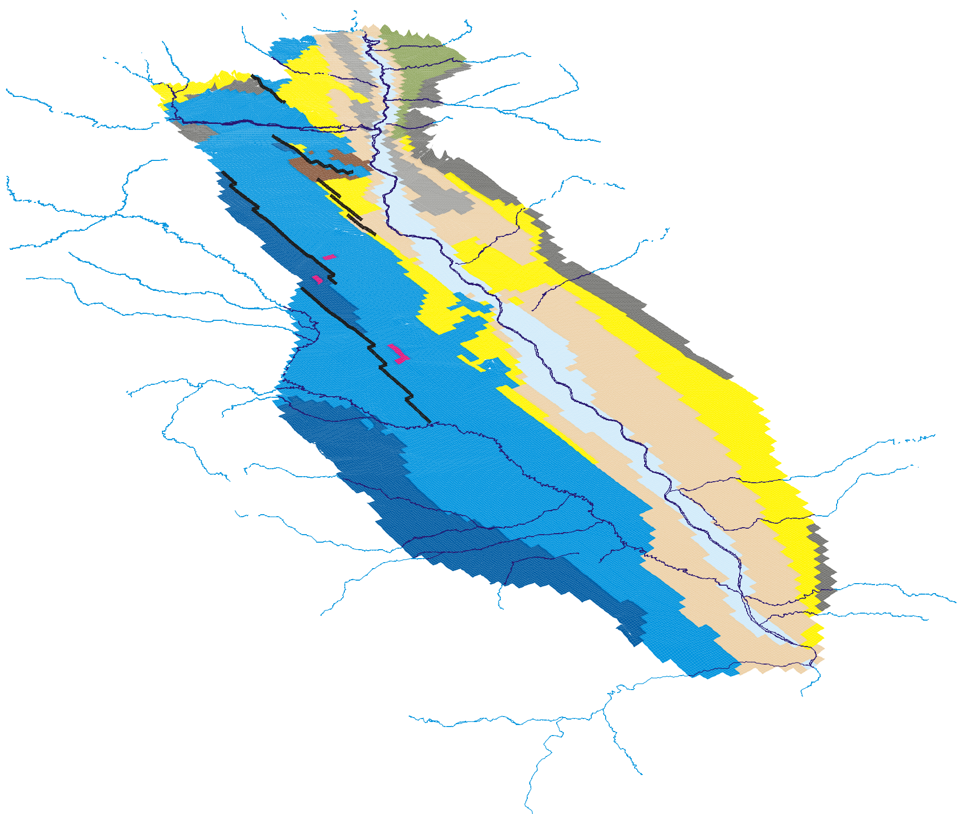
SIMULATION OF GROUND-WATER FLOW IN THE MIDDLE RIO GRANDE BASIN BETWEEN COCHITI AND SAN ACACIA, NEW MEXICO



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

Water-Resources Investigations Report 02-4200

Prepared in cooperation with the
NEW MEXICO OFFICE OF THE STATE ENGINEER
and the
CITY OF ALBUQUERQUE PUBLIC WORKS DEPARTMENT

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By Douglas P. McAda and Peggy Barroll

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2002

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
inch	2.54	centimeter
foot	0.3048	meter
mile	1.609	kilometer
per foot	3.281	per meter
acre	4,047	square meter
square mile	2.590	square kilometer
gallon	3.785	liter
cubic foot	0.02832	cubic meter
acre-foot	1,233	cubic meter
acre-foot per acre	0.3048	cubic meter per square meter
gallon per day	0.003785	cubic meter per day
cubic foot per second	0.02832	cubic meter per second

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

SIMULATION OF GROUND-WATER FLOW IN THE MIDDLE RIO GRANDE BASIN BETWEEN COCHITI AND SAN ACACIA, NEW MEXICO

By Douglas P. McAda, U.S. Geological Survey, and

Peggy Barroll, New Mexico Office of the State Engineer

ABSTRACT

This report describes a three-dimensional, finite-difference, ground-water-flow model of the Santa Fe Group aquifer system within the Middle Rio Grande Basin between Cochiti and San Acacia, New Mexico. The aquifer system is composed of the Santa Fe Group of middle Tertiary to Quaternary age and post-Santa Fe Group valley and basin-fill deposits of Quaternary age.

Population increases in the basin since the 1940's have caused dramatic increases in ground-water withdrawals from the aquifer system, resulting in large ground-water-level declines. Because the Rio Grande is hydraulically connected to the aquifer system, these ground-water withdrawals have also decreased flow in the Rio Grande. Concern about water resources in the basin led to the development of a research plan for the basin focused on the hydrologic interaction of ground water and surface water (McAda, D.P., 1996, Plan of study to quantify the hydrologic relation 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.). A multiyear research effort followed, funded and conducted by the U.S. Geological Survey and other agencies (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.). The modeling work described in this report incorporates the results of much of this work and is the culmination of this multiyear study.

The purpose of the model is (1) to integrate the components of the ground-water-flow system, including the hydrologic interaction between the surface-water systems in the basin, to better understand the geohydrology of the basin and (2) to provide a tool to help water managers plan for and administer the use of basin water resources. The aquifer system is represented by nine model layers extending from the water table to the pre-Santa Fe Group basement rocks, as much as 9,000 feet below the NGVD 29. The horizontal grid contains 156 rows and 80 columns, each spaced 3,281 feet (1 kilometer) apart. The model simulates predevelopment steady-state conditions and historical transient conditions from 1900 to March 2000 in 1 steady-state and 52 historical stress periods. Average annual conditions are simulated prior to 1990, and seasonal (winter and irrigation season) conditions are simulated from 1990 to March 2000. The model simulates mountain-front, tributary, and subsurface recharge; canal, irrigation, and septic-field seepage; and ground-water withdrawal as specified-flow boundaries. The model simulates the Rio Grande, riverside drains, Jemez River, Jemez Canyon Reservoir, Cochiti Lake, riparian evapotranspiration, and interior drains as head-dependent flow boundaries.

Hydrologic properties representing the Santa Fe Group aquifer system in the ground-water-flow model are horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield. Variable horizontal anisotropy is applied to the model so that hydraulic conductivity in the north-south direction (along model columns) is greater than hydraulic conductivity in the east-west direction (along model rows) over much of the model. This pattern of horizontal anisotropy was simulated to reflect the generally north-south orientation of faulting over much of the modeled area. With variable horizontal anisotropy, horizontal hydraulic conductivities in the model range from 0.05 to 60 feet per day. Vertical hydraulic conductivity is specified in the model as a horizontal to vertical anisotropy ratio (calculated to be 150:1 in the model) multiplied by the horizontal hydraulic conductivity along rows. Specific storage was estimated to be 2 x 10^{-6} per foot in the model. Specific yield was estimated to be 0.2 (dimensionless).

A ground-water-flow model is a tool that can integrate the complex interactions of hydrologic boundary conditions, aquifer materials, aquifer stresses, and aquifer-system responses. This ground-water-flow model provides a reasonable representation of the geohydrologic processes of the basin and simulates many historically measured trends in flow and water levels. By simulating these complex

interactions, the ground-water-flow model described in this report can provide a tool to help water managers plan for and administer the use of basin water resources. Nevertheless, no ground-water model is unique, and numerous sources of uncertainty remain. When using results from this model for any specific problem, those uncertainties should be taken into consideration.

INTRODUCTION

In 1995, the U.S. Geological Survey (USGS) and other agencies (including the New Mexico Bureau of Geology and Mineral Resources, the New Mexico Office of the State Engineer, the City of Albuquerque, and the University of New Mexico) began a series of investigations to improve the understanding of the hydrology, geology, and land-surface characteristics of the Middle Rio Grande Basin (Bartolino, 1997). The USGS Middle Rio Grande Basin Study includes the area of the Rio Grande Rift (fig. 1) between Cochiti and San Acacia, New Mexico. A primary focus of the study is "to improve the understanding of the water resources of the basin" and "to provide the scientific information needed for water-resources management" (Bartolino, 1997, p. 2). For the purpose of this report, the Middle Rio Grande Basin is defined as the extent of Cenozoic deposits within the Rio Grande Rift between Cochiti and San Acacia.

The Middle Rio Grande Basin between Cochiti and San Acacia covers an area of about 3,060 square miles (fig. 2). This area, also called the Albuquerque Basin, ranges in altitude from about 4,800 feet above NGVD 29 near the outflow of the Rio Grande in the southern part of the basin to about 6,500 feet above NGVD 29 near the Jemez Mountains in the northern part of the basin. The climate within the basin is semiarid. Average annual precipitation ranges from about 6 to 16 inches, and the basinwide area-weighted average is about 9.4 inches (Thorn and others, 1993, p. 14). Annual potential evaporation ranges from slightly less than 50 inches to greater than 60 inches, and the basinwide area-weighted average is about 57 inches (Thorn and others, 1993, p. 16, 21).

The Middle Rio Grande Basin had a population of about 690,000 people in 2000, about 38 percent of the New Mexico population (Bartolino and Cole, 2002, table 2.2; U.S. Bureau of Census, 2001). Currently (2002), ground water is the principal source of water for municipal, domestic, commercial, and industrial uses in the basin. Surface water from the Rio Grande, which extends the length of the basin, is the principal source of water for irrigated agriculture.

Population growth in the basin has increased dramatically since the 1940's (Bjorklund and Maxwell, 1961; Thorn and others, 1993; Bartolino and Cole, 2002, table 2.2). Much of this growth has centered in the Albuquerque area. The city of Albuquerque grew from a population of about 35,000 in 1940 to about 201,000 in 1960, 333,000 in 1980, and 449,000 in 2000. The city of Rio Rancho, the next largest population center in the basin, was established in the 1960's and grew to become the fourth largest city in New Mexico in 2000 (population of 52,000; U.S. Bureau of Census, 2001). The population of the Middle Rio Grande Basin has increased from about 315,000 in 1970 to about 419,000 in 1980, 564,000 in 1990, and 690,000 in 2000 (Thorn and others, 1993, p. 10; Bartolino and Cole, 2002, table 2.2).

These population increases over the last half-century have caused dramatic increases in ground-water withdrawals from the aquifer system, resulting in large ground-water-level declines (Thorn and others, 1993; Kernodle and others, 1995). Because the Rio Grande is hydraulically connected to the aquifer system, these ground-water withdrawals also have decreased flow in the Rio Grande (McAda, 1996, p. 3; 2001, p. 60-63). Concern about water resources in the basin led to the development of a research plan for the basin focused on the hydrologic interaction of ground water and surface water (McAda, 1996). A multiyear research effort followed, funded and conducted by the USGS and numerous agencies (including the New Mexico Bureau of Geology and Mineral Resources, the New Mexico Office of the State Engineer, the City of Albuquerque, and the University of New Mexico) (Bartolino and Cole, 2002). The modeling work described in this report incorporates the results of much of this work and is the culmination of this multiyear study.

Purpose and Scope

This report describes a ground-water-flow model of the Middle Rio Grande Basin that integrates newly available geohydrologic data with data and results from previous studies. Knowledge obtained during previous model development for the basin (Kernodle and others, 1995; Kernodle, 1998b; Tiedeman and others, 1998; and Barroll, 2001) is also included. The objectives of

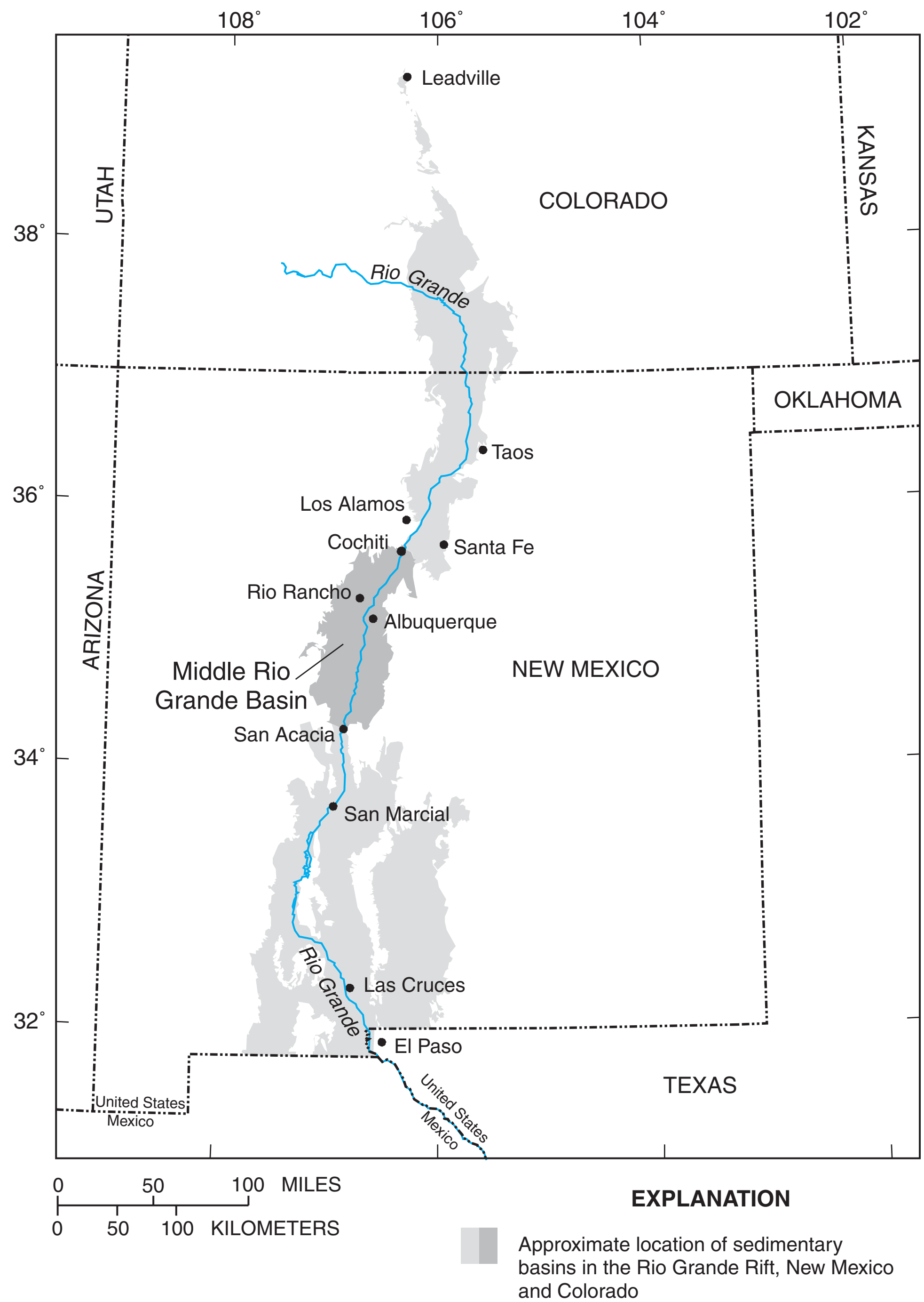


Figure 1. Location of the Middle Rio Grande Basin and sedimentary basins in the Rio Grande Rift (modified from Dane and Bachman, 1965).

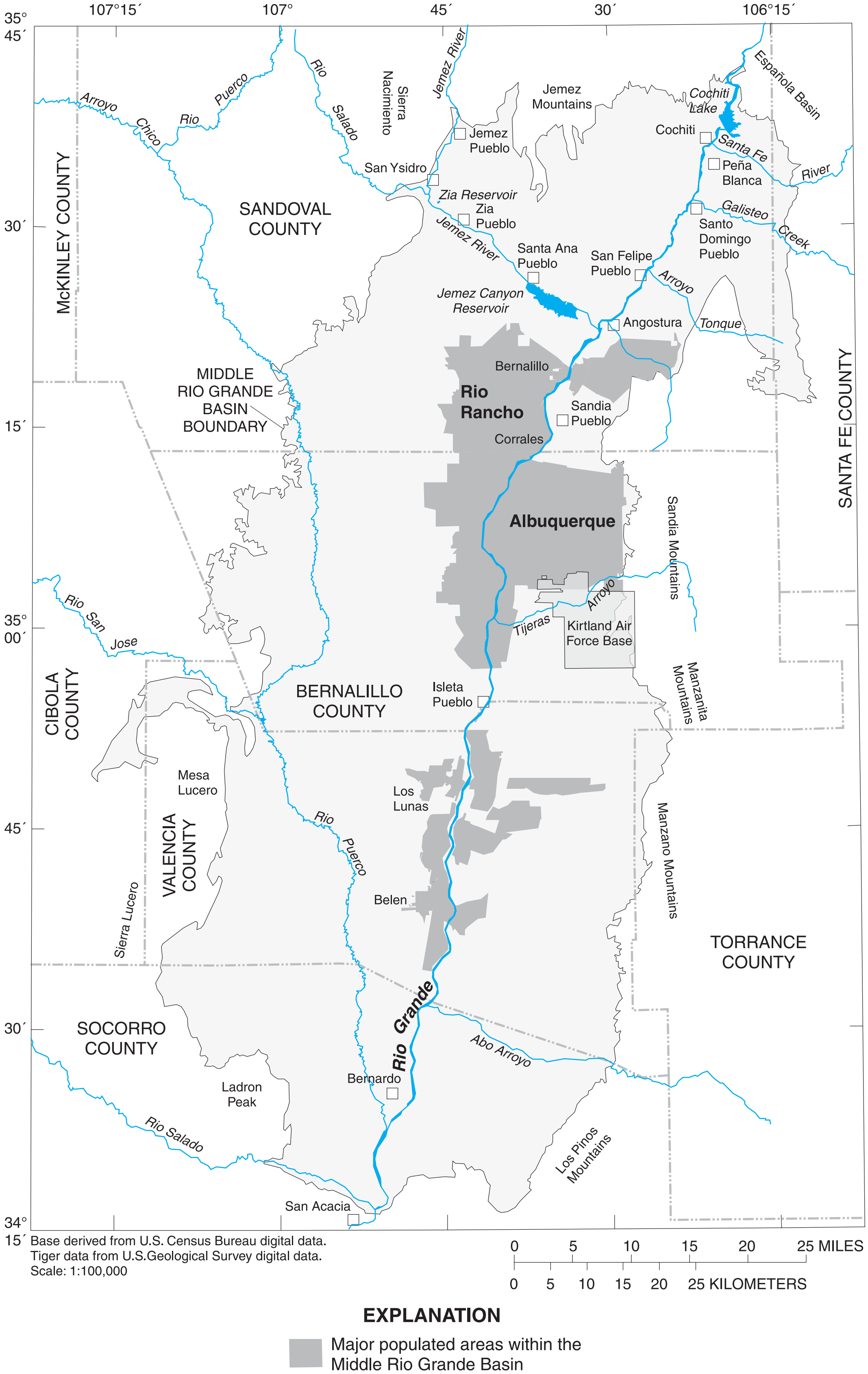


Figure 2. Cultural and physiographic features in the Middle Rio Grande Basin.

the ground-water-flow model are to (1) integrate the components of the ground-water-flow system, including the hydrologic interaction between the surface-water systems in the basin, (2) better understand the geohydrology of the basin, and (3) provide a tool to help water managers plan for and administer the use of basin water resources.

Previous Investigations

Thorn and others (1993), McAda (1996), and Bartolino and Cole (2002) discussed previous hydrologic investigations in the Middle Rio Grande Basin between Cochiti and San Acacia, and Hawley and Haase (1992), Connell (2001), and Bartolino and Cole (2002) discussed previous geologic investigations. The reader is referred to these publications for further details.

Possibly the first ground-water model of the basin was published by Reeder and others (1967). This model predicted ground-water drawdown in the vicinity of Albuquerque through 2000. Kernodle and Scott (1986) and Kernodle and others (1987) constructed steady-state and transient models, respectively, on the basis of the geohydrologic understanding of the basin presented by Bjorklund and Maxwell (1961). Kernodle and others (1995) developed a ground-water-flow model of the basin and projected ground-water-level declines from 1994 to 2020. This model was based on the geologic framework presented by Hawley and Haase (1992) and the hydrologic conditions presented by Thorn and others (1993). Kernodle (1998b) updated the Kernodle and others (1995) model to include an additional year of historical transient simulation and revised some of the hydraulic-conductivity zones. Tiedeman and others (1998) used the basic geologic framework in the Kernodle and others (1995) model and developed a ground-water-flow model using nonlinear regression calibration techniques. Barroll (2001) revised the Tiedeman model to develop a water-management tool for the Middle Rio Grande Basin. McAda (1996) developed a plan of study to improve the understanding of ground water and surface water in the basin and to help improve ground-water-flow models for this purpose.

Several ground-water-flow models have been developed for subareas of the Middle Rio Grande Basin. A model of the Rio Rancho area was developed by Zimmerman and Updegraff (1996). Sandia National Laboratories (1997) constructed a model of the Kirtland Air Force Base area. Zimmerman and others (2000) developed a model to analyze a multiple pumping-well aquifer test in the vicinity of the Rio Grande in Albuquerque. A model of a single pumping-well aquifer test of a different area but also near the Rio Grande in Albuquerque was constructed by McAda (2001).

Acknowledgments

Early discussions with John Hawley (NMBGMR, retired) and more recently with Sean Connell (NMBGMR) were helpful in developing the authors' understanding of the geohydrologic system. Discussions with Greg Gates (CH2MHill, consulting for Albuquerque), Nabil Shafike (New Mexico Interstate Stream Commission), Dave Romero (Balleau Groundwater), and Mike Kernodle (USGS, retired) were helpful in developing various aspects of the model. Laura Bexfield (USGS) prepared several components of data input to the model from geographic information system (GIS) coverages. Roger Durall (USGS) prepared GIS coverages that were used in the preparation of model input for simulation of canals and drains. The authors thank Alan Burns, Arlen Harbaugh, and Tom Reilly (USGS) for providing insight into the causes of large volumetric budget errors in some of the model simulations and Arlen Harbaugh for providing a modified layer property flow (LPF) package code specific to this problem. The authors also thank Tom Morrison and Eric Keyes (New Mexico Office of the State Engineer) and Larry Putnam and Nathan Myers (USGS) for their technical reviews of this report. The authors thank Greg Ruskoff of INTERA for sharing his insight into basin hydrology. The authors appreciate the many participants in recent studies conducted in the Middle Rio Grande Basin for the increased knowledge of the geohydrologic system that has resulted.

GEOHYDROLOGY OF THE MIDDLE RIO GRANDE BASIN

Geologic Setting

The Middle Rio Grande Basin is one of a series of generally south trending structural basins composing the Rio Grande Rift (fig. 1). The rift is an area of Cenozoic crustal extension originating in central Colorado and extending through New Mexico to Mexico and Texas (fig. 1). The Middle Rio Grande Basin is bounded on the north and south by convergence of the eastern and western structural boundaries of the rift (fig. 3). The Sandia, Manzano, Los Pinos, and Joyita Uplifts form most of the boundary on the east, and the Lucero, Ladron, and Socorro Uplifts and the San Juan structural basin form the boundary on the west. To the north and northwest, the Jemez and Nacimiento Uplifts and the Jemez Caldera constrict the basin. The boundary between the Middle Rio Grande Basin and the adjacent rift basin to the north, the Española Basin, is the La Bajada Escarpment (Kelley, 1952). The boundary between the Middle Rio Grande Basin and the Socorro Basin to the south is the San Acacia constriction, formed by the Socorro and Joyita Uplifts.

The uplifts along the east side of the basin are composed of Precambrian plutonic and metamorphic rocks, unconformably overlain by Paleozoic limestone, sandstone, and shale (Hawley and Haase, 1992; Hawley and others, 1995). The Joyita and Socorro Uplifts are composed of Precambrian rock cores (Hawley and others, 1995). The Ladron Uplift comprises Precambrian granite and metamorphic rocks, and the Lucero Uplift comprises Paleozoic limestone, sandstone, and shale and Cenozoic basalt flows (Hawley and others, 1995). Overlain by Paleozoic and Mesozoic rocks, the Nacimiento Uplift is composed of Precambrian plutonic and metamorphic rocks (Hawley and others, 1995). Cenozoic volcanic rocks make up the Jemez volcanic center. The basement rocks that underlie the sedimentary basin fill of the Middle Rio Grande Basin are composed of lower and middle Tertiary rocks in the central part of the basin (primarily sandstone and mudstone) with Mesozoic, Paleozoic, and Precambrian rocks near the basin margins (Hawley and others, 1995, figs. 2 and 3).

The sedimentary fill of the Middle Rio Grande Basin is composed of middle Tertiary to Quaternary Santa Fe Group and Quaternary post-Santa Fe Group valley and basin-fill deposits. The Santa Fe Group is as much as about 14,000 feet thick in the basin and is divided into lower, middle, and upper parts (Hawley and Haase, 1992; Hawley and others, 1995; Stone and others, 2001). Sediments in the lower part of the Santa Fe Group contain a predominance of piedmont-slope, eolian, and basin-floor playa deposits and may be as much as 3,500 feet thick (Hawley and Haase, 1992). The middle part of the Santa Fe Group contains piedmont-slope deposits, fluvial basin-floor deposits (primarily fine to medium sand), and basin-floor playa deposits (Hawley and Haase, 1992). This middle part of the Santa Fe Group contains the largest accumulation of sediment—as much as 9,000 feet—and was likely deposited during a time when fluvial systems from the north, northeast, and southwest terminated in playa lakes in the southern part of the basin (Lozinsky, 1988; Hawley and Haase, 1992). The upper part of the Santa Fe Group was deposited during development of an ancestral Rio Grande and contains intertonguing piedmont-slope and fluvial basin-floor deposits as thick as 1,500 feet (Hawley and Haase, 1992). The coarsest sediments are made up of ancestral Rio Grande axial-channel deposits contained in the upper part of the Santa Fe Group and post-Santa Fe Group sediments that underlie the present-day Rio Grande in the inner valley (fig. 4).

The alluvium in the inner valley consists of post-Santa Fe Group deposits from the most recent erosion and deposition sequence of the Rio Grande (Hawley and Haase, 1992, p. II-7). Hawley and Haase reported that these channel and flood-plain sediments may be as thick as 120 feet but generally average about 80 feet thick. Thinner post-Santa Fe Group fluvial deposits are also found along the Jemez River and other tributaries to the Rio Grande.

Faults within and bounding the Santa Fe Group (fig. 3) have offset depositional sequences of Santa Fe Group sediments throughout the basin. The faults primarily are oriented north-south (fig. 3). Sediments of differing lithology are often juxtaposed across these faults, and many of the faults may be cemented to some degree. Juxtaposed lithologic units of different hydraulic conductivities reduce hydraulic conductivity across the faults. Additionally, the presence of cementation or clay-rich fault gouge may further decrease hydraulic conductivity across faults.

Surface-Water Hydrology

The dominant surface-water feature of the Middle Rio Grande Basin is the Rio Grande, which flows through the basin from north to south (fig. 4). The Rio Grande is a perennial stream, although during drought years some reaches may go dry. The Rio Grande carries an average of about 1,000,000 acre-feet per year of surface water into the basin (S.S. Papadopulos and Associates, Inc., 2000; Ortiz and

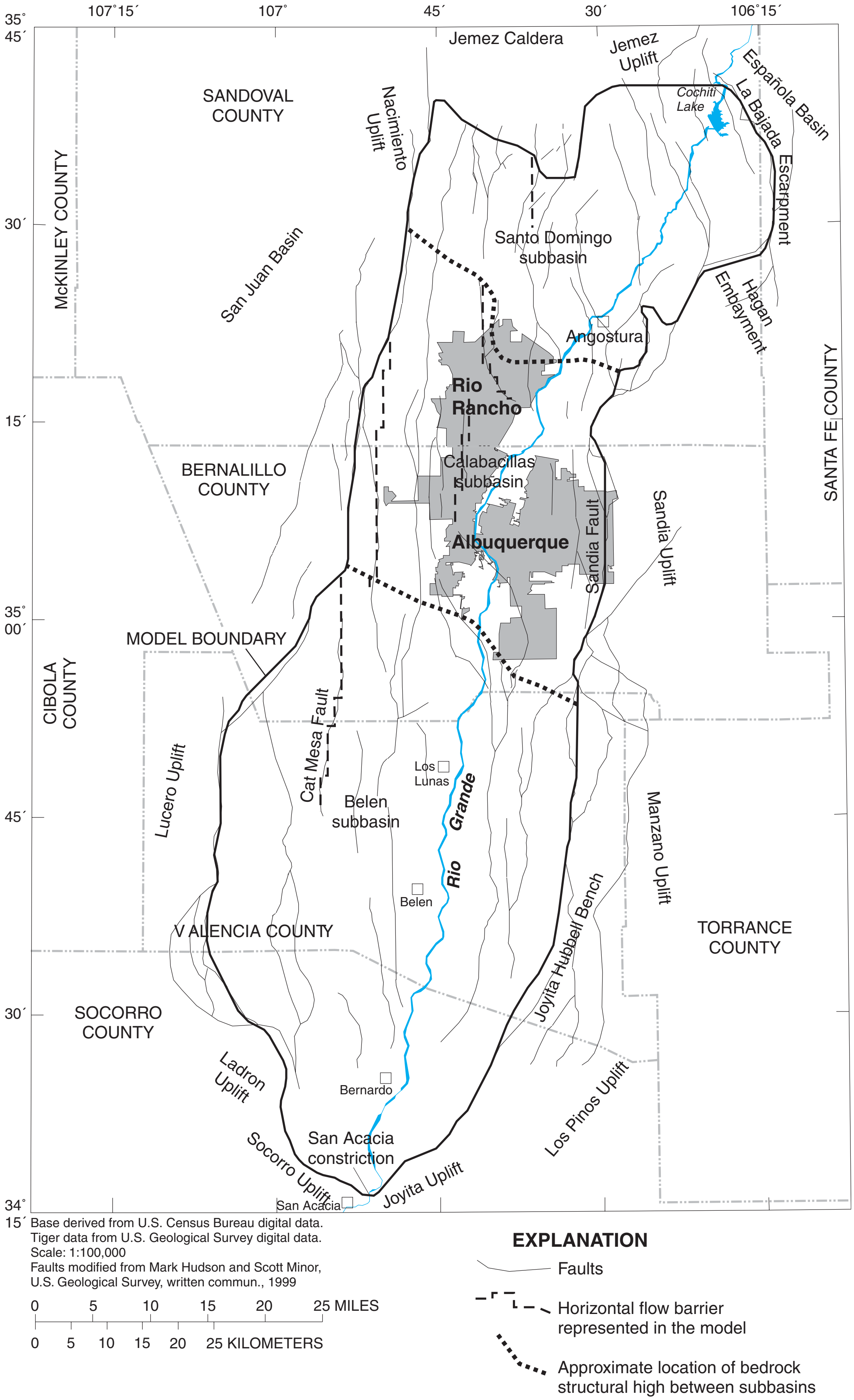


Figure 3. Major tectonic features and model boundary in the Middle Rio Grande Basin.

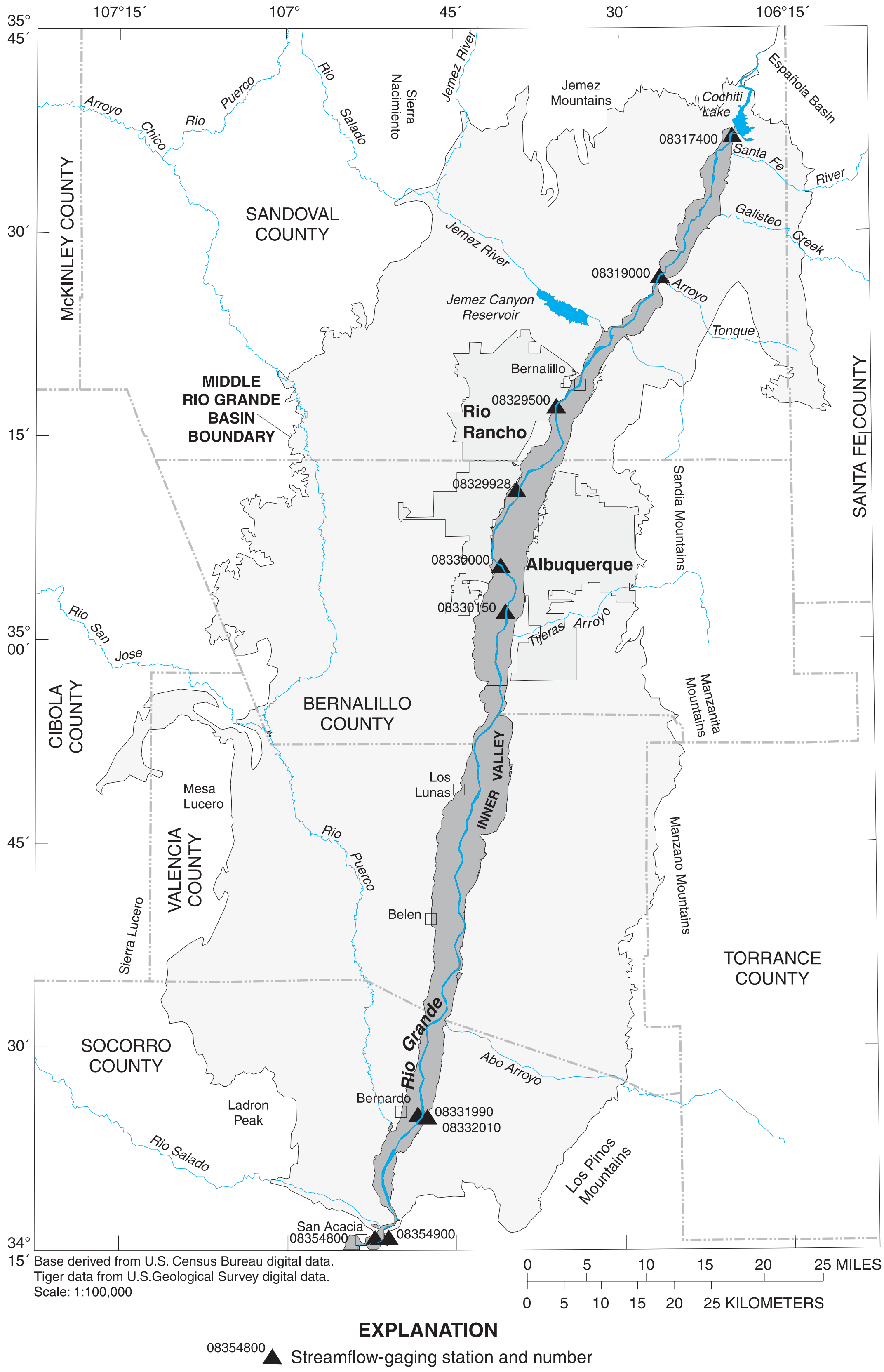


Figure 4. Streamflow-gaging stations in the Middle Rio Grande Basin.

others, 2001, p. 125). The Jemez River, which is perennial through most of its length within the basin, is the largest tributary to the Rio Grande within the basin and provides an average of about 45,000 acre-feet per year of surface water to the Rio Grande (S.S. Papadopulos and Associates, Inc., 2000; Ortiz and others, 2001, p. 135). The Rio Grande and Jemez River predominantly lose water to the aquifer system, although some reaches gain water. The remaining tributaries to the Rio Grande within the basin are ephemeral where they enter the Rio Grande, but many are perennial or intermittent at the basin margins. The Santa Fe River, Galisteo Creek, Tijeras Arroyo, Abo Arroyo, Rio Puerco, and Rio Salado (in the southern part of the basin) often flow at the basin margins, but only ephemeral flow from storm-water runoff reaches the Rio Grande. Two of those, the Rio Puerco and Rio Salado, have been gaged near their confluence with the Rio Grande. The Rio Puerco contributes an average of about 30,000 acre-feet per year to the Rio Grande (Ortiz and others, 2001, p. 184), and the Rio Salado contributes about 5,900 acre-feet per year (average of 1974-84 flow; Thorn and others, 1993, p. 84). A number of arroyos are also tributary to the Rio Grande. These ephemeral channels occasionally contribute flow to the Rio Grande from storm-water runoff. The flow of the Rio Grande as it exits the basin near San Acacia (combined flow of all conveyances of Rio Grande water) averages about 1,000,000 acre-feet per year (Ortiz and others, 2001, p. 192). A more detailed discussion of the Rio Grande and its tributaries in the basin can be found in Thorn and others (1993, p. 80-84).

A network of canals and drains throughout the inner Rio Grande Valley and a network of canals along the Jemez River play a role in the Middle Rio Grande Basin surface-water system. Water is diverted from the Rio Grande and Jemez River at a number of diversion dams for irrigation. The canal and drain network along the Rio Grande extends throughout the inner valley. Although a system of canals has existed for irrigation in the inner valley for hundreds of years (Thorn and others, 1993, p. 4-6), the current (2002) canal and drain system along the Rio Grande was constructed beginning in the late 1920’s and 1930’s and is overseen by the Middle Rio Grande Conservancy District (MRGCD). The MRGCD combined the operation of many private, community, and pueblo acequias into common diversion structures and canal systems. The canal system along the Jemez River, upstream from Jemez Canyon Reservoir, is less extensive than in the Rio Grande inner valley and does not include a system of drains. The majority of canals along the Rio Grande and Jemez River are constructed so to allow water to flow down onto irrigated fields and, therefore, the canal bed is above the water table. Most canals are unlined, and water from the canals seeps into the ground and recharges ground water. An extensive network of drains throughout the inner Rio Grande Valley was constructed by the MRGCD to lower the water table and reclaim crop lands that had become waterlogged from applied irrigation water, canal seepage, and seepage from the Rio Grande. These drains consist of riverside and interior drains and are primarily open channels dug below the water table.

