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

Water-Resources Investigations Report 01-4069

Prepared in cooperation with the

CITY OF ALBUQUERQUE

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By D. Michael Roark

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Albuquerque, New Mexico
2001

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day	0.09290	meter squared per day
square mile	2.590	square kilometer

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

Altitude, as used in this report, refers to distance above sea level.

Estimation of Hydraulic Characteristic 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

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ABSTRACT

In 1977, the U.S. Geological Survey conducted a hydrologic investigation of the surface-water/ground-water interaction of the Rio Grande and the surrounding alluvium and the Santa Fe Group aquifer system in an area near the Rio Bravo Bridge, south of Albuquerque, New Mexico. A set of existing wells and new wells were instrumented to monitor water levels in a section perpendicular to the Rio Grande on the east side of the river. Equipment to measure stream stage was installed at two sites—on the Albuquerque Riverside Drain and on the Rio Grande. A short-duration river pulse and a long-duration river pulse were used to stress the ground-water system while the changes in water levels were monitored. A ground-water flow-model simulation using the principle of superposition was used to estimate the hydraulic characteristics of the local ground-water system. Simulated horizontal hydraulic conductivities varied from 0.03 to 100 feet per day, and vertical hydraulic conductivities varied from 1.5×10^{-6} to 0.01 foot per day. The specific yield of layer 1 was estimated to be 0.3. Specific storage for layers 2 through 11 was 1.0×10^{-6}. Water entering the model from the river along a 300-foot-wide cross section during simulation of the short-duration pulse averaged 7.46×10^{-3} cubic foot per second and during the long-duration pulse was 1.66×10^{-3} cubic foot per second. The average flux from the model to the drain during the short-duration pulse was 3.18×10^{-3} cubic foot per second. The average flux for the long-duration pulse was 7.14×10^{-3} cubic foot per second from the drain to the model.

INTRODUCTION

Ground water is the principal source of water for municipal use in the Albuquerque area (Thorn and others, 1993, p. 1). Because of the rapid growth of population in the area, ground-water withdrawals have substantially increased. In the past, water managers assumed for simplicity that the amount of water pumped in the Albuquerque area was replaced by water from the Rio Grande recharging the aquifer. As increasing volumes of ground water are pumped, water managers and others have raised questions about how much the Rio Grande recharges the Santa Fe Group aquifer system. The amount of recharge from the river is controlled by the hydraulic properties of the aquifer adjacent to the river.

The U.S. Geological Survey (USGS), in cooperation with the City of Albuquerque, conducted a project to estimate hydraulic properties of the Santa Fe Group aquifer system (Thorn and others, 1993, p. 1) adjacent to the Rio Grande and the associated Albuquerque Riverside Drain near the Rio Bravo Bridge, south of Albuquerque (fig. 1). The Santa Fe Group aquifer system consists of the upper Rio Grande alluvium underlain by the Santa Fe Group aquifer of Quaternary age.

Purpose and Scope

This report describes the results of a river-pulse study on a reach of the Rio Grande near the Rio Bravo Bridge, south of Albuquerque, New Mexico, from February to May 1997. Ground-water levels, surface-water stage, and discharge data were collected along a section perpendicular to the Rio Grande. The report describes

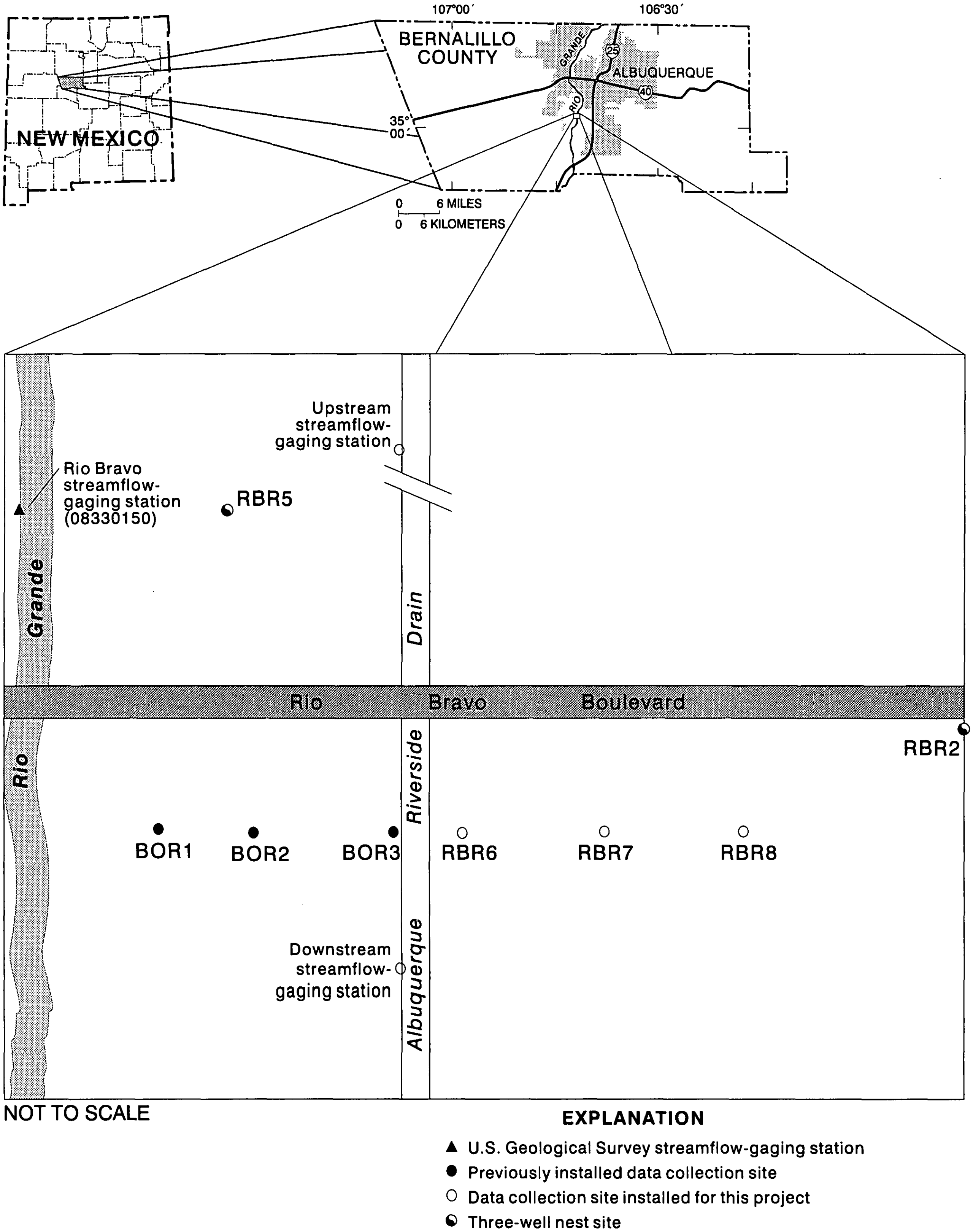


Figure 1. Rio Bravo study area and wells in the Rio Bravo study area, near Albuquerque, New Mexico.

the methods used, the data collected, and the ground-water simulation used to estimate the hydraulic properties of the aquifer. Hydraulic properties were estimated by using a two-dimensional cross-sectional ground-water flow model to simulate aquifer-system responses to a short-duration (3 days) and a long-duration (39 days) increase in river and drain stages.

Previous Studies

Several studies have been conducted on surface-water/ground-water interaction of the Rio Grande in and near Albuquerque and the determination of aquifer properties of the Santa Fe Group aquifer system. The Bureau of Reclamation (1995) completed a flood-pulse study in 1994 that estimated aquifer properties between the river and the drain using a river-pulse and computer simulation. In the Rio Grande alluvium, the horizontal hydraulic conductivity was estimated to range from about 200 to 400 feet per day (ft/d) and the horizontal to vertical hydraulic-conductivity ratio was estimated to range from about 10 to 200. In the Santa Fe Group aquifer, the horizontal hydraulic conductivity was estimated to range from about 15 to 30 ft/d and the horizontal to vertical hydraulic-conductivity ratio was estimated to be about 200. The specific yield of the Santa Fe Group aquifer was estimated by the Bureau of Reclamation (1995) to be 0.15 and the specific storage to be 2×10^{-6} per foot (ft). Because of the lack of a sufficient magnitude of stress to the ground-water system from the pulse, the investigators could detect no water-level changes in wells east of the Albuquerque Riverside Drain (fig. 1). The question still remained about the effect of the river on the aquifer east of the drain.

Following the development of a conceptual model of the flow system by Thorn and others (1993), Kernodle and others (1995) completed a simulation of the ground-water flow system in the Middle Rio Grande Valley. In the Rio Grande alluvium, the horizontal hydraulic conductivity was estimated to be about 40 ft/d and the horizontal to vertical hydraulic-conductivity ratio was estimated to be 200. In the Santa Fe Group, the horizontal hydraulic conductivity was estimated to be about 15 ft/d near the Rio Bravo Bridge and the horizontal to vertical hydraulic-conductivity ratio was estimated to be 200. Kernodle and others (1995) estimated specific yield in the Santa Fe Group aquifer system from their model to be 0.15 and assumed that the confined layers had a specific storage of 2×10^{-6} per foot.

Ground-water flow and aquifer properties were estimated for the Santa Fe Group aquifer system in the inner valley of the Rio Grande and, in particular, for the Rio Bravo area (Peter, 1987). A horizontal hydraulic conductivity ranging from about 100 to 1,000 ft/d was estimated for the sand and gravel layers. A horizontal hydraulic conductivity of 0.001 ft/d and a horizontal to vertical hydraulic-conductivity ratio of 1.5 were estimated for the clay and silt layers. Storage values were not estimated in the Peter (1987) study.

The differences in estimated values of the aquifer properties among the three studies previously discussed are likely due to the scale of the study. The study conducted by Kernodle and others (1995) was at a basin scale, and the estimated values were influenced by the area surrounding the Rio Bravo study area. Outside influences could have interfered with the values estimated for aquifer properties. The studies by Peter (1987) and Bureau of Reclamation (1995) were localized, and estimated values of horizontal hydraulic conductivity were much higher than values estimated by Kernodle and others (1995). The values estimated for vertical hydraulic conductivity among the three studies varied because of the method of estimation used. Peter (1987) reported separate values for layers of sand and gravel and for layers of clay and silt; Bureau of Reclamation (1995) and Kernodle and others (1995) reported average values for the entire matrix of sand, gravel, silt, and clay.

Description of the Study Area

The study area, southwest of Albuquerque, is about 1 square mile and is east of the Rio Grande near the Rio Bravo Bridge (fig. 1). This area was chosen because of the streamflow-gaging station and monitoring wells that were previously installed, the lack of tributary inflow in the study area, and the lack of interference from canals and ditches along the Albuquerque Riverside Drain in the study area.

The Bureau of Reclamation installed three observation wells (BOR1, BOR2, and BOR3) (fig. 1) for a flood-wave study (Bureau of Reclamation, 1995). The three 2-inch-(in.) diameter wells were completed in the alluvial aquifer at depths of 8, 11.5, and 12.5 ft, respectively. Each well has a 3.5-ft screened interval at the bottom of the casing (fig. 2).

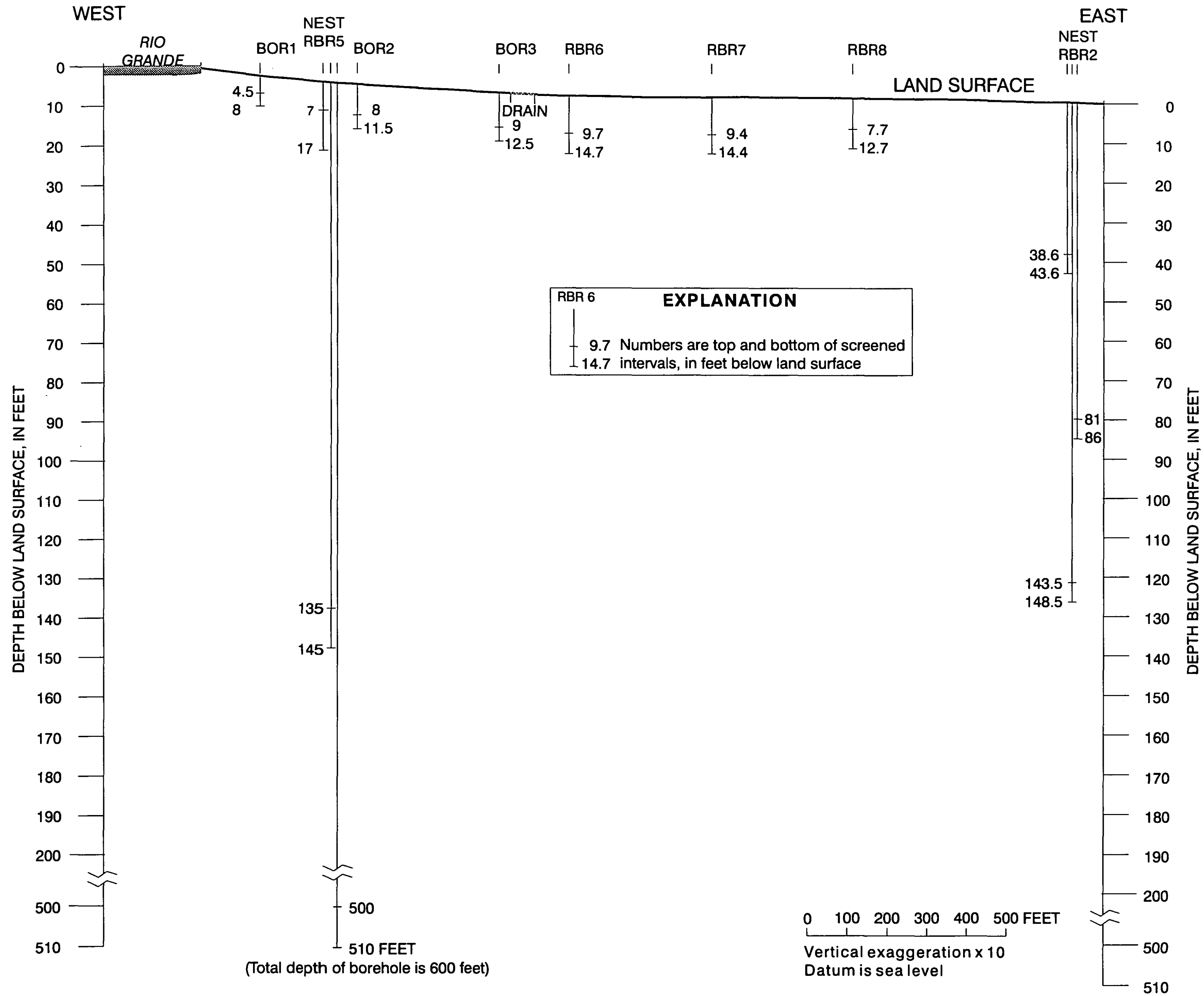


Figure 2. Depths of observation wells and open intervals of wells in the Rio Bravo study area, near Albuquerque, New Mexico.

USGS personnel had installed two observation well clusters (RBR2 and RBR5, fig. 1) for previous studies. At cluster RBR2, the wells consist of three 5-in.-diameter casings and have 5-ft screened intervals from 38.6 to 43.6 ft, 81 to 86 ft, and 143.5 to 148.5 ft (fig. 2). At cluster RBR5, the three 4-inch-diameter wells have 10-ft screened intervals from 7 to 17 ft, 135 to 145 ft, and 500 to 510 ft. The Rio Grande at Rio Bravo Bridge gaging station (08330150) (fig. 1) was installed as part of a previous water-budget study of the river.

USGS personnel also installed three observation wells (RBR6, RBR7, and RBR8) (fig. 1) in the alluvial aquifer in 1997 at depths of 14.7, 14.4, and 12.7 ft, respectively. The three 2-inch-diameter wells are constructed of galvanized pipe and have 4-ft screened intervals at the bottom.

Acknowledgments

The author is grateful for the cooperation of the Bureau of Reclamation for use of their shallow monitoring wells in the Rio Bravo study area and for data from previous studies. Appreciation is also extended to the Middle Rio Grande Conservancy District for access to their property and approval for installation of streamflow-gaging stations on the drain. This study could not have been completed without the cooperation of the City of Albuquerque Parks and Recreation Department for access to their property and of local land owners for permission to install monitoring wells on their property.

HYDROLOGY

Surface water in the study area flows in both the Rio Grande and the Albuquerque Riverside Drain. The bottom of the drain intercepts the water table in the study area and acts as a discharge area in the winter and a recharge area in the summer.

Discussion of geology in this report is limited to geologic information pertinent to the study of the ground-water flow system in the upper part of the Santa Fe Group, which includes the alluvium, and construction of the ground-water flow model.

Surface Water

In the study area, most of the water in the Rio Grande is derived from the release of water at Cochiti and Jemez Reservoirs (not shown on map), located about 50 miles (mi) upstream from the Rio Bravo study area. Some flow is derived from local runoff that collects in concrete-lined flood-control channels and enters the river north of Albuquerque. Flows in the river are usually high during snowmelt runoff from April to July.

The Rio Grande was an aggrading stream until the early 1970's. When Cochiti Dam was constructed, the sediment load of the river decreased downstream from the dam. The riverbed elevation is about 3 ft higher than the surrounding land surface in the Rio Bravo study area. Levees were constructed by the Bureau of Reclamation to contain the river during flood periods.

The Albuquerque Riverside Drain (fig. 1) was constructed to lower the elevation of the ground-water table near the river after recharge from excess irrigation applications raised the water table near and in some cases above land surface. During the winter, flow in the drain is derived from ground water. In March of each year, the Middle Rio Grande Conservancy District diverts water into the drain about 5 mi upstream from the study area for transport to irrigation canals south of Albuquerque.

Ground Water

Ground water in the study area flows through alluvium of Quaternary age, which ranges from about 80 to 120 ft thick (Peter, 1987, p. 9), and the underlying Santa Fe Group of Tertiary age, which can be as much as 14,000 ft thick in the middle of the basin (Thorn and others, 1993). Alluvial deposits in the study area are composed of cobbles, gravel, sand, silt, and clay (Peter, 1987). A hydrologic boundary may not exist between the alluvium and the Santa Fe Group in the study area (Peter, 1987, p. 9). A generalized stratigraphic column of unconsolidated deposits in the study area is shown in figure 3.

During installation of the first observation well (RBR6), the drive point became lodged in a shallow clay and silt unit at about 16 ft and could be driven no further. The well point was pumped dry, and the drive point was left in the clay and silt unit to see how

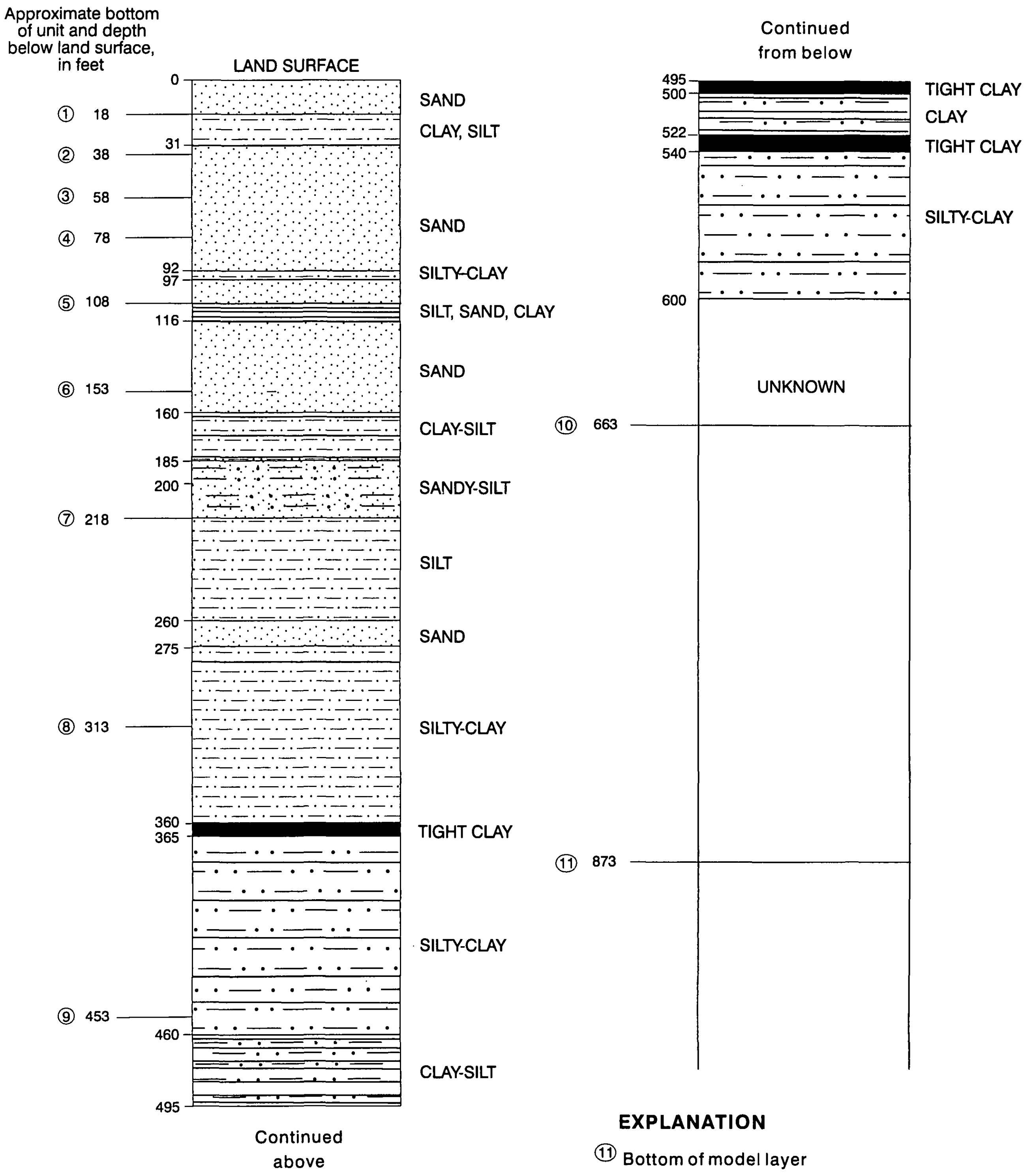


Figure 3. Generalized stratigraphic column of the RBR5 deep well in the Rio Bravo study area, near Albuquerque, New Mexico.

quickly water would enter the well. After 3 days, no measurable water had entered the well because of the extremely low hydraulic conductivity of the deposit or because the screen was plugged. The well was then plugged and abandoned; another well was installed and completed just above the clay and silt unit. In the study area, the bottom of the Albuquerque Riverside Drain is near the top of the clay and silt unit. The location, depth, and thickness of the clay and silt unit were measured at each well site using a truck-mounted geoprobe, which uses a direct-push method coring device. The clay and silt unit was present in 9 of 12 observation wells in the study area; the exceptions were the three wells at site RBR5. The thickness of the unit, where present, was about 12 ft. Cores could not be collected from the bottom of the river; therefore, the extent of the clay and silt unit under the river, if it exists, is unknown.

