

**Prepared in cooperation with the Bureau of Reclamation acting as fiscal agent for the Middle Rio Grande Endangered Species Collaborative Program**

# **Groundwater Hydrology and Estimation of Horizontal Groundwater Flux from the Rio Grande at Selected Locations in Albuquerque, New Mexico, 2003–9**

Scientific Investigations Report 2012–5007



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By Dale R. Rankin, Kurt J. McCoy, Geoff J.M. Moret, Jeffrey A. Worthington,  
and Kimberly M. Bandy-Baldwin

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

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Suggested citation:

Rankin, D.R., McCoy, K.J., Moret, G.J.M., Worthington, J.S., and Bandy-Baldwin, K.M., 2013, Groundwater hydrology and estimation of horizontal groundwater flux from the Rio Grande at selected locations in Albuquerque, New Mexico, 2003–9: U.S. Geological Survey Scientific Investigations Report 2012-5007, 75 p.

## Acknowledgments

The authors would like to recognize the efforts of others who contributed to the completion of this study. The City of Albuquerque's Open Space Division granted permission for the USGS to install and maintain piezometers in the Rio Grande riparian zone along the river. The Middle Rio Grande Conservancy District granted permission for the USGS to install and maintain surface-water gages at various locations in the Corrales, Atrisco, and Albuquerque Riverside Drains. The Bernalillo County Commission granted permission for the USGS to install and maintain piezometers at various locations near the I-25 bridge and the Barelás bridge.

The authors wish to recognize the support of committees associated with the Middle Rio Grande Endangered Species Collaborative Program, including the Executive Committee, the Science Subcommittee, and, in particular, members of the Species and Water Management Committee (SWM). We wish to acknowledge the assistance and guidance provided by Charles Fischer and Valda Terauds of the Bureau of Reclamation. In addition, we would like to thank the U.S. Army Corps of Engineers for the initial funding of the monitoring network, the installation of which preceded the interpretive work done in cooperation with the Bureau of Reclamation Endangered Species Collaborative Program.

We would also like to acknowledge the technical assistance provided by Jeb Brown, a hydrologic technician in the New Mexico Water Science Center, who performed the discharge measurements for the seepage investigation.

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## Conversion Factors and Datums

Multiply		To obtain
<b>Length</b>		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<b>Area</b>		
acre	0.004047	square kilometer (km <sup>2</sup> )
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
<b>Volume</b>		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m <sup>3</sup> )
cubic foot (ft <sup>3</sup> )	0.02832	cubic meter (m <sup>3</sup> )
<b>Flow rate</b>		
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)
cubic foot per day (ft <sup>3</sup> /d)	0.02832	cubic meter per day (m <sup>3</sup> /d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallons per day (gal/d)	0.003785	cubic meter per day (m <sup>3</sup> /d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
<b>Temperature</b>		
degree Fahrenheit (°F)	°F-32/1.8	degree Celsius (°C)
<b>Thermal Conductivity</b>		
British thermal unit <sub>IT</sub> per hour foot degree Fahrenheit (BTU <sub>IT</sub> hr <sup>-1</sup> ft <sup>-1</sup> °F <sup>-1</sup> )	1.730	watt per meter Kelvin (W m <sup>-1</sup> K <sup>-1</sup> )
<b>Volumetric Heat Capacity</b>		
British Thermal Unit (International Steam Table Calorie) per cubic foot degree Fahrenheit (BTU <sub>IT</sub> ft <sup>-3</sup> °F <sup>-1</sup> )	67070	joule per cubic meter Kelvin (J m <sup>-3</sup> K <sup>-1</sup> )

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).



# Groundwater Hydrology and Estimation of Horizontal Groundwater Flux from the Rio Grande at Selected Locations in Albuquerque, New Mexico, 2003–9

By Dale R. Rankin,<sup>1</sup> Kurt J. McCoy,<sup>2</sup> Geoff J.M. Moret,<sup>3</sup> Jeffrey A. Worthington,<sup>1</sup> and Kimberly M. Bandy-Baldwin<sup>4</sup>

## Abstract

The Albuquerque, New Mexico, area has two principal sources of water: groundwater from the Santa Fe Group aquifer system and surface water from the San Juan-Chama Diversion Project. From 1960 to 2002, groundwater withdrawals from the Santa Fe Group aquifer system have caused water levels to decline more than 120 feet in some places within the Albuquerque area, resulting in a great deal of interest in quantifying the river-aquifer interaction associated with the Rio Grande.

In 2003, the U.S. Geological Survey in cooperation with the Bureau of Reclamation, the Middle Rio Grande Endangered Species Collaborative Program, and the U.S. Army Corps of Engineers began a detailed characterization of the hydrogeology of the Rio Grande riparian corridor in the Albuquerque, New Mexico, area to provide hydrologic data and enhance the understanding of rates of water leakage from the Rio Grande to the alluvial aquifer, groundwater flow through the aquifer, and discharge of water from the aquifer to the riverside drains.

A simple conceptual model of flow indicates that the groundwater table gently slopes from the Rio Grande towards riverside drains and the outer boundaries of the inner valley. Water infiltrating from the Rio Grande initially moves vertically below the river, but, as flow spreads farther into the Rio Grande inner valley alluvial aquifer, flow becomes primarily horizontal. The slope of the water-table surface may

be strongly controlled by the riverside drains and influenced by other more distal hydrologic boundary conditions, such as groundwater withdrawals by wells.

Results from 35 slug tests performed in the Rio Grande inner valley alluvial aquifer during January and February 2009 indicate that hydraulic-conductivity values ranged from 5 feet per day to 160 feet per day with a median hydraulic-conductivity for all transects of 40 feet per day. Median annual horizontal hydraulic gradients in the Rio Grande inner valley alluvial aquifer ranged from 0.011 to 0.002.

Groundwater fluxes through the alluvial aquifer calculated by using median slug-test results ( $q_{slug}$ ) and Darcy's law ranged from about 0.1 feet per day to about 0.7 feet per day. Groundwater fluxes calculated by using the Suzuki-Stallman method ( $q_{heat}$ ) ranged from 0.52 feet per day to 0.23 feet per day.

Results from the Darcy's law and Suzuki-Stallman flux calculations were compared to discharge measured in riverside drains on both sides of the river north of the Montaña Bridge on February 26, 2009. Flow in the Corrales Riverside Drain increased by 1.4 cubic feet per second from mile 2 to mile 4, about 12 cubic feet per day per linear foot of drain. Flow in the Albuquerque Riverside Drain increased by 15 cubic feet per second between drain miles 0 and 3, about 82 cubic feet per day per linear foot of drain.

The flux of water from the river to the aquifer was calculated to be 2.2 cubic feet per day per linear foot of river by using the median  $q_{slug}$  of 0.09 feet per day at Montaña transects west of the river. The total flux was calculated to be 6.0 cubic feet per day per linear foot of river by using the mean  $q_{heat}$  of 0.24 feet per day for the Montaña transects west of the river. Assuming the Corrales Riverside Drain intercepted all of this flow, the  $q_{slug}$  or  $q_{heat}$  fluxes account for 18 to 50 percent, respectively, of the increase of flow in the drain. The flux of water from the river to the aquifer was calculated to be 15 cubic feet per day per linear foot of river by using the median  $q_{slug}$  of 0.30 feet per day at the Montaña transects east of the river. The flux of water from the river to the aquifer was calculated to be 17 cubic feet per day per linear foot of river by using the mean flux calculated from the

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Suzuki-Stallman method for the Montañño East transects of 0.34 feet per day. Assuming the Albuquerque Riverside Drain intercepted all this flow, the  $q_{slug}$  or  $q_{heat}$  fluxes would only account for 18 to 21 percent, respectively, of the increase in flow in the drain.

The comparison of these results with those of previous investigations suggests that calculated flux through the Rio Grande inner valley alluvial aquifer is strongly scale dependent and that the thickness of aquifer through which river water flows may be greater than indicated by the vertical temperature profiles.

### Introduction

The Albuquerque area (fig. 1) is the major population center in New Mexico and covers about 400 square miles (mi<sup>2</sup>). With a population of approximately 535,000 people in 2000, the Albuquerque area accounts for 29 percent of the State's population (U.S. Census Bureau, 2000). Currently (2009), there are two principal sources of water for municipal, domestic, commercial, and industrial uses in this area: groundwater from the Santa Fe Group aquifer system, and surface water from the San Juan-Chama Diversion Project. The Rio Grande, which extends the length of New Mexico, is the principal source of water for irrigated agriculture (McAda, 1996). Estimates indicated that from 1960 to 2002, groundwater withdrawals from the Santa Fe Group aquifer system have caused water levels to decline more than 120 feet (ft) in some places within the Albuquerque area (Bexfield and Anderholm, 2002 and fig. 2). This has resulted in a great deal of interest in quantifying the river-aquifer interaction associated with the Rio Grande.

The aquifer system (middle Tertiary to Quaternary age) in the Albuquerque area consists of the Santa Fe Group aquifer and the post-Santa Fe Group (Quaternary age) Rio Grande inner valley alluvial aquifer (alluvial aquifer). The Santa Fe Group aquifer system is hydraulically connected to the Rio Grande (McAda, 1996) where fluvial gravel, sand, silt, and clay deposits form a thin but extensive aquifer zone below the Rio Grande flood plain (Hawley and Whitworth, 1996). The post-Santa Fe Group Rio Grande inner valley alluvial aquifer is composed of channel, flood plain, terrace, and tributary deposits that are as much as 120 ft thick. Previous researchers have used streambed permeameters (Gould, 1994), the transient response of the aquifer to a flood pulse (Roark, 2001), vertical profiles of temperature measurements (Bartolino and Niswonger, 1999), and calibrated numerical models (Kernodle and others, 1995; Tiedeman and others, 1998) to estimate the flux between the Rio Grande and the Santa Fe Group aquifer system. Currently, a basin-scale groundwater model is used in the assessment of surface stream depletion (Barroll, 2001). In contrast to previous more regional-scale studies, a study was designed to focus on the upper alluvial aquifer and provide spatially detailed information about the amount of water that discharges

from the Rio Grande to the adjacent aquifer in the Albuquerque area.

In 2003, the U.S. Geological Survey (USGS) in cooperation with the Bureau of Reclamation (BOR), the Middle Rio Grande Endangered Species Collaborative Program (MRGESCP), and the U.S. Army Corps of Engineers (USACE) began a detailed characterization of the hydrogeology of the Rio Grande riparian corridor in the Albuquerque, New Mexico, area to provide hydrologic data and enhance the understanding of rates of water leakage from the Rio Grande to the alluvial aquifer, groundwater flow through the aquifer, and discharge of water from the aquifer to the riverside drains. Beginning in late 2003 through 2006, a total of 10 east-west trending hydrologic transects were installed along both sides of the Rio Grande through the Albuquerque area at five selected locations (fig. 1). Each location consisted of paired transects of piezometers installed between the river and riverside drains to evaluate the rate of leakage from the river to riverside drains. In some cases (figs. 3a, 3c-3e), piezometers were installed at various distances outside the drains. Surface-water-stage gages also were installed in the river and in the east and west riverside drains. Lithologic information collected during drilling, and hourly groundwater-level and water-temperature data, and vertical temperature profile data collected during the study were used to define a conceptual model of flow in the Rio Grande inner valley alluvial aquifer adjacent to the river. Two methods are presented to quantify the rate of groundwater flux at depths less than 30 ft. In the first method, Darcy's law and estimates of hydraulic conductivity from slug tests and the literature are used to assess the variability in river leakage attributed to temporal changes in hydraulic gradient. In the second method, the Suzuki-Stallman one-dimensional analytical solution to the heat-transport equation are used to model annual groundwater-temperature changes within the aquifer resulting from river leakage. Temperature models provide additional detail on rates of groundwater flux with depth and distance from the river in the Albuquerque area.

### Purpose and Scope

This report documents the collection and analysis of geologic, groundwater, and surface-water data from the inner valley of the Albuquerque area. The data are used to describe the groundwater hydrology of the Rio Grande inner valley alluvial aquifer and to estimate horizontal groundwater flux from the Rio Grande to the riverside drains. The report presents a simple conceptual model of groundwater flow and a comparison of groundwater-flux results derived from two methods: Darcy's law and the Suzuki-Stallman solution of heat transport in an aquifer. Data used in this report were collected from 10 transects located near the Paseo del Norte, Montañño, Barelás, Rio Bravo, and I-25 bridges (fig. 1). Groundwater and surface-water levels, temperature and slug-test data, seepage measurements, and core samples were collected from December 2003 to early 2009.

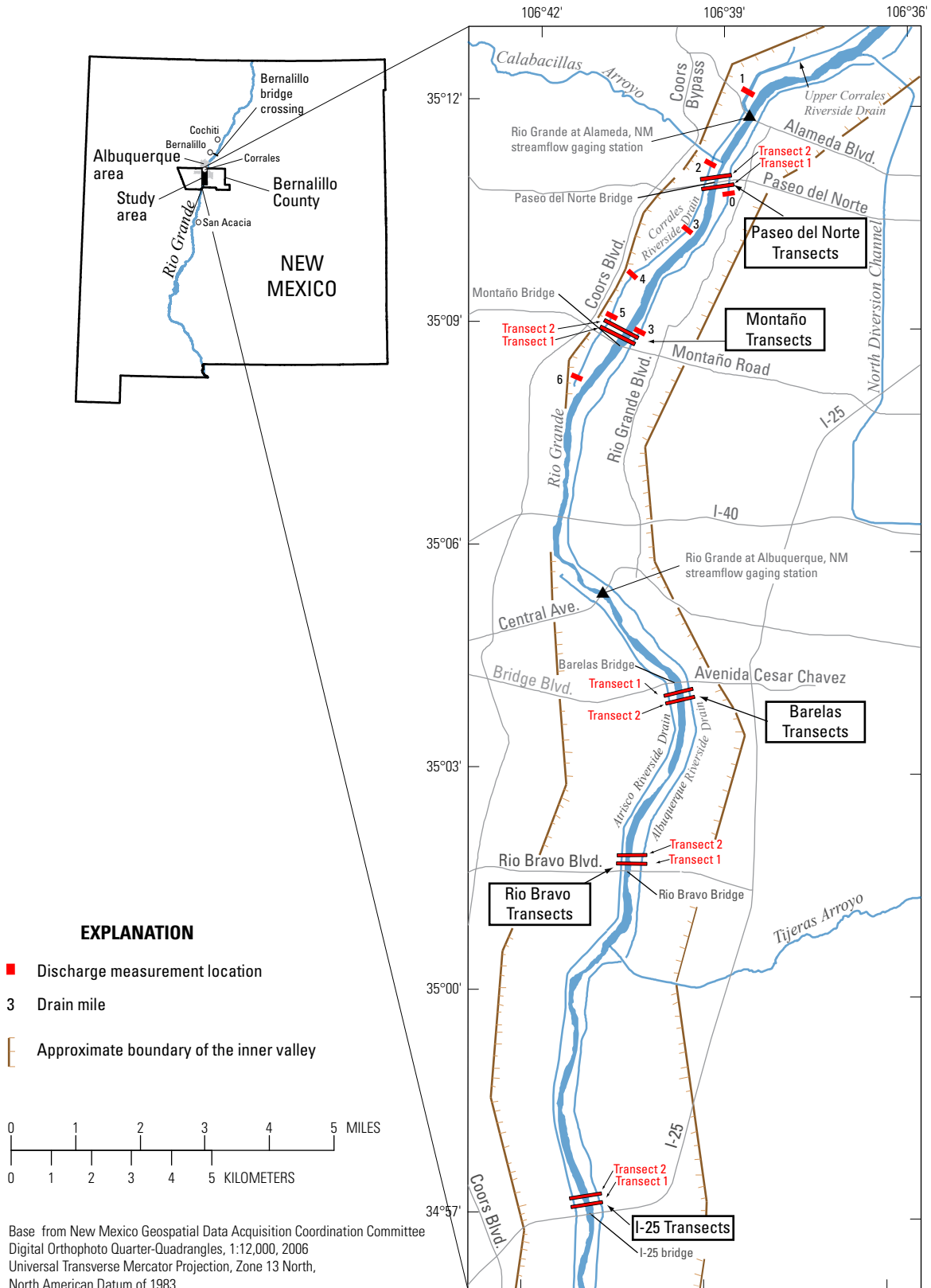
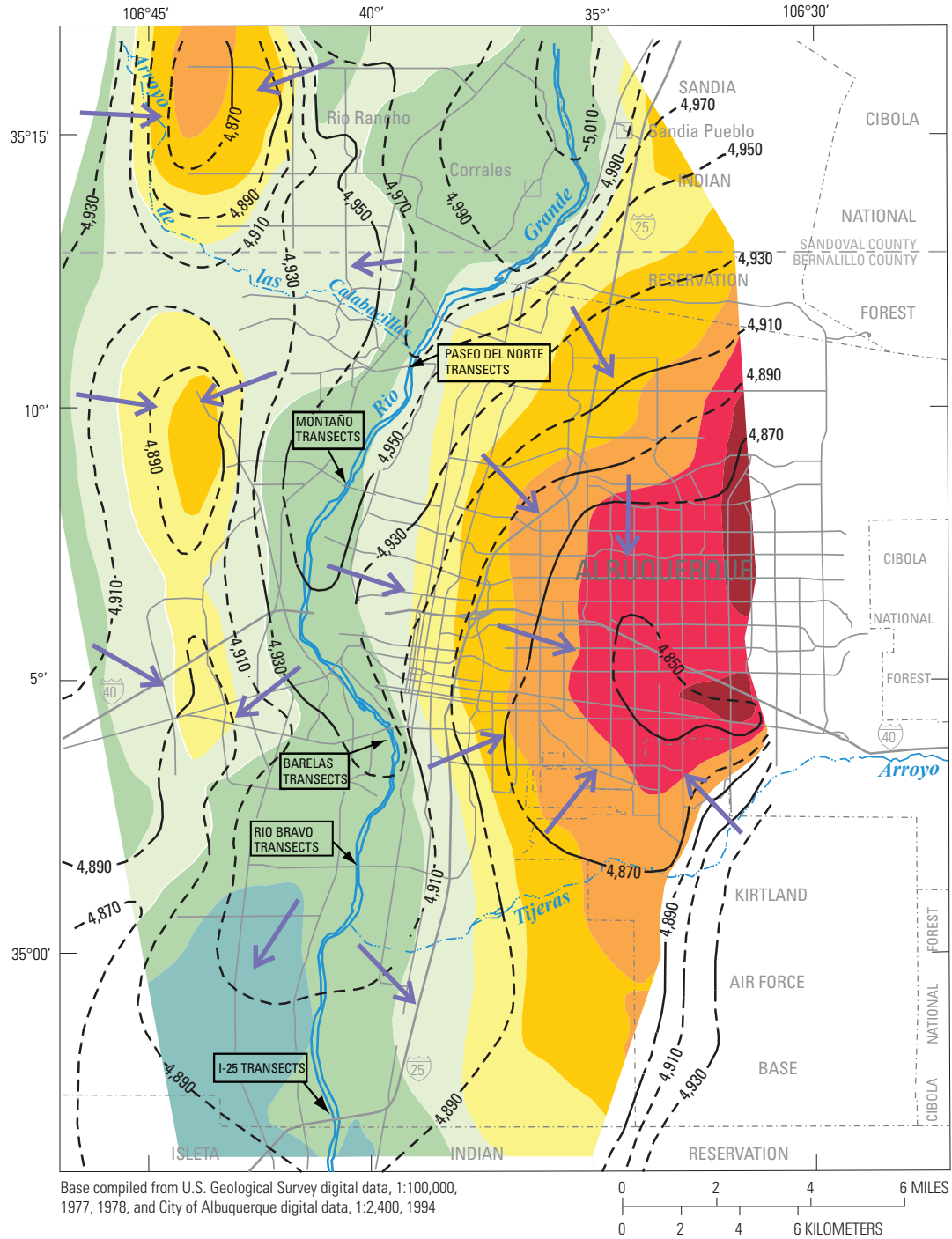


Figure 1. Location of study area and transects in the Albuquerque area, New Mexico.

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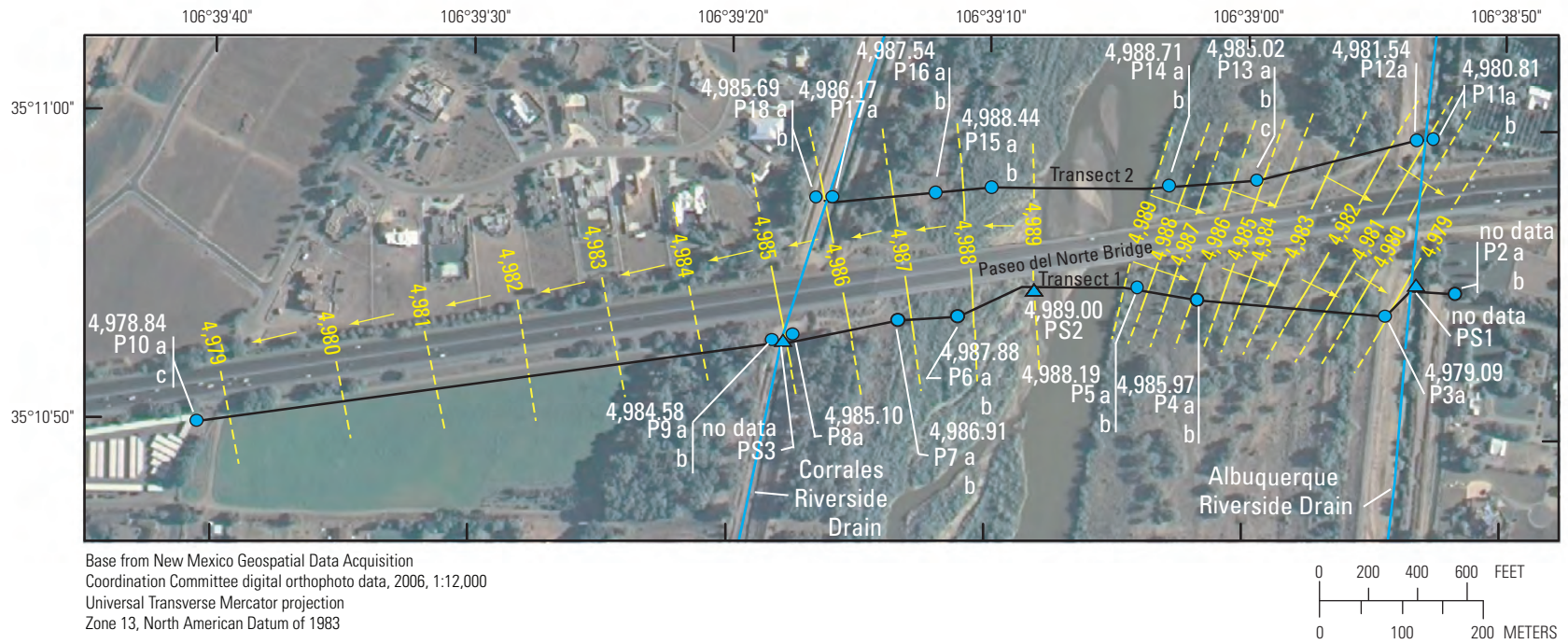
**EXPLANATION**

**Estimated water-level decline, in feet, 1960 to 2002**

- No decline
- 0 to 20
- 20 to 40
- 40 to 60
- 60 to 80
- 80 to 100
- 100 to 120
- More than 120
- Decline not estimated

- 4930 Water-level contour—Interval 20 feet. Dashed where inferred. Datum is NGVD 29
- Generalized direction of groundwater flow

**Figure 2.** Groundwater-level-elevation contours in the Santa Fe Group aquifer in the Albuquerque area and estimated groundwater-level declines from 1960 to 2002.

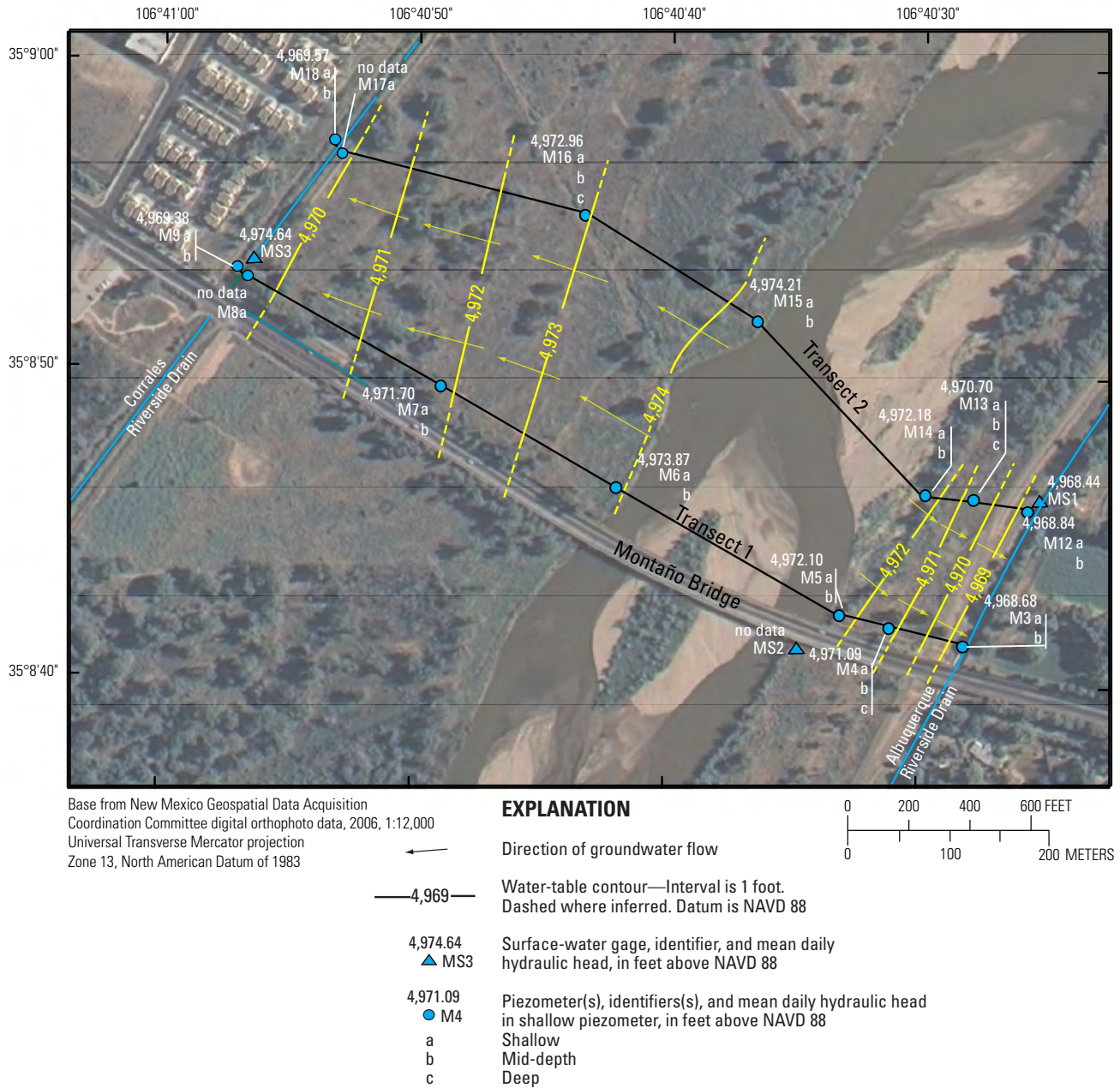


**EXPLANATION**

- ← Direction of groundwater flow
- 4,980 — Water-table contour—Interval is 1 foot.  
Dashed where inferred. Datum is NAVD 88
- 4,989.00 ▲ PS2 Surface-water gage, identifier, and mean daily hydraulic head, in feet above NAVD 88
- 4,985.02 ● P13 Piezometer(s), identifier(s), and mean daily hydraulic head in shallow piezometer, in feet above NAVD 88
- a Shallow
- b Mid-depth
- c Deep

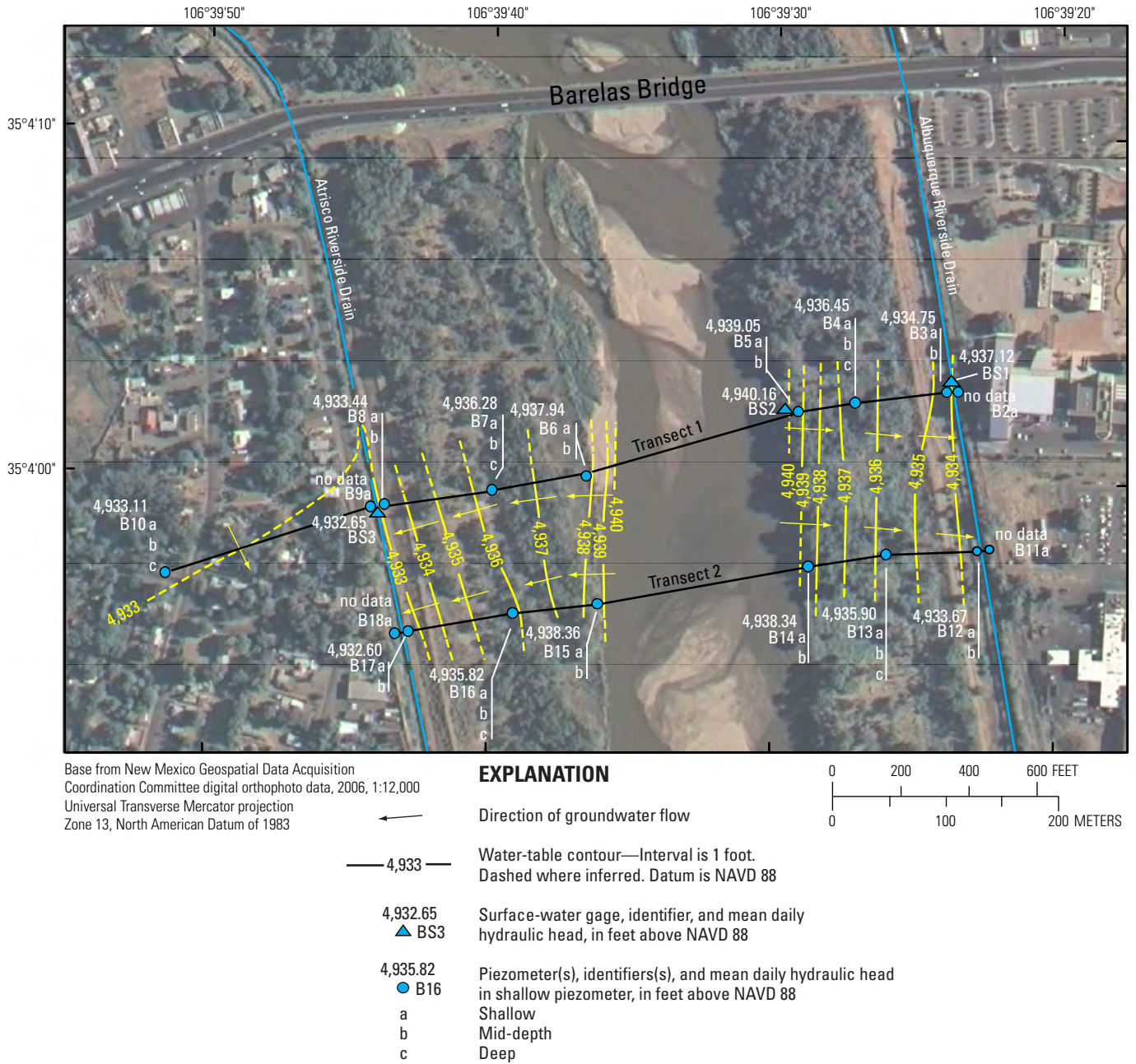
**Figure 3a.** Location of piezometer nests and surface-water gages and water-table contours showing direction of groundwater flow at the Paseo del Norte transects, November 13, 2008.

