 38	5.9	Median 118
	Winter 20	5.7	Median 39.4
Rio Grande at Rio Bravo Bridge to Rio Grande near Bernalillo 21.9 miles	Winter 22	7.9	Median 87.1



EXPLANATION

+	Highway 44 Bridge and Isleta at I-25 Bridge (32 miles) (Hansen, 1995)
X	Rio Grande near Alameda and Rio Grande at Rio Bravo Bridge (12.9 miles) (Thorn, 1995)
*	Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge (21.9 miles) (current study, 1996-2000)
3●	Rio Grande near Alameda to Rio Grande at Rio Bravo Bridge (12.9 miles)
2●	Rio Grande near Alameda to Rio Grande at Albuquerque (8.0 miles)
1●	Rio Grande at Albuquerque to Rio Grande at Rio Bravo Bridge (4.85 miles)

Figure 21. Percent daily mean flow loss of the Rio Grande for three measurement studies and three streamflow-gaging stations. Location of gaging stations shown in figure 2.



EXPLANATION

+ Highway 44 Bridge and Isleta at I-25 Bridge (32 miles) (Hansen, 1995)

X Rio Grande near Alameda and Rio Grande at Rio Bravo Bridge (12.9 miles) (Thorn, 1995)

* Rio Grande near Bernalillo and Rio Grande at Rio Bravo Bridge (21.9 miles) (current study, 1996-2000)

3● Rio Grande near Alameda to Rio Grande at Rio Bravo Bridge (12.9 miles)

2● Rio Grande near Alameda to Rio Grande at Albuquerque (8.0 miles)

1● Rio Grande at Albuquerque to Rio Grande at Rio Bravo Bridge (4.85 miles)

Figure 22. Median flow loss of the Rio Grande for three measurement studies and three streamflow-gaging stations by reach length. Location of gaging stations shown in figure 2.

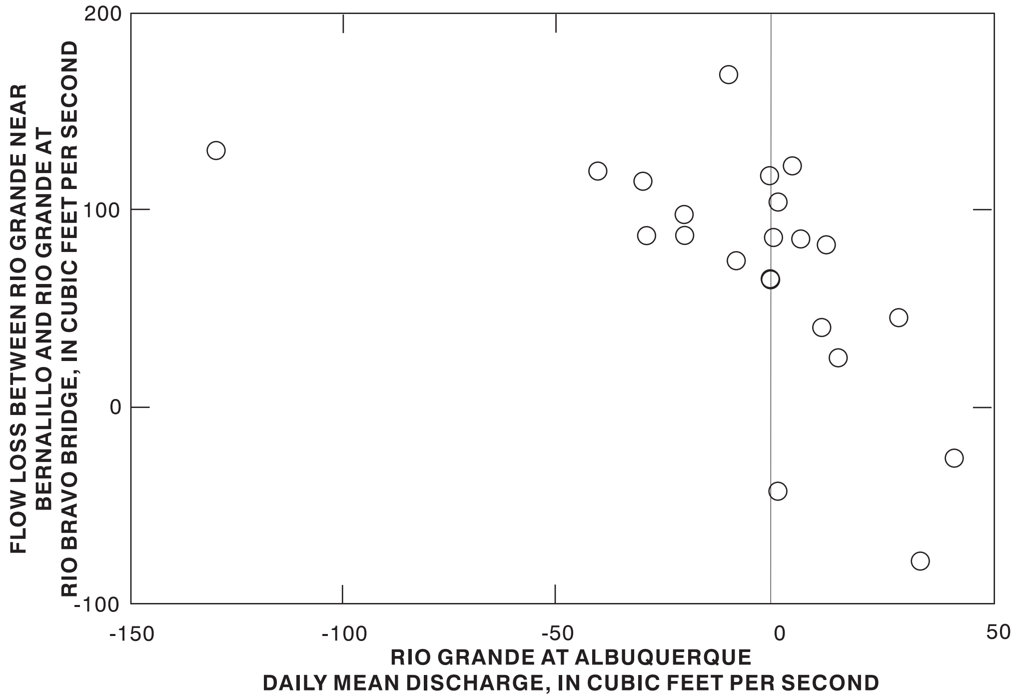


Figure 23. Flow loss in relation to the change for 2 consecutive days of daily mean flow at the Rio Grande at Albuquerque streamflow-gaging station, 1996-2000. Location of gaging stations shown in figure 2.

Mean and median loss by reach length for all three daily mean flow stations and all three cross-sectional measurement reaches showed consistent flow loss per mile by season with allowance for nonideal river conditions for the initial measurement studies. Unsteady measurement conditions were reflected in the regression equation mean-square error and ultimately in the change in daily mean discharge at the Rio Grande at Albuquerque gaging station during the measurement period.

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