The deepest well is in well cluster RBR5 (fig. 2). This well was drilled to a depth of 600 ft below land surface and screened from 500 to 510 ft. The lithology below 150 ft was described from drill cuttings (fig. 3).

RIVER-PULSE DATA COLLECTION

A short-duration river pulse and a long-duration river pulse were used to stress the ground-water system. The short-duration pulse was an engineered increase in the stage of the Rio Grande of about 1 ft for a 3-day period from February 19 through 21, 1997. The long-duration pulse was the normal increase in stage in the Rio Grande from snowmelt runoff. The long-duration pulse started on March 13, 1997, and continued through the end of the data collection period in early May 1997.

Because the increases in stage during the short-duration pulse were less than 1 ft, the changes in ground-water levels were expected to be small. High-sensitivity transducers (accuracy within 0.01 ft) measured the small changes in stage and ground-water levels. Ground-water levels were measured frequently with a steel tape to verify the accuracy of the pressure-transducer measurements.

Surface Water

Stage data for the Rio Grande were collected at a temporary streamflow-gaging station near Rio Bravo Bridge (fig. 1). A float and digital recorder measured stage to an accuracy of 0.01 ft at 15-minute intervals. Stage data for the study period are shown in figure 4. During the study, the stage ranged from about 3.21 to 4.46 ft.

Two gaging stations were installed on the Albuquerque Riverside Drain (fig. 1): one near the southern boundary of the study area (downstream site) and one about 3 mi upstream from the downstream site (upstream site). The gaging stations were equipped with pressure transducers and enameled outside staff gages. Stage data were recorded electronically every 15 minutes; data for the downstream site are presented graphically in figure 5. Streamflow measurements in the Albuquerque Riverside Drain (table 1) were made using standard USGS streamflow-gaging methods described in Rantz and others (1982). Concurrent streamflow measurements at the two gaging stations on the Albuquerque Riverside Drain on February 20, 1997, and March 4, 1997, indicate that ground-water inflow to the 3-mi reach of the drain was 4.6 and 4.9 cubic feet per second (ft^3/s), respectively (table 1). The measurements were made when the drain was receiving all its water from ground-water inflow. Because stage in the Rio Grande varied less than 0.25 ft and the drain varied less than 0.08 ft during the measurement periods, the river/drain ground-water system was assumed to be near equilibrium.

Two concurrent measurements also were made later in March 1997 when water used for irrigation was diverted into the Albuquerque Riverside Drain. The difference in the measurements indicates that the 3-mi section of the drain was losing 34.6 ft^3/s on March 10 and 38.5 ft^3/s on March 19 to the ground-water system. The loss of drain water to the ground-water system is likely due to the increased depth of water in the drain in comparison to depth to the ground-water table. The difference in heads created a temporary reversal in gradient.

The effect of the short-duration pulse on flow in the drain was minimal: the stage increased 0.05 ft as a direct response. This minimal response was likely due to the short duration of the stress (3 days) to the ground-water system and the attenuation of the amplitude of the stress. Irrigation water was diverted into this part of the Albuquerque Riverside Drain in the study

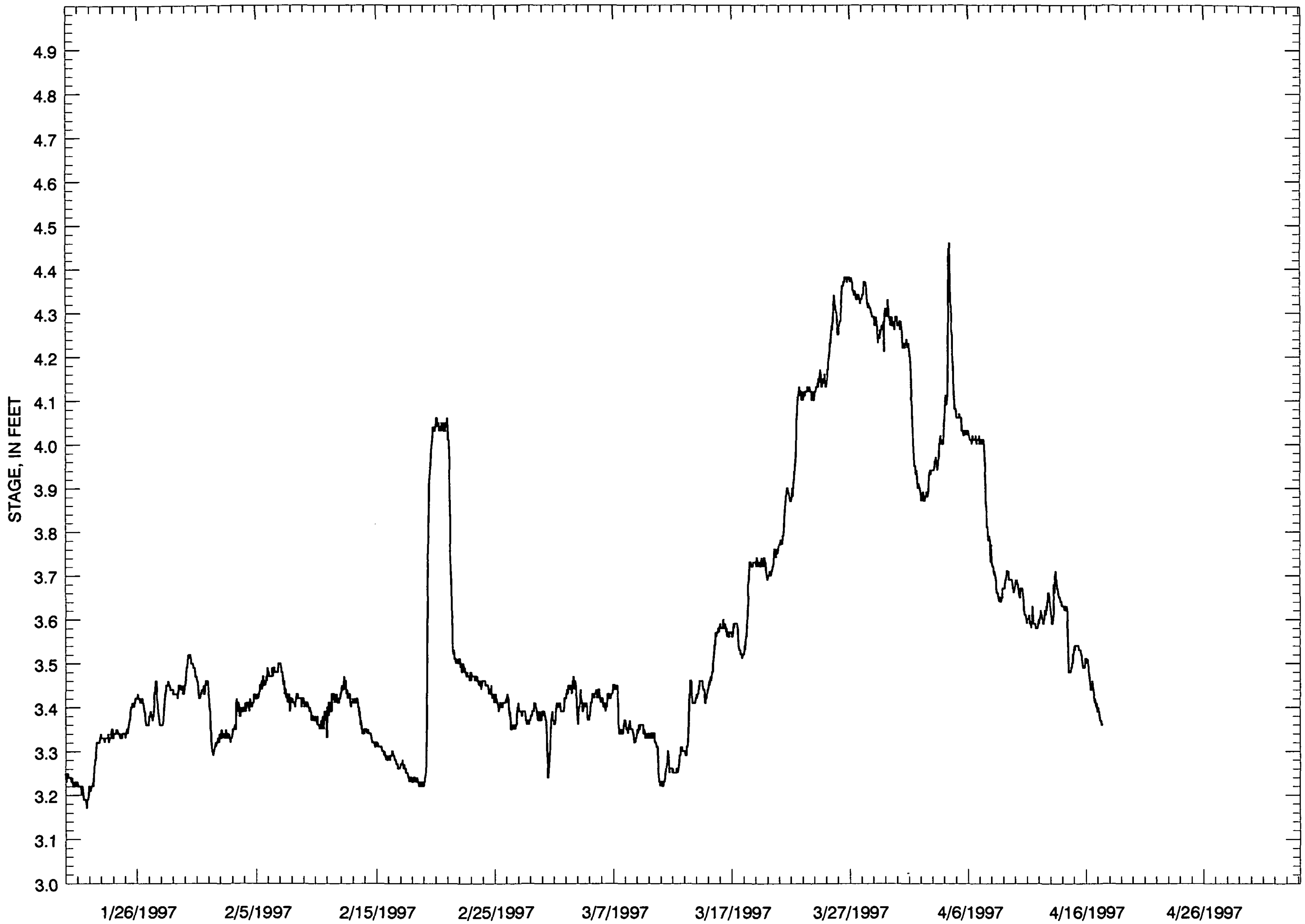


Figure 4. Stage at Rio Grande at Rio Bravo Bridge (08330150) in the Rio Bravo study area, near Albuquerque, New Mexico (see figure 1 for location).

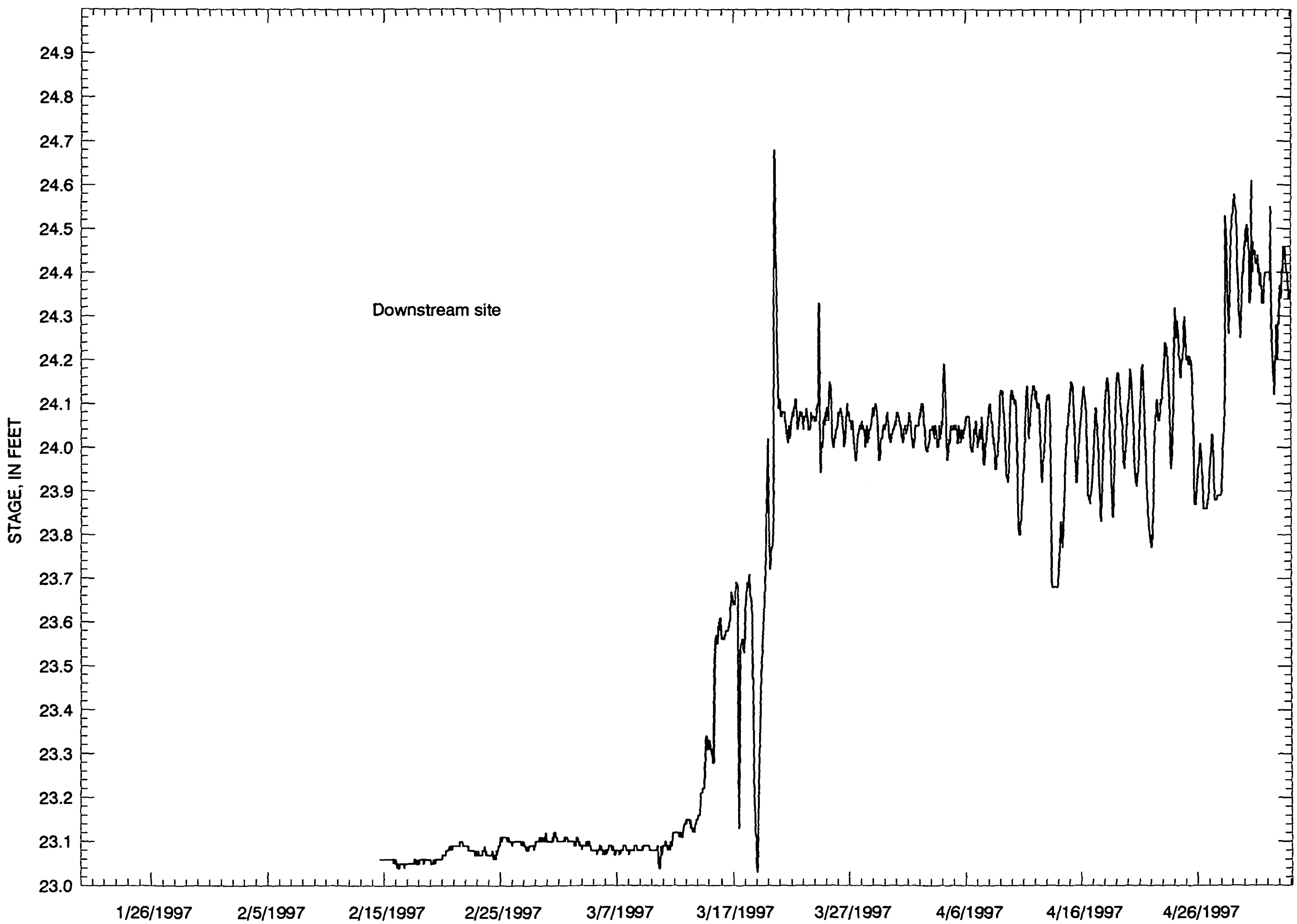


Figure 5. Stage at downstream streamflow-gaging station on the Albuquerque Riverside Drain in the Rio Bravo study area, near Albuquerque, New Mexico.

Table 1. *Streamflow measurements in the Albuquerque Riverside Drain in the Rio Bravo study area, near Albuquerque, New Mexico*

[*, gain or loss could not be determined because upstream measurement was not made on this date]

Site (fig. 1)	Date	Streamflow (cubic feet per second)	Gain (+) or loss (-) to the ground-water system (cubic feet per second)
Upstream	02/20/97	13.9	
Downstream		18.5	-4.6
Upstream	03/04/97	12.6	
Downstream		17.5	-4.9
Upstream	03/10/97	52.3	
Downstream		17.7	+34.6
Upstream	03/19/97	94.6	
Downstream		56.1	+38.5
Downstream	04/28/97	107	*
Downstream	05/02/97	115	*
Downstream	05/19/97	118	*

area on March 10. Flow of irrigation water was stopped several times from March 16 to March 19. The stage in the drain ranged from 23.68 to 24.34 ft from March 22 to April 28. After the irrigation water was diverted into the drain, all discharge from the ground-water system was masked by the greater flow of irrigation water.

Ground Water

Each observation well was equipped with a pressure transducer to measure water levels. The water levels were recorded at 5-minute intervals using an electronic data logger. Each transducer was calibrated by developing a relation between the water level measured by steel tape (in feet) and the millivolt output of the pressure transducer. Hydrographs showing water levels measured in each of the 12 wells are shown in figure 6 (A-L). During each site visit, a water-level measurement was made with a steel tape to verify the recorded water levels. If corrections to the water-level record were needed, datum corrections were prorated by time to make the corrections. Water-level measurements are shown in table 5 (at back of report). Water levels indicate that ground water flows generally toward the east, perpendicular to the river.

The change in water levels in wells BOR1, BOR2, and BOR3 caused by the short-duration pulse (February 19-21) ranged from about 0.6 ft in BOR1 (fig. 6A) to about 0.12 ft in BOR3 (fig. 6C). The response to the pulse at well BOR3 was substantially attenuated in comparison to BOR1 and BOR2. A clear response to the short-duration pulse also was seen in the shallow (0.65 ft) and intermediate- (0.36 ft) depth wells in RBR5 (figs. 6G-H). The deep well in RBR5 (fig. 6I) showed a possible response to the short-duration pulse. Well RBR6 (fig. 6J), which is just east of the drain from the river, had a small response to the short-duration pulse (less than 0.07 ft). The two other shallow wells between well RBR6 (fig. 6J) and the RBR2 well nest (figs. 6D-F), RBR7 (fig. 6K) and RBR8 (fig. 6L), showed no discernible water-level change during the short-duration river pulse. Water levels ranged from about 0.09 ft in wells RBR2 shallow and intermediate to about 0.2 ft in well RBR2 deep. A possible reason for the responses observed in well RBR2, in comparison to no measurable response in wells RBR7 and RBR8, is that the RBR2 wells are completed below the discontinuous clay layer. The response to the short-duration pulse above the clay layer might be dampened by the drain but might not be dampened beneath the clay. If the clay layer does not extend under the river, the sudden change in river stage would cause a pressure change in the semiconfined alluvium below the clay, which would cause a water-level change in the RBR2 wells.

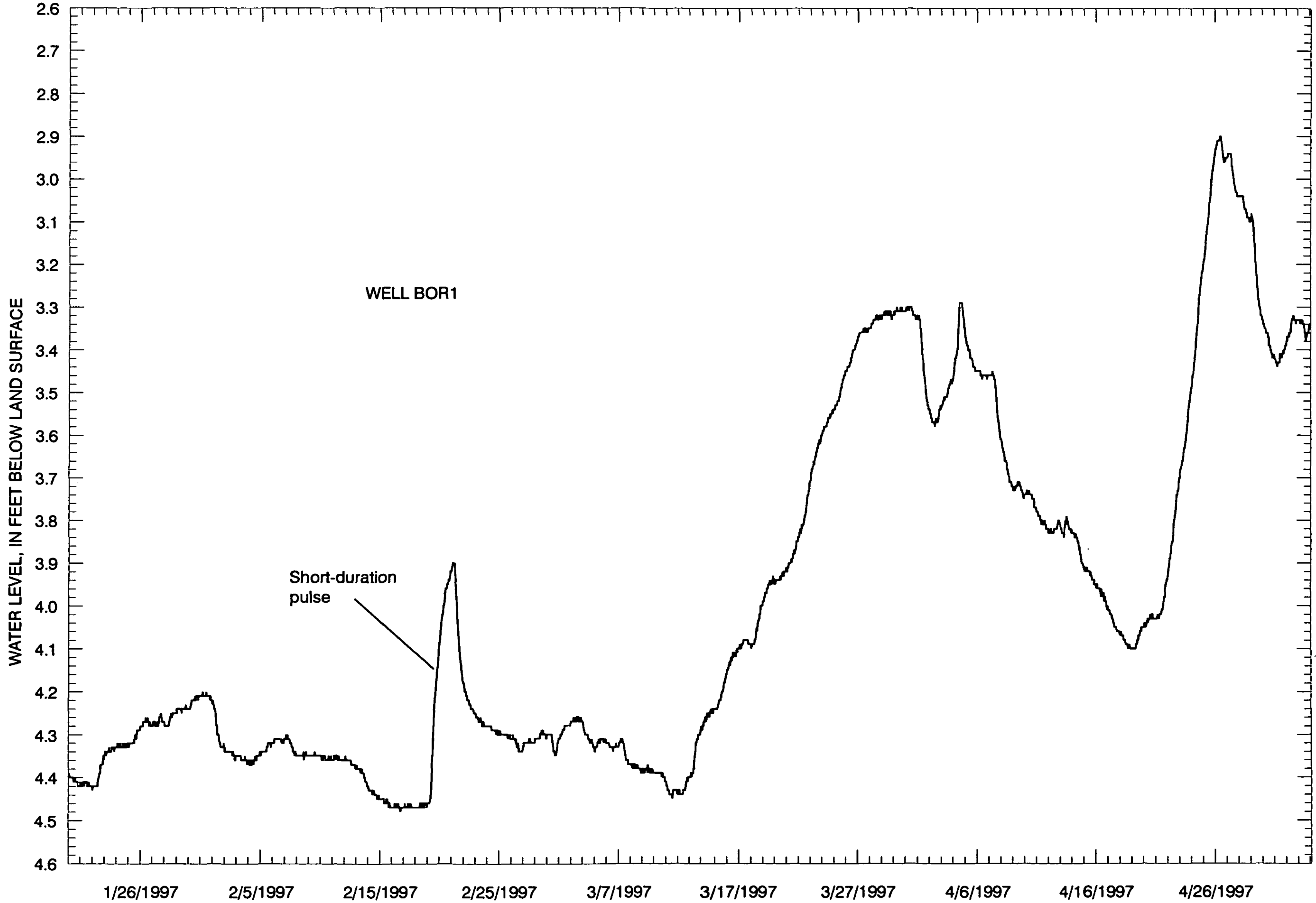


Figure 6A. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico.