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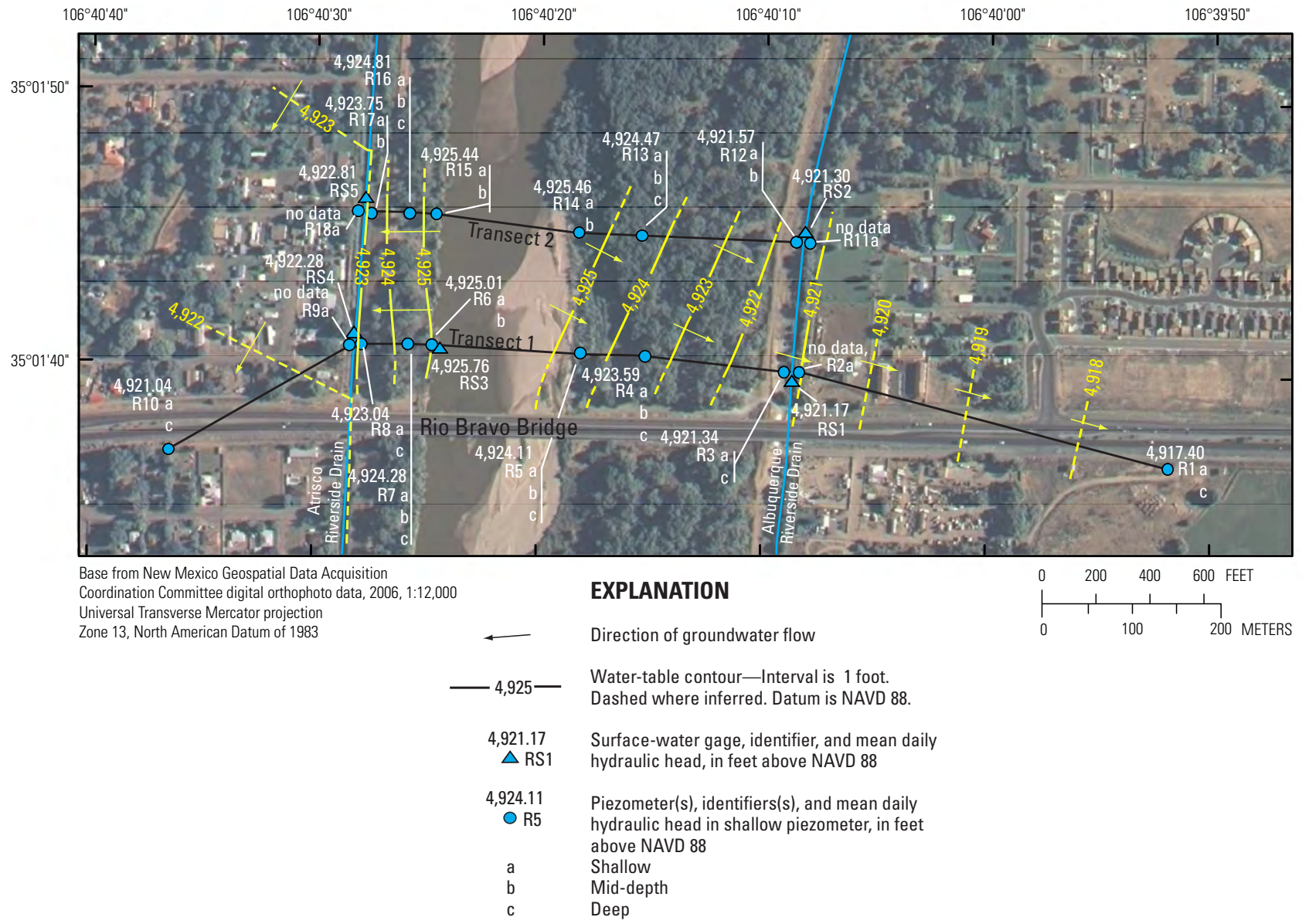


**Figure 3b.** Location of piezometer nests and surface-water gages and water-table contours showing direction of groundwater flow at the Montaña transects, February 7, 2008.





**Figure 3c.** Location of piezometer nests and surface-water gages and water-table contours showing direction of groundwater flow at the Barelas transects, February 7, 2008.



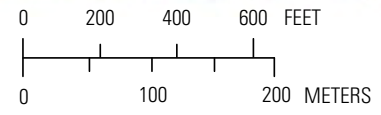
**Figure 3d.** Location of piezometer nests and surface-water gages and water-table contours showing direction of groundwater flow at the Rio Bravo transects, February 7, 2008.



Base from New Mexico Geospatial Data Acquisition Coordination Committee digital orthophoto data, 2006, 1:12,000 Universal Transverse Mercator projection Zone 13, North American Datum of 1983

**EXPLANATION**

- ← Direction of groundwater flow
- 4,902 — Water-table contour—Interval is 1 foot. Dashed where inferred. Datum is NAVD 88.
- 4,898.46 ▲ IS1 Surface-water gage, identifier, and mean daily hydraulic head, in feet above NAVD 88
- 4,899.15 ● I4 Piezometer(s), identifiers(s), and mean daily hydraulic head in shallow piezometer, in feet above NAVD 88
- a Shallow
- b Mid-depth
- c Deep



**Figure 3e.** Location of piezometer nests and surface-water gages and water-table contours showing direction of groundwater flow at the I-25 transects, February 7, 2008.

## Description of the Study Area

The study area extends about 18 miles (mi) along the Rio Grande in the Albuquerque area from the Paseo del Norte bridge to the I-25 bridge (fig. 1). The east and west edges of the study area are limited to areas within the inner valley adjacent to the Upper Corrales, Corrales, Albuquerque, and Atrisco Riverside Drains (fig. 1); the inner valley is approximately 2-3 mi wide and slopes about 5-6 feet per mile (ft/mi) southward through the Albuquerque area. The Rio Grande has a densely vegetated riparian area that supports a variety of biological communities. The riverside drains are ditches generally separated from the river by levees that are designed to intercept lateral groundwater flow from the river and prevent waterlogged-soil conditions east and west of the inner valley. Seepage to the riverside drains constitutes one of the main sources of groundwater discharge from the shallow alluvium (Kernodle and others, 1995).

## Rio Grande Inner Valley Alluvial Aquifer

The Rio Grande inner valley alluvial aquifer consists of coarse-grained axial channel deposits and post-Santa Fe Group sediments that underlie the present-day Rio Grande flood plain (Hawley and Haase, 1992). In the Albuquerque area, the alluvium consists of unconsolidated to poorly consolidated, fine- to coarse-grain sand and rounded gravel with subordinate, discontinuous lens-shaped interbeds of fine-grain sand, silt, and clay (Connell and others, 2007). These deposits form an extensive shallow aquifer along the Rio Grande in the Albuquerque area and represent the last cut-and-fill cycle of the expansion of the Rio Grande fluvial system. Hawley and Haase (1992) indicate that these channel and flood-plain deposits may be as much as 120 ft thick with an average thickness of 80 ft. Connell and others (2007) suggest that the inner valley probably was excavated during the Pleistocene epoch (about 1.8 million to 11,500 years before present) and subsequently was filled to near its present level by the middle Holocene epoch (about 8,000 to 5,000 years before present). The alluvial aquifer is overlain by and interfingers with valley border deposits of late Pleistocene and Holocene age derived from the major tributary drainages. The top of this unit has formed through deposition and includes the flood plain and channel of the Rio Grande.

## Santa Fe Group Aquifer System

The Santa Fe Group aquifer system, which underlies the alluvial aquifer, is composed primarily of gravel, sand, silt, and clay. Most of these sediments were transported into fault-bounded basins of the Rio Grande by rivers and drainages from surrounding areas (Bartolino and Cole, 2002). The spatial distribution of sedimentary facies of these deposits

tends to be complex and three-dimensional rather than a simple, layered system (Bartolino and Cole, 2002).

Approximately 14,000 ft thick in parts of the basin, the Santa Fe Group is divided into upper, middle, and lower hydrostratigraphic units (Hawley and Haase, 1992). Sediments in the upper Santa Fe unit were deposited during the development of the ancestral Rio Grande and contain intertongued piedmont-slope and fluvial basin-floor deposits as thick as 1,200 ft (Hawley and Haase, 1992). Coarse-grain sediments comprise the ancestral Rio Grande axial-channel deposits contained in the upper unit of the Santa Fe Group. Sediments in the middle Santa Fe unit include piedmont-slope deposits, fluvial basin-floor deposits, and basin-floor playa deposits (Hawley and Haase, 1992). This middle unit contains the largest accumulation of sediment and is as much as 10,000 ft thick. Sediments in the lower Santa Fe unit are predominantly piedmont-slope, eolian, and basin-floor playa deposits and are as much as 3,500 ft thick (Hawley and Haase, 1992).

## Previous Investigations

The interaction of groundwater and surface water in the Albuquerque area has been the focus of a number of investigations. McAda (1996) described the components of the Rio Grande and Santa Fe Group aquifer system in the Albuquerque area and prioritized activities to better understand groundwater and surface-water interaction. Peter (1987) compared differences in the configuration of the water table near the Rio Grande in the Albuquerque area from 1936 to 1986 and briefly described groundwater/surface-water interaction. Engdahl and others (2010) examined the effects of lithologic heterogeneity on the exchange of water between the surface and subsurface near the Rio Bravo bridge. Bartolino (2003) used groundwater levels and temperature data to evaluate groundwater fluxes in a single piezometer transect near the Paseo del Norte bridge. Bartolino and Niswonger (1999) measured groundwater-temperature profiles and groundwater levels near the Paseo del Norte and Rio Bravo bridges to simulate vertical groundwater flux and estimate vertical hydraulic conductivity. Bartolino and Sterling (2000) delineated specific areas on both sides of the river between the Paseo del Norte bridge and Rio Bravo bridge that contain hydrologically significant clay-rich layers.

The projected movement of groundwater in the Albuquerque area has been described by Kernodle and others (1995) and Bexfield and McAda (2003); the authors simulated historic and hypothetical groundwater flow in the Santa Fe Group aquifer system. Water-level declines in the Santa Fe Group aquifer have been estimated by Bexfield and Anderholm (2002); the authors report that contours of water-level data collected from 1999 to 2002 indicate that groundwater-flow direction in the Albuquerque

area has changed significantly since 1961 because of increased pumping.

McAda and Barroll (2002) simulated groundwater flow using a three-dimensional groundwater-flow model of the Santa Fe Group aquifer system from Cochiti to San Acacia. Sanford and others (2003) used environmental tracers to estimate aquifer parameters for a predevelopment groundwater-flow model in the Middle Rio Grande Basin.

Kues (1986) described the movement of shallow groundwater near the Rio Grande between the Barelás bridge and the I-25 bridge based on single measurements of water levels from 44 wells. Anderholm and Bullard (1987) described the installation of piezometers in the Albuquerque area and provided lithologic descriptions from monitoring wells drilled along Rio Bravo Boulevard and Montaña Road. Roark (2001) evaluated river flood pulses to estimate hydraulic characteristics of the Santa Fe Group aquifer system.

In general, the studies discussed above have either been very site-specific (Bartolino and Niswonger, 1999) or have been more regional in nature (McAda and Barroll, 2002). The study described in this report was designed to provide geohydrologic data and interpretations at a higher spatial resolution over a longer reach of the Rio Grande than has been provided by previous studies. Additionally, this study focuses on the geohydrology of the upper part of the alluvial aquifer.

## Methods of Data Collection and Analysis

### Piezometer Installation and Core Descriptions

Piezometers and surface-water gages were installed in paired transects near five bridges in the Albuquerque area (fig. 1, table 1). Each transect included nested piezometers (multiple monitoring wells with screen openings at different depths) and surface-water-stage gages configured in roughly straight lines and oriented perpendicular to the river and riverside drains (fig. 3). At each location, transects extended from the Rio Grande to just outside the riverside drains on both sides of the river and were spaced about 500 ft apart. The paired-transect configuration was chosen to facilitate definition of horizontal and vertical gradients at each location.

Piezometer nests generally were installed with the deep piezometer screen at 45 to 50 ft and the mid-depth piezometer screen at 30 to 35 ft. The shallow piezometer screen typically was installed at 5 to 10 ft to intersect the expected range in seasonal depths to the water table. The deep piezometer was installed first. The water level measured in the deep piezometer was then used to determine the depths for the

mid-depth and shallow piezometer screens. Each piezometer is labeled—the capital letter and number indicate location, and the small letter indicates piezometer depth (a, shallow; b, mid-depth; and c, deep). Each surface-water gage is labeled—the first capital letter and number indicate location, and the second capital letter (S) indicates a surface-water gage (fig. 3).

Piezometers were installed using direct-push drilling technology. Piezometers were constructed of 1-inch diameter, flush-threaded schedule 40 polyvinyl chloride (PVC) pipe. Each piezometer, from the bottom up, consists of a 5-ft long blank section of casing capped at the bottom (the sump), a 5-ft long screen with 0.010-inch wide screen slots, and blank casing to the land surface. Each piezometer was completed by backfilling the outside annulus surrounding the PVC with soil to a depth of about 5 ft below land surface. Bentonite pellets were then placed in the annulus from the top of the backfill to land surface. Each piezometer was developed using compressed air to pump water out of the casing.

Continuous subsurface core samples were collected at each transect from 2004 to 2006 by using direct-push drilling technology. Core samples were obtained to (1) ensure that piezometer screens were placed in sand and gravel, and not clay; and, (2) identify and locate any substantial changes in subsurface lithology that could potentially affect either horizontal or vertical groundwater movement. In total, 36 locations were cored within the study area. Coring locations generally corresponded to piezometer sites and included locations adjacent to the river, between the river and riverside drains on both sides of the river, and adjacent to both riverside drains. Coring depths ranged from 25 to 55 ft, depending on the depth of the deepest piezometer.

Cores were collected in acetate tubes; each tube was capped and labeled. Cores were described in the field at the time of collection. Core descriptions include the depth interval that was cored, the amount of recovery from each interval, the lithology (grain size, sorting, rock type, and color), and miscellaneous remarks.

### Water-Level and Temperature Data

Groundwater and surface-water levels were measured in piezometers and surface-water bodies for this study. Submersible water-pressure sensors (transducers) were installed in each piezometer to measure and record hourly groundwater levels; some of the transducers also were capable of recording hourly temperatures. Surface-water-stage gages were constructed to measure and record water levels in the Rio Grande and in the riverside drains; streamflow was not computed for these gages. A total of 164 piezometers and 17 surface-water gages were installed; the number of piezometers and surface-water gages in each set of transects varied for each location.

**Table 1.** Site data for piezometers and surface-water data collection sites, Rio Grande inner valley, Albuquerque, New Mexico.

[S, surface-water stage gage; B, Barelás; I, I-25; M, Montaña; P, Paseo del Norte; R, Rio Bravo; a, shallow piezometer; b, mid-depth piezometer; c, deep piezometer; MP, measuring point; na, not applicable; NAVD 88, North American Vertical Datum of 1988]

Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
Paseo del Norte transects							
P2a	351055106385101	22	12-17	4994.53	Uninstrumented during study		na
P2b	351055106385102	40	30-35	4994.53	11/07/2007	03/04/2009	Vented
P3a	351054106385401	25	15-20	4992.11	11/07/2007	03/04/2009	Vented
P4a	351054106390101	16	6-11	4993.29	11/07/2007	03/04/2009	Vented
P4b	351054106390102	35	25-30	4993.29	11/07/2007	03/04/2009	Vented
P5a	351054106390401	16	6-11	4993.53	11/07/2007	03/04/2009	Vented
P5b	351054106390402	35	25-30	4993.53	11/07/2007	03/04/2009	Vented
P6a	351055106391101	16	6-11	4992.03	11/07/2007	03/04/2009	Unvented
P6b	351055106391102	31	21-26	4992.03	11/07/2007	03/04/2009	Unvented
P7a	351054106391301	16	6-11	4993.47	11/07/2007	03/04/2009	Unvented
P7b	351054106391302	31	21-26	4993.47	11/07/2007	03/04/2009	Unvented
P8a	351052106391701	16	6-11	4990.86	11/07/2007	03/04/2009	Unvented
P9a	351053106391701	23	13-18	4996.34	11/07/2007	03/04/2009	Unvented
P9b	351053106391702	27	17-22	4996.34	11/07/2007	03/04/2009	Unvented
P10a	351050106394001	22	12-17	4991.09	11/13/2007	03/04/2009	Vented
P10c	351050106394002	46	36-41	4991.09	Uninstrumented during study		na
P11a	351059106385201	22	12-17	4991.37	10/17/2008	03/03/2009	Unvented
P11b	351059106385202	37	27-32	4991.37	10/17/2008	03/03/2009	Unvented
P12a	351059106385301	22	12-17	4991.77	10/17/2008	03/03/2009	Unvented
P13a	351058106385901	17	7-12	4993.36	10/17/2008	03/03/2009	Unvented
P13b	351058106385902	32	22-27	4993.36	10/17/2008	03/03/2009	Unvented
P13c	351058106385903	52	42-47	4993.36	10/17/2008	03/03/2009	Unvented
P14a	351058106390301	15	5-10	4993.76	10/17/2008	03/03/2009	Unvented
P14b	351058106390302	30	20-25	4993.76	10/17/2008	03/03/2009	Unvented
P15a	351058106391001	16	6-11	4992.33	10/15/2008	03/03/2009	Unvented
P15b	351058106391002	31	21-26	4992.33	10/15/2008	03/03/2009	Unvented

Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
Paseo del Norte transects—Continued							
P16a	351058106391101	16	6-11	4993.26	10/15/2008	03/03/2009	Unvented
P16b	351058106391102	40	30-35	4993.26	10/15/2008	03/03/2009	Unvented
P17a	351058106391501	16	6-11	4989.73	10/15/2008	03/03/2009	Unvented
P18a	351058106391601	20	10-15	4991.50	10/15/2008	03/03/2009	Unvented
P18b	351058106391602	35	25-30	4991.50	10/15/2008	03/03/2009	Unvented
PS1	351054106385310	na	na	4984.21	10/17/2008	03/04/2009	Unvented
PS2	351055106390810	na	na	4993.49	10/15/2008	03/04/2009	Unvented
PS3	351053106391710	na	na	4989.62	10/15/2008	03/04/2009	Unvented
Montaño transects							
M3a	350843106402801	17	7-12	4974.14	12/05/2005	10/31/2008	Unvented
M3b	350843106402802	31	21-26	4974.14	12/05/2005	08/22/2006	Unvented
M4a	350842106403101	15	5-10	4978.85	01/09/2006	10/31/2008	Unvented
M4b	350842106403102	30	20-25	4978.85	06/13/2005	10/31/2008	Unvented
M4c	350842106403103	49	39-44	4978.85	06/13/2005	10/31/2008	Unvented
M5a	350842106403201	15	5-10	4978.20	01/09/2006	10/31/2008	Unvented
M5b	350842106403202	32	22-27	4978.20	06/13/2005	10/31/2008	Unvented
M6a	350848106404703	13	3-8	4978.86	10/12/2005	10/31/2008	Unvented
M6b	350848106404704	28	18-23	4978.86	10/12/2005	10/31/2008	Unvented
M7a	350848106404701	15	5-10	4977.89	10/12/2005	10/31/2008	Unvented
M7b	350848106404702	30	20-25	4977.89	10/12/2005	10/31/2008	Unvented
M8a	350852106405601	16	6-11	4979.78	10/12/2005	01/24/2007	Unvented
M9a	350853106405701	15	5-10	4977.39	10/12/2005	10/31/2008	Unvented
M9b	350853106405702	30	20-25	4977.39	06/13/2005	10/31/2008	Unvented
M12a	350847106402501	17	7-12	4977.26	01/09/2006	11/03/2008	Unvented
M12b	350847106402502	32	22-27	4977.26	01/09/2006	10/31/2008	Unvented (01/09/2006 - 08/22/2006), vented (03/16/2007 - 10/31/2008)
M13a	350846106402801	16	6-11	4977.37	03/16/2007	10/31/2008	Vented
M13b	350846106402802	31	21-26	4977.37	01/09/2006	10/31/2008	Unvented
M13c	350846106402803	47	37-42	4977.37	01/09/2006	10/31/2008	Unvented

**Table 1.** Site data for piezometers and surface-water data collection sites, Rio Grande inner valley, Albuquerque, New Mexico.—Continued

[S, surface-water stage gage; B, Barelás; I, I-25; M, Montaña; P, Paseo del Norte; R, Rio Bravo; a, shallow piezometer; b, mid-depth piezometer; c, deep piezometer; MP, measuring point; na, not applicable; NAVD 88, North American Vertical Datum of 1988]

Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
Montaña transects—Continued							
M14a	350846106402804	18	8-13	4979.83	11/17/2006	10/31/2008	Vented
M14b	350846106402805	33	23-28	4979.83	01/13/2006	04/29/2008	Vented
M15a	350851106403801	13	3-8	4977.80	02/01/2006	10/31/2008	Vented
M15b	350851106403802	28	18-23	4977.80	02/01/2006	10/31/2008	Vented
M16a	350854106404201	17	7-12	4978.62	02/01/2006	10/31/2008	Vented
M16b	350854106404202	32	22-27	4978.62	02/01/2006	10/31/2008	Vented
M16c	350854106404203	46	36-41	4978.62	02/01/2006	10/31/2008	Vented
M17a	350855106405401	18	8-13	4978.88	02/01/2006	01/26/2007	Vented
M18a	350857106405401	18	8-13	4978.17	02/01/2006	10/31/2008	Vented
M18b	350857106405402	33	23-28	4978.17	02/01/2006	10/31/2008	Vented
MS1	350846106402510	na	na	4972.61	06/20/2006	10/31/2008	Vented
MS2	350841106403510	na	na	4978.52	06/20/2006	07/22/2008	Vented
MS3	350854106405610	na	na	4979.11	06/20/2006	10/31/2008	Vented
B2a	350403106392201	16	6-11	4940.68	10/30/2008	03/10/2009	Unvented
Barelás transects							
B3a	350403106392301	15	5-10	4941.86	10/07/2005	03/10/2009	Unvented
B3b	350403106392302	30	20-25	4941.86	06/13/2005	03/10/2009	Unvented
B4a	350402106392601	16	6-11	4942.18	10/07/2005	03/10/2009	Unvented
B4b	350402106392602	31	21-26	4942.18	06/13/2005	10/30/2008	Unvented
B4c	350402106392603	52	42-47	4942.18	06/13/2005	03/10/2009	Unvented
B5a	350402106392901	15	5-10	4943.08	10/07/2005	03/10/2009	Unvented
B5b	350402106392902	30	20-25	4943.08	06/13/2005	10/30/2008	Unvented
B6a	350400106393701	17	7-12	4942.40	10/07/2005	03/10/2009	Unvented
B6b	350400106393702	32	22-27	4942.40	06/13/2005	03/10/2009	Unvented
B7a	350359106393901	17	7-12	4943.03	10/07/2005	03/10/2009	Unvented
B7b	350359106393902	32	22-27	4943.03	04/21/2005	10/22/2008	Unvented
B7c	350359106393903	52	42-47	4943.03	04/21/2005	03/10/2009	Unvented
B8a	350359106394401	16	6-11	4940.23	10/05/2005	03/10/2009	Unvented
B8b	350359106394402	34	24-29	4940.23	04/21/2005	10/22/2008	Unvented



Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
Barelas transects—Continued							
B9a	350359106394501	20	10-15	4943.21	Uninstrumented during study		na
B10a	350354106395201	17	7-12	4940.77	06/27/2005	03/10/2009	Unvented
B10b	350354106395202	32	22-27	4940.77	07/13/2005	03/10/2009	Unvented
B10c	350354106395203	48	38-43	4940.77	07/13/2005	03/10/2009	Unvented
B11a	350358106392201	16	6-11	4939.91	10/31/2008	03/10/2009	Unvented
B12a	350358106392301	16	6-11	4939.88	02/01/2006	03/10/2009	Vented
B12b	350358106392302	31	21-26	4939.88	02/01/2006	03/10/2009	Vented
B13a	350358106392601	15	5-10	4941.91	01/30/2006	03/10/2009	Vented
B13b	350358106392602	30	20-25	4941.91	01/30/2006	03/10/2009	Vented
B13c	350358106392603	40	30-35	4941.91	01/30/2006	03/10/2009	Vented
B14a	350357106392901	15	5-10	4943.41	01/30/2006	03/10/2009	Vented
B14b	350357106392902	30	20-25	4943.41	01/30/2006	03/10/2009	Vented
B15a	350356106393601	16	6-11	4943.14	01/30/2006	10/22/2008	Vented
B15b	350356106393602	31	21-26	4943.14	01/30/2006	01/15/2008	Vented
B16a	350356106393901	16	6-11	4943.59	01/30/2006	03/10/2009	Vented
B16b	350356106393902	31	21-26	4943.59	01/30/2006	03/10/2009	Vented
B16c	350356106393903	51	41-46	4943.59	01/30/2006	03/10/2009	Vented
B17a	350354106394201	16	6-11	4939.60	01/27/2006	03/10/2009	Vented
B17b	350354106394202	31	21-26	4939.60	01/30/2006	03/10/2009	Vented
B18a	350353106394301	20	10-15	4943.14	Uninstrumented during study		na
BS1	350403106392410	na	na	4942.04	06/21/2006	03/10/2009	Vented
BS2	350402106392810	na	na	4942.86	06/21/2006	03/10/2009	Vented
BS3	350359106394410	na	na	4935.89	06/21/2006	03/10/2009	Vented
R1a	350137106395101	27	17-22	4931.35	01/01/2004	10/27/2008	Unvented
R1c	350137106395102	59	49-54	4931.35	01/01/2004	10/27/2008	Unvented
Rio Bravo transects							
R2a	350141106400701	16	6-11	4927.27	10/28/2008	03/12/2009	Unvented
R3a	350141106400801	17	7-12	4927.51	01/01/2004	03/12/2009	Unvented
R3c	350141106400802	57	47-52	4927.51	01/01/2004	10/27/2008	Unvented

**Table 1.** Site data for piezometers and surface-water data collection sites, Rio Grande inner valley, Albuquerque, New Mexico.—Continued

[S, surface-water stage gage; B, Barelás; I, I-25; M, Montañó; P, Paseo del Norte; R, Rio Bravo; a, shallow piezometer; b, mid-depth piezometer; c, deep piezometer; MP, measuring point; na, not applicable; NAVD 88, North American Vertical Datum of 1988]

Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
Rio Bravo transects—continued							
R4a	350138106401102	22	12-17	4929.91	01/01/2004	03/15/2009	Unvented
R4b	350138106401104	30	20-25	4929.91	07/12/2005	10/28/2008	Unvented
R4c	350140106401701	56	46-51	4929.91	01/01/2004	03/15/2009	Unvented
R5a	350140106401704	19	9-14	4930.49	07/12/2005	03/15/2009	Unvented
R5b	350140106401703	30	20-25	4930.49	07/12/2005	03/15/2009	Unvented
R5c	350140106401702	54	44-49	4930.49	01/01/2004	04/14/2008	Unvented
R6a	350143106402401	15	5-10	4928.75	07/12/2005	03/15/2009	Unvented
R6b	350143106402402	30	20-25	4928.62	10/05/2005	03/15/2009	Unvented
R7a	350143106402503	15	5-10	4928.79	07/12/2005	03/15/2009	Unvented
R7b	350143106402501	35	25-30	4928.99	01/01/2004	08/15/2006	Unvented
R7c	350143106402502	54	44-49	4928.99	01/01/2004	03/15/2009	Unvented
R8a	350142106402701	15	5-10	4928.32	01/01/2004	03/12/2009	Unvented
R8c	350142106402702	50	40-45	4928.32	01/01/2004	03/12/2009	Unvented
R9a	350142106402801	14	4-9	4927.73	10/29/2008	03/12/2009	Unvented
R10a	350137106403501	30	20-25	4925.90	01/01/2004	03/12/2009	Unvented
R10c	350137106403502	49	39-44	4925.90	01/01/2004	03/12/2009	Unvented
R11a	350144106400703	18	8-13	4926.48	10/28/2008	03/12/2009	Unvented
R12a	350144106400701	16	6-11	4929.06	08/15/2006	03/12/2009	Vented
R12b	350144106400702	31	21-26	4929.06	08/15/2006	03/12/2009	Vented
R13a	350144106401101	15	5-10	4929.13	02/15/2005	03/15/2009	Unvented
R13b	350144106401102	30	20-25	4929.13	02/16/2005	10/28/2008	Unvented
R13c	350144106401103	56	46-51	4929.13	02/16/2005	03/15/2009	Unvented
R14a	350146106401801	15	5-10	4929.92	01/25/2005	03/15/2009	Unvented
R14b	350146106401802	30	20-25	4929.69	01/25/2005	03/15/2009	Unvented
R15a	350147106402601	15	5-10	4929.77	10/05/2005	03/15/2009	Unvented
R15b	350147106402602	30	20-25	4929.77	06/02/2005	03/15/2009	Unvented
R16a	350147106402501	15	5-10	4928.70	10/05/2005	03/15/2009	Unvented
R16b	350147106402502	30	20-25	4928.70	06/02/2005	10/29/2008	Unvented
R16c	350147106402503	54	44-49	4928.70	06/02/2005	03/15/2009	Unvented

Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
Rio Bravo transects—Continued							
R17a	350147106402801	16	6-11	4928.18	10/05/2005	03/12/2009	Unvented
R17b	350147106402802	31	21-26	4928.18	10/05/2005	03/12/2009	Unvented
R18a	350147106402701	15	5-10	4929.11	10/29/2008	03/12/2009	Unvented
RS1	350141106400810	na	na	4925.22	09/29/2006	03/12/2009	Vented
RS2	350145106400810	na	na	4926.52	04/10/2006	03/12/2009	Vented
RS3	350143106402301	na	na	4934.74	01/01/2004	03/15/2009	Unvented
RS4	350142106402810	na	na	4927.49	04/07/2006	03/12/2009	Vented
RS5	350147106402810	na	na	4928.69	10/13/2006	03/12/2009	Vented
I-25 transects							
I1a	350358106391301	16	6-11	4904.92	11/29/2005	02/21/2008	Unvented
I1b	350358106391302	31	21-26	4904.92	06/01/2005	12/11/2006	Unvented
I1c	350358106391303	56	46-51	4904.92	06/01/2005	10/21/2008	Unvented
I2a	345703106403901	16	6-11	4902.76	06/01/2005	10/21/2008	Unvented
I2b	345703106403902	31	21-26	4902.76	06/01/2005	10/21/2008	Unvented 06/01/2005 - 02/17/2007), vented (03/21/2007 - 10/21/2008)
I3a	345703106404001	16	6-11	4902.35	11/29/2005	10/21/2008	Unvented
I4a	345701106404501	14	4-9	4903.47	11/29/2005	10/21/2008	Unvented
I4b	345701106404502	29	19-24	4903.47	06/01/2005	10/21/2008	Unvented
I4c	345701106404503	54	44-49	4903.47	06/01/2005	12/11/2006	Unvented
I5a	345701106404601	14	4-9	4904.60	11/29/2005	10/21/2008	Unvented
I5b	345701106404602	29	19-24	4904.60	06/01/2005	10/21/2008	Unvented
I6a	345707106410101	14	4-9	4905.91	11/30/2005	10/24/2008	Unvented
I6b	345707106410102	29	19-24	4905.91	06/01/2005	11/19/2007	Unvented (06/01/2005 - 06/28/2006), vented (06/28/2006 - 11/19/2007)
I7a	345706106410201	14	4-9	4905.12	11/29/2005	10/24/2008	Unvented
I7b	345706106410202	29	19-24	4905.12	06/01/2005	10/24/2008	Unvented
I7c	345706106410203	49	39-44	4905.12	04/22/2005	10/24/2008	Unvented
I8a	345704106410701	15	5-10	4901.90	11/29/2005	10/24/2008	Unvented
I8b	345704106410702	30	20-25	4901.90	06/01/2005	10/24/2008	Unvented
I10a	345703106411201	13	3-8	4900.97	06/01/2005	10/22/2008	Unvented

**Table 1.** Site data for piezometers and surface-water data collection sites, Rio Grande inner valley, Albuquerque, New Mexico.—Continued

[S, surface-water stage gage; B, Barelás; I, I-25; M, Montañó; P, Paseo del Norte; R, Rio Bravo; a, shallow piezometer; b, mid-depth piezometer; c, deep piezometer; MP, measuring point; na, not applicable; NAVD 88, North American Vertical Datum of 1988]

Other identifier (fig. 3a-e)	Site identifier	Piezometer depth (feet below land surface, rounded to nearest foot)	Screened interval (feet below land surface, rounded to nearest foot)	Land surface <sup>1</sup> or MP <sup>2</sup> elevation (feet above NAVD 88)	Period of record presented in this report		Type of transducer in well for period of record presented in this report
					Start Date	End Date	
I-25 transects—Continued							
I10b	345703106411202	28	18-23	4900.97	06/01/2005	11/05/2007	Unvented
I10c	345703106411203	48	38-43	4900.97	06/01/2005	10/23/2008	Unvented
I11a	345707106404101	13	3-8	4902.27	02/23/2007	10/20/2008	Vented
I11b	345707106404102	28	18-23	4902.27	01/20/2006	10/20/2008	Vented
I12a	345707106404103	13	3-8	4902.28	Uninstrumented during study		na
I13a	345706106404701	14	4-9	4904.21	03/09/2007	10/21/2008	Vented
I13b	345706106404702	29	19-24	4904.21	12/12/2006	11/06/2007	Unvented
I13c	345706106404703	49	34-39	4904.21	12/12/2006	10/21/2008	Vented
I14a	345706106404704	14	4-9	4904.06	03/09/2007	10/21/2008	Vented
I14b	345706106404705	29	19-24	4904.06	01/20/2006	10/21/2008	Unvented
I15a	345713106410604	14	4-9	4906.50	10/13/2006	10/27/2008	Vented
I15b	345713106410605	29	19-24	4906.50	10/13/2006	10/27/2008	Unvented
I16a	345713106410601	16	6-11	4908.22	Uninstrumented during study		na
I16b	345713106410602	31	21-26	4908.22	01/23/2006	10/27/2008	Vented
I16c	345713106410603	49	39-44	4908.22	01/23/2006	10/27/2008	Vented
I17a	345713106411001	13	3-8	4903.46	03/09/2007	10/23/2008	Vented
I17b	345713106411002	28	18-23	4903.46	01/23/2006	10/23/2008	Vented
IS1	345703106404010	na	na	4903.63	04/07/2006	10/21/2008	Vented
IS2	345705106405810	na	na	4905.14 <sup>3</sup> 4906.66 <sup>4</sup>	08/10/2005	10/23/2008	Unvented (08/10/2005 - 06/28/2006), vented (07/06/2006 - 10/23/2008)
IS3	345705106410810	na	na	4902.04 <sup>5</sup> 4903.23 <sup>6</sup>	04/07/2006	10/23/2008	Vented

<sup>1</sup>Land-surface elevation for piezometers only<sup>2</sup>Measuring-point elevation for surface-water stage gages only<sup>3</sup>MP valid through May 2, 2006<sup>4</sup>MP valid after May 2, 2006<sup>5</sup>MP valid through May 8, 2008<sup>6</sup>MP valid after May 8, 2008

Groundwater-level data were measured using vented and unvented transducers (table 1). Transducers with vented cable are automatically compensated for changes in barometric pressure, but transducers with unvented cable are not. With unvented transducers, a calculation is required to correct the recorded water levels for changes in barometric pressure. Unvented transducers record total pressure (water + air) and convert this value to a water level. Any change in air pressure needs to be subtracted from an initial barometric pressure (pressure at the start of the water level data set being corrected) and the result subtracted from the recorded total water level in order to attain a corrected water level (Freeman and others, 2004). Hourly barometric pressure values from the Albuquerque airport (National Climatologic Data Center, 2011) were used to correct all water level data collected using unvented transducers. Water-level barometric corrections ranged from 0 to about 0.5 ft.