The riverside drains parallel the Rio Grande and were installed to intercept leakage from the Rio Grande that previously contributed to waterlogging of soils in the adjacent valley areas. These drains are in direct connection to the aquifer system. Riverside drain beds at the head of a particular drain are below river and water-table altitudes. However, the drain-bed altitude rises relative to river altitude in the downstream direction so that water at the lower end of the drain can be returned to the river. Where a drain bed has risen relative to the water table so that it no longer functions as a drain, an overlap drain begins alongside the primary drain to take over the drain function. Canals often terminate at the drains so that excess irrigation water can be returned to the Rio Grande through the drains. Parts of riverside drains also function as conveyance channels during the irrigation season, causing drain stage to be above the water table. Therefore, riverside drains can either lose or gain water from the aquifer system depending on the drain stage and drain-bed altitude relative to the water table.

The interior-drain system extends outward from the riverside drains and intercepts seepage from canals and applied irrigation water in the inner valley. The water intercepted by the interior drains is discharged to the riverside drains and ultimately to the Rio Grande. Excess water from canals is also discharged to the interior drains. Although the purpose of interior drains was to drain water from the shallow aquifer system, a small number of the interior-drain reaches are used for conveyance of irrigation water. Identification and characterization of the drain reaches used for conveyance were beyond the scope of this investigation. Many interior drains in the Albuquerque vicinity no longer function as drains because the water table remains below the drain bottom as a result of ground-water withdrawal.

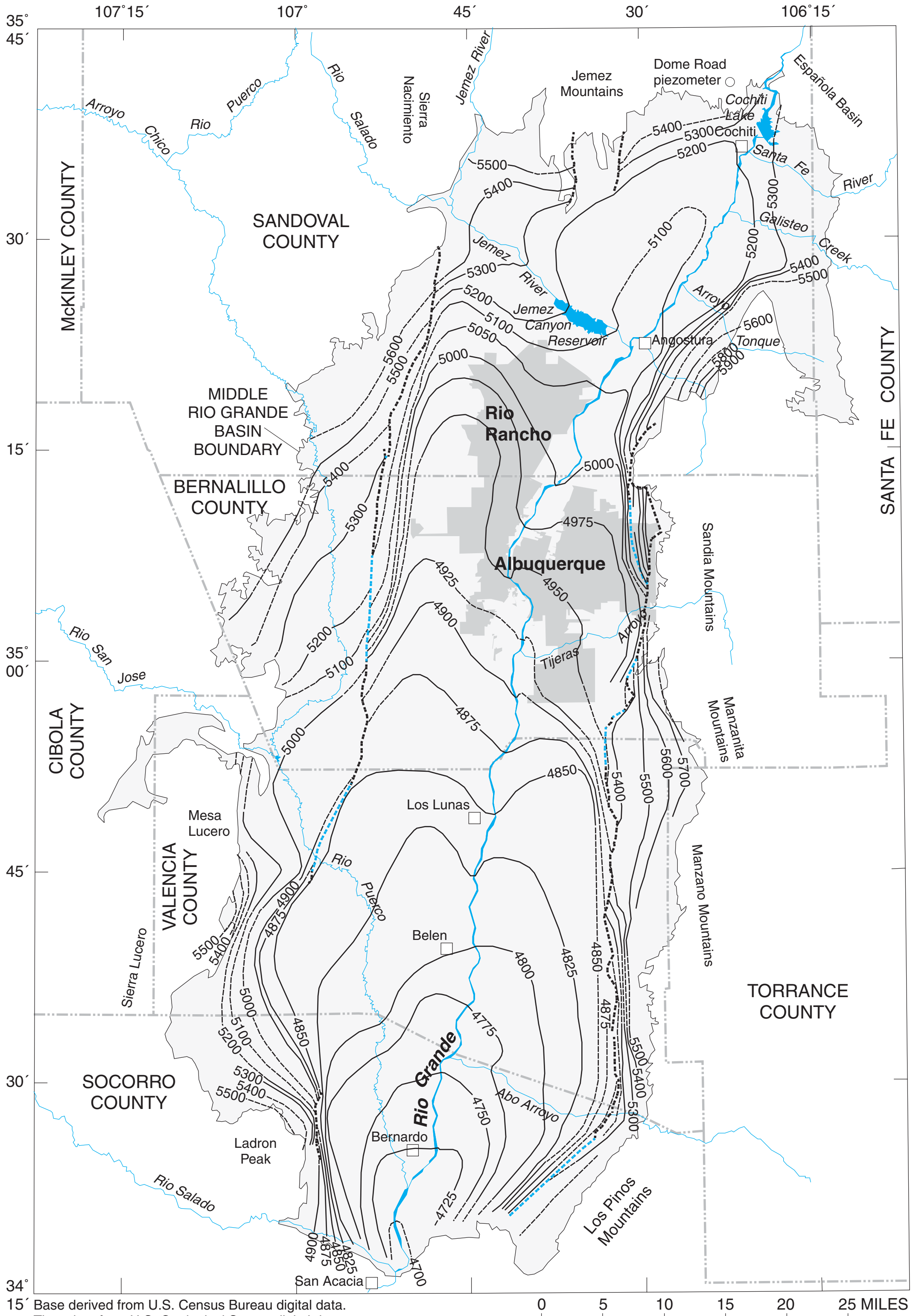
Two dams provide flood and sediment control within the basin: Cochiti Dam, which forms Cochiti Lake, and Jemez Canyon Dam, which forms Jemez Canyon Reservoir. Cochiti Lake began storing water in November 1973 and has a substantial recreational pool. Seepage from the lake has caused ground-water levels to rise in the vicinity of the lake and downstream from the dam (Blanchard, 1993). Much of this seepage reappears downstream in the Rio Grande below the Dam. Jemez Canyon Reservoir was constructed for sediment control and flow detainment when the Rio Grande is in flood stage. Jemez Canyon Reservoir began permanently storing water in about 1979, but stored water on a short-term basis prior to this time. Neither reservoir provides storage for irrigation water; the MRGCD's surface-water storage is in reservoirs considerably upstream from the Middle Rio Grande Basin.

Ground-Water Hydrology

The aquifer system in the Middle Rio Grande Basin as defined for this report consists of the Santa Fe Group and post-Santa Fe Group alluvial units within the Rio Grande inner valley (and, to a lesser extent, along other tributaries). The most permeable parts of the aquifer system are composed of axial-channel deposits of the ancestral Rio Grande in the upper part of the Santa Fe Group and the post-Santa Fe Group recent river-channel alluvium in the inner Rio Grande Valley. The western boundary of the aquifer system is associated with cemented faults (fig. 3), which restrict ground-water flow within Santa Fe Group sediments in the basin (fig. 5; Kernodle and others, 1995, p. 12). The northern boundary of the aquifer system as defined for this study is the approximate contact of Santa Fe Group sediments with Cenozoic volcanic rocks of the Jemez Mountains. The northeastern boundary is the La Bajada Escarpment, where Santa Fe Group sediments of the Española Basin are uplifted across the La Bajada Fault relative to Santa Fe Group sediments in the Middle Rio Grande Basin (fig. 3). These north and northeast boundaries are similar to the boundaries defined for the ground-water-flow model of the Albuquerque Basin by Kernodle and others (1995). This boundary is likely not a distinct geohydrologic boundary. It has been suggested that the Middle Rio Grande Basin (Albuquerque Basin) extends beneath the volcanics of the Jemez Mountains and that it has a significant geohydrologic connection with the Española Basin to the northeast (Hawley and Grant, 1997; Grant, 1999). This geohydrologic connection contributes a substantial amount of subsurface ground-water recharge across the northern and northeastern boundary of the aquifer system as defined for this study. Faults separating the Hagan Embayment from the main part of the Middle Rio Grande Basin define the aquifer-system boundary southwest of the La Bajada Escarpment. The eastern boundary of the aquifer system is associated with faults along the Sandia, Manzano, and Los Pinos Uplifts (fig. 3), which offset saturated Santa Fe Group sediments against older, less permeable geologic units. Although the aquifer-system boundary is adjacent to the Sandia Uplift at the Sandia Fault, the boundary near the Manzano and Los Pinos Uplifts is shifted basinward to the west side of the Joyita-Hubbell Bench (fig. 3). The Santa Fe Group is only thinly saturated on the bench, and the Joyita-Hubbell Faults (on the west side of the bench) form a distinct hydrologic boundary (fig. 5; Kernodle and others, 1995, p. 12). The southern boundary of the aquifer system is formed by the Socorro and Joyita Uplifts (fig. 3). The older, pre-Santa Fe Group rocks that surround the aquifer system in plan view and underlie the aquifer system are, in general, much less permeable than the Santa Fe Group sediments.

Mountain-Front and Tributary Recharge

Mountain-front recharge results from surface runoff or shallow underflow originating from mountains adjacent to the basin that infiltrates into the upper part of the aquifer system near the mountain fronts. Tributary recharge occurs as seepage from streams and arroyos tributary to the Rio Grande that have surface flows extending into the Middle Rio Grande Basin. Many of the tributary streams near the eastern mountain front contain persistent flow for only a few hundred meters beyond the mountain front (Niswonger and Constantz, 2001); therefore this recharge is indistinguishable from mountain-front recharge on a basinwide scale. Recharge from ephemeral arroyos decreases significantly with distance from the mountain front (Nimmo and others, 2001; Niswonger and Constantz, 2001; Stewart and Constantz, 2001). Mountain-front recharge and tributary recharge are combined in this discussion because these recharge components are often combined in recharge estimates. Mountain-front recharge comes from the Sandia, Manzanita, Manzano, and Los Pinos Mountains along the east side of the



EXPLANATION

- 4900 —— Water-level contour--Interval, in feet, is variable. Dashed where inferred. Datum NGVD 29
- -------- Major fault located in the vicinity of a large hydraulic discontinuity
- -------- Area of apparent hydraulic discontinuity, not located near a known fault

Figure 5. Predevelopment water-level contours in the Middle Rio Grande Basin (modified from Bexfield and Anderholm, 2000).

basin; Ladron Peak in the southwestern part of the basin; and the Sierra Nacimiento and Jemez Mountains in the northern part of the basin. Tributary streams that likely contribute substantial recharge to the aquifer system beyond the mountain front include the Santa Fe River, Galisteo Creek, Tijeras Arroyo, Abo Arroyo, Rio Salado, and Rio Puerco.

Mountain-front and tributary recharge along the eastern side of the basin, from the Arroyo Tonque watershed on the north to the Los Pinos Mountains on the south, has been estimated by several investigators. The following estimates include tributary recharge from Tijeras Arroyo and Abo Arroyo. Jack Dewey (U.S. Geological Survey, written commun., 1982; cited in Kernodle and Scott, 1986) estimated this recharge to be about 72,000 acre-feet per year using a water-budget method. Kernodle and others (1995) used these values in a ground-water-flow model of the basin. Tiedeman and others (1998) used non-linear regression modeling techniques to estimate this recharge to be about 36,000 to 49,000 acre-feet per year. Anderholm (2001) calculated the recharge along most of this mountain front (excluding the Arroyo Tonque watershed) to be 11,000 acre-feet per year using a chloride-balance method. Anderholm (2001) compared that number to the water-yield regression methods of Hearne and Dewey (1988), which resulted in a recharge value of 36,000 acre-feet per year, and of Waltemeyer (1994), which resulted in a recharge value of 38,000 acre-feet per year.

Mountain-front recharge along Ladron Peak was calculated by Dewey (U.S. Geological Survey, written commun., 1982; cited in Kernodle and Scott, 1986) to be about 1,300 acre-feet per year. This value was used in the models of Kernodle and others (1995) and Tiedeman and others (1998), although the value was input as subsurface recharge.

Recharge has been estimated for particular tributaries by several investigators. Kernodle and others (1995) estimated recharge from the Santa Fe River and Galisteo Creek to be about 4,000 and 3,600 acre-feet per year, respectively, based on streamflow records. Thomas and others (2000) measured streamflow at the upstream (USGS gaging station 08317200) and downstream (USGS gaging station 08317207) ends of a 2.5-kilometer reach of the Santa Fe River where it enters the basin at the La Bajada Escarpment from the end of June 1997 to early October 1997. During this time, flow at the upstream gaging station ranged from 3.5 to 10.2 cubic feet per second and averaged 6.5 cubic feet per second (calculated from Thomas and others, 2000, table 5). The average streamflow over the 1970-99 period of record for that station (Ortiz and others, 2000) is 11.4 cubic feet per second. By using simple linear regression, streamflow at the upper and lower ends of the reach, with a time lag of 45 minutes to compensate for travel time (745 observations; Thomas and others, 2000, table 5), correlates with a coefficient of determination (R^2) of 0.80. The resulting regression equation ($Y=0.20 + 0.83 X$; where Y is the flow $[L^3/T]$ at station 08317207 and X is the flow $[L^3/T]$ at station 08317200) can be used to estimate average streamflow at the lower end of the reach and, therefore, average streamflow loss in the reach that would result from the average flow measured at the upper gage. The average flow expected at the lower gage resulting from 11.4 cubic feet per second of flow at the upper gage would be 9.7 cubic feet per second; therefore, the estimated streamflow loss in the reach would be 1.7 cubic feet per second over the 2.5-mile reach. Thomas and others (2000) estimated that of the streamflow loss they calculated, only about 2-8 percent was accounted for by evaporation and that about 92-98 percent was infiltration from the stream.

Infiltration rates from Tijeras Arroyo near the mountain front have been estimated by Thomas (1995). The average rate calculated for October 1989 through May 1992, 5.9 feet per day, and an average channel width of 4 feet result in an estimated 400 acre-feet of water per year infiltrating from a 2,000-foot reach of Tijeras Arroyo near the mountain front (C.L. Thomas, U.S. Geological Survey, oral commun., 1998; cited in Tiedeman and others, 1998). For comparison, the water-budget method of Jack Dewey (U.S. Geological Survey, written commun., 1982; cited in Kernodle and Scott, 1986) results in a recharge of about 10,600 acre-feet per year for the arroyo and mountain front in the vicinity of the arroyo. The method of Hearne and Dewey (1988) results in a recharge value of 7,960 acre-feet per year, the method of Waltemeyer (1994) results in a value of 6,420 acre-feet per year, and the method of Anderholm (2001) results in a value of 1,790 acre-feet per year. These last three values apply to the arroyo and mountain front.

Recharge from Abo Arroyo was estimated by Nimmo and others (2001) using a technique referred to as the Darcian-steady-state centrifuge method. They estimated that about 1,300 acre-feet per year recharges the aquifer system from Abo Arroyo, and of that amount, about 1,040 acre-feet per year recharges within 7.5 miles (12 kilometers) of the mountain front. This total recharge compares favorably with the 1,280 acre-feet per year of recharge calculated by Anderholm (2001) using the chloride-balance method. The recharge from Abo Arroyo and adjacent mountain front calculated by Dewey (U.S. Geological Survey, written commun., 1982; cited in Kernodle and Scott, 1986) was 15,400 acre-feet per year, by the Hearne and Dewey (1988) method was 4,220 acre-feet per year, and by the Waltemeyer (1994) method was 17,320 acre-feet per year (latter two cited by Anderholm, 2001).

Recharge from the Rio Salado at the southern boundary of the aquifer system was estimated by Jack Dewey (U.S. Geological Survey, written commun., 1982; cited in Kernodle and Scott, 1986) as about 13,100 acre-feet per year. Kernodle and others (1995) and Tiedeman and others (1998) reduced that amount to about 7,200 acre-feet per year in their ground-water-flow models of the basin.

Recharge from the Rio Puerco was estimated by Jack Dewey (U.S. Geological Survey, written commun., 1982; cited in Kernodle and Scott, 1986) to be about 10,400 acre-feet per year. A portion of that recharge was attributed to reaches of the Rio Puerco beyond the boundary of the aquifer system as defined for this report. The portion of that recharge within the aquifer boundary is about 5,600 acre-feet per year. Kernodle and others (1995) applied this portion of recharge in their model along the Rio Puerco and the remainder (about 4,800 acre-feet per year) to the nearby model boundary. Tiedeman and others (1998) estimated values ranging from 1,500 to 3,800 acre-feet per year for the reach within the model boundary using nonlinear-regression modeling techniques. In preliminary nonlinear-regression modeling using water ages, Sanford and others (2001) estimated Rio Puerco recharge within the model to be about 2,000 acre-feet per year.

The Sierra Nacimiento and Jemez Mountains provide mountain-front recharge to the aquifer system in the northern part of the basin. Kernodle and others (1995) did not specifically estimate mountain-front recharge in this area but included recharge in this area as subsurface recharge and recharge along the Jemez River Valley north of the confluence of the Rio Salado and Jemez River. These recharge amounts are discussed in the sections below. The combination of these recharge amounts specified by Kernodle and others (1995) was about 12,800 acre-feet per year.

Mountain-front and tributary recharge to the aquifer system was estimated by Thorn and others (1993, p. 92) to be about 139,000 acre-feet per year. The estimate of Kernodle and others (1995) was about 110,000 acre-feet per year. Tiedeman and others (1998) estimated mountain-front and tributary recharge to be about 90,000 acre-feet per year. Recent work by Anderholm (2001) and Plummer and others (2001) and preliminary estimates made by Sanford and others (2001) indicate that total mountain-front and tributary recharge is likely smaller than the values listed above.

Subsurface Recharge

Subsurface recharge occurs as ground-water inflow from adjacent basins or mountains. Subsurface recharge comes from the vicinity of the Jemez Mountains, Española Basin, and Hagan Embayment in the north-northeastern part of the basin and from Sierra Lucero to the San Juan Basin in the western part of the Middle Rio Grande Basin.

A substantial amount of subsurface recharge enters the basin from the Jemez Mountains and Española Basin areas (Hawley and Grant, 1997; Grant, 1999). Ground-water-flow modeling in the Española Basin resulted in estimated subsurface flow from the Española Basin to the Middle Rio Grande Basin ranging from about 8,800 acre-feet per year (Frenzel, 1995) to about 12,600 acre-feet per year (McAda and Wasiolek, 1988). Kernodle and others (1995) used the latter value (12,600 acre-feet per year) for subsurface recharge from the Española Basin and estimated an additional amount of subsurface recharge of 7,000 acre-feet per year from the Jemez Mountains for a total of 19,600 acre-feet per year along the northern and northeastern aquifer-system boundary. Tiedeman and others (1998) used approximately the same amount. Sanford and others' (2001) preliminary estimates are significantly smaller (a total of 11,000 acre-feet per year for this recharge plus recharge from the Santa Fe River, Galisteo Creek, and Hagan Embayment). Grant (1999, p. 434), referring to the combined Española-Albuquerque aquifer systems west of the Rio Grande, speculated that "there may be large volumes of unaccounted for water that recharge the underground system."

Subsurface recharge from the Hagan Embayment was estimated by Kernodle and others (1995) as about 700 acre-feet per year. Tiedeman and others (1998) used the same value.

Subsurface recharge along Sierra Lucero and Mesa Lucero was estimated by Jack Dewey (U.S. Geological Survey, written commun., 1982) to be about 1,100 acre-feet per year. Kernodle and Scott (1986, fig. 5) located about 5,200 acre-feet per year of recharge as underflow along Mesa Lucero. J.M. Kernodle (U.S.

Geological Survey, oral commun., 1996) determined that recharge along Mesa Lucero was intended as recharge from the Rio San Jose at its confluence with the Rio Puerco. Tiedeman and others (1998, fig. 5) showed the distribution of recharge in this area as intended by Dewey (U.S. Geological Survey, written commun., 1982).

Subsurface recharge from the San Juan Basin was estimated by Frenzel and Lyford (1982) to be about 1,200 acre-feet per year and estimated by Kernodle and Scott (1986) to be about 1,300 acre-feet per year. Subsurface recharge from the San Juan Basin used in Kernodle and others (1995) and Tiedeman and others (1998) was 1,200 acre-feet per year.

Estimates of recharge along the entire western aquifer margin (north of the southern Rio Salado to the boundary adjacent to the Sierra Nacimiento) can be compared. These estimates exclude any recharge attributed to the Jemez River along the western aquifer margin. The recharge used by Kernodle and others (1995, fig. 5) along the entire western margin was about 13,600 acre-feet per year. This included about 4,700 acre-feet per year of recharge from the reach of the Rio Puerco that was on or outside their model boundary. Tiedeman and others (1998) estimated 11,200 acre-feet per year of recharge for the entire western margin. The difference from the Kernodle and others (1995) estimate is that Tiedeman and others (1998) estimated half the amount of recharge from the reach of the Rio Puerco on or outside their model boundary. Sanford and others (2001) preliminarily estimated recharge along this boundary to be about 2,000 acre-feet per year using carbon-14 ground-water age dates.

Ground-Water Withdrawal

Currently (2002), ground water is the principal source of water for municipal, domestic, commercial, and industrial uses in the Middle Rio Grande Basin. Early (prior to about 1900) wells in the basin were primarily shallow, hand-dug wells in the inner Rio Grande Valley (Thorn and others, 1993). The City of Albuquerque withdraws the largest amount of ground water in the basin. The City’s ground-water withdrawal has increased from about 2,000 acre-feet in 1930 (Bjorklund and Maxwell, 1961) to a maximum of about 127,000 acre-feet in 1989 (City of Albuquerque files). Over the last 5 years (1997-2001), the City’s withdrawal has ranged from 110,000 to 114,000 acre-feet per year. Thorn and others (1993, table 4) estimated total ground-water withdrawal in the basin to be about 97,000 acre-feet in 1970, about 131,000 acre-feet in 1980, and about 152,700 acre-feet in 1990. Estimated ground-water withdrawal in the Middle Rio Grande Basin during the 1990’s has ranged from about 150,000 to about 160,000 acre-feet per year (files of the Office of the New Mexico State Engineer, Albuquerque), peaking in the middle part of the decade (1994-95). Some of the water withdrawn by wells is not consumed and returns to the surface-water system through municipal water-reclamation systems. This return is estimated as approximately half the water withdrawn by municipal water systems (Thorn and others, 1993, p. 54-55, 81-82). A relatively small amount of water withdrawn by wells may recharge ground water through septic systems. This septic-field seepage was estimated by Kernodle and others (1995) to be about 8,000 acre-feet per year.

Ground-Water Flow and Ground-Water/Surface-Water Interaction

In general terms, ground water in the aquifer system flows from the basin margins, inward and southward toward the Rio Grande inner valley (fig. 5). An apparent trough in water levels is located west of the Rio Grande and north of the Jemez River (5,100-foot contour, fig. 5). Smith and Kuhle (1998) mapped channel gravels in the Santo Domingo subbasin; the trough may reflect a relatively high permeability pathway for ground water provided by these channel gravels. Water-level measurements in a recently (1998) drilled piezometer just north of the basin boundary (fig. 5, Dome Road piezometer, USGS site 354056106215801; data available at *http://waterdata.usgs.gov/nm/nwis/*) show water-level altitudes of 5,206 feet above sea level, indicating that this trough may extend northward to the Española Basin. This piezometer is in an area with little ground-water development and reflects near-predevelopment conditions. The contours extending from 5,200 to 5,400 feet above NGVD 29 south of the Jemez Mountains in figure 5 could reflect perched ground-water zones from mountain-front recharge as it infiltrates to the regional aquifer system. On the east side of the Rio Grande in the Albuquerque vicinity, another trough in predevelopment ground-water levels is shown. Hawley and Haase (1992) have shown axial-channel gravels of the ancestral Rio Grande in this area. Through aquifer tests, these channel gravels were demonstrated to have higher hydraulic-conductivity values than sediments to the east and west (summarized by Thorn and others, 1993, table 2).

A trough in ground-water levels exists on the west side of the Rio Grande, extending from Rio Rancho to south of Albuquerque (fig. 5; Meeks, 1949; Bjorklund and Maxwell, 1961, pls. 1a and 1b). This trough is not associated with high-permeability sediments (Hawley and Haase, 1992) such as may be the case in the other two troughs. In addition, ground-water chemistry data indicate that water recharged from the Rio Grande is not identifiable beyond about 1 to 3 miles west of the Rio Grande (Plummer and others, 2001). Because the ground-water hydraulic gradient is from the Rio Grande to this west-basin trough (fig. 5), water with the Rio Grande chemical signature would be expected within the area of the trough if the trough were not relatively isolated by low-permeability sediments, juxtaposition of sediments across faults, or low-permeability fault zones. Figure 3 shows the north-south orientation of major faults through much of the basin. The faults align with the axis of the trough and support the conclusion that at least some faults cause horizontally anisotropic conditions in the aquifer system. In general, permeability in the east-west direction is reduced relative to the north-south direction.

The ground-water flow system has changed because of ground-water development (fig. 6). The most noticeable of these is the change in apparent ground-water flow directions in Albuquerque on the east side of the Rio Grande. Predevelopment water levels (fig. 5) show the ground-water hydraulic gradient to the southwest toward the Rio Grande. The 1994-95 water levels (fig. 6) show the gradient from the Rio Grande to the east toward the cones of depression at the pumping centers in east Albuquerque. Although not as dramatic as in the east Albuquerque area, the influences of ground-water withdrawal are also indicated in the Rio Rancho and west Albuquerque areas. Other apparent differences between the predevelopment (fig. 5; modified from Bexfield and Anderholm, 2000) and 1994-95 (fig. 6; modified from Kernodle, 1998b; Tiedeman and others, 1998) water-level contour maps may be differences in the availability of data for different time periods and differing interpretations of some data by the authors of these maps. For example, differing interpretations of the same data resulted in the differences in the 5,100-foot contours between the two maps in the northern part of the basin (Kernodle, 1998b, fig. 18; Bexfield and Anderholm, 2000).

The largest recharge and discharge components associated with the ground-water system are in the inner valley of the Rio Grande and the Jemez River. Within these river valleys, complex interactions between ground water and surface water are associated with the Rio Grande and Jemez River, irrigation canals, irrigated crops, riparian vegetation, drains (in the Rio Grande inner valley), and reservoirs. Before the development of large-scale irrigation and urbanization in the basin, ground-water discharge occurred in the inner valley, mostly through evapotranspiration from riparian vegetation and wetlands (Kernodle and others, 1995, p. 66). Ground water flowed to the inner valley from the basin margins, and the inner valley was also recharged by losses from the Rio Grande. Some reaches of the Rio Grande gained water from the aquifer system; however, the Rio Grande in the basin as a whole is thought to have always lost water to the aquifer system, providing water to phreatophytes.

Since the development of large-scale irrigation and urbanization in the Middle Rio Grande Basin, sources of recharge and discharge have become more complex, particularly in the inner valley where most of the ground-water/surface-water interaction in the basin occurs. Seepage from canals provides substantial amounts of recharge to the ground-water system. Reported transportation losses associated with the entire MRGCD, which extends beyond the southern boundary of the Middle Rio Grande Basin, range from about 100,000 to 225,000 acre-feet per year (S.S. Papadopulos and Associates, Inc., 2000). The Middle Rio Grande Basin contains most of the MRGCD and, therefore, many of these losses probably occur within the basin. The portion of transportation losses not lost to evapotranspiration would recharge the aquifer system. The Bureau of Reclamation (1997d) estimated canal seepage in the Middle Rio Grande Basin to range from about 52,000 to about 116,000 acre-feet per year between 1935 and 1993. Some of the irrigation water applied to crops infiltrates below the root zone and becomes ground-water recharge. The Bureau of Reclamation (1997d) estimated this seepage of applied irrigation water in the basin to range from about 23,000 to about 39,000 acre-feet per year between 1935 and 1993. Kernodle and others (1995) estimated this recharge to be about 44,000 acre-feet in 1960 and about 28,000 acre-feet in 1994.

Ground-water discharge by phreatophyte evapotranspiration has been estimated by several investigators. Thorn and others (1993) estimated

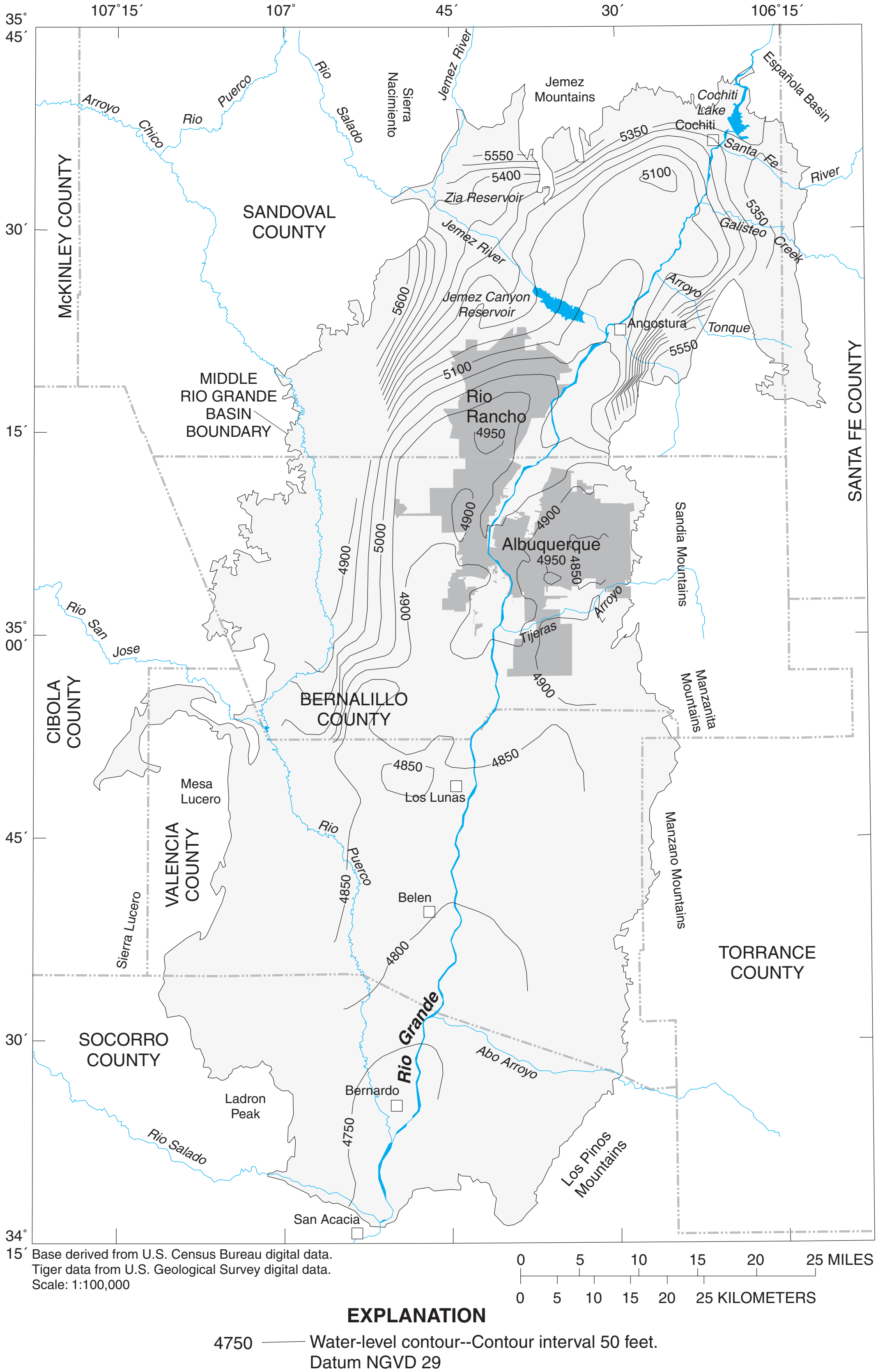


Figure 6. Water-level contours representing winter 1994-95 conditions in the Middle Rio Grande Basin (modified from Kernodle, 1998, fig. 16; and Tiedeman and others, 1998, fig. 4).

evapotranspiration from riparian vegetation in the Jemez River and Rio Grande Valleys to be about 112,000 acre-feet per year. The Action Committee of the Middle Rio Grande Water Assembly (1999) estimated riparian evapotranspiration to range from about 75,000 to 195,000 acre-feet per year for the area including the Middle Rio Grande Basin (as defined for this report) and extending along the Rio Grande about 17 miles north of the basin. A relatively small amount of riparian area is in the 17-mile reach to the north; therefore, most of this evapotranspiration would apply to the Middle Rio Grande Basin. S.S. Papadopulos and Associates, Inc. (2000) estimated that more than 100,000 acre-feet of water per year is now consumed by phreatophytes within the basin. The Bureau of Reclamation (1997d) estimated riparian evapotranspiration to be about 130,000 acre-feet per year. Kernodle and others (1995) estimated evapotranspiration by riparian vegetation and wetlands in the basin to be about 260,000 acre-feet per year under predevelopment conditions and about 89,000 acre-feet per year in 1994. This reduction from predevelopment to 1994 results from a reduction in area covered by wetlands and riparian vegetation and from a lowering of the water table in the inner Rio Grande Valley by drains and ground-water withdrawal by wells. Estimating the amount of evapotranspiration from ground water by phreatophytes is complicated because some of the evapotranspiration could be intercepted surface water that has not yet recharged the aquifer system.

Ground-water discharge to the drain system in the inner Rio Grande Valley may have become the largest discharge component from the ground-water system (Kernodle and others, 1995, p. 67-68). Ground-water-flow simulations by Kernodle and others (1995) estimated ground-water discharge to the riverside and interior drain system to be about 219,000 acre-feet in 1994. Ground-water discharge to the drain system is difficult to measure because of the complexity of the drain system, the many returns of excess irrigation water from canals to the drains, and the lack of sufficient flow-measurement data.

The large quantities of water flowing in the Rio Grande through the basin make it difficult to separate out base-flow gain/loss from/to ground water from typical measurement error (generally 10 percent or larger for the Rio Grande). However, qualitative measurements can be made for some reaches of the Rio Grande. The reach of the Rio Grande surface-water system from below Cochiti Dam (gaging station 08317400, fig. 4) to Bernalillo (gaging station 08329500) appears to gain water. In recent times, part of this gain would probably be associated with seepage out of Cochiti Lake. Gains or losses in the main stem of the Rio Grande in the reach between Bernardo and San Acacia (fig. 4) are too small to detect from daily gage data. The combination of the Rio Grande, riverside drains, and non-riverside drains is thought to gain water in the southern part of the Middle Rio Grande Basin. Recent seepage studies (S.S. Papadopulos and Associates, Inc., 2002) indicate that the main stem of the Rio Grande loses water between Isleta Pueblo and San Acacia and that the riverside drains have both gaining and losing reaches. The riverside-drain reaches that were studied predominantly gain water. Much of the water gained by riverside drains is likely water lost from the Rio Grande.

To deal with the problem of separating base-flow gain or loss from measurement error, Veenhuis (2002) took numerous flow measurements from 1996 to 2000 in the Rio Grande and associated riverside drains in a 22-mile reach from Bernalillo (gaging station 08329500, fig. 4) to Rio Bravo Bridge (gaging station 08330150). His data were obtained during the winter to minimize the effects of evapotranspiration and irrigation and when flow out of Cochiti Lake and Jemez Canyon Reservoir was maintained at constant rates. He calculated the median winter loss in this reach of the Rio Grande and riverside drains to be about 84 cubic feet per second. However, this value has considerable uncertainty; the standard deviation of the measurements was 59 cubic feet per second.

Seepage out of Cochiti Lake into ground water presumably is closely related to losses unaccounted for in a water budget of the reach between the Otowi gage (gaging station 08313000; location and data available at *http://nm.water.usgs.gov*) and the gage below Cochiti Lake (gaging station 08317400, fig. 4). The water budget explicitly considers all inflows (streamflow and precipitation), outflows (reservoir releases), and net evaporation from Cochiti Lake on a monthly basis (current information can be accessed at *http://www.spa.usace.army.mil*). The calculations include a larger section of the lake than is included within the boundary of the aquifer system but should give a reasonable estimate of the magnitude of variation in reservoir seepage. Analysis of these data suggests that seepage out of Cochiti is bimodal. When the reservoir is at normal stage (5,320-5,340 feet above NGVD 29), the losses unaccounted for are about 2,000 acre-feet per month (33 cubic feet per second); at high stage (5,390-5,410 feet above NGVD 29), the losses unaccounted for are about 15,000 acre-feet per month (250 cubic feet per second).

Seepage has been investigated along the Jemez River. Fischer and Borland (1983) reported that the results of seepage investigations conducted in 1981 were inconclusive. Craigg (1992) conducted two seepage investigation in 1984, one in March and one in August. The winter results indicated a gain in flow between Jemez Pueblo and Zia Reservoir of about 18 cubic feet per second, a possible loss of flow between Zia Reservoir and Zia Pueblo of about 5 cubic feet per second, and a gain in flow between Zia and Santa Ana Pueblos of about 8 cubic feet per second. The possible uncertainty of these estimates, based on streamflow measurement errors (Craigg, 1992, table 3), is +/- 6 to 7 cubic feet per second. The summer results indicated that the upper reach of the Jemez River gained flow but that the reach between Zia and Santa Ana Pueblos lost about 11 (+/- 4) cubic feet per second of flow. Craigg (1992) concluded that the loss in the lower reach was likely due to evapotranspiration by phreatophytes.