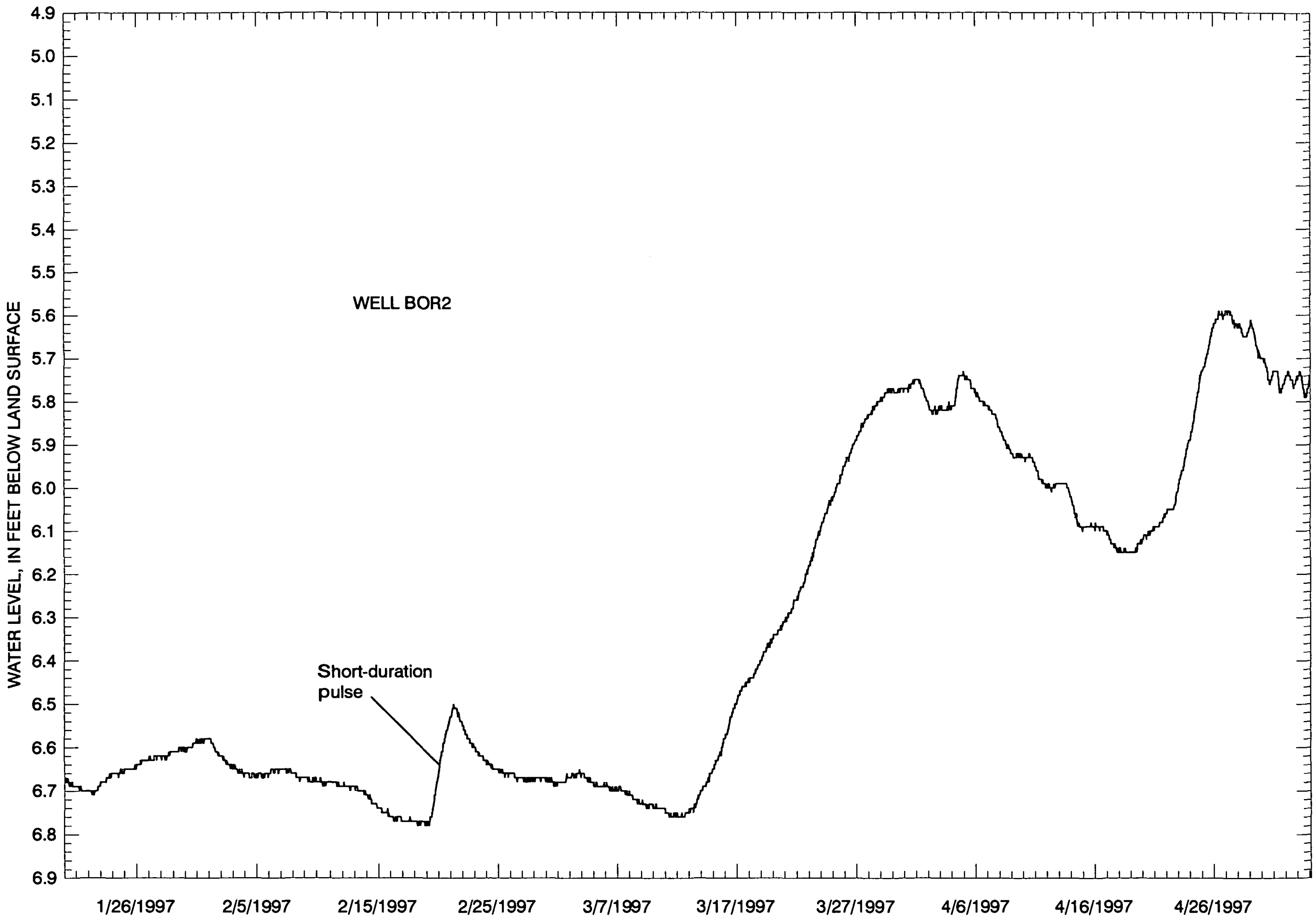


Figure 6B. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

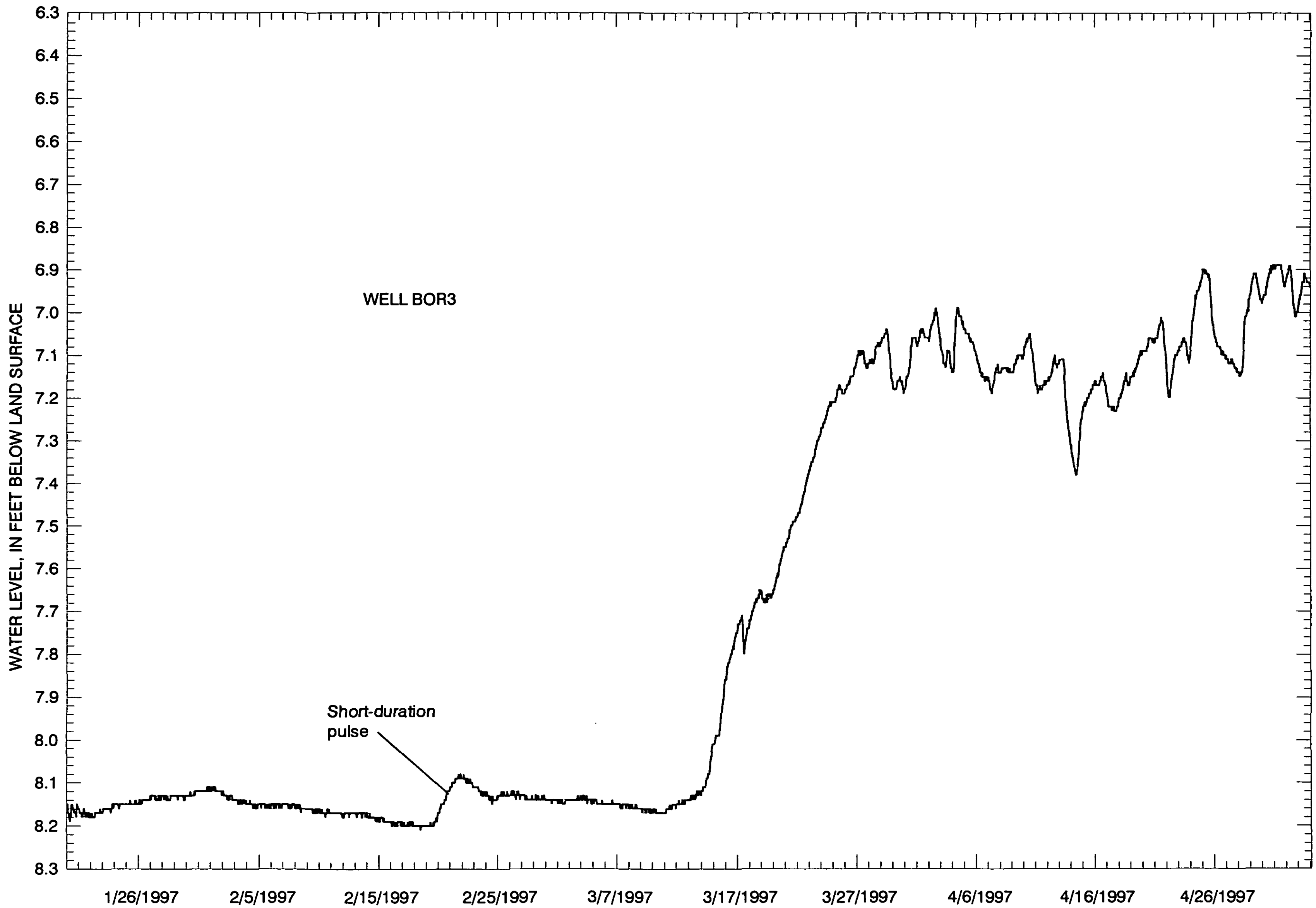


Figure 6C. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

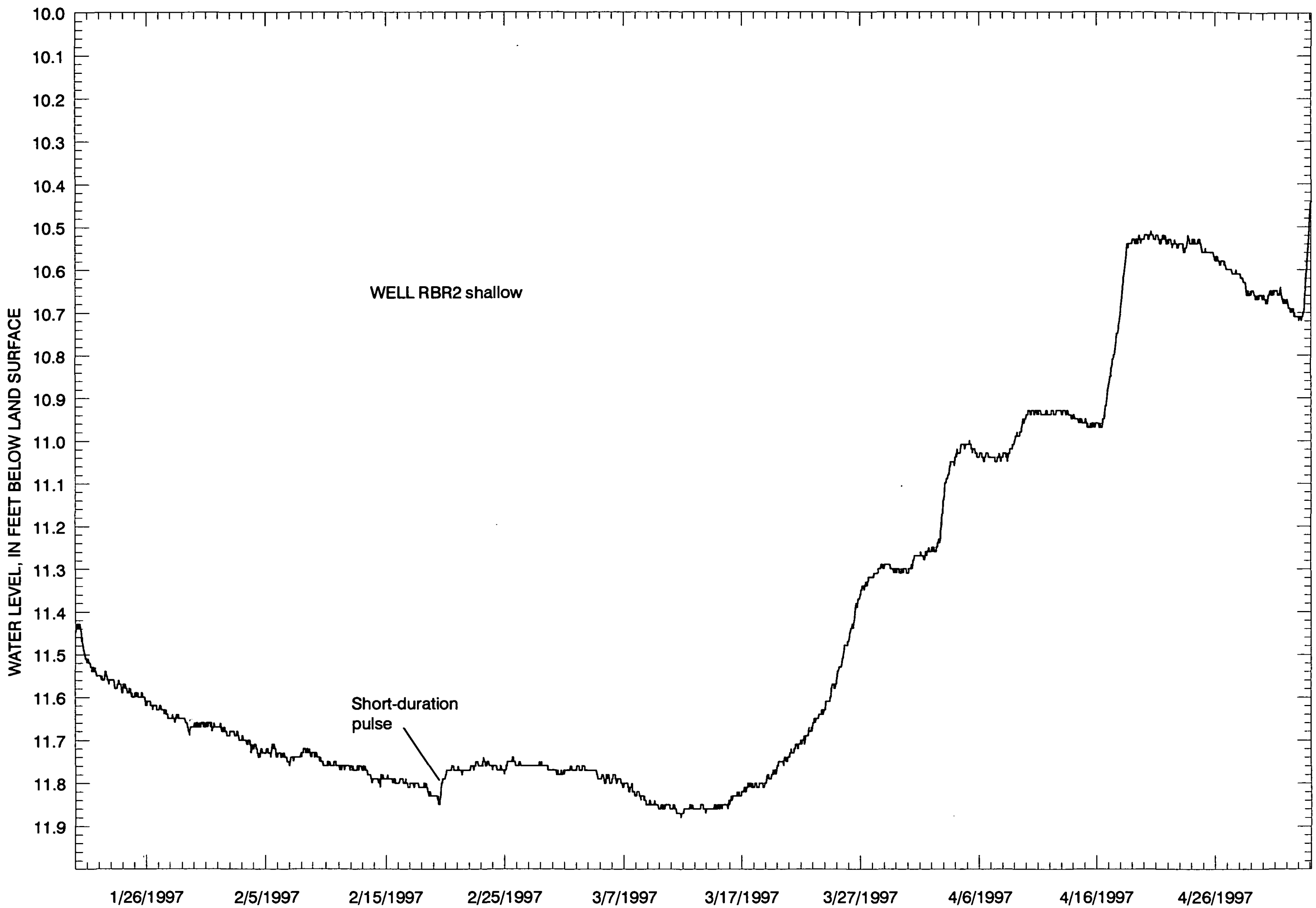


Figure 6D. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

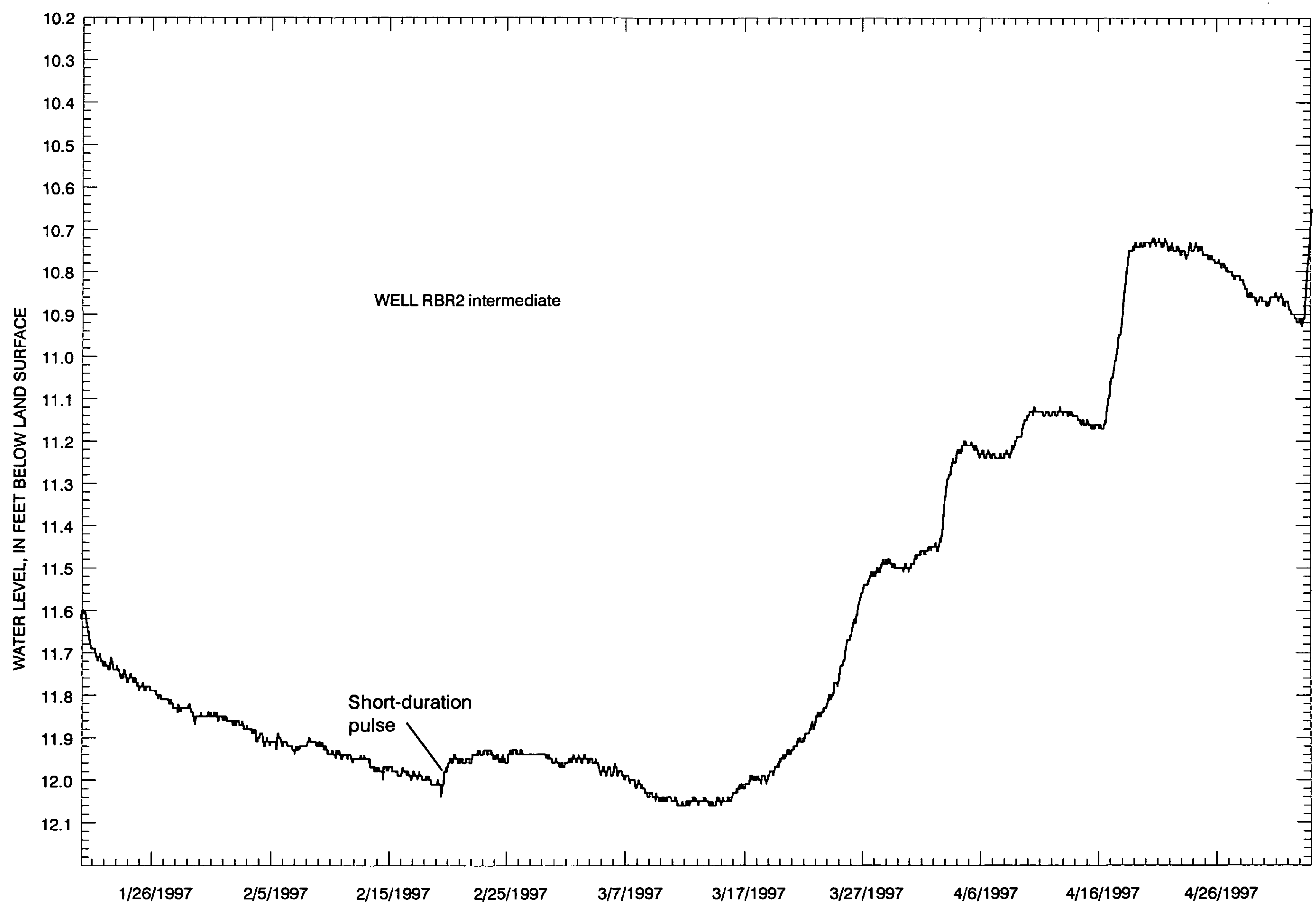


Figure 6E. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

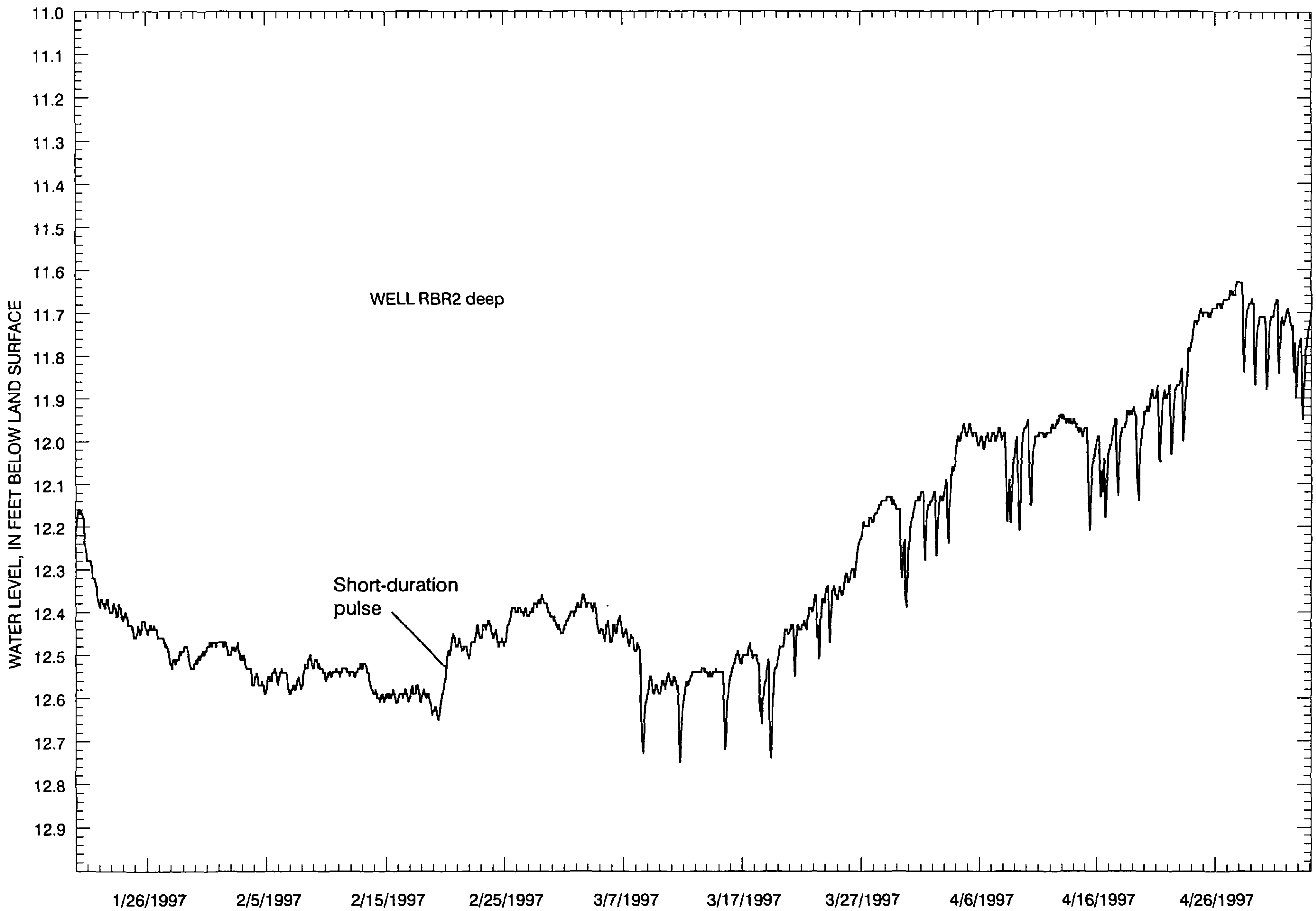


Figure 6F. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

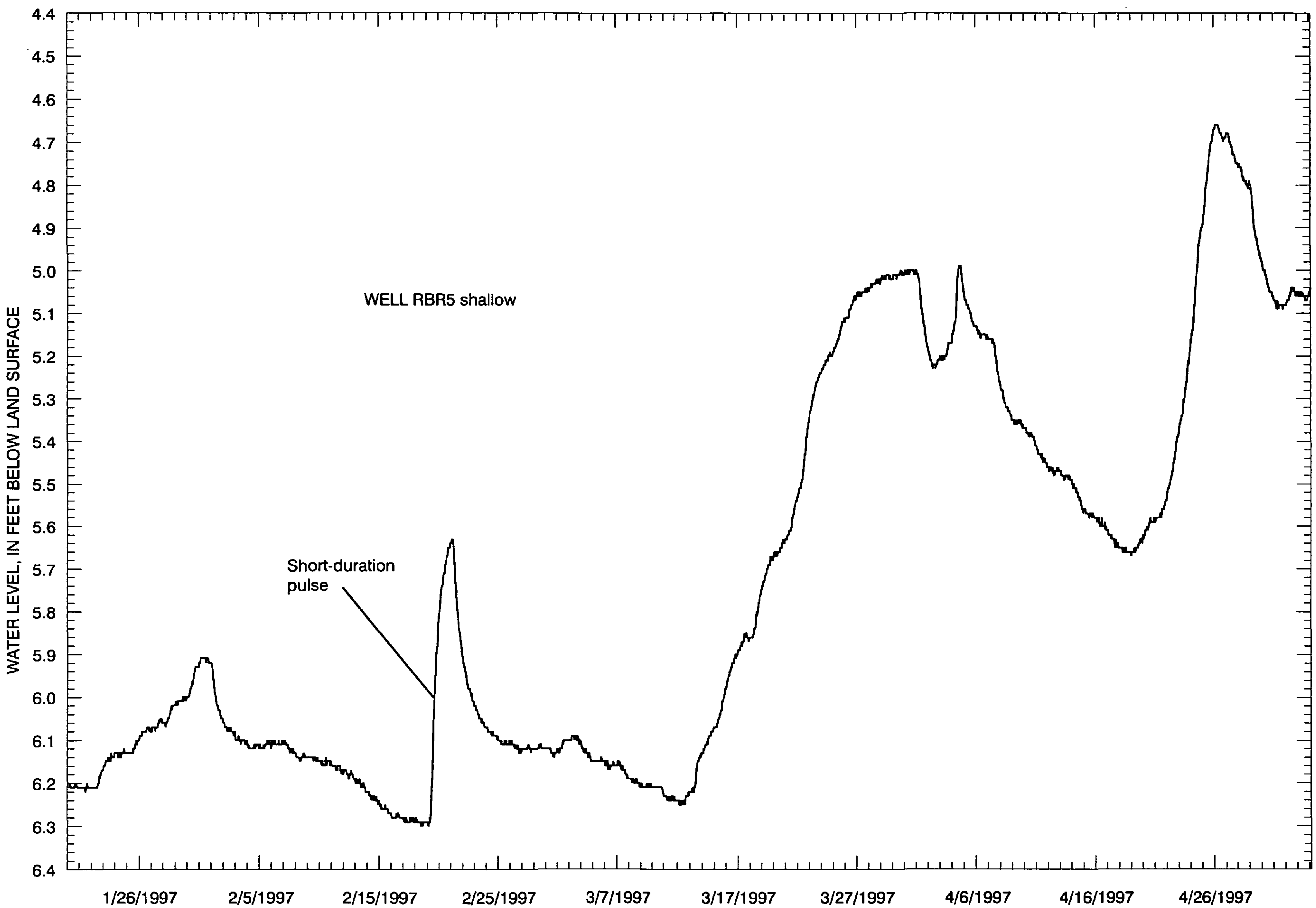


Figure 6G. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

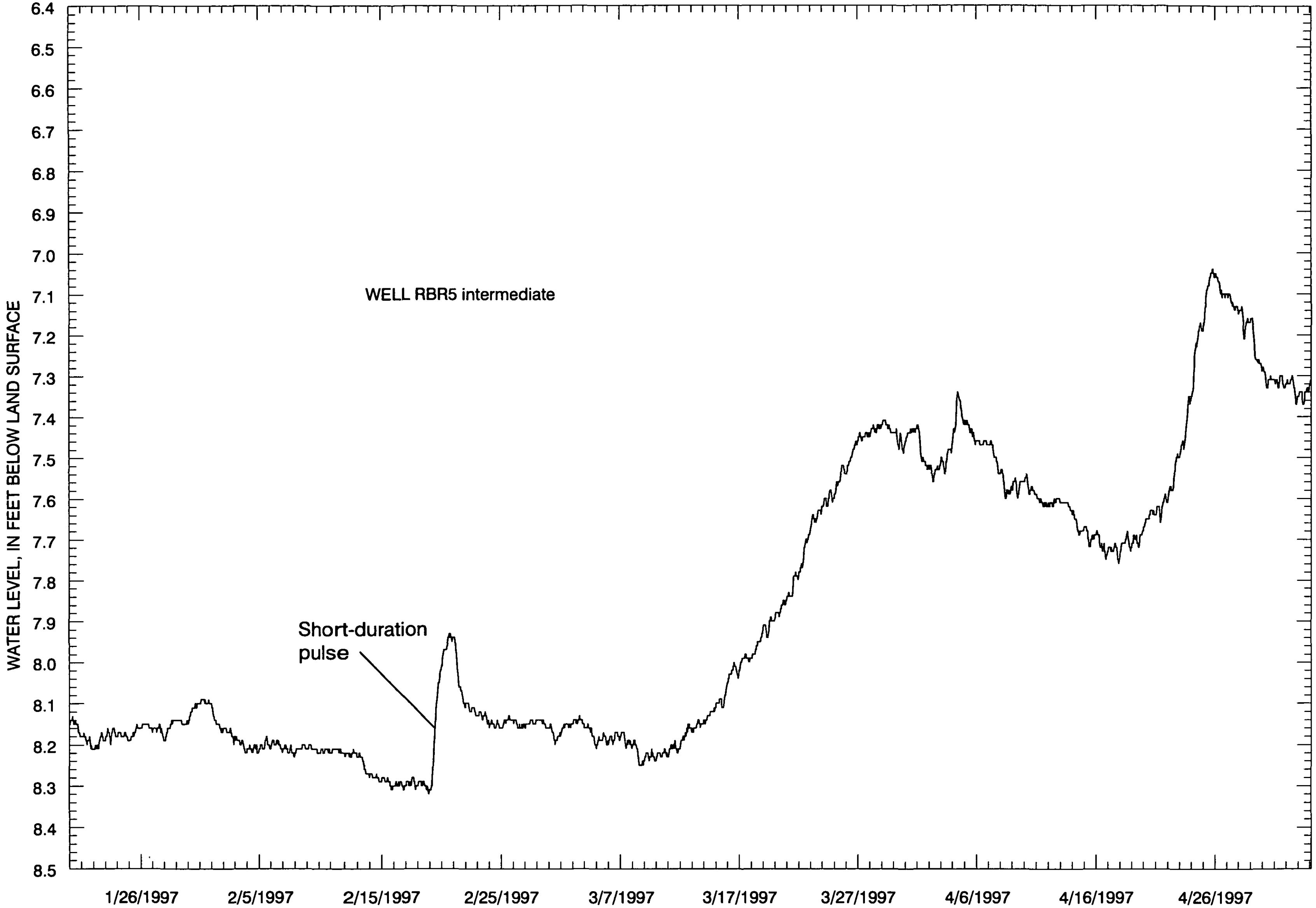


Figure 6H. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

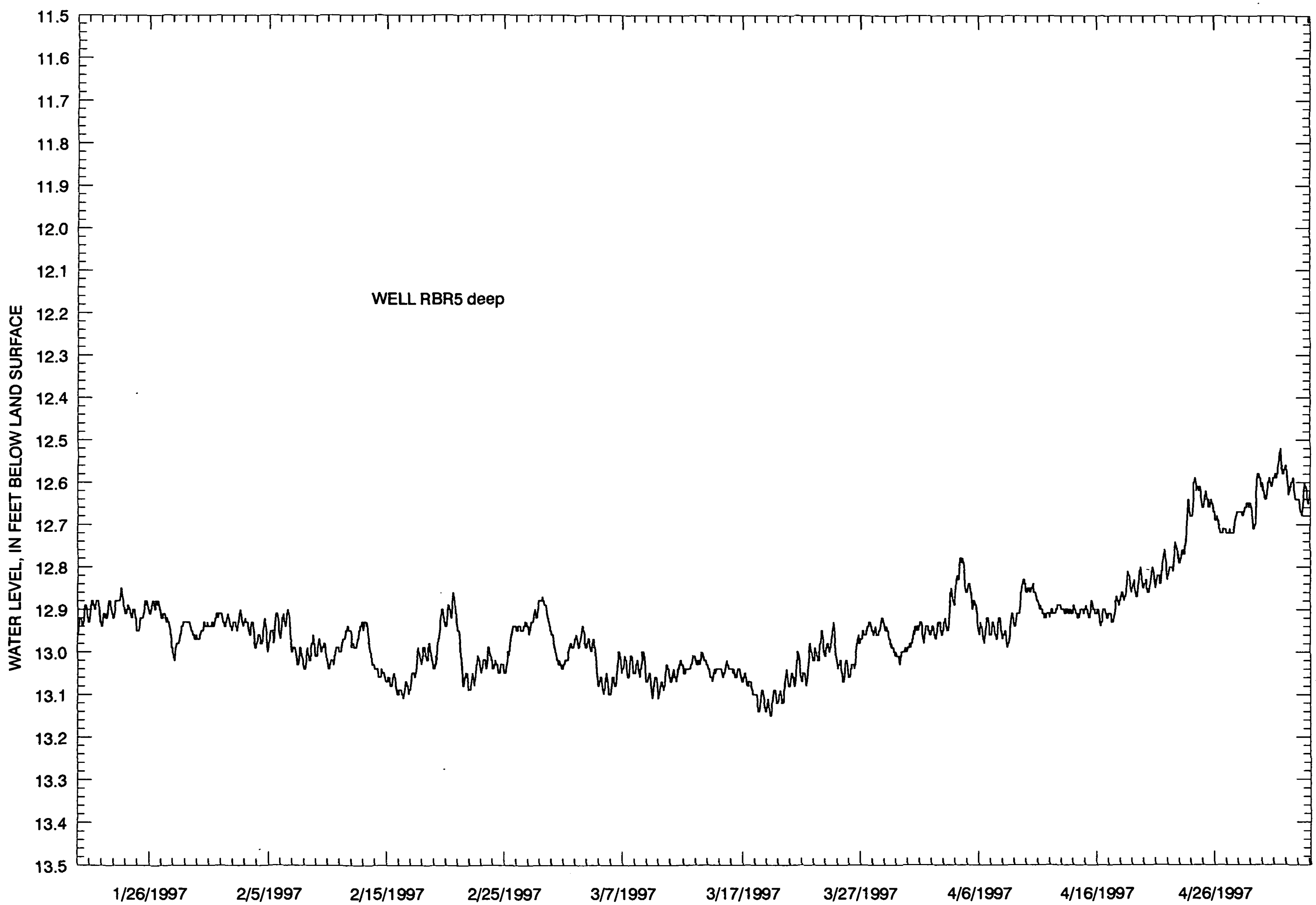


Figure 6l. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

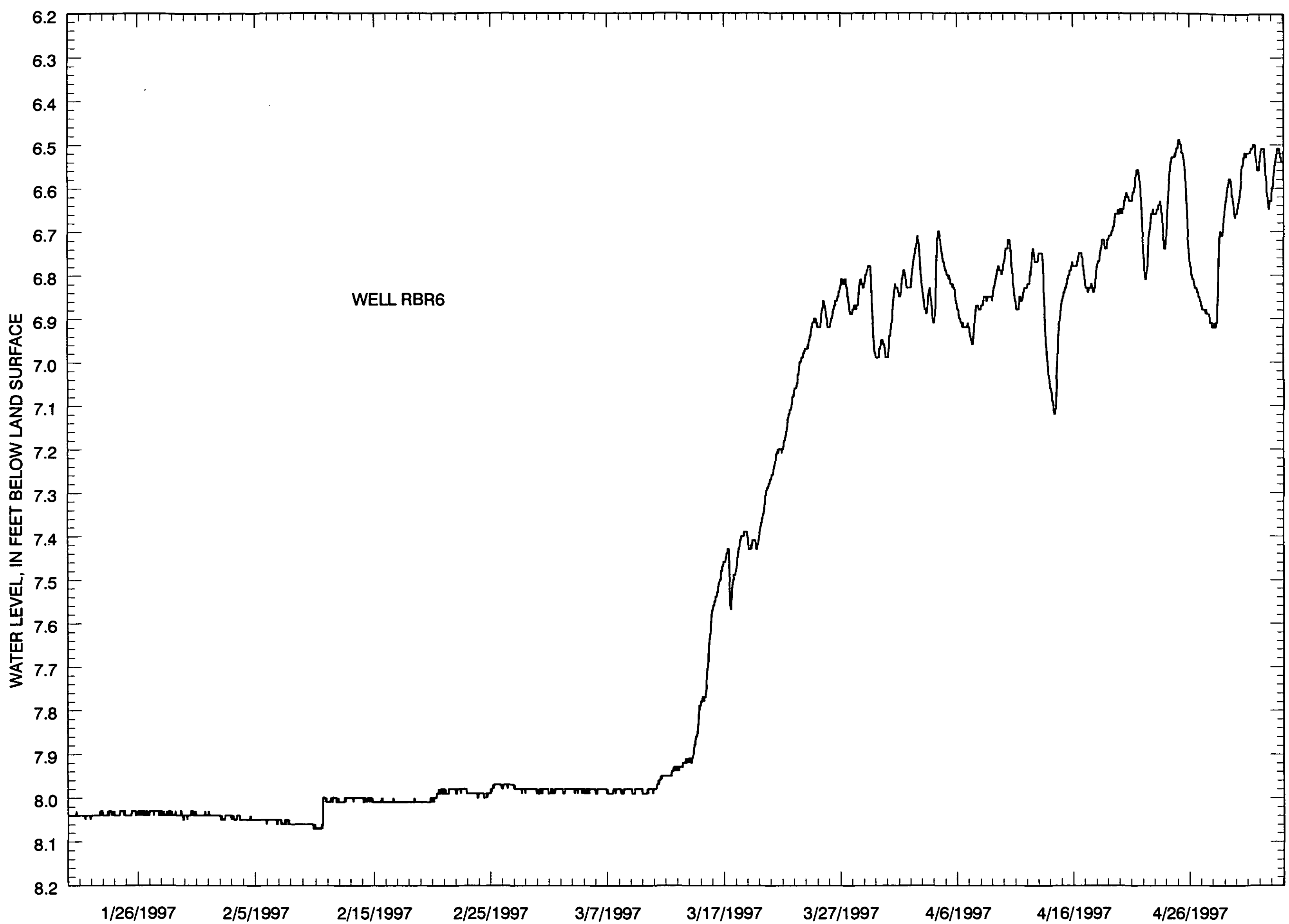


Figure 6J. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

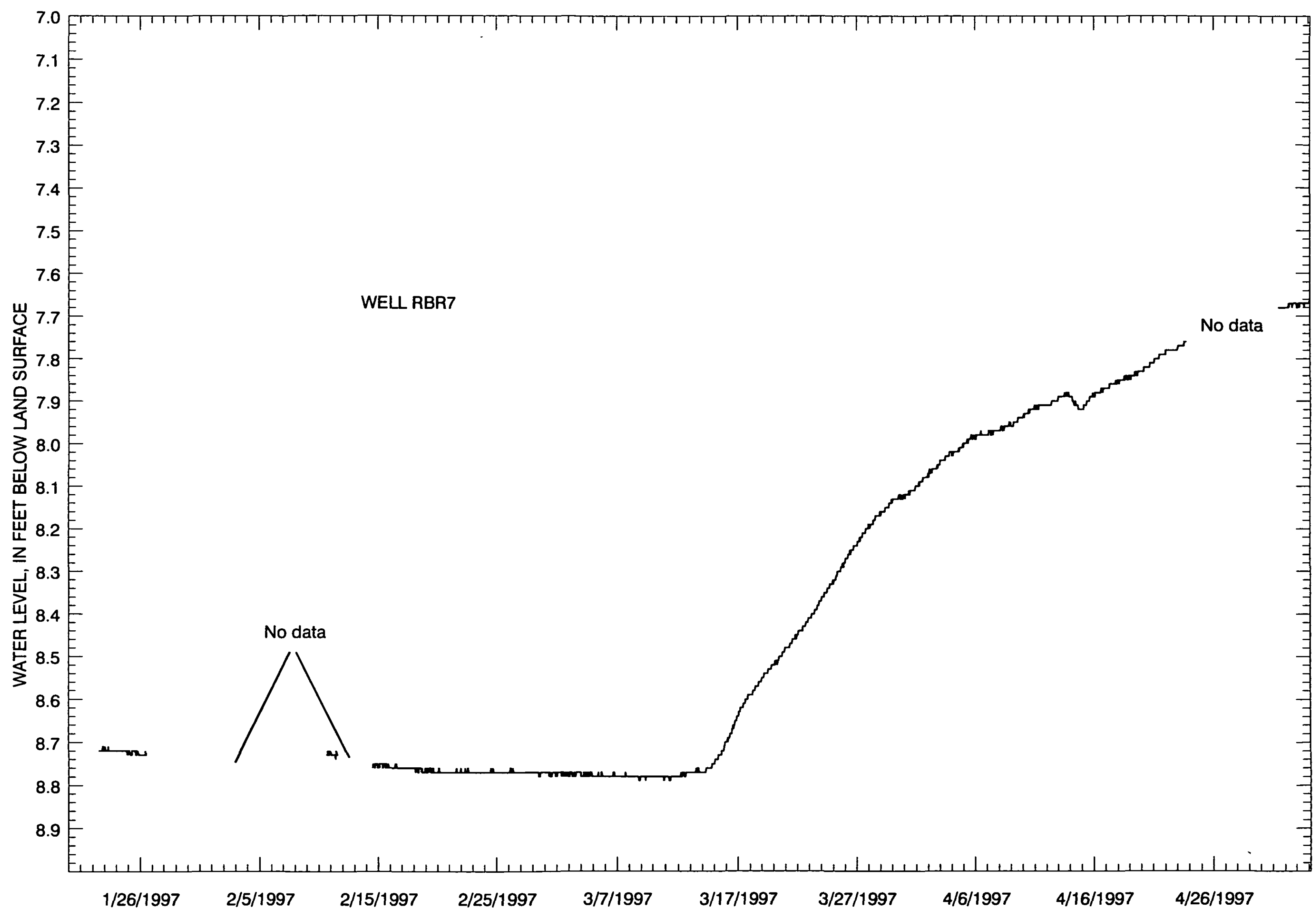


Figure 6K. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

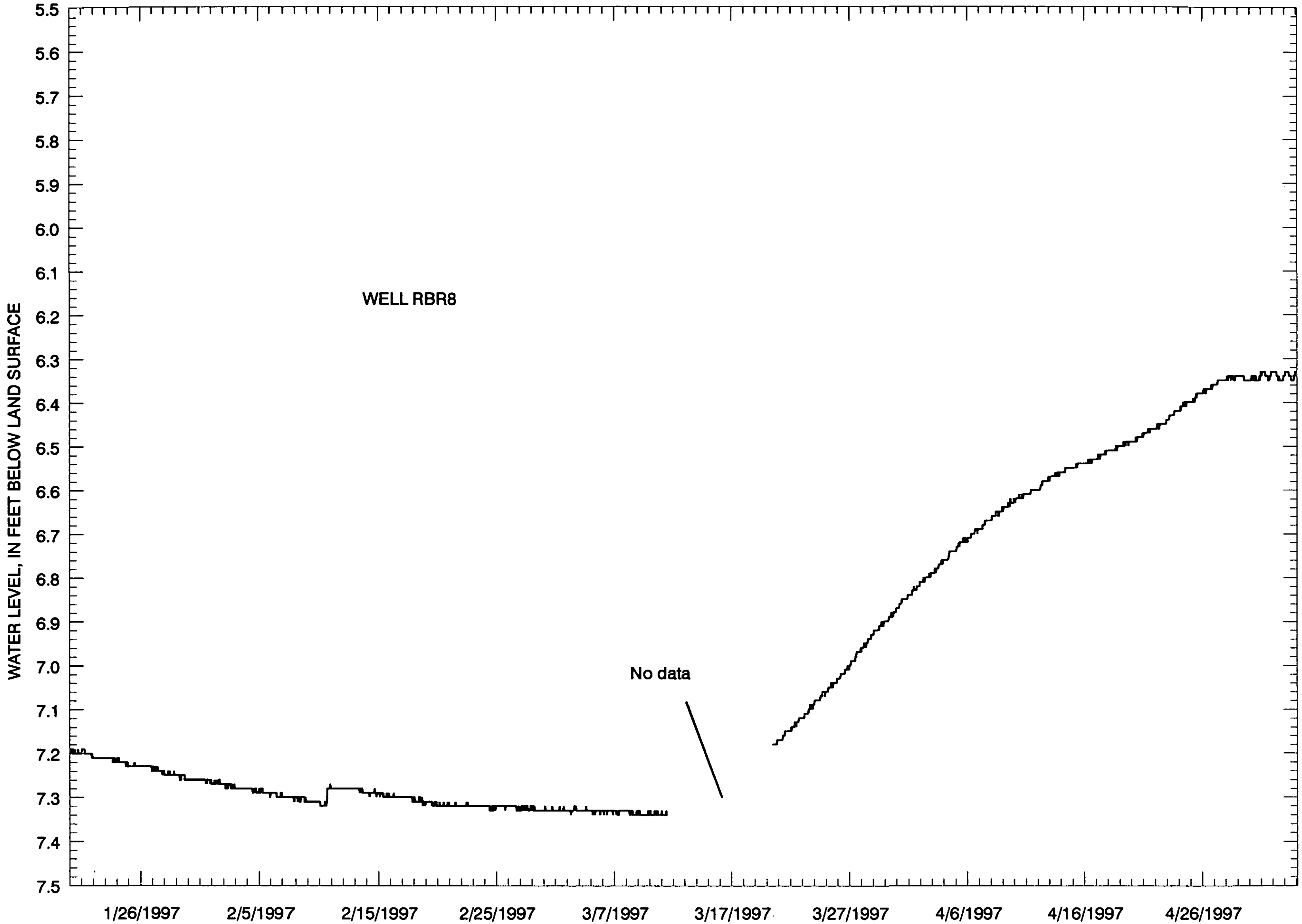


Figure 6L. Water levels in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Concluded.

All observation wells had large water-level changes caused by the long-duration river pulse and the diversion of irrigation water into the drain. When water-level changes (fig. 6) in wells BOR1, BOR2, and RBR 5 (shallow and intermediate) are compared to stage changes in the Rio Grande and Albuquerque Riverside Drain (figs. 4 and 5), the water-level changes appear to be more a reflection of stage in the river than of stage in the drain. The increase in water levels from about March 13 to April 1 and the subsequent rise and decline of water levels from