### Slug Tests

The spatial variability of aquifer properties at each of the transect locations was estimated by conducting slug tests during January and February 2009. Analytical results from slug tests, a type of aquifer test, need to be interpreted carefully because the continuity and distribution of hydrologically distinguishable lithologies are unique to different parts of the alluvial aquifer. Type-curve matching methods are the most common analytical techniques used for slug-test analysis and provide an estimate of aquifer characteristics in different portions of the aquifer.

Slug tests were conducted by the rapid introduction of a 60-inch long weighted PVC slug, with a diameter of 0.75 inch, into a 1-inch diameter piezometer to induce a positive displacement of water in the piezometer of 1 ft or more. Water levels were recorded prior to and during the slug tests to record initial head, slug insertion, and water-level recovery to static conditions. After water levels recovered to within 5 percent of initial water levels (Butler, 1998), the slug was removed and the subsequent water-level recovery was recorded at 1-second intervals by using pressure transducers. Slug tests were performed at 15 shallow piezometers, 19 mid-depth piezometers, and 1 deep piezometer at the Paseo Del Norte, Montaña, Barelás, Rio Bravo, and I-25 transects.

Hydraulic-conductivity estimates were determined by the Bouwer and Rice (1976) and Butler (1998) methods for slug-test analysis in unconfined aquifers. The Butler (1998) method is an extension of the Bouwer and Rice (1976) method to account for slug tests conducted in highly permeable aquifers with an oscillatory response during recovery. For both methods, the recovery data are analyzed by using a family of type curves to determine the hydraulic conductivity of the aquifer. The Bouwer and Rice (1976) method is used to estimate hydraulic conductivity through the following equation:

$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L} \frac{1}{t} \ln \frac{y_0}{y_t} \tag{1}$$

where

- $K$  is hydraulic conductivity (length/time (L/t)),
- $r_c$  is casing radius (L),
- $R_e$  is effective radius of influence (L),
- $r_w$  is borehole radius (L),
- $L$  is length of open interval of the well (L),
- $t$  is time (t),
- $y_0$  is initial water level (L), and
- $y_t$  is water level at time  $t$  (L).

The Butler (1998) method for an unconfined, highly permeable aquifer is used to estimate hydraulic conductivity through the following equation:

$$K_r = \frac{t_d^* r_c^2 \ln(R_e/r_w)}{t^* 2b_s C_D^*} \tag{2}$$

where

- $K_r$  is radial hydraulic conductivity (L/t),
- $t_d^*$  is dimensionless time parameter  $(\frac{g}{L_e})^{1/2} t$ ,  
where  $g$  is gravitational acceleration, and  $L_e$  is effective length of water column in well, and  $t$  is time.
- $t^*$  is time (t),
- $r_c$  is casing radius (L),
- $R_e$  is effective radius of influence (L),
- $r_w$  is borehole radius (L),
- $b_s$  is screen length (L), and
- $C_D^*$  is dimensionless damping parameter.

Use of either method assumes (1) the aquifer is unconfined and infinite in areal extent; (2) the aquifer is homogeneous, isotropic, and uniform in thickness; (3) the water table is initially horizontal; (4) the well is fully or partially penetrating; (5) the water level in the well is stable; (6) the slug is introduced rapidly into the well; and (7) the screened interval is completely saturated during testing.

### Darcy's Law

Temporal changes in the rate of Rio Grande seepage to the alluvial aquifer were computed by using Darcy's law. Darcy flux, or specific discharge, is a rate of groundwater movement defined by a hydraulic gradient acting across a

homogeneous aquifer under laminar flow conditions (Fetter, 1994). In equation form, Darcy's law is:

$$Q = -KA \frac{dh}{dl} \quad (3)$$

where

- $Q$  is volumetric groundwater flow ( $L^3/t$ ),
- $K$  is hydraulic conductivity ( $L/t$ ),
- $A$  is cross-sectional area through which groundwater flow occurs ( $L^2$ ), and
- $h$  is hydraulic gradient (dimensionless but, by convention, is negative in the direction of groundwater flow).

Dividing both sides by the cross-sectional area ( $A$ ), and setting  $q=Q/A$ , the Darcy flux through a unit area of aquifer can be stated as:

$$q = -K \frac{dh}{dl} \quad (4)$$

where

- $q$  is the Darcy flux of water through the aquifer ( $L/t$ ).

The hydraulic conductivity values used in the Darcy flux calculations in this report are considered bulk values that characterize the aquifer as a homogeneous mixture of sediments. Bulk hydraulic conductivity values represent average conditions in the aquifer and were defined on the basis of the results of slug tests conducted for this study and on the basis of values obtained from published literature (Tiedeman and others, 1998; Bartolino and Niswonger, 1999; McAda, 2001; Sanford and others, 2003; Moret, 2007).

Horizontal hydraulic gradients used in the Darcy flux calculations were calculated by using the three-point method to determine the strike (compass direction) and dip (slope) of rock outcrops (Compton, 1962), and which has been used by Myers and others (1999) to calculate hydraulic gradients in an alluvial aquifer at Fort Riley, Kansas. Daily hydraulic gradients were calculated by using the three-point method and 2006-08 daily mean water levels to compute the slope of the water surface between selected sets of shallow piezometers. Daily mean water levels were not uniformly available at all transects from 2006-08 (table 1). For each of the paired transects, hydraulic gradients were calculated for three-piezometer combinations of adjacent, triangle-forming piezometers (piezometer triangles) between the river and the riverside drain on each side of the Rio Grande (fig. 4). For each set of six piezometers, a total of eight piezometer triangles were defined on each side of the river (fig. 4). After

the daily mean hydraulic gradient was calculated for each of the eight piezometer triangles, the daily mean hydraulic gradient for each side of the river was calculated as the average of the daily mean hydraulic gradients of the eight piezometer triangles.

### Suzuki-Stallman Method

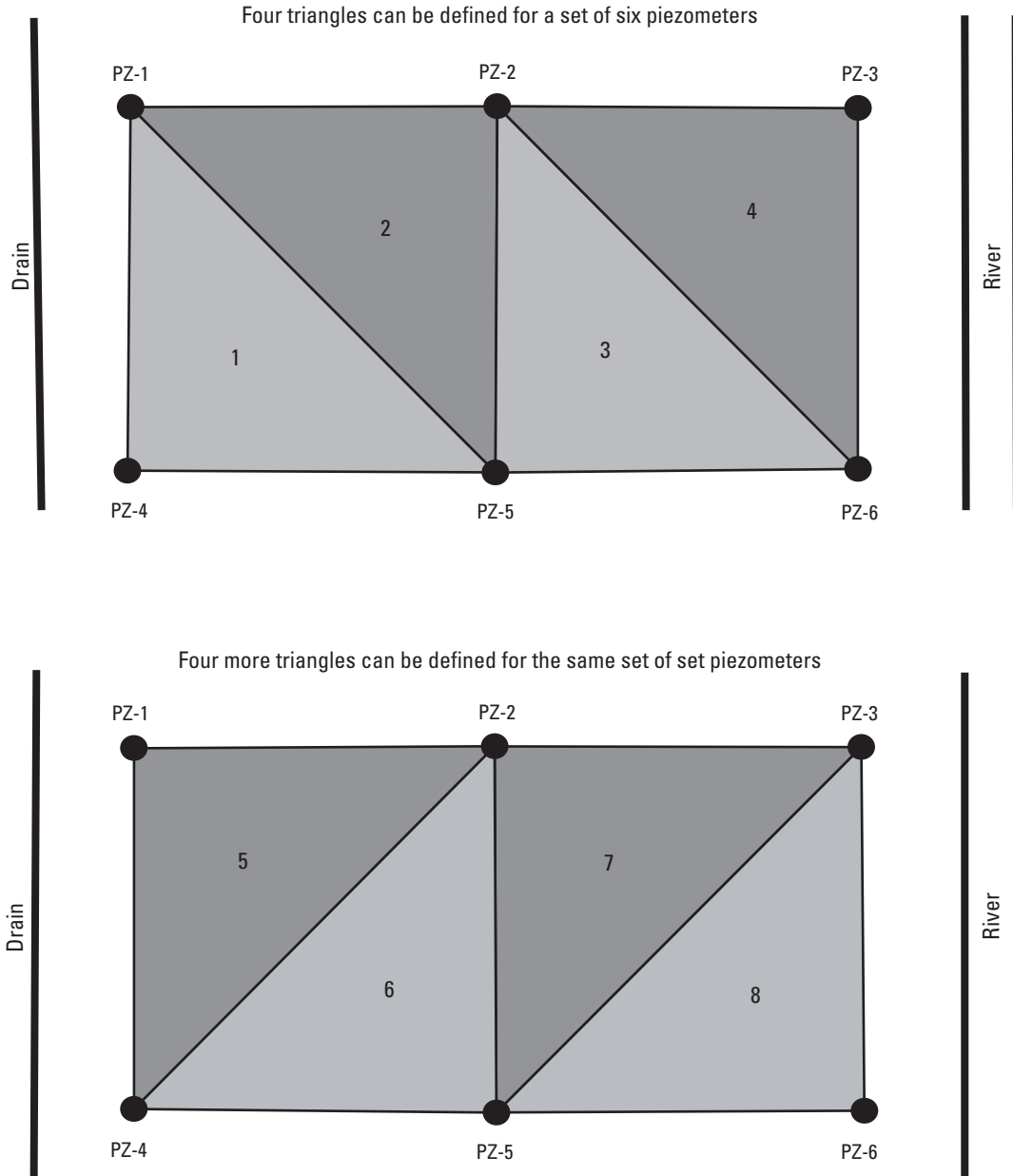
In addition to specific fluxes calculated from hydraulic conductivities and hydraulic gradients by using the Darcy equation, specific fluxes also were computed with the temperature data collected at 10- and 20-ft depths in the alluvial aquifer by using the analytical method developed by Suzuki (1960) and Stallman (1965) that was applied to horizontal flux by Moret (2007). Suzuki (1960) developed an equation and approximate analytical solution for 1-dimensional (vertical) advective and conductive heat transport into rice paddy soils assuming saturated, vertical, steady-state flow in a homogenous medium with a sinusoidal daily surface temperature. Later, on the basis of Suzuki's work, Stallman (1965) developed an exact analytic solution for 1-dimensional (vertical) advective and conductive heat transfer in an aquifer. The Suzuki-Stallman method relies only on temperature data, providing an independent method that can be used to check the Darcy flux estimates generated by using measured hydraulic conductivity values and hydraulic gradients. For a more complete discussion of using heat as a groundwater tracer see Anderson (2005), Blasch and others (2007), or Constantz and others (2008).

The equation describing one-dimensional, vertical transport is (Suzuki, 1960):

$$k \frac{\partial^2 T}{\partial z^2} + \rho_w c_w q_s \frac{\partial T}{\partial z} = \rho c \frac{\partial T}{\partial t} \quad (5)$$

where

- $k$  is the thermal conductivity of the saturated aquifer sediment and water ( $BTU_{IT}/t L^\circ F$ ,
- $T$  is the temperature in the aquifer ( $^\circ F$ ),
- $\rho_w c_w$  is the heat capacity of the water ( $BTU_{IT}/L^3^\circ F$ ) [British Thermal Unit (International Steam Table Calorie) per cubic foot-degrees Fahrenheit,
- $q_s$  is the specific flux of water through the aquifer ( $L/t$ ),
- $\rho c$  is the heat capacity of the saturated aquifer (sediment and water) ( $BTU_{IT}/L^3^\circ F$ ),
- $z$  is distance ( $L$ ), and
- $t$  is time ( $t$ ).



**Figure 4.** Diagram of sets of piezometers used to compute daily mean hydraulic gradients on each side of the Rio Grande for each paired transect. For six piezometers, eight triangles can be defined for use in gradient calculations.

Moret (2007) adapted the heat transport equation (Suzuki, 1960) and analytical solution (Stallman, 1965) to use annual temperature variations in river temperature and their propagation into the adjacent aquifer to estimate rates of horizontal river seepage. For the horizontal flux, Moret (2007) uses Equation 5, but substitutes horizontal distance  $x$  for the vertical distance  $z$ . Temperature variations in the river affect the solution to equation 5; consequently Moret (2007) adapted Stallman's (1965) method for incorporating diurnal heating and cooling of the land surface to correct for changes in river temperature. To use the solution proposed by Stallman, Moret found it necessary to assume that the aquifer is bounded at  $x=0$  by a fully penetrating river and that all flow is uniform and horizontal in the positive  $x$  direction. Following Suzuki (1960) and Stallman (1965), Moret (2007) stated that the temperature of the river,  $T_{river}$ , varies sinusoidally with a period of 1 year:

$$T_{river} = T_{avg} + T_0 \sin\left(\frac{2\pi}{\tau}t + \varphi\right) \quad (6)$$

where

- $T_{avg}$  is the average river temperature (°F),
- $T_0$  is the magnitude of temperature oscillation in the river (°F),
- $\tau$  is the period of the oscillation (t),
- $\varphi$  is the phase lag in temperature signal of the river (t), and
- $t$  is time (t).

If the temperature dependence of the viscosity of water is ignored, the analytical solution for advective and conductive heat transport proposed by Suzuki (1960) and further developed by Stallman (1965) can be used to model the temperature oscillations in groundwater ( $T_{osc}$ ) that are attributable to river water temperature oscillations ( $T_{river}$ ):

$$T_{osc} = T_0 e^{-ax} \sin\left(\frac{2\pi}{\tau}t - bx + \varphi\right) \quad (7)$$

where

- $T_0$ ,  $\tau$ ,  $t$ ,  $x$ , and  $\varphi$  are as previously defined for equations 5 and 6,

$$a = \left[ \sqrt{K_T^2 + \frac{V^4}{4}} + \frac{V^2}{2} \right]^{\frac{1}{2}} - V, \text{ and} \quad (8)$$

$$b = \left[ \sqrt{K_T^2 + \frac{V^4}{4}} - \frac{V^2}{2} \right]^{\frac{1}{2}} \quad (9)$$

The parameter  $a$ , with units of  $\text{ft}^{-1}$ , controls the attenuation of the temperature wave. The spatial frequency  $b$ , with units of radians per foot (rad/ft), controls the propagation of the wave through space. The parameters  $K_T$  and  $V$  are defined by:

$$K_T = \frac{\pi\rho c}{k\tau} \quad (10)$$

$$V = \frac{\rho_w c_w q_s}{2k} \quad (11)$$

where  $\rho c$ ,  $k$ ,  $\tau$ ,  $\rho_w c_w$ , and  $q_s$  are as previously defined in equations 5 and 6.

Figure 5 shows how theoretical values of  $a$  and  $b$ , calculated through use of equations 8 and 9, vary as a function of changes in the flux term ( $q_s$ ) in equation 11. Type curves in figure 5 were constructed by using the average of the four values obtained by Bartolino and Niswonger (1999) for the thermal conductivity (1.25  $\text{BTU}_{IT}/\text{hr ft } ^\circ\text{F}$ ), and saturated heat capacity (155  $\text{BTU}_{IT}/\text{ft}^3 \text{ } ^\circ\text{F}$ ) of the inner valley alluvial aquifer.

For  $a$  and  $b$  determined from observations, the specific flux through the aquifer,  $q_s$ , can be estimated from type curves such as those in figure 5. The parameters  $a$  and  $b$  can be estimated by using temperature records from two wells at distances  $x_1$  and  $x_2$  from the river. The differences between the maximum and minimum temperatures in these records,  $\Delta T_{x_1}$  and  $\Delta T_{x_2}$ , can be used to estimate  $a$ :

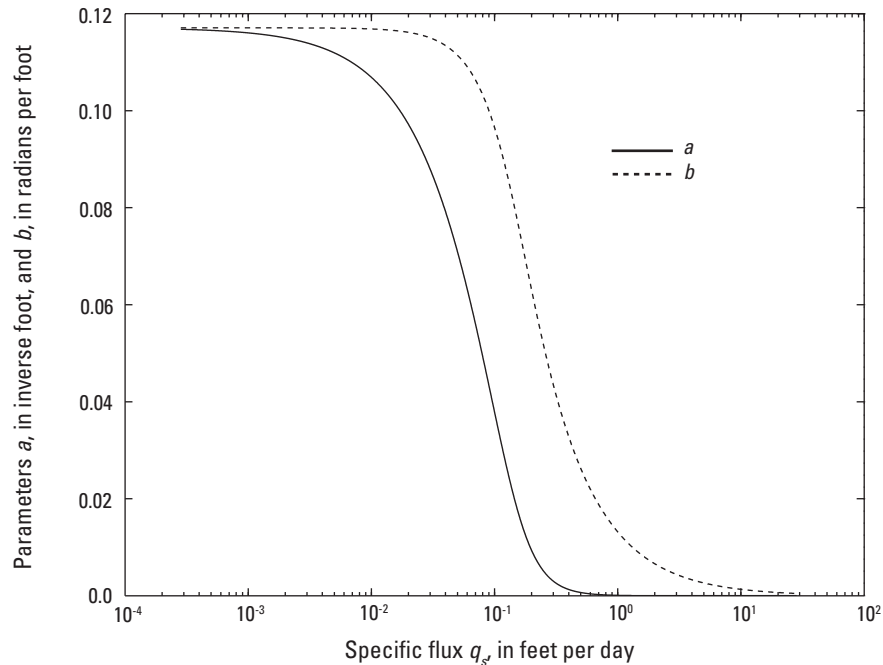
$$a = \frac{-1}{x_2 - x_1} \log\left(\frac{\Delta T_{x_1}}{\Delta T_{x_2}}\right) \quad (12)$$

The phase lag between the two temperature records,  $\Delta t$ , yields  $b$ :

$$b = \frac{2\pi\Delta t}{(x_2 - x_1)\tau} \quad (13)$$

Moret (2007) found that the best way to estimate specific flux,  $q_s$ , is to plot the measured values of  $a$  and  $b$  on type curves such as figure 5. With this method, the user can determine whether  $a$  and  $b$  are physically realistic and consistent with each other and assess the sensitivity of  $q_s$  to





**Figure 5.** Type curves for the Suzuki-Stallman method, showing values of the parameters  $a$  and  $b$  as a function of specific flux. Type curves generated using equations 8, 9, 10, and 11.

measurement error. The Suzuki-Stallman method can only be used to estimate flux in regions of the curves where  $a$  and  $b$  vary as a function of  $q_s$  (fig. 5).

In this study, there were four steps used to estimate flux with temperature data. First, two type curves ( $a$  and  $b$ ) were developed by using thermal properties of the aquifer and equations 8-11 for a range of specific flux values (fig. 5). Second, values for  $a$  and  $b$  were calculated using equations 12 and 13 and temperatures measured in the piezometers. Third, the values of  $a$  and  $b$  calculated in the previous step were plotted on their respective type curves and matched with the corresponding flux ( $q_a$  and  $q_b$ ). Fourth, the  $q_a$  and  $q_b$  estimates were averaged to obtain  $q_{\text{heat}}$ .

## Limitations and Assumptions

According to Moret (2007), the Suzuki-Stallman method used in this study does not fully represent all of the factors that contribute to aquifer temperature signals, but in many cases it may represent the system sufficiently well to produce a useful estimate of groundwater flux. Some of the limitations and assumptions with this method are described in this section. A

complete discussion of data limitations associated with use of the Suzuki-Stallman method is found in Moret (2007).

## Range of Applicability

The Suzuki-Stallman method can only be used to estimate flux in regions of the curve where  $a$  and  $b$  vary detectably as a function of specific flux ( $q_s$ ). Figure 5 shows how the values of  $a$  and  $b$  vary as a function of specific flux by using average thermal properties of the aquifer that were determined by Bartolino and Niswonger (1999). The exact limits of detectability depend on the accuracy of the temperature data, the magnitude of the original temperature signal oscillation, and the distance between measuring points, but for the aquifer parameters used in this study, fluxes between  $10^{-3}$  and 1 ft/d should be detectable.

## Flow Direction

The heat-transport equation (Suzuki, 1960) was developed to measure vertical infiltration and assumes that the flux is one-dimensional and calculated along the flow-path. Seepage of water from the Rio Grande into the adjacent aquifer is not one-dimensional. The hydraulic gradients are

primarily horizontal, but vertical gradients do exist. The paired piezometer transects in this study were not oriented directly along the flow-paths of river seepage and  $q_{heat}$  was calculated between pairs of wells along each individual transect. Based on these limitations, the  $q_{heat}$  calculations likely systematically underestimate the flux.

### Aquifer Heterogeneity

The Suzuki equation (1960) assumes a uniform flow field, a condition not met in a heterogeneous aquifer. If temperature signals measured at points with different flow rates are compared, then the estimated fluxes will be incorrect. Moret (2007) advised measuring the temperature at a number of depths in as many observation wells as are available to limit the effect of time series recorded in nonrepresentative locations.

### Variable Recharge

Bartolino and Niswonger (1999) determined that the flux through the riverbed at the Paseo Del Norte site varied by roughly an order of magnitude over the course of the year, but the Suzuki (1960) equation assumes a constant flux. Moret (2007) modeled aquifer temperature by using both variable monthly recharge estimates and a constant annual flux. The two models agreed reasonably well, and Moret (2007) concluded that the Suzuki-Stallman method represents aquifers with annual variations in river recharge reasonably well.

### Spatial Aliasing

The spatial wavelength,  $\lambda$ , of a temperature wave described by equation 7 is defined by:

$$\lambda = \frac{2\pi}{b} \quad (14)$$

As shown on figure 5, fluxes of  $10^{-3}$  and 1 ft/d result from  $b$  values of 0.117 and 0.0132 rad/ft, respectively, and wavelengths of about 54 and 476 ft, respectively. For example, if  $q=10^{-3}$  ft/d, then  $b=0.117$  (from fig. 5) and  $\lambda=2\pi/0.117$ , or 54 ft; if  $q=1$ , then  $b=0.0132$  (from fig. 5), and  $\lambda=2\pi/0.0132$ , or 476 ft. When the wells used to measure temperature are separated by more than one wavelength, the apparent lag between the temperature series will be incorrect. This phenomenon is known as “spatial aliasing.” In this situation,  $b$  will be greatly underestimated. A measured value of  $b$  can be evaluated by plotting it along with the measured  $a$  value for the same time series pair on a plot generated by using equation 9 (for example, fig. 5). If the  $q$  values that correspond to  $a$  and  $b$  do not agree reasonably well, then 1-year increments can be added to the measured lag.

### Surface Temperature Variations

Temperatures in shallow parts of the alluvial aquifer can be affected by the annual variation in the ground-surface temperature. The ground-surface temperature generally is an attenuated version of the atmospheric-temperature signal (Smerdon and others, 2004). Because of the exponential decay of ground-surface temperature signals with depth (Carslaw and Jaeger, 1959), groundwater temperatures measured more than approximately 5 ft below ground surface may not be substantially affected by surface warming (Moret, 2007; Silliman and Booth, 1993).

At the Paseo del Norte site, Bartolino (2003) recorded temperatures at 7 or 10, 13 or 15, 20, 26, and 33 ft below ground surface in eight piezometers installed in an east-west configuration between the riverside drains east and west of the river. In piezometers P06 and P07 from Bartolino’s (2003) dataset, Moret (2007) found no substantial difference between the temperatures recorded at depths of 7 or 10 ft and the temperatures recorded at 13 or 15 ft, indicating that the effect of atmospheric temperature variations is small. There was a 6.5 °F difference in the magnitudes of the temperature waves recorded at 7 and 15 ft in piezometer P08 (Bartolino, 2003). This difference, however, is greater than what would be expected if it was attributable to the atmospheric-temperature effect and is likely due to lower hydraulic conductivity of the sediments at the 7 ft depth than the deeper sediments (Moret, 2007).

### Temperature Dependence of Hydraulic Conductivity

Hydraulic conductivity depends inversely on fluid viscosity and depends directly on fluid density, whereas both viscosity and density depend on temperature. The viscosity of liquid water at 32 °F is twice that of water at 77 °F (Vennard and Street, 1982). Surface-water recharge fluxes can vary substantially with the temperature of the water (Constantz and others, 1994). A fundamental limitation of the Suzuki-Stallman method is that it does not consider the effect of temperature on hydraulic conductivity. Moret (2007) evaluated this limitation by using a two-dimensional finite-element model and concluded that if temperature time-series data appear to be sinusoidal, then the temperature dependence of hydraulic conductivity does not limit the applicability of the Suzuki-Stallman method. For additional details see Moret (2007).

### Uncertainty in Thermal Properties

The thermal properties of the aquifer,  $k$  and  $\rho c$ , are generally not well known, but for aquifers consisting of unconsolidated sediments, the range of  $k$  values reported in the literature is not large (Moret 2007). Moret (2007) found that if site-specific measurements are not readily available, a thermal conductivity chosen based solely on the aquifer’s lithology will introduce an uncertainty into the estimate of  $q_s$  of a few tens of percent. In this study, we used the average of

the four values obtained by Bartolino and Niswonger (1999) for the thermal conductivity ( $2.16 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$ ), and saturated heat capacity ( $3.2 \times 10^6 \text{ J }^\circ\text{C}^{-1} \text{ m}^{-3}$ ) of the upper Santa Fe Group aquifer.

### Data Error

Another possible limitation in the interpretation of temperature oscillations using the Suzuki-Stallman method is uncertainty in the estimation of best fit sinusoids for the observed data series, which would result in uncertainty in  $a$  and  $b$ . Errors in sinusoid fitting are likely to be greatest closer to the source of the surface-water recharge (Moret, 2007).

## Groundwater Hydrology

The hydrologic characteristics of groundwater movement in the study area were examined using slug-test, hydraulic-head, and water-temperature data. Slug-test data from 35 sites were used to determine the hydraulic conductivity of the alluvial aquifer (slug-test archive, files of USGS New Mexico Water Science Center, Albuquerque). Daily mean hydraulic-head data were used to establish groundwater gradients at transect locations, and vertical water-temperature profile data were collected at selected locations to evaluate the depth of penetration of river-water recharge into the aquifer. Finally, a simple conceptual model of groundwater flow away from the river was constructed to demonstrate water-table conditions and characteristics.

### Hydraulic Conductivity

During slug tests, the water-level responses in 16 piezometers were nonoscillatory and were analyzed using the Bouwer and Rice (1976) slug-test analysis method. The water-level responses at 19 piezometers exhibited oscillatory behavior and were analyzed using the Butler (1998) slug-test analysis method. Results from 35 slug tests performed in the alluvial aquifer for this study indicate that the spatial variability of hydraulic properties in the alluvial aquifer is small (fig. 6). Hydraulic-conductivity values ranged from 5 ft/d (I-25 transects) to 160 ft/d (Montaño transects) (table 2). The median hydraulic-conductivity value for all transects was 40 ft/d. Slug-test results from piezometers on the east side of the river were not substantially different from those on the west side.

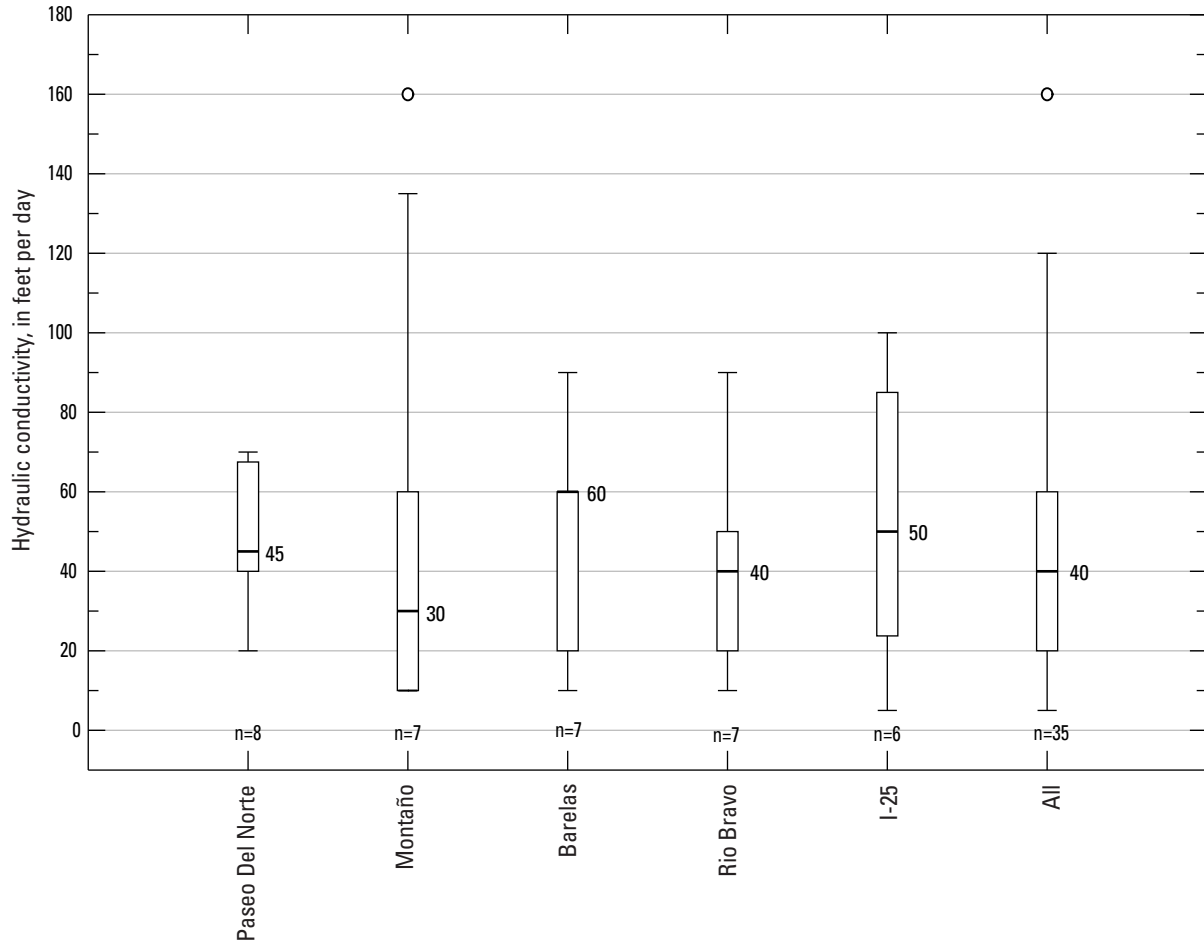
Slug tests performed for this study hydraulically stressed only a limited portion of the aquifer surrounding each piezometer; however, the range of estimated hydraulic conductivities used in previous investigations (10 to 150 ft/d [Kernodle and others, 1995; Tiedeman and others, 1998; and McAda, 2001]) was similar to the range of median hydraulic-conductivity values estimated in this study. Lithologic variability, attributable to complexly interfingering gravels, sands, silts, and clays in the alluvial aquifer, was noted in

cores to occur over distances of a few tens of feet or less. Because coring was performed, in part, so the screened interval of each piezometer was placed in sandy material to ensure communication with the aquifer, the slug-test results provide a measurement of the heterogeneity of sandy zone hydraulic conductivities within the alluvial aquifer but do not provide an overall measurement of the heterogeneity of hydraulic conductivity in the aquifer. Literature-cited values determined from regional-scale modeling (Sanford and others, 2003), aquifer tests (McAda, 2001), and well-to-well heat-transport modeling (Moret, 2007) provide a basis to extrapolate the heterogeneities to the scale of the current study.