Data that would allow estimation of seepage from Jemez Canyon Reservoir were not available for this study. Prior to 1979, when the reservoir began permanently storing water, the reservoir operated to desilt flows above 30 cubic feet per second by a 1-day detention and to provide flood protection. Although water would have seeped from the reservoir during temporary-storage periods, the seepage likely was relatively small compared with the amount of seepage that occurred during permanent storage.

Hydrologic Properties

The post-Santa Fe Group inner-valley alluvium consists of channel and flood-plain deposits associated with the modern Rio Grande and Jemez River. The alluvium forms a band under and along each river, several miles wide and as much as 120 feet thick (Hawley and Haase, 1992). The unit is variable in composition, consisting of highly permeable sands and gravels interbedded with less permeable silts and clays that in some areas constitute a substantial part of the unit (Thorn and others, 1993). Hydraulic-conductivity estimates for these deposits vary widely. The Bureau of Reclamation (1997c) estimated values ranging from 90 to 350 feet per day using an auger-hole method. Willis (1993) estimated 0.2 foot per day for silty clays and 65 feet per day for gravelly coarse sands in these deposits. Recent testing by the City of Albuquerque resulted in hydraulic conductivities ranging from 5 to 325 feet per day (CH2MHill, 1999). McAda (2001) found that a value of 45 feet per day performed well in a simulation of a lengthy aquifer test in the Albuquerque area.

Aquifer-test data for the Santa Fe Group aquifer system typically come from wells that are screened over several hundred feet. Analyses of many of these tests are summarized in Thorn and others (1993, table 2) in terms of transmissivity and in estimated hydraulic conductivity (calculated using the screened interval as the saturated thickness term). Hydraulic-conductivity estimates for wells that penetrate the upper part of the Santa Fe Group range from 4 to 150 feet per day (Thorn and others, 1993, table 2). The most highly permeable zone of the upper part of the Santa Fe Group consists of the axial deposits of the ancestral Rio Grande; the largest hydraulic-conductivity estimates (as much as 150 feet per day for individual well tests; Thorn and others, 1993, table 2) come from wells located on Albuquerque's east side. A widespread, but less transmissive subunit of the upper part of the Santa Fe Group consists of alluvial-fan and piedmont-slope facies (Hawley and Haase, 1992). The hydraulic conductivity of this subunit, 12-15 feet per day, is fairly well constrained in the Albuquerque area by aquifer testing (Thorn and others, 1993; McAda, 2001).

Hydraulic conductivities estimated from aquifer tests in wells penetrating the middle and lower parts of the Santa Fe Group tend to be systematically lower than those in the upper part. McAda (2001) estimated hydraulic conductivities for Middle Santa Fe Group deposits in the Albuquerque area to be 4 to 11 feet per day, based on work by Hawley and Haase (1992). For their regional ground-water model, Kernodle and others (1995) and Kernodle (1998b) estimated hydraulic conductivities to be 0.5 to 40 feet per day for river-valley alluvium, 10 to 70 feet per day for the upper part of the Santa Fe Group, 4 feet per day for the middle part of the Santa Fe Group, and 2 to 10 feet per day for the lower part of the Santa Fe Group.

The stratigraphy of post-Santa Fe and Santa Fe Group units is dominated by interlayering of more and less permeable subunits, suggesting significant vertical anisotropy. This is supported by piezometer data that demonstrate the existence of substantial vertical hydraulic gradients within the aquifer system (discussed later in this report). Previous calibrated ground-water models of the basin have used horizontal to vertical anisotropy ratios of 450:1 to 3,500:1

(Tiedeman and others, 1998) and 200:1 (Kernodle and others, 1995). McAda's (2001) intensive analysis of an aquifer test near the Rio Grande in Albuquerque yielded an anisotropy value of 82:1.

The numerous north-south striking faults within the basin probably impede ground-water flow across the fault planes, either by the juxtaposition of more permeable beds with less permeable beds and (or) by cemented sediments or fault gouge within the fault plane itself. The multitude of these faults suggests the likelihood that flow parallel to the strike of these faults (north-south) may be considerably less impeded than flow across the strike of these faults (east-west), so horizontal anisotropy may be a significant factor within the aquifer. Horizontal anisotropy through much of the basin is supported by several sources of information. Plummer and others (2001) identified 12 hydrochemical recharge zones in the Middle Rio Grande Basin. These zones show a distinct north to south pattern (Plummer and others, 2001, fig. C-1). In addition, the pattern of sedimentation in the basin is generally oriented north-south (Hawley and others, 1995, fig. 2), contributing to enhanced permeability north-south relative to east-west. Greg Ruskauff (INTERA, Longmont, Colo., written commun., June 2001) found that hydrologic data for the Kirtland Air Force Base (fig. 2) area were best explained by horizontal anisotropy.

Specific yields in basin fill, such as in the Santa Fe Group aquifer system, typically range from about 0.1 to 0.25 (Johnson, 1967, p. 1). Ground-water-flow models of the aquifer system have used specific yields of 0.15 to 0.20 (Kernodle and others, 1995; Tiedeman and others, 1998; Barroll, 2001). Heywood (1998; 2001) calculated elastic specific storage of the basin sediments to be 2 x 10^{-6} per foot from extensometer data. McAda's (2001) analysis of an aquifer test near the Rio Grande in Albuquerque yielded a specific-storage value of 1.2 x 10^{-6} per foot.

MODEL DESCRIPTION

Movement of water through an aquifer can be expressed by differential equations (Pinder and Bredehoeft, 1968). However, solving these equations analytically generally is not possible because of the complexity of hydrologic boundaries and the heterogeneity and anisotropy of aquifer materials. A digital ground-water-flow model can be used to solve the ground-water-flow equation numerically through the use of a computer. A solution using this method is not unique in that any number of reasonable variations in representation of the aquifer system in the model may produce equally acceptable results. Nevertheless, the model is a tool that can be used to help understand an aquifer system and project aquifer responses to assumed stresses. Assumptions and simplifications are made in the formulation and solution of the mathematical equations; therefore, a ground-water-flow model is only an approximation of the aquifer system, and simulation results need to be interpreted with this in mind.

Numerical Method

Ground-water flow in the Middle Rio Grande Basin was simulated using the modular, three-dimensional, finite-difference, ground-water-flow model MODFLOW-2000 (Harbaugh and others, 2000). By assuming that Cartesian coordinate axes x, y, and z are aligned with the principal components of hydraulic conductivity, three-dimensional ground-water flow through porous medium can be expressed as (McDonald and Harbaugh, 1988, p. 2-1):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where K_{xx}, K_{yy}, and K_{zz} = values of hydraulic conductivity along the x, y, and z coordinate axes (LT^{-1});
h = potentiometric head (L);
W = volumetric flux per unit volume and represents sources and (or) sinks of water (T^{-1});
S_s = specific storage of the porous medium (L^{-1}); and
t = time (T).

The partial-differential flow equation (eq. 1) can be approximated by replacing the derivatives with finite differences. MODFLOW-2000 represents the aquifer system with cells using a sequence of layers and a series of rows and columns extending through each layer. Aquifer properties are assumed to be uniform within each model cell, and hydraulic heads are assumed to be at the center of each cell. For a model with N cells, N simultaneous equations are formulated with the hydraulic heads as unknown. MODFLOW-2000 solves the finite-difference equations simultaneously using one of several numerical-solver algorithms and accounts for ground-water flow between cells and between cells and external sources or sinks of water, such as stream-aquifer hydraulic interaction, aquifer recharge, or ground-water withdrawal by wells. A version of the LPF package modified by A.W. Harbaugh (U.S. Geological Survey, written commun., 2002; see “Supplemental information” section) was used for this model. The preconditioned conjugate-gradient (PCG) method (Hill, 1990; Harbaugh and others, 2000) was used as the solution algorithm.

Spatial Discretization

The ground-water-flow model described in this report covers about 2,350 square miles within the Middle Rio Grande Basin (fig. 7). The model area is smaller in extent than that defined for the basin, which is the extent of Cenozoic deposits within the Rio Grande Rift between Cochiti and San Acacia. The northern and southern model boundaries are the same as the basin boundaries; the eastern and western model boundaries extend to selected faults, which are thought to form distinct hydrologic boundaries (Kernodle and others, 1995, p. 12). The model extends vertically from the base of the Santa Fe Group, as much as 9,000 feet below NGVD 29, to the water table, which varies from about 4,700 to 5,600 feet above NGVD 29. Simulated aquifer-system thickness ranges from less than 100 feet at some basin margins to about 14,000 feet in the deepest parts of the Calabacillas and Belen subbasins.

The Santa Fe Group aquifer system within the Middle Rio Grande Basin is represented by nine model layers (fig. 8). Each layer is divided into cells by a grid containing 156 rows and 80 columns (fig. 7). The grid is equally spaced throughout the model area, consisting of cells 3,281 feet (1 kilometer) on each side. The grid is oriented north-south to align with the general north-south strike of major faults in most of the basin (fig. 3; Mark Hudson and Scott Minor, U.S. Geological Survey, written commun., 1999) and, therefore, to align with the principal directions of anisotropy. The top of layer 1 is defined as the water table from the steady-state simulated head. The bottom of layer 5 is 800 feet below the bottom of the Rio Grande, measured from a surface defined by extending altitude contours at the river, orthogonally from the trend of the inner Rio Grande Valley to the margins of the basin. Layers 1-5 are variable in thickness, depending on the water-table altitude relative to the bottom altitude of layer 5 (fig. 8). The initial steady-state thicknesses of layers 1, 2, 3, 4, and 5 were 30, 50, 100, 220, and 400 feet, respectively, directly below the Rio Grande and vary in proportionate dimensions elsewhere. The thickness of layer 1 is relatively thin to simulate ground-water/surface-water interaction in the inner valley. Layer 6 is a constant 600 feet thick and layer 7 is a constant 1,000 feet thick. Cells in layers 1-7 are active where the center of the cell is higher in altitude than the base of Santa Fe Group basin fill (defined by digital data from James C. Cole, U.S. Geological Survey, written commun., 1999). The thicknesses of layers 8 and 9 are one-third and two-thirds, respectively, of the Santa Fe Group thickness below layer 7. Cells in model layers 8 and 9 are active only where their combined thickness is at least 1,200 feet.

With one exception, model layers were not defined to represent particular lithologic units within the aquifer system. The differences in lithologic units are represented in the model by differences in simulated hydraulic properties. The exception is layers 1 and 2, which were defined to represent post-Santa Fe Group alluvium within the inner valley. Outside the inner valley, layers 1 and 2 do not represent particular units.

Layers 4, 5, and the upper part of 6 correspond with the vertical section of the aquifer system where most ground-water withdrawal in the basin occurs (based on well screen locations). Layer 5 contains the largest amount of simulated ground-water withdrawal for any single layer; therefore, it is considered to be most representative of the aquifer production zone for most areas of the model.

Model layers 1-4 are represented as convertible from confined to unconfined conditions (Harbaugh and others, 2000); that is, active cells in which the simulated hydraulic head is above the designated layer top are simulated under confined conditions, and cells in which the simulated hydraulic head is below the layer top are simulated under water-table conditions. This allows the simulated water table to transfer to the next lower cell as simulated water levels decline below the bottom of a cell. Model layers 5-9 are represented as always confined. None of the simulations created conditions in which water levels in layer 4 dropped below the bottom of layer 4.

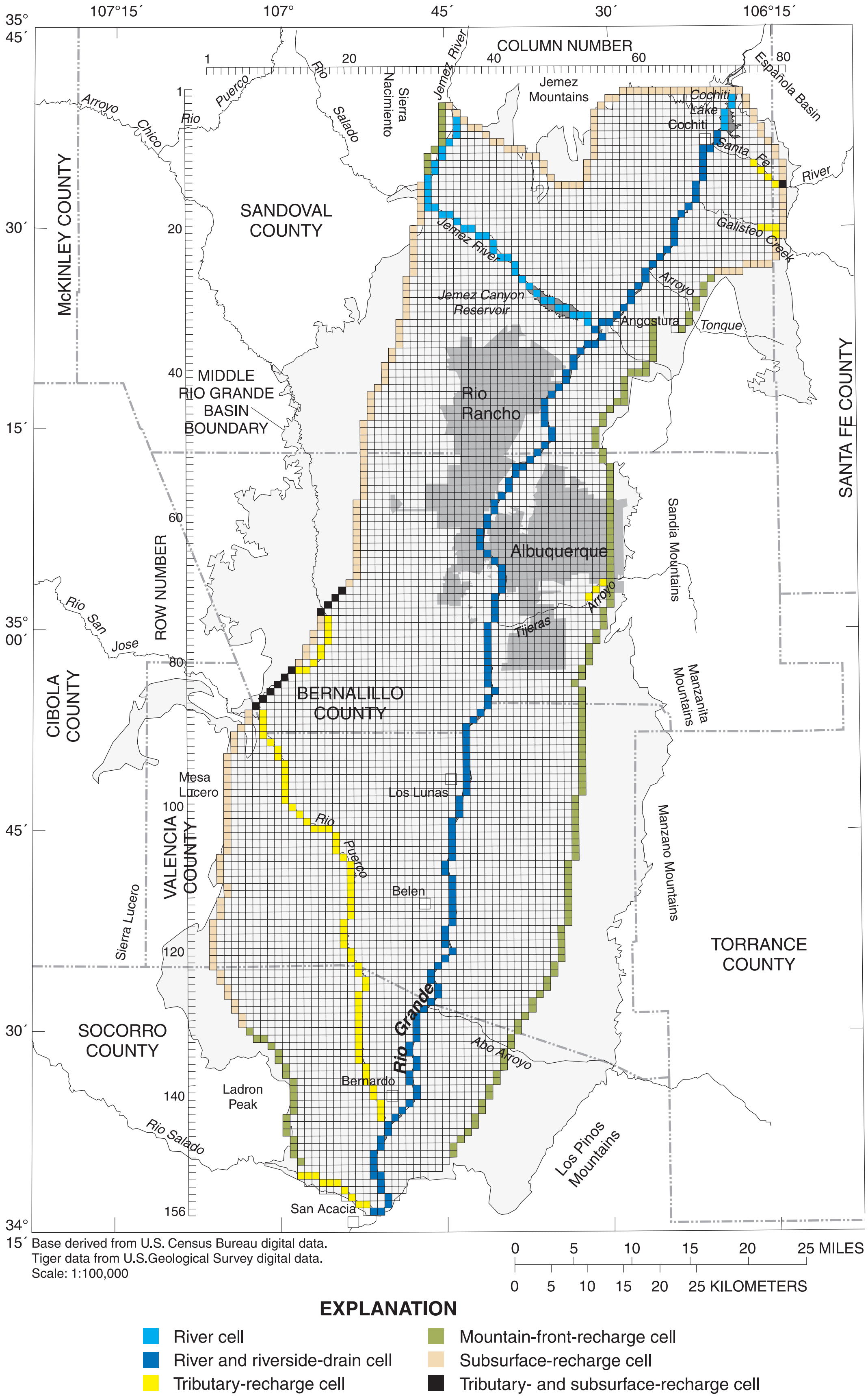


Figure 7. Model grid and active model cells in layer 1.

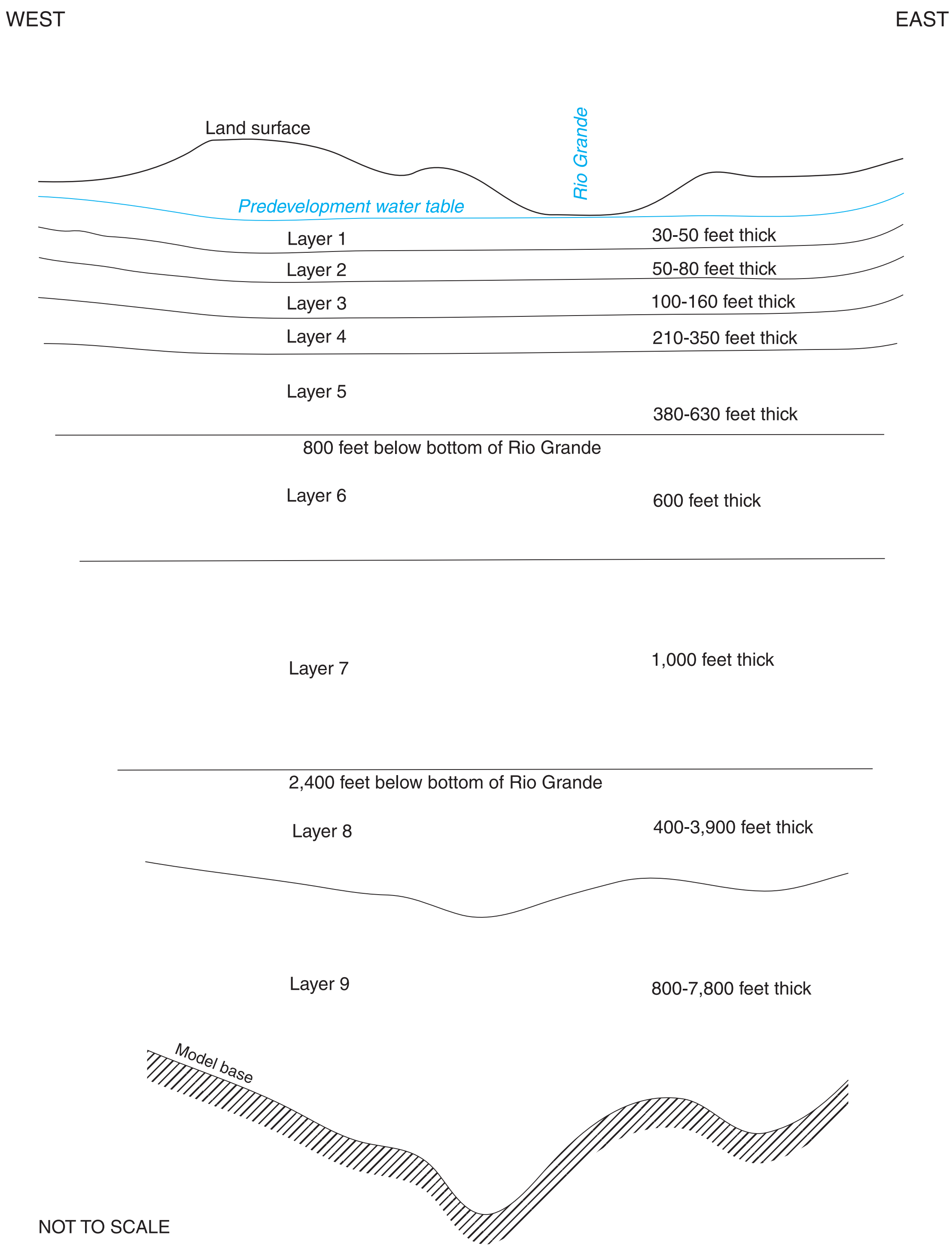


Figure 8. Model-layer configuration.

Time Discretization

Ground-water flow in the Middle Rio Grande Basin was simulated from 1900 to March 2000. Steady-state conditions assumed to exist prior to 1900 were simulated before each transient simulation of the 1900 to 2000 historical period. Although ground-water development existed prior to 1900, it was limited primarily to hand-dug wells in the Rio Grande inner valley where the influence of the river and irrigation kept ground-water levels relatively stable In addition, ground-water development prior to 1900 was relatively insignificant compared with development during the 20th century.

The historical period, 1900 to 2000, was simulated with 51 stress periods ranging in length from 5 years for the early part of the period to 2 1/2 months for the recent part. All years of the simulation are assumed to be 365.25 days long. Five-year stress periods are used from 1900 through 1974, 1-year stress periods are used from 1975 through 1989, and seasonal stress periods are used beginning in 1990. The first seasonal stress period is a short winter period that extends from January 1, 1990, through March 15, 1990. March is the beginning of the irrigation season in the Middle Rio Grande Basin. Although the main irrigation canals begin carrying water at the beginning of the month, all ditches and laterals may not be in full operation until the middle of March. Each of the 1990 through 2000 irrigation-season stress periods extends from March 16 through October. Although irrigation slows during October, the ditches continue to operate through the end of October. Starting in 1990, winter-season stress periods extend from November 1 to March 15.

Boundary Conditions

Hydrologic features adjacent to and within the model domain must be represented in the model by mathematical boundary conditions. These boundary conditions describe how water enters or leaves the simulated aquifer system. A detailed discussion of boundary conditions in ground-water-flow simulations can be found in Reilly (2001). Two general boundary types are used in this model: (1) specified flow and (2) head-dependent flow. At a specified-flow boundary, water is recharged or discharged independent of simulated head. A no-flow boundary is a specific case of a specified-flow boundary and is implied at the bottom of model layer 9. At a head-dependent flow boundary, water is recharged or discharged as a function of simulated hydraulic head in the aquifer and a head external to the model, such as river stage.

Specified Flows

Mountain-front, tributary, and subsurface recharge; canal, crop-irrigation, and septic-field seepage; and ground-water withdrawal are simulated in the model as specified-flow boundaries. Some of the tributaries simulated as specified-flow boundaries, such as the Rio Puerco, may have reaches that are hydrologically connected to the ground-water system, but these reaches are probably limited in extent, and no attempt has been made to simulate them specifically. The majority of canals along the Rio Grande and Jemez River are constructed so that the canal bed is high enough to allow water to flow down onto irrigated fields. Therefore, the majority of canal beds are above the water table, and lowering the water table would not induce a significant amount of additional recharge. Although head-dependent flow boundaries have been used to simulate canals in previous models of this aquifer system (Kernodle and others, 1995; Tiedeman and others, 1998), simulated heads were sufficiently below simulated canal bottoms to cause almost all these features to act as specified-flow boundaries. In this model, canals are represented by specified-flow boundaries.

Head-Dependent Flows

The Rio Grande, riverside drains, Jemez River, Jemez Canyon Reservoir, and Cochiti Lake are simulated in the model as head-dependent flow boundaries. Special types of head-dependent flow boundaries, where water is allowed only to discharge, are used in the model for riparian evapotranspiration and interior drains.

Aquifer Representation

Hydrologic properties representing the Santa Fe Group aquifer system in the ground-water-flow model are horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield. These properties are specified in the model using the LPF Package of MODFLOW-2000 (Harbaugh and others, 2000). Variable horizontal anisotropy is applied to the model so that hydraulic conductivity along columns is greater than hydraulic conductivity along rows over much of the model. Vertical hydraulic conductivity is specified in the model as a horizontal to vertical anisotropy ratio. Specific storage, applied to the confined model cells, and specific yield, applied to unconfined model cells, are each assumed to be constant over the model domain.

MODEL DEVELOPMENT AND CALIBRATION

The model was calibrated using a judgmental trial-and-error procedure of adjusting aquifer properties and boundary conditions in an effort to minimize the difference between measured and simulated water-level data and flow data. The Observation Process for MODFLOW-2000 (Hill and others, 2000) was used to aid in the calculation of the residuals (the difference between the measured and simulated values).

Calibration Targets

The primary targets used for model calibration were water levels measured in wells and piezometers and calculations of flow between surface-water bodies and the aquifer system. The constraint on achieving these targets was to maintain aquifer hydrologic properties and flow at boundaries within a plausible range of values.

Water-Level Data

Calibration targets for the steady-state, predevelopment model simulation were obtained from the predevelopment water-level map of the Middle Rio Grande Basin by Bexfield and Anderholm (2000). These authors combined water-level measurements collected prior to 1961, for areas of ground-water development, with whatever measurements were available, regardless of date, for areas without significant ground-water development, to create a consistent water-table surface. Such an approach combines water levels from different depth intervals and different parts of the aquifer system, but existing data do not allow distinction of head variation with depth for predevelopment. This approach also assumes that water levels have not been drawn down significantly in areas where ground-water development is minimal, which, depending on the level of hydrologic connection to developed areas, may or may not be true. In general, water levels measured in the minimally developed areas after 1960 should represent a lower limit for predevelopment water levels in such areas.

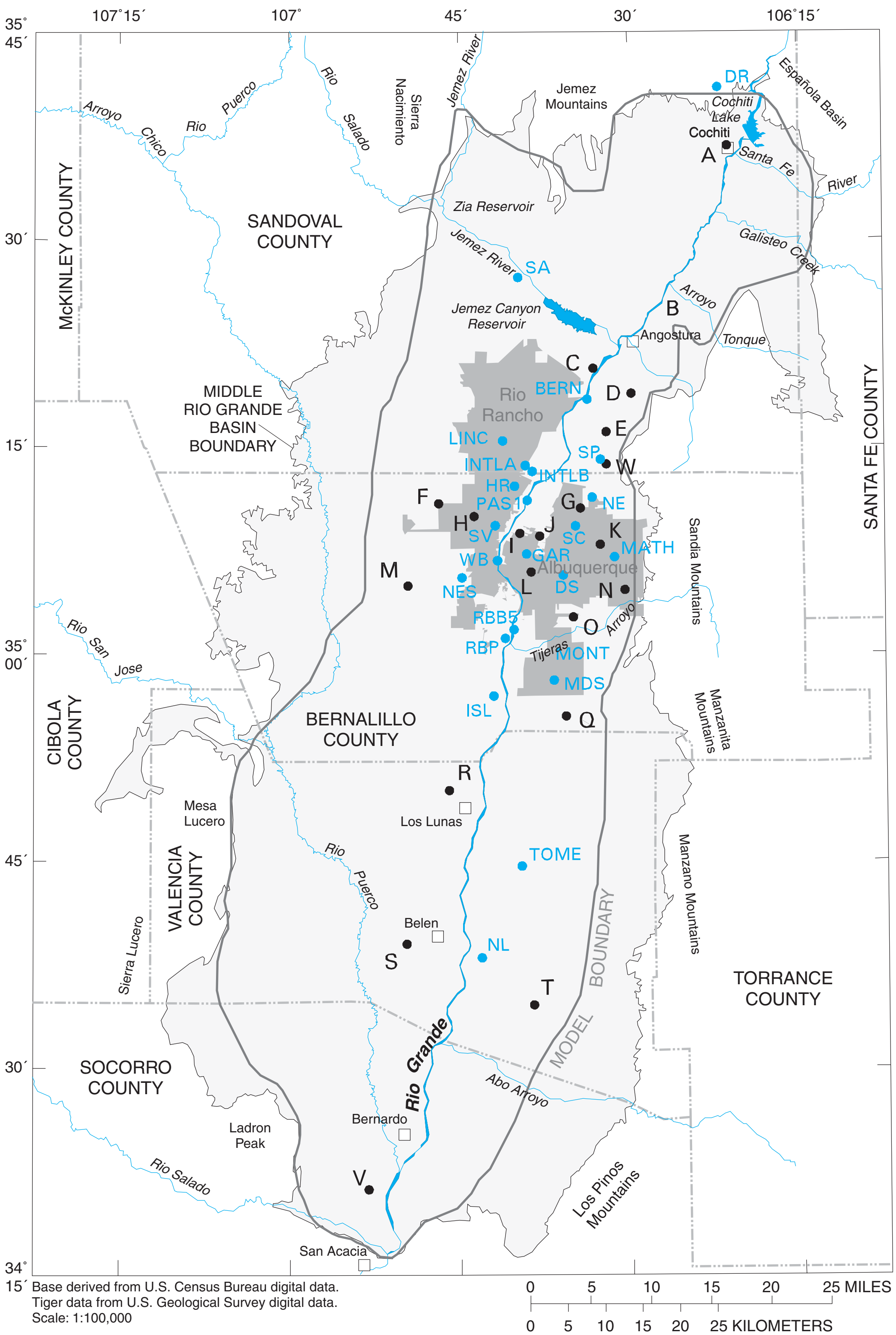
Data for the northeastern boundary of the basin were adjusted to reflect the belief of the authors that the water level in the Dome Road piezometer (DR in fig. 9) is representative of the regional aquifer system in this area. The higher heads measured in shallower wells nearby are assumed to reflect perched conditions, which the model does not attempt to simulate.

Calibration targets for the transient-model simulation consist of well hydrographs that show the aquifer system's response over time at given locations and of water-level maps created using recent data from the mid-1990's and 2000. A number of wells in GWSI have tabulated data that cover a number of years. The measured hydrograph records for those wells with a significant period of record and wells located in areas of particular interest were compared with model-simulated hydrographs. These "hydrograph wells" and letter identifiers (fig. 9) are the same as those compared to simulation results by Kernodle and others (1995) and Tiedeman and others (1998). Water levels measured in 1993-94 were compared with simulated water levels for the corresponding time, and water levels obtained from piezometers in 2000 were used to test model simulation of the water-table and potentiometric-surface altitudes in the production zone of the aquifer in the Albuquerque area.

The model's ability to simulate the known variation of head with depth (vertical hydraulic gradients) was tested by comparing modeled hydraulic heads with water levels recorded in piezometers in the basin (fig. 9). Almost all these piezometers have been installed within the last 10 years, so the period of record is short and predevelopment vertical gradients are unknown.

Flow Data

Flow data are important for the calibration of a ground-water model to minimize the non-uniqueness of the model solution. However, many components of flow, such as natural recharge and evapotranspiration, cannot be accurately measured for a basin-scale model. The flow measurements made by Veenhuis (2002) for the 22-mile reach of the Rio Grande and riverside drains and the seepage-loss calculations for Cochiti Lake described earlier in this report are used as calibration targets.



EXPLANATION

V ● Well and letter identifier--Letter identifies the hydrograph show in figure 17 for the well

ISL ● Piezometer nest and abbreviated name--Abbreviation identifies the piezometers in table 2 (DR and PAS1 are single piezometers and are not included in table 2)

Figure 9. Location of selected wells and piezometer nests.

Some qualitative observations can be made for other reaches of the Rio Grande:

(1) The reach of the Rio Grande surface-water system from below Cochiti Dam (gaging station 08317400, fig. 4) to Bernalillo (gaging station 08329500) appears to gain water. Since 1973, when Cochiti Lake began storing water, part of this gain would probably be associated with seepage out of the lake.

(2) Gains or losses in the main stem of the Rio Grande from the reach between Bernardo and San Acacia (fig. 4) are too small to detect from daily gage data. The combination of the main stem of the Rio Grande, riverside drains, and non-riverside drains is thought to gain water in the southern part of the Middle Rio Grande. Recent seepage studies (S.S. Papadopulos and Associates, Inc., 2002) indicate that the main stem of the Rio Grande loses water between Isleta Pueblo and San Acacia and that the riverside drains have both gaining and losing reaches. The riverside drain reaches that were studied predominantly gain water. Much of the water gained by riverside drains is likely water lost from the Rio Grande.

Development and Adjustments of Model Parameters

During the model-calibration process, boundary conditions and aquifer properties were adjusted in an effort to minimize the difference between measured and simulated water-level and flow data. The initial values of these model parameters and the adjustments made during model calibrations are described in this section of the report.

Mountain-Front Recharge

Mountain-front recharge rates in the calibrated model are shown in figure 10. The volumetric rates shown in figure 10 are distributed equally to the cells indicated by alternate shaded patterns. Values of mountain-front recharge along the Sandia, Manzanita, Manzano, and Los Pinos Mountains are the amounts calculated by Anderholm (2001, p. 17), except that part of the amount calculated for the Tijeras Arroyo subarea (700 acre-feet per year) is extended into the basin as tributary recharge (fig. 10). The recharge rates from Anderholm (2001) were fixed and not adjusted during model calibration. Mountain-front recharge rates in other areas of the basin were assumed for initial model runs and adjusted during model calibration. Although mountain-front recharge likely varies depending on the amount of precipitation falling in the mountains, sufficient information to adequately quantify this variation is not available. Therefore, the mountain-front recharge rates simulated in the model are representative of long-term averages. The total amount of mountain-front recharge applied to the model (omitting Jemez Mountains recharge, which is described below) is 12,000 acre-feet per year (sum of values in fig. 10 marked "MT" rounded to two significant figures) for all stress periods.

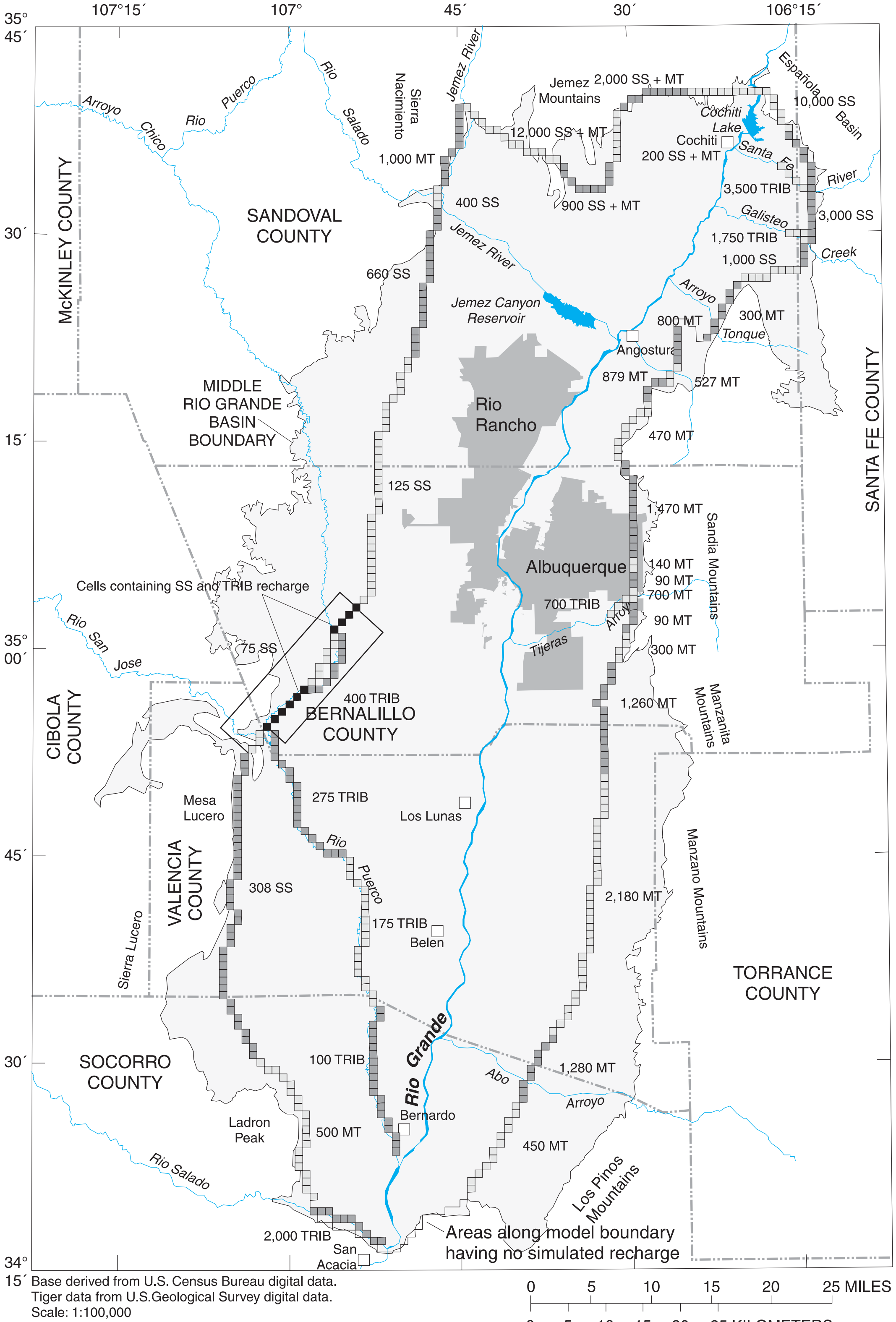
Mountain-front recharge and subsurface recharge occur at the northern model boundary in the Jemez Mountains. Sufficient information is not available to quantitatively differentiate the amounts of water entering as mountain-front and subsurface recharge. Therefore, a total amount of subsurface recharge (about 15,000 acre-feet per year, noted as "SS + MT" in fig. 10), which enters the model in layers 1 through 3, was applied to represent both types.

Recharge rates around the basin margins (fig. 10) are smaller than the rates used in previous ground-water-flow models of the basin (such as Kernodle and others, 1995; and Tiedeman and others, 1998). These smaller recharge amounts are indicated by the work of Anderholm (2001) and the preliminary ground-water-flow modeling of Sanford and others (2001).

Mountain-front recharge was applied to the uppermost active layer of the model using the recharge package of Harbaugh and others (2000). The recharge package internally multiplies an entered flux rate (L/T) by the cell area to calculate the volumetric flow rate (L^3/T). Therefore, the values entered into the recharge package are the volumetric rates described above divided by cell area.

Tributary Recharge

The tributary-recharge rates in the calibrated model are shown in figure 10. Initial values for the Santa Fe River, and by comparison, Galisteo Creek, were based on the streamflow measurements of Thomas and others (2000) and the estimated flow loss of 1.7 cubic feet per second in the 2.5-kilometer reach they studied, described previously in this report. The estimated rate per kilometer was applied to four model cells covering about 5 kilometers of the Santa Fe River, resulting in about 2,500 acre-feet per year of recharge. Because the average flow of Galisteo Creek is about half the flow of the Santa Fe River (Thorn and others, 1993, table 5), half that amount (1,250 acre-feet per year) was estimated for recharge from Galisteo Creek.