April 1 to April 17 are similar to the change of stage in the river. Water-level changes in wells BOR3, RBR6, RBR7, and RBR8 appear to be affected by the drain (fig. 5) more than the river. This can be seen in the general lack of water-level declines from April 1 to April 17, when the stage of the river decreased but the stage in the drain did not change substantially.

Although some response to the short-duration pulse in RBR2 was evident, the change in water levels from March 8 to about May 4 (when the data loggers were removed) appears to be affected by an outside source other than the river or drain. Influences from ground-water pumpage in the area affecting the deep RBR2 well are shown in figure 6J. The effect from pumping is shown as numerous declines in water levels of less than 1 day starting about March 1. This effect is superimposed on the long-term, water-level changes caused by the change in river stage. The location of the well or wells that were pumping during the study is unknown.

ESTIMATION OF HYDRAULIC CHARACTERISTICS BY COMPUTER SIMULATION

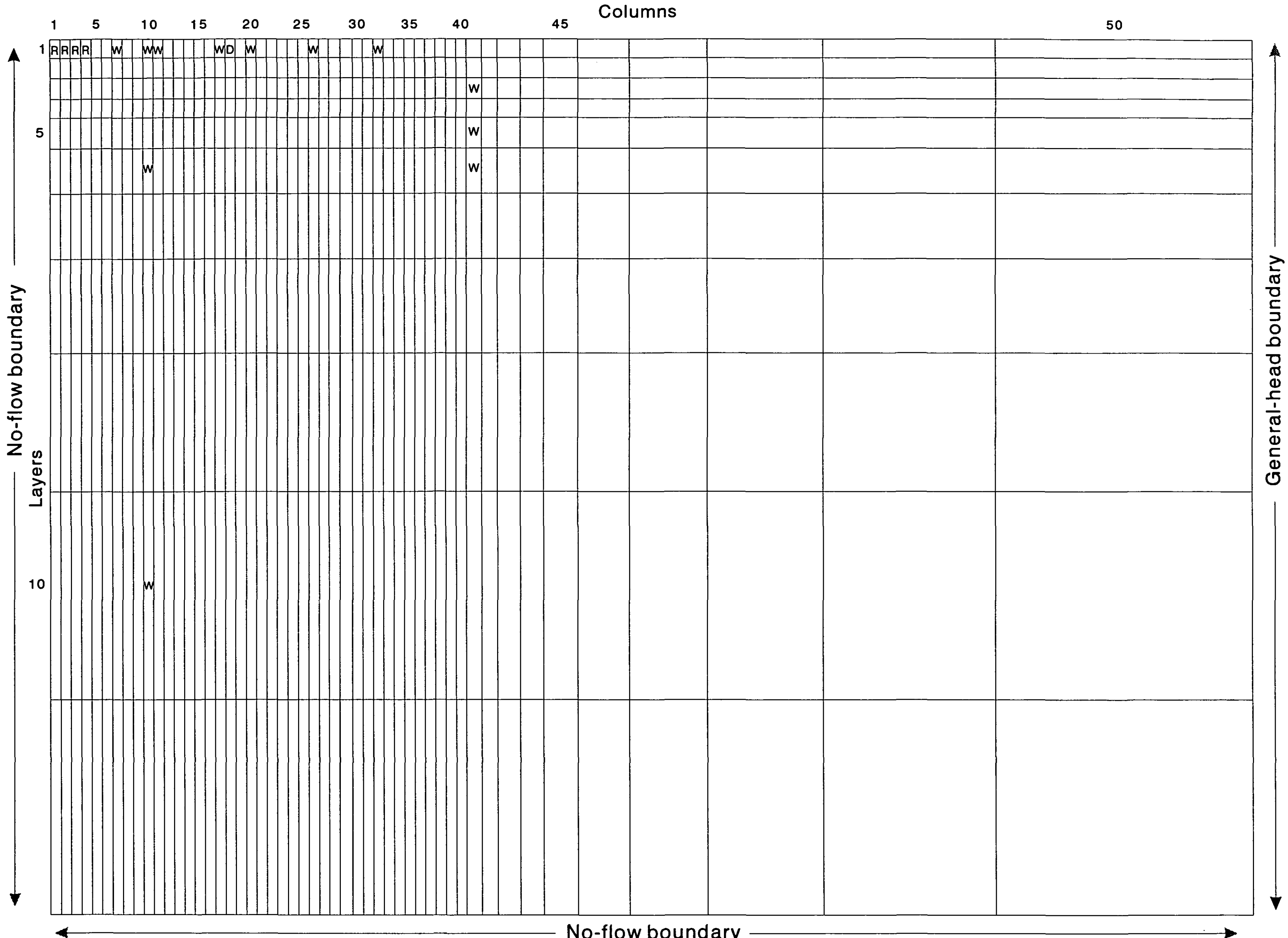
The response of the aquifer system and the drain to changes in the stage of the river and the drain was simulated by using the USGS program MODFLOW-96 (Harbaugh and McDonald, 1996). For this study, the numerical, two-dimensional model simulates a cross section of the ground-water system perpendicular to the river and drain. The two-dimensional layer is oriented vertically. To adequately simulate the surface-water/ground-water system, all ground-water flow must be perpendicular to the river and drain. This condition is met, as shown in the potentiometric maps constructed by Peter (1987) and Thorn and others (1993) in the Rio Bravo study area.