### Groundwater Levels and Temperatures

Hourly groundwater-level data were recorded from 164 piezometers screened at different intervals within the alluvial aquifer. Daily mean water levels are shown in figure 7.

Groundwater-level data were used to evaluate water-level trends, measure response to increases or decreases in river stage, and calculate horizontal hydraulic gradients. In the study area, diurnal and seasonal fluctuations in water levels were common, but no substantial upward or downward long-term water-level trends were discernible from 2004 through early 2009 (fig. 7). Groundwater-level responses to stage changes in the river were measurable; water levels in piezometers closest to the river showed a more pronounced response to change in river stage than did piezometers next to or outside the drains. Similar heads typically were measured in the shallow and mid-depth piezometers; however, there were exceptions, most notably at piezometers B16a, b, and c and R4a, b, and c, where clay-rich sediments were observed in sediment cores. Horizontal hydraulic gradients indicated that groundwater movement generally was away from the river and toward the drains (fig. 3, table 3). This direction of groundwater movement makes sense because the riverside drains were designed to extend below the groundwater table, except near the tail ends of the drains where they have to empty back into the river. While drain water levels generally were lower than adjacent groundwater levels, there were instances where the water level in a drain was substantially higher than adjacent groundwater levels. For example, at the Montaño transects, the water level at MS3, near the downstream end of the Corrales Riverside Drain, was more than 5 ft higher than the water levels at M9a and M18a on February 7, 2008 (fig. 3b). The depth of water in the drain at this location was about 3 to 4 ft, so the bottom of the drain probably was also higher than the water table. These data indicate that the hydraulic interaction between the drain and groundwater at this location is minimal; this condition is likely to persist from one year to the next. In February, 2009, discharge was measured along this portion of the Corrales Riverside Drain as part of the seepage investigation. Measurements made between drain miles 4 and 6 (fig. 1) of 3.0 and 2.6 ft<sup>3</sup>/s, respectively, demonstrated that the drain was losing water to the aquifer.



**EXPLANATION**

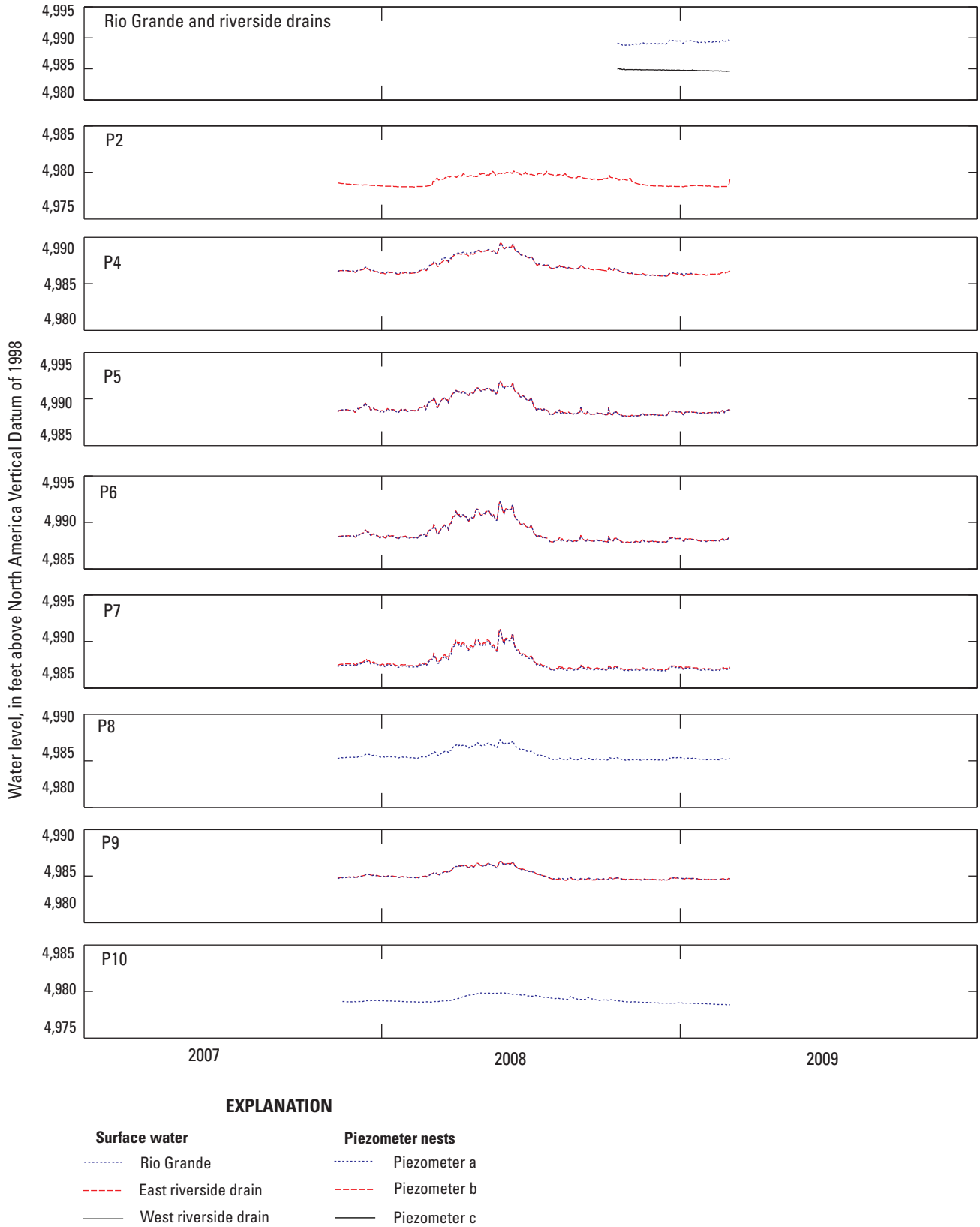
- outlier (value is between 1.5 and 2 times the interquartile range)
- 1.5 times the interquartile range or the largest value
- 75th percentile
- 40 median (50th percentile) and median value
- 25th percentile
- -1.5 times the interquartile range or the smallest value
- n=35 number of values

**Figure 6.** Summary of hydraulic conductivities estimated from slug tests conducted at selected locations in the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico.

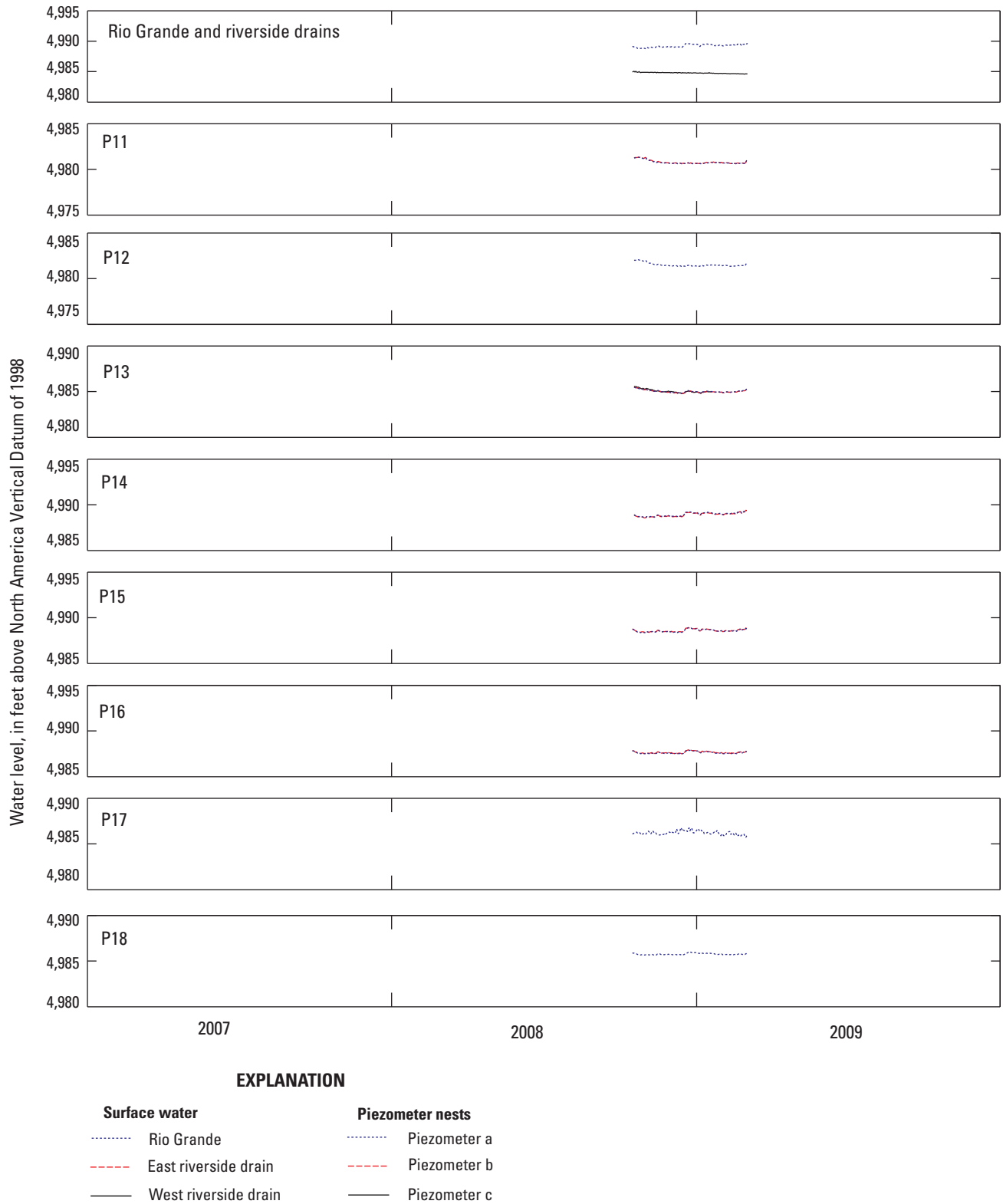
**Table 2.** Summary of Bouwer and Rice (1976) and Butler (1998) slug-test results from piezometers in the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico.

[B, Barelás; I, I-25; M, Montaña; P, Paseo del Norte; R, Rio Bravo; a, shallow piezometer; b, mid-depth piezometer; c, deep piezometer; nd, not determined]

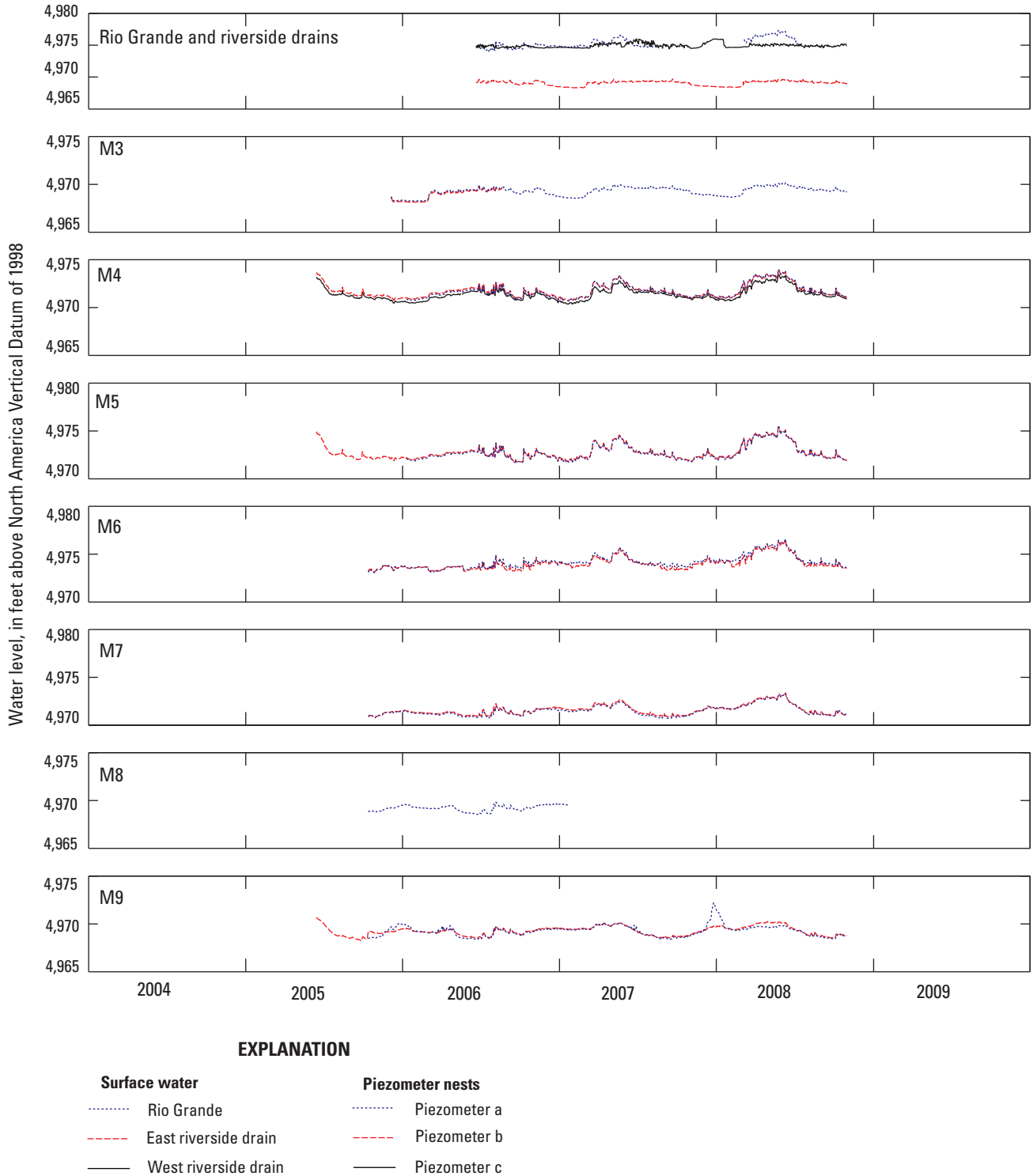
Site identifier	Other Identifier (figs. 3a-e)	Test date	Slug test hydraulic conductivity (feet per day)	Method of analysis	Piezometer depth (feet)	Screened interval (feet)	Dominant lithology of screened interval	Water level (feet below land surface)
351054106390101	P4a	2/2/2009	50	B&R (1976)	16	6-11	silty sand	6.81
351054106390102	P4b	2/2/2009	40	Butler (1998)	35	25-30	silty sand	7.47
351054106390401	P5a	2/2/2009	40	B&R (1976)	16	6-11	silty sand	4.95
351054106390402	P5b	2/2/2009	40	Butler (1998)	35	25-30	silty sand	5.08
351055106391101	P6a	1/30/2009	70	Butler (1998)	16	6-11	nd	4.03
351055106391102	P6b	1/30/2009	20	B&R (1976)	31	21-26	nd	4.10
351054106391301	P7a	1/30/2009	60	B&R (1976)	16	6-11	sand	6.17
351054106391302	P7b	1/30/2009	70	Butler (1998)	31	21-26	sand	6.08
350842106403101	M4a	1/28/2009	30	B&R (1976)	15	5-10	sand	7.70
350842106403102	M4b	1/28/2009	160	Butler (1998)	30	20-25	silty sand	7.80
350842106403201	M5a	1/28/2009	20	B&R (1976)	15	5-10	nd	5.79
350842106403202	M5b	1/28/2009	60	Butler (1998)	32	22-27	clayey sand	6.40
350848106404703	M6a	1/28/2009	30	B&R (1976)	13	3-8	nd	7.35
350848106404704	M6b	1/28/2009	10	B&R (1976)	28	18-23	nd	5.42
350848106404702	M7b	1/28/2009	10	B&R (1976)	30	20-25	sand	6.71
350402106392601	B4a	1/30/2009	20	B&R (1976)	16	6-11	sand	5.27
350402106392602	B4b	1/30/2009	10	B&R (1976)	31	21-26	silty sand	5.79
350402106392902	B5b	1/30/2009	60	Butler (1998)	30	20-25	silty sand	3.98
350400106393701	B6a	1/30/2009	60	Butler (1998)	17	7-12	nd	4.53
350400106393702	B6b	1/30/2009	90	Butler (1998)	32	22-27	silty sand	4.84
350359106393901	B7a	1/30/2009	60	Butler (1998)	17	7-12	silty sand	6.42
350359106393902	B7b	1/30/2009	50	Butler (1998)	32	22-27	silty sand	6.46
350143106402401	R6a	1/29/2009	50	B&R (1976)	15	5-10	silty sand	2.81
350143106402402	R6b	1/29/2009	50	Butler (1998)	34	24-29	silty sand	3.05
350143106402503	R7a	1/29/2009	30	B&R (1976)	15	5-10	silty sand	3.35
350143106402501	R7b	1/29/2009	20	B&R (1976)	35	25-30	silty sand	4.31
350144106401101	R13a	2/6/2009	10	Butler (1998)	15	5-10	silty sand	3.98
350144106401102	R13b	2/6/2009	90	Butler (1998)	30	20-25	silty sand	4.02
350144106401103	R13c	2/6/2009	40	Butler (1998)	56	46-51	sand gravel	4.19
345701106404501	I4a	1/29/2009	30	B&R (1976)	14	4-9	silty sand	3.81
345701106404502	I4b	1/29/2009	60	Butler (1998)	29	19-24	sand	4.52
345701106404601	I5a	1/29/2009	5	B&R (1976)	14	4-9	nd	4.18
345701106404602	I5b	1/29/2009	80	Butler (1998)	29	19-24	nd	4.76
345707106410102	I6b	1/29/2009	100	Butler (1998)	29	19-24	silty sand	4.38
345706106410202	I7b	1/29/2009	40	Butler (1998)	29	19-24	silty sand	4.41



**Figure 7a.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Paseo Del Norte transect 1, November 7, 2007-March 4, 2009. Piezometer locations are shown on figure 3a.

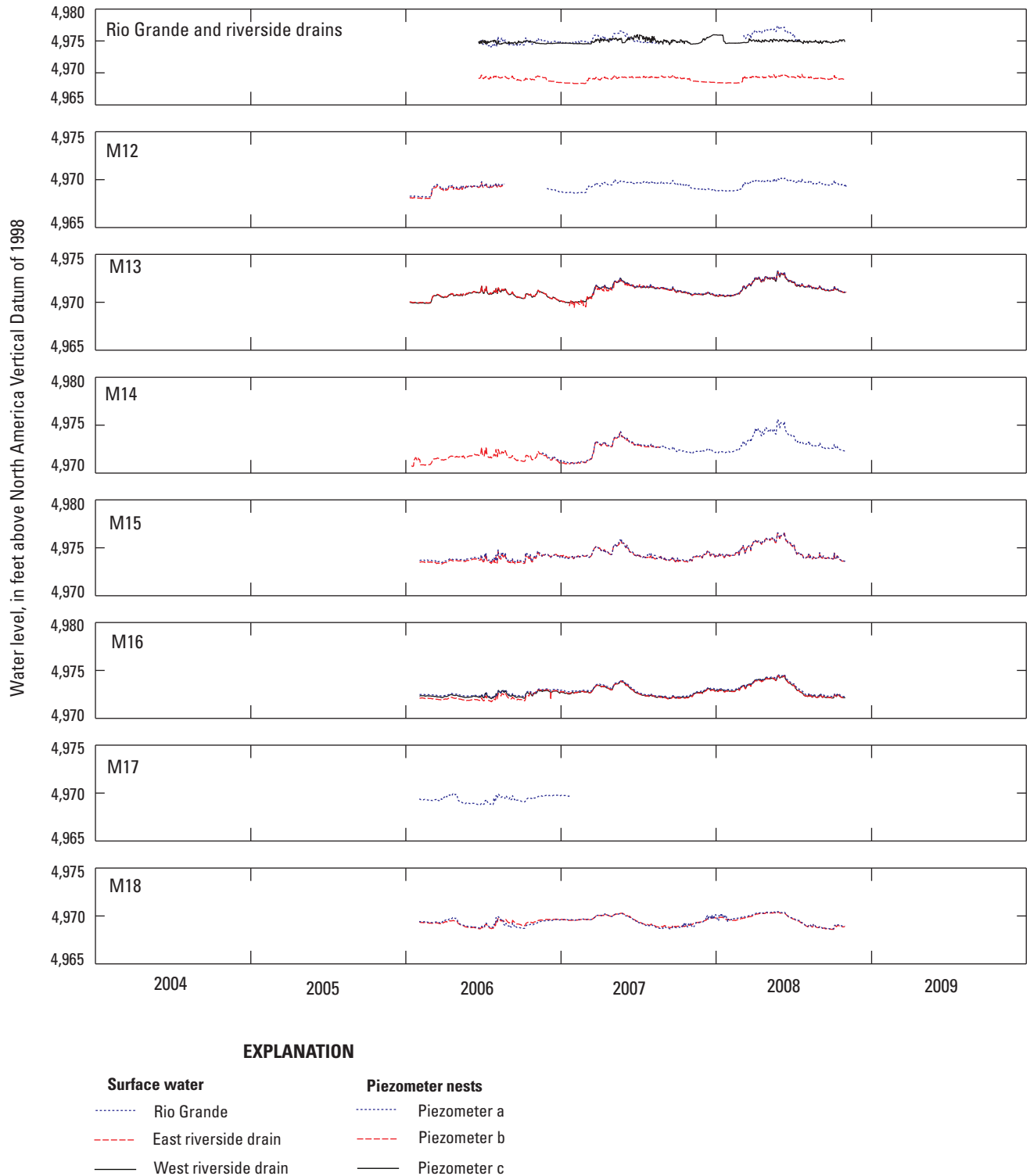


**Figure 7b.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Paseo del Norte transect 2, October 15, 2008-March 4, 2009. Piezometer locations are shown in figure 3a.

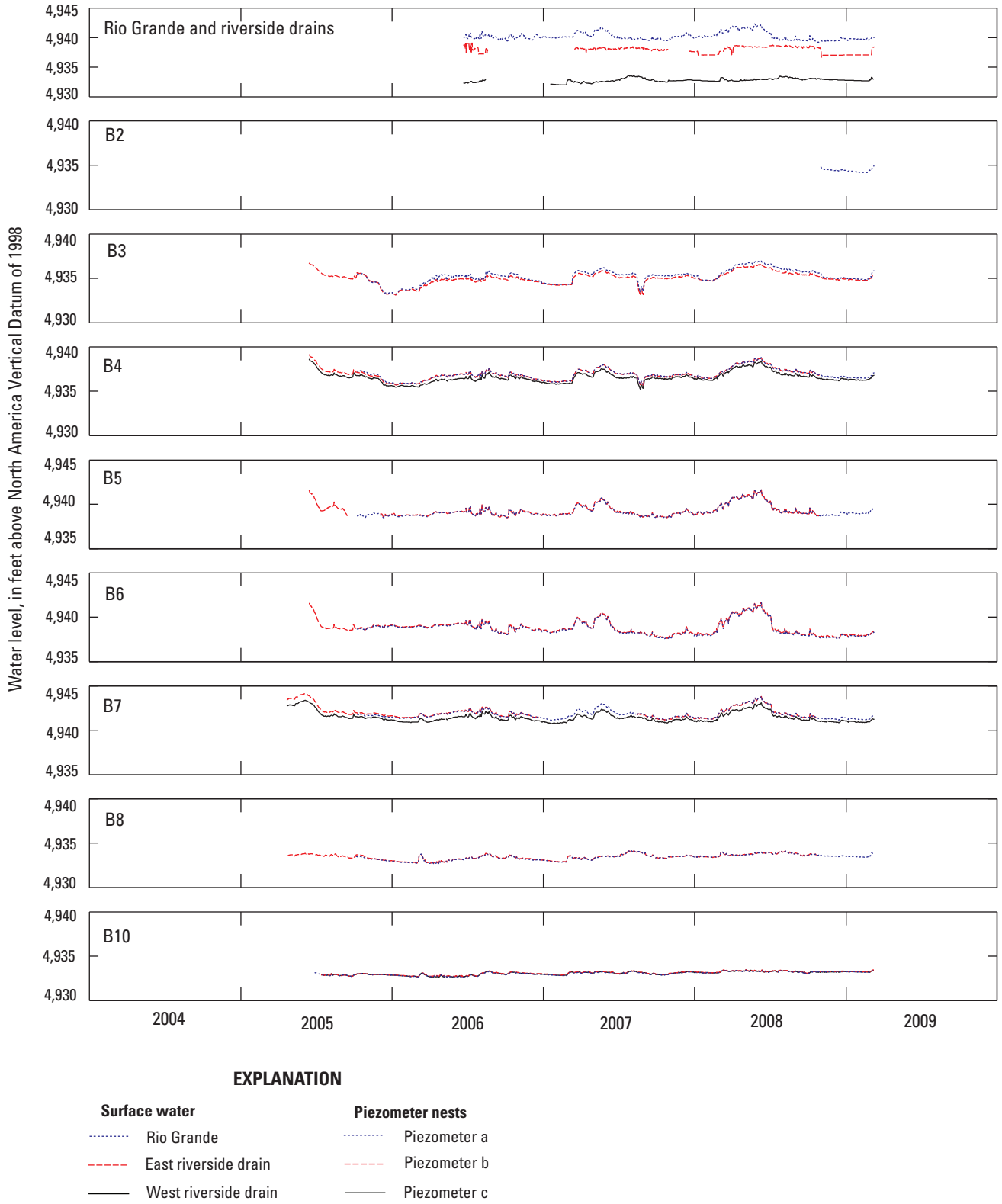


**Figure 7c.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Montaña transect 1, June 13, 2005–October 31, 2008. Piezometer locations are shown in figure 3b.

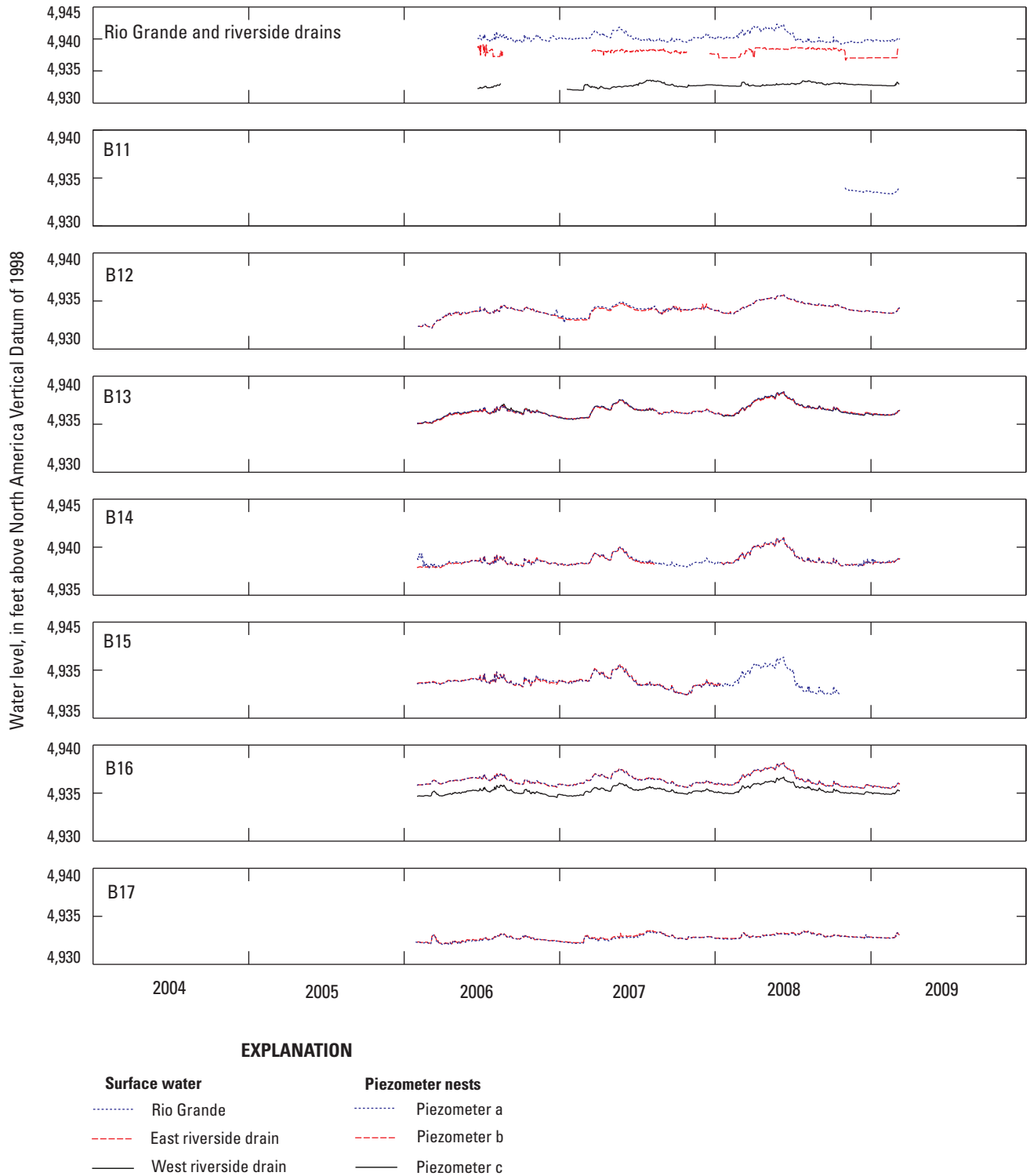




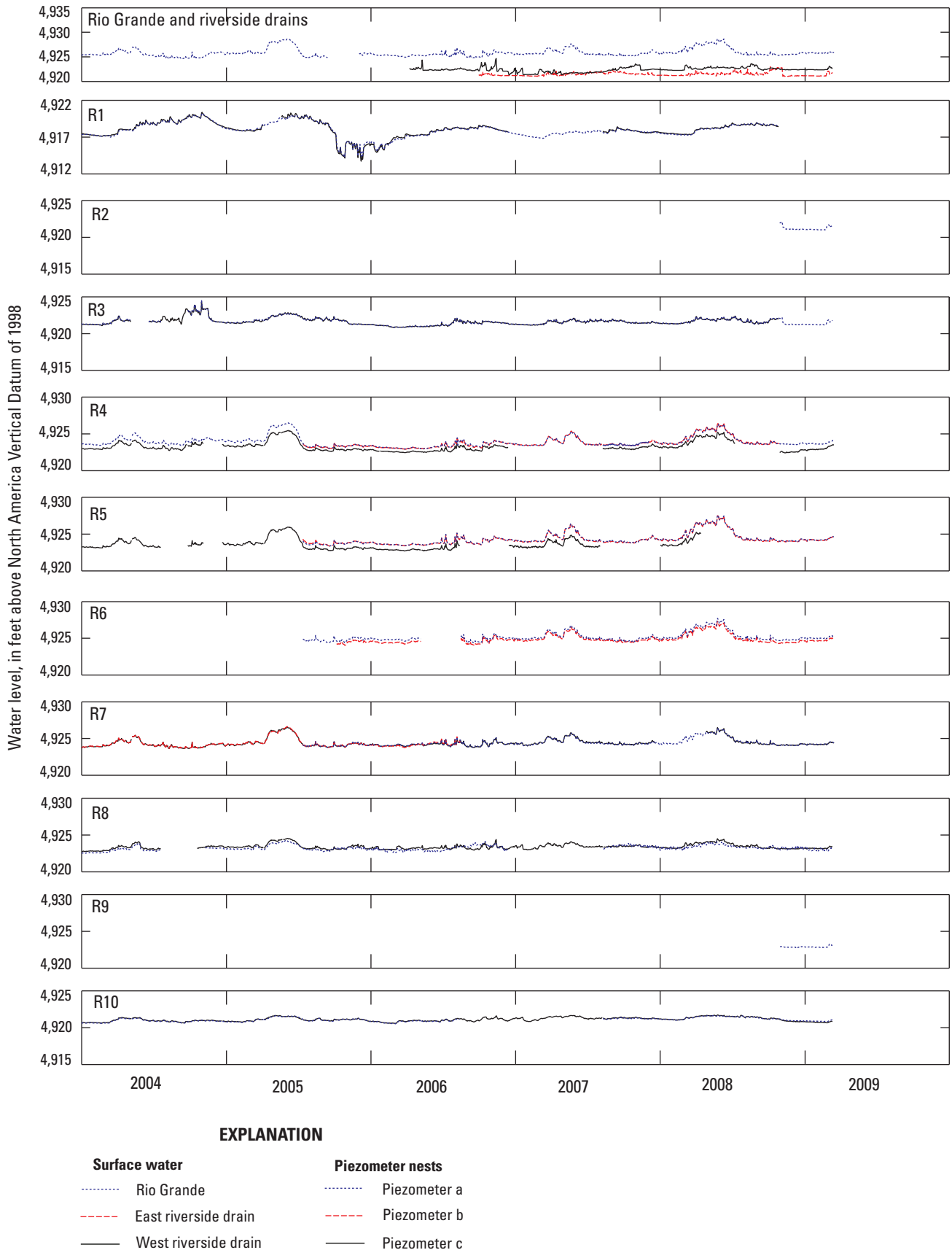
**Figure 7d.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Montaña transect 2, January 9, 2006–October 31, 2008. Piezometer locations are shown in figure 3b.