EXPLANATION

450 MT — Cell group containing type of recharge--Number is recharge amount applied to cell group, in acre-feet per year

Figure 10. Distribution of mountain-front (MT), tributary (TRIB), and subsurface (SS) recharge simulated in the model.

Both values were increased by 40 percent (to 3,500 and 1,750 acre-feet per year, respectively) during model calibration. The initial values for the Rio Puerco and Rio Salado (south part of the basin) were estimated on the basis of average values of Tiedeman and others (1998) and were adjusted to smaller values during model calibration. The value shown in figure 10 for Tijeras Arroyo is a portion of mountain-front recharge calculated for the Tijeras Arroyo subarea by Anderholm (2001). The total amount of tributary recharge applied to the model is 8,900 acre-feet per year (sum of values in fig. 10 marked “TRIB” rounded to two significant figures) for all stress periods.

Tributary recharge is applied to the uppermost active layer of the model using the recharge package of Harbaugh and others (2000). The values entered into the recharge package are the volumetric rates divided by cell area.

Subsurface Recharge

Figure 10 shows the distribution of subsurface recharge in the calibrated model. Subsurface recharge at the northern boundary of the model is larger than the recharge used in the Kernodle and others (1995) model (28,100 acre-feet per year compared with 19,600 acre-feet per year). Grant’s (1999) discussion of recharge unaccounted for from this region of the basin and the channel gravels in this area described by Smith and Kuhle (1998) provide support for larger values. Subsurface recharge along the western model boundary (1,568 acre-feet per year, fig. 10) is significantly smaller than in the models of Kernodle and others (1995) and Tiedeman and others (1998) (about 11,200 to 13,600 acre-feet per year) but is consistent with the estimate by Sanford and others (2001) (2,000 acre-feet per year), which was based on ground-water ages. Subsurface recharge is distributed to layers 1 through 3 using the well package of Harbaugh and others (2000) with the modification described in the “Modification to well package” section of this report. The total amount of subsurface recharge applied to the model is 31,000 acre-feet per year (sum of values in fig. 10 marked “SS” and “SS + MT” rounded to two significant figures) for all stress periods.

Canal Seepage

A GIS coverage constructed primarily from MRGCD records and maps (R.A. Durall, U.S. Geological Survey, written commun., 2001) was used to describe the canal network (including features classified as canal, lateral, feeder canal, or ditch) throughout the inner Rio Grande Valley. This GIS coverage contains information related to the time when many canal features were constructed and (or) abandoned and to some of the physical characteristics of the features, such as width and operating depth. Where physical characteristics of features were not attributed in the GIS coverage, their characteristics were estimated on the basis of average conditions of attributed features in the same feature class. On the basis of average seepage rates determined by the Bureau of Reclamation (1997b) and an assumed canal-bed thickness of 1 foot, McAda (1996, p. 12) estimated average hydraulic conductivity of the canal bed to be 0.14 foot per day. Kernodle and others (1995) estimated the average hydraulic conductivity of canal beds to be 0.15 foot per day. On the basis of this information, initial values of canal seepage were calculated for each row-column model location by assuming a canal-bed hydraulic conductivity of 0.15 foot per day (McAda, 1996, p. 12), a bed thickness of 1 foot, and width, depth, and length estimated in the GIS coverage. Canal seepage was computed as:

$$Q_{cs} = \sum_{i=1}^{n} \frac{K_{CB} W_i L_i D_i}{M_{CB}} \qquad (2)$$

where Q_{cs} = canal seepage applied to a row-column model location (L^3/T);
n = number of canal features in the row-column location;
K_{CB} = hydraulic conductivity of the canal bed (L/T);
W_i = width of the canal (L);
L_i = length of the canal within the row-column location (L);
D_i = depth of water above the base of the canal bed under normal operating conditions (L); and
M_{CB} = canal-bed thickness (L).

Features known to be concrete lined are not included. The seepage amounts were adjusted during calibration to better match canal seepage estimated by the Bureau of Reclamation (1997d). The final values of canal seepage are one-half the initial values. This discrepancy is not excessive given the significant uncertainty in the values of canal-bed hydraulic conductivity, water depth, and bed thickness. Additionally, many of the ditches do not operate continuously during the irrigation season, which would require a downward estimate of seepage amounts based on hydraulic properties alone.

Some of the canals constructed in the inner Rio Grande Valley were abandoned during the 1900-2000 period; therefore, the amount and location of simulated canal seepage may change in successive simulation stress periods. Although many canals were used prior to the establishment of the MRGCD, little digital information is available to describe the network throughout the inner Rio Grande Valley. Therefore, seepage from canals is not explicitly simulated prior to 1930—it is assumed to be a part of crop-irrigation seepage. Canal seepage, simulated beginning in 1930, is based on the construction and abandonment dates in the GIS coverage cited above and the existence of features in GIS coverages constructed by the Bureau of Reclamation for 1955, 1975, and 1992 (Bureau of Reclamation digital data). Canal features existing in 1935 are simulated beginning in the 1930 stress period. Canal features that likely existed during 1935-55, 1955-75, 1975-92, and 1992-present are assumed to represent the conditions beginning in the 1935, 1965, 1984, and 1990 stress periods, respectively. The canal-seepage rates simulated in the model for stress periods of annual or greater duration (1900-89) are 63 percent (230 of 365 days) of seepage rates for the irrigation-season stress periods to account for the canals being active only for about 230 days a year. No canal seepage is simulated during winter-season stress periods.

The Bureau of Reclamation coverages of hydrography for 1955 and 1975 include the Jemez River Valley in addition to the inner Rio Grande Valley. Both coverages contain basically the same canal features as those in the USGS Digital Line Graphs (DLG's) based on 1978 1:100,000-scale maps. The physical characteristics of these canals were not available without further investigation, which was beyond the scope of this study. Seepage from these canals was estimated in the same manner as was done for the canals along the Rio Grande, except that all dimensions were assumed. The larger canal features were assumed to be 3 feet wide and the depth of flow approximately 3 feet deep. The laterals from the larger canals were assumed to be 2 feet wide and the depth of flow approximately 2 feet. Canal-bed thicknesses were assumed to be 1 foot, and hydraulic conductivity was assumed to be 0.15 foot per day. These calculated seepage values were not adjusted during calibration and are considered to be only gross estimates. Zia Reservoir, a small reservoir fed by water from the canal system, is located near Zia Pueblo. This reservoir was calculated to be about 28 acres in size on the basis of USGS DLG's. Collecting specific information on estimated seepage rates from this reservoir was beyond the scope of this investigation. This reservoir was assumed to leak at the rate of 1 inch per day over the 28-acre area throughout the year (about 852 acre-feet per year). Canal-seepage rates simulated along the Jemez River for stress periods of annual or greater duration (1900-89) are 63 percent (230 of 365 days) of seepage rates for the irrigation-season stress periods to account for the canals being active only for about 230 days a year. No canal seepage is simulated during winter-season stress periods. Seepage from the reservoir is not adjusted for different stress periods.

Canal seepage is applied to the uppermost active layer of the model using the recharge package of Harbaugh and others (2000). The flux rates entered into the recharge package are the volumetric seepage rates calculated by equation 2 divided by cell area. Canal seepages applied to the model total about 90,000 acre-feet per year in the 1990-2000 stress periods.

Crop-Irrigation Seepage

Crop-irrigation seepage is water applied to agricultural lands that infiltrates below the root zone to the water table and becomes ground-water recharge. In the counties composing most of the irrigated area in the basin (Sandoval, Bernalillo, and Valencia Counties), 95 percent of crop-irrigation water is obtained from surface-water diversions, whereas 5 percent is from ground-water withdrawal (Wilson, 1992, table 4).

The Bureau of Reclamation (1997a, table 8) estimated the amount of crop-irrigation water infiltrating to below the root zone to range from 0.10 to 1.22 acre-feet per acre per year depending on crop type and soil type. A weighted-average ground-water recharge rate from crop-irrigation seepage was calculated on the basis of the number of acres planted in each crop type for Sandoval, Bernalillo, and Valencia Counties for 1991 and 1993 (Lansford and others, 1993) and of the assumption of an equal distribution of soil types throughout the irrigated areas of the basin. The calculated weighted-average recharge rate for all crops was 0.7 acre-foot per acre per year for 1991 and 1993. When fallow agricultural land was included in the calculation, the recharge rate was 0.5

acre-foot per acre per year for 1991 and 1993. Because crop types and fallow land are rotated over the years, 0.5 acre-foot per acre per year was applied to all identified agricultural cropland for model simulations.

GIS coverages of land use, depicting agricultural croplands in the inner Rio Grande Valley for 1935 (National Biological Service digital data) and for 1955, 1975, and 1992 (Bureau of Reclamation digital data) were used to distribute crop-irrigation seepage to the appropriate model cells. Crop-irrigation seepage is simulated throughout the 1900-2000 historical period. The earliest digital data available showing the distribution of agricultural cropland are for 1935, which is after establishment of the MRGCD and the draining of a substantial amount of waterlogged agricultural lands (Thorn and others, 1993, p. 4-7). Therefore, crop-irrigation seepage prior to 1930 was distributed to model cells in proportion to the 1935 distribution of cropland but at a reduced rate (one-third the amount) because of the waterlogging of soils. The distributions of irrigated cropland for 1935, 1955, 1975, and 1992 were simulated beginning in the 1930, 1950, 1965, and 1984 stress periods, respectively. The crop-irrigation seepage rates simulated in the model for stress periods of annual or greater duration (1900-89) are 63 percent (230 of 365 days) of the seepage rates for the irrigation-season stress periods to account for irrigation being active only for 230 days a year. No crop-irrigation seepage is simulated during winter-season stress periods.

Bureau of Reclamation coverages of land use for 1955 and 1975 (Bureau of Reclamation digital data) include the Jemez River Valley. These two coverages were used to distribute crop-irrigation seepage to the cropland along the Jemez River in the same manner as was done for the inner Rio Grande Valley. The same decreased rates of crop-irrigation seepage were applied to annual and greater stress periods. The distribution of irrigated cropland along the Jemez River for 1955 was used to apportion crop-irrigation seepage for all transient stress periods through 1964. The cropland distribution for 1975 was used to apportion crop-irrigation seepage in the 1965-69 and later stress periods.

Crop-irrigation seepage is applied to the uppermost active layer of the model using the recharge package of Harbaugh and others (2000). The crop-irrigation flux rates entered into the recharge package are 0.5 acre-foot per acre per year times the cropland area in a model cell divided by the cell area. The amount of crop-irrigation seepage applied to the model totals about 35,000 acre-feet per year in the 1984-2000 stress periods.

Septic-Field Seepage

Septic tanks and leach fields are used in populated areas of the Middle Rio Grande Basin that are not served by sewage systems. Septic-field seepage is water from septic leach fields that is assumed to reach the water table and become aquifer recharge. U.S. Bureau of Census (1970; 1980; 1990) tract data for 1970, 1980, and 1990 were used to estimate population densities throughout the Middle Rio Grande Basin, excluding areas with sewer systems. Census tract data for 2000 were not available during this phase of model development. The septic-field seepage applied to each model cell was calculated as:

$$Q_{SF} = \left(\sum_{i=1}^{n} P_i A_i \right) Q_p \qquad (3)$$

where Q_{SF} = septic-field seepage applied to a row-column model location (L^3/T);

n = number of areas with differing population densities in the row-column location;

P_i = population density (persons/L^2);

A_i = area containing the population density within the row-column location (L^2); and

Q_p = rate of septic-field seepage per person (L^3/person/T).

Wilson (1992, p. 18, table 3.2) showed average per capita indoor water use to be about 64 gallons per person per day. Probably about 90 to 95 percent of indoor water use is not consumed; therefore, the rate of seepage per person was assumed to be 60 gallons per day. Not all septic water may reach the water table, especially where the water table is deep, but because the calculated septic-field seepage is small (total of 4,000 acre-feet at the end of the historical simulation) compared with other water-budget components of the model, no attempt was made to refine this component by estimating the amount of seepage that might be intercepted and lost before reaching the water table.

Septic-field seepage based on the 1970, 1980, and 1990 population densities was simulated beginning in the 1960, 1975, and 1985 stress periods, respectively. Although septic leach fields were operated prior to 1960, they are not simulated in the model. The majority of the population not served by sewer systems prior to 1960 lived in the inner valley where the Rio Grande surface-water system maintained stable ground-water levels. Therefore, septic-field seepage was assumed to have an insignificant effect on water levels prior to 1960. The amount of septic-field seepage applied to the model totals about 4,000 acre-feet per year in the 1985-2000 stress periods.

Septic-field seepage is applied to the uppermost active layer of the model using the recharge package of Harbaugh and others (2000). The flux rates entered into the recharge package are the volumetric seepage rates calculated by equation 3 divided by cell area.

Ground-Water Withdrawal

The rate of ground-water withdrawal by all wells simulated in the model ranges from 307 acre-feet per year for the 1900-04 stress period to 195,000 acre-feet per year for the summer 1994 stress period (230 days long). Simulated withdrawal was based on records from files of the New Mexico Office of the State Engineer and the City of Albuquerque and from Bjorklund and Maxwell (1961). Withdrawals from a few wells known to exist before well records were available were extrapolated to early times as described by Kernodle and others (1995, p. 22-25). This was done for Albuquerque, University of New Mexico, Kirtland Air Force Base, and two local power-plant supply wells (Kernodle and others, 1995). Albuquerque supply wells are simulated beginning in the 1900-04 stress period, University of New Mexico supply wells beginning in the 1940-44 stress period, Kirtland Air Force Base supply wells beginning in the 1945-50 stress period, and power-plant supply wells beginning in the 1955-59 stress period. Withdrawals for wells other than those listed above and domestic wells are simulated for years only for which records are available. Most of these records are available beginning in the 1960's and, except for municipal-supply wells, contain numerous missing values. Unless a missing value could be easily estimated using adjacent years, no attempt was made to fill in missing values. Therefore, except for municipal-well withdrawal, simulated withdrawal is likely underestimated in the model.

Ground-water withdrawal for each well is assigned to model layers in proportion to the percentage of well screen within each layer. However, if the well screen extends across more than one layer and the screen overlap with a layer is less than 25 percent of the layer thickness, or if less than 5 percent of the well withdrawal would be assigned to that layer, that proportion of withdrawal is assigned to the adjacent layer. For many wells, the well depth is known but the screened interval is unknown. If the bottom of these wells is in layer 3 or above, the well is assumed to produce water only from the deepest layer penetrated by the well. If the bottom of these wells is in layer 4 or below, the well is assumed to produce water from the deepest layer penetrated by the well and from the layer immediately above. For wells for which both the well depth and screened interval are unknown, a well depth was estimated on the basis of depths of other wells in the vicinity, and the above rules were applied to determine the layer(s) from which the well withdraws water.

Domestic wells are simulated beginning in the 1960-64 stress period. Although many domestic wells existed prior to 1960, they were primarily shallow wells in the inner valley where the surface-water system maintained stable ground-water levels. Therefore, domestic-well withdrawal was assumed to have an insignificant effect on water levels for earlier stress periods. Populated areas not served by a municipal water system were assumed to be supplied water from private domestic wells. U.S. Bureau of Census (1970; 1980; 1990) tract data for 1970, 1980, and 1990 were used to estimate population densities throughout the Middle Rio Grande Basin, excluding areas with municipal water systems. Census tract data for 2000 were not available during this phase of model development. The ground-water withdrawal rate from domestic wells applied to each model-cell location was calculated as:

$$Q_{DW} = \left(\sum_{i=1}^{n} P_i A_i \right) Q_p \qquad (4)$$

where Q_{DW} = domestic ground-water withdrawal applied to a row-column model location (L^3/T);

n = number of areas with differing population densities in the row-column location;

P_i = population density (persons/L^2);

A_i = area containing the population density within the row-column location (L^2); and

Q_p = rate of ground-water withdrawal per person (L^3/person/T).

Wilson (1992, table 6) estimated self-supplied domestic water use (indoor and outdoor) to range from about 64 to 150 gallons per person per day in the counties of the Middle Rio Grande Basin. The rate of 100 gallons per person per day was assumed for the above calculation. Domestic-well withdrawal at the end of the historical simulation is about 7,000 acre-feet per year.

Domestic well-construction information was not compiled for this study. Where depth to the water table is less than 50 feet below land surface, mostly in the inner valley, domestic wells were assumed to withdraw from model layer 3. Where depth to the water table is 50 to 300 feet below land surface, domestic wells were assumed to withdraw from model layer 2. In locations where depth to the water table is greater than 300 feet below land surface, which would be toward the margins of the basin, domestic wells would likely be drilled to a depth somewhat below the first water penetrated and were, therefore, assumed to withdraw from model layer 1.

Ground-water withdrawal is simulated using the well package of Harbaugh and others (2000) with a modification that transfers fluxes in cells that go dry to the next lower active cell. Without this modification, the specified flux assigned to a model cell is terminated if and when the water level drops below the bottom of that layer. Because simulated withdrawals are for the most part based on withdrawal records and layer assignments of withdrawal are estimates at best, reassignment of withdrawal to lower model layers probably is more realistic than terminating a portion of simulated withdrawal. This modification is described in the “Modification to well package” section of this report.

Rio Grande

The Rio Grande is in hydraulic connection with the Santa Fe Group aquifer system—that is, the saturated part of the aquifer directly contacts the saturated riverbed. Therefore, changes in water-table altitude in the aquifer system adjacent to the river can influence seepage between the river and the aquifer system. The Rio Grande is simulated as a head-dependent flow boundary using the River Package of MODFLOW-2000 (Harbaugh and others, 2000). The connection between the Rio Grande and the aquifer system is simulated in the model as the hydraulic conductance of the riverbed, which is calculated as:

$$C_{RB} = \frac{A_{RB}K_{RB}}{L_{RB}} \qquad (5)$$

where C_{RB} = hydraulic conductance of the riverbed (L^2/T);

A_{RB} = area of the riverbed in a model cell (L^2);

K_{RB} = hydraulic conductivity of the riverbed (L/T); and

L_{RB} = thickness of the riverbed (L).

The Rio Grande is hydraulically connected to the aquifer system vertically through and around clay beds below the river and horizontally through fairly permeable sediments. Therefore, an effective hydraulic conductivity and an effective riverbed thickness representative of the vertical and horizontal hydraulic connection are necessary for equation 5. The estimation of effective values for these parameters is best achieved by adjusting the values through model calibration to match measured losses or gains in surface-water flow.

Hydraulic conductivity divided by riverbed thickness was initially estimated by assuming a hydraulic conductivity of 0.5 foot per day and a riverbed thickness of 1 foot (Kernodle and others, 1995). This combined value of 0.5 per day was decreased to 0.1 per day during model calibration to more closely match the flow loss estimated by Veenhuis (2002) for the combined Rio Grande and riverside drains. Whether this decrease is a result of a lower effective hydraulic conductivity or a thicker effective riverbed thickness cannot be determined primarily because this value is representative of water moving between the river and the aquifer both horizontally and vertically. In addition, riverside drains tend to buffer the loss from the river, making the distinction between the hydraulic conductance of the river and that of the riverside drains less certain. Except for the seasonal stress periods (1990-2000), the specified stage of the river was assumed to be the stage determined from USGS topographic maps. The specified river stages for seasonal stress periods are discussed later in this section.

Riverbed area in each cell was estimated on the basis of National Biological Service (NBS) GIS coverages for 1935 and 1989 (Roelle and Hagenbuck, 1994). These coverages were chosen because they designate areas of the Rio Grande channel that were perennially flooded and that were seasonally flooded. Next the flow rates associated with perennially and with seasonally flooded conditions were estimated on the basis of historically measured flows in October (the month of lowest measured flow, assumed to correspond to perennially flooded conditions) and May (the month of highest measured flow, assumed to correspond to seasonally flooded conditions). Discharge of the Rio Grande at the Albuquerque streamflow gage (station 08330000, fig. 4) was used to determine the wetted riverbed area for both conditions. The earliest 20 years of record (1943-62) along with the 1935 NBS GIS coverage were used for the annual average condition for the 1900-59 simulated period. Average streamflow for the 1943-62 period was 1,000 cubic feet per second, the average for October (lowest flow month) was 263 cubic feet per second, and the average for May (highest flow month) was 2,840 cubic feet per second. Therefore, the area within each cell for the 1900-59 simulated period was calculated as the perennially flooded area plus 29 percent ([1,005 - 263] / [2,840 - 263] X 100 percent) of the seasonally flooded area. The Bureau of Reclamation altered the channel of the Rio Grande in about 1960 by adding jetty jacks; therefore, the 1989 NBS GIS coverage is probably more representative of the channel from the 1960's to the present (2002) than the NBS 1935 coverage. The 1974-89 average discharge of the Rio Grande at Albuquerque for May (3,302 cubic feet per second) and for October (390 cubic feet per second) was used to estimate representative conditions during the high- and low-flow months for the 1989 coverage. The 1974-89 time period was chosen because the 1989 river condition from the GIS coverage would have represented river conditions after the filling of Cochiti Lake, which began in November 1973, and before 1990. The average streamflow for 1960-74 was 964 cubic feet per second. Therefore, the area within each cell for the 1960-74 simulated period was calculated as the perennially flooded area plus 20 percent ([964 - 390] / [3,302 - 390] X 100 percent) of the seasonally flooded area. Although average annual flow for the 1960-74 period is not that different from the 1943-62 period (964 cubic feet per second compared with 1,005 cubic feet per second), it is significantly smaller than that for the 1974-89 period (1,449 cubic feet per second) and therefore resulted in a smaller percentage of seasonally flooded area being wet on average than other stress periods. The area within each cell for the 1975-89 simulated period was calculated as the perennially flooded area plus 36 percent ([1,449 - 390] / [3,302 - 390] X 100 percent) of the seasonally flooded area.

The seasonality of the river is simulated for the 1990-2000 winter- and irrigation-season stress periods. The area and river stage for the seasonal stress periods were adjusted on the basis of average flow during those stress periods. Table 1 shows the calculation for the area within each cell for the seasonal stress periods.

The river stage is adjusted in each cell for each of the 1990-2000 seasonal stress periods on the basis of the average flow during the stress period and the ratio of the perennially flooded area to the perennially and seasonally flooded area within each model cell. This ratio is an index of relative increase or decrease in river stage as discharge increases or decreases. For example, if this ratio is near 100 percent, then a change in flow has little effect on riverbed area but changes river stage. Alternatively, if the ratio is small, then a change in flow has a greater effect on riverbed area than on river stage. An assumed relation was developed to estimate the potential stage change between low-flow and high-flow conditions (fig. 11). This assumed relation is based partially on stage change at five streamflow-gaging stations on the Rio Grande (08317400, 08319000, 08329928, 08330000, and 08330150; fig. 4), between the 1974-89 average low-flow-month discharge of 390 cubic feet per second and the average high-flow-month discharge of 3,302 cubic feet per second, and the ratio of areas calculated for the model cells that contain those gaging-station locations. Additionally, the relation was assumed to exponentially approach zero potential change in stage as the percentage of permanent to seasonal channel area decreases. The stage-change value applied to each river cell is then a linear interpolation based on the average flow of the

Table 1. Calculation of riverbed area in model cells for 1990-2000 stress periods

[**Stress period:** Only years are shown. Winter 1990 stress period is from January 1, 1990, to March 15, 2000. All other winter stress periods are from November 1 to March 15 of the following year. Irrigation stress periods are from March 16 to October 31 of the same year. **Average flow for period:** Average of monthly flow over the time of the stress period from the Rio Grande at Albuquerque streamflow-gaging station (station 08330000, fig. 4). Because March is split between the winter and irrigation seasons, it is given half the weight of the monthly flows in either season. **Percentage of seasonally flooded area:** Percentage of the seasonally flooded area added to the perennially flooded area to calculate the area of the riverbed in each model cell. Based on the 1974-89 average low-flow-month discharge of 390 cubic feet per second and the average high-flow-month discharge of 3,302 cubic feet per second]

Winter stress period			Irrigation-season stress period		
Stress period	Average flow for period, in cubic feet per second	Percentage of seasonally flooded area[1]	Stress period	Average flow for period, in cubic feet per second	Percentage of seasonally flooded area[1]
1990	656	9.1	1990	656	9.1
1990-91	945	[2]19	1991	1,864	51
1991-92	1,092	24	1992	1,822	49
1992-93	1,047	23	1993	2,385	68
1993-94	1,134	26	1994	2,043	57
1994-95	1,294	31	1995	2,690	79
1995-96	1,243	29	1996	592	7.0
1996-97	856	16	1997	1,954	54
1997-98	1,161	26	1998	1,284	31
1998-99	897	17	1999	1,547	40
1999-00	801	14			

[1]Abbreviated notation for "Ratio of perennially flooded channel area to seasonally flooded channels area, in percent" as shown in figure 11.

[2]Example calculation: [945 – 390] / [3,302 – 390] X 100 percent = 19 percent.

river during each stress period. Zero stage change would be applied if the average flow equaled the midpoint between the low flow and the high flow. Although this did not occur, it would have been represented as a value of 50 percent of seasonally flooded area in table 1. An increase of one-half the potential stage change would be applied if average flow for the stress period equaled the high-flow condition (3,302 cubic feet per second), and a decrease of one-half the potential stage change would be applied if average flow for the stress period equaled the low-flow condition (390 cubic feet per second). Because 50-percent seasonally flooded area would be zero stage change, the stage change for each model cell that represents a river reach can be calculated as:

$$\Delta h_i = \frac{psf - 50\%}{100\%} Psc_i \qquad (6)$$

where Δh_i = change in river stage for a model cell (L);

psf = percentage of seasonally flooded area from table 1; and

Psc_i = potential stage change for a model cell from figure 11 (L).

The 1995 irrigation season is used as an example of estimated stage-change calculations. Average flow for the 1995 irrigation season was 2,690 cubic feet per second, and the percentage of seasonally flooded area

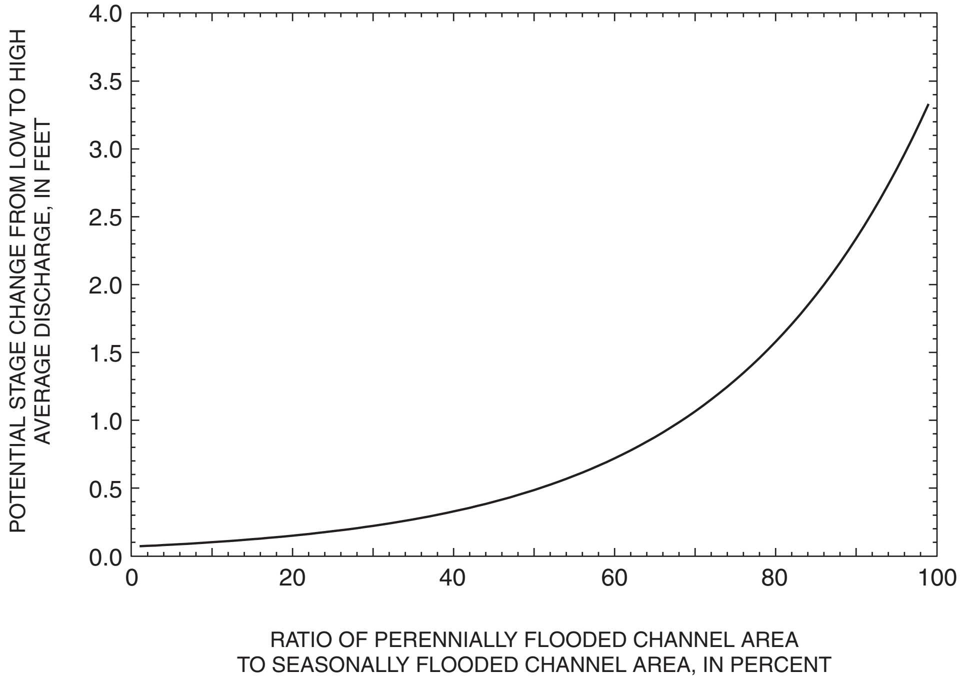


Figure 11. Assumed relation between potential simulated Rio Grande stage change and ratio of perennially flooded channel area to seasonally flooded channel area.

is then 79 percent (table 1). Therefore, *psf* in equation 6 is 79 percent. From figure 11, a river reach in a model cell that has 70 percent of perennially flooded channel area to seasonally flooded channel area would have 1.1 feet of potential stage change (Psc_i). Using equation 6, the river-stage change applied to the reach in that model cell would then be an increase of 0.32 foot ([79-50] X 1.1 / 100). If *psf* were 31 percent, then the river-stage change applied to the same river reach would be a decrease of 0.21 foot ([31-50] X 1.1 / 100).

Riverside Drains

Riverside drains are found on either side of the Rio Grande throughout most of the Middle Rio Grande Basin and are in direct connection with the aquifer system. These drains were installed beginning in the late 1920's and early 1930's to intercept leakage from the Rio Grande that previously contributed to waterlogging of soils in the adjacent valley areas. Riverside drains were reconditioned in the late 1950's. Because the riverside drains are closely associated with the river and because the horizontal dimensions of the model cells are 1 kilometer on a side, the riverside drains are simulated in the same model cells as the Rio Grande. Drain-bed altitudes relative to the Rio Grande vary throughout the area. The drain beds at the head of a particular drain are below the river and water-table altitudes. However, the drain-bed altitude rises relative to river altitude in the downstream direction so that water at the lower end of the drain can be returned to the river. Where a drain bed has risen relative to the water table so that it no longer can function as a drain, another overlapping drain begins alongside the primary drain to take over the drain function. Parts of riverside drains also function as conveyance channels during the irrigation season, causing drain stage to be above the water table. Therefore, riverside drains can either lose or gain water from the aquifer system depending on the drain stage and drain-bed altitude relative to the water table. The riverside drains are simulated using the River Package of MODFLOW-2000 (Harbaugh and others, 2000) rather than the Drain Package so that they can be simulated to either lose or gain water.

The physical characteristics of the riverside drains were obtained from the GIS coverage constructed by R.A. Durall (U.S. Geological Survey, written commun., 2001) and in the same manner as were the physical characteristics of the canals (see the

“Canal seepage” section of this report). In addition to physical characteristics, drain-bed and drain-stage altitudes must be specified in the river package. The altitudes and drain slopes are specified in the GIS coverage for several locations along the drains. This information and data consisting of measured Albuquerque Riverside Drain-stage altitude relative to river stage (J.E. Veenhuis, U.S. Geological Survey, written commun., 2000) were used to estimate average drain-bed and stage altitudes relative to river altitude for each drain reach in each model cell containing riverside drains. A model cell may contain one to four drain reaches depending on the existence of drains and overlap drains on each side of the river. Each drain reach has differing altitudes and was, therefore, kept separate in the river package. The hydraulic conductance of the drain beds is calculated in the same manner as the riverbed hydraulic conductance shown in equation 5. The hydraulic conductivity of the drain beds was assumed to be 1 foot per day, and the drain-bed thickness was assumed to be 1 foot. Because the drains are periodically dredged to remove sediment, the assumed hydraulic conductivity is larger that the values used for the riverbed.

Riverside drains identified as existing prior to about 1955 are simulated beginning in the 1930-34 stress period. Riverside drains identified as existing after the reconditioning of the drains in the late 1950’s are simulated beginning in the 1960-64 stress period.

Interior Drains

Interior drains were installed beginning in the 1920’s and early 1930’s to drain waterlogged land in the Rio Grande inner valley. They intercept seepage from canals and applied crop-irrigation water in the inner valley and discharge to the riverside drains. Although the purpose of these drains is to drain water from the shallow part of the aquifer system in the inner valley, a small number of the interior-drain reaches are used for conveyance of irrigation water. Identification and characterization of those reaches used to convey water were beyond the scope of this investigation. All identified interior drains are simulated in the ground-water-flow model using the Drain Package of MODFLOW-2000 (Harbaugh and others, 2000) and, therefore, are allowed only to gain water.

The physical characteristics of the interior drains were obtained from the GIS coverage constructed by R.A. Durall (U.S. Geological Survey, written commun., 2001) and in the same manner as were the physical characteristics of the canals (see the “Canal seepage” section of this report). In addition to physical characteristics, drain-stage altitudes must be specified in the drain package. Altitude information specified in the GIS coverage, which is specified at several locations along the drains, was used to estimate average drain stage relative to land surface. A single drain reach was simulated in a model cell if one or more interior-drain reaches were identified for a model cell. The specified hydraulic conductance of drain bed was calculated as the sum of all the drain-bed areas times an assumed drain-bed hydraulic conductivity of 1 foot per day and an assumed drain-bed thickness of 1 foot. Interior drains are also dredged periodically; therefore, the hydraulic conductivity and thickness of the interior-drain beds are the same as those assumed for the riverside-drain beds. The specified drain stage for each cell was calculated as the land-surface altitude at the cell node minus the average drain-stage depth below land surface.

Interior drains existing in 1935 are simulated beginning in the 1930-34 stress period. Drains existing during 1935-55, 1955-75, 1975-92, and 1992-present are simulated beginning in the 1935, 1955, 1975, and 1991-92 winter stress periods, respectively.

Jemez River

The Jemez River is in hydraulic connection with the aquifer system over most of its length in the basin, so changes in water-table altitude in the aquifer system adjacent to the river can influence seepage between the river and the aquifer system. The Jemez River is simulated as a head-dependent flow boundary using the River Package of MODFLOW-2000 (Harbaugh and others, 2000). The hydraulic conductance of the riverbed is calculated in the same manner as the riverbed hydraulic conductance shown in equation 5. However, the necessary information that would allow definition of the hydraulic-conductance value (area times riverbed hydraulic conductivity divided by riverbed thickness) of the riverbed was not specifically available. Therefore, the hydraulic conductance of the riverbed was estimated on the basis of the length of the riverbed (from the area term in eq. 5) in a model cell times a factor that incorporates channel width, riverbed hydraulic conductivity, and riverbed thickness (the remaining terms in eq. 5). Although the depth of flow varies along the river, a river stage of 1 foot above channel altitude and a riverbed bottom of 1 foot below channel altitude were assumed for the entire length of the Jemez River. The river was split into two reaches for the application of the hydraulic-conductance factor: above the confluence with the northern Rio Salado and below the confluence. The upper reach has a steeper gradient and a higher flow energy than the lower reach, resulting in a greater proportion of coarse material in the riverbed; therefore, the upper reach was assumed to have a relatively larger riverbed hydraulic conductivity than the lower reach. Downstream from the Rio Salado, the riverbed tends to widen, the flow energy is decreased, and the flow is shallower than in the upper reach, resulting in finer grained riverbed material than in the upper reach; therefore, the lower reach was assumed to have a smaller riverbed hydraulic conductivity than the upper reach. The factors applied to reach length for estimating riverbed hydraulic conductance were adjusted during model calibration. The resulting hydraulic-conductance values are 75 feet per day for each foot of length for the upper reach and 25 feet per day for each foot of length for the lower reach. The section of the Jemez River that would be inundated by water stored in Jemez Canyon Reservoir is simulated differently for the times that water in the reservoir is simulated, as described below.

Jemez Canyon Reservoir

Jemez Canyon Reservoir (fig. 2) began permanently storing water in about 1979. The reservoir was built for sediment control and stored water only on a short-term basis before 1979. Only the Jemez River channel at the reservoir is simulated in the model prior to 1979. The River Package of MODFLOW-2000 was used to simulate the reservoir beginning in the 1979 stress period. The approximate average annual reservoir stage was used in the model simulation. The reservoir stage of 5,163 feet above NGVD 29 was used for 1979-84; 5,190 feet for 1985, 1990, 1996, and 1999; 5,195 feet for 1988, 1989, 1991-95, 1997, and 1998; and 5,199 feet for 1986 and 1987 (USGS Water-Data Reports for New Mexico, various years; data available at *http://nm.water.usgs.gov*). Seasonal changes in reservoir stage are not simulated—only average annual stage is used. The simulation ends March 15, 2000; therefore, only 2.5 months of 2000 are simulated, and the 1999 stage was continued for the last stress period. The reservoir-bottom area was estimated for each simulated stage using USGS 30-meter 1:24,000 Digital Elevation Models (DEM's). Information on reservoir-bottom thickness and hydraulic conductivity was not available; therefore, hydraulic conductance of the reservoir bed was estimated as a factor of hydraulic conductivity divided by bed thickness and applied to the reservoir area. The hydraulic conductance was estimated by model calibration. Because the specific components of hydraulic conductance could not be identified individually, no attempt was made to account for differences between the reservoir-surface area and the reservoir-bottom area. The factor applied to the reservoir area for 1979-84 is 0.0015 per day (units of hydraulic conductivity, in feet per day, divided by bed thickness, in feet), and the factor applied to subsequent years is 0.001 per day. The slightly lower rate after the first 5 years of permanent storage in the reservoir is consistent with a buildup of additional sediment in the reservoir, creating a thicker, less permeable bed.