The model analysis described in this report uses the principle of superposition for simulating river-pulse effects. This principle is applicable to a linear problem and, as applied to a ground-water system, means that the result of multiple stresses on an aquifer system is equal to the sum of the results of the individual stresses. Because part of the aquifer is unconfined, transmissivity changes as a result of drawdown of the water table and the differential equations describing the problem are not strictly linear. If the drawdown is small relative to the aquifer's saturated thickness (about 10 percent or less), the error associated with this nonlinearity generally is acceptably small (Reilly and others, 1987). Because water-level changes in the observation wells in response to the river pulses were substantially less than 10 percent of aquifer thickness, the error introduced as a result of using the superposition approach is considered small. For a detailed discussion of the application of superposition to ground-water problems, the reader is referred to Reilly and others (1987).

To apply the principle of superposition to a ground-water flow model, the initial simulated hydraulic head for the aquifer and all model boundaries are equal to zero, which makes all initial fluxes in the model also equal to zero. Top and bottom altitudes of a layer are specified in the model in relation to the initial water-table altitude to conform with the initial hydraulic-head values and to assure that layer thicknesses are calculated correctly within the model code. All simulated changes in hydraulic head and fluxes result from the simulated stress to the ground-water system from the river and drain pulses.

Discretization of the Cross Section

The vertical cross section was discretized into a non-uniform, rectangular grid composed of cells (fig. 7). The grid is 6,975 ft wide and 875 ft deep, and all cells are active. Unlike horizontal grids composed of rows and columns, the grid used in this simulation consists of 50 columns and 11 layers. The width of the cells ranged from 60 to 1,500 ft. The widths of the columns near the river are much smaller than those of columns farther from the river, so that the area near the river, drain, and observation wells has a finer resolution than other areas. The thickness of the 11 layers ranges from 3.78 to 210 ft. The width of the model cross section was set to 300 ft.



EXPLANATION

W OBSERVATION WELL

D DRAIN CELL (HEAD-DEPENDENT BOUNDARY)

R RIVER CELL (HEAD-DEPENDENT BOUNDARY)

VERTICAL EXAGGERATION X 8

Figure 7. Schematic showing model grid and boundaries.

Layer 1 is simulated as an unconfined layer with an initial saturated thickness of 3.78 ft at column 50 to 15.32 ft under the river at column 1. Water-level changes in layer 1 can cause the saturated thickness to vary. This initial saturated thickness was chosen because of the clay layer that is present under most of the study area. The top of the clay layer was chosen as the bottom of layer 1. Layer 2 simulates 20 ft of saturated deposits, which includes about 12 ft of the clay unit, using the confined- or unconfined-layer option described in McDonald and Harbaugh (1988, p. 5-26). This option allows the storage term in a cell to be converted from confined to unconfined when the water level declines below the top of the cell. Layers 3 through 11 were simulated using the confined-layer option described in McDonald and Harbaugh (1988, p. 5-26). Layer characteristics are shown in table 2.

head-dependent flux boundaries is shown in figure 7. The top of the water table is simulated as a free-surface boundary and is the boundary between the saturated flow field and the atmosphere. The position of the free-surface boundary can rise or decline with time, thus changing the geometry of the flow system (Franke and others, 1984). Because of the changing geometry and heads, the simulation of the first layer is nonlinear.

No-flow boundaries are outside the model domain along column 1 and at the bottom of layer 11 (fig. 7). The ground-water system and drain on the west side of the river were assumed to be independent of the east side; thus, the center of the river is a no-flow boundary. As a result of the no-flow boundary, there is no horizontal flow across a vertical line that extends downward from the center of the river. The bottom of layer 11 was assumed to be far enough away from the hydraulic stresses of the river and drain that there would be no flow at that boundary.

Table 2. *Layer characteristics of the cross-sectional model in the Rio Bravo study area, near Albuquerque, New Mexico*

Layer	Type of layer	Top of layer (feet below land surface)	Bottom of layer (feet below land surface)
1	Unconfined	Variable	3.78 - 15.32
2	Confined/unconfined	3.78 - 15.32	23.78 - 35.32
3	Confined	23.78 - 35.32	43.78 - 55.32
4	Confined	43.78 - 55.32	63.78 - 75.32
5	Confined	63.78 - 75.32	93.78 - 105.32
6	Confined	93.78 - 105.32	138.78 - 150.32
7	Confined	138.78 - 150.32	203.78 - 215.32
8	Confined	203.78 - 215.32	298.78 - 310.32
9	Confined	298.78 - 310.32	438.78 - 450.32
10	Confined	438.78 - 450.32	648.78 - 660.32
11	Confined	648.78 - 660.32	858.78 - 870.32

Boundary Conditions

The physical and hydrologic limits of the simulated ground-water flow system are defined as the boundaries of that system. The model can simulate different mathematical representations of these boundaries. Head-dependent flux, free-surface, and no-flow boundaries, as described by Franke and others (1984), are used in the cross-sectional simulation. Recharge to and discharge from the model are simulated as head-dependent flux boundaries through the drain, river, and general-head boundary. The location of cells with

In the simulation, there are only two sources of recharge: the river and the drain. During the period of the two river pulses, there were no precipitation events or other means of recharge to the study area. Both the river and the drain were simulated using the river package described by McDonald and Harbaugh (1988, p. 5-26). The drain was simulated in this manner because the drain acts as both a point of recharge and discharge, depending on the difference in head.

The computation at a river cell requires elevation of river stage, riverbed, and conductance as inputs to the model. River- and drain-stage data collected by recorders before and during the river pulses were used to determine heads for each stress period for the simulation in both the river and the drain. No completed studies of river and drain-bed conductivity were available at the time of this study; therefore, these values were estimated. The initial estimates of conductance of the river and drain cells were calculated by using the values of vertical hydraulic conductivity of the shallow aquifer estimated by the Bureau of Reclamation (1995). The conductance was varied during calibration, and final values are shown in table 3. The river and drain bed, determined from surveyed river- and drain-bed elevations, were both estimated to be 1 ft deep.

In the simulation there are three areas of discharge: the drain in column 18, the general-head boundary (GHB) in column 50, and the river in columns 1-3 during the recession of the river pulse. All cells in column 50 are GHB cells, described by McDonald and Harbaugh (1988, p. 11-1), that simulate flow out of the cross section into the ground-water system east of the study area. As inputs to the model, GHB cells have conductance between the source and the cell and constant hydraulic head for each stress period. The initial conductance value was calculated on the basis of a horizontal hydraulic conductivity of 100 ft/d reported by the Bureau of Reclamation (1995). Conductance values were varied during the calibration process by calculating a new value for each layer. The values were based on the horizontal hydraulic conductivity in row 50 in each layer. Final conductance values are listed in table 3.

Hydraulic Properties

Horizontal hydraulic-conductivity values of the deposits adjacent to the Rio Grande in the Albuquerque area are known in only a few locations. The initial horizontal hydraulic conductivity was estimated on the basis of lithologic descriptions from driller logs and geophysical logs. During calibration, horizontal hydraulic-conductivity values were varied within appropriate ranges to match measured water levels. The final value used for horizontal hydraulic conductivity in each layer is shown in figure 8.

During calibration, simulated water levels were closer to measured water levels when horizontal hydraulic-conductivity values were decreased in columns 41 through 50. Values of 50 and 100 ft/d in layer 1 are reasonable because of the large percentage of sand

Table 3. *Final conductance values for river, drain, and general-head boundary cells in the cross-sectional simulation of the Rio Bravo study area, near Albuquerque, New Mexico*

Cell	Conductance (feet squared per day)
All river cells	0.2
Drain	3.0
General-head boundary layer 1	.0002
General-head boundary layer 2	.0002
General-head boundary layer 3	.0000
General-head boundary layer 4	.0000
General-head boundary layer 5	.0001
General-head boundary layer 6	.0005
General-head boundary layer 7	.0007
General-head boundary layer 8	.0011
General-head boundary layer 9	.0016
General-head boundary layer 10	.0024
General-head boundary layer 11	.0024

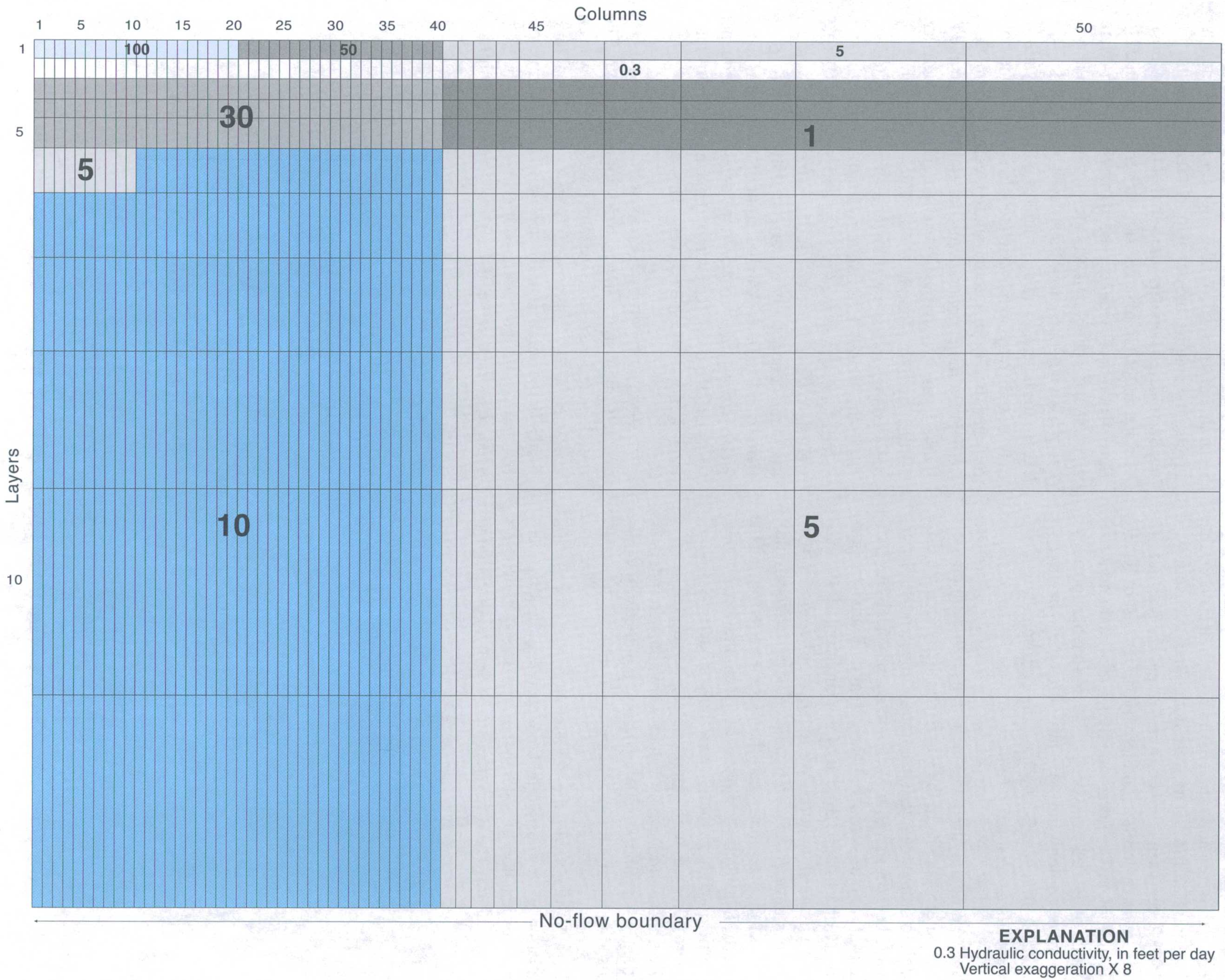


Figure 8. Schematic showing distribution of horizontal hydraulic conductivity.

in this layer. Layer 2 represents the discontinuous clay layer; thus, the horizontal hydraulic-conductivity value is small (0.3 ft/d). Data were not collected east of RBR2, represented in column 42, and the reason for the lower hydraulic-conductivity values east of RBR2 is unknown. The horizontal hydraulic-conductivity value of 10 ft/d in layers 6-11 is reasonable considering the lithology (fig. 3). Thirty ft/d also appears reasonable in layers 3-5 because the corresponding deposits are primarily sand.

Vertical hydraulic-conductivity values in unconsolidated deposits in the Rio Bravo study area are difficult to define. Many discontinuous clay and silt layers have been observed in well and geophysical logs. An initial ratio of vertical to horizontal hydraulic conductivity of 1 to 200 (Bureau of Reclamation, 1995) was used in the simulation. Vertical hydraulic-conductivity values in each layer were adjusted during the simulations to approximate head changes measured during the study. During the first phase of the calibration, both the vertical and horizontal hydraulic-conductivity values were adjusted. In the later phases, the vertical hydraulic-conductivity values were adjusted independently. The final vertical hydraulic-conductivity values used in the simulation are shown in table 4.

Vertical hydraulic-conductivity values for the simulation are low, as would be expected, indicating that the vertical flow of water in the simulated system is very constrained. The low values in the vertical direction in comparison to the horizontal direction represent an impediment to flow from the intervening clay and silt layers, and small-scale depositional features in the unconsolidated deposits indicate that the vertical flow of water in the simulated system is very constrained. Several points of evidence lead to this conclusion. Many clay/silt and tight clay layers are present, which is typical of alluvial deposition. Each layer in the model, except for layers 3 and 4, simulates either a clay/silt, clay, or tight clay layer, which would constrain the flow of water (fig. 3). In a horizontally layered system, the vertical hydraulic conductivity generally is controlled by the layers having the lowest hydraulic conductivity. Vertical hydraulic-conductivity values have been reported that are as low or lower than the simulated values in this model. Horizontal hydraulic-conductivity values for clay, reported in Spitz and Moreno (1996), were as low as 2.83×10^{-6} ft/d, and the ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity was 1 to 0.66. Another point of evidence is the lack of a substantial change in water levels in the deeper wells (RBR5 deep, for example) during the short- and long-duration river-pulse events (fig. 6).

Storage properties in unconsolidated alluvial deposits in the study area also are not well known. The initial value for specific yield in layers 1 and 2 was an average of 0.20 (Lohman, 1979, p. 8). The initial and final storage coefficient for layers 2-11 was estimated by multiplying the thickness of each layer by the specific-storage value of 1.0×10^{-6} per foot (Lohman,

Table 4. *Final vertical hydraulic-conductivity values for each layer in the cross-sectional simulation of the Rio Bravo study area, near Albuquerque, New Mexico*

Layers in model	Vertical hydraulic conductivity (feet per day)
Between 1 and 2	1×10^{-4} - 1×10^{-2}
Between 2 and 3	1×10^{-2}
Between 3 and 4	1×10^{-2}
Between 4 and 5	1×10^{-2}
Between 5 and 6	8×10^{-4}
Between 6 and 7	2×10^{-6}
Between 7 and 8	3×10^{-6}
Between 8 and 9	3×10^{-6}
Between 9 and 10	1.5×10^{-6}
Between 10 and 11	3×10^{-6}

1979, p. 8). The initial values were adjusted during simulation to approximate the change in heads with time. The final value for specific yield was estimated to be 0.3 for layer 1, a reasonable value because the material from cores representing layer 1 was described as well-sorted medium to course sand.

Calibration

The stresses applied to the ground-water system resulting from changes in stage in the Rio Grande and the Albuquerque Riverside Drain were used to calibrate the model. The changes in stage in the Rio Grande were caused by an engineered short-duration and a naturally occurring long-duration river pulse. The changes in stage in the drain were caused by the diversion of irrigation water into the drain. The change in stage in the river was slightly less during the short-duration pulse than during the long-duration pulse. Because of the short duration of increased stage during the short-duration pulse, the resulting stress to the ground-water system was much less. During the short-duration pulse, the change in stage in the drain was due only to increased seepage of ground water into the drain upstream from the study area. During the long-duration pulse, however, the increase in stage in the drain was due to a combination of increased seepage upstream from the section and the diversion of irrigation water into the drain.

The simulation had a total of 74 stress periods: twenty-one 6-hour stress periods simulating February 19-24 and fifty-three 24-hour stress periods simulating February 24 through April 17. The 6-hour stress periods were used for the short-duration river pulse. The long-duration pulse was simulated from March 13 through April 17 (stress periods 38 to 74). The 17 days between the two pulses were simulated by stress periods 21 to 37.

The model was calibrated through trial and error by varying horizontal hydraulic conductivity, vertical hydraulic conductivity, conductance of the river and the drain, conductance of the GHB, specific yield, and storage coefficient during numerous simulations. The goal of the calibration is to minimize differences between the measured and simulated changes in water levels in the 12 observation wells. The calibration process continued until further incremental adjustments to model-input parameters produced no perceivable improvement in model results. The changes in simulated head were from cells that correspond to the location of the screened intervals of the observation wells both in depth and distance from the middle of the river. Simulated water levels compared to measured water levels in each well are shown in figure 9 (A-L).

The comparison of measured to simulated water levels indicates stresses affecting water-level changes other than change in stage of the river and drain (fig. 9A-L). The trend of water-level changes was closely simulated in four wells (BOR1, BOR2, RBR5 shallow, and RBR5 intermediate); however, the magnitude of the change was not as closely matched. An example is well RBR6 (fig. 9J), in which the magnitude of the water-level change from stress period 48 to the end of the simulation is higher than the simulated water-level change. The magnitude of the measured water-level change in the wells was even greater than the change in stage in the drain.

The trend and magnitude in water-level changes in four wells (RBR2 shallow, RBR2 intermediate, RBR2 deep, and RBR5 deep) could not be closely matched. The timing of the increase in water levels and the magnitude of the change could not be simulated closely, although the general trend was approximated in most wells.

The simulation of water-level changes in wells BOR1, BOR2, BOR3, and the shallow and intermediate RBR5 wells closely matched measured water levels because the source of the recharge, the river, was known. Some problems occurred during calibration of well BOR2 and the shallow RBR5 well. These two wells are in adjacent cells in layer 1, but when parameters were varied in one well, the match between measured and simulated water levels got worse in the other well. This relation probably results from the variation in the lithology of the alluvium near the river and the approximate 800-ft distance that RBR5 is offset to the north from wells BOR1 and BOR2. In the deep RBR5 well (fig. 9I), the approximate match between measured and simulated water levels can be attributed primarily to depth of the well and interference from local pumped wells. Calibrating to well RBR5 deep was important in determining the vertical hydraulic conductivity of the aquifer in layers 5-10.

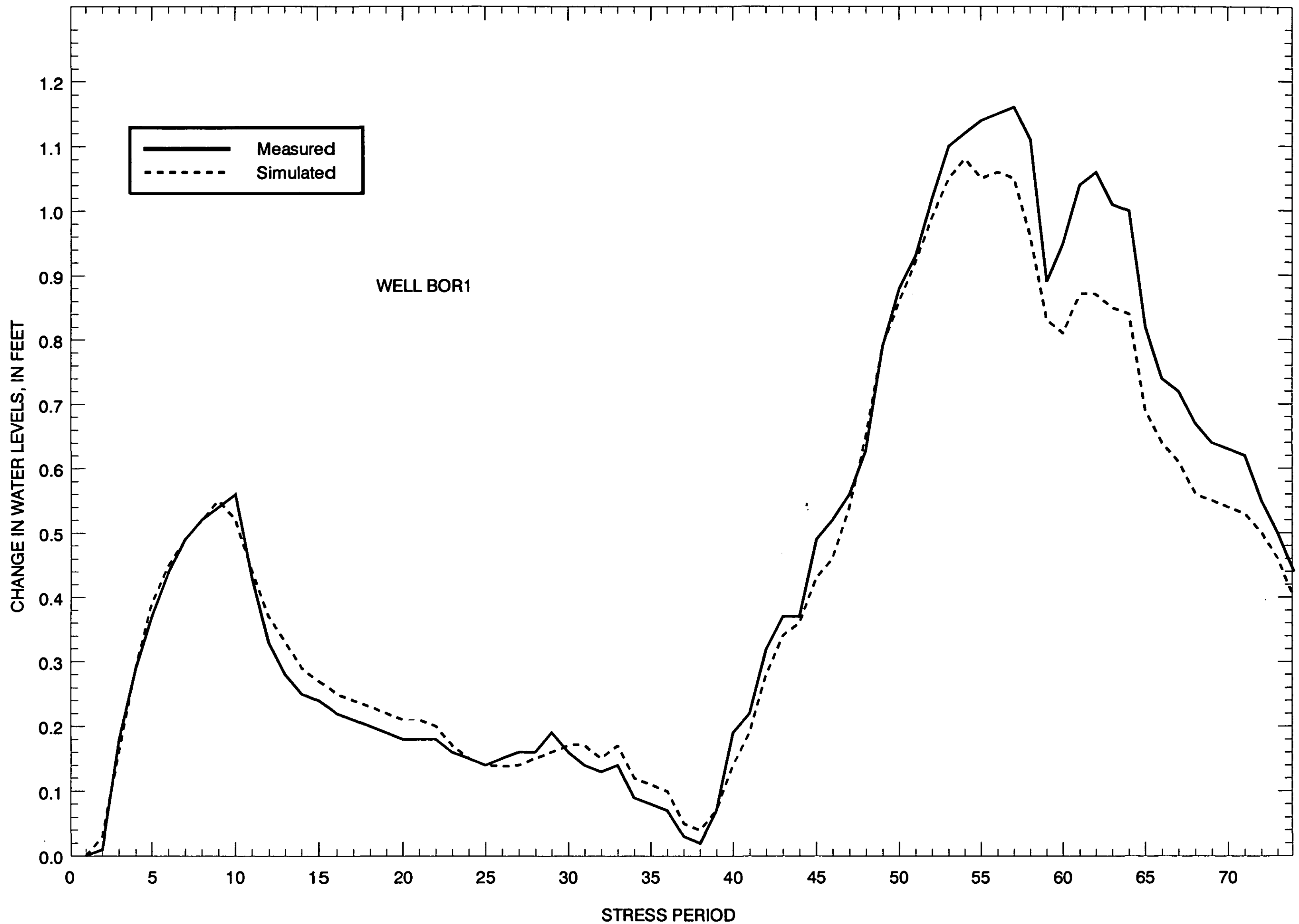


Figure 9A. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico.