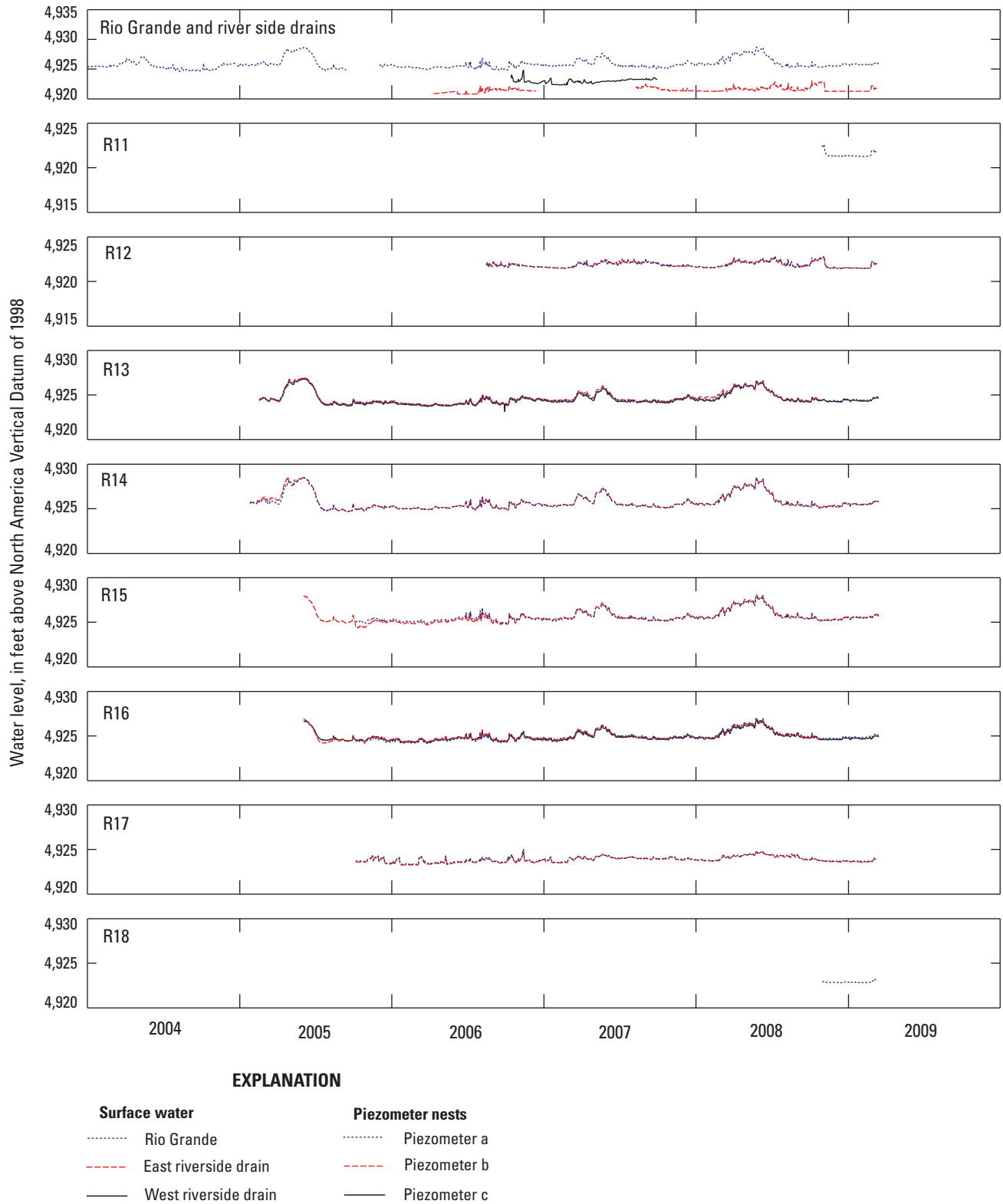
**Figure 7e.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Bareltras transect 1, April 21, 2005-March 10, 2009. Piezometer locations are shown in figure 3c.



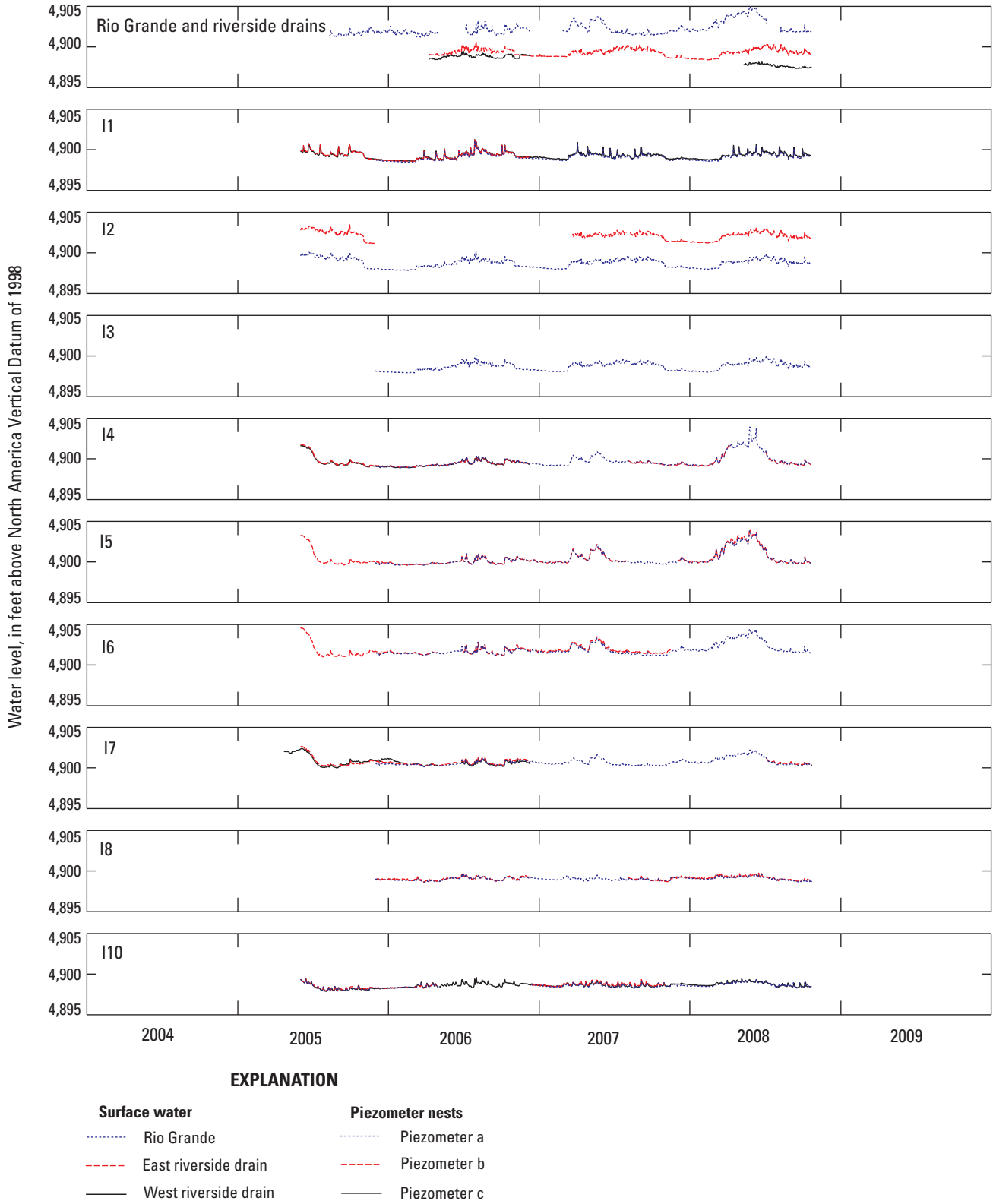
**Figure 7f.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Barelás transect 2, January 27, 2006-March 10, 2009. Piezometer locations are shown in figure 3c.



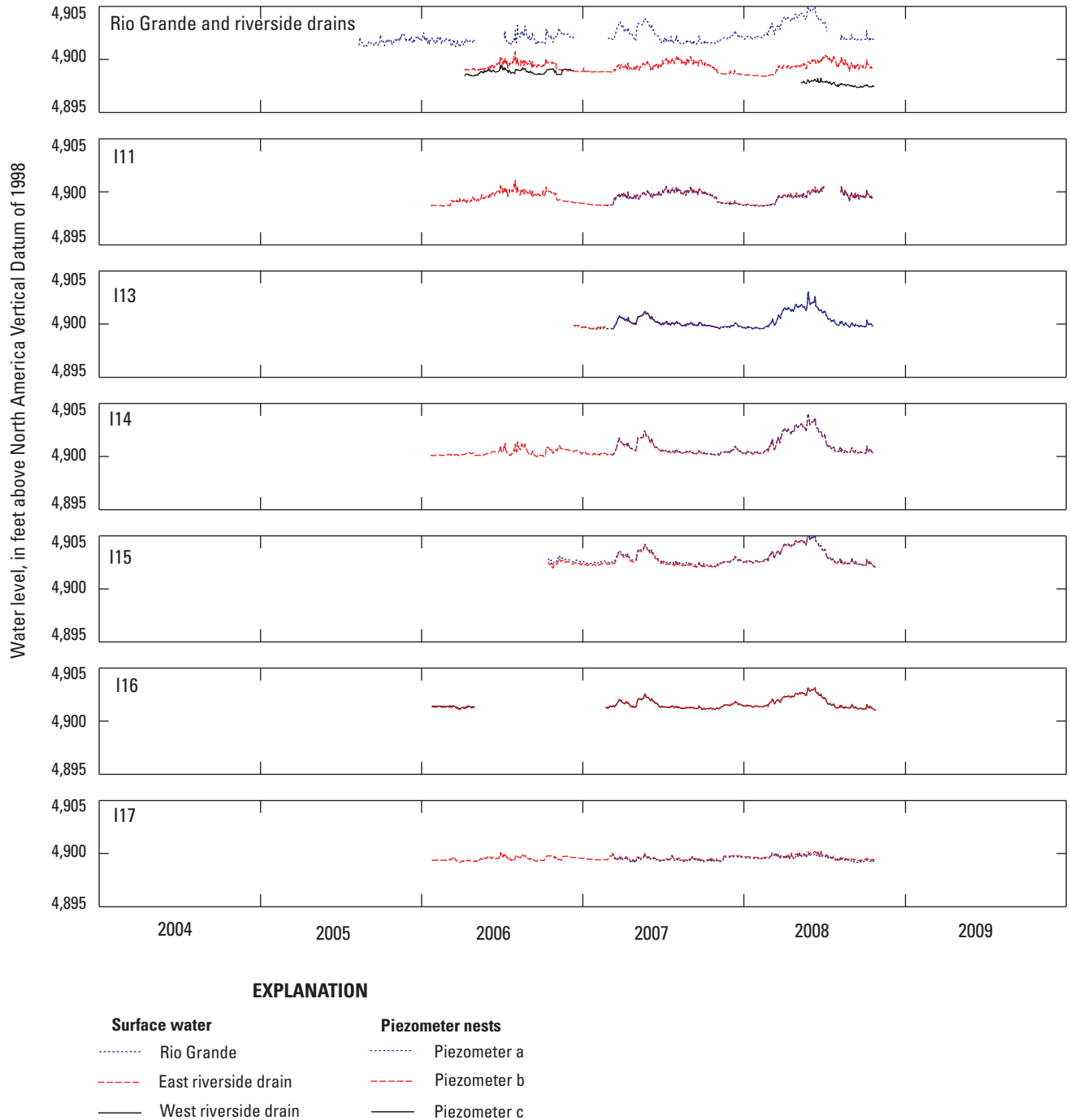
**Figure 7g.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Rio Bravo transect 1, January 1, 2004-March 15, 2009. Piezometer locations are shown in figure 3d.



**Figure 7h.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at Rio Bravo transect 2, January 1, 2004-March 15, 2009. Piezometer locations are shown in figure 3d.



**Figure 7i.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at I-25 transect 1, April 22, 2005-October 24, 2008. Piezometer locations are shown in figure 3e.



**Figure 7j.** Hydrographs showing daily mean stage of the Rio Grande and riverside drains and daily mean groundwater levels in piezometers at I-25 transect 2, August 10, 2005-October 27, 2008. Piezometer locations are shown in figure 3e.

**Table 3.** Median annual magnitude of groundwater horizontal hydraulic gradient and direction of groundwater flow at piezometer transects, Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico, 2006-9.

[Site locations shown in figs. 3a-e; CW, clockwise from downstream direction of channel; CCW, counter clockwise from downstream direction of channel. Groundwater flow direction is relative to the downstream direction of the Rio Grande channel at each transect.]

Transect location	Median annual horizontal hydraulic gradient (feet per foot)	Direction of groundwater flow (degrees)
Paseo Del Norte		
East	0.010	89 CCW
West	.005	78 CW
Montaño		
East	.010	89 CCW
West	.003	77 CW
Barelas		
East	.009	87 CCW
West	.011	77 CW
Rio Bravo		
East	.005	73 CCW
West	.007	76 CW
I-25		
East	.002	71 CCW
West	.005	68 CW

The effect of this loss of water from the drain was not evident in the February 7, 2008 groundwater-level data and so is not reflected in the water-level contours (fig. 3b). At the Barelas transects, the water level at BS1 in the Albuquerque Riverside Drain was more than 2 ft higher than the water levels in piezometers B3a and B12a on February 7, 2008 (fig. 3c). These water-level differences are attributable to a point of diversion structure in the drain about 900 ft downstream from B12a that obstructs flow and elevates the water level in the drain so that the water level in the drain upstream from the diversion was substantially higher than downstream from the structure.

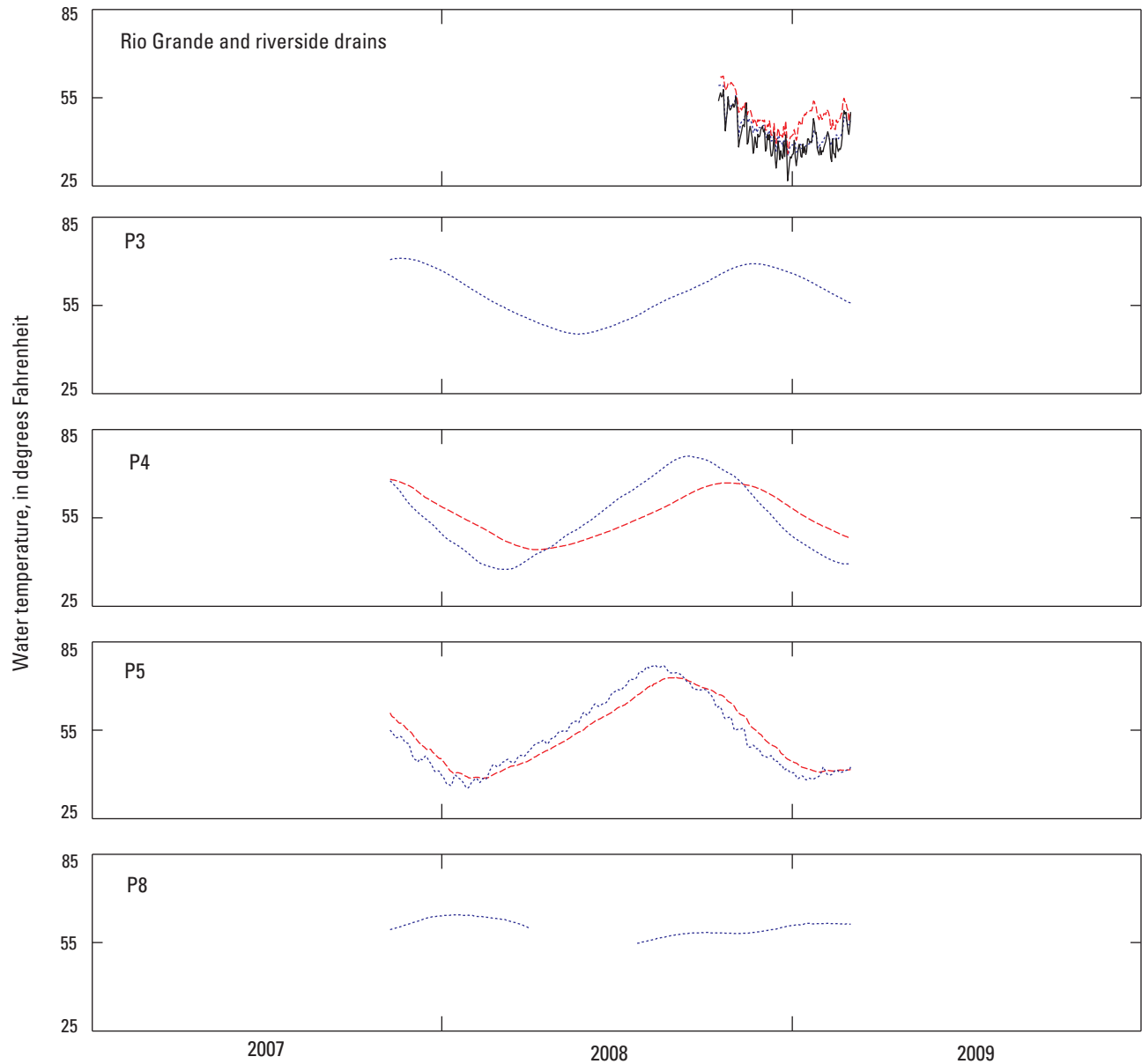
Hourly groundwater temperatures were recorded at depths of 10 and 20 ft in selected piezometer nests. Daily mean water temperature for all measurement points are shown in figures 8a-8j. Large ranges in surface-water temperature are apparent: surface-water temperatures ranged from 37°F in the winter to 79°F in the summer. Surface-water temperatures in the drains typically were similar to temperatures measured in the Rio Grande, but the magnitude of fluctuations in the river were somewhat larger. Maximum and minimum water temperatures in piezometers generally indicate a decrease

in amplitude and an increase in time lag of the temperature signal with increasing depth and distance from the river. High frequency temperature fluctuations of a few degrees in shallow piezometers installed adjacent to the river rapidly dissipated with depth or distance from the river. For example, the high frequency temperature fluctuations that are evident in piezometer P5a, next to the river, are not evident in piezometers P4a and P3a (fig. 8a), which are farther away from the river (fig. 3a). The high-frequency fluctuations were not recorded in mid-depth piezometers or shallow piezometers located greater than a few hundred feet from the river. For example, short-term temperature variations recorded in M15a, a shallow piezometer adjacent to the river, are substantially attenuated in M15b, an intermediate-depth piezometer a few feet from M15a, and are not evident in M16b, 400 to 500 ft to the west of M15a (fig. 8d).

Vertical temperature profiles were collected during the months of October 2008 and January and February 2009 in the deepest piezometer at selected piezometer nests during the nonirrigation season (fig. 9). Temperature-profile data were collected to evaluate the depth of the alluvial aquifer that is influenced by leakage from the river. Temperatures were recorded at 5-ft intervals from about 0.5 ft below the water surface to the bottom of each piezometer. Although piezometers were constructed with a screened interval of 5 ft near the bottom of the piezometer, the temperature of water in blank (nonscreened) casing was assumed to be the same as the temperature of water outside the casing. Groundwater-temperature profiles in figure 9 form envelopes that generally are bracketed by warmest temperatures in October and coolest temperatures in February. Groundwater temperatures recorded throughout the nonirrigation season were most variable at depths less than 30 ft and generally ranged from 40 to 70°F.

Temperature envelopes in figure 9 generally can be classified as fan- or tulip-shaped depending on the direction and velocity of groundwater flow. At M7, M9, R3, R8, I3, I4, and I5 the fan-shape of the temperature envelope shows the seasonal temperature extinction depth (the depth at which seasonal temperature variations are not observed) during the nonirrigation season ranges from 20 to 30 ft. The temperature ranges near the water table in these fan-shaped envelopes generally were 20°F or less for the period between October 2008 and February 2009. The compressed nature of fan-shaped temperature envelopes is indicative of areas where (1) vertical groundwater flow is limited, and (2) horizontal advective transport of heat is relatively uniform. At the remaining piezometer nests, temperature ranges near the water table generally were greater than 20°F for the period between October 2008 and February 2009. These temperature envelopes generally are more tulip-like in shape with seasonal temperature extinction depths below the depths of observation and broad changes in temperature throughout the depths of observation. Temperature inflections with depth in tulip-shaped temperature envelopes show sharp changes in heat fluxes associated with heterogeneous groundwater-flow patterns (Constantz and others, 2003).

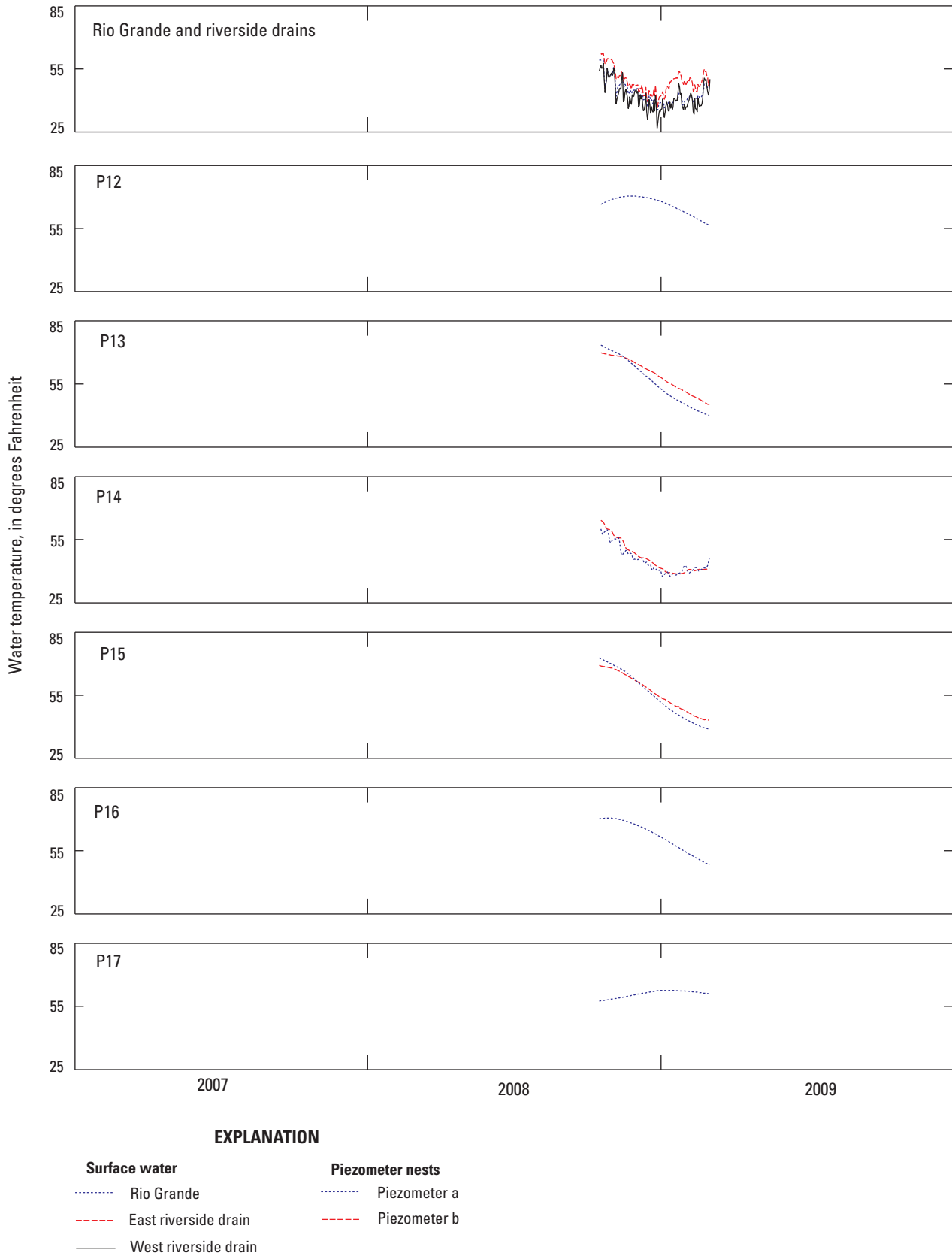




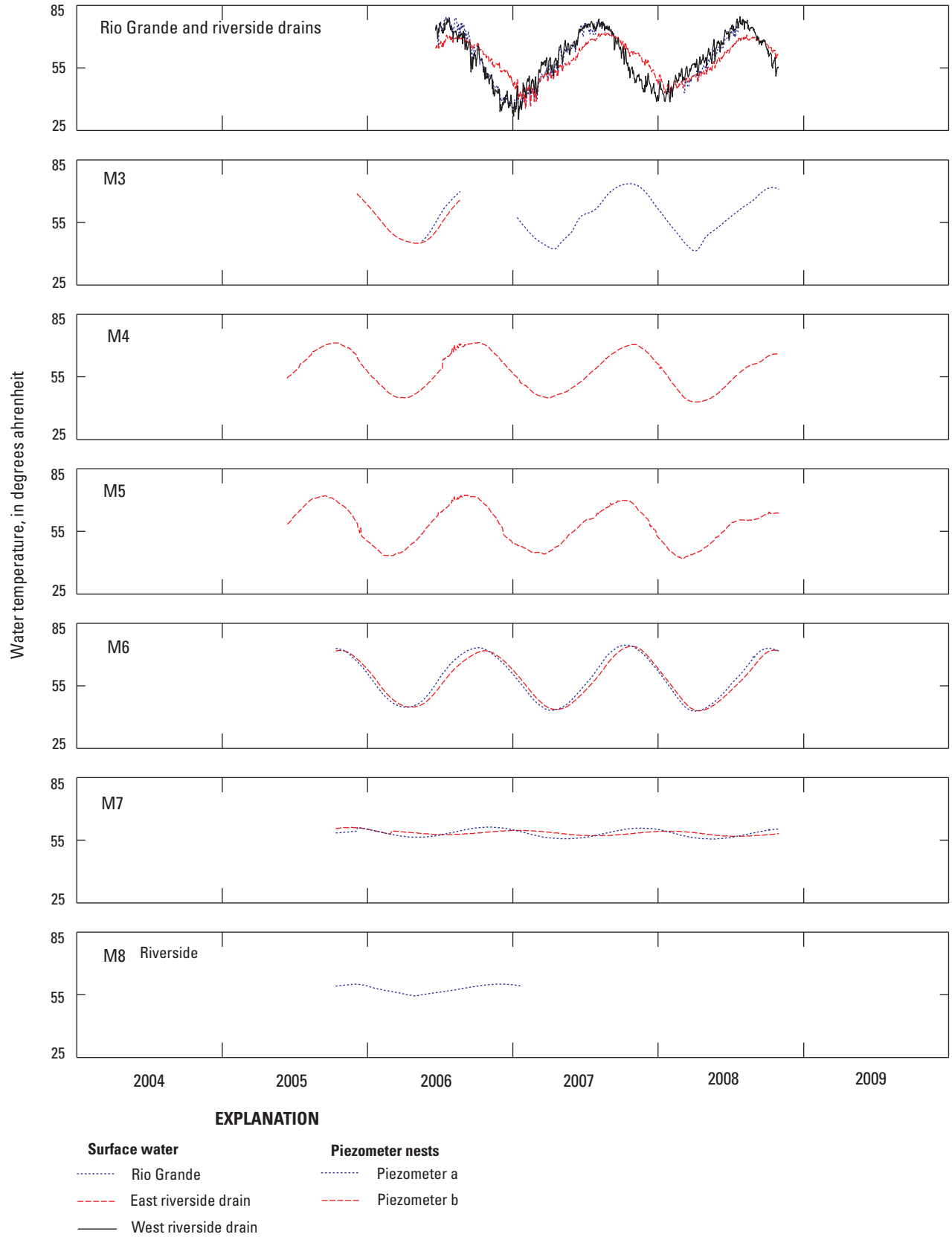
**EXPLANATION**

- |                      |                      |                         |              |
|----------------------|----------------------|-------------------------|--------------|
| <b>Surface water</b> |                      | <b>Piezometer nests</b> |              |
| .....                | Rio Grande           | .....                   | Piezometer a |
| -----                | East riverside drain | -----                   | Piezometer b |
| _____                | West riverside drain |                         |              |

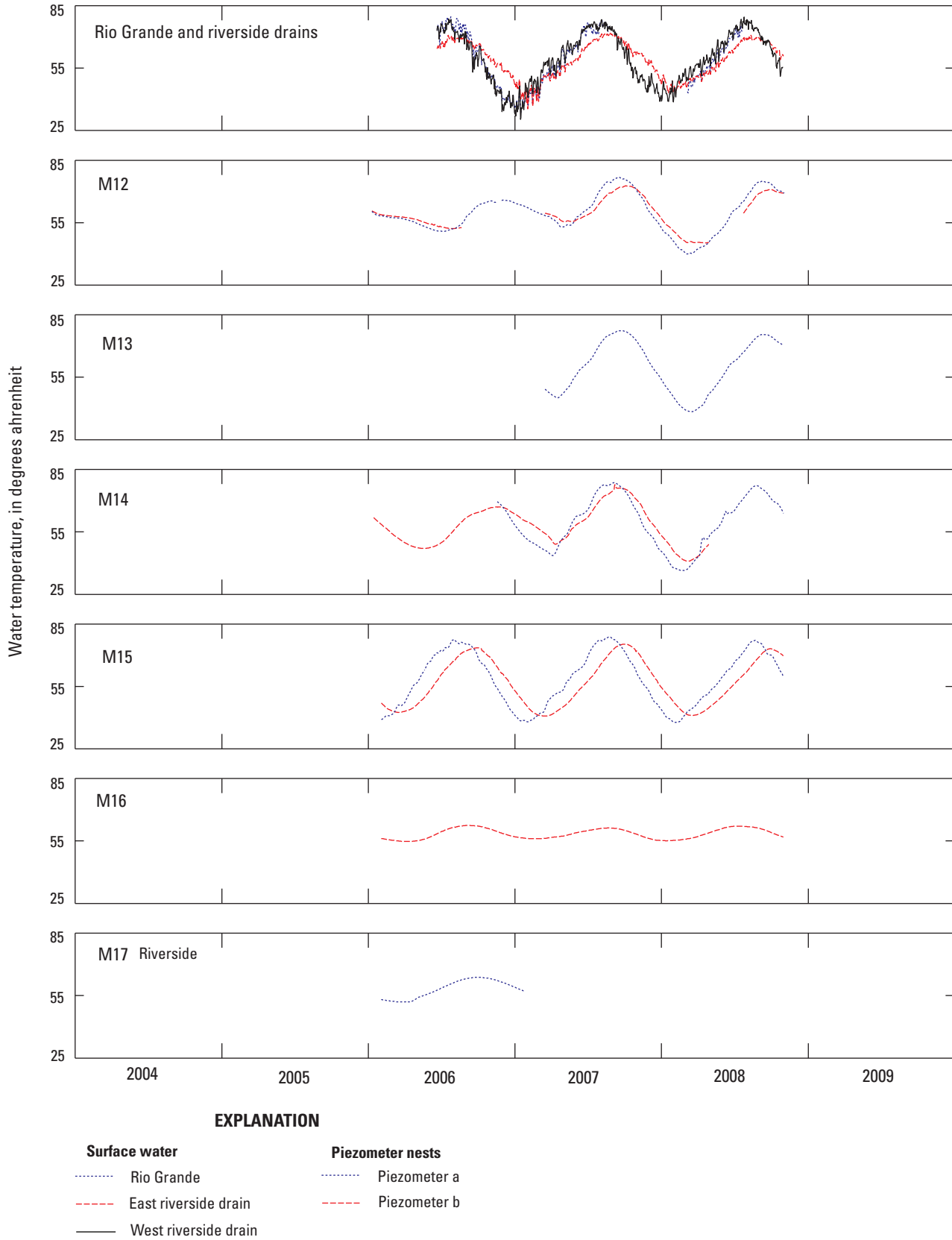
**Figure 8a.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Paseo del Norte transect 1, November 7, 2007-March 4, 2009. Piezometer locations are shown on figure 3a.