Cochiti Lake

Cochiti Lake began storing water in November 1973. Because 1974 is part of the 1970-74 5-year stress period, this reservoir is simulated in the model beginning in the 1975 stress period. Cochiti Lake is simulated using the River Package of MODFLOW-2000 (Harbaugh and others, 2000). Information on the hydraulic conductance of the reservoir bed was not available; instead, model conductances were obtained by calibrating the simulated Cochiti Lake seepage to match seepage estimates based on measurements. A water balance on Cochiti Lake historical inflow, outflow, storage, and evaporation data indicates that seepage from the Cochiti reach of the Rio Grande ranges from about 2,000 acre-feet per month (33 cubic feet per second) when reservoir stage is 5,320-5,340 feet above NGVD 29 to 15,000 acre-feet per month (250 cubic feet per second) when reservoir stage is 5,390-5,410 feet above NGVD 29. The average reservoir stage simulated in the model was never above 5,390 feet above NGVD 29; therefore, the average of the two estimates (8,500 acre-feet per month) was used for the measured seepage for reservoir stages between 5,340 and 5,390 feet above NGVD 29.

The approximate average annual stage of the reservoir is used in the simulation. The reservoir stage of 5,297 feet above NGVD 29 was used for 1975; 5,323 feet for 1976-78 and 1980-82; 5,331 feet for 1979, 1983-84, 1989, and 1990; 5,340 feet for 1991-99; 5,348 feet for 1988; 5,368 feet for 1986; and 5,378 feet for 1985 and 1987 (USGS Water-Data Reports for New Mexico, various years; data available at *http://nm.water.usgs.gov)*. Seasonal changes in reservoir stage are not simulated, and the 1999 stage is continued through the end of the simulation (March 15, 2000). Information on the hydraulic conductance of the reservoir bed was not available; therefore, hydraulic conductance of the reservoir bed was estimated through model calibration. A factor for hydraulic conductivity divided by bed thickness was applied to the reservoir area. The reservoir area was estimated for each of the simulated stages using USGS 10-meter 1:24,000 DEM's. More detailed DEM's were necessary for Cochiti Lake than for Jemez Canyon Reservoir (10-meter compared with 30-meter DEM's) because of the steeper land-surface gradients in the vicinity of Cochiti Lake. The factors applied to the reservoir area range from 0.001 to 0.003 per day. The smaller numbers were applied to lower reservoir stages, and the larger numbers were applied to higher reservoir stages. Bottom sediments in contact with reservoir water are likely to have smaller average permeability at low stage compared with sediments in contact with reservoir water at high stage. In addition, the sides of the reservoir, which are in contact with the water at high stage, provide a larger area for leakage than the low-stage surface area of the reservoir.

Riparian Evapotranspiration

Evapotranspiration from the water table in riparian areas along the inner Rio Grande Valley and the Jemez River is simulated in the model using the Evapotranspiration Segments Package of MODFLOW-2000 (Banta, 2000). Agricultural cropland and urban areas, such as yards, parks, and golf courses, are irrigated. Evapotranspiration on these areas is assumed to come from applied irrigation water; therefore, evapotranspiration from ground water is not simulated in those areas. Riparian areas along the Rio Grande were delineated on the basis of GIS coverages of land use in the inner valley for 1935 (National Biological Service digital data) and for 1955, 1975, and 1992 (Bureau of Reclamation digital data). Areas of evapotranspiration developed on the basis of 1935 land-use data along the Rio Grande were used in the predevelopment steady-state simulation and beginning in the 1900-04 historical stress period. Evapotranspiration derived from 1955, 1975, and 1992 land-use conditions along the Rio Grande is simulated beginning in the 1945-49, 1965-69, and 1984 stress periods, respectively. Only the 1955 and 1975 land-use coverages showed the riparian areas along the Jemez River. Very little riparian area that could contribute to evapotranspiration from the water table was located where Cochiti Reservoir now exists and therefore is not simulated. Evapotranspiration values derived from 1955 land-use conditions along the Jemez River are simulated in the predevelopment steady-state simulation and beginning in the 1900-04 stress period. Evapotranspiration values derived from 1975 land-use conditions along the Jemez River are simulated beginning in the 1945-69 stress period. Evapotranspiration from the water table is excluded from the area beneath Jemez Canyon Reservoir beginning in 1979, the year during which a permanent reservoir pool was established.

A maximum evapotranspiration rate of 5.0 feet per year applied to the riparian areas was used when the simulated water table is at or above land surface. The evapotranspiration rate linearly decreases from 5.0 feet per year at land surface to 2 feet per year 9 feet below land surface. These numbers result from work done near Bernardo (fig. 2) by the Bureau of Reclamation (1973b), which determined that evapotranspiration from salt cedar ranges from 4.5 to 1.8 feet per year when the water table is between 0 and 9 feet below land surface. The evapotranspiration rate then linearly decreases from 2.0 feet per year to 0.75 foot per year when the simulated water table is 16 feet below land surface. Robinson (1958) reported that "most willow growth occurs where the depth to the water table is less than 15 feet." The evapotranspiration rate then linearly decreases from 0.75 foot per year to zero when the simulated water table is 30 feet or greater below land surface. Robinson (1958) reported that 30 feet to the water table is near the limit at which cottonwoods can survive in an arid environment.

Evapotranspiration rates are adjusted for seasonal stress periods during which evapotranspiration is simulated only during the irrigation season and is assumed to be zero during the winter season. The simulated maximum rate during irrigation-season stress periods is 5.0 feet per 230 days, the length of the simulated irrigation season, and the simulated maximum rate for annual or greater stress periods is 5.0 feet per 365.25 days, the length of the average year. The simulated rates at intermediate depths adjust proportionately.

Aquifer Properties

The initial framework for specifying zones of hydraulic conductivity for the model was modified from a three-dimensional digital geologic model of hydrostratigraphic units in the Middle Rio Grande

Basin described by Cole (2001). These initial zones were modified during model development and calibration on the basis of information from several sources. Geologic information developed by Hawley and Haase (1992), Hawley and others (1995), Connell and others (1998), Smith and Kuhle (1998), and Connell (2001) were used as guides for the modifications. Geochemical information for the basin developed by Plummer and others (2001) and information from ground-water-flow models done for the Rio Rancho area (Zimmerman and Updegraff, 1996), Kirtland Air Force Base (Sandia National Laboratories, 1997; 1998), and parts of the City of Albuquerque (Zimmerman and others, 2000; McAda, 2001) were also used as guides. The distribution of hydraulic conductivity along rows for the nine model layers is shown in figure 12. Hydraulic conductivity along model rows (east-west) ranges from 0.05 to 45 feet per day.

Horizontal anisotropy, defined as the ratio of hydraulic conductivity along model columns to hydraulic conductivity along model rows, varies by location in the model. Figure 13 shows the distribution of horizontal anisotropy for model layers 1 though 8. A horizontal anisotropy ratio of 1 (isotropic conditions) was assumed to exist in model layer 9. An anisotropy ratio greater than 1 was applied in areas of the model where hydrologic information, such as measured water levels, indicated that model calibration could be improved by adding horizontal anisotropy and where geologic information supported the conclusion that anisotropic conditions oriented along the primary axes of the grid can exist. A horizontal anisotropy ratio of 2 (2:1) or 5 (5:1) is used in most of the Calabacillas and Belen subbasins (figs. 3, 13). Faulting in this area generally is oriented north-south (fig. 3 of this report; Connell, 2001, fig. 4). The columns in the model are oriented north-south on the assumption that the general north-south orientation of faults is a significant factor in controlling the principal directions of anisotropy (see "Numerical methods" section of this report). These faults often juxtapose lithologic units of different hydraulic conductivities, in effect creating large to small hydrologic-conductivity transitions across the faults. Many of the faults may be cemented to some degree or contain clay-rich fault gouge, further decreasing hydraulic conductivity across the faults. The hydraulic conductivities along columns resulting from the horizontal-anisotropy ratios range from 0.05 foot per day (the 0.05-foot-per-day zone with a 1:1 ratio applied) to 60 feet per day (the 30-foot-per-day zone with a 2:1 ratio applied; figs. 12 and 13).

The largest horizontal-anisotropy ratio is applied to an area on the west side of the Calabacillas subbasin where a water-level trough exists (Meeks, 1949; Bjorklund and Maxwell, 1961, pls. 1a and 1b; Tiedeman and others, 1998, fig. 4; Bexfield and Anderholm, 2000). Geohydrologic evidence does not support the conclusion that an extensive area of large hydraulic conductivity is responsible for creating the trough. Tiedeman and others (1998) tested the value of hydraulic conductivity that would be necessary to develop the trough without applying horizontal anisotropy and found the value to be about 130 to 140 feet per day and noted that these large values are not supported by the evidence. Various configurations of horizontal anisotropy and horizontal flow barriers were tested during model development and calibration. Some of these configurations were more successful in developing a water-level trough than the final configuration (fig. 13). However, those configurations also resulted in hydraulic conductivities along columns that could not be supported by the geohydrologic evidence (discussed in the "Ground-water hydrology" section of this report). Although the final configuration does not replicate the trough completely, the resulting hydraulic conductivities are plausible. The largest value of hydraulic conductivity along columns resulting from the 5:1 anisotropy ratio is 7.5 feet per day (1.5 feet per day along rows times 5; figs. 12 and 13).

Isotropic conditions were assumed for the Santo Domingo subbasin, the east and west margins of the Calabacillas and Belen subbasins, and the recent alluvium in the inner Rio Grande Valley. Hydrologic and geologic information did not suggest strong anisotropy or a definable dominant direction of anisotropy in these areas of the model.

Water-level information indicates that some faults form significant hydrologic barriers to ground-water flow; the Cat Mesa Fault (fig. 3) is an example of this. Water levels measured on both sides of the fault show very different hydraulic heads, as illustrated in the predevelopment water-level contours constructed by Bexfield and Anderholm (2000; shown in fig. 5).

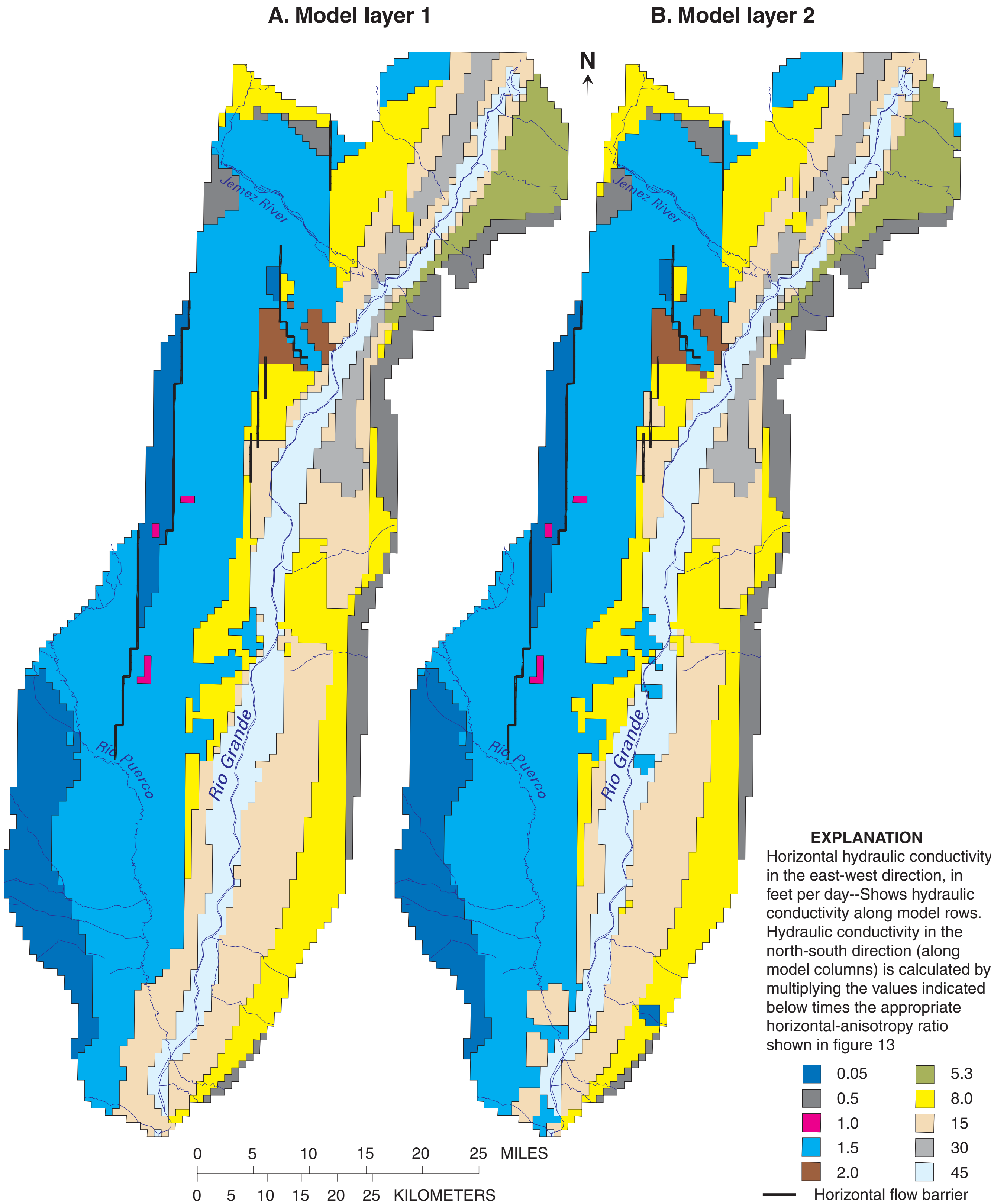


Figure 12. Distribution of simulated horizontal hydraulic conductivity in the east-west direction.

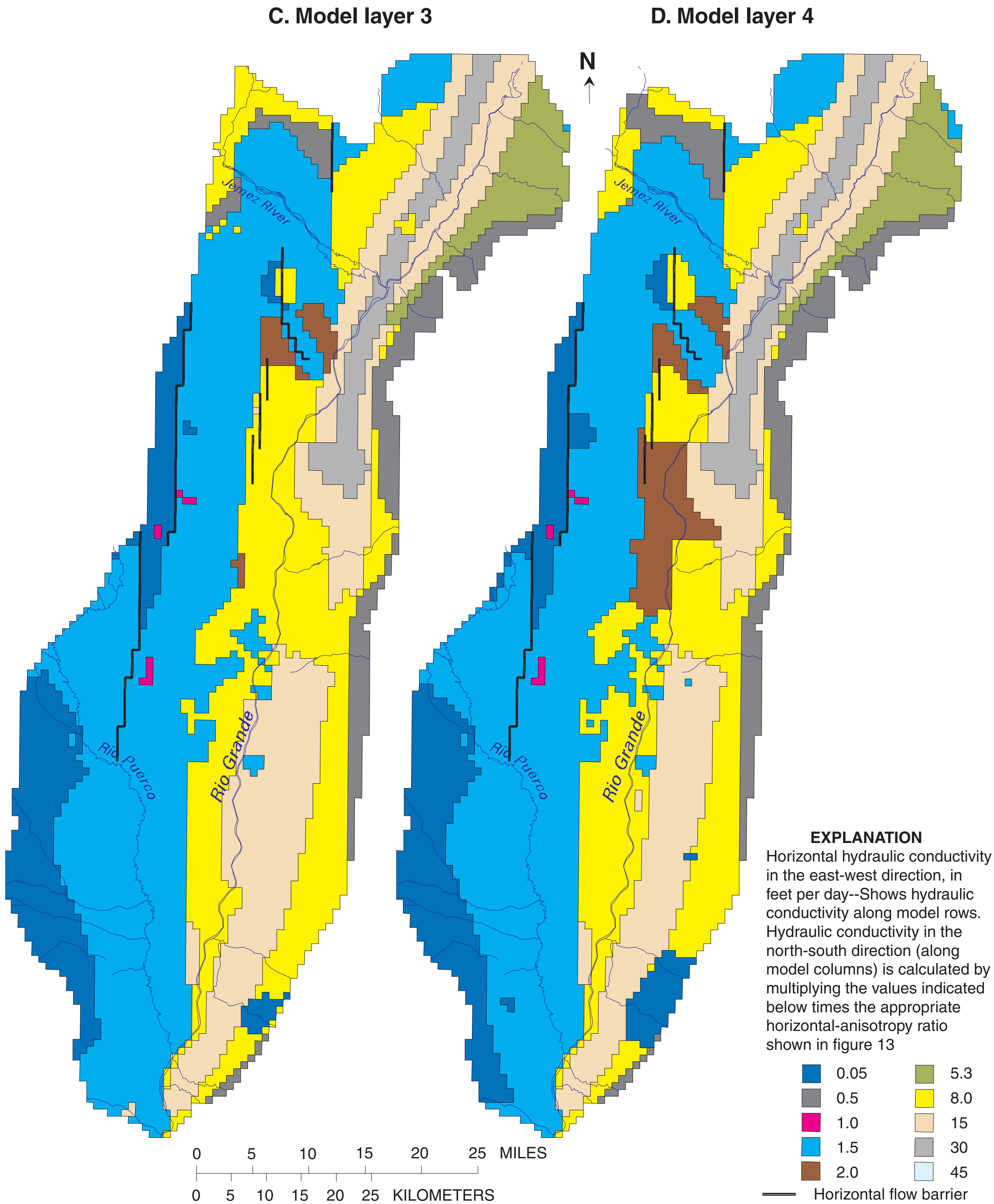


Figure 12. Distribution of simulated horizontal hydraulic conductivity in the east-west direction--Continued.

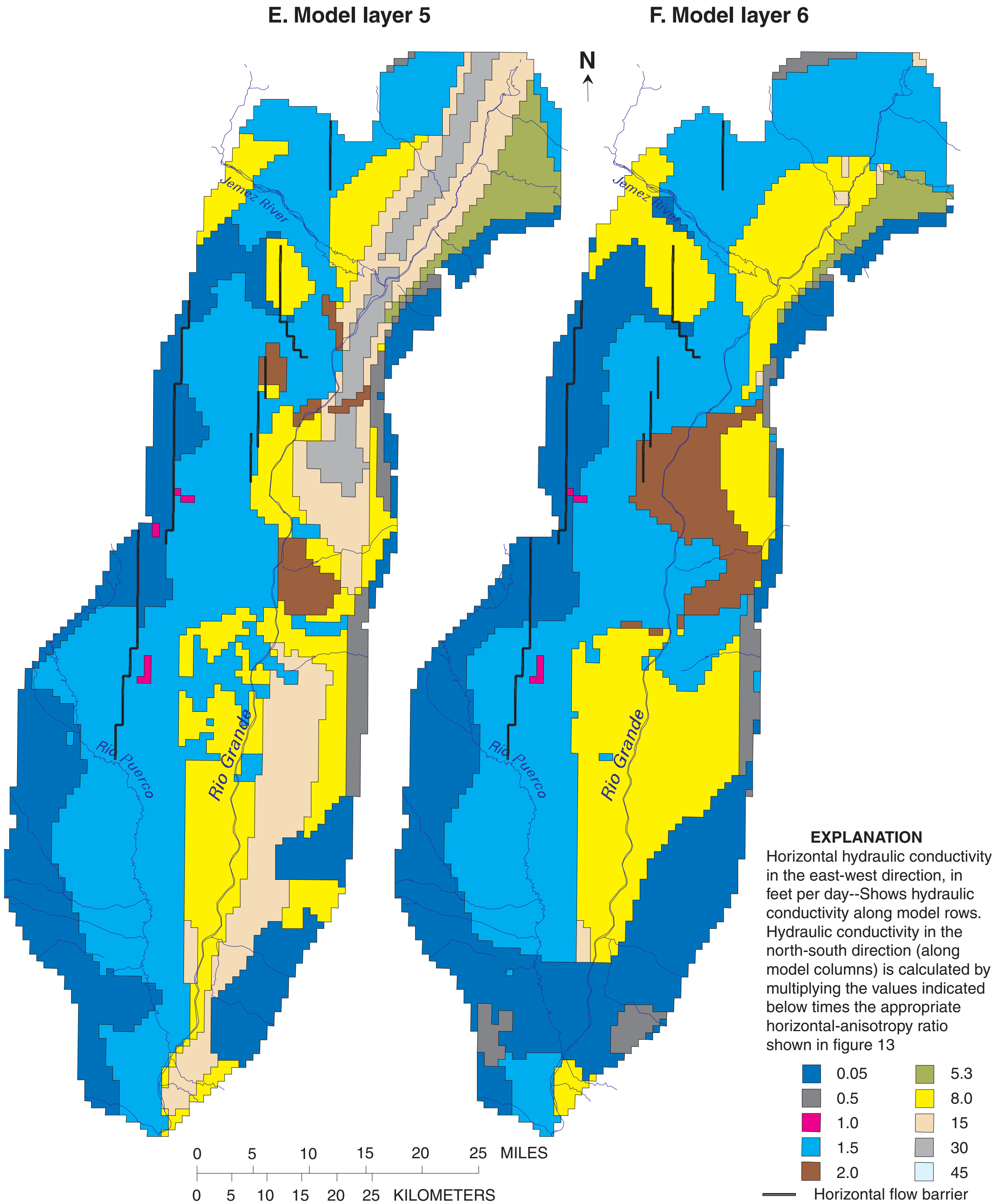


Figure 12. Distribution of simulated horizontal hydraulic conductivity in the east-west direction--Continued.

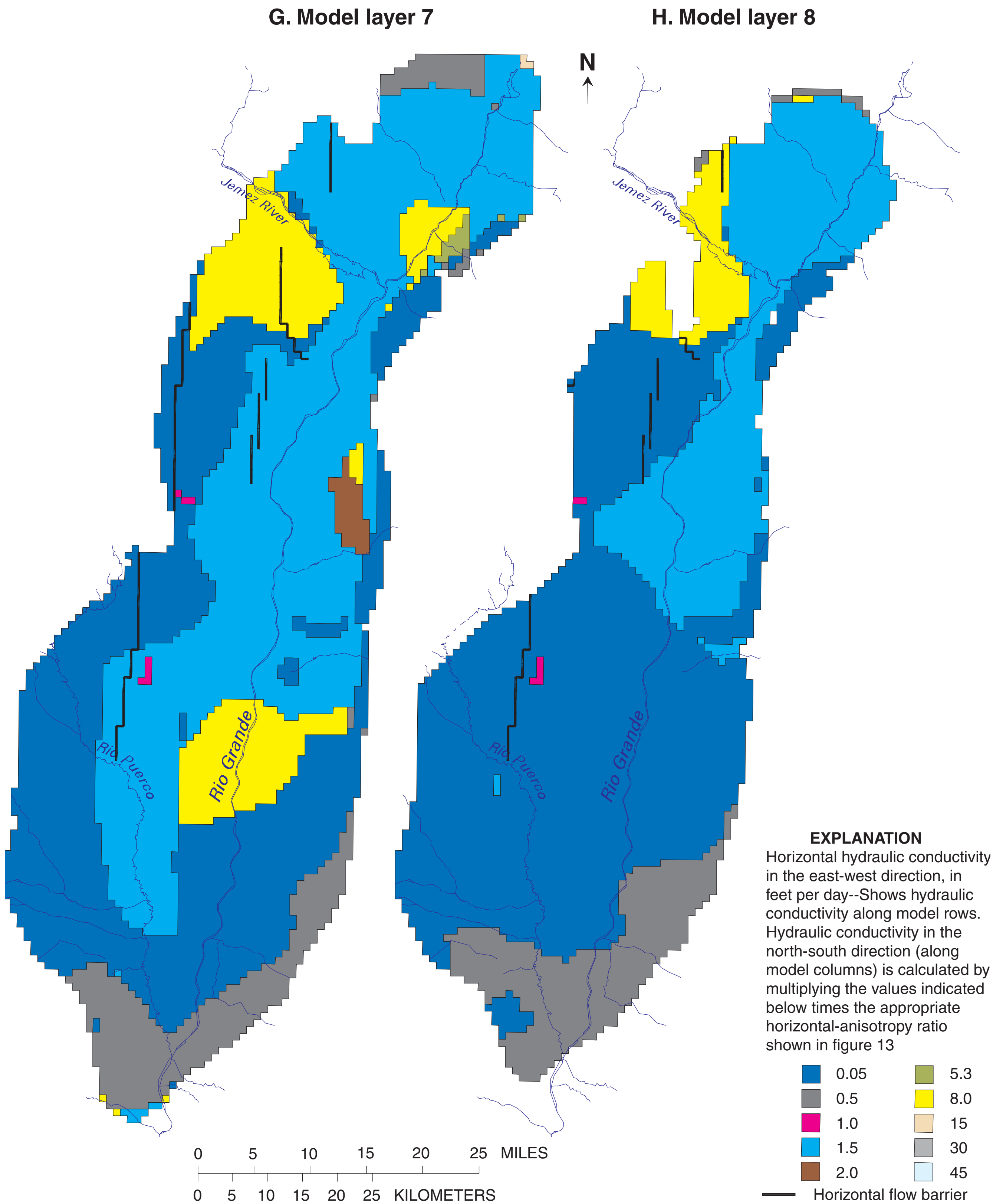


Figure 12. Distribution of simulated horizontal hydraulic conductivity in the east-west direction--Continued.

I. Model layer 9

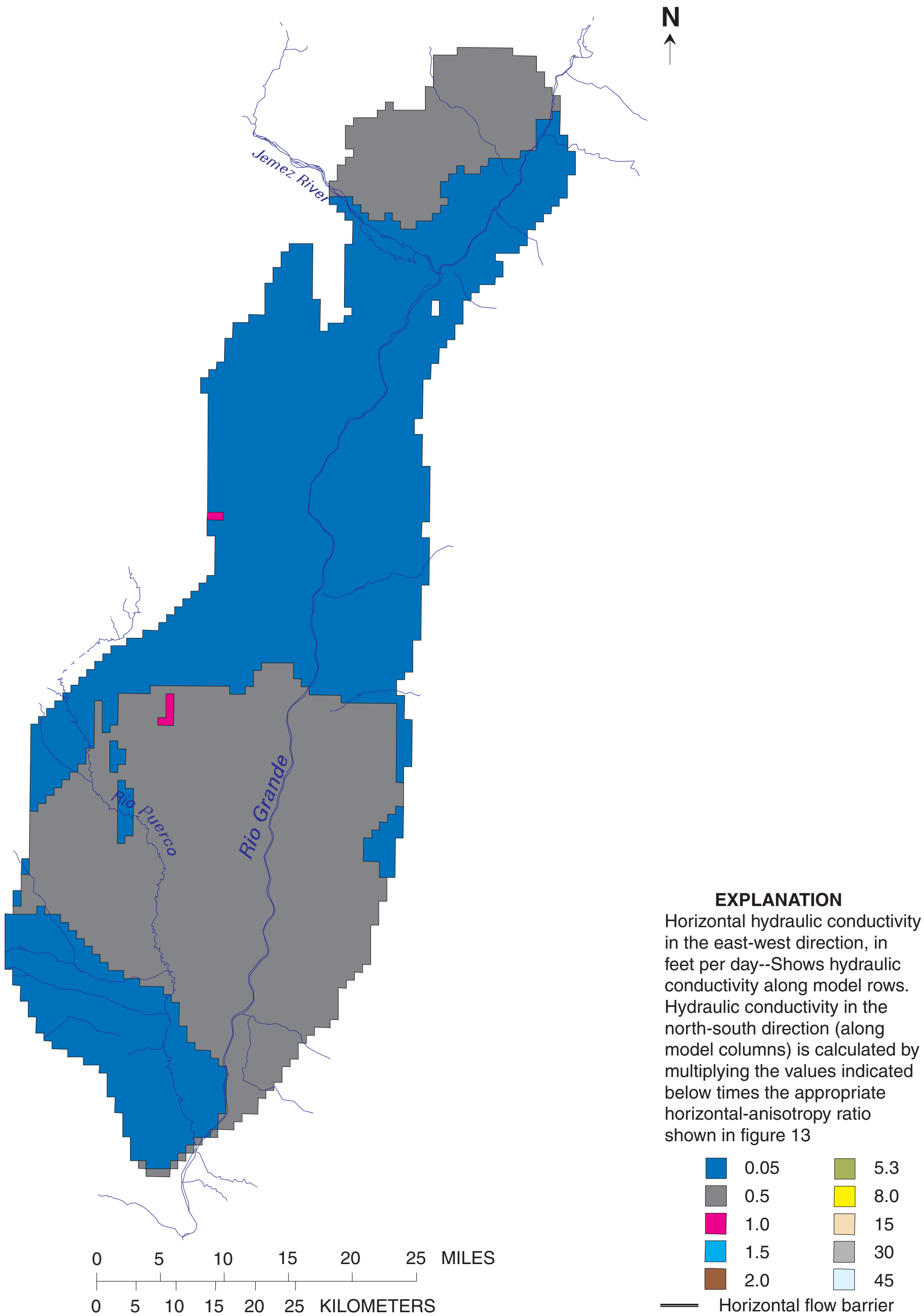


Figure 12. Distribution of simulated horizontal hydraulic conductivity in the east-west direction--Concluded.

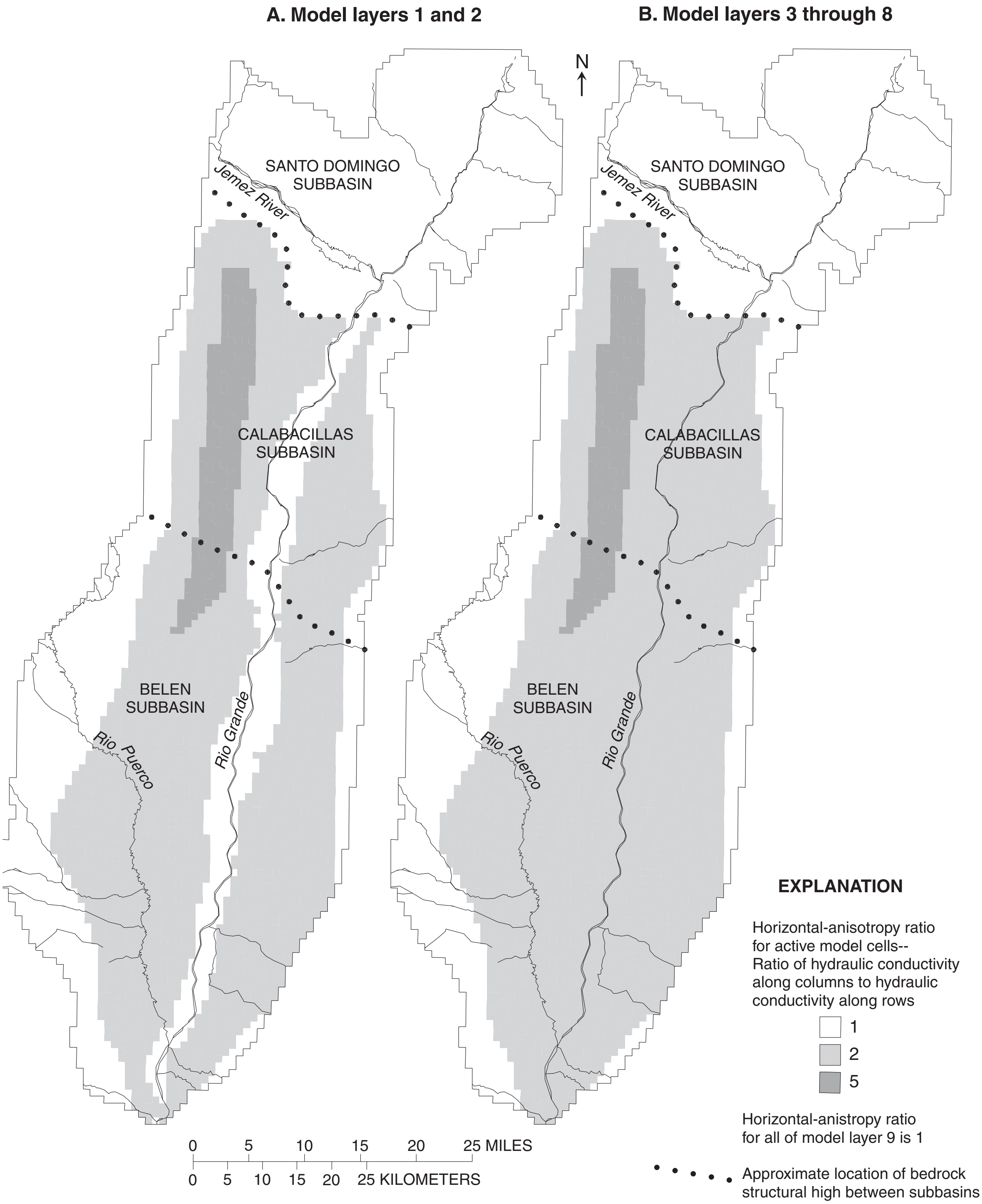


Figure 13. Distribution of simulated horizontal anisotropy in the model.

Where hydrologic information was available to indicate that particular faults were significant flow barriers, the Horizontal Flow Barrier (HFB) package of MODFLOW-2000 (Harbaugh and others, 2000) was used to decrease horizontal hydraulic conductance between model cells. The locations of horizontal flow barriers simulated in the model are shown in figures 3 and 12. The hydrologic property input to the HFB package is the hydraulic conductivity of the barrier (in a direction perpendicular to the barrier) divided by the thickness of the barrier. The value of this hydrologic property is not known for the faults represented in the model and it likely varies by fault and within a particular fault. Because information is not available to vary this property, it was assumed to be constant for all simulated barriers and was estimated by model calibration. The final value used in this model is 0.0001 per day (feet per day divided by feet).

Vertical hydraulic conductivity is calculated in the model as a horizontal to vertical anisotropy ratio (horizontal hydraulic conductivity divided by vertical hydraulic conductivity) times the horizontal hydraulic conductivity along rows. Various ground-water-flow models in the basin have used horizontal to vertical anisotropy ratios ranging from about 80:1 (McAda, 2001) to more than 1,000:1 (Tiedeman and others, 1998), a reasonable range of average values for the aquifer system. The horizontal to vertical anisotropy ratio was adjusted during model calibration. The resulting value is 150:1 applied uniformly in the model.

Values of specific storage and specific yield were assumed to be uniform throughout the modeled area. Specific storage applies to all cells in the model representing confined aquifer conditions—that is, the hydraulic head is above the top of the layer. Specific yield applies to all cells representing unconfined, or water-table, conditions. Specific-storage values for an aquifer system are approximately 10^{-6} per foot of thickness (Lohman, 1979, p. 8) and, as described previously, values of 1.2×10^{-6} per foot (McAda, 2001, p. 36) to 2×10^{-6} per foot (Heywood, 1998; 2001) have been calculated for this basin. Model results were relatively insensitive to specific storage (see "Model sensitivity" section in this report). The methodology used by Heywood (1998; 2001) (using extensometers) is considered to be most accurate; therefore, specific storage was set to a value of 2×10^{-6} per foot. Specific yield was adjusted within the plausible range of 0.1 to 0.25 (see "Hydrologic properties" section of this report), resulting in a value of 0.2.

Calibration Results

Model calibration is evaluated on the basis of measured and simulated hydraulic heads and water-budget components at various time periods of the model simulation. Many of these comparisons are quantitative, whereas some, particularly the water-budget comparisons, are qualitative.

Predevelopment Heads

The simulated water table (heads in layer 1) for the predevelopment, steady-state simulation are contoured in figure 14, and the residuals associated with the measured predevelopment water levels are shown. A number of very large positive residuals (greater than 150 feet) are found along the edge of the simulated aquifer system. Reproducing these water levels with any reasonable, and converging, model was not possible. These basin margins have thinner and less permeable sequences of Santa Fe Group sediments than the central part of the basin and are on the upthrown sides of faults (Hawley and others, 1995, fig. 4, table 1). The faults likely isolate the water-bearing zones in these margin areas from the central part of the basin to some extent. In addition, the uplifted, less permeable sediments in these margin areas may tend to create perched conditions relative to sediments on the downthrown side of the faults. Therefore, those large residuals were assumed to reflect measurements representing water-bearing zones that are not in good hydrologic connection with the rest of the simulated aquifer system, and minimizing those residuals was not continued. These points are shown in figure 14 but are omitted in the statistical analysis.

In general, the model-simulated predevelopment water table matches measured predevelopment water levels quite well throughout most of the basin. The model simulates ground-water flow in the observed directions, flow that originates in the basin margins and flows generally southward and toward the inner valley of the Rio Grande. Simulated heads differ from measured heads by less than 20 feet in the Albuquerque area, in the southern part of the basin, and along the Rio Grande.