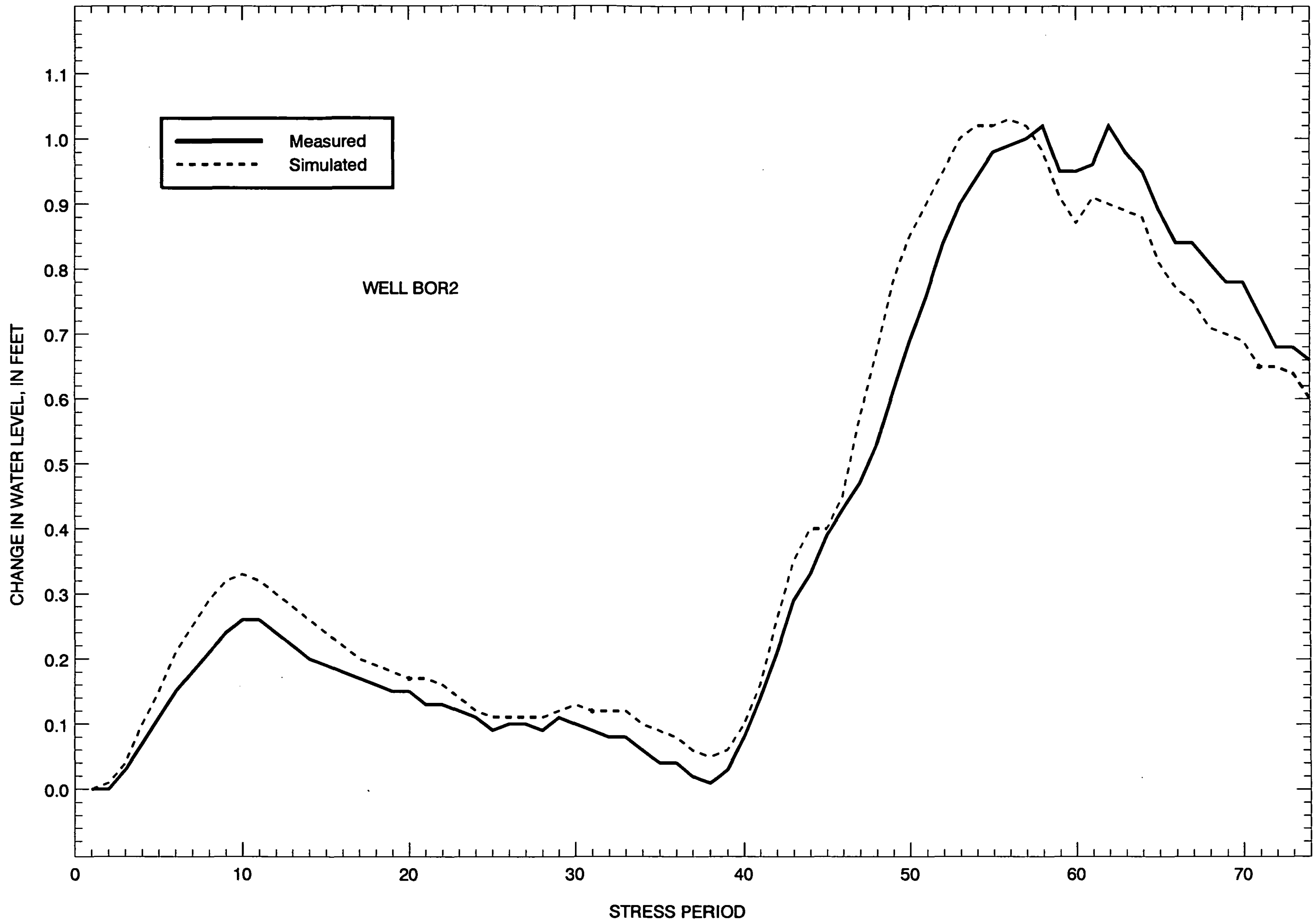


Figure 9B. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

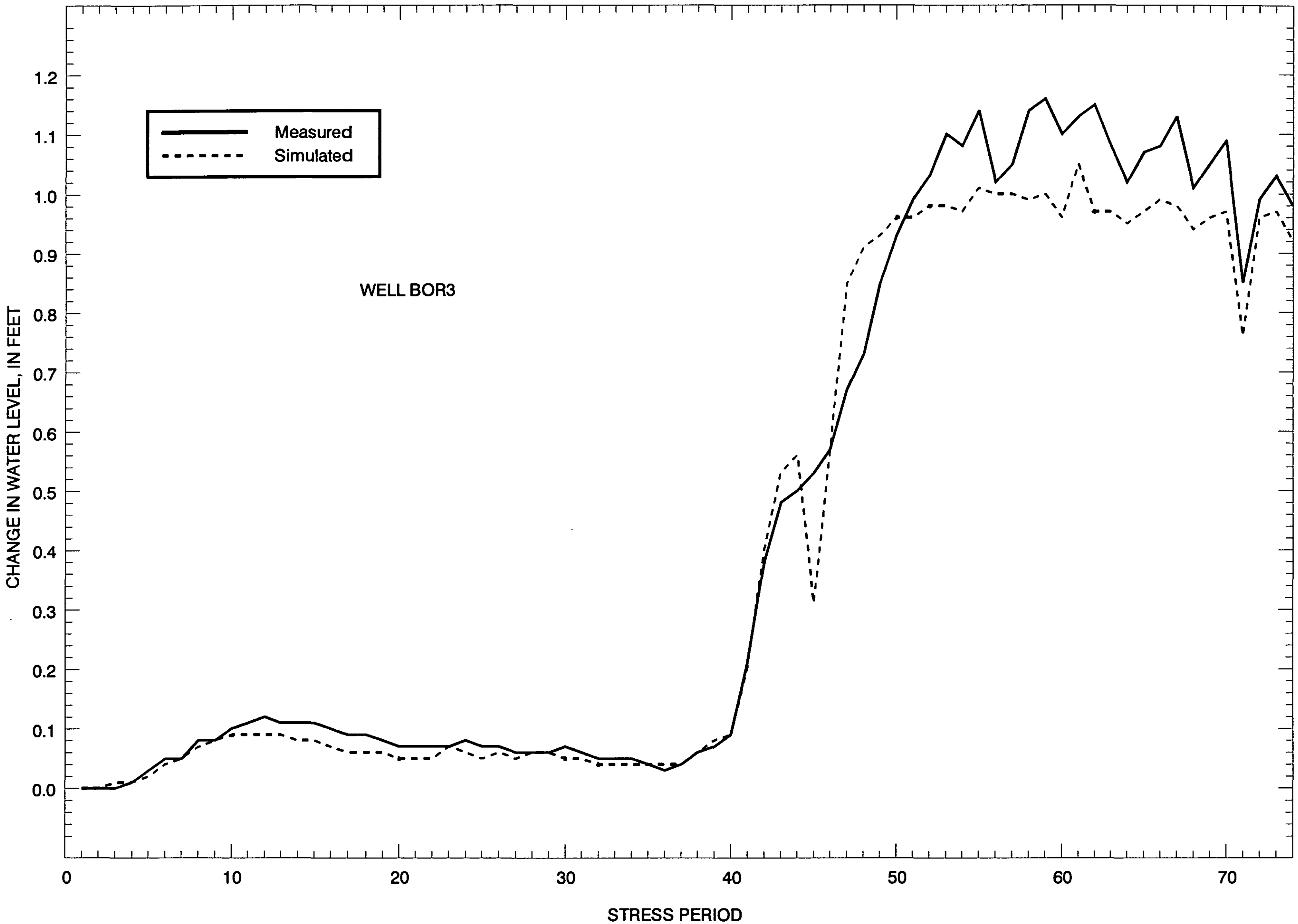


Figure 9C. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

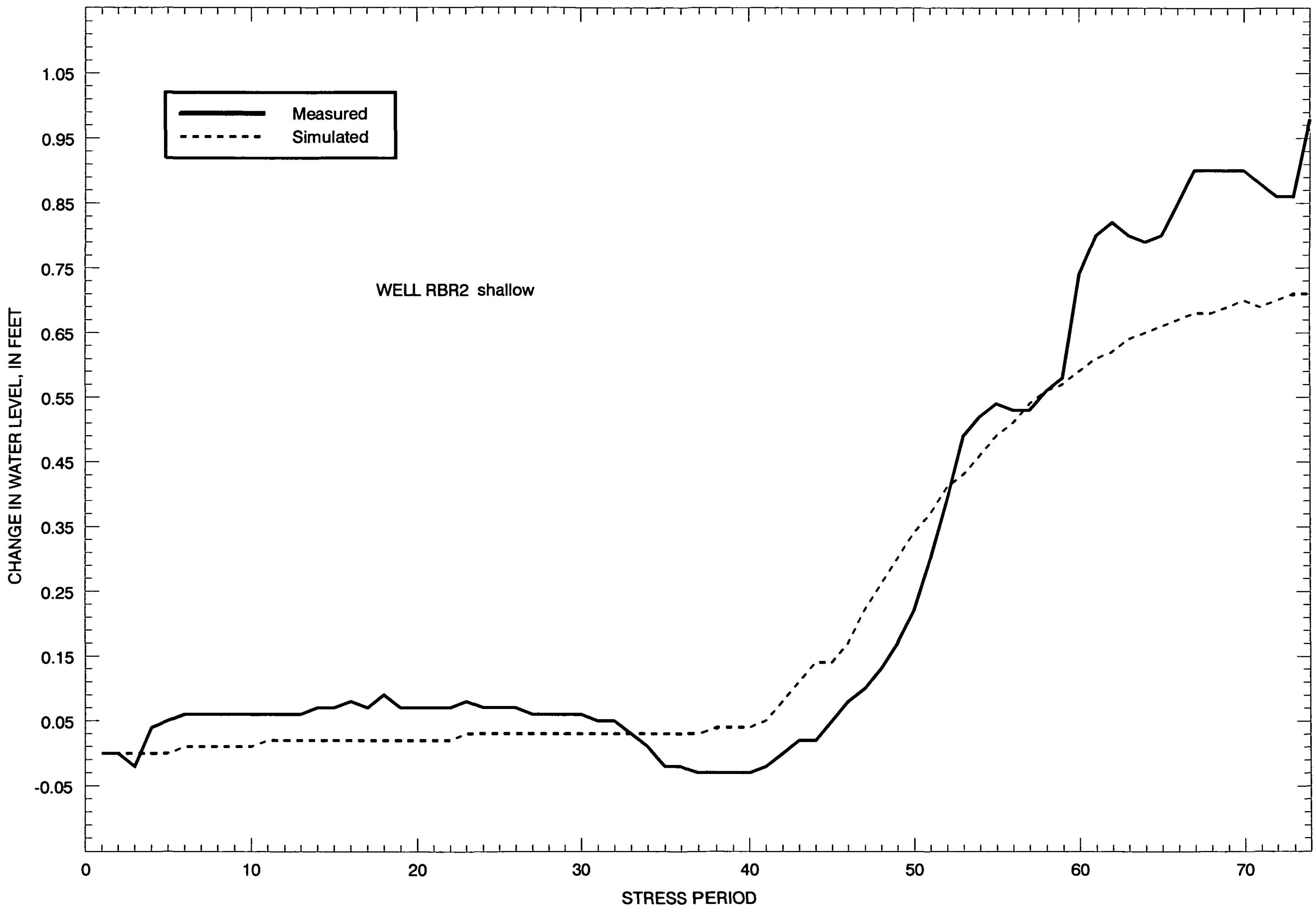


Figure 9D. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

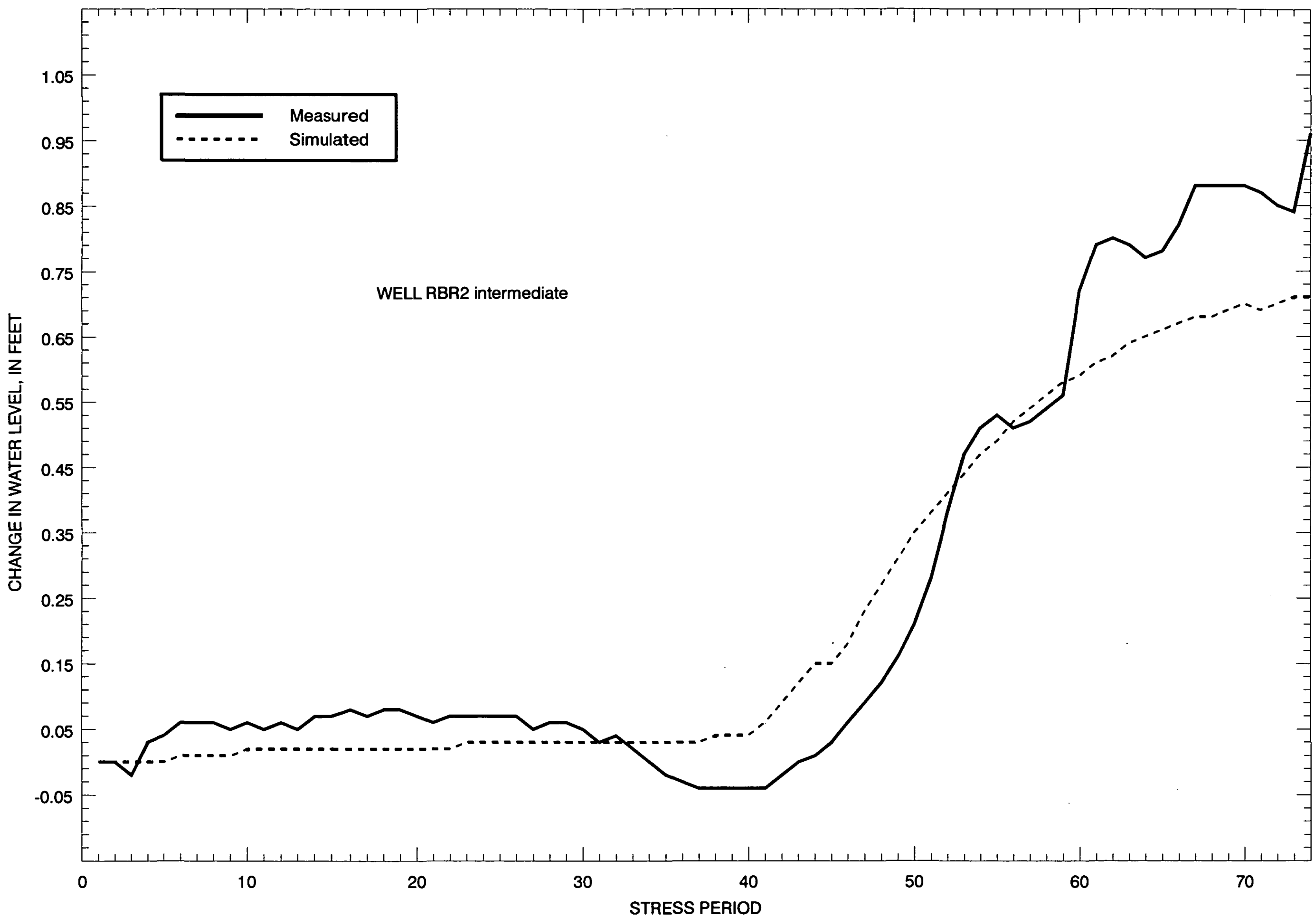


Figure 9E. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

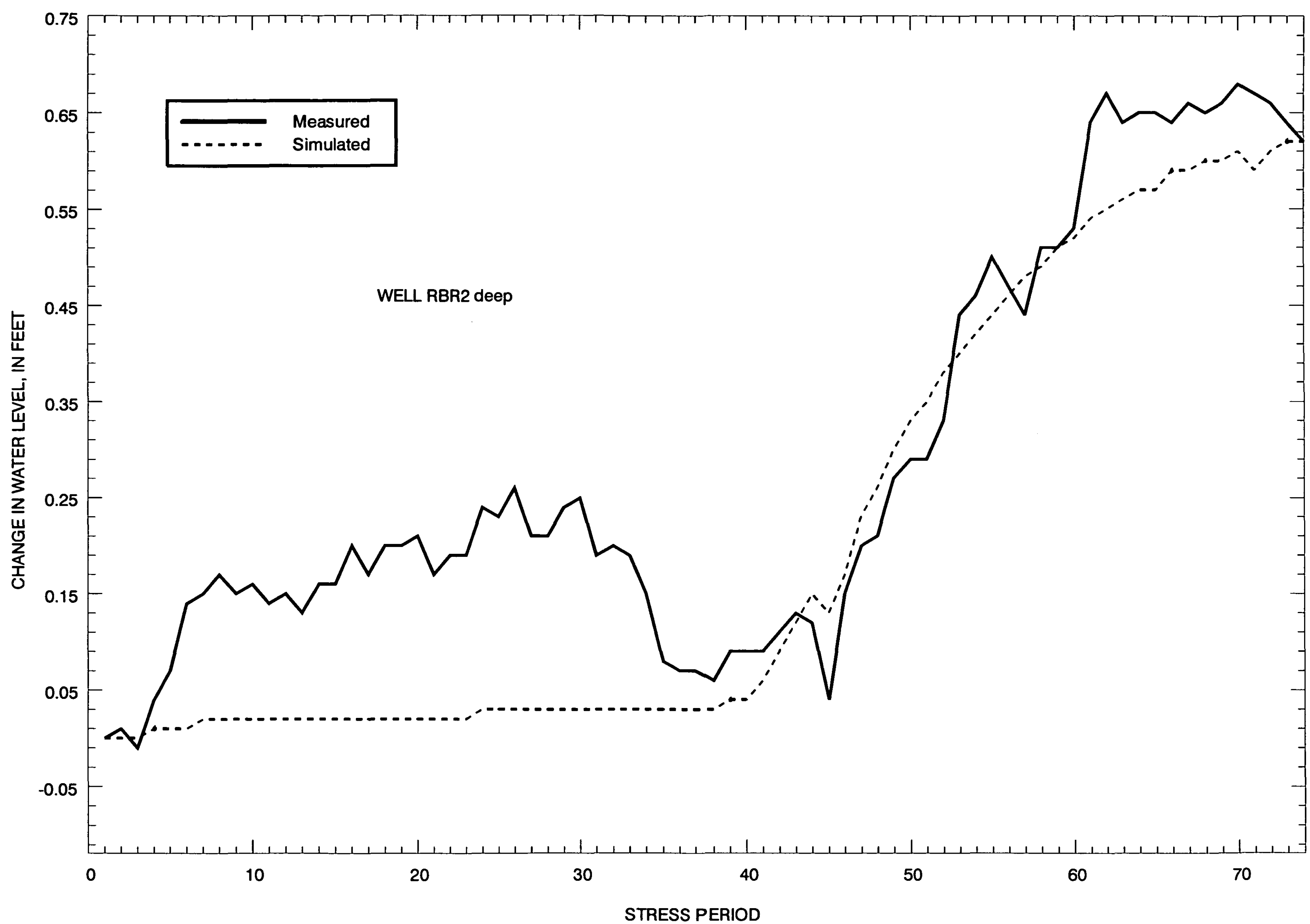


Figure 9F. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

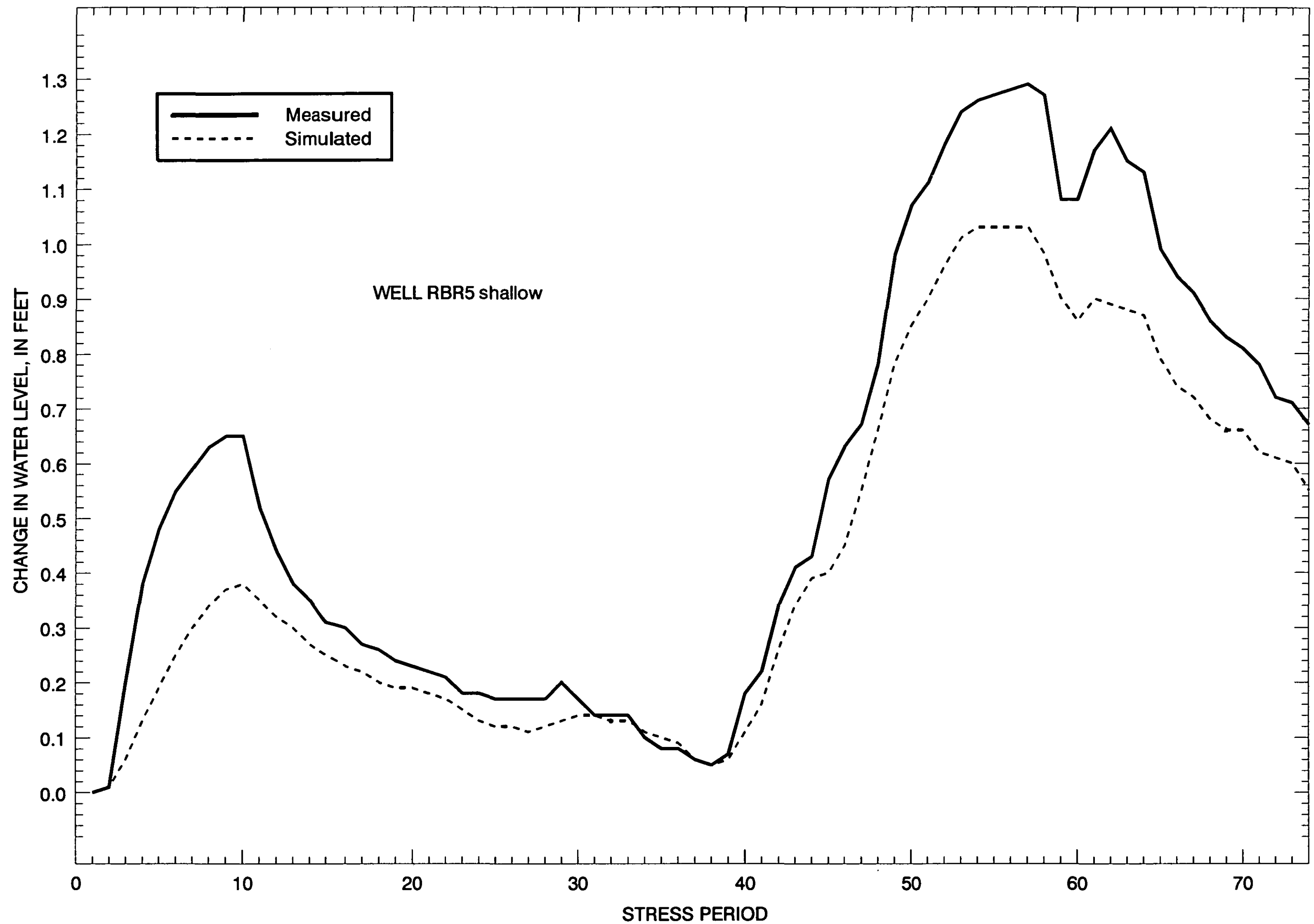


Figure 9G. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

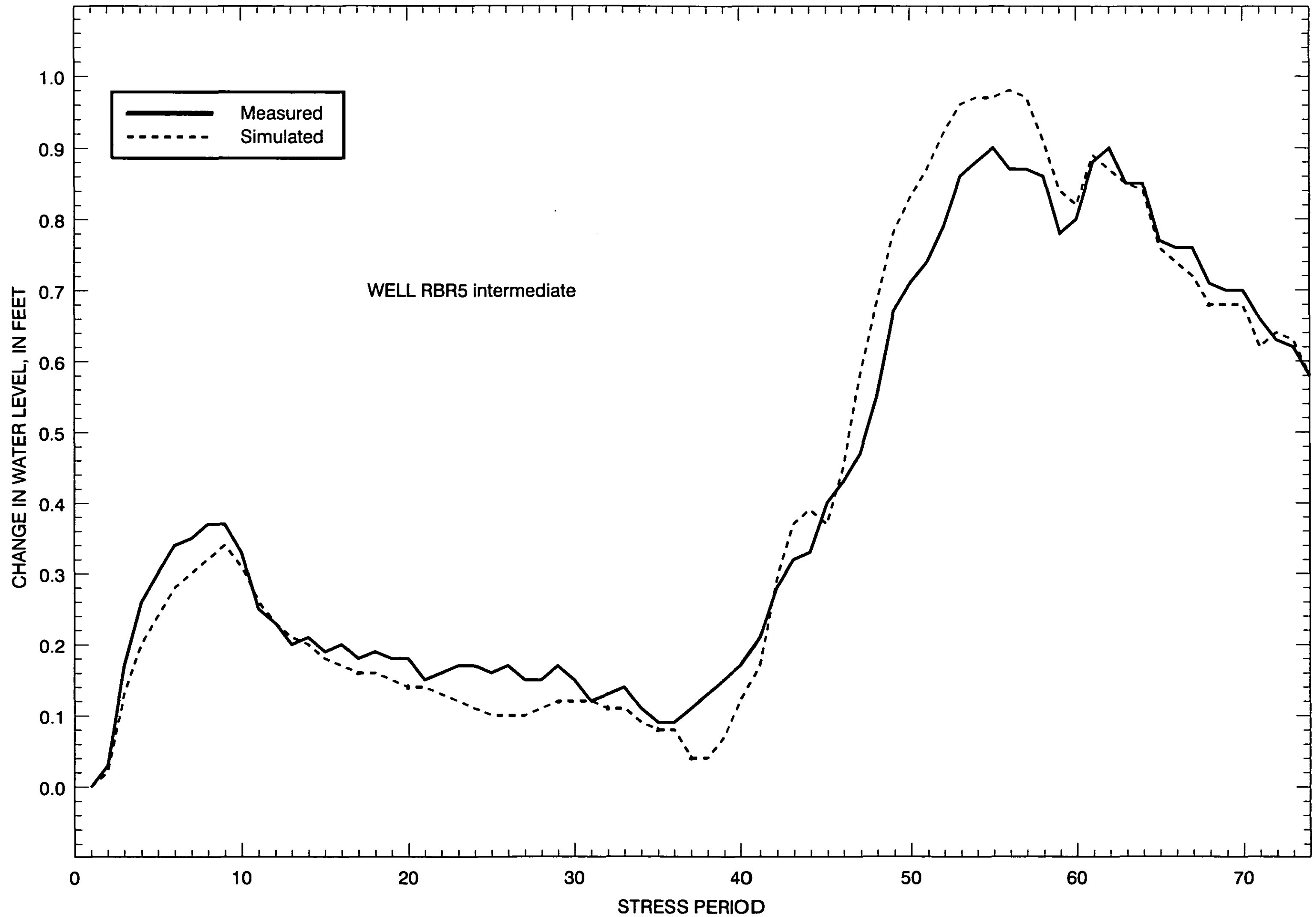


Figure 9H. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

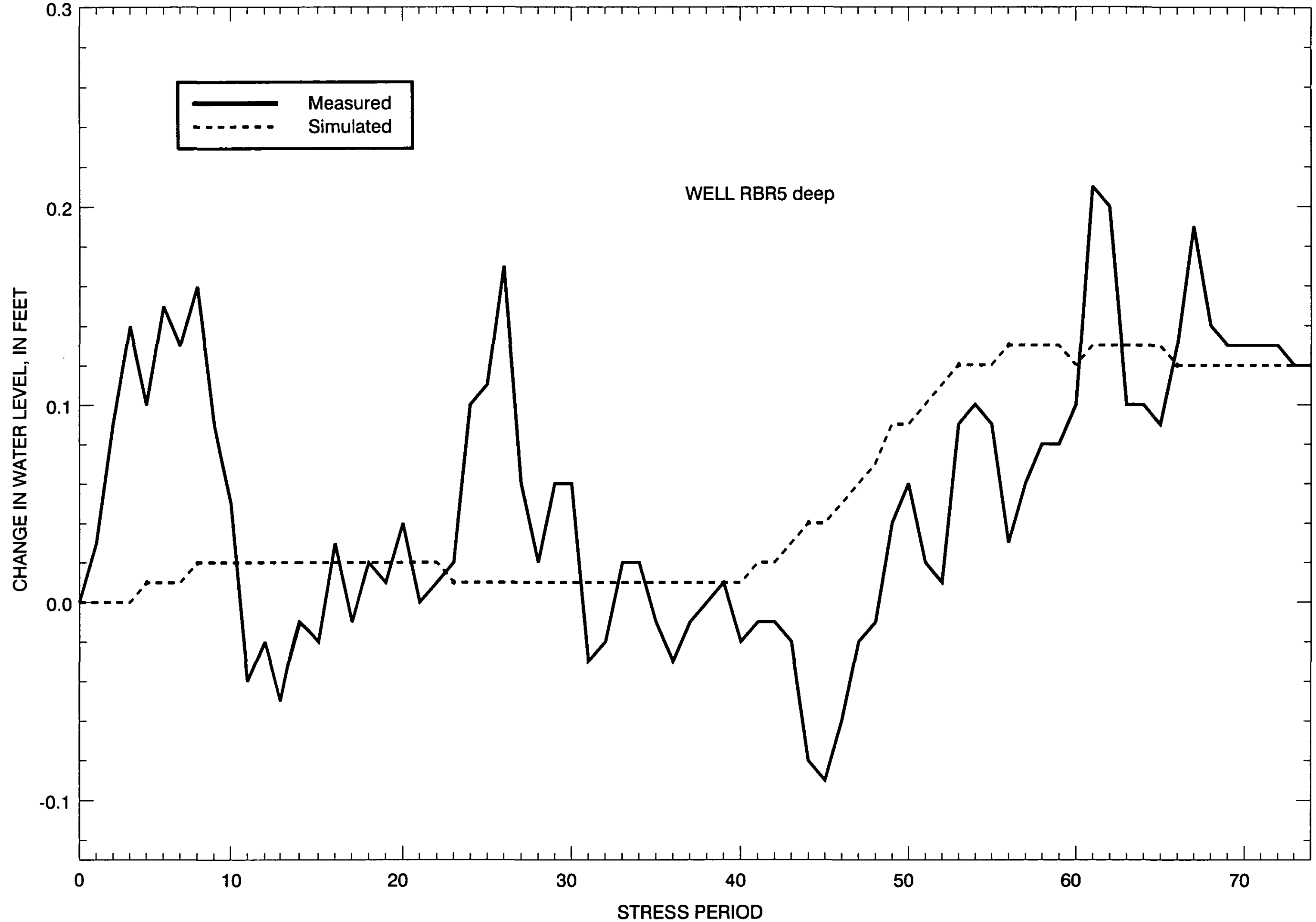


Figure 9l. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

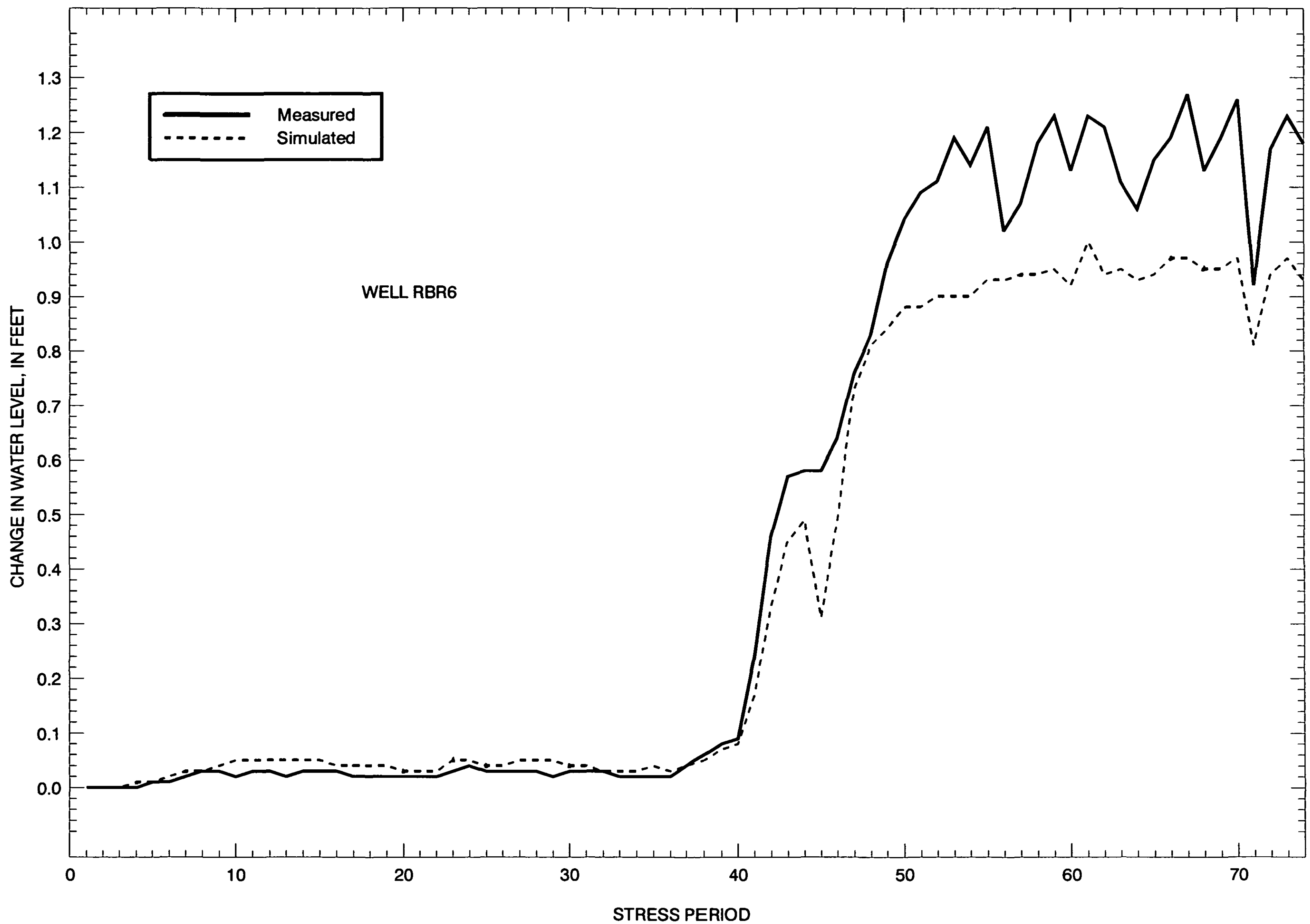


Figure 9J. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

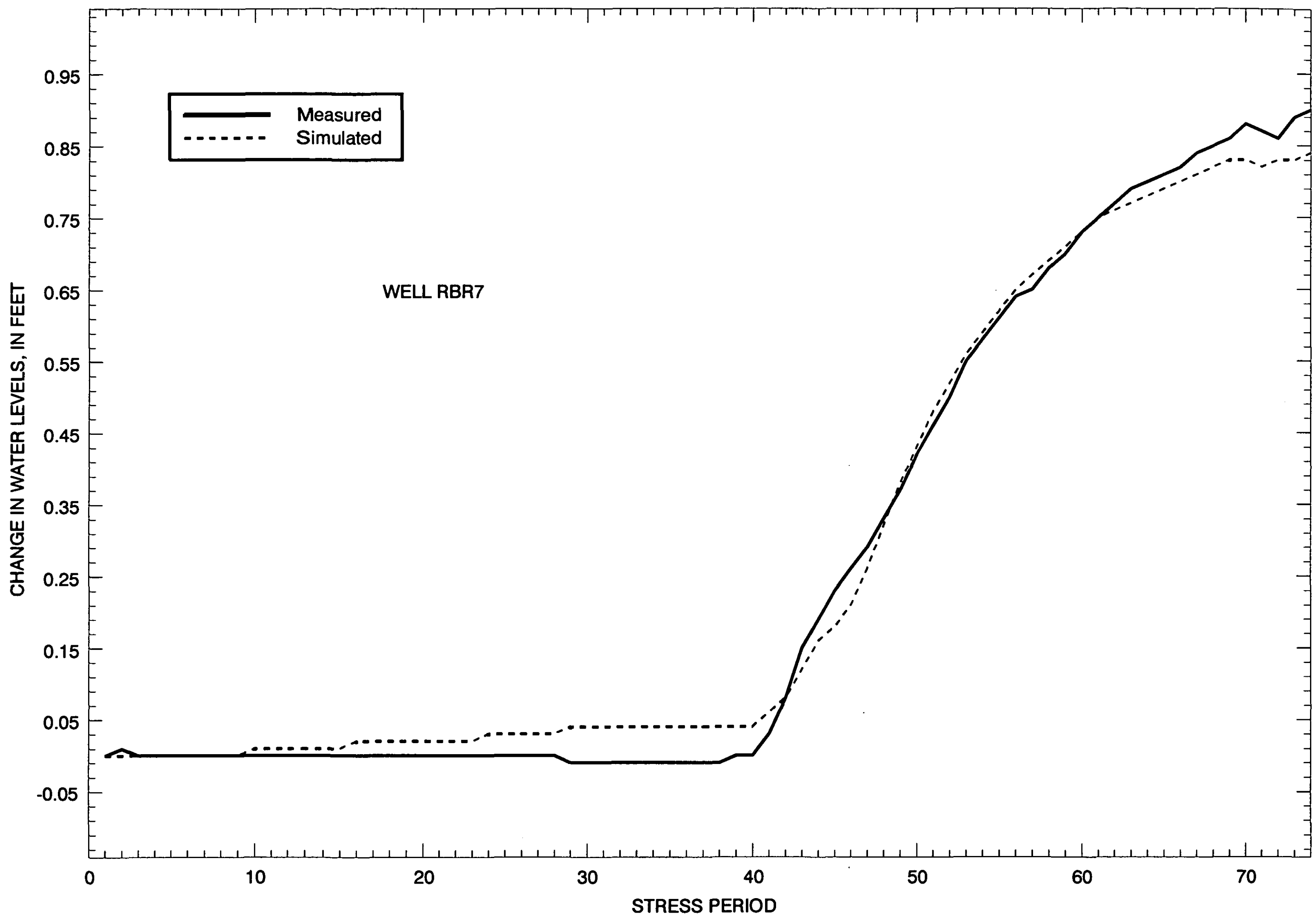