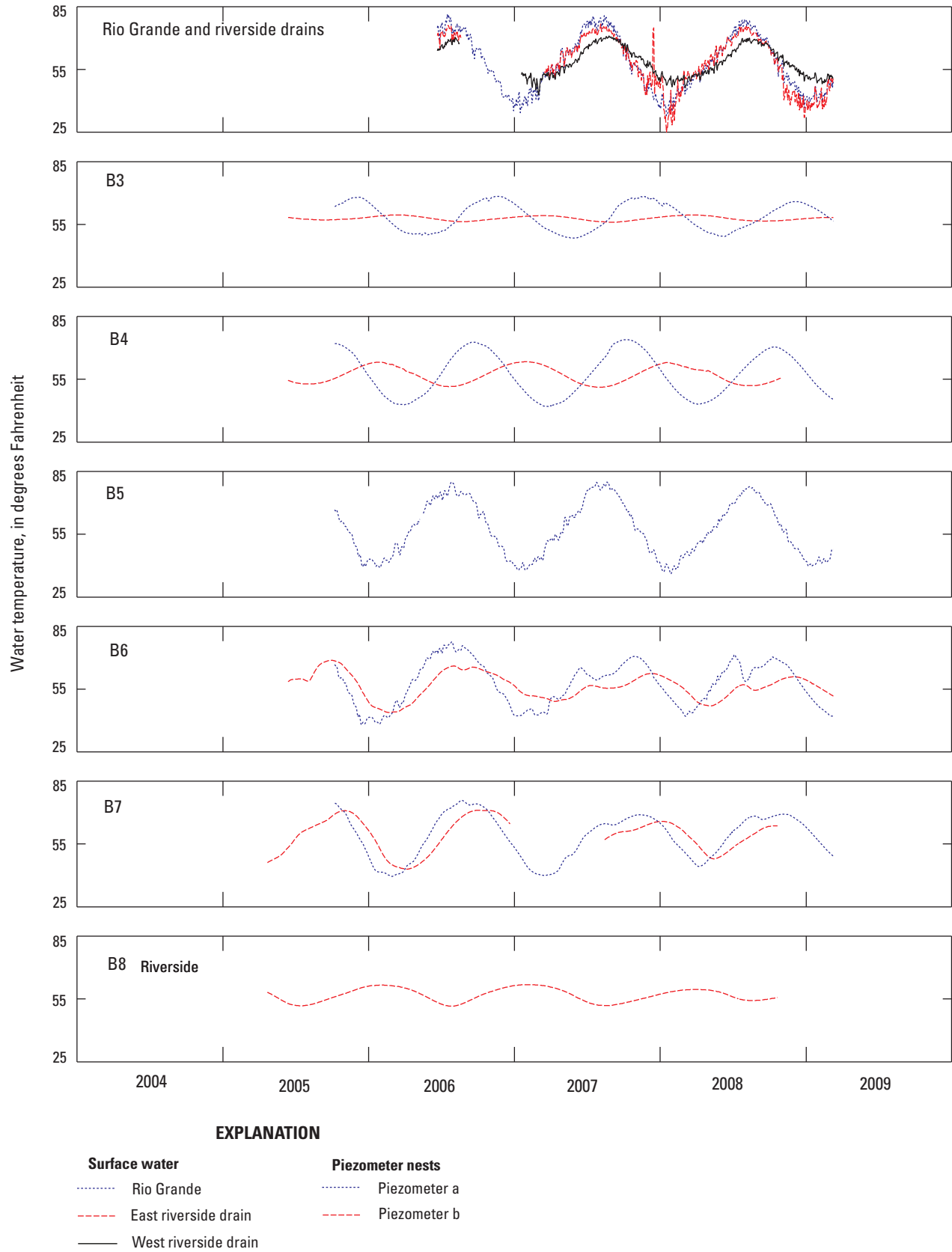
**Figure 8b.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Paseo Del Norte transect 2, October 15, 2007-March 4, 2009. Piezometer locations are shown on figure 3a.



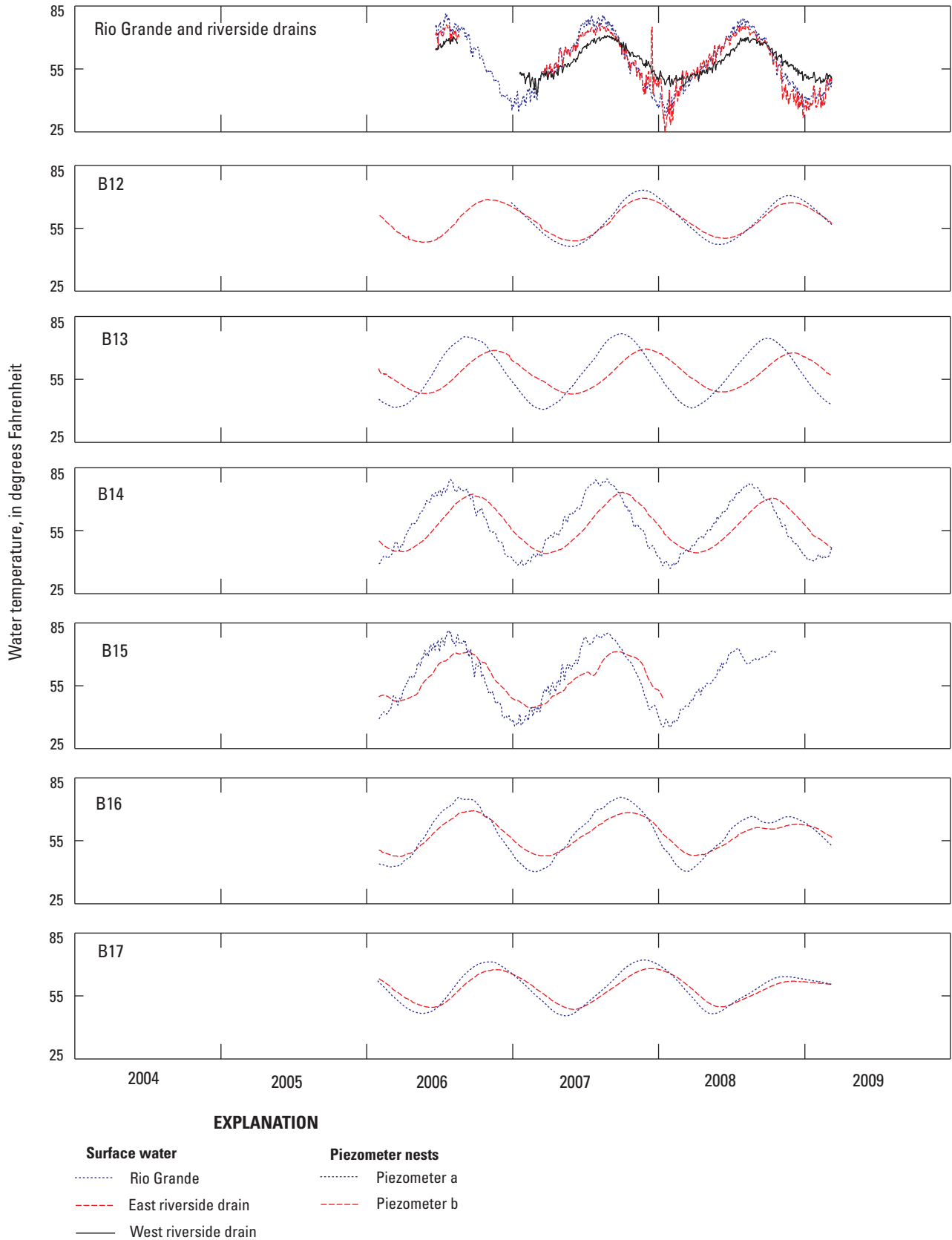
**Figure 8c.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Montaño transect 1, June 13, 2005–October 31, 2008. Piezometer locations are shown on figure 3b.



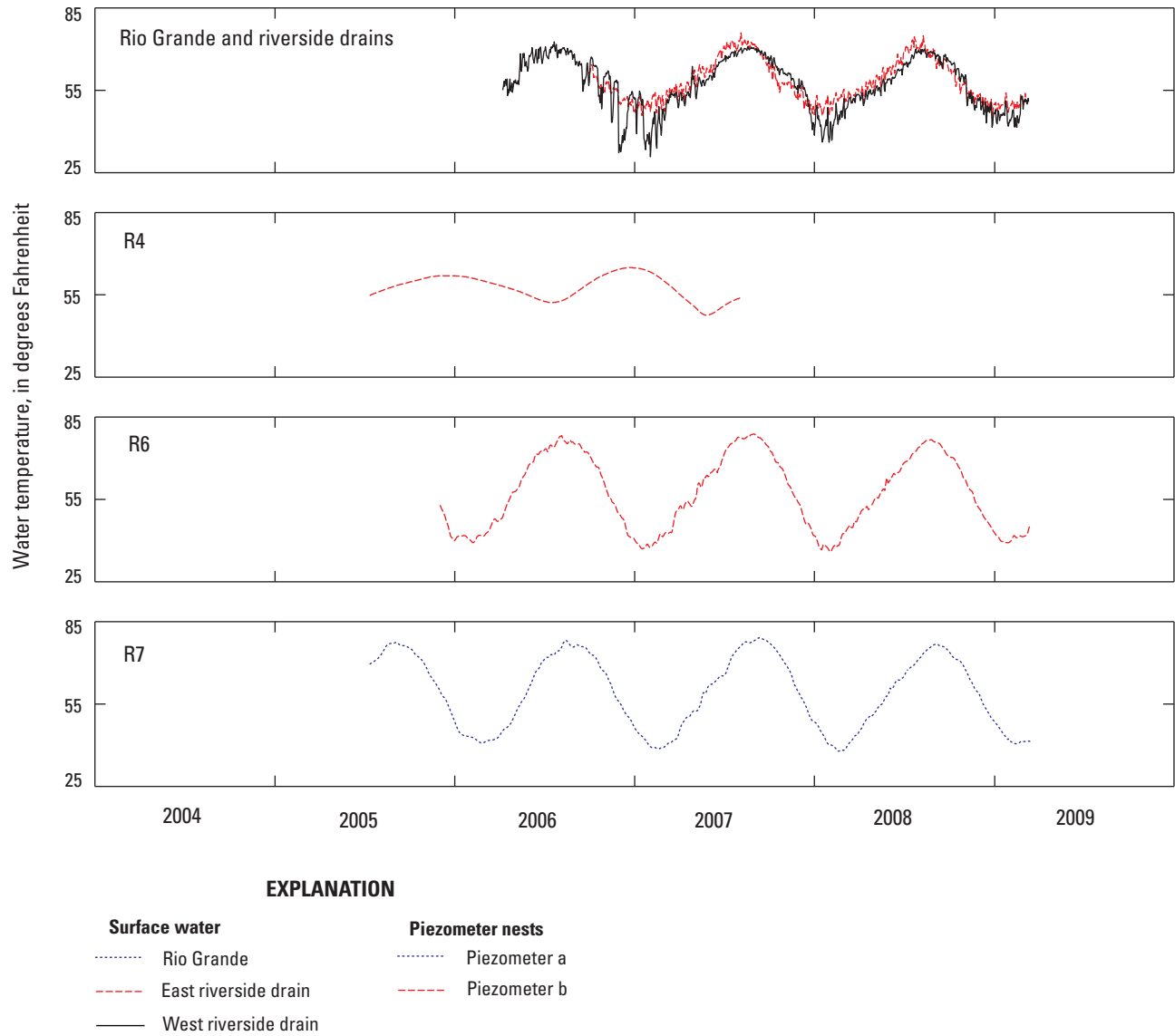
**Figure 8d.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Montaño transect 2, January 9, 2006–October 31, 2008. Piezometer locations are shown on figure 3b.



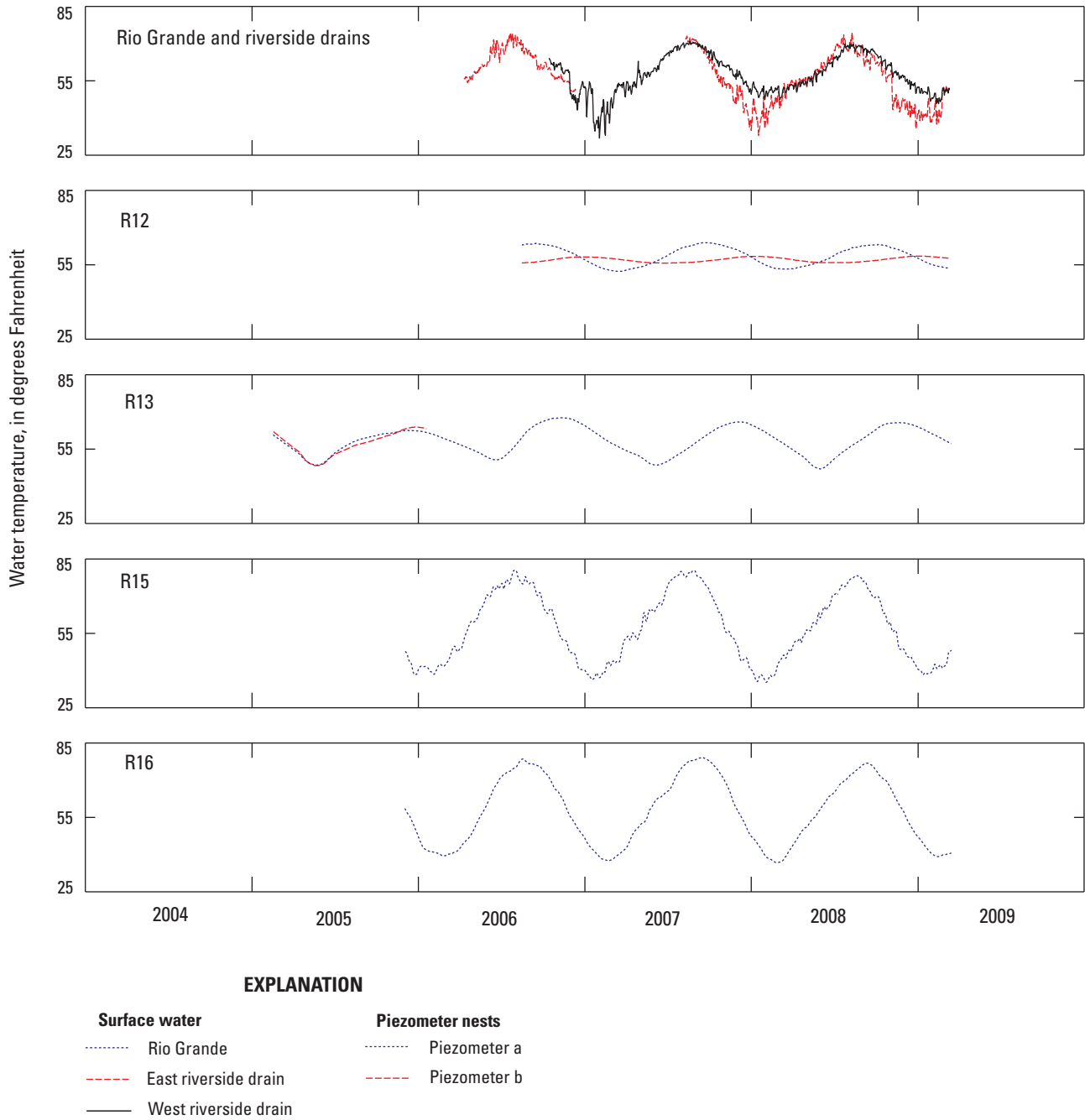
**Figure 8e.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Barelás transect 1, April 21, 2005-March 10, 2009. Piezometer locations are shown on figure 3c.



**Figure 8f.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Bareltras transect 2, January 27, 2006-March 10, 2009. Piezometer locations are shown on figure 3c.

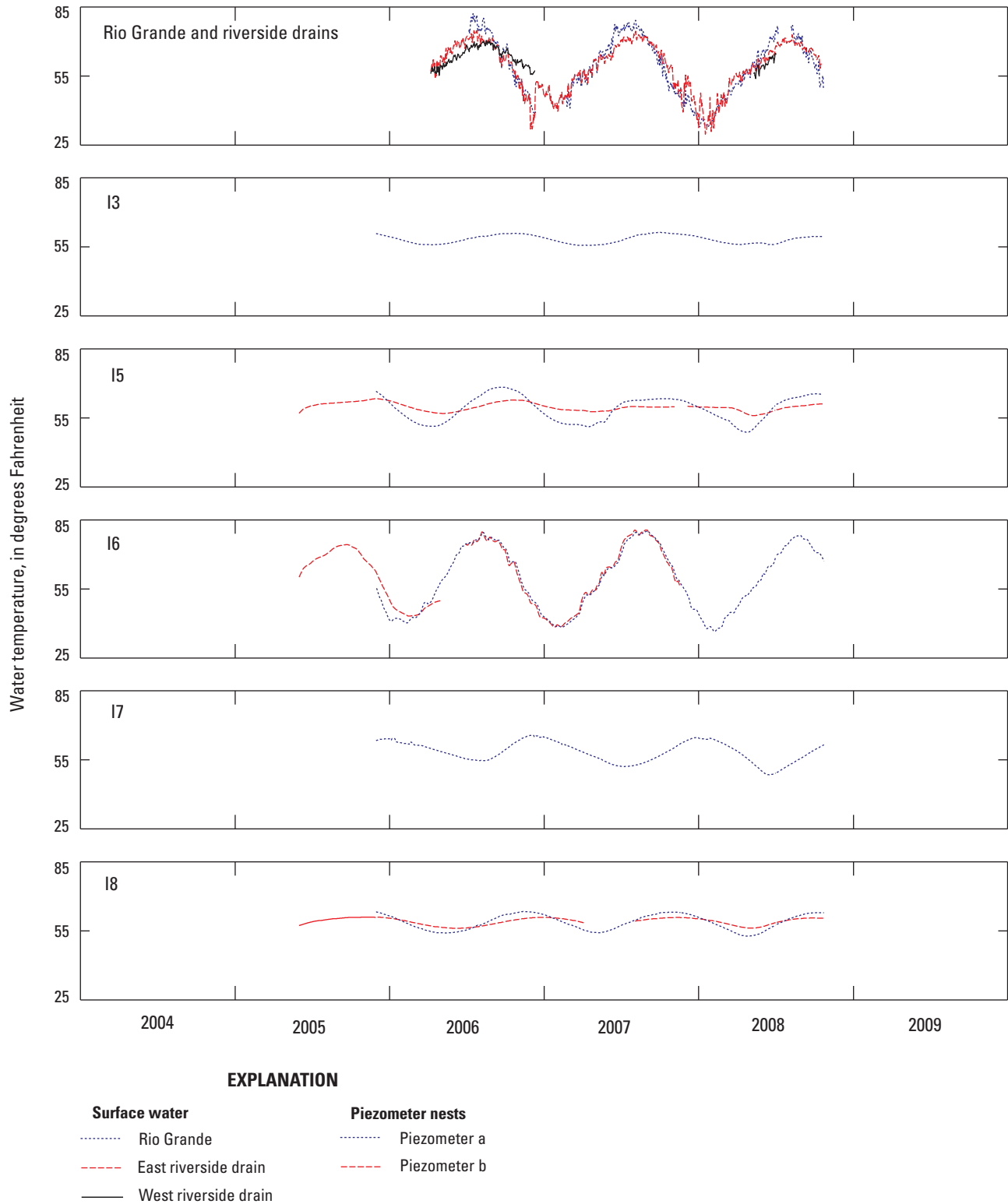


**Figure 8g.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Rio Bravo transect 1, June 3, 2005-March 15, 2009. Piezometer locations are shown on figure 3d.

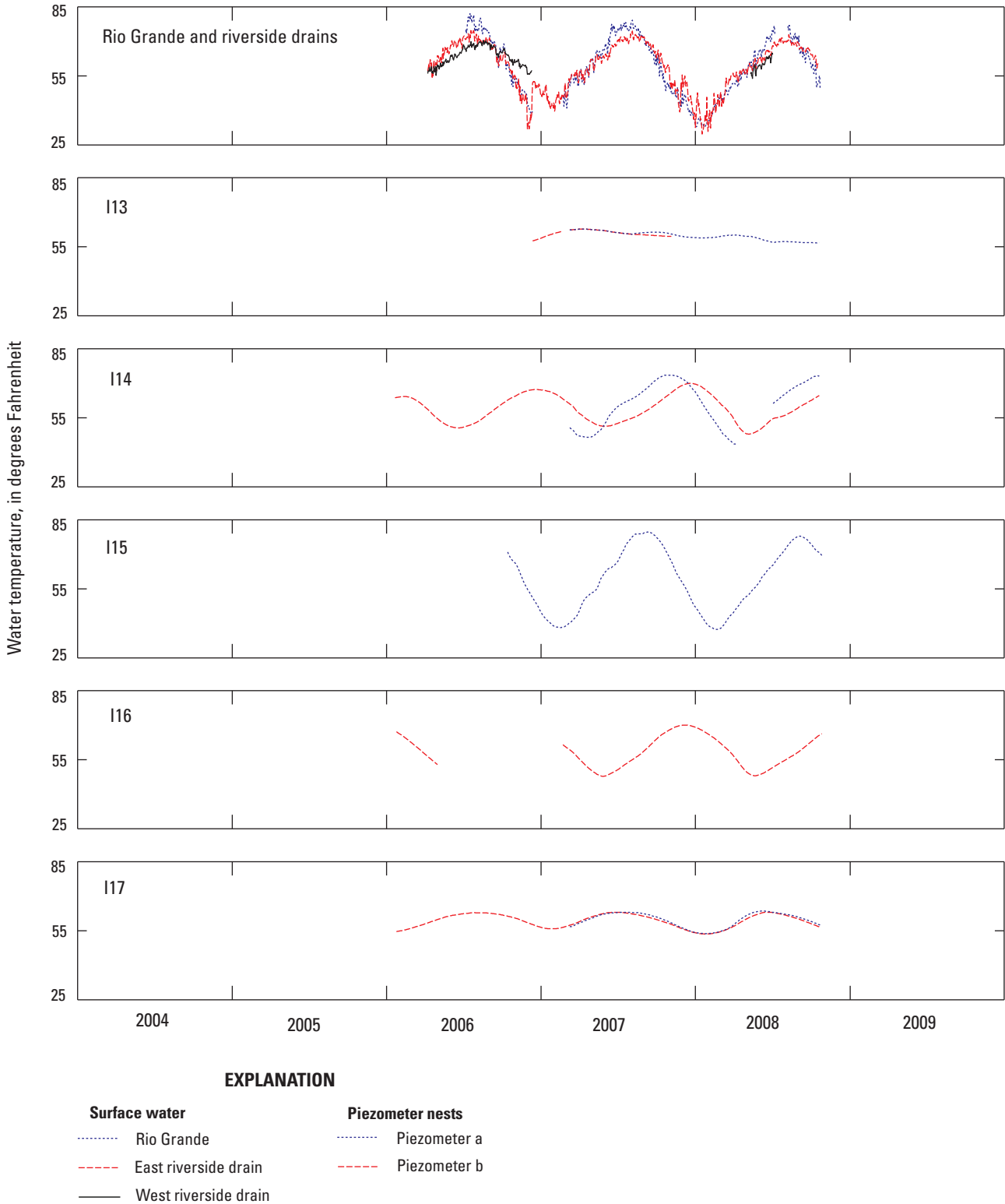


**Figure 8h.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at Rio Bravo transect 2, February 16, 2005-March 15, 2009. Piezometer locations are shown on figure 3d.

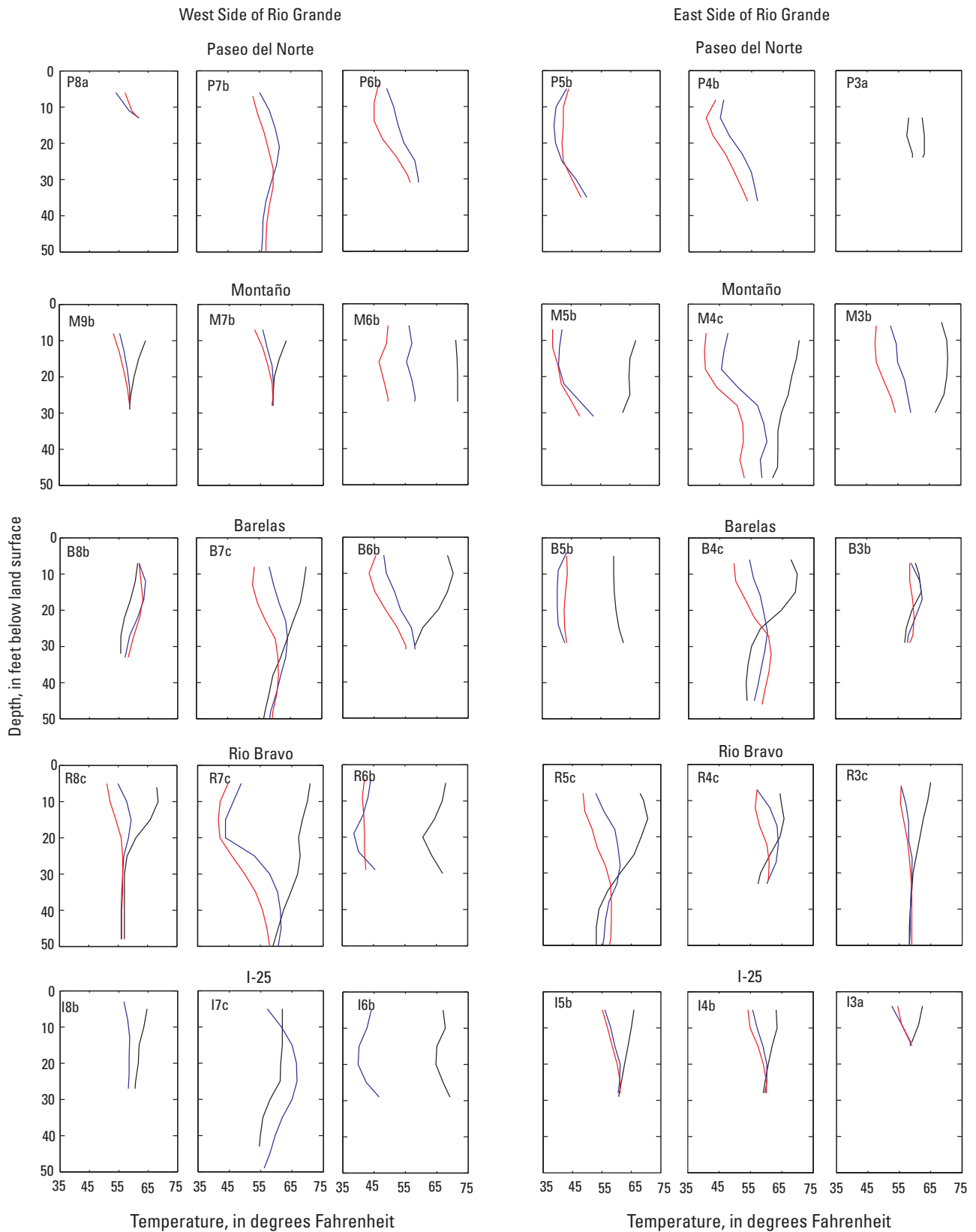




**Figure 8i.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at I-25 transect 1, April 22, 2005-October 24, 2008. Piezometer locations are shown on figure 3e.



**Figure 8j.** Daily mean water temperature in the Rio Grande and riverside drains and daily mean groundwater temperature in piezometers at I-25 transect 2, January 21, 2006-October 27, 2008. Piezometer locations are shown on figure 3e.



**EXPLANATION**

— October 2008    — January 2009    — February 2009

**Figure 9.** Vertical temperature profiles in piezometers, winter nonirrigation season, October 2008, January 2009, and February 2009.

Tulip-shaped temperature envelopes in figure 9, for example M3, M4, R5, and R7) show inflections between depths of 10 and 20 ft that suggest heat fluxes from the Rio Grande are greatly reduced below about 30 ft. Similar results from Bartolino and Niswonger (1999) indicate that heat flux from the Rio Grande is limited below about 16 ft.

To distinguish between horizontal and vertical flow, Reiter (2001) presented temperature profiles in the Albuquerque area that alluded to the importance of cool horizontal flow; vertical flow alone could not cool water deeper in the aquifer to temperatures below those he observed at shallower depths. Reiter's (2001) conclusions can be applied to temperature profiles at piezometer nest I6, for example, where a negative temperature gradient to a depth of about 20 ft is shown. At 20 ft the temperature is 4°F to 5°F cooler than is observed at the shallower depths, indicating that cool horizontal flow is needed to reduce groundwater temperatures below that observed near the water table. Similarly, the importance of horizontal flux from the Rio Grande can be noted in temperature profiles from piezometer nests P4, P5, P6, P7, M3, M4, M5, B4, B6, B7, R4, R5, R6, R7, R8, I6, and I7 (fig. 9).

On the east side of the river, at the Montaña transects, temperature profiles indicate that the seasonal temperature-extinction depth is below the depth of observation. The shape of the temperature envelope at piezometer nest M4 indicates that heat from the Rio Grande is transported to depths greater than 50 ft and that horizontal flux from the Rio Grande must be high to account for a range of 10°F at that depth. The curvature of the M4 profiles indicates that multiple zones of horizontal flow exist at depths of 10 to 20 ft and 45 ft. These zones may be separated by less permeable material in the interval from 30 to 40 ft. The compressed nature of the temperature profiles at M7, M9, R3, R8, I3, I4, and I5 provide a sharp contrast to the variability in temperature profiles on the east side of the Rio Grande at Montaña. Compressed profiles generally indicate the presence of a discharge zone or low rates of groundwater flux (Reiter, 2001; Anderson, 2005).

## Conceptual Model

The volume of water infiltrating from the Rio Grande that is intercepted by the riverside drains is dependent on the local hydraulic gradient, aquifer properties, and configuration of the groundwater-flow field. In the Albuquerque area, alluvial aquifer hydrology is complicated by a heterogeneous distribution of aquifer properties and anthropogenic influences on the system. Groundwater data collected at each transect in this study were used to evaluate geologic and anthropogenic influences and present a general understanding of groundwater flow in the alluvial aquifer.

A simple conceptual model of flow in figure 10 indicates that the groundwater table gently slopes from the Rio Grande towards riverside drains and the outer boundaries of the inner valley. Water infiltrating from the Rio Grande initially moves

in a vertical direction below the bed of the river (Bartolino and Niswonger, 1999). As flow spreads farther into the alluvial aquifer, vertical gradients become small relative to horizontal gradients at depths less than 30 ft and flow becomes primarily horizontal. The slope of the water-table surface may be strongly controlled by the riverside drains and, in a broader sense, influenced by other more distal hydrologic boundary conditions, such as groundwater withdrawals by wells. Riverside drains may induce localized vertical gradients that result in flow converging on the drain from all directions (West Riverside Drain in fig. 10). Alternatively, drains may intercept groundwater flow only from the shallowest part of the aquifer (East Riverside Drain in fig. 10).