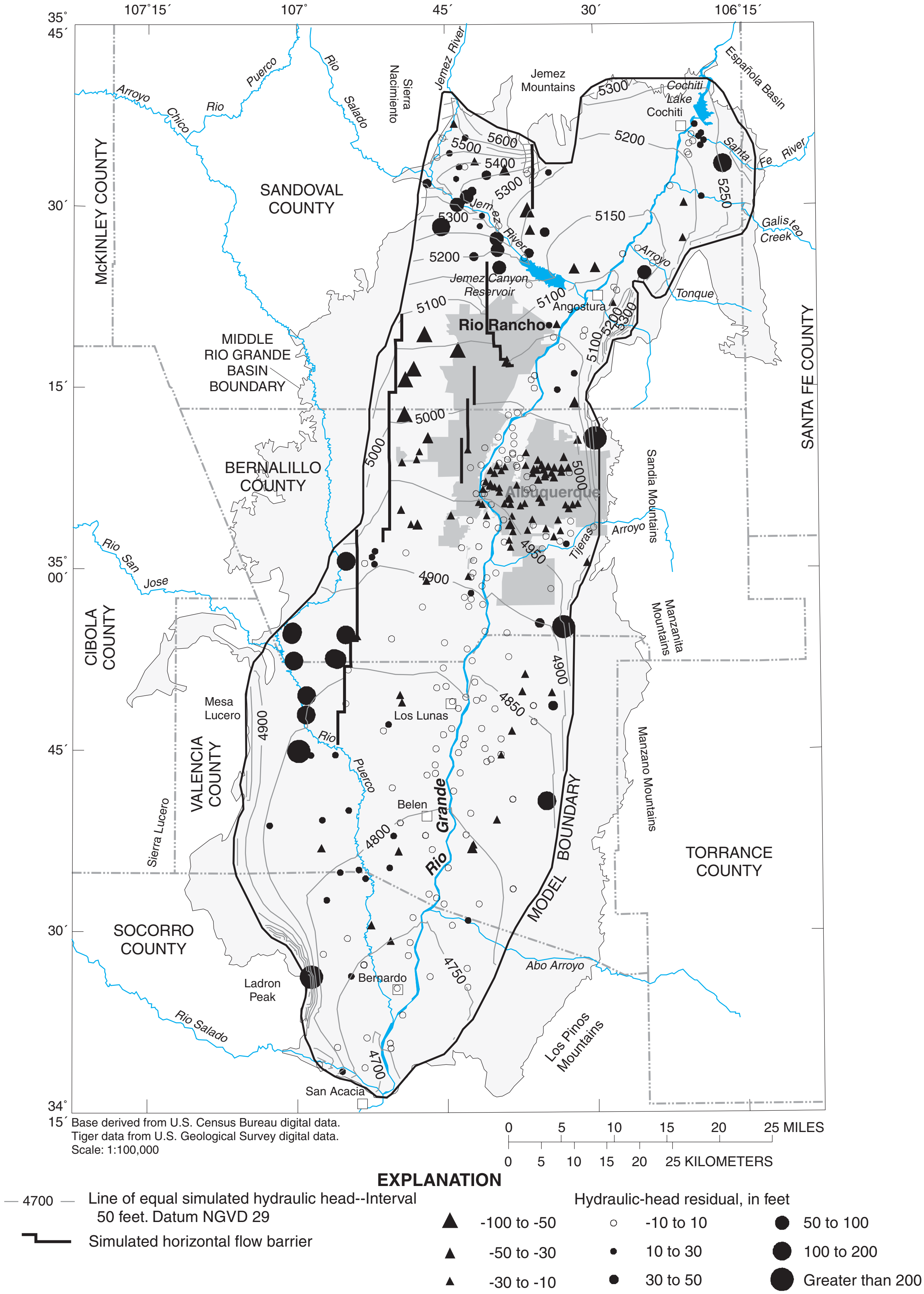


Figure 14. Simulated steady-state water table and hydraulic-head residuals (measured minus simulated heads).

The match between measured and model-simulated heads worsens at distance from the Rio Grande. Heads are poorly simulated in the vicinity of the Cat Mesa Fault, where measured heads drop by about 200 feet over a few miles (Bexfield and Anderholm, 2000). Despite the very low hydraulic conductivity associated with this feature in the model, in reality the west side of this feature appears to be even more poorly connected to the rest of the aquifer system than has been simulated by the model.

Another area of relatively poor head match is west of Albuquerque, where measured water levels show a trough and anomalously low heads have been measured. Simulated contours in figure 14 show the beginnings of a trough, but modeled heads are still 90 feet too large. In previous modeling studies (Tiedeman and others, 1998), the form and magnitude of the trough were best simulated by a zone of anomalously high hydraulic conductivity (200 feet per day). The existence of such a zone of large hydraulic conductivity is not supported by any available geohydrologic evidence (described in the “Ground-water hydrology” section). Instead, the trough is thought, in part, to result from the hydrologic effect of numerous south-trending faults that retard ground-water flow from west to east compared with flow along strike from north to south. It has been suggested that the trough is a transient feature; therefore water levels are not in equilibrium with the conditions in other parts of the aquifer system (J.W. Hawley, New Mexico Bureau of Geology and Mineral Resources, oral commun., 1995; L.N. Plummer, L.M. Bexfield, S.K. Anderholm, W.E. Sanford, and E. Busenberg, U.S. Geological Survey, written commun., 2002). Such a transient feature cannot be accurately represented in the steady-state model. The beginnings of the trough in figure 14 are the best that could be done in the present study while keeping the values of hydraulic conductivity within what are currently believed to be reasonable ranges. However, the hydrologic properties along the strike of the faults themselves (for example, dissolution of cements in indurated zones) possibly may enhance the north-south hydraulic conductivity beyond the values in the present model.

Previous basinwide ground-water models have had difficultly simulating the heads around the Jemez River and within the subbasin north of the Jemez River. The performance of the present model in this area is still not as good as elsewhere but is an improvement over previous models. Heads simulated by the present model are as much as 40 to 60 feet lower than measured heads in these areas and are systematically low along the Jemez River. The geologic and hydrologic complexity in this area, associated with faulting, is likely to be responsible for the difficulty in accurate simulation. More detailed local geohydrologic data will be necessary to accurately simulate this area, and a local submodel, based upon such data, may be required if hydrologic problems arise specific to this area.

Residual analysis, neglecting the edge outliers, is shown in figures 15 and 16. Forty-seven percent of residuals are within 10 feet of measured values, and 72 percent are within 20 feet of measured values. A large number of large positive residuals at greater than +100 feet remain (fig. 16), even after the egregious edge outliers are omitted; for the most part, these large positive residuals represent wells located west of the Cat Mesa Fault and other potential edge outliers. A group of large negative residuals still remains; most of these are associated with the trough.

Well Hydrographs

Ground-water levels in the Middle Rio Grande Basin have been observed to have dropped substantially since predevelopment times. Ground-water withdrawals in excess of 100,000 acre-feet per year have led to substantial water-level declines, particularly in the Albuquerque area, and to the development of considerable vertical gradients associated with the production zones of major well fields. The performance of the Middle Rio Grande Basin model was tested against both individual well hydrographs and the areal head distribution in recent times for both the water table and the production zone.

Well hydrographs are shown in figure 17 for a number of wells with a substantial period of record. These wells (with the same letter designations shown in fig. 9) were used for hydrographs by Kernodle and others (1995, fig. 26) and by Tiedeman and others (1998, fig. 22). There is a relatively fixed offset between the modeled and measured hydrographs of many wells, which reflects imperfection in the simulation of predevelopment heads. The main features of the transient performance of the hydrographs, however, are simulated very well. Wells in which water levels were observed to remain fixed are also simulated as having small changes in head (examples: SNFEL, SNTA2, TRRMR, SDECW2, GRSLND, BLNAP, MCLAU, and SEV1; fig. 17B-E, R-V). Wells in which tens of feet of drawdown were

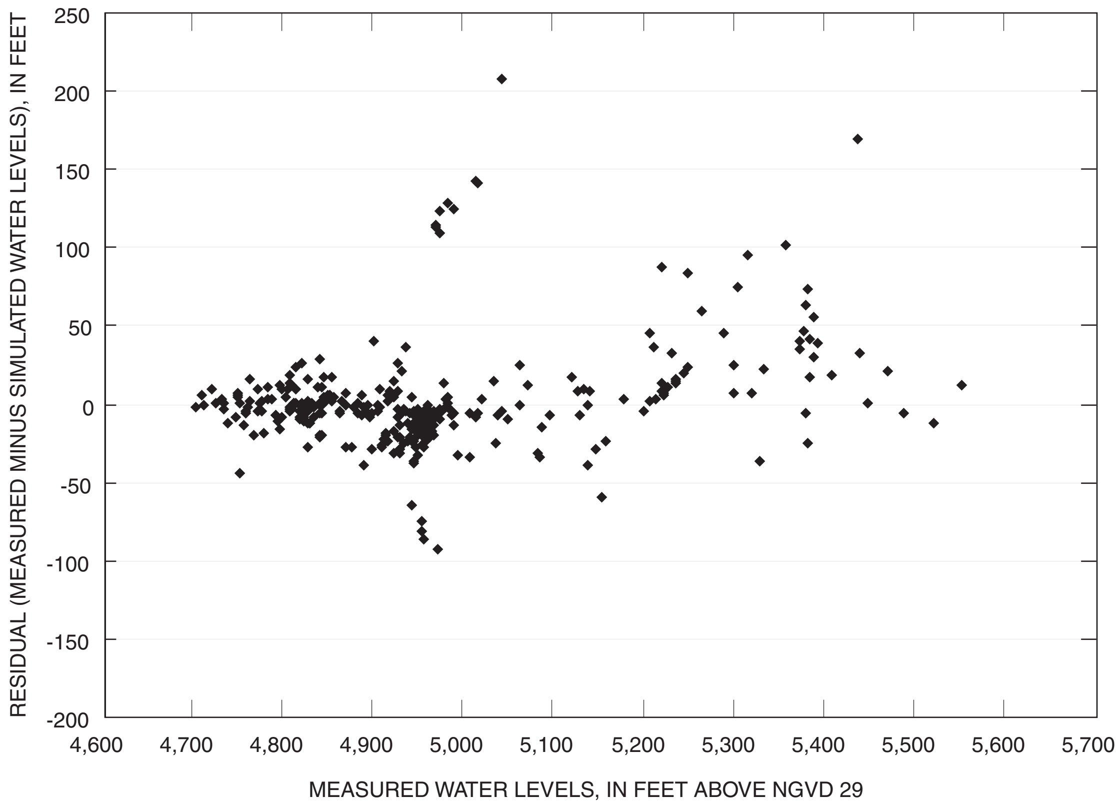


Figure 15. Comparison of hydraulic-head residuals and measured water levels for the predevelopment steady-state simulation. Edge outliers omitted, as discussed in text.

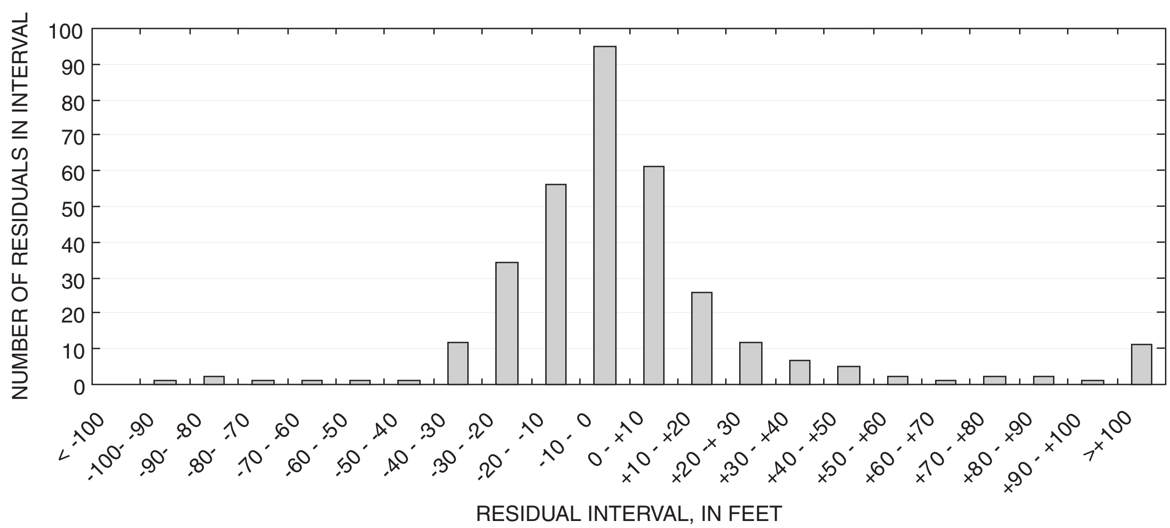


Figure 16. Water-level residuals for the predevelopment steady-state simulation. Edge outliers omitted, as discussed in text.

measured through the period of record are also simulated as having tens of feet of decline (examples: WM2, COR1, VC1, CTY3, CTY2, THOM2, CTY1, LOM1, SND2, ISECW3, and SDECW1; fig. 17 F-L, N-Q, W). The most poorly simulated hydrograph (COCHI, fig. 17A) is near the base of Cochiti Lake, where measured water levels rose and fell dramatically, repeatedly, after the construction of Cochiti Dam. The simulated ground-water levels rise more gradually and not as much as the measured levels, indicating that the water in the reservoir and ground water at the well location are more dynamically connected in reality than the model simulates.

Recent Water-Level Maps

Simulated water levels and posted residuals are shown for 1994 and 2000 in figures 18, 19, and 20. The last period for which a relatively complete water-level data set exists over the entire basin is 1993-95. The model-simulated water table is contoured over the whole basin for the winter of 1994 (fig. 18), with residuals shown comparing the simulated values with the measured values for 1993 through 1995 from relatively shallow wells.

Figures 19 and 20 show the Albuquerque area simulated water levels from the water table and from layer 5, respectively; layer 5 generally represents the production zone of the aquifer. Posted on these maps are residuals comparing model-simulated and measured water levels in wells of appropriate depths for those zones of the aquifer. In general, the water-table maps show residuals from wells sampling layers 1-4, and the production-zone maps show residuals from layers 4-7. Water-table contours constructed from measured water levels in shallow wells are superimposed on figure 19 for comparison with simulated water-table contours. Contours of measured production-zone water levels produced by Bexfield and Anderholm (2002) are superimposed on figure 20 for comparison with simulated layer 5 hydraulic-head contours.

The water-level comparison map for winter 1994 (fig. 18) appears similar to its predevelopment equivalent (fig. 14). Again, the water-table surface looks reasonable, and residuals are small in most of the southern and central parts of the basin, including the Albuquerque area. A number of edge outliers have large residuals, suggesting that these wells actually are outside the extent of the hydrologically connected aquifer simulated here. Residuals also are large west of the Cat Mesa Fault, which continues to be poorly simulated by this model. Residuals are also somewhat large near the Jemez River and near Cochiti Reservoir, suggesting that the simulated response to ground-water withdrawal in that area may be a problem, in addition to the problems expected from the geohydrologic complexity near that basin boundary. Residual analysis shows that 45 percent of the simulated heads are within 10 feet of the measured values and 67 percent are within 20 feet.

The modeled water-table contours for winter 2000 in the Albuquerque area (fig. 19) show the cones of depression associated with Albuquerque area pumping east and (to a lesser extent) west of the Rio Grande. The measured water-table contours extend only far enough from the Rio Grande to indicate the existence of these cones of depression. Simulated contours are very close to measured contours, although the fit is not quite as good in the cones of depression. Residuals generally are small, although there is some indication of overprediction of drawdown near the simulated cone of depression east of the Rio Grande. This overprediction does not necessarily indicate a problem with model hydrologic properties. Uncertainties in the actual distribution of pumping with depth for each well and uncertainties in the representation of measured heads by particular model layers introduce a substantial margin of error into the comparison of measured and simulated heads in areas of large ground-water withdrawal and large vertical gradients. In addition, the City of Albuquerque water-distribution system and sewer system leak, as is typical with municipal systems. Part of these losses could recharge the aquifer, which would tend to decrease drawdowns. The volume of this leakage is not known and is not simulated in the ground-water-flow model.

The modeled and measured production-zone head map for winter 2000 in the Albuquerque area (fig. 20) shows the cone of depression west of Albuquerque even more clearly than figure 19 does. The fit between simulated and measured contours is not as good as with the water table, in part because of the difficulty in determining which piezometric data correspond to the production interval; the likelihood of subsurface heterogeneity, which may create more than one production zone with differing heads; and the uncertainty of the actual volume of water each well withdraws from which depth intervals. Still, residuals are generally within reasonable ranges. The cone of depression shown in the measured contours in the Rio

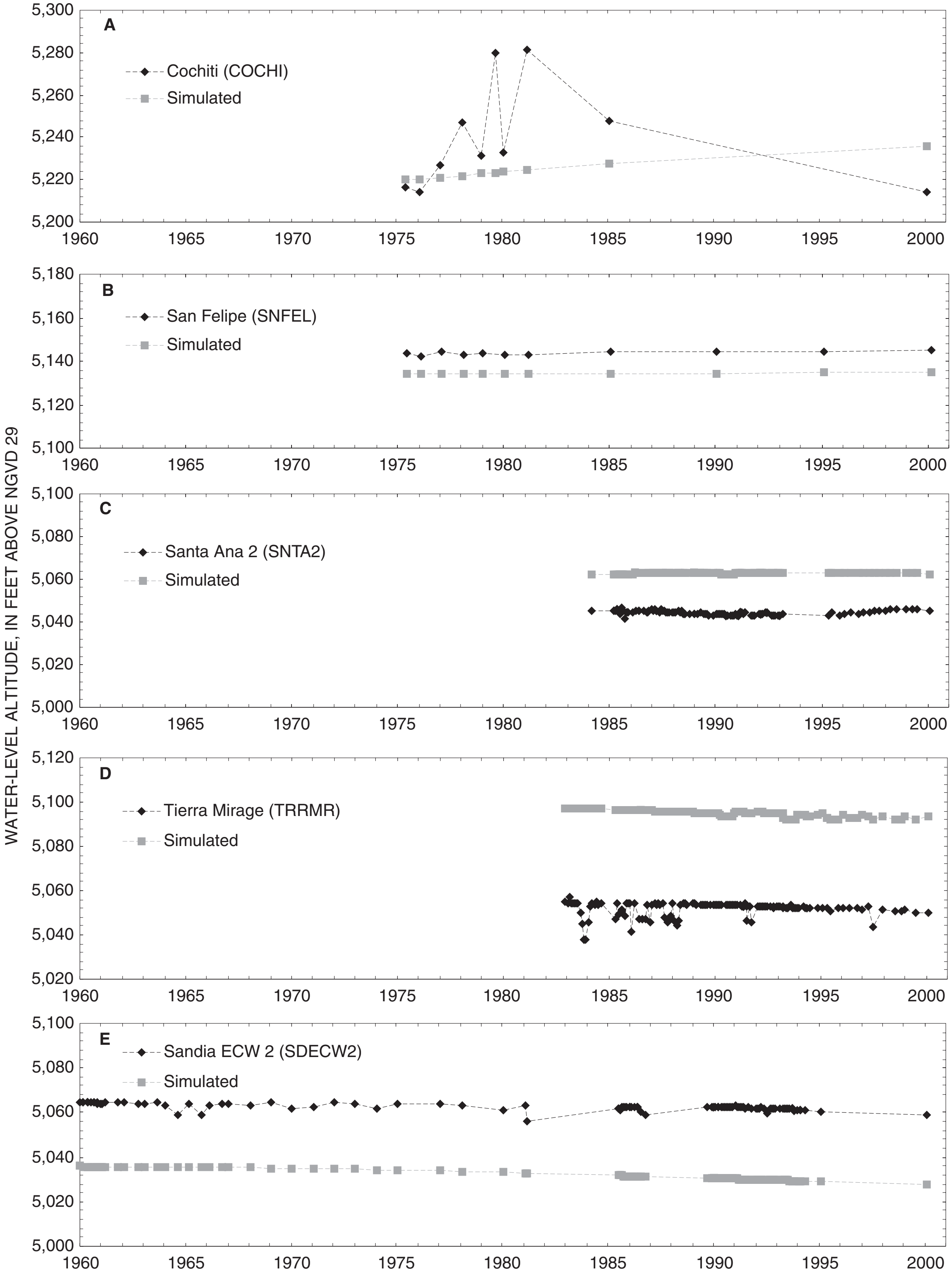


Figure 17. Measured and simulated hydraulic head for selected wells (locations shown in figure 9).

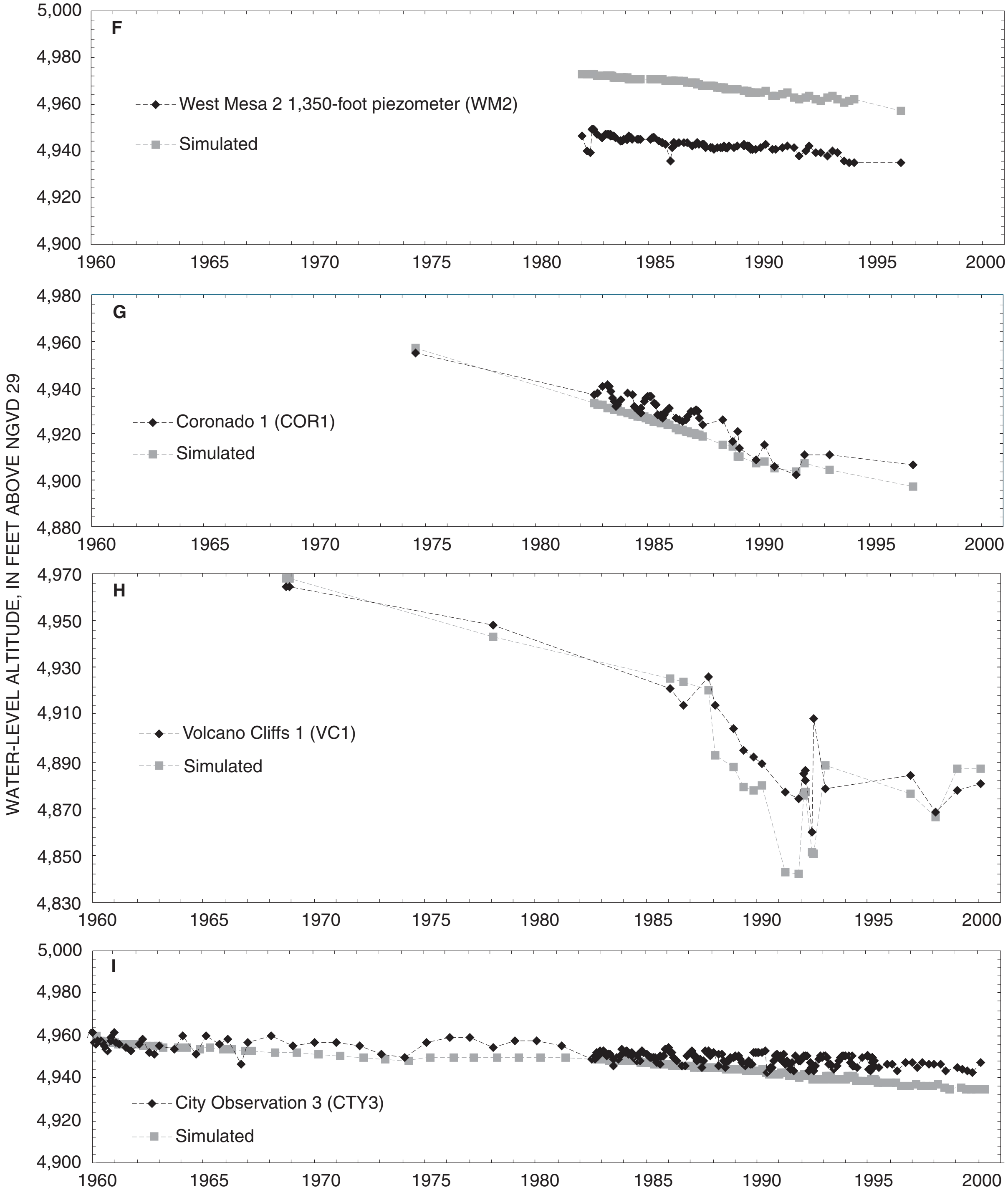


Figure 17. Measured and simulated hydraulic head for selected wells (locations shown in figure 9)--Continued.

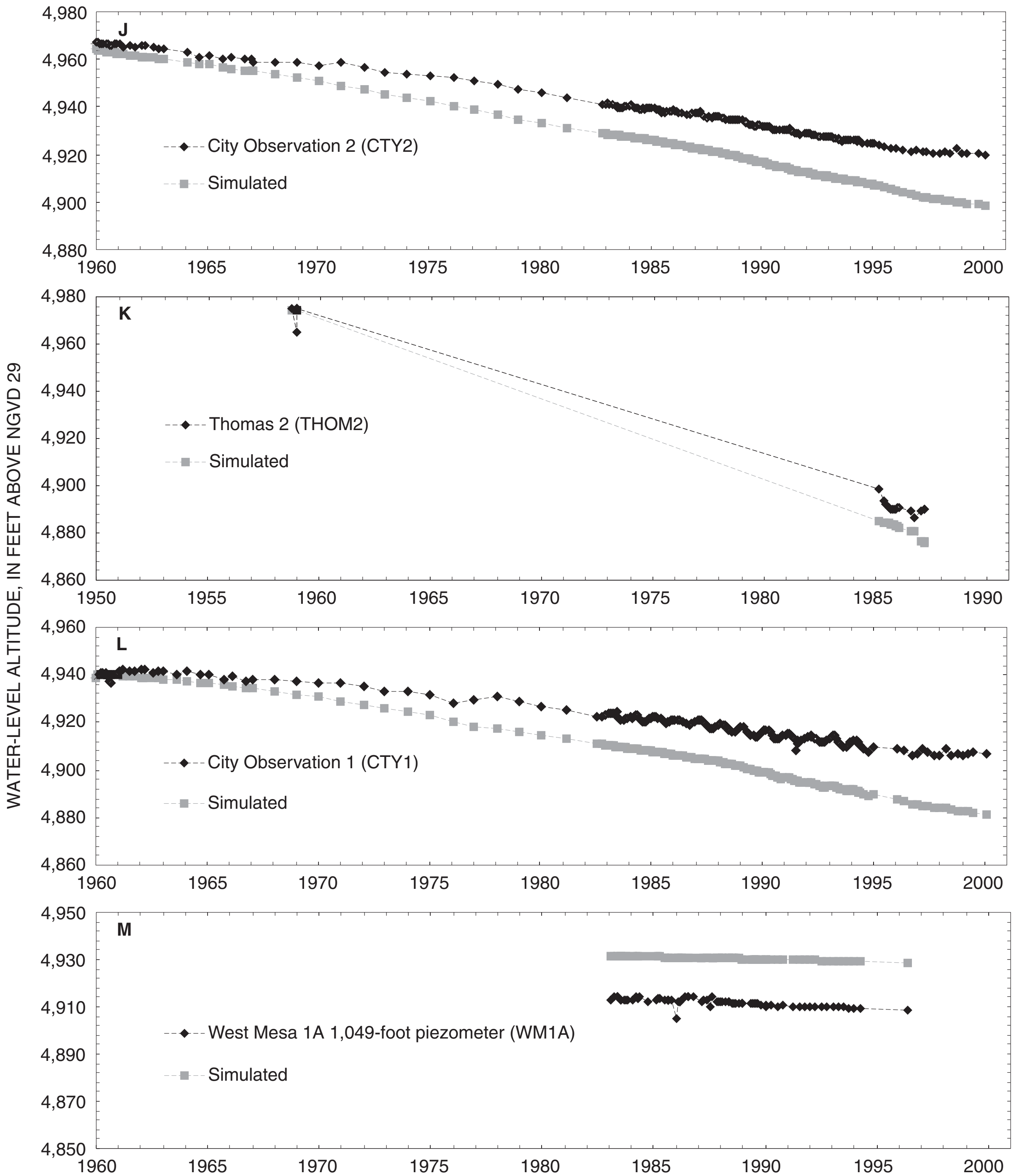


Figure 17. Measured and simulated hydraulic head for selected wells (locations shown in figure 9)--Continued.

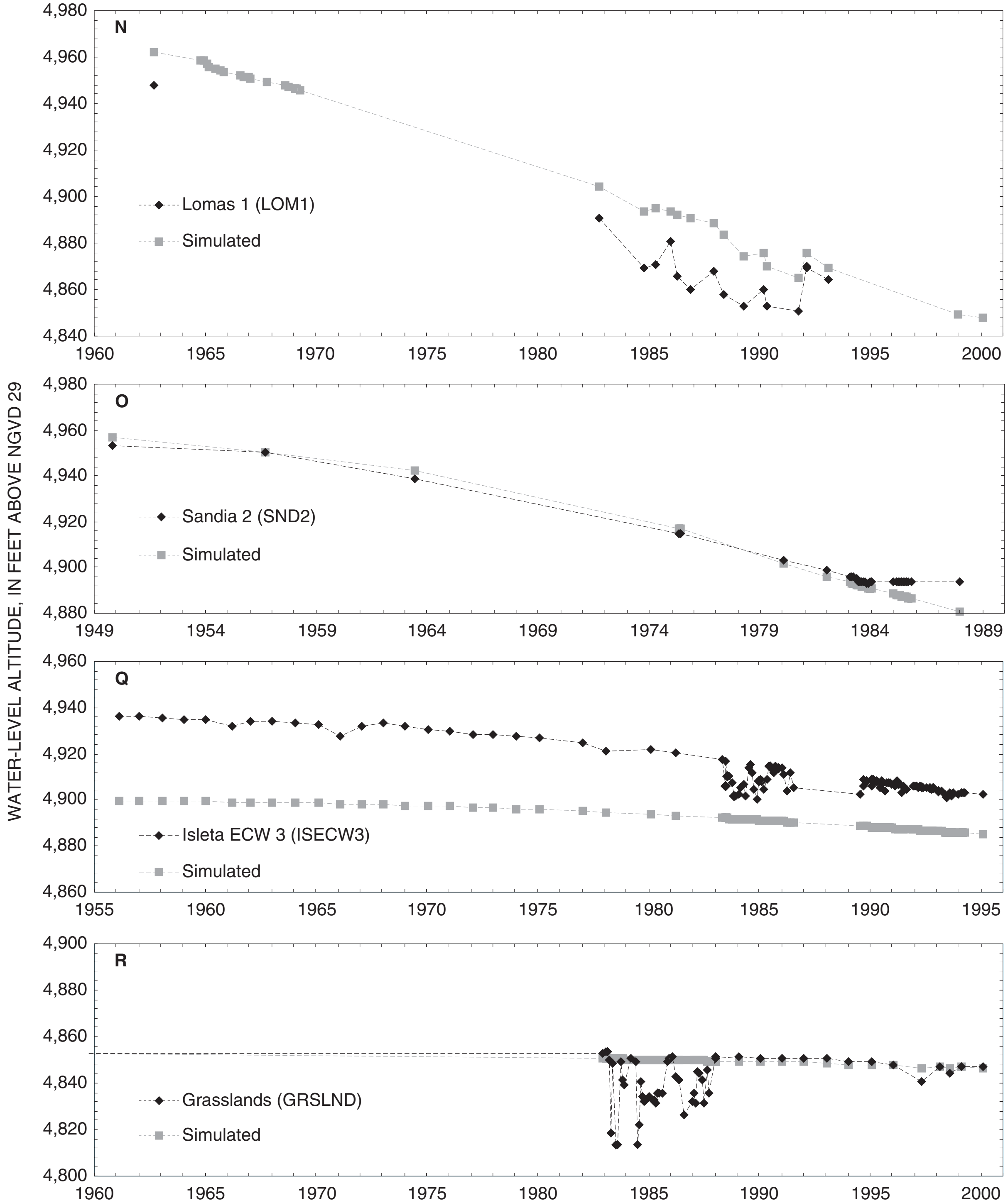


Figure 17. Measured and simulated hydraulic head for selected wells (locations shown in figure 9)--Continued.

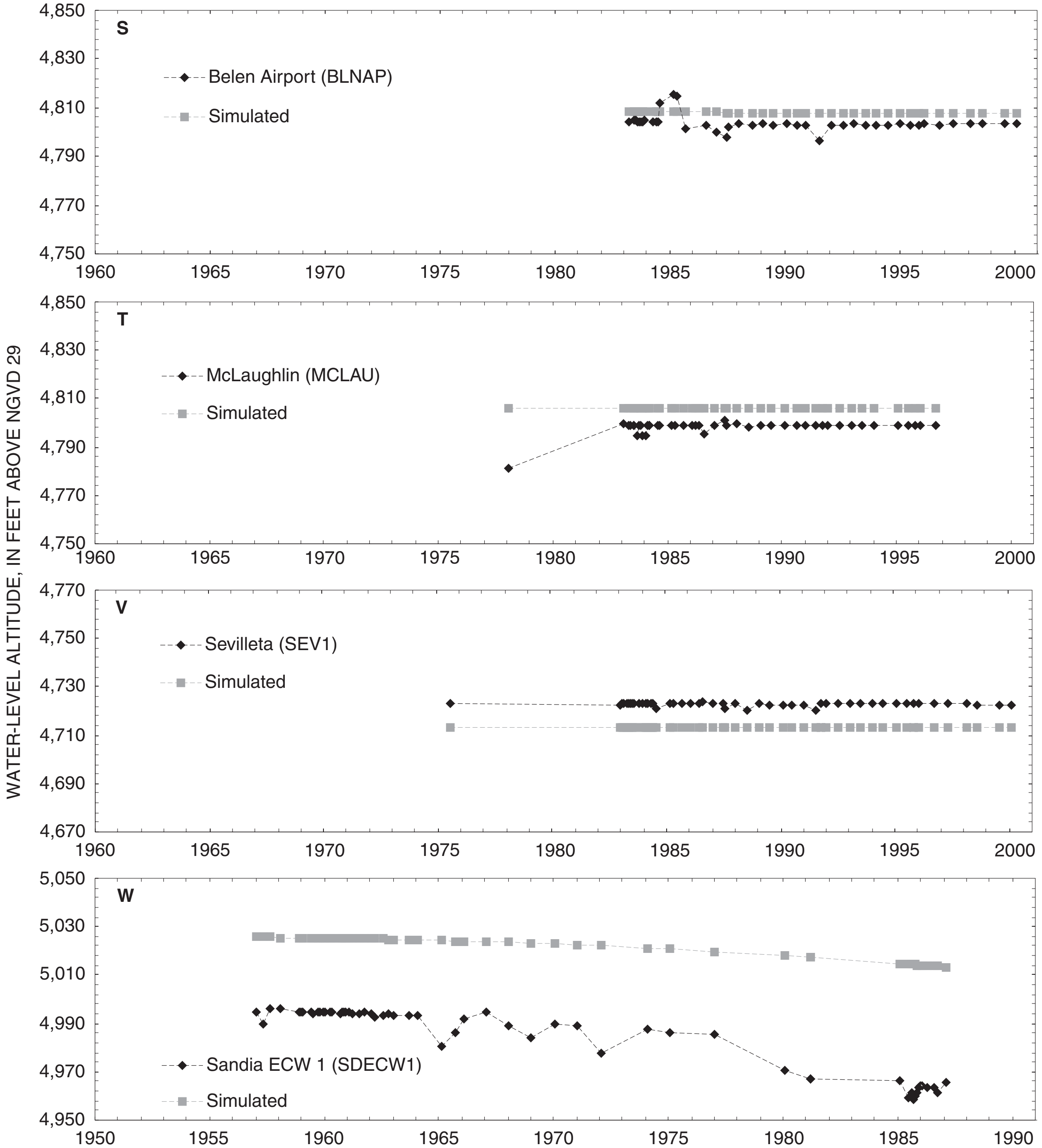
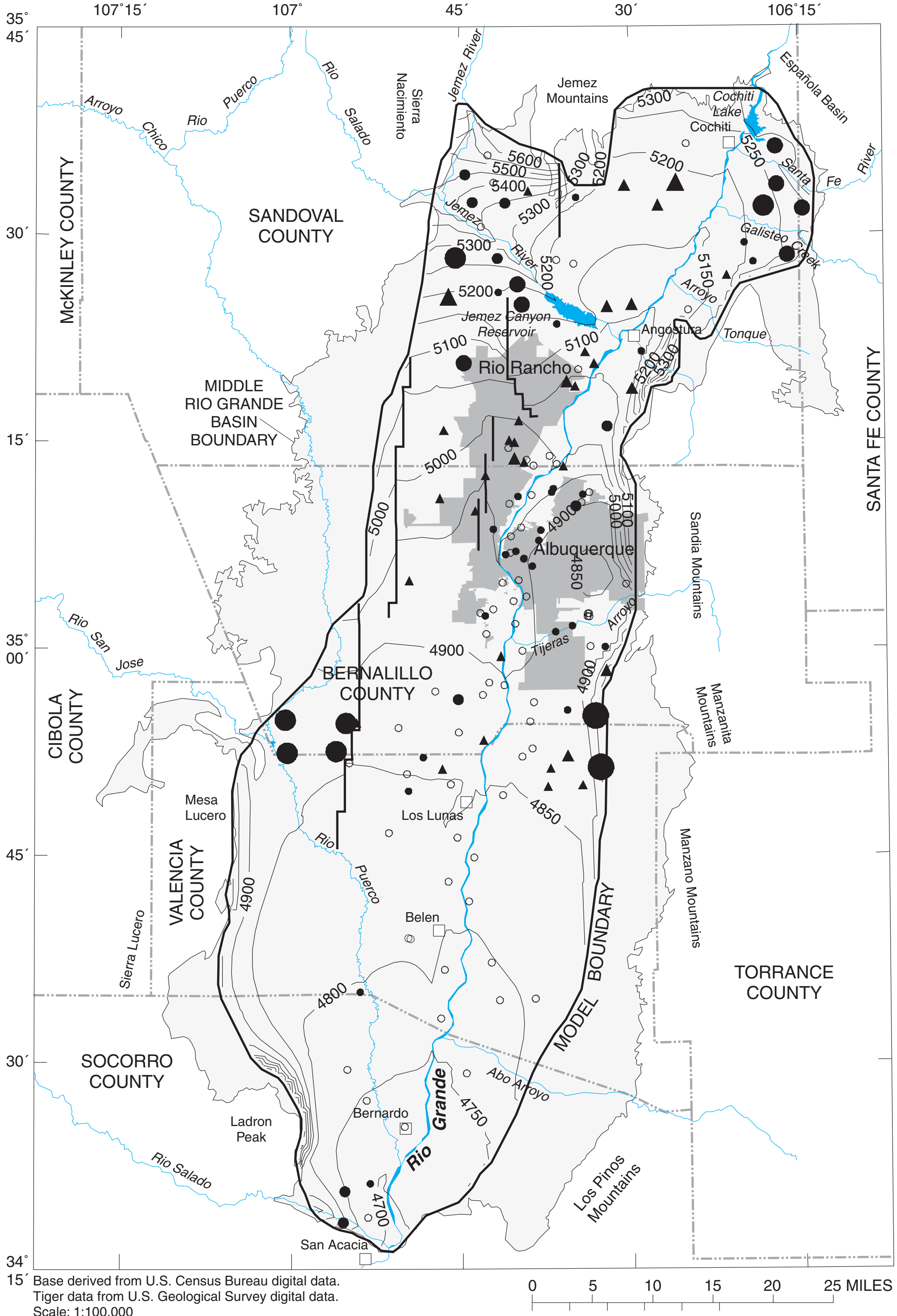


Figure 17. Measured and simulated hydraulic head for selected wells (locations shown in figure 9)--Concluded.