Figure 9K. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Continued.

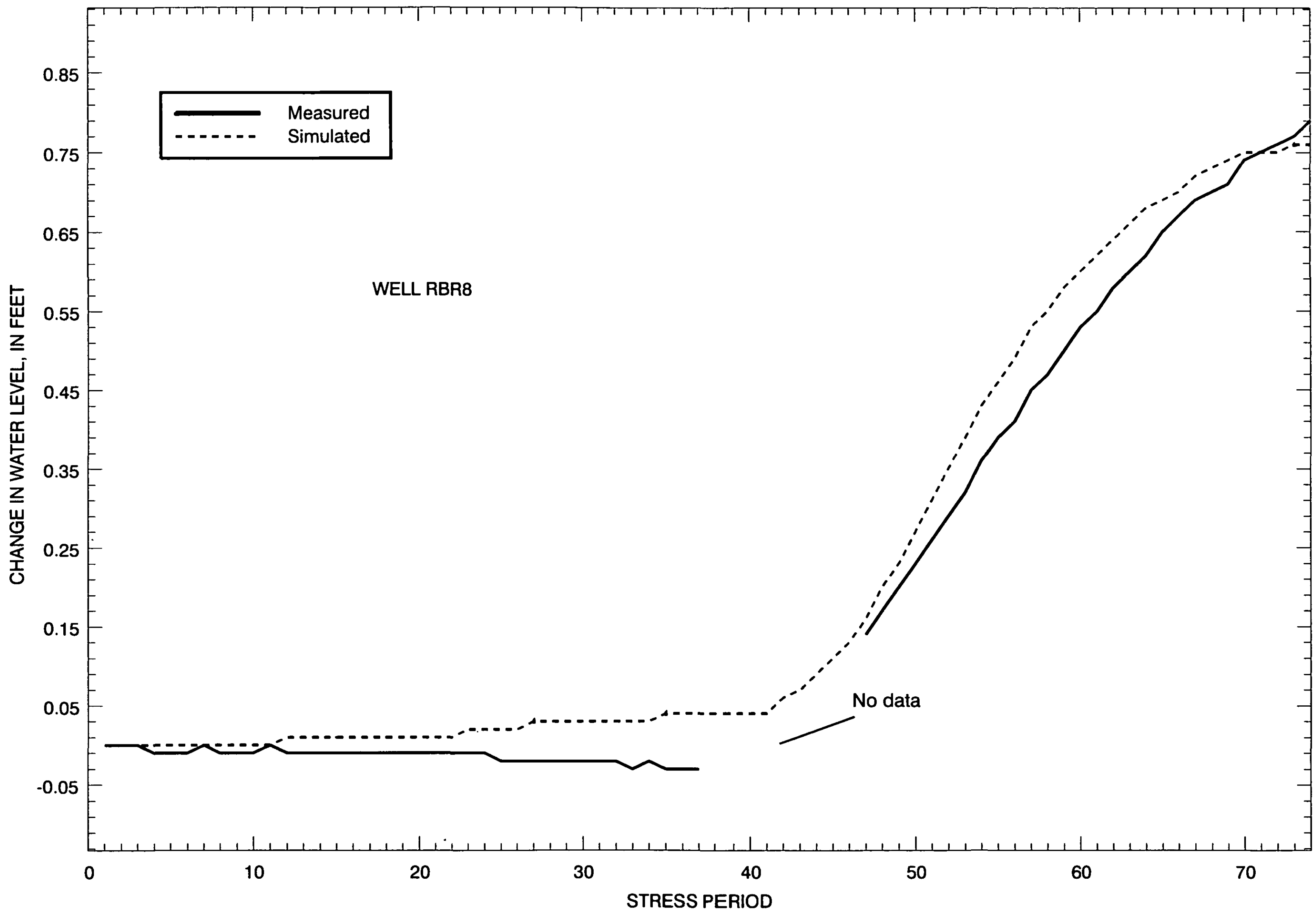


Figure 9L. Measured and simulated water levels in the Rio Bravo study area, near Albuquerque, New Mexico--Concluded.

The simulated flow of water into the drain was the only known flux used in calibration of the model. Other fluxes (storage, seepage to and from the river, seepage from the drain, and GHB) were monitored to ensure that values were reasonable (table 6, in back of report).

The seepage from the river during simulation of the short-duration pulse averaged 7.46×10^{-3} ft^3/s for the 300-ft-deep cross section. The highest flux during the simulation of the short-duration pulse was 7.43×10^{-2} ft^3/s in stress period 3 (fig. 10). The average flux from the river into the model for the 17 days between the short- and long-duration river pulses was 1.25×10^{-3} ft^3/s. During simulation of the long-duration pulse, the average flux from the model to the river was 1.66×10^{-3} ft^3/s.