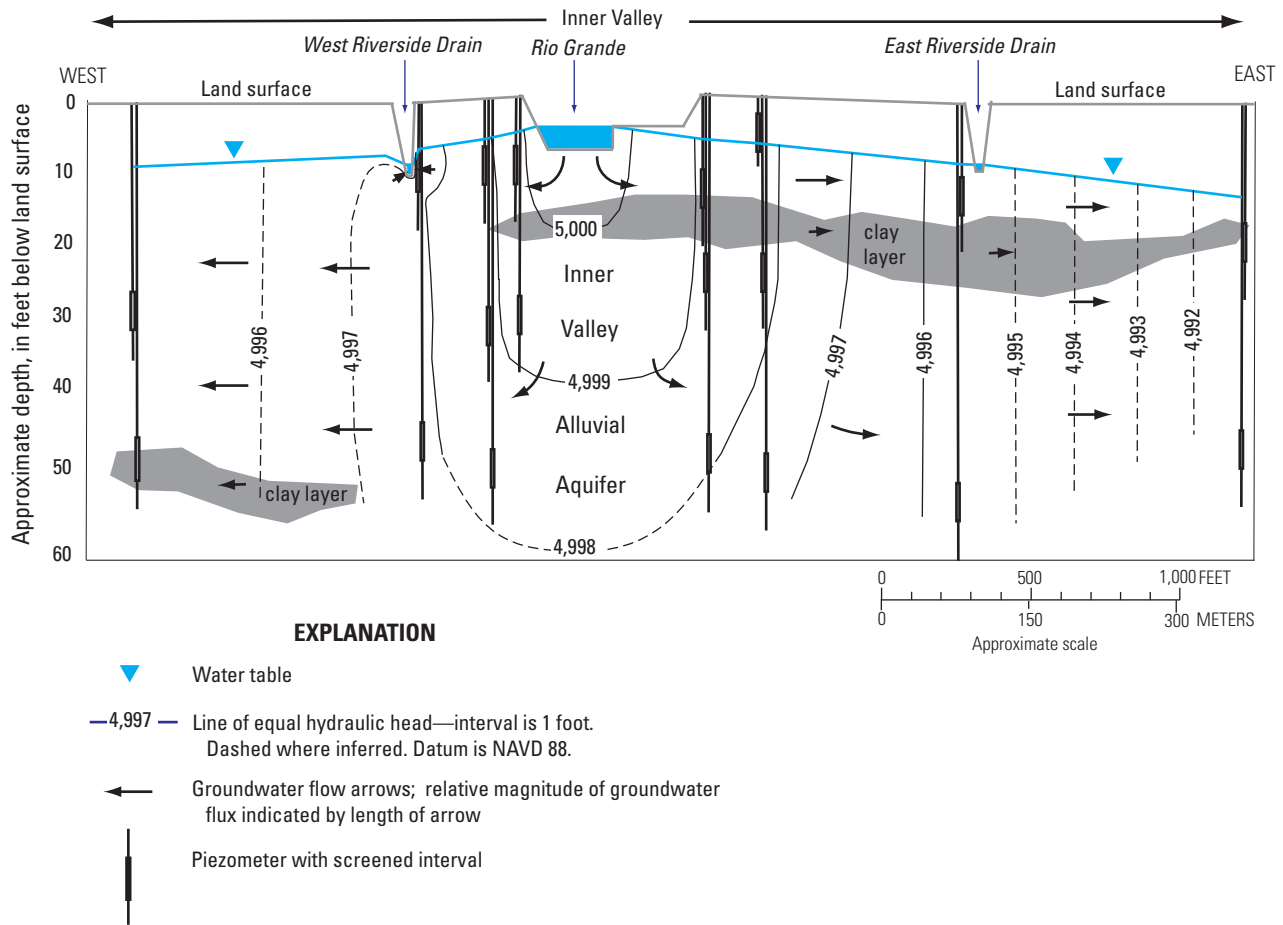
Aquifer hydraulic conductivity also influences the slope of the water-table surface and rates of flux from the river. Deposits comprising the alluvial aquifer are a heterogeneous mix of sediments that overlie the more competent and coarser material of the Santa Fe Group aquifer system (Hawley and Haase, 1992). In general, descriptions of core from the alluvial aquifer indicate that the sediments of the alluvial aquifer grades from cobbles, gravels, sands, and silts to gravels, sands, silts, and clays in a downstream direction through the Albuquerque area. Clay layers can be hydrologically significant between the Barelás and Rio Bravo bridges (Bartolino and Sterling, 2000) where clay-layer thicknesses of 13 ft have been observed (Roark, 2001). The influence of these local-scale heterogeneities is dependent on the continuity and extent of the deposit and its location within the flow system. Fine-grain deposits with low hydraulic conductivity can locally impede groundwater flow and reduce the rates of horizontal flow through the alluvial aquifer. Coarser-grain sands and gravels may allow higher rates of horizontal groundwater flow and infiltration from the river.

## Estimation of Horizontal Groundwater Flux from the Rio Grande

Horizontal groundwater flux from the Rio Grande to the alluvial aquifer east and west of the river was estimated using results from calculations of horizontal hydraulic gradients (determined from analysis of hydraulic-head data), analysis of slug-test data, and heat-transport modeling. In the following report sections the portions of transect 1 and 2 that are east of river are referred to as the "east transects" and the portion of transects 1 and 2 that are west of the river are referred to as the "west transects".

### Horizontal Hydraulic Gradients

Water-level data from shallow piezometers indicated that the median annual horizontal hydraulic gradients in the alluvial aquifer ranged from 0.011 (Barelás west) to 0.002 (I-25 east) (table 3). Generally, horizontal hydraulic gradients



**Figure 10.** Conceptual model of groundwater flow from the Rio Grande through the Rio Grande inner valley alluvial aquifer.

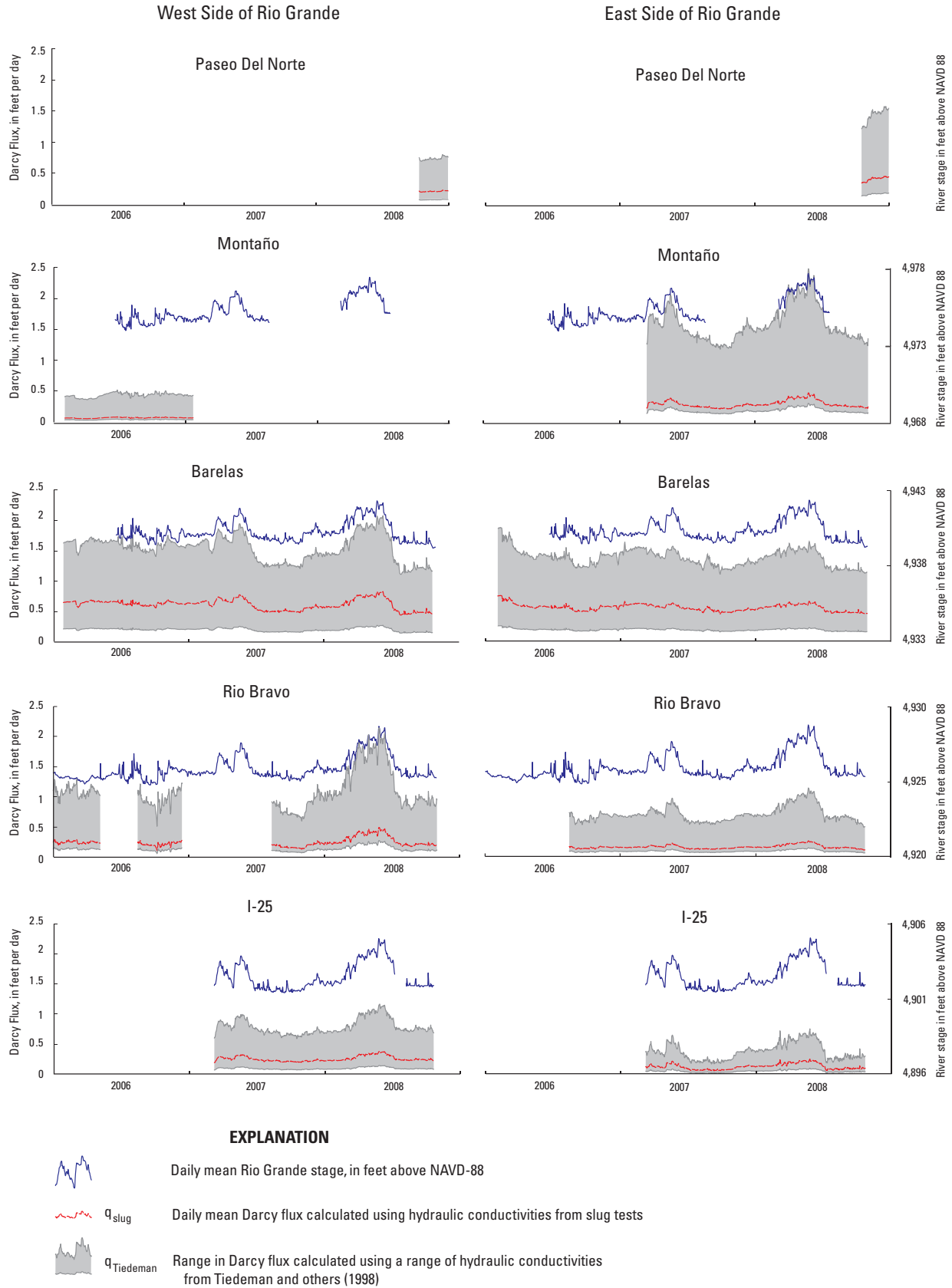
increased from the Paseo del Norte to the Barelás transects, and decreased from the Barelás to the I-25 transects. Hydraulic gradients on the east and west sides of the Rio Grande differed by a factor of 1.6 or less at the Paseo Del Norte, Barelás, and Rio Bravo transects and differed by a factor of 2.5 or more at the Montañó and I-25 transects (table 3).

Relative to the downstream direction of the Rio Grande channel at each transect, the direction of groundwater flow on the east side of the river ranged from 71 to 89 degrees counterclockwise from the channel and on the west side ranged from 68 to 78 degrees clockwise from the channel (table 3). Between the Paseo Del Norte and Barelás bridges, the direction of flow relative to the river varied by less than 3 degrees, although noticeable differences in gradient directions were computed for the east and west sides of this reach of the Rio Grande (table 3). East of the Rio Grande between the Paseo Del Norte transects and the Barelás transects, flow was nearly perpendicular to the river. On both sides of the river, the direction of groundwater flow away from the river became less perpendicular in the downstream direction.

### Darcy Flux

Darcy flux through the alluvial aquifer at each of the five transect locations was calculated using daily mean hydraulic gradients, which were calculated using shallow piezometer data and median hydraulic conductivities from slug-test results (this study) and hydraulic conductivities report by Tiedeman and others (1998) (fig. 11). The periods for which Darcy flux was calculated varied from transect to transect, depending on the availability of water-level data, from early 2006 through late 2008 (Barelás) to November-December 2008 (Paseo Del Norte) (fig. 11).

The Darcy fluxes shown in figure 11 represent the linear flux of groundwater flowing through a unit area (in this case one square foot) of aquifer material per day. Groundwater fluxes through the alluvial aquifer calculated by using median hydraulic conductivities from slug tests ( $q_{slug}$ ) (fig. 6) ranged from about 0.1 ft/d (Rio Bravo east and Montañó west) to about 0.7 ft/d (Barelás west) (fig. 11). The differences in  $q_{slug}$  from one location to another appear to be a function of both hydraulic gradient (table 3) and hydraulic conductivity



**Figure 11.** Daily mean Rio Grande stage and daily mean Darcy fluxes calculated from hydraulic gradients and hydraulic conductivities from slug tests, and from hydraulic gradients and a range of hydraulic conductivities (Tiedeman and others, 1998), Rio Grande inner valley alluvial aquifer, 2006-8 .

(table 2). The  $q_{slug}$  results indicate that the highest rates of groundwater flow through the alluvial aquifer occurred on the east and west sides of the river at the Barelás transects and correspond to the highest median hydraulic conductivity (60 ft/d) from slug test analysis (fig. 6) and high daily mean hydraulic gradients (table 3). The slowest rates of groundwater flow were found to correspond to transects with the lowest daily mean gradients (Montaño west and I-25 east).

With the exception of the Montaño and I-25 transects, the range of  $q_{slug}$  values near each respective bridge location generally were similar on both sides of the river. The differing values of  $q_{slug}$  at Montaño east and Montaño west were attributed to much lower gradients on the west side than on the east side of this location. Increases in  $q_{slug}$  corresponded to periods of high flow in the Rio Grande at all locations. The Darcy flux  $q_{slug}$  response to stage changes in the Rio Grande varied from 18 percent about the mean at Montaño east to 97 percent about the mean at Rio Bravo west. Although fluxes east and west of the river at the Barelás and Rio Bravo bridge locations were relatively uniform, hydraulic gradients on the west side of these transects were slightly more responsive to changes in river stage.

A range of fluxes ( $q_{tiedeman}$ ) through the alluvial aquifer was calculated by using a plausible range of hydraulic conductivities (20 to 150 ft/d) compiled by Tiedeman and others (1998) and the daily mean hydraulic gradients calculated in this study (fig. 11). Daily mean  $q_{slug}$  values (fig. 11) plot near the lower end of the  $q_{tiedeman}$  range because the Darcy flux  $q_{slug}$  was constrained by site-scale hydraulic conductivities ranging from 5 to 160 ft/d. The difference between  $q_{slug}$  values relative to the range of  $q_{tiedeman}$  values was likely the result of differences in bulk aquifer properties measured at different scales. Inverse modeling, also at basin scale, by Tiedeman and others (1998), resulted in a slightly larger range of hydraulic conductivities (73 to 209 ft/d). Simulated hydraulic gradients produced when Tiedeman and others (1998) used a hydraulic conductivity of 73 ft/d best match the hydraulic gradients calculated for this study. Other simulations at basin scale have used hydraulic conductivities of 24 ft/d (Sanford and others, 2003) and 45 ft/d (McAda and Barroll, 2002). The refinement of scale offered by the present study indicates that the magnitude of computed flux in the alluvial aquifer based solely on hydraulic-conductivity estimates from slug tests generally is consistent with that computed in large-scale models.

## Heat-Transport Modeling

Results of calculations of horizontal groundwater flux in the alluvial aquifer using the Suzuki-Stallman method of heat-transport modeling are listed in table 4. Application of the Suzuki-Stallman method yields one set of  $q_a$  and  $q_b$  values for each temperature time-series pair analyzed. A temperature time-series pair consists of concurrent daily mean water-temperature data from two piezometers or from

a surface-water gage and a piezometer. Because the water temperatures were observed to have a wavelength of about a year,  $q_a$  and  $q_b$  values are considered to represent mean annual flux. Some variance in the annual mean  $q_a$  and  $q_b$  values probably resulted from analyzing temperature data sets with differing time spans (table 4). Only one temperature time-series pair was available for analysis at the Rio Bravo east and Rio Bravo west transects, and no data were available for the Paseo Del Norte west transects. Values of  $a$  (the attenuation of the temperature wave) calculated from temperatures collected at 10 ft and 20 ft below land surface ranged from  $2.0 \times 10^{-4}$  to  $7.2 \times 10^{-3}$  ft<sup>-1</sup> and  $1.3 \times 10^{-4}$  to  $2.7 \times 10^{-2}$  ft<sup>-1</sup>, respectively. Similarly, values of  $b$  (the spatial frequency) calculated from daily mean temperatures collected at both the 10-ft and 20-ft depths ranged from  $2.0 \times 10^{-2}$  to  $1.0 \times 10^{-1}$  rad/ft. All values of  $a$  and  $b$  were consistent for temperature time-series pairs that had multiple years of data.

Values of  $a$  and  $b$  were transformed to specific flux values of  $q_a$  and  $q_b$  by using type curves (fig. 5, table 4). At 10 ft, the specific flux values of  $q_a$  and  $q_b$ , collectively, ranged from 0.09 to 0.74 ft/d. At 20 ft, values of  $q_a$  and  $q_b$ , collectively, ranged from 0.10 to 0.85 ft/d. The average absolute deviation from the mean of all  $q_a$  and  $q_b$  values from 10 and 20 ft was 0.12, which indicates a relatively small range of  $q_a$  and  $q_b$  and lends confidence to the results in table 4. Of some concern is the fact that the estimates of  $q_b$  were systematically lower than the estimates of  $q_a$ . Moret (2007) suggests this may indicate that temperature signal phases were slightly distorted by the effects of temperature on water viscosity (cold water moves more slowly through the aquifer than warm water, so the timing of the arrival of temperature peaks and troughs at various locations in the aquifer would be slightly different than predicted by Stallman's (1965) equations).

The one-dimensional Suzuki-Stallman method assumes that groundwater flow in the alluvial aquifer was oriented orthogonal to the Rio Grande channel for all temperature time-series pairs used in this study. Gradient orientations (table 3), however, indicate groundwater flow was not orthogonal to the channel, so the assumption of orthogonality likely introduced some error into the analytical results for paired transects summarized in figure 12. This error can be accounted for by adjusting the distance between measuring points in equations 12 and 13.

In addition, all of the temperature time-series pairs used in this study were spatially aliased. The values of  $a$  and  $b$  were determined by iteratively adding 1-year increments to measured time lags until modeled sinusoidal curves matched observed data. In general, observed and modeled data fit well. Results of temperature time-series pair analyses were rejected if temperature time-series curves were not sinusoidal or if the values of  $q_a$  and  $q_b$  disagreed by more than 50 percent.

Values of  $q_a$  and  $q_b$  determined for each temperature time-series pair were averaged to get a mean annual specific flux ( $q_{heat}$  in table 4). Box plots of  $q_{heat}$  show the highest median value at Paseo Del Norte east (0.52 ft/d) and the lowest median value at I-25 east (0.23 ft/d) (fig. 12).

**Table 4.** Suzuki-Stallman results for horizontal flux between temperature time-series pairs in the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico, 2006-8.

[Site locations shown in figures 3a-e; B, Barelás; I, I-25; M, Montaña; P, Paseo del Norte; R, Rio Bravo; a, shallow (10-foot depth) piezometer; b, mid-depth (20-foot depth) piezometer;  $q_a$  and  $q_b$ , specific fluxes calculated from a, temperature wave and b, spatial frequency;  $q_{heat}$ , average of  $q_a$  and  $q_b$ ; —, no data]

Transect location	Temperature time-series pair	Year	a (feet-1)	$q_a$ (feet per day)	b (radians per foot)	$q_b$ (feet per day)	$q_{heat}$ (feet per day)
Paseo Del Norte	P5a/P4a	2008	3.8E-04	0.60	0.03	0.43	0.52
Paseo Del Norte	P5a/P3a	2008	6.4E-04	.50	.02	.55	.52
Paseo Del Norte	P4a/P3a	2008	7.3E-04	.48	.02	.58	.53
Paseo Del Norte	P5b/P4b	2008	1.8E-03	.36	.03	.42	.39
Montaña	MS2/M3a	2006	7.6E-04	.48	.03	.49	.48
Montaña	M14a/M13a	2007	7.6E-04	.48	.06	.21	.34
Montaña	M14a/M12a	2007	1.4E-03	.39	.05	.28	.34
Montaña	M13a/M12a	2007	—	—	—	—	—
Montaña	MS2/M12a	2006	3.0E-03	.30	.04	.32	.31
Montaña	M6a/M7a	2006	3.6E-03	.28	.06	.22	.25
Montaña	M6a/M7a	2007	3.6E-03	.28	.06	.22	.25
Montaña	M6a/M8a	2006	1.2E-03	.41	.03	.39	.40
Montaña	M7a/M8a	2006	—	—	—	—	—
Montaña	MS2/M6a	2006	4.2E-03	.27	.08	.16	.22
Montaña	MS2/M7a	2006	4.2E-03	.27	.05	.24	.26
Montaña	M15a/M17a	2006	8.5E-04	.46	.03	.46	.46
Montaña	MS2/M15a	2006	7.2E-03	.22	.05	.24	.23
Montaña	M5b/M4b	2005	6.7E-04	.50	.05	.27	.38
Montaña	M5b/M4b	2006	5.1E-04	.54	.05	.27	.40
Montaña	M5b/M4b	2007	1.3E-04	.85	.05	.27	.56
Montaña	MS2/M5b	2006	2.5E-03	.32	.04	.33	.32
Montaña	MS2/M4b	2006	1.7E-03	.36	.04	.31	.34
Montaña	M14b/M12b	2007	6.7E-04	.50	.02	.56	.53
Montaña	MS2/M14b	2006	8.8E-03	.20	.07	.16	.18
Montaña	M6b/M7b	2006	5.3E-03	.25	.05	.24	.24
Montaña	M6b/M7b	2007	5.2E-03	.25	.05	.24	.24
Montaña	MS2/M6b	2006	4.8E-03	.25	.08	.16	.20
Montaña	MS2/M7b	2006	5.8E-03	.24	.06	.23	.24
Montaña	M15b/M16b	2006	3.8E-03	.28	.06	.20	.24
Montaña	M15b/M16b	2007	4.5E-03	.26	.06	.20	.23
Montaña	MS2/M15b	2006	1.6E-02	.16	.06	.20	.18
Montaña	MS2/M16b	2006	4.9E-03	.25	.05	.26	.26
Barelás	B5a/B4a	2006	8.0E-04	.47	.04	.37	.42
Barelás	B5a/B4a	2007	7.5E-04	.48	.04	.37	.42
Barelás	B5a/B4a	2008	1.1E-03	.43	.04	.36	.40
Barelás	B5a/B3a	2006	1.5E-03	.38	.03	.39	.38
Barelás	B5a/B3a	2007	1.2E-03	.40	.03	.39	.40
Barelás	B5a/B3a	2008	1.2E-03	.41	.03	.39	.40
Barelás	B4a/B3a	2006	1.8E-03	.36	.06	.23	.30
Barelás	B4a/B3a	2007	1.4E-03	.39	.06	.23	.31
Barelás	B4a/B3a	2008	1.5E-03	.38	.06	.23	.30



**Table 4.** Suzuki-Stallman results for horizontal flux between temperature time-series pairs in the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico, 2006-8.—Continued

[Site locations shown in figures 3a-e; B, Barelás; I, I-25; M, Montañó; P, Paseo del Norte; R, Rio Bravo; a, shallow (10-foot depth) piezometer; b, mid-depth (20-foot depth) piezometer;  $q_a$  and  $q_b$ , specific fluxes calculated from a, temperature wave and b, spatial frequency;  $q_{heat}$ , average of  $q_a$  and  $q_b$ ; —, no data]

Transect location	Temperature time-series pair	Year	a (feet-1)	$q_a$ (feet per day)	b (radians per foot)	$q_b$ (feet per day)	$q_{heat}$ (feet per day)
Barelás	BS2/B5a	2007	1.7E-03	.37	.06	.23	.30
Barelás	BS2/B5a	2008	1.8E-03	.36	.06	.23	.30
Barelás	BS2/B4a	2007	1.9E-03	.35	.08	.15	.25
Barelás	BS2/B4a	2008	2.8E-03	.31	.08	.15	.23
Barelás	BS2/B3a	2007	2.5E-03	.32	.04	.30	.31
Barelás	BS2/B3a	2008	2.2E-03	.34	.04	.30	.32
Barelás	B14a/B13a	2006	7.1E-04	.49	.03	.48	.48
Barelás	B14a/B13a	2007	6.8E-04	.50	.03	.48	.49
Barelás	B14a/B12a	2007	8.5E-04	.46	.03	.45	.46
Barelás	B13a/B12a	2007	1.1E-03	.42	.03	.49	.46
Barelás	BS2/B14a	2007	2.7E-03	.31	.04	.34	.32
Barelás	BS2/B13a	2007	1.2E-03	.41	.03	.48	.44
Barelás	BS2/B12a	2007	7.6E-04	.48	.03	.45	.46
Barelás	B6a/B7a	2006	7.1E-04	.49	.03	.45	.47
Barelás	B6a/B7a	2007	7.1E-04	.49	.03	.45	.47
Barelás	B6a/B7a	2008	6.8E-04	.50	.03	.44	.47
Barelás	BS2/B6a	2007	6.1E-03	.23	.09	.13	.18
Barelás	BS2/B6a	2008	5.1E-03	.25	.09	.12	.18
Barelás	BS2/B7a	2007	1.7E-03	.37	.05	.24	.30
Barelás	BS2/B7a	2008	2.0E-03	.35	.05	.24	.30
Barelás	B15a/B16a	2006	3.8E-04	.60	.03	.43	.52
Barelás	B15a/B16a	2007	5.4E-04	.53	.03	.43	.48
Barelás	B15a/B17a	2006	8.8E-04	.46	.03	.51	.48
Barelás	B15a/B17a	2007	7.3E-04	.48	.03	.51	.50
Barelás	B16a/B17a	2006	2.1E-04	.73	.02	.73	.73
Barelás	B16a/B17a	2007	2.0E-04	.74	.02	.73	.74
Barelás	BS2/B15a	2007	3.0E-03	.30	.06	.19	.24
Barelás	BS2/B16a	2007	4.4E-04	.57	.03	.44	.50
Barelás	BS2/B17a	2007	7.3E-04	.48	.03	.51	.50
Barelás	B4b/B3b	2006	5.2E-03	.25	.06	.23	.24
Barelás	B4b/B3b	2007	5.3E-03	.25	.06	.23	.24
Barelás	B4b/B3b	2008	5.6E-03	.24	.06	.22	.23
Barelás	BS2/B4b	2007	—	—	.10	.10	.10
Barelás	BS2/B4b	2008	—	—	.10	.10	.10
Barelás	BS2/B3b	2007	—	—	.08	.15	.15
Barelás	BS2/B3b	2008	—	—	.08	.15	.15
Barelás	B14b/B13b	2006	8.1E-04	.47	.03	.46	.46
Barelás	B14b/B13b	2007	7.9E-04	.47	.03	.46	.46
Barelás	B14b/B12b	2007	7.2E-04	.49	.03	.50	.50
Barelás	B13b/B12b	2007	1.8E-04	.77	.02	.57	.67
Barelás	BS2/B14b	2007	2.7E-02	.12	.06	.22	.17

**Table 4.** Suzuki-Stallman results for horizontal flux between temperature time-series pairs in the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico, 2006-8.—Continued

[Site locations shown in figures 3a-e; B, Barelás; I, I-25; M, Montañó; P, Paseo del Norte; R, Rio Bravo; a, shallow (10-foot depth) piezometer; b, mid-depth (20-foot depth) piezometer;  $q_a$  and  $q_b$ , specific fluxes calculated from a, temperature wave and b, spatial frequency;  $q_{heat}$ , average of  $q_a$  and  $q_b$ ; —, no data]

Transect location	Temperature time-series pair	Year	a (feet-1)	$q_a$ (feet per day)	b (radians per foot)	$q_b$ (feet per day)	$q_{heat}$ (feet per day)
Barelás	BS2/B13b	2007	2.1E-03	.34	.03	.39	.36
Barelás	BS2/B12b	2007	1.1E-03	.42	.03	.45	.44
Barelás	BS2/B6b	2007	1.1E-02	.19	.09	.12	.16
Barelás	BS2/B6b	2008	1.1E-02	.19	.09	.12	.16
Barelás	BS2/B7b	2008	3.7E-03	.28	.06	.21	.24
Barelás	BS2/B8b	2007	2.1E-03	.34	.05	.24	.29
Barelás	BS2/B8b	2008	2.1E-03	.34	.05	.24	.29
Barelás	B15b/B16b	2006	6.7E-04	.50	.03	.43	.46
Barelás	B15b/B17b	2006	6.2E-04	.51	.03	.48	.50
Barelás	B16b/B17b	2006	5.3E-04	.54	.02	.68	.61
Barelás	B16b/B17b	2007	1.5E-04	.82	.02	.68	.75
Barelás	BS2/B16b	2007	2.2E-03	.33	.05	.24	.28
Barelás	BS2/B17b	2007	1.2E-03	.41	.04	.35	.38
Rio Bravo	R13a/R12a	2007	8.4E-04	.46	.04	.34	.40
Rio Bravo	R13a/R12a	2008	7.6E-04	.48	.04	.34	.41
Rio Bravo	R15a/R16a	2006	1.0E-03	.43	.10	.09	.26
Rio Bravo	R15a/R16a	2007	8.1E-04	.47	.10	.09	.28
I-25	I14b/I13b	2007	5.9E-03	.24	.09	.13	.18
I-25	I16b/I17b	2007	1.5E-03	.38	.03	.38	.38
I-25	I6a/I7a	2006	3.7E-03	.28	.04	.31	.30
I-25	I6a/I7a	2007	3.3E-03	.29	.04	.30	.30
I-25	IS2/I13b	2007	6.1E-03	.23	.05	.26	.24
I-25	IS2/I14a	2007	6.4E-03	.23	—	—	.23
I-25	IS2/I14b	2007	1.3E-02	.18	.05	.28	.23
I-25	IS2/I17b	2007	2.0E-03	.35	.04	.30	.32
I-25	IS2/I5a	2007	—	—	—	—	—
I-25	IS2/I15a	2007	6.5E-04	.50	.05	.27	.38
I-25	IS2/I5b	2007	—	—	—	—	—
I-25	IS2/I6a	2007	2.9E-04	.66	.03	.41	.54
I-25	IS2/I16b	2007	2.0E-03	.34	.03	.44	.39
I-25	IS2/I7a	2007	2.8E-03	.31	.04	.36	.34

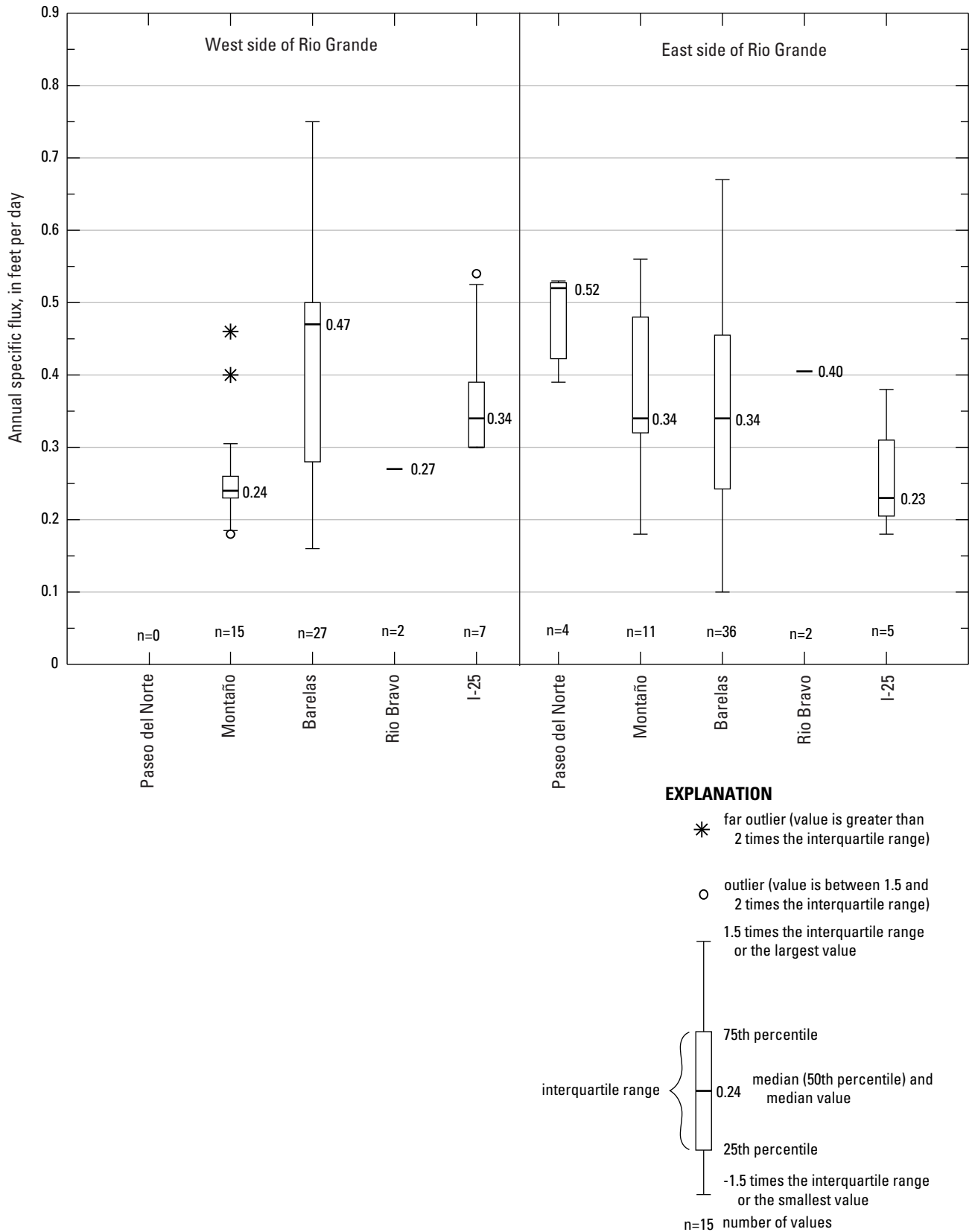


Figure 12. Summary of mean annual specific flux through the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico, calculated using Suzuki-Stallman method.

For all the east transects combined and all the west transects combined, the median of the mean annual  $q_{heat}$  values from the east side of the river is higher (0.35 ft/d) than the median from the west side of the river (0.32 ft/d). Inspection of boxplots in figure 12 indicates that variance about the median increases with sample size. This is an indication that more temperature time-series pairs would have to be analyzed to fully characterize the range of specific flux at each set of transects. The relatively large sample sizes for both sides of the river at the Barelas transects (fig. 12) indicates that local scale geologic heterogeneities can result in a range of specific fluxes. The range of heterogeneities observed at the Barelas transects is likely present at all paired transect locations but not as well characterized by the smaller sample sizes at the other four transect locations.

## Model Comparison

Median flux values computed from Darcy's law ranged from about 0.09 to 0.66 ft/d (table 5); annual median flux values computed from the Suzuki-Stallman method ranged from 0.23 to 0.52 ft/d (table 5). The two methods of computing flux agreed reasonably well, although in general, fluxes from the Suzuki-Stallman method were slightly higher than those computed through the use of Darcy's law (table 5). By using median annual gradients in table 3 and annual median specific fluxes computed by using the Suzuki-Stallman method, the horizontal hydraulic conductivity of the alluvial aquifer was estimated at each paired transect by using equation 4 and solving for hydraulic conductivity. Hydraulic-conductivity values from this analysis ranged from 30 ft/d (Montaño east) to 115 ft/d (I-25 east). The hydraulic conductivities calculated from the results of temperature analysis bracketed the median hydraulic-conductivity results (30 to 60 ft/d) from the slug tests (fig. 6). The results computed using Darcy's law and results computed using the Suzuki-Stallman method (table 5) showed that groundwater fluxes through the alluvial aquifer generally are larger at and upstream of the Barelas transects than downstream.