EXPLANATION

— 4700 — Line of equal simulated hydraulic head--Interval 50 feet. Datum NGVD 29

Simulated horizontal flow barrier

Hydraulic-head residual, in feet

-100 to -50
-50 to -30
-30 to -10
-10 to 10
10 to 30
30 to 50
50 to 100
100 to 200
Greater than 200

Figure 18. Simulated winter 1994 water table and hydraulic-head residuals (measured minus simulated heads).

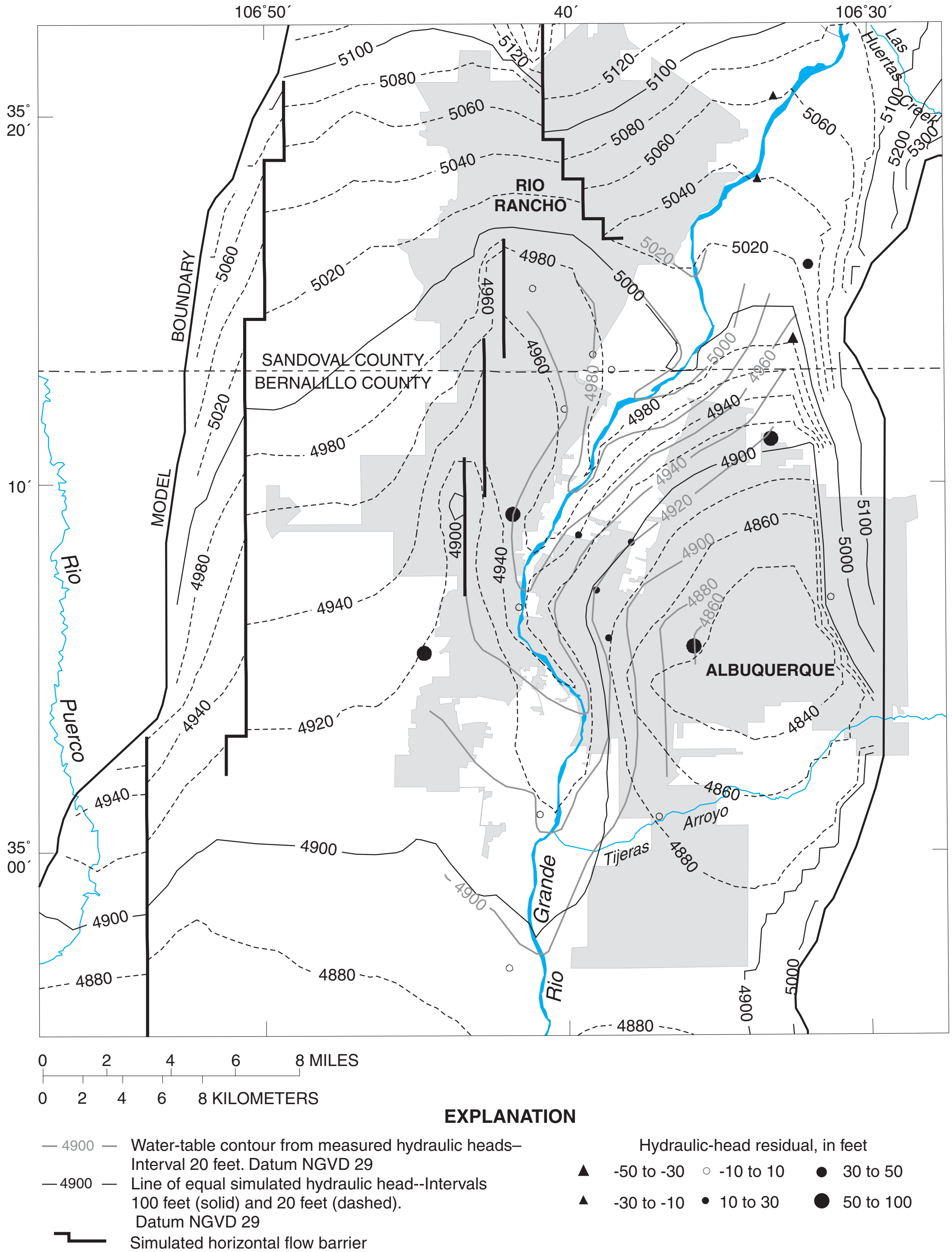
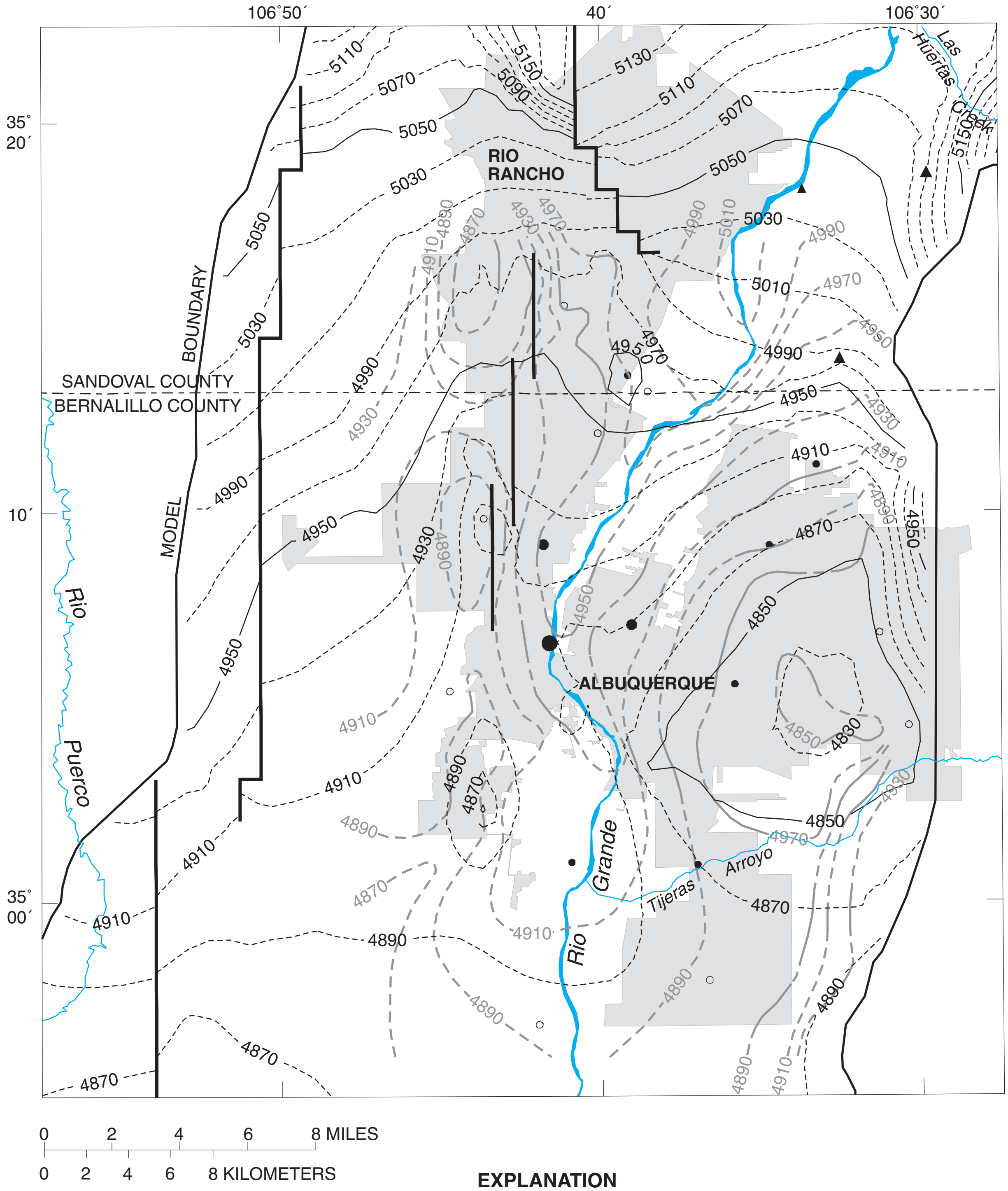


Figure 19. Simulated winter 2000 water table and hydraulic-head residuals (measured minus simulated heads).



EXPLANATION

— 4890 — Hydraulic-head contour from measured hydraulic heads--Interval 20 feet. Datum NGVD 29. Dashed where approximately located. Modified from Bexfield and Anderholm (2002)

— 4950 — Line of equal simulated hydraulic head--Intervals 100 feet (solid) and 20 feet (dashed). Datum NGVD 29

Simulated horizontal flow barrier

Hydraulic-head residual, in feet

▲ -50 to -30 ○ -10 to 10 ● 30 to 50

▲ -30 to -10 • 10 to 30 ● 50 to 100

Figure 20. Simulated winter 2000 hydraulic head in model layer 5 and hydraulic-head residuals (measured minus simulated heads).

Rancho area (fig. 20) was inferred by Bexfield and Anderholm (2002) on the basis of air-line measurements from production wells that had been shut down for a period of several hours to days. Bexfield and Anderholm (2002) indicated that these measurements are not true static levels and are likely less accurate than measurements used to construct the remainder of the contour map, but are reasonable when compared with more accurate measurements in areas adjacent to the depression. Although the uncertainty of water levels used to define the depression may explain some differences between modeled and measured contours, a primary reason for the discrepancy is likely the inability of the model to represent the water-level trough, as discussed previously (see "Predevelopment heads" section of this report). The difference in measured and simulated contours in the Rio Rancho cone of depression shown in figure 20 (averaging about 80 feet) are similar to the difference described earlier for predevelopment conditions (about 90 feet).

Vertical Hydraulic Gradients

The recent (late 1980's to 2000) availability of piezometric data for the basin (fig. 9) allows comparison of vertical hydraulic gradients simulated in the model with vertical hydraulic gradients calculated from measured piezometric heads. Table 2 shows the simulated difference in head between the top and bottom piezometer of each nest for which data of adequate quality exist. The top piezometer at most of the piezometer sites in the Albuquerque area is completed at the water table, and the bottom piezometer is completed near the base of the water-production zone in the City wells. The vertical hydraulic gradient between the two shallowest piezometers for the MATH piezometer nest (MATH2 and 3) is omitted from table 2; the anomalously high water level obtained at the MATH3 piezometer is believed to represent a perched zone rather than the regional aquifer system.

Simulated vertical gradients are generally consistent with measured gradients. Gradients that induce downward ground-water flow, toward the production zone, are prevalent throughout the area of ground-water development in the greater Albuquerque area, and the model simulates this effect very well. The magnitude of the simulated hydrologic gradients are typically on the right order, although a few (such as West Bluff; WB in table 2) seem too high. It is unlikely that the magnitude of the vertical gradients would be exactly matched at any individual site because the vertical-anisotropy ratio distribution in the aquifer is poorly understood. Because of the lack of data, this property is not highly discretized in the model and is simulated as a constant value for most units, although this property likely varies considerably throughout the system.

Rio Grande Surface-Water System

The only quantitative flow targets for this ground-water model are, as described previously, the baseflow loss between Bernalillo and Rio Bravo determined by Veenhuis (2002) using flow measurements and the seepage loss from Cochiti Reservoir estimated by a water balance.

Comparison of the simulated losses from the Rio Grande between Bernalillo and Rio Bravo Bridge (streamflow gages 08329500 and 08330150; fig. 4) is shown for the 1990-2000 seasonal stress periods in figure 21. The median measured value (84 cubic feet per second; 61,000 acre-feet per year) for 1996-2000 is shown with a range of 50 percent of measured values (the 25th- and 75th-percentile error bars). Simulated losses vary seasonally by about 15 cubic feet per second and are within the 25th- and 75th-percentile error bars.

Simulated seepage from Cochiti Lake ranges from about 30 cubic feet per second (22,000 acre-feet per year) during times of average reservoir stage to about 95 cubic feet per second (69,000 acre-feet per year) during times of high reservoir stage. The seepage during times of average stage agrees closely with the value obtained by water-budget calculations: 33 cubic feet per second (24,000 acre-feet per year). The high-stage value is considerably smaller than the maximum seepage value estimated during high-stage periods: 250 cubic feet per second (180,000 acre-feet per year). This sort of discrepancy is not unexpected; the model's time discretization is coarse enough that the highest stage events are averaged into longer stress periods with average lower stage. In addition, uncertainties in the water-budget estimates of seepage are considerable.

Water Budget

The simulated annual water budgets for the predevelopment steady-state and the 1999 (average of the two seasonal stress periods ending in March 1999 and October 1999) simulation periods are listed in table 3. The change in the model water budget throughout the simulation period is summarized in figure 22, which is based on the standard water-budget output of MODFLOW-2000. This figure combines the

Table 2. Comparison of simulated and measured vertical head differences and gradient orientations

[Model layers: model layer or layers used in calculating simulated hydraulic head; two layers listed indicates that simulated head was interpolated on the basis of location of the midpoint of the depth interval relative to the cell midpoints of the two layers. Hydraulic head is reported for the end of the simulation, March 2000, except for RBB5, which is March 1997; INTLA and INTLB, which are March 1999; and SA and ZIA, which are November 1987]

Piezometer data (listed from top to bottom interval of each piezometer nest)							Vertical head difference, in feet (positive values indicate downward gradient and negative values indicate upward gradient)			
Location		Depth interval		Hydraulic head, in feet above NGVD 29		Residual, in feet	Between piezometer interval and next lower interval		Between top and bottom piezometer intervals	
Map ID (fig. 9) and model row, column (fig. 7)	Piezometer interval ID	Feet below land surface	Model layers	Measured	Simulated	Measured minus simulated head	Measured	Simulated	Measured	Simulated
RBB5 72, 40	RBB5-S	7-17	2	4,925.0	4,922.0	3.0	2	3	8	18
	RBB5-M	135-145	2, 3	4,922.7	4,919.3	3.4	5	16		
	RBB5-D	500-510	4, 5	4,917.5	4,903.6	13.9				
SC 58, 49	SC2	789-794	4, 5	4,889.9	4,871.0	18.9	-2	0	-2	0
	SC1	1,298-1,303	5, 6	4,891.9	4,870.8	21.1				
DS 65, 47	DS3	315-415	3	4,860.0	4,842.2	17.8	-4	0	-15	-7
	DS2	832-837	5	4,864.4	4,842.1	22.3	-10	-7		
	DS1	1,557-1,562	6, 7	4,874.5	4,848.9	25.6				
HR 53, 41	HR3	148-228	2, 3	4,958.5	4,962.4	-3.8	2	1	18	32
	HR6	238-258	3	4,956.6	4,961.4	-4.8	1	1		
	HR5	295-300	3, 4	4,955.7	4,960.4	-4.7	4	1		
	HR4	349-354	3, 4	4,952.0	4,959.2	-7.2	8	14		
	HR2	845-850	5, 6	4,944.1	4,944.7	-0.6	3	15		
	HR1	1,508-1,513	6, 7	4,940.8	4,930.0	10.8				
WB 63, 38	WB6	143-163	1	4,950.4	4,949.5	0.9	1	7	14	61
	WB5	244-249	2, 3	4,949.5	4,942.6	6.9	0	10		
	WB4	318-323	3, 4	4,949.5	4,932.6	16.9	1	22		
	WB3	422-427	4	4,948.9	4,910.8	38.0	12	14		
	WB2	679-684	4, 5	4,937.2	4,896.3	40.9	1	8		
	WB1	1,085-1,090	5, 6	4,936.0	4,888.4	47.6				
GAR 62, 42	GAR3	43-83	3	4,919.1	4,896.3	22.8	2	7	3	9
	GAR2	552-572	4, 5	4,917.2	4,889.7	27.5	1	3		
	GAR1	995-1,010	5, 6	4,916.6	4,886.9	29.7				
NES 65, 33	NES4	388-433	2	4,927.7	4,917.8	9.9	24	8	30	20
	NES3	739-744	4, 5	4,904.1	4,910.2	-6.2	8	8		
	NES2	1,102-1,107	5, 6	4,896.1	4,902.7	-6.6	-1	5		
	NES1	1,534-1,539	6	4,897.4	4,897.8	-0.4				
NE 55, 51	NE3	538-598	3	4,916.6	4,908.3	8.3	-2	7	-4	14
	NE2	1,183-1,188	5, 6	4,918.8	4,901.1	17.7	-2	6		
	NE1	1,515-1,520	6	4,920.9	4,894.8	26.1				
SV 58, 38	SV3	140-200	2	4,960.2	4,946.3	13.9	4	28	30	36
	SV2	918-923	5, 6	4,956.4	4,918.2	38.2	26	8		
	SV1	1,634-1,639	6, 7	4,930.4	4,910.3	20.1				
MONT 74, 45	MONT3	260-320	3	4,885.9	4,876.8	9.1	2	6	0	6
	MONT2	698-703	4, 5	4,884.3	4,871.1	13.2	-2	1		
	MONT1	1,618-1,623	6, 7	4,886.2	4,870.3	15.9				

Table 2. Comparison of simulated and measured vertical head differences and gradient orientations -- Concluded

Piezometer data (listed from top to bottom interval of each piezometer nest)							Vertical head difference, in feet (positive values indicate downward gradient and negative values indicate upward gradient)			
Location		Depth interval		Hydraulic head, in feet above NGVD 29		Residual, in feet	Between piezometer interval and next lower interval		Between top and bottom piezometer intervals	
Map ID (fig. 9) and model row, column (fig. 7)	Piezometer interval ID	Feet below land surface	Model layers	Measured	Simulated	Measured minus simulated head	Measured	Simulated	Measured	Simulated
MDS	MDS2	990-1,010	5	4,878.0	4,882.2	-4.2	-13	4	-13	4
79, 46	MDS1	1,580-1,620	6, 7	4,890.6	4,878.0	12.6				
MATH	MATH3	600-700	not used	4,994.4	Dry					
63, 54	MATH2	1,020-1,040	4, 5	4,857.7	4,866.8	-9.1	-2	21	-2	21
	MATH1	1,460-1,500	5, 6	4,860.2	4,845.9	14.3				
	ISL4	10-40	1, 2	4,893.7	4,887.9	5.8	1	0		
ISL	ISL3	175-180	3, 4	4,893.1	4,888.0	5.1	1	5	10	8
81, 38	ISL2	805-810	5, 6	4,892.1	4,883.0	9.1	9	3		
	ISL1	1,330-1,335	6, 7	4,883.5	4,879.7	3.8				
LINC	LINC3	490-590	2, 3	4,961.4	4,968.2	-6.8	6	3		
47, 39	LINC2	810-830	4, 5	4,955.1	4,964.9	-9.8	0	6	7	9
	LINC1	1,200-1,240	5, 6	4,954.7	4,958.9	-4.2				
SP	SP3	485-525	2, 3	4,949.6	4,982.7	-33.1	7	4		
49, 52	SP2	1,015-1,020	5	4,943.0	4,978.3	-35.3	0	0	7	5
	SP1	1,295-1,300	5, 6	4,942.7	4,977.9	-35.2				
TOME	TOME3	225-265	2	4,826.7	4,833.9	-7.2	1	0		
104, 41	TOME2	695-705	4, 5	4,825.9	4,834.0	-8.1	0	-1	1	-1
	TOME1	1,185-1,195	5, 6	4,825.5	4,834.6	-9.2				
NL	NL2	675-685	4, 5	4,793.4	4,799.9	-6.5	0	-1	0	-1
116, 36	NL1	1,166-1,176	5, 6	4,793.2	4,801.1	-7.9				
RBP	RBP2	200-205	3, 4	4,922.6	4,914.8	7.8	4	14	4	14
74, 39	RBP1	585-590	5	4,918.6	4,901.2	17.4				
BERN	BERN2	300-310	4	5,014.4	5,038.8	-24.4	6	0	6	0
41, 50	BERN1	1,175-1,185	6, 7	5,008.6	5,039.1	-30.5				
	INTLA1	220-240	2	4,984.1	4,976.5	7.6	10	0		
	INTLA2	275-295	2, 3	4,974.1	4,976.1	-2.0	9	3		
INTLA	INTLA3	390-430	3, 4	4,964.8	4,973.6	-8.8	18	15	47	56
50, 42	INTLA4	610-660	4, 5	4,946.8	4,958.1	-11.3	7	25		
	INTLA5	925-1,000	5, 6	4,939.3	4,933.4	5.9	3	13		
	INTLA6	1,600-1,700	6, 7	4,936.7	4,920.2	16.5				
INTLB	INTLB1	30-50	1, 2	4,989.0	4,983.7	5.3	19	4		
51, 43	INTLB2	190-230	3, 4	4,969.7	4,979.7	-10.0	23	29	42	33
	INTLB3	710-790	5, 6	4,947.0	4,950.4	-3.4				
SA	SATOP	190-210	3	5,291.2	5,243.7	47.5	-14	14		
25, 41	SAMID	472-492	4, 5	5,305.1	5,229.8	75.3	-11	11	-25	25
	SADEEP	730-750	4, 5	5,316.6	5,219.1	97.5				
ZIA	ZIATOP	280-300	3, 4	5,377.5	5,332.8	44.7	-4	13		
20, 35	ZIAMID	486-506	4, 5	5,382.0	5,319.9	62.1	-1	9	-5	22
	ZIADEEP	750-770	4, 5	5,382.6	5,310.5	72.1				

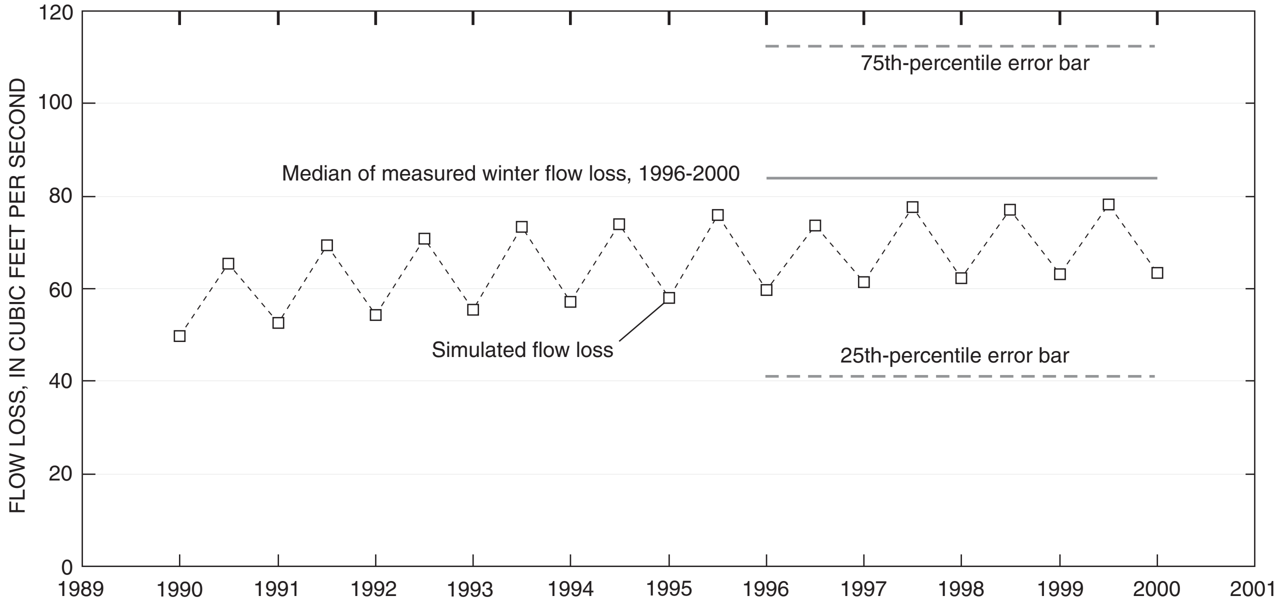


Figure 21. Comparison of simulated and measured Rio Grande and riverside-drain flow loss between Bernalillo and Rio Bravo Bridge (gaging stations 08329500 and 08330150).

main stem of the Rio Grande, Jemez River, and riverside drains. Individual reaches of the Rio Grande and Jemez River also were examined separately using the observation package of MODFLOW-2000; the response of the riverside drains was separated out from that of the Rio Grande main stem by the same method.

During predevelopment (steady-state simulation) before any drains or canals are simulated, the Rio Grande is simulated to have a net loss of about 63,000 acre-feet per year. Simulated predevelopment loss rates are largest in the central reaches, averaging about 1 cubic foot per second (about 724 acre-feet per year) per mile between Bernalillo and Bernardo.

The water budget of the Rio Grande surface-water system changes dramatically through the historical simulation as surface-water irrigation begins and riverside and interior drains are added to the model structure (fig. 22). Once drains and canals are installed (simplified in the model to occur in 1930), the model simulates the Rio Grande main stem as losing about 316,000 acre-feet per year, whereas the riverside drains gain 208,000 acre-feet per year (for 1999; table 3). Thus, the main stem of the Rio Grande and the riverside drains set up a short circuit, in which losses from one appear in the other. The interior drains are simulated to gain volumes of water ranging from 70,000 to 150,000 acre-feet per year over the historical period (fig. 22). Many of these interior-drain gains are actually recapture of part of the 90,000 to 130,000 acre-feet per year of canal and crop-irrigation seepage (the difference between net recharge before and after 1930, fig. 22). For the 1970’s and 1980’s, some increases in surface-water losses to the aquifer system associated with Cochiti Lake are shown in figure 22. Also, the effects of ground-water development on the surface-water system probably influence the trends of net drain and river losses.

The upper reach of the Rio Grande main stem, below Cochiti and above Bernalillo, is simulated to lose water throughout the 100-year simulation. Once riverside drains came on line, their gains exceeded main-stem seepage losses, and the gains of the interior

Table 3. Simulated annual water budgets for the Middle Rio Grande Basin ground-water model, steady state and year ending October 1999

[All values are in acre-feet per year]

Mechanism	Steady state		Year ending October 1999	
	Inflow (to aquifer)	**Outflow (from aquifer)**	**Inflow (to aquifer)**	**Outflow (from aquifer)**
Mountain-front recharge	12,000	0	12,000	0
Tributary recharge	9,000	0	9,000	0
Subsurface recharge	31,000	0	31,000	0
Canal seepage	0	0	90,000	0
Crop-irrigation seepage	0	0	35,000	0
Rio Grande and Cochiti Lake	63,000	0	316,000	0
Riverside drains	0	0	0	208,000
Interior drains	0	0	0	133,000
Jemez River and Jemez Canyon Reservoir	15,000	0	17,000	0
Ground-water withdrawal	0	0	0	150,000
Septic-field seepage	0	0	4,000	0
Riparian evapotranspiration	0	129,000	0	84,000
Subtotal	**130,000**	**129,000**	**514,000**	**575,000**
Inflow from or outflow to aquifer storage	**0**	**0**	**60,000**	**0**
Total	**130,000**	**129,000**	**574,000**	**575,000**
Error (inflow minus outflow)	**1,000**		**-1,000**	

drains make the net gains of this reach greater still. Some of this gain represents recapture of irrigation water diverted from the Rio Grande, and some represents the reappearance of seepage from Cochiti Lake.

The middle reach of the main stem of the Rio Grande between Bernalillo and Rio Bravo Bridge (gaging stations 08329500 and 08330150, fig. 4) is simulated to lose water throughout the 100-year simulation, only part of which reappears in the riverside drains. Interior drains originally gained quite a bit of water, offsetting, at first, the net losses of the main stem and riverside drains. However, interior-drain flows in this reach decreased considerably after 1950, probably in response to declining water levels associated with ground-water development in the Albuquerque area.

The lower reach of the main stem of the Rio Grande (below gaging station 08330150) is simulated to lose water throughout the 100-year simulation. Once riverside drains come on line, part of this water reappears in the riverside drains. This is consistent with the seepage-study findings described previously in this report. Interior drains are simulated as gaining sufficient water, however, that the simulated Rio Grande and drain system as a whole (main stem, riverside drains, interior drains) gain water.

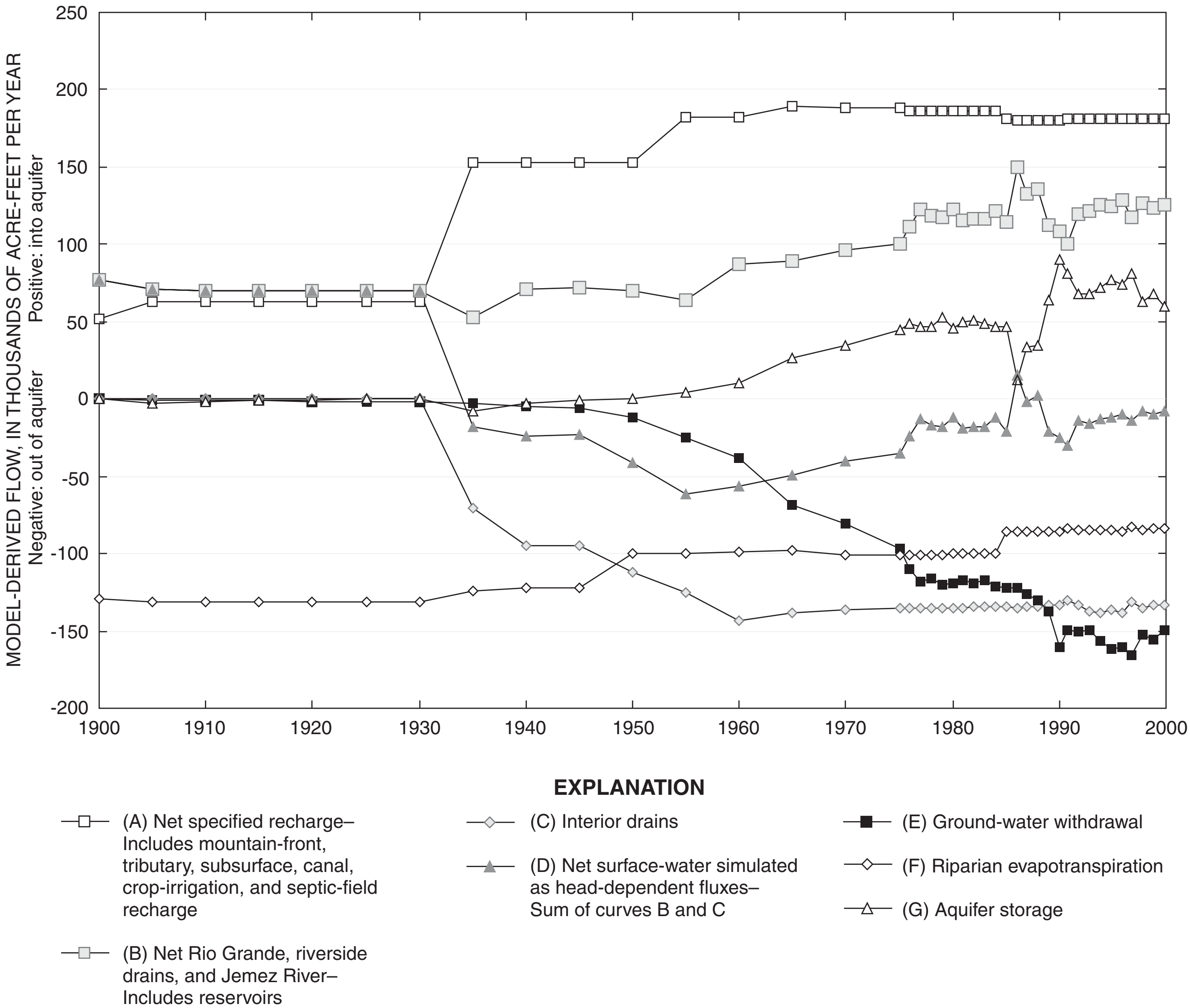


Figure 22. Selected water-budget elements from the historical model simulation. Seasonally varying data after 1990 have been averaged.

The Jemez River is simulated to gain water in its upper reach (above its confluence with the northern Rio Salado) and to lose water in its reaches below the Rio Salado confluence. Gains in the upper reach generally are consistent with measurements and seepage work by Craigg (1992). Simulated loss in the reach below the confluence is not entirely consistent with Craigg's (1992) seepage data, which indicates that the reach of the Jemez River between Zia and Santa Ana Pueblos gains water in the winter and loses water (presumably to evapotranspiration) in the summer. The model does predict a decrease in loss in this reach in winter, but no actual gain. The inability of the model to simulate this gain may be related to the simulated heads near the Jemez River that are still too low, and there may be considerable subsurface geologic structure not represented in this model. The reach of the Jemez River below Santa Ana Pueblo is simulated to lose water, and once Jemez Canyon Reservoir is added to the model in the lower reach of the Jemez River, the reservoir loses water as well (from 4,000 acre-feet per year in years of low stage to 11,000 acre-feet per year in years of high stage). This finding is consistent with the understanding of that reach from seepage and water-budget considerations (Craigg, 1992).

Phreatophyte consumption of ground water by evapotranspiration is the main simulated discharge of the model during predevelopment time. This discharge is simulated to be about 129,000 acre-feet per year in steady state (table 3). The model simulates a decrease in phreatophyte consumption over time to about 84,000 acre-feet per year in 1999, largely in response to a decrease in area covered by native riparian vegetation and wetlands and a lowering of the water table in some areas. These values are consistent with available estimates of phreatophyte consumption (Bureau of Reclamation, 1997d), but such estimates are very poorly constrained.

MODEL SENSITIVITY

Model sensitivity to changes in simulated hydrologic properties was tested using changes in the sum of squared weighted residuals for the entire simulation period. This approach combines head and flow residuals (see previous "Calibration targets" section). The weights applied to the residuals reflect the relative reliability of the measurements and were applied as the inverse of the estimated variance in the measurements (see discussions in Hill, 1998, p. 45; and Hill and others, 2000). In addition to giving larger weights to more reliable measurements, this method of applying weights accounts for the different units of measurement between head and flow measurements. The measurements and weights were applied using the Observation Process for MODFLOW-2000 (Hill and others, 2000). Although the Sensitivity Process was used successfully for calculating sensitivities (Hill and others, 2000) for some parameters representing hydrologic properties, the solutions to the sensitivity equations did not converge for several properties. This nonconvergence is likely the consequence of model nonlinearity, which results as water levels in unconfined cells decline, cells become dry, and cells in lower layers convert from confined to unconfined conditions. Therefore, the sensitivity analysis was done by manually modifying one hydrologic property while the others were held at the calibrated value and comparing the resulting changes in the sum of squared weighted residuals. The two graphs in figure 23 show the sensitivity of the model to changes in simulated hydrologic properties. Two graphs rather than one are used for improved readability. Overall the model is most sensitive to the aquifer property of hydraulic conductivity.