Water entered the drain from the model during the short-duration pulse and the time between the short- and long-duration pulses, but entered the model from the drain during simulation of the long-duration pulse. The change in flux direction is due to the increased stage in the drain and the accompanying decrease in hydraulic gradient during the long-duration pulse. The average flux into the drain during the short-duration pulse was 3.18×10^{-3} ft^3/s; the average flux between short- and long-duration pulses was 1.78×10^{-3} ft^3/s. The average flux between the pulses is reasonable compared to measured gains in discharge in the drain (table 1). The average flux for the long-duration pulse was 7.14×10^{-3} ft^3/s from the drain to the model. The greatest flux from the drain to the model was 2.46×10^{-2} ft^3/s during stress period 46 (fig. 10).

Water flowed from the model to the GHB during the entire simulation. During simulation of the short-duration pulse, the average flux to the GHB was 3.32×10^{-5} ft^3/s, between pulses was 3.03×10^{-5} ft^3/s, and during the long-duration pulse was 2.29×10^{-4} ft^3/s.

Sensitivity Analysis

Sensitivity analysis evaluates the response of the model to incremental changes in parameters and determines which parameters have the greatest effect on results—for example, water levels and horizontal hydraulic conductivity. If improvement of the model is desired, additional data collection would be directed toward refining the most sensitive parameter. Sensitivity analysis also provides an indication of the magnitude of error that might be associated with incorrectly specified values or poorly known model parameters. A sensitivity analysis was done using the transient-state calibration of the model by multiplying and dividing the hydraulic parameters by two. The net water-budget output for storage, river seepage, drain seepage, and GHB were used in the analysis, as well as the absolute difference between the measured and the simulated change in water levels. Results of the analysis are shown in table 7 (in back of report).

The parameters affecting the change in water levels the greatest were the horizontal hydraulic conductivity of layers 1 and 5 and the vertical hydraulic conductivity between layers 1 and 2. Doubling or halving these parameters leads to changes (greater than 0.01 ft) in the sum of the absolute values of measured and simulated water-level changes. The most sensitive parameter to both the change in water level and the change in flux is the horizontal hydraulic conductivity of layer 1. Doubling or halving this parameter leads to water-level changes of -0.04 and -0.14 ft and changes in flux greater than 0.01 in water in storage, river seepage, and drain seepage.

Doubling or halving the river and drain conductance produces small changes in water levels and fluxes. When the conductance of the river and of the drain were compared, the river conductance was the most sensitive and produced the greatest changes.

Limitations of the Model

The model constructed for this study is useful for evaluating the flow system to meet the objectives of this study. However, results are a simulation of the system, and the following model limitations need to be considered.

(1) Two-dimensional cross-sectional modeling was used because of the hydraulic gradients in the Rio Bravo study area in relation to the Rio Grande. A cross-sectional model can only be used to simulate a ground-water system that has a hydraulic gradient perpendicular to the river.

(2) The geologic materials that compose the Santa Fe Group vary greatly from area to area; therefore, the hydraulic parameters used to calibrate the model are site specific.

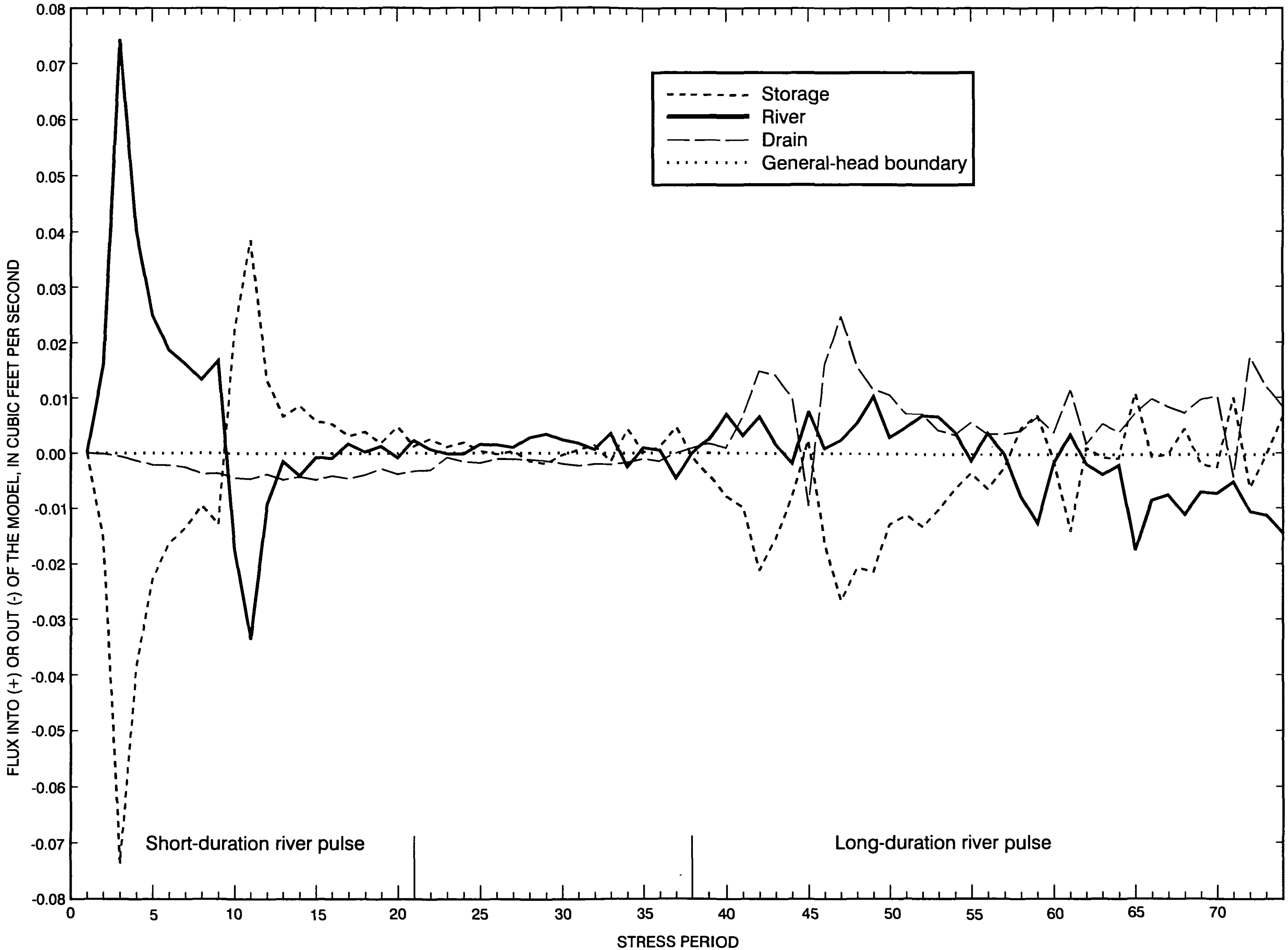


Figure 10. Simulated water budget for model fluxes.

(3) The model results for Santa Fe Group unconsolidated deposits in the Rio Bravo study area are not unique because different combinations of data entered into the model could yield similar results. Calibration used a finite range of changes in stage in the river and drain; thus, other stresses might be affecting water levels and fluxes in the study area. As other stresses are better understood, the model can be refined to better estimate hydraulic properties. Any simulation with this model that uses stresses outside the range of stresses used to calibrate the model needs to be regarded with caution.

SUMMARY

Ground water is the principal source of drinking water in the Albuquerque area. As increasing volumes of ground water are pumped, water managers and others have raised questions about how much the Rio Grande recharges the surrounding aquifer. The USGS, in cooperation with the City of Albuquerque, conducted a project in 1997 to estimate hydraulic properties in the upper part of the Santa Fe Group aquifer system in the Rio Bravo study area, near Albuquerque. These properties were estimated from the results of a short-duration and long-duration surface-water pulse conducted in the Rio Grande and Albuquerque Riverside Drain.

The study area, southwest of Albuquerque, is about 1 square mile and is east of the Rio Grande, near Rio Bravo Bridge. This area was chosen because a streamflow-gaging station and three monitoring wells had been installed during a previous study, and the study area lacked surface-water interference from canals and ditches in the study area. Three observation wells were installed east of the Albuquerque Riverside Drain, and two well nests, each consisting of three observation wells, were installed in the northern part of the study area.

Stage data were collected from the Rio Grande and two streamflow-gaging stations installed on the Albuquerque Riverside Drain. One station was installed in the southern part of the study area (downstream site) and one station was installed about 3 mi upstream (upstream site) from the downstream site.

A short-duration pulse and long-duration pulse were used to stress the ground-water system. The 3-day, short-duration pulse was an engineered increase in the stage of the Rio Grande from February 19 through February 21. The long-duration pulse (from March 13 to the end of data collection) was the normal increase in stage in the Rio Grande from snowmelt runoff.

A cross-sectional model was constructed to simulate the response of the aquifer system to the short- and long-duration pulses. The model used the principle of superposition to simulate the effects of the river pulses. The study area was discretized into a two-dimensional, non-uniform, vertical, rectangular grid consisting of 50 columns and 11 layers. The width of the cells ranged from 60 to 1,500 ft. Simulated horizontal hydraulic-conductivity values varied from 0.3 to 100 ft/d; vertical hydraulic-conductivity values varied from 1.5×10^{-6} to 0.01 ft/d. Specific yield was estimated to be 0.3 for layer 1. Specific storage was 1.0×10^{-6} per ft for layers 2 through 11. Water entering the model from the river during simulation of the short-duration pulse averaged 7.46×10^{-3} ft^3/s for the 300-ft-wide section. During simulation of the long-duration pulse, the average flux was 1.66×10^{-3} ft^3/s from the model to the river. The average flux was 3.18×10^{-3} ft^3/s from the model to the drain during the short-duration pulse and was 7.14×10^{-3} ft^3/s during the long-duration pulse. The parameters affecting the change in water levels the greatest were the horizontal hydraulic conductivity of layers 1 and 5 and the vertical hydraulic conductivity between layers 1 and 2.

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Table 5. *Water-level measurements in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico*

Well	Date	Water level (feet below land surface)
BOR1	11/22/1996	4.44
	12/20/1996	4.55
	01/22/1997	4.40
	02/10/1997	4.35
	02/14/1997	4.43
	02/27/1997	4.31
	03/11/1997	4.43
	03/20/1997	3.95
	04/17/1997	4.04
	05/01/1997	3.44
	05/30/1997	1.91
BOR2	11/22/1996	6.63
	12/20/1996	6.61
	01/22/1997	6.71
	02/10/1997	6.68
	02/14/1997	6.77
	02/27/1997	6.67
	03/11/1997	6.74
	03/20/1997	6.34
	04/17/1997	6.12
	05/01/1997	5.74
BOR3	01/09/1997	8.09
	01/22/1997	8.13
	02/10/1997	8.13
	02/14/1997	8.13
	02/27/1997	8.09
	03/11/1997	8.10
	03/20/1997	7.59
	04/17/1997	7.18
	05/01/1997	6.83
	05/30/1997	6.81
RBR2 SHALLOW	11/18/1996	10.62
	12/20/1996	11.12
	12/27/1996	11.18
	01/01/1996	11.28
	01/22/1997	11.53
	02/14/1997	11.81
	02/27/1997	11.76
	03/20/1997	11.76
	04/17/1997	10.82
	04/30/1997	10.69

Table 5. *Water-level measurements in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued*

Well	Date	Water level (feet below land surface)
RBR2 SHALLOW--Continued	05/30/1997	10.32
RBR2 INTERMEDIATE	11/18/1996	10.77
	12/20/1996	11.29
	12/27/1996	11.33
	01/02/1997	11.41
	01/22/1997	11.69
	02/14/1997	11.96
	02/27/1997	11.92
	03/20/1997	11.92
	04/17/1997	10.99
	04/30/1997	10.85
	05/30/1997	10.51
RBR2 DEEP	11/13/1996	11.92
	11/18/1996	11.92
	12/20/1996	12.02
	12/27/1996	11.95
	01/02/1997	12.05
	01/22/1997	12.36
	02/14/1997	12.60
	02/27/1997	12.35
	03/20/1997	12.46
	04/17/1997	12.00
	04/30/1997	11.85
	05/30/1997	11.59
RBR5 SHALLOW	10/01/1996	6.30
	10/16/1996	6.25
	10/17/1996	6.30
	11/08/1996	6.05
	11/13/1996	6.19
	11/18/1996	6.23
	12/27/1996	6.05
	01/02/1997	6.22
	01/22/1997	6.21
	02/14/1997	6.24
	02/27/1997	6.11
	03/20/1997	5.64
	04/17/1997	5.64
	04/24/1997	4.88
	04/29/1997	4.93
	05/30/1997	2.14

Table 5. *Water-level measurements in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Continued*

Well	Date	Water level (feet below land surface)
RBR5 INTERMEDIATE	10/01/1996	8.13
	10/15/1996	8.00
	10/17/1996	8.05
	11/13/1996	8.04
	11/18/1996	8.06
	12/27/1996	8.03
	01/02/1997	8.10
	01/22/1997	8.20
	02/14/1997	8.29
	02/27/1997	8.15
	03/20/1997	7.87
	04/17/1997	7.73
	04/24/1997	7.24
	04/29/1997	7.25
	05/30/1997	5.47
RBR5 DEEP	10/01/1996	13.63
	10/16/1996	13.52
	10/17/1996	13.04
	11/08/1996	12.90
	11/13/1996	12.86
	11/18/1996	12.85
	12/27/1996	12.89
	01/02/1997	12.86
	01/22/1997	12.94
	02/14/1997	13.10
	02/27/1997	12.94
	03/20/1997	13.13
	04/17/1997	12.93
	04/24/1997	12.72
	04/29/1997	12.70
	05/30/1997	12.54
RBR6	12/27/1996	7.93
	01/02/1997	7.96
	01/09/1997	7.97
	01/22/1997	7.97
	02/10/1997	8.00
	02/14/1997	8.00
	02/27/1997	7.98
	03/11/1997	7.96
	03/20/1997	7.35
	04/17/1997	6.82

Table 5. *Water-level measurements in observation wells in the Rio Bravo study area, near Albuquerque, New Mexico--Concluded*

Well	Date	Water level (feet below land surface)
RBR6--Continued	05/01/1997	6.52
	05/30/1997	6.74
RBR7	12/27/1996	8.58
	01/09/1997	8.62
	01/22/1997	8.66
	02/10/1997	8.73
	02/14/1997	8.76
	02/27/1997	8.76
	03/11/1997	8.76
	03/20/1997	8.53
	04/17/1997	7.85
	05/01/1997	7.67
	05/01/1997	7.67
	05/30/1997	7.79
RBR8	12/27/1996	7.03
	01/09/1996	7.10
	01/22/1997	7.16
	02/10/1997	7.27
	02/14/1997	7.29
	02/27/1997	7.33
	03/11/1997	7.34
	03/20/1997	7.20
	04/17/1997	6.53
	04/30/1997	6.36
	05/30/1997	6.47

Table 6. *Simulated water budget in the Rio Bravo study area, near Albuquerque, New Mexico*

[All values are rounded and reported in cubic feet per second for the 300-foot width of the cross-sectional model]

Stress period	Flux into model: Storage	Flux into model: Seepage from river	Flux into model: Seepage from drain	Flux into model: General-head boundary	Flux into model: Total flux in	Flux out of model: Storage	Flux out of model: Seepage to river	Flux out of model: Seepage to drain	Flux out of model: General-head boundary	Flux out of model: Total flux out	Difference (flux in minus flux out)
5	0.00000	0.02493	0.00000	0.00000	0.02493	0.02274	0.00000	0.00218	0.00001	0.02493	0.00000
10	.02600	.00000	.00000	.00000	.02600	.00404	.01735	.00456	.00004	.02601	.00000
15	.00641	.00000	.00000	.00000	.00641	.00070	.00079	.00487	.00005	.00641	.00000
20	.00515	.00000	.00000	.00000	.00515	.00039	.00086	.00386	.00004	.00515	.00000
25	.00080	.00152	.00000	.00000	.00233	.00048	.00000	.00182	.00003	.00233	.00000
30	.00019	.00241	.00000	.00000	.00260	.00056	.00000	.00201	.00003	.00260	.00000
35	.00056	.00096	.00000	.00000	.00151	.00040	.00000	.00108	.00003	.00151	.00000
40	.00000	.00700	.00092	.00000	.00791	.00789	.00000	.00000	.00003	.00791	.00000
45	.01018	.00742	.00000	.00000	.01760	.00793	.00000	.00965	.00011	.01760	.00000
50	.00000	.00280	.01038	.00000	.01318	.01296	.00000	.00000	.00023	.01318	.00000
55	.00310	.00000	.00547	.00000	.00857	.00679	.00148	.00000	.00030	.00857	.00000
60	.00338	.00005	.00361	.00000	.00704	.00483	.00190	.00000	.00031	.00704	.00000
65	.01394	.00000	.00714	.00000	.02107	.00316	.01759	.00000	.00032	.02107	.00000
70	.00016	.00000	.01025	.00000	.01040	.00272	.00738	.00000	.00031	.01041	.00000
74	.00802	.00000	.00828	.00000	.01630	.00145	.01454	.00000	.00030	.01630	.00000

Table 7. *Sensitivity analyses of simulated water budget output values and the absolute difference between measured and simulated water-level changes in the Rio Bravo study area, near Albuquerque, New Mexico*

	Net flow rate (cubic feet per second) Positive numbers indicate flow into model and negative numbers indicate flow out of model				Sum of absolute difference in water-level change between measured and simulated (feet)
	Storage	River seepage	Drain seepage	General-head boundary	
Calibrated simulation with no changes	-0.17276	-0.00510	0.18529	-0.00744	0.771
Horizontal hydraulic-conductivity analysis					
Layer 1 doubled	-0.18313	-0.02694	0.21786	-0.00780	0.815
Layer 1 halved	-.15895	.01164	.15444	-.00714	.907
Layer 2 doubled	-.17300	-.00515	.18559	-.00745	.772
Layer 2 halved	-.17264	-.00507	.18514	-.00744	.771
Layer 3 doubled	-.17750	-.00772	.19289	-.00768	.776
Layer 3 halved	-.16969	-.00346	.18044	-.00730	.779
Layer 4 doubled	-.17698	-.00637	.19100	-.00766	.775
Layer 4 halved	-.17008	-.00425	.18164	-.00732	.776
Layer 5 doubled	-.17843	-.00607	.19223	-.00774	.782
Layer 5 halved	-.16874	-.00417	.18016	-.00725	.782
Layer 6 doubled	-.17863	-.00257	.18887	-.00767	.775
Layer 6 halved	-.16931	-.00627	.18290	-.00733	.766
Layer 7 doubled	-.17301	-.00483	.18566	-.00783	.772
Layer 7 halved	-.17252	-.00530	.18503	-.00721	.771
Layer 8 doubled	-.17267	-.00500	.18545	-.00779	.771
Layer 8 halved	-.17281	-.00517	.18518	-.00720	.772
Layer 9 doubled	-.17261	-.00503	.18539	-.00776	.769
Layer 9 halved	-.17287	-.00514	.18521	-.00720	.772
Layer 10 doubled	-.17261	-.00506	.18536	-.00770	.769
Layer 10 halved	-.17288	-.00513	.18523	-.00723	.774
Layer 11 doubled	-.17263	-.00507	.18534	-.00766	.769
Layer 11 halved	-.17287	-.00513	.18523	-.00725	.772
Vertical hydraulic-conductivity analysis					
Layer 1 doubled	-0.17022	-0.00572	0.18317	-0.00724	0.788
Layer 1 halved	-.17063	-.00197	.18001	-.00742	.775
Layer 2 doubled	-.16950	-.00782	.18422	-.00691	.828
Layer 2 halved	-.17118	-0.00167	.18023	-.00738	.774
Layer 3 doubled	-0.17310	-0.00591	0.18646	-0.00746	0.770

Table 7. *Sensitivity analyses of simulated water budget output values and the absolute difference between measured and simulated water-level changes in the Rio Bravo study area, near Albuquerque, New Mexico--Concluded*

	Net flow rate (cubic feet per second) Positive numbers indicate flow into model and negative numbers indicate flow out of model				Sum of absolute difference in water-level change between measured and simulated (feet)
	Storage	River seepage	Drain seepage	General-head boundary	
Vertical hydraulic-conductivity analysis--Continued					
Layer 3 halved	-0.17219	-0.00373	0.18333	-0.00742	0.774
Layer 4 doubled	-.17285	-.00532	.18561	-.00745	.771
Layer 4 halved	-.17259	-.00469	.18472	-.00744	.771
Layer 5 doubled	-.17346	-.00538	.18632	-.00749	.772
Layer 5 halved	-.17177	-.00497	.18408	-.00735	.772
Layer 6 doubled	-.17450	-.00362	.18711	-.00900	.781
Layer 6 halved	-.17190	-.00633	.18365	-.00543	.766
Layer 7 doubled	-.17267	-.00490	.18559	-.00802	.774
Layer 7 halved	-.17301	-.00536	.18487	-.00651	.767
Layer 8 doubled	-.17263	-.00504	.18538	-.00771	.772
Layer 8 halved	-.17298	-.00518	.18514	-.00698	.768
Layer 9 doubled	-.17266	-.00507	.18534	-.00763	.773
Layer 9 halved	-.17294	-.00515	.18520	-.00711	.769
Layer 10 doubled	-.17275	-.00509	.18529	-.00746	.771
Layer 10 halved	-.17277	-.00510	.18528	-.00741	.771
River- and drain-conductance analysis					
River conductance doubled	-0.17169	-0.00497	0.18409	-0.00743	0.777
River conductance halved	-.17348	-.00358	.18448	-.00743	.773
Drain conductance doubled	-.17296	-.00542	.18582	-.00745	.771
Drain conductance halved	-.17235	-.00446	.18423	-.00743	.772

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BOOK RATE

D. Michael Roark—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 WRIR 01-4069