## Riverside Drain Seepage Investigation

To test the validity of the results from the Darcy's law and Suzuki-Stallman flux calculations, discharge was measured in riverside drains on both sides of the river north of the Montaño bridge (fig. 1) during a period of low flow on February 26, 2009 (table 6, fig. 7). All discharge measurements were conducted while wading, using a SonTek Flowtracker Handheld Acoustic Doppler Velocimeter (Rantz and others, 1982). On the Corrales Riverside Drain (west side of river), measurements were made at approximately 1-mi intervals for about 5.6 mi from below the head of the drain near Corrales to near the discharge point of the drain to the Rio Grande, south of the Montaño bridge. On the Albuquerque Riverside Drain (east side of river), one measurement was

made near the Paseo del Norte bridge and another 3 mi downstream near the Montaño bridge. The uncertainty in discharge measurements (Sauer and Meyer, 1992) ranged from 2.4 percent at east drain mile 3 to 4.8 percent at west drain mile 1 (table 6). Flow in the Rio Grande was not measured during this time; however, daily mean streamflow at the USGS Rio Grande at Alameda gaging station was 864 ft<sup>3</sup>/s and at the Rio Grande at Albuquerque gaging station was 696 ft<sup>3</sup>/s (see fig. 1 for locations). The daily mean streamflows would indicate that there was an average loss of water from the river to the aquifer of 168 ft<sup>3</sup>/s on February 26, 2009, between the two gages. But, the error in the daily mean streamflow at these gages probably was on the order of 10 percent of the total flow or  $\pm 86$  ft<sup>3</sup>/s at the Rio Grande at Alameda gaging station, and  $\pm 70$  ft<sup>3</sup>/s at the Rio Grande at Albuquerque gaging station. The spans of possible error (172 ft<sup>3</sup>/s at the Rio Grande at Alameda gaging station and 140 ft<sup>3</sup>/s at the Rio Grande at Albuquerque gaging station) indicate that the difference in daily mean streamflow between the two gages (168 ft<sup>3</sup>/s) is within the range of, and could be attributable to, measurement error.

On the day that discharge was measured in the drains, the daily mean hydraulic gradients in the alluvial aquifer at the Paseo Del Norte west transects (0.005) was the same as the median annual hydraulic gradient calculated for the Paseo Del Norte west transects (table 3). Because river stage strongly influences hydraulic gradient and because river stage in February 2009 (figs. 7a and 7b) was relatively invariant, the hydraulic gradients at the Paseo Del Norte east and Montaño east and west transects presumably were similar to their respective median annual values (table 3).

Flow in the Corrales Riverside Drain increased by 1.4 ft<sup>3</sup>/s from mile 2 to mile 4 (table 6) and decreased by 0.4 ft<sup>3</sup>/s from mile 4 to mile 6. Because there were no surface-water inflows to the drain between miles 2 and 4, the increased flow in the drain is attributable to seepage of groundwater from the aquifer to the drain. Groundwater discharging to the drain could have originated as seepage from the river to the aquifer or could have come from areas farther west of the drain. The increase in flow between drain miles 2 and 4 (10,500 ft) represents seepage of groundwater to the drain at an average rate of about 12 cubic feet per day (ft<sup>3</sup>/d) per linear foot of drain.

The decrease in flow from mile 4 to 6 represents seepage of water from the drain to the aquifer. By design, a riverside drain slopes at a lower gradient than the river, thus ensuring that the drain terminus is higher than the river and that water in the drain can flow into the river. A consequence of this engineered design is that the water level in the drain for some distance upstream from the drain terminus is higher than the water level in the river and the groundwater table. The decrease in flow from mile 4 to 6 occurs near the downstream end of the Corrales Riverside Drain, where the drain design causes the water level in the drain to be higher than the groundwater table (compare water levels in fig. 3b and fig. 7c for Corrales Riverside Drain gage MS3 and piezometer M9a).

**Table 50.** Comparison of Darcy's law and Suzuki-Stallman calculations of horizontal groundwater flux in the Rio Grande inner valley alluvial aquifer, Albuquerque, New Mexico.

[Site locations shown in figs. 3a-e; ft, foot; rad, radians; q, Darcy flux; —, not reported.]

<b>Transect Location</b>	<b>Darcy's law<sup>1</sup> median <math>q</math> (<math>q_{slug}</math>, in feet per day)</b>	<b>Suzuki-Stallman median <math>q</math> (<math>q_{heat}</math>, in feet per day)</b>
Paseo del Norte		
West	0.23	—
East	0.36	0.52
Montaño		
West	0.09	0.24
East	0.30	0.34
Barelas		
West	0.66	0.47
East	0.54	0.34
Rio Bravo		
West	0.25	0.27
East	0.18	0.40
I-25		
West	0.25	0.34
East	0.10	0.23

<sup>1</sup>Calculated using median value of hydraulic conductivity from results of slug-test analyses (table 2).

**Table 6.** Seepage investigation discharge measurements in the Corrales and Albuquerque Riverside drains, Albuquerque, New Mexico, February 26, 2009.

[Site locations shown in fig. 1; DDMSS.S, degrees minutes seconds]

<b>Measurement location1 (locations shown in figure 1)</b>	<b>Latitude (DDMMSS.S, Datum is NAD 83)</b>	<b>Longitude (DDMMSS.S, Datum is NAD 83)</b>	<b>Measured discharge (cubic feet per second)</b>	<b>Measurement uncertainty (percent)</b>	<b>Approximate distance from last measurement point (feet)</b>	<b>Cumulative distance along drain (feet)</b>
Corrales Riverside Drain mile 1	351217.6	-1063830.5	1.0	4.8	0	0
Corrales Riverside Drain mile 2	351115.0	-1063908.8	1.6	2.9	7,400	7,400
Corrales Riverside Drain mile 3	351025.5	-1063928.3	2.3	3.3	5,200	12,600
Corrales Riverside Drain mile 4	350947.3	-1064011.6	3.0	3.1	5,300	17,900
Corrales Riverside Drain mile 5	350855.0	-1064054.0	2.7	2.8	6,500	24,400
Corrales Riverside Drain mile 6	350810.1	-1064121.8	2.6	3.1	5,200	29,600
Albuquerque Riverside Drain mile 0	351055.2	-1063852.9	58	3.0	0	0
Albuquerque Riverside Drain mile 3	350844.7	-1064025.9	73	2.4	15,800	15,800

<sup>1</sup> Mile marker location is approximate. More exact distances are shown in last two columns.

Flow in the Albuquerque Riverside Drain increased by 15 ft<sup>3</sup>/s between drain miles 0 and 3. This increase in flow, which occurred over a distance of 15,800 ft, represents seepage of groundwater to the drain of at an average rate of about 82 ft<sup>3</sup>/d per linear foot of drain. No surface-water inputs or overlapping drains were observed, so this increase in flow is attributable to seepage of groundwater from the aquifer to the drain.

Temperature profiles at the Montañito west transects (fig. 9) indicate that seasonal transport of heat from the Rio Grande during winter nonirrigation periods does not extend below 20-25 ft. The flux of water from the river to the aquifer was calculated to be 2.2 ft<sup>3</sup>/d per linear foot of river by using (1) the median  $q_{slug}$  at Montañito west of 0.09 ft/d (table 5), (2) a 1-foot width of aquifer measured parallel to the river, and (3) an assumption that all of the leakage from the Rio Grande is contained in the upper 25 ft of the aquifer at the Montañito west transects. Under the same assumptions and by using the median  $q_{heat}$  (0.24 ft/d) calculated from the Suzuki-Stallman method for the Montañito west transects (table 5), the total flux was calculated to be 6.0 ft<sup>3</sup>/d per linear foot of river. Assuming the Corrales Riverside Drain intercepted all of this flow, the  $q_{slug}$  or  $q_{heat}$  fluxes would only account for 18 to 50 percent, respectively, of the increase of flow in the drain (12 ft<sup>3</sup>/d per linear foot of drain) between miles 2 and 4 on February 26, 2009. Given a median annual hydraulic gradient of 0.003 at Montañito west (table 3), the hydraulic conductivity of the upper 25 ft of alluvium would have to be 160 ft/d for discharge from the aquifer to the drain to account for 100 percent of the increase in flow in the riverside drain on February 26, 2009. As discussed previously, the design of the Corrales Riverside Drain at the Montañito west transects causes the water level in the drain to be higher than the groundwater table. So, the Darcy flux  $q_{slug}$  and the Suzuki Stallman flux  $q_{heat}$  probably are smaller than if they were measured in an area where the drain water level is lower than the groundwater table. Indeed, at the Paseo Del Norte west transects the median Darcy flux  $q_{slug}$  is 0.23 ft/d (5.75 ft<sup>3</sup>/d per linear foot of river) and would account for about 48 percent of the increase in flow in the drain between miles 2 and 4 on February 26, 2009.

Temperature profiles at the Montañito east transects (fig. 9) indicate seasonal transport of heat from the Rio Grande during winter nonirrigation periods extends to depths greater than 50 ft. The flux of water from the river to the aquifer was calculated to be 15 ft<sup>3</sup>/d per linear foot of river by using (1) the median  $q_{slug}$  at the Montañito east transects of 0.30 ft/d (table 5), (2) a 1-foot width of aquifer measured parallel to the river, and (3) assuming that all of the leakage from the Rio Grande is contained in the upper 50 ft of the aquifer at the Montañito east transects. Under the same assumptions and by using the mean flux calculated from the Suzuki-Stallman method for the Montañito east transects of 0.34 ft/d (table 5), the flux of water from the river to the aquifer was calculated to be 17 ft<sup>3</sup>/d

per linear foot of river. Assuming the Albuquerque Riverside Drain intercepted all this flow, the  $q_{slug}$  or  $q_{heat}$  fluxes would only account for 18 to 21 percent, respectively, of the increase in flow (82 ft<sup>3</sup>/d per linear foot of drain) measured in the drain on February 26, 2009. Given an average annual hydraulic gradient of 0.010 at the Montañito east transects (table 3) the hydraulic conductivity of the upper 50 ft of alluvium would have to be about 160 ft/d for discharge from the aquifer to the drain to account for 100 percent of the increase in flow in the riverside drain on February 26, 2009.

For all locations, flux rates for  $q_{slug}$  ranged from 0.09 ft/d at the Montañito west transects to 0.66 ft/d at the Barelitas west transects and flux rates for  $q_{heat}$  ranged from 0.23 ft/d at the I-25 east transects to 0.52 ft/d at the Paseo del Norte east transects (table 5). Assuming that water leaking from the river to the aquifer is transmitted to the drains through a uniform 30 ft aquifer thickness in the Albuquerque area, the  $q_{slug}$  flux rates would range from 2.7 to 20 ft<sup>3</sup>/d per linear foot of river and the  $q_{heat}$  flux rates would range from 6.9 to 16 ft<sup>3</sup>/d per linear foot of river.

At more local scales, Roark (2001) estimated river leakage to range from 0.47 to 2.1 ft<sup>3</sup>/d per linear foot of river, Thorn (1995) indicated that leakage from the river averaged 74 ft<sup>3</sup>/d per linear foot of river between the Paseo del Norte and Rio Bravo bridges, and Veenhuis (2002) indicated that leakage from the river averaged 123 ft<sup>3</sup>/d per linear foot of river between the Bernalillo bridge and the Rio Bravo bridge. The comparison of these results with those of previous investigations suggests that calculated flux through the alluvial aquifer is strongly scale dependent and that the thickness of aquifer through which river water flows may be greater than indicated by the vertical temperature profiles. Depth of river-water penetration into the aquifer could be further investigated using water chemistry to establish the boundary between water from the river and deeper aquifer water.

## Summary

The Albuquerque area is the major population center in New Mexico and has two principal sources of water for municipal, domestic, commercial, and industrial uses in this area: groundwater from the Santa Fe Group aquifer system and surface water from the San Juan-Chama Diversion Project. Estimates indicated that from 1960 to 2002, groundwater withdrawals from the Santa Fe Group aquifer system have caused water levels to decline more than 120 feet in some places within the Albuquerque area. This has resulted in a great deal of interest in quantifying the river-aquifer interaction associated with the Rio Grande.

Previous researchers have used streambed permeameters, the transient response of the aquifer to a flood pulse, vertical profiles of temperature measurements, and calibrated

numerical models to estimate the flux between the Rio Grande and the Santa Fe Group aquifer system. In contrast to previous more regional-scale studies, a study was designed to provide spatially detailed information about the amount of water that discharges from the Rio Grande to the adjacent aquifer in the Albuquerque area.

In 2003, the U.S. Geological Survey in cooperation with the Bureau of Reclamation, the Middle Rio Grande Endangered Species Collaborative Program, and the U.S. Army Corps of Engineers began a detailed characterization of the hydrogeology of the Rio Grande riparian corridor in the Albuquerque, New Mexico, area to provide hydrologic data and enhance the understanding of rates of water leakage from the Rio Grande to the alluvial aquifer, groundwater flow through the aquifer, and discharge of water from the aquifer to the riverside drains.

The study area extends about 18 miles along the Rio Grande in the Albuquerque area and the east and west edges of the study area are limited to areas within the inner valley adjacent to the Upper Corrales, Corrales, Albuquerque, and Atrisco Riverside Drains. The inner valley is approximately 2-3 miles wide and slopes about 5-6 feet per mile southward through the Albuquerque area. The riverside drains are ditches generally separated from the river by levees that are designed to intercept lateral groundwater flow from the river and prevent waterlogged-soil conditions east and west of the inner valley. Seepage to the riverside drains constitutes one of the main sources of groundwater discharge from the shallow alluvium.

The Rio Grande inner valley alluvial aquifer (alluvial aquifer) consists of coarse-grained axial channel deposits and post-Santa Fe Group sediments that underlie the present-day Rio Grande flood plain. The alluvium consists of unconsolidated to poorly consolidated, fine- to coarse-grain sand and rounded gravel with subordinate, discontinuous lens-shaped interbeds of fine-grain sand, silt, and clay. These deposits form an extensive shallow aquifer along the Rio Grande in the Albuquerque area and may be as much as 120 feet thick with an average thickness of 80 feet. The underlying Santa Fe Group aquifer system is composed primarily of gravel, sand, silt, and clay deposits that are approximately 14,000 feet thick in parts of the basin.

Piezometers and surface-water gages were installed in paired transects near five bridges in the Albuquerque area. Each transect included nested piezometers and surface-water-stage gages configured in roughly straight lines and oriented perpendicular to the river and riverside drains. At each location, transects extended from the Rio Grande to just outside the riverside drains on both sides of the river and were spaced about 500 feet apart. The paired-transect configuration was chosen to facilitate definition of horizontal and vertical gradients at each location.

Continuous subsurface core samples were collected at each transect. Core samples were obtained to ensure that

piezometer screens were placed in sand and gravel and to identify and locate any substantial changes in subsurface lithology that could potentially affect either horizontal or vertical groundwater movement. In total, 36 locations were cored within the study area at depths ranging from 25 to 55 feet.

Results from 35 slug tests performed in the alluvial aquifer for this study during January and February 2009 indicate that hydraulic-conductivity values ranged from 5 feet per day to 160 feet per day, with a median hydraulic-conductivity for all transects of 40 feet per day. Slug-test results from piezometers on the east side of the river were not substantially different from those on the west side.

Hourly groundwater-level data were recorded from 164 piezometers screened at different intervals within the alluvial aquifer. Groundwater-level data were used to evaluate water-level trends, measure response to increases or decreases in river stage, and to calculate horizontal hydraulic gradients. Horizontal hydraulic gradients indicated that groundwater movement generally was away from the river and toward the drains.

Hourly groundwater temperatures were recorded at depths of 10 and 20 feet in selected piezometer nests. Large ranges in surface-water temperature were apparent: surface-water temperatures ranged from 37°F in the winter to 79°F in the summer. Surface-water temperatures in the drains typically were similar to temperatures measured in the Rio Grande, but the magnitudes of fluctuations in the river were somewhat larger. Maximum and minimum water temperatures in piezometers generally indicate a decrease in amplitude and an increase in time lag of the temperature signal with increasing depth and distance from the river.

Vertical temperature profiles were collected during the months of October 2008 and January and February 2009 in the deepest piezometer at selected piezometer nests during the nonirrigation season. Temperature-profile data were collected to evaluate the depth of the alluvial aquifer that is influenced by leakage from the river. Temperatures were recorded at 5-foot intervals from about 0.5 feet below the water surface to the bottom of each piezometer. Although piezometers were constructed with a screened interval of 5 feet near the bottom of the piezometer, the temperature of water in blank (nonscreened) casing was assumed to be the same as the temperature of water outside the casing. Groundwater temperatures recorded throughout the nonirrigation season were most variable at depths less than 30 feet and generally ranged from 40 to 70°F.

A simple conceptual model of flow indicates that the groundwater table gently slopes from the Rio Grande towards riverside drains and the outer boundaries of the inner valley. Water infiltrating from the Rio Grande initially moves in a vertical direction below the bed of the river. As flow spreads farther into the alluvial aquifer, vertical gradients become small relative to horizontal gradients at depths less than

30 feet and flow becomes primarily horizontal. The slope of the water-table surface may be strongly controlled by the riverside drains and, in a broader sense, influenced by other more distal hydrologic boundary conditions, such as groundwater withdrawals by wells. Riverside drains may induce localized vertical gradients that result in flow converging on the drain from all directions. Alternatively, drains may intercept groundwater flow only from the shallowest part of the aquifer.

Water-level data from shallow piezometers indicated that the median annual horizontal hydraulic gradients in the alluvial aquifer ranged from 0.011 to 0.002. Generally, horizontal hydraulic gradients increase from the Paseo del Norte to the Barelás transects, and decrease from the Barelás to the I-25 transects. Hydraulic gradients on the east and west sides of the Rio Grande differed by a factor of 1.6 or less at the Paseo Del Norte, Barelás, and Rio Bravo transects and differed by a factor of 2.5 or more at the Montaña and I-25 transects. Relative to the downstream direction of the Rio Grande channel at each transect, the direction of groundwater flow on the east side of the river ranged from 71 to 89 degrees counterclockwise from the channel and on the west side ranged from 68 to 78 degrees clockwise from the channel.

Groundwater fluxes through the alluvial aquifer calculated using median hydraulic conductivities from slug-tests ( $q_{slug}$ ) ranged from about 0.1 feet per day to about 0.7 feet per day. The differences in  $q_{slug}$  from one location to another appear to be a function of both hydraulic gradient and hydraulic conductivity. The  $q_{slug}$  results indicate that the highest rates of groundwater flow through the alluvial aquifer occurred on the east and west sides of the river at the Barelás transects and correspond to the highest median hydraulic conductivity from slug test analysis and high hydraulic gradients.

With the exception of the Montaña and I-25 transects, the range of  $q_{slug}$  values near each respective bridge location generally were similar on both sides of the river. The differing values of  $q_{slug}$  at Montaña east and Montaña west were attributed to much lower gradients on the west side than on the east side of this location. Although fluxes east and west of the river at the Barelás and Rio Bravo Bridge locations were relatively uniform, hydraulic gradients on the west side of these transects were slightly more responsive to changes in river stage. A range of fluxes ( $q_{piedeman}$ ) through the alluvial aquifer was calculated by using a plausible range of hydraulic conductivities (20 to 150 feet per day) compiled from the literature and the daily mean hydraulic gradients calculated in this study. The difference between  $q_{slug}$  values relative to the range of  $q_{piedeman}$  values was likely the result of differences in bulk aquifer properties measured at different scales. Results of calculations of horizontal groundwater flux ( $q_{heat}$ ) show that highest median value was at Paseo Del Norte east (0.52 feet per day) and the lowest median value at I-25 east (0.23 feet

per day). For all transects, the median of the mean annual  $q_{heat}$  values from the east side of the river is higher than the median from the west side of the river. Flux values computed from Darcy's law and from the Suzuki-Stallman method agreed reasonably well, although in general, fluxes from the Suzuki-Stallman method were slightly higher than those computed through the use of Darcy's law.

To test the validity of the results from the Darcy's law and Suzuki-Stallman flux calculations, discharge was measured in riverside drains on both sides of the river north of the Montaña Bridge during a period of low flow on February 26, 2009. Flow in the Corrales Riverside Drain increased by 1.4 cubic feet per second from mile 2 to mile 4 and decreased by 0.4 cubic feet per second from mile 4 to mile 6. The increase in flow between drain miles 2 and 4 represents seepage of groundwater to the drain of at an average rate of about 12 cubic feet per day per linear foot of drain. The decrease in flow from mile 4 to 6 represents seepage of water from the drain to the aquifer. Flow in the Albuquerque Riverside Drain increased by 15 cubic feet per second between drain miles 0 and 3. This increase in flow represents seepage of groundwater to the drain at an average rate of about 82 cubic feet per day per linear foot of drain.

The flux of water from the river to the aquifer was calculated to be 2.2 cubic feet per day per linear foot of river by using the median  $q_{slug}$  at Montaña west of 0.09 feet per day, a 1-foot width of aquifer measured parallel to the river, and an assumption that all of the leakage from the Rio Grande is contained in the upper 25 feet of the aquifer. Under the same assumptions and by using the mean  $q_{heat}$  calculated from the Suzuki-Stallman method for the Montaña west transects of 0.24 feet per day, the total flux was calculated to be 6.0 cubic feet per day per linear foot of river. Assuming the Corrales Riverside Drain intercepted all of this flow, the  $q_{slug}$  or  $q_{heat}$  fluxes would only account for 18 to 50 percent, respectively, of the increase of flow in the drain (12 cubic feet per day per linear foot of drain) between miles 2 and 4 on February 26, 2009. Given a median annual hydraulic gradient of 0.003 at Montaña west, the hydraulic conductivity of the upper 25 feet of alluvium would have to be 160 feet per day for discharge from the aquifer to the drain to account for 100 percent of the increase in flow in the riverside drain on February 26, 2009.

The flux of water from the river to the aquifer was calculated to be 15 cubic feet per day per linear foot of river by using the median  $q_{slug}$  at the Montaña east transects of 0.30 feet per day, a 1-foot width of aquifer measured parallel to the river, and assuming that all of the leakage from the Rio Grande is contained in the upper 50 feet of the aquifer at the Montaña east transects. Under the same assumptions and by using the mean flux calculated from the Suzuki-Stallman method for the Montaña east transects of 0.34 feet per day, the flux of water from the river to the aquifer was calculated to be 17 cubic feet per day per linear foot of river.



Assuming the Albuquerque Riverside Drain intercepted all this flow, the  $q_{slug}$  or  $q_{heat}$  fluxes would only account for 18 to 21 percent, respectively, of the increase in flow (82 cubic feet per day per linear foot of drain) measured in the drain on February 26, 2009. Given an average annual hydraulic gradient of 0.010 at the Montañito east transects the hydraulic conductivity of the upper 50 feet of alluvium would have to be about 160 feet per day for discharge from the aquifer to the drain to account for 100 percent of the increase in flow in the riverside drain on February 26, 2009. For all locations, assuming that water leaking from the river to the aquifer is transmitted to the drains through a uniform 30 feet aquifer thickness in the Albuquerque area, the  $q_{slug}$  flux rates would range from 2.7 to 20 cubic feet per day per linear foot of river and the  $q_{heat}$  flux rates would range from 6.9 to 16 cubic feet per day per linear foot of river.

The comparison of these results with those of previous investigations suggests that calculated flux through the alluvial aquifer is strongly scale dependent and that the thickness of aquifer through which river water flows may be greater than indicated by the vertical temperature profiles. Depth of river-water penetration into the aquifer could be further investigated using water chemistry to establish the boundary between water from the river and deeper aquifer water.

## References

- Anderholm, S.K., and Bullard, T.F., 1987, Description of piezometer nests and water levels in the Rio Grande valley near Albuquerque, Bernalillo County, New Mexico: U.S. Geological Survey Open-File Report 87-122, 51 p.
- Anderson, M.P., 2005, Heat as a ground water tracer: *Ground Water*, v. 43, no. 6, p. 951-968, November.
- Barroll, Peggy, 2001, Documentation of the administrative groundwater model for the Middle Rio Grande Basin: Santa Fe, New Mexico Office of the State Engineer, Hydrology Bureau Report 99-3, 22 p.
- Bartolino, J.R., 2003, The Rio Grande—Competing demands for a desert river, chap. 2 of Stonestrom, D.A., and Constantz, Jim, eds., Heat as a tool for studying the movement of ground water near streams: U.S. Geological Survey Circular 1260, p. 8-16.
- Bartolino, J.R., and Cole, J.C., 2002, Ground-water resources of the Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Circular 1222, 132 p.
- Bartolino, J.R., and Niswonger, R.G., 1999, Numerical simulation of vertical ground-water flux of the Rio Grande from ground-water temperature profiles, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 99-4212, 34 p.
- Bartolino, J.R., and Sterling, J.M., 2000, Electromagnetic surveys to detect clay-rich sediment in the Rio Grande inner valley, Albuquerque, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00-4003, 45 p.
- Bexfield, L.M., and Anderholm, S.K., 2002, Estimated water-level declines in the Santa Fe Group aquifer system in the Albuquerque area, central New Mexico, predevelopment to 2002: U.S. Geological Survey Water-Resources Investigations Report 02-4233, 1 p.
- Bexfield, L.M., and McAda, D.P., 2003, Simulated effects of ground-water management scenarios on the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico, 2001-40: U.S. Geological Survey Water-Resources Investigations Report 03-4040, 39 p.
- Blasch, K.W., Constantz, Jim, and Stonestrom, David A., 2007, Thermal methods for investigating ground-water recharge, in Stonestrom, D.A., Constantz, Jim, Ferre, Ty P.A., and Leake, S.A., eds., Ground-water recharge in the arid and semiarid southwestern United States: U.S. Geological Survey Professional Paper 1703, Appendix 1, p. 351-373.
- Bouwer, Herman, and Rice, R.C., 1976, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells: *Water Resources Research*, v. 12, no. 3, p. 423-428.
- Butler, J.J., 1998, The design, performance, and analysis of slug tests: Boca Raton, Fla., Lewis Publishers, 252 p.
- Carlsaw, H.S., and Jaeger, J.C., 1959, Conduction of heat in solids (2d ed.): New York, Oxford University Press, 510 p.
- Compton, R.R., 1962, Manual of field geology: New York, Wiley, 378 p.
- Constantz, J.E., Niswonger, R.G., and Stewart, A.E., 2008, Analysis of temperature gradients to determine stream exchanges with ground water in Rosenberry, D.O., and LaBaugh, J.W., eds., Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods 4-D2, 128 p.
- Constantz, Jim, Thomas, C.L., and Zellweger, G. W., 1994, Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge: *Water Resources Research*, v. 30, no. 12, p. 3253-3264.

- Constantz, Jim, Tyler, S.W., and Kwicklis, Edward, 2003, Temperature-profile methods for estimating percolation rates in arid environments: *Vadose Zone Journal*, v. 2, p. 12-24.
- Connell, S.D., Love, D.W., and Dunbar, N.W., 2007, Geomorphology and stratigraphy of inset fluvial deposits along the Rio Grande Valley in the central Albuquerque Basin, New Mexico: *New Mexico Geology*, v. 29, no. 1, p. 31.
- Engdahl, N.B., Vogler, E.T., and Weissman, G.S., 2010, Evaluation of aquifer heterogeneity effects on river flow loss using a transition probability framework: *Water Resources Research*, v. 46, no. 1 [variously paged]. (Also available at <http://dx.doi.org/10.1029/2009WR007903>.)
- Fetter, C.W., 1994, *Applied hydrogeology* (3d ed.): New York, Prentice-Hall, 690 p.
- Freeman, L.A., Carpenter, M.C., Rosenberry, D.O., Rousseau, J.P., Unger, Randy, and McLean, J.S., 2004, Use of submersible pressure transducers in water-resources investigations: U.S. Geological Survey Techniques of Water-Resources Investigations 8-A3, 52 p.
- Gould, Jaci, 1994, Middle Rio Grande channel permeameter investigations: Bureau of Reclamation Albuquerque Area Office, Middle Rio Grande Water Assessment Supporting Document, no. 11 [variously paged].
- Hawley, J.W., and Haase, C.S., 1992, Hydrogeologic framework of the northern Albuquerque Basin: Socorro, N. Mex., New Mexico Bureau of Mines and Mineral Resources, Open-File Report 387, 176 p.
- Hawley, J.W., and Whitworth, T.M., 1996, Hydrogeology and potential recharge areas for the basin and valley-fill aquifer systems and hydrogeochemical modeling of proposed artificial recharge of the Upper Santa Fe Aquifer, northern Albuquerque Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-File Report 402-D, 68 p.
- Kernodle, J.M., McAda, D.P., and Thorn, C.R., 1995, Simulation of ground-water flow in the Albuquerque Basin, central New Mexico, 1901-1994, with projections to 2020: U.S. Geological Survey Water-Resources Investigations Report 94-4251, 114 p.
- Kues, Georgianna, 1986, Ground-water levels and direction of ground-water flow in the central part of Bernalillo County, New Mexico, summer 1983: U.S. Geological Survey Water-Resources Investigations Report 85-4325, 24 p.
- McAda, D.P., 1996, Plan of study to quantify the hydrologic relations between the Rio Grande and the Santa Fe Group aquifer system near Albuquerque, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 96-4006, 58 p.
- McAda, D.P., 2001, Simulation of a long-term aquifer test conducted near the Rio Grande, Albuquerque, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 99-4260, 58 p.
- McAda, D.P., and Barroll, Peggy, 2002, Simulation of ground-water flow in the middle Rio Grande Basin between Cochiti and San Acacia, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02-4200, 81 p.
- Moret, G.J.M., 2007, Annual variations in groundwater temperature as a tracer of river-aquifer interactions: State College, Pennsylvania State University, Ph.D. dissertation, 153 p.
- Myers, N.C., Finnegan, P.J., and Breedlove, J.D., 1999, Analysis of water-level data and ground-water flow modeling at Fort Riley, Kansas: U.S. Geological Survey Water-Resources Investigations Report 99-4115, 6 p.
- National Climatic Data Center, 2011, Quality controlled local climatological data: National Oceanic and Atmospheric Administration, accessed December 1, 2011, at <http://cdo.ncdc.noaa.gov/qclcd/QCLCD?prior=N>.
- Peter, K.D., 1987, Ground-water flow and shallow-aquifer properties in the Rio Grande inner valley south of Albuquerque, Bernalillo County, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 87-4015, 29 p.
- Rantz, S.E., and others, 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, 2 v., 631 p.
- Reiter, Marshall, 2001, Using precision temperature logs to estimate horizontal and vertical groundwater flow components: *Water Resources Research*, vol. 37, no. 3, p. 663-674.
- Roark, D.M., 2001, Estimation of hydraulic characteristics in the Santa Fe Group aquifer system using computer simulations of river and drain pulses in the Rio Bravo study area, near Albuquerque, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 01-4069, 52 p.

- Sanford, W.E., Plummer, L.N., McAda, D.P., Bexfield, L.M., and Anderholm, S.K., 2003, Use of environmental tracers to estimate parameters for a predevelopment-ground-water-flow model of the Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 03-4286, 102 p.
- Sauer, V.B., and Meyer, R.W., 1992, Determination of error in individual discharge measurements: U.S. Geological survey Open-File Report 92-144, 21 p.
- Silliman, S.E., and Booth, D.F., 1993, Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana: *Journal of Hydrology*, v. 146, p. 131-148.
- Smerdon, J.E., Pollack, H.N., Cermak, Vladimir, Enz, J.W., Kresl, Milan, Safanda, Jan, and Wehmiller, J.F., 2004, Air-ground temperature coupling and subsurface propagation of annual temperature signals: *Journal of Geophysical Research*, v. 109, no. 21, D21107, 10 p.
- Stallman, R.W., 1965, Steady one-dimensional fluid flow in a semi-infinite porous medium with sinusoidal surface temperature: *Journal of Geophysical Research*, v. 70, no. 12, p. 2,821-2,827.
- Suzuki, Seitaro, 1960, Percolation measurements based on heat flow through soil with special reference to paddy fields: *Journal of Geophysical Research*, v. 65, no. 9, p. 2883-2885.
- Thorn, C.R., 1995, Surface-water discharge and evapotranspiration rates for grass and bare soil along a reach of the Rio Grande, Albuquerque, New Mexico, 1989-95: U.S. Geological Survey Open-File Report 95-419, 23 p.
- Tiedeman, C.R., Kernodle, J.M., and McAda, D.P., 1998, Application of nonlinear-regression methods to a ground-water flow model of the Albuquerque Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 98-4172, 90 p.
- U.S. Census Bureau, 2003, Census of population and housing, New Mexico 2000—Summary population and housing characteristics: PHC-1-33, 114 p.
- Veenhuis, J.E., 2002, Summary of loss between selected cross sections on the Rio Grande in and near Albuquerque, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 02-4131, 30 p.
- Vennard, J.K., and Street, R.L., 1982, *Elementary fluid mechanics* (6th ed.): New York, Wiley, 689 p.