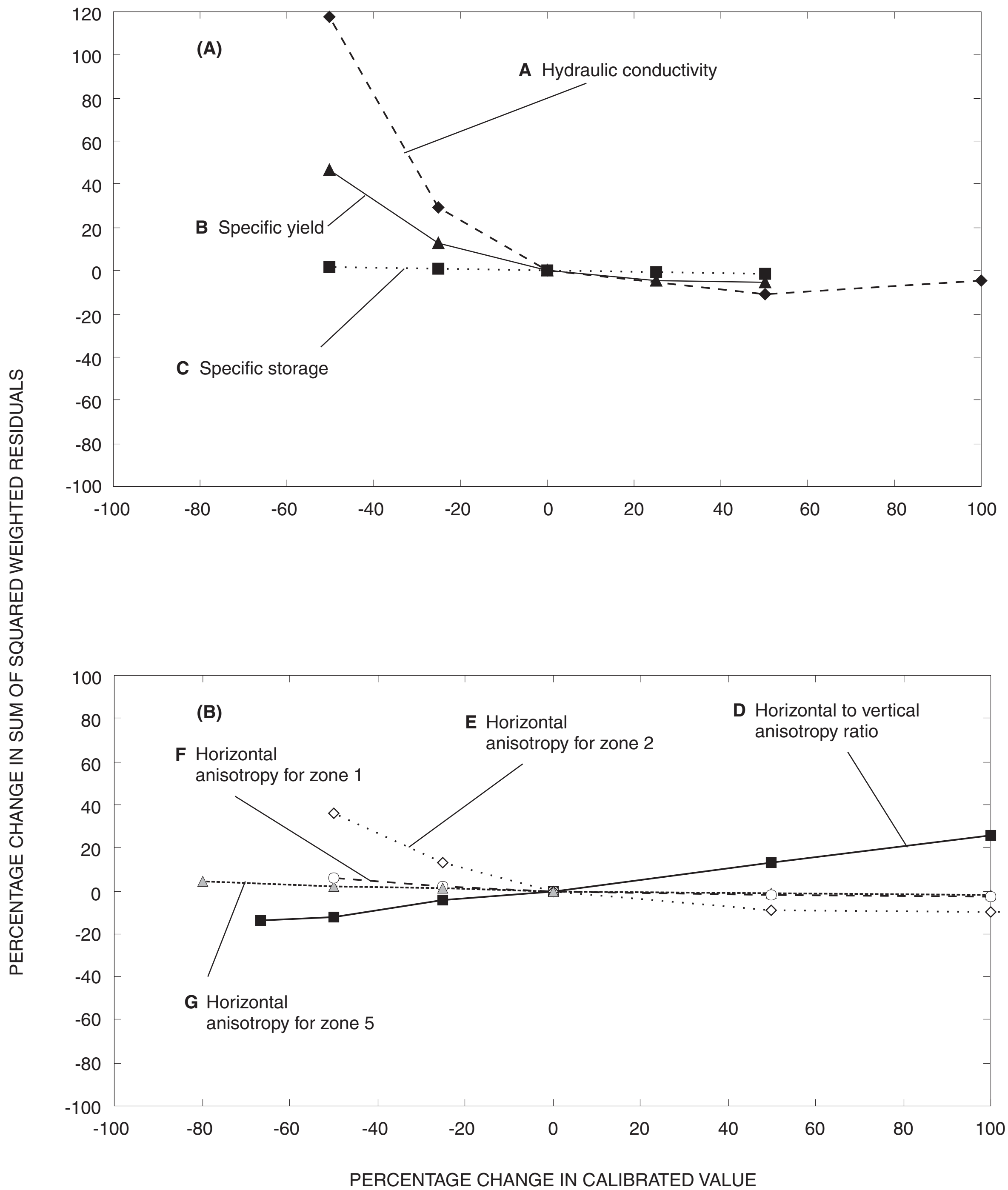
As illustrated by several curves in figure 23, sensitivity of the sum of squared weighted residuals to changes in the simulated properties is dependent on the value of the property. The model is most sensitive to lower than calibrated values of hydraulic conductivity, specific yield, and horizontal anisotropy for zone 2 but is relatively insensitive for greater than calibrated values of these properties (fig. 23A and B, curves A, B, and F). The calibrated values of these properties are very near the point on the curves at which a slope significantly changes, indicating a change from sensitive to relatively insensitive. Changing the values of these aquifer properties further to gain small improvements in the sum of squared weighted residuals was not attempted.

The model is fairly sensitive to the horizontal to vertical anisotropy ratio (fig. 23B, curve D). Although the sum of squared weighted residuals could be improved by decreasing the horizontal to vertical anisotropy ratio to below the calibrated value, the authors chose to maintain this aquifer property within the reasonable range of values (between 80:1 and 1,000:1; see "Aquifer properties" section). The decrease in the sum of squared weighted residuals resulting from lowering this property further could be compensating for unknown errors in other parts of the model; therefore, the calibrated value was not lowered further. The calculated value was left at 150:1.

The remaining sensitivity curves (C, F, and G) in figure 23 show relative model insensitivity to changes in specific storage and to horizontal anisotropy for zones 1 and 5. Specific yield is a sensitive property probably because it is a larger component of aquifer storage than specific storage is. The sum of squared weighted residuals is more sensitive to horizontal anisotropy for zone 2 than for zones 1 or 5 because there are fewer measurements in zones 1 and 5.

SUMMARY AND CONCLUSIONS

The Middle Rio Grande Basin between Cochiti and San Acacia, also called the Albuquerque Basin, has been the focus of investigations by the USGS and other agencies to improve the understanding of the hydrology, geology, and land-surface characteristics in the basin. The Santa Fe Group aquifer system in the Middle Rio Grande Basin consists of a thick sequence (as much as 14,000 feet) of Santa Fe Group and post-Santa Fe Group sediments. Population growth in the basin has increased dramatically since the 1940's.



[Horizontal-anisotropy zone numbers correspond with the values shown in figure 13]

Figure 23. Sensitivity of weighted residuals to changes in simulated aquifer properties.

These population increases have caused dramatic increases in ground-water withdrawals from the aquifer system, resulting in large ground-water-level declines. Because the Rio Grande is hydraulically connected to the aquifer system, these ground-water withdrawals have also decreased flow in the Rio Grande.

This report describes a ground-water-flow model of the Middle Rio Grande Basin developed (1) to integrate the components of the ground-water-flow system, including the hydrologic interaction between the surface-water systems in the basin, to better understand the geohydrology of the basin and (2) to provide a tool to help water managers plan for and administer the use of basin water resources. The three-dimensional, finite-difference, ground-water-flow model of the Santa Fe Group aquifer system within the Middle Rio Grande Basin was developed using MODFLOW-2000. The aquifer system is represented by nine model layers extending from the water table to the pre-Santa Fe Group basement rocks, as much as 9,000 feet below NGVD 29. The layers are divided into cells by a uniform grid containing 156 rows and 80 columns, each spaced 3,281 feet (1 kilometer) apart. The model simulates predevelopment steady-state conditions and historical transient conditions from January 1900 to March 2000 in 1 steady-state and 52 historical stress periods. Average annual conditions are simulated prior to 1990, and seasonal (winter and irrigation season) conditions are simulated from 1990 to March 2000. The model simulates mountain-front, tributary, and subsurface recharge; canal, irrigation, and septic-field seepage; and ground-water withdrawal as specified-flow boundaries. The model simulates the Rio Grande, riverside drains, Jemez River, Jemez Canyon Reservoir, Cochiti Lake, riparian evapotranspiration, and interior drains as head-dependent flow boundaries.

Hydrologic properties representing the Santa Fe Group aquifer system in the ground-water-flow model are horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield. Variable horizontal anisotropy is applied to the model to simulate the effect of numerous south-trending faults in the basin so that hydraulic conductivity along columns (north-south) is greater than hydraulic conductivity along rows (east-west) over much of the model. Resulting horizontal hydraulic conductivities range from 0.05 to 60 feet per day. Vertical anisotropy simulates the effect of sedimentary bedding that includes sublayers of low-permeability sediments. Vertical anisotropy is specified in the model as a horizontal to vertical anisotropy ratio (calculated to be 150:1 in the model) multiplied by the horizontal hydraulic conductivity along rows. Specific storage was estimated to be 2×10^{-6} per foot in the model. Specific yield was estimated to be 0.2 (dimensionless).

Model sensitivity to changes in simulated hydrologic properties was tested using changes in the sum of squared weighted residuals for the entire simulation period. The ground-water-flow model is most sensitive to lower than calibrated values of hydraulic conductivity, specific yield, and horizontal anisotropy for part of the modeled area (zone 2) but is relatively insensitive for greater than calibrated values of these properties. The model is fairly sensitive to the horizontal to vertical anisotropy ratio. The model is relatively insensitive to changes in specific storage and horizontal anisotropy for zones 1 and 5.

The net annual water budget simulated by the model for 1999, calculated as the time-weighted average of the two seasonal stress periods ending in March 1999 and October 1999, is listed below (positive numbers are inflow (sources of water) to the aquifer and negative numbers are outflow (discharges of water) from the aquifer).

Mountain-front recharge:	12,000 acre-feet
Tributary recharge:	9,000 acre-feet
Subsurface recharge:	31,000 acre-feet
Canal seepage:	90,000 acre-feet
Crop-irrigation seepage:	35,000 acre-feet
Rio Grande and Cochiti Lake:	316,000 acre-feet
Riverside drains:	-208,000 acre-feet
Interior drains:	-133,000 acre-feet
Jemez River and Jemez Canyon Reservoir:	17,000 acre-feet
Ground-water withdrawal:	-150,000 acre-feet
Septic-field seepage:	4,000 acre-feet
Riparian evapotranspiration:	-84,000 acre-feet
Aquifer storage:	60,000 acre-feet

A ground-water-flow model is a tool that can integrate the complex interactions of hydrologic boundary conditions, aquifer materials, aquifer stresses, and aquifer-system response. It can help in the understanding of these complexities and be used to estimate the effects of particular stresses on the aquifer and river system. The ground-water-flow model described in this report provides a reasonable representation of the geohydrologic processes of the basin and simulates many historically measured trends in flow and water levels. By simulating these complex interactions, this ground-water-flow model can provide a tool to help water managers plan for and administer the use of basin water resources. However, a solution using the ground-water-flow modeling technique is not unique because any number of reasonable variations in the representation of the aquifer system used in the model may produce equally acceptable results. Uncertainties in our knowledge of the ground-water system remain. Some of these uncertainties are reflected in the range of values that have been estimated for various components of the aquifer-system water budget and in the plausible ranges of hydrologic characteristics estimated for various physical components of the aquifer system. These sources of uncertainty need to be considered when applying this model to any specific problem.

The ground-water-flow model described in this report is a culmination of the 6-year effort by the USGS and other agencies (including the New Mexico Bureau of Geology and Mineral Resources, the New Mexico Office of the State Engineer, the City of Albuquerque, and the University of New Mexico) to improve the understanding of the hydrology, geology, and land-surface characteristics of the Middle Rio Grande Basin. Although more remains to be learned about the basin, this effort has resulted in an improved understanding of the aquifer system. This increased understanding has been incorporated into this ground-water-flow model.

REFERENCES

Action Committee of the Middle Rio Grande Water Assembly, 1999, Middle Rio Grande water budget, averages for 1972-1997: Middle Rio Grande Water Assembly pamphlet, 10 p.

Anderholm, S.K., 2001, Mountain-front recharge along the eastern side of the Middle Rio Grande Basin, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00-4010, 36 p.

Banta, E.R., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model —Documentation of packages for simulating evapotranspiration with a segmented function (ETS1) and drains with return flow (DRT1): U.S. Geological Survey Open-File Report 00-466, 127 p.

Barroll, Peggy, 2001, Documentation of the administrative groundwater model for the Middle Rio Grande Basin: New Mexico Office of the State Engineer, Technical Services Unit, Hydrology Bureau Report 99-3, variously paged.

Bartolino, J.R., ed., 1997, U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the First Annual Workshop, Denver, Colorado, November 12-14, 1996: U.S. Geological Survey Open-File Report 97-116, 91 p.

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.

Bexfield, L.M., and Anderholm, S.K., 2000, Predevelopment water-level map of the Santa Fe Group aquifer system in the Middle Rio Grande Basin between Cochiti Lake and San Acacia, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00-4249, 1 sheet.

———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 sheet.

Bjorklund, L.J., and Maxwell, B.W., 1961, Availability of ground water in the Albuquerque area, Bernalillo and Sandoval Counties, New Mexico: New Mexico State Engineer Technical Report 21, 117 p.

Blanchard, P.J., 1993, Ground-water-level fluctuations in the Cochiti Dam—Peña Blanca area, Sandoval County, New Mexico, 1976-89: U.S. Geological Survey Water-Resources Investigations Report 92-4193, 72 p.

Bureau of Reclamation, 1973a, Evapotranspirometer studies of salt cedar near Bernardo, New Mexico: Albuquerque Development Office, 30 p.

———1973b, Progress report—Phreatophyte investigations—Bernardo evapotranspirometers: Middle Rio Grande Project Office, 50 p.

———1997a, Middle Rio Grande Water Assessment—Analysis of soils textures and permeabilities and deep percolation for Kentucky bluegrass: Albuquerque Area Office, Supporting document number 7, variously paged.

———1997b, Middle Rio Grande Water Assessment—Canal seepage field investigations: Albuquerque Area Office, Supporting document number 12, variously paged.

———1997c, Middle Rio Grande Water Assessment—Drilling, logging, monitoring, well installation, hydraulic conductivity tests, and infiltration gallery feasibility evaluation technical memoranda: Albuquerque Area Office, Supporting document number 8, variously paged.

1997d, Middle Rio Grande Water Assessment—Middle Rio Grande Basin surface water budget for calendar years 1935, 1955, 1975, and 1993: Albuquerque Area Office, Supporting document number 15, variously paged.

Bureau of Reclamation, 1997e, Middle Rio Grande Water Assessment—Middle Rio Grande channel permeameter investigations: Albuquerque Area Office, Supporting document number 11, variously paged.

CH2MHill, 1999, City of Albuquerque Public Works Department water resources strategy implementation, diversion options task 2.1.1.1.3, Hydrogeologic field investigation report: Consulting report prepared for the City of Albuquerque Public Works Department, Albuquerque, New Mexico, variously paged.

Cole, J.C., 2001, 3-D geologic modeling of regional hydrostratigraphic units in the Albuquerque segment of the Rio Grande Rift, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 26-28.

Connell, S.D., 2001, Stratigraphy of the Albuquerque Basin, Rio Grande Rift, central New Mexico—A progress report, *in* Connell, S.D., Lucas, S.G., and Love, D.W., eds., Stratigraphy and tectonic development of the Albuquerque Basin, central Rio Grande Rift: Socorro, New Mexico Bureau of Mines and Mineral Resources Open-File Report 454B, p. A-1 – A27.

Connell, S.D., Allen, B.D., and Hawley, J.W., 1998, Subsurface stratigraphy of the Santa Fe Group from borehole geophysical logs, Albuquerque area, New Mexico: New Mexico Geology, v. 20, no. 1, p. 21-27.

Craigg, S.D., 1992, Water resources on the Pueblos of Jemez, Zia, and Santa Ana, Sandoval County, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 89-4091, 122 p., 4 pls.

Dane, C.H., and Bachman, G.O., 1965, Geologic map of New Mexico: U.S. Geological Survey, 2 sheets, scale 1:500,000.

Fischer, R.L., and Borland, J.P., 1983, Estimation of natural streamflow in the Jemez River at the boundaries of Indian lands, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 82-4113, 27 p.

Frenzel, P.F., 1995, Geohydrology and simulation of ground-water flow near Los Alamos, north-central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 95-4091, 92 p.

Frenzel, P.F., and Lyford, F.P., 1982, Estimates of vertical hydraulic conductivity and regional ground-water flow rates in rocks of Jurassic and Cretaceous age, San Juan Basin, New Mexico and Colorado: U.S. Geological Survey Water-Resources Investigations Report 82-4015, 59 p.

Grant, P.R, Jr., 1999, Subsurface geology and related hydrologic conditions, Santa Fe Embayment and contiguous areas, New Mexico, *in* Pazzaglia, F.J., and Lucas, S.G., eds., Albuquerque Geology: New Mexico Geological Society Fiftieth Annual Field Conference, September 22-25, 1999, p. 425-435.

Grauch, V.J.S., 1999, Principal features of high-resolution aeromagnetic data collected near Albuquerque, New Mexico: New Mexico Geological Society Guidebook 50, p. 115-118.

Grauch, V.J.S., Gillespie, C.L., and Keller, G.R., 1999, Discussion of new gravity maps for the Albuquerque Basin area: New Mexico Geological Society Guidebook 50, p. 119-124.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model – User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hawley, J.W., and Grant, P.R., Jr., 1997, Boundaries of the Albuquerque geohydrologic basin, north-central New Mexico [abs.]: New Mexico Geology, v. 19, no. 2, p. 60.

Hawley, J.W., and Haase, C.S., 1992, Hydrogeologic framework of the northern Albuquerque Basin: Socorro, New Mexico Bureau of Mines and Mineral Resources Open-File Report 387, variously paged.

Hawley, J.W., Haase, C.S., and Lozinsky, R.P., 1995, An underground view of the Albuquerque Basin, *in* Ortega-Klett, C.T., ed., The water future of Albuquerque and the Middle Rio Grande Basin: Proceedings of the 39th Annual New Mexico Water Conference, November 3-4, 1994, New Mexico Water Resources Research Institute WRRI Report No. 290, p. 37-55.

Hearne, G.A., and Dewey, J.D., 1988, Hydrologic analysis of the Rio Grande Basin north of Embudo, New Mexico, Colorado and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 86-4113, 244 p.

Heywood, C.E., 1998, Piezometric-extensometric estimations of specific storage in the Albuquerque Basin, New Mexico, *in* Borchers, J.W., ed., Land subsidence case studies and current research: Proceedings of the Dr. Joseph F. Poland Symposium, Special Publication No. 8, Association of Engineering Geologists, Sacramento Section and Association of Engineering Geologists Subsidence Committee, Belmont, Calif., Star Publishing Company, p. 435-440.

———2001, Piezometric-extensometric test results, *in* Thorn, C.R., Analytical results of a long-term aquifer test conducted near the Rio Grande, Albuquerque, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00-4291, p. 8-11.

Hill, M.C, 1990, Preconditioned Conjugate-Gradient 2 (PCG2), a computer program for solving ground-water flow equations: U.S. Geological Survey Water-Resources Investigations Report 90-4048, 43 p.

———1998, Methods and guidelines for effective model calibration: U.S. Geological Survey Water-Resources Investigations Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., and Andernam, E.R., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model – User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

Johnson, A.I., 1967, Specific yield—Compilation of specific yields for various materials: U.S. Geological Survey Water-Supply Paper 1662-D, 74 p.

Kelley, V.C., 1952, Tectonics of the Rio Grande Depression of central New Mexico, *in* Johnson, R.B., and Read, C.B., eds., Guidebook to Rio Grande country, central New Mexico: New Mexico Geological Society, Third Field Conference, p. 93-105.

Kernodle, J.M., 1998a, Computer input and output files associated with ground-water-flow simulations of the Albuquerque Basin, central New Mexico, 1901-94, with projections to 2020 (Supplement one to U.S. Geological Survey Water-Resources Investigations Report 94-4251): U.S. Geological Survey Open-File Report 96-208, 5 p., 2 compact discs.

———1998b, Simulation of ground-water flow in the Albuquerque Basin, central New Mexico, 1901-95, with projections to 2020 (Supplement two to U.S. Geological Survey Water-Resources Investigations Report 94-4251): U.S. Geological Survey Open-File Report 96-209, 54 p.

———1998c, Computer input and output files associated with ground-water-flow simulations of the Albuquerque Basin, central New Mexico, 1901-95, with projections to 2020 (Supplement three to U.S. Geological Survey Water-Resources Investigations Report 94-4251): U.S. Geological Survey Open-File Report 96-210, 5 p., 2 compact discs.

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.

Kernodle, J.M., Miller, R.S., and Scott, W.B., 1987, Three-dimensional model simulation of transient ground-water flow in the Albuquerque-Belen Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 86-4194, 86 p.

Kernodle, J.M., and Scott, W.B., 1986, Three-dimensional model simulation of steady-state ground-water flow in the Albuquerque-Belen Basin, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 84-4353, 58 p.

Lansford, R.R., Dominguez, Larry, Gore, Charles, Wilken, W.W., Wilson, Brian, and Coburn, C.S., 1993, Sources of irrigation water and irrigated and dry cropland acreages in New Mexico, by county and hydrologic unit, 1991-1993: Las Cruces, New Mexico State University Agricultural Experiment Station Technical Report 21, 83 p.

Lohman, S.W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Lozinsky, R.P., 1988, Stratigraphy, sedimentology, and sand petrology of the Santa Fe Group and pre-Santa Fe Group Tertiary deposits in the Albuquerque Basin, central New Mexico: Socorro, New Mexico Institute of Mining and Technology, Ph.D. dissertation, 298 p.

McAda, D.P., 1996, Plan of study to quantify the hydrologic relation 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.

———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, 66 p.

McAda, D.P., and Wasiolek, Maryann, 1988, Simulation of the regional geohydrology of the Tesuque aquifer system near Santa Fe, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 87-4056, 71 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 6, chap. A1, 586 p.

Meeks, T.O., 1949, The occurrence of ground water in the Tijeras Soil Conservation District, Bernalillo County, New Mexico: U.S. Department of Agriculture Regional Bulletin 109, Geological Series I, Soil Conservation Service Region 6, variously paged.

Mehl, S.W., and Hill, M.C., 2001, MODFLOW-2000, the U.S. Geological Survey modular ground-water model – User guide to the Link-AMG (LMG) package for solving matrix equations using an algebraic multigrid solver: U.S. Geological Survey Open-File Report 01-177, 33 p.

Nimmo, J.R., Lewis, A.M., and Winfield, K.A., 2001, Discernable large- and small-scale features affecting recharge in Abo Arroyo and similar basins, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 41-43.

Niswonger, Richard, and Constantz, Jim, 2001, Determination of streamflow loss to estimate mountain-front recharge at Bear Canyon, New Mexico, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 38-40.

Ortiz, David, Lange, Kathy, and Beal, Linda, 2000, Water resources data, New Mexico, water year 1999, Volume 1. The Rio Grande Basin, the Mimbres River Basin, and the Tularosa Valley Basin: U.S. Geological Survey Water-Data Report NM-99-1, 402 p.

———2001, Water resources data, New Mexico, water year 2000: U.S. Geological Survey Water-Data Report NM-00-1, 411 p.

Pinder, G.F., and Bredehoeft, J.D., 1968, Application of a digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

Plummer, L.N., Bexfield, L.M., Anderholm, S.K., Sanford, W.E., and Busenberg, Eurybaides, 2001, Geochemical characterization of ground-water flow in parts of the Santa Fe Group aquifer system, Middle Rio Grande Basin, New Mexico, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 7-10.

Reeder, H.O., Bjorklund, L.J., and Dinwiddie, G.A., 1967, Quantitative analysis of water resources in the Albuquerque area, New Mexico – Computed effects on the Rio Grande of pumping ground water, 1960-2000: New Mexico State Engineer Technical Report 33, 34 p.

Reilly, T.E., 2001, System and boundary conceptualization in ground-water flow simulation: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 7, chap. B8, 29 p.

Robinson, T.W., 1958, Phreatophytes: U.S. Geological Survey Water-Supply Paper 1423, 84 p.

Roelle, J.E., and Hagenbuck, W.W., 1994, Surface cover maps of the Rio Grande floodplain from Velarde to Elephant Butte Reservoir, New Mexico: National Biological Survey, Midcontinent Ecological Science Center, Fort Collins, Colo., 57 p.

S.S. Papadopulos and Associates, Inc., 2000, Middle Rio Grande water supply study: Consulting report prepared for the U.S. Army Corps of Engineers and the New Mexico Interstate Stream Commission, variously paged.

———2002, Assessment of flow conditions and seepage on the Rio Grande and adjacent channels, Isleta to San Marcial, summer 2001: Consulting report prepared for the New Mexico Interstate Stream Commission, variously paged.

Sandia National Laboratories, 1997, Evaluation of groundwater flow and hydrogeologic conceptual model, Kirtland Air Force Base, Albuquerque, New Mexico: Environmental Restoration Project Report, U.S. Department of Energy, Albuquerque Operations Office, variously paged.

———1998, Site-wide hydrogeologic characterization project, 1995 annual report (revised February 1998): Environmental Restoration Project Report, U.S. Department of Energy, Albuquerque Operations Office, variously paged.

Sanford, W.E., Plummer, N.L., McAda, D.P., Bexfield, L.M., and Anderholm, S.K., 2001, Estimation of hydrologic parameters for the ground-water model of the Middle Rio Grande Basin using carbon-14 and water-level data, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 4-6.

Smith, G.A., and Kuhle, A.J., 1998, Hydrostratigraphic implications of new geological mapping in the Santo Domingo Basin, New Mexico: New Mexico Geology, v. 20, no. 1, p. 21-27.

Stewart, A.E., and Constantz, Jim, 2001, Determination of streamflow patterns to estimate stream loss along Abo Arroyo, New Mexico, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 35-37.

Stone, B.D., Cole, J.C., and Sawyer, D.A., 2001, Regional stratigraphic framework for an integrated three-dimensional geologic model of the Rio Grande Rift, *in* Cole, J.C., ed., U.S. Geological Survey Middle Rio Grande Basin Study—Proceedings of the Fourth Annual Workshop, Albuquerque, New Mexico, February 15-16, 2000: U.S. Geological Survey Open-File Report 00-488, p. 11-13.

Thomas, C.L., 1995, Infiltration and quality of water for two arroyo channels, Albuquerque, New Mexico, 1988-92: U.S. Geological Survey Water-Resources Investigations Report 95-4070, 63 p.

Thomas, C.L., Stewart, A.E., and Constantz, Jim, 2000, Determination of infiltration and percolation rates along a reach of the Santa Fe River near La Bajada, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 00-4141, 65 p.

Thorn, C.R., 2001, Analytical results of a long-term aquifer test conducted near the Rio Grande, Albuquerque, New Mexico, *with a section on* Piezometric-extensometric test results by C.E. Heywood: U.S. Geological Survey Water-Resources Investigations Report 00-4291, 19 p.

Thorn, C.R., McAda, D.P., and Kernodle, J.M., 1993, Geohydrologic framework and hydrologic conditions in the Albuquerque Basin, central New Mexico: U.S. Geological Survey Water-Resources Investigations Report 93-4149, 106 p.

Tiedeman, C.R., Kernodle, J.R., 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. Bureau of Census, 1970, Master reference file for 1970 census.

———U.S. Bureau of Census, 1980, Master reference file for 1980 census.

———U.S. Bureau of Census, 1990, Master reference file for 1990 census.

———2001, Table 6. Population for the 15 largest counties and incorporated places in New Mexico, 1990 and 2000: Census 2000 redistricting data (P.L. 94-171) summary file, table PL1, and 1990 census, available on the World Wide Web at *http://factfinder.census.gov*

Veenhuis, J.E., 2002, Summary of flow 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.

Waltemeyer, S.D., 1994, Methods for estimating streamflow at mountain fronts in southern New Mexico: U.S. Geological Survey Water-Resources Investigations Report 93-4213, 17 p.

Willis, W.S., 1993, Middle Rio Grande ground-water studies—Memorandum to Middle Rio Grande Study Group, June 30, 1993, *in* Bureau of Reclamation, 1997, Middle Rio Grande Water Assessment—Analysis of soils textures and permeabilities and deep percolation for Kentucky bluegrass: Albuquerque Area Office, Supporting document number 7, variously paged.

Wilson, B.C., 1992, Water use by categories in New Mexico counties and river basins, and irrigated acreage in 1990: New Mexico State Engineer Technical Report 47, 141 p.

Zimmerman, D.A., Bowles, N.A., and Jones, M.A., 2000, Groundwater modeling analysis of the July 1998 Duranes Site aquifer test: Consulting report prepared for New Mexico Office of the State Engineer Hydrology Bureau by Gram, Inc., Albuquerque, New Mexico, 89 p.

Zimmerman, D.A., and Updegraff, C.D., 1996, Analysis of impacts on the Rio Grande and the groundwater table from proposed deep well pumping—Rio Rancho's 12,000 acre-foot/year permit request: Consulting report prepared for the Water and Wastewater Utilities Department, City of Rio Rancho, New Mexico, by Gram, Inc., Albuquerque, New Mexico, variously paged.

SUPPLEMENTAL INFORMATION

Modification to Well Package

The Well Package of MODFLOW-2000 (Harbaugh and others, 2000) was modified to transfer the specified flux to the next lower active cell when a cell goes dry. Although the subsurface underflow in the model is specified using the Well Package, the cells that go dry in the model most often are the ones containing ground-water withdrawal. Without this modification, the specified flux assigned to the dry model cell is terminated. Because simulated withdrawals are for the most part based on withdrawal records and layer assignments of withdrawals are estimates at best, reassignment of withdrawals to lower model layers probably is more realistic than terminating a portion of the simulated withdrawal.

The two subroutines modified are GWF1WEL6FM and GWF1WEL6BD from the Well package of MODFLOW-2000, version 1.10. The modifications in each subroutine and a brief description of the modifications are provided below. The changes made to the subroutines are listed in bold type.

Subroutine GWF1WEL6FM

Subroutine GWF1WEL6FM subtracts the volumetric flow rate specified for the Well package from the right-hand side (RHS) of the flow equation. The modification moves the specified flow rate to the next lower active cell if the specified cell has gone dry.

```
      SUBROUTINE GWF1WEL6FM(NWELLS,MXWELL,RHS,WELL,IBOUND,
     1        NCOL,NROW,NLAY,NWELVL)
C
C-----VERSION 11JAN2000 GWF1WEL6FM
C           with modifications by P. Barroll 8/01
C
C     ******************************************************************
C     SUBTRACT Q FROM RHS
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DIMENSION RHS(NCOL,NROW,NLAY),WELL(NWELVL,MXWELL),
     1            IBOUND(NCOL,NROW,NLAY)
C     ------------------------------------------------------------------
C1------IF NUMBER OF WELLS <= 0 THEN RETURN.
      IF(NWELLS.LE.0) RETURN
C
C2------PROCESS EACH WELL IN THE WELL LIST.
      DO 100 L=1,NWELLS
      IR=WELL(2,L)
      IC=WELL(3,L)
      IL=WELL(1,L)
      Q=WELL(4,L)
C
cc**************************************************************************
cc2aa Well deepening: if cell has gone dry, put pumping in next active
c        deeper layer.              P Barroll 8/01
C2A-----IF THE CELL IS INACTIVE THEN BYPASS PROCESSING.
cc      IF(IBOUND(IC,IR,IL).LE.0) GO TO 100
c
       ilinit=il
 2      continue
cc2ab If cell is inactive, and is not in bottom layer, move it down one layer,
c       then recheck.
       if(ibound(ic,ir,il).eq.0.and.il.lt.nlay)then
       il=il+1
       goto 2
       end if
cc2ac If cell is inactive and is in bottom layer, ignore it
       if(ibound(ic,ir,il).eq.0.and.il.ge.nlay)goto 100
cc2ad if cell is constant head, ignore it
       if(ibound(ic,ir,il).lt.0)goto 100
cc**************************************************************************
C
C2B-----IF THE CELL IS VARIABLE HEAD THEN SUBTRACT Q FROM
C       THE RHS ACCUMULATOR.
      RHS(IC,IR,IL)=RHS(IC,IR,IL)-Q
  100 CONTINUE
C
C3------RETURN
      RETURN
      END
```

Subroutine GWF1WEL6BD

Subroutine GWF1WEL6BD applies the volumetric flow rate specified for the Well package to the volumetric budget of the specified cell. The first 47 lines of subroutine GWF1WEL6BD contain no modifications and are not included in this listing. The modification applies the specified flow rate to the volumetric budget of the next lower active cell if the specified cell has gone dry. The modification also prints a message to the LST file stating that the pumping was moved to a lower layer.

```
C5------LOOP THROUGH EACH WELL CALCULATING FLOW.
      DO 100 L=1,NWELLS
C
C5A-----GET LAYER, ROW & COLUMN OF CELL CONTAINING WELL.
      IR=WELL(2,L)
      IC=WELL(3,L)
      IL=WELL(1,L)
      Q=ZERO
C
c*****************************************************************************
cc5ba Well deepening: if pumped cell goes dry, move pumping into next active
cc      deeper layer.               P Barroll 8/01

       ilinit=il
C5B-----IF THE CELL IS NO-FLOW OR CONSTANT_HEAD, IGNORE IT.
cc      IF(IBOUND(IC,IR,IL).LE.0)GO TO 99

cc5bb If cell is constant head, ignore it
       if(ibound(ic,ir,il).lt.0)goto 99

cc5bc If cell is variable head, cell is still active--skip this fix
       if(ibound(ic,ir,il).ge.1)goto 60

2      continue
cc5bd If cell is no-flow, and is at bottom of the model, ignore it
       if(ibound(ic,ir,il).eq.0.and.il.ge.nlay)goto 99
cc5be If cell is no-flow and is not at bottom of model, deepen pumping and
cc      check again
           if(ibound(ic,ir,il).eq.0.and.il.lt.nlay)then
           il=il+1
           goto 2
           end if
cc5bf If pumping was deepened successfully, print warning
       write(iout,55)ir,ic,ilinit,il
55     format('Well Stress placed in row:',i4,', col:',i4,' layer: ',i4,
     c ' moved to layer ',i4)

60     continue

c****************************************************************************
C
C5C-----GET FLOW RATE FROM WELL LIST.
      Q=WELL(4,L)
      QQ=Q
C
C5D-----PRINT FLOW RATE IF REQUESTED.
      IF(IBD.LT.0) THEN
         IF(IBDLBL.EQ.0) WRITE(IOUT,61) TEXT,KPER,KSTP
   61    FORMAT(1X,/1X,A,'   PERIOD ',I4,'   STEP ',I3)
         WRITE(IOUT,62) L,IL,IR,IC,Q
   62    FORMAT(1X,'WELL ',I6,'   LAYER ',I3,'   ROW ',I5,'   COL ',I5,
     1       '   RATE ',1PG15.6)
         IBDLBL=1
      END IF
C
C5E-----ADD FLOW RATE TO BUFFER.
      BUFF(IC,IR,IL)=BUFF(IC,IR,IL)+Q
C
C5F-----SEE IF FLOW IS POSITIVE OR NEGATIVE.
      IF(Q) 90,99,80
C
C5G-----FLOW RATE IS POSITIVE (RECHARGE). ADD IT TO RATIN.
   80 RATIN=RATIN+QQ
```

```
      GO TO 99
C
C5H-----FLOW RATE IS NEGATIVE (DISCHARGE). ADD IT TO RATOUT.
   90 RATOUT=RATOUT-QQ
C
C5I-----IF CELL-BY-CELL FLOWS ARE BEING SAVED AS A LIST, WRITE FLOW.
C5I-----OR IF RETURNING THE FLOW IN THE WELL ARRAY, COPY FLOW TO WELL.
   99 IF(IBD.EQ.2) CALL UBDSVB(IWELCB,NCOL,NROW,IC,IR,IL,Q,
     1                  WELL(1,L),NWELVL,NAUX,5,IBOUND,NLAY)
      IF(IWELAL.NE.0) WELL(NWELVL,L)=Q
  100 CONTINUE
C
C6------IF CELL-BY-CELL FLOWS WILL BE SAVED AS A 3-D ARRAY,
C6------CALL UBUDSV TO SAVE THEM.
      IF(IBD.EQ.1) CALL UBUDSV(KSTP,KPER,TEXT,IWELCB,BUFF,NCOL,NROW,
     1                          NLAY,IOUT)
C
C7------MOVE RATES, VOLUMES & LABELS INTO ARRAYS FOR PRINTING.
  200 RIN=RATIN
      ROUT=RATOUT
      VBVL(3,MSUM)=RIN
      VBVL(4,MSUM)=ROUT
      VBVL(1,MSUM)=VBVL(1,MSUM)+RIN*DELT
      VBVL(2,MSUM)=VBVL(2,MSUM)+ROUT*DELT
      VBNM(MSUM)=TEXT
C
C8------INCREMENT BUDGET TERM COUNTER(MSUM).
      MSUM=MSUM+1
C
C9------RETURN
      RETURN
      END
```

Modification to Layer Property Flow Package

The Layer Property Flow Package of MODFLOW-2000, version 1.10 was modified by A.W. Harbaugh (U.S. Geological Survey, written commun., 2002) to remove the vertical leakage correction for conditions in which a partially saturated cell is immediately below a fully or partially saturated cell (Harbaugh and others, 2000, p. 31-33). The vertical leakage correction simulates perched conditions within an aquifer system. Localized perched conditions have been documented on Kirtland Air Force Base (Sandia National Laboratories, 1998) and may exist elsewhere in the basin because of clayey lenses within the basin sediments. However, perched conditions are not known to be widespread on a basin scale. The vertical leakage correction adds an additional nonlinear term to the model (A.W. Harbaugh, U.S. Geological Survey, written commun., 2002), which resulted in several of the numerical solvers (SIP (strongly implicit procedures), SOR (slice-successive overrelaxation), and PCG (Hill, 1990; Harbaugh and others, 2000) not coming to a solution and the LMG (link-algebraic multigrid; Mehl and Hill, 2001) solver providing unacceptable volumetric budget errors. Because the model described in this report is designed to simulate ground-water flow on a regional scale and simulating localized perched zones was beyond the scope of this study, the modified version of the LPF (layer-property flow) package was used. Use of the PCG solver with the modified version of the LPF package resulted in a solution with acceptable volumetric budget errors.

The five subroutines modified by A.W. Harbaugh (U.S. Geological Survey, written commun., 2002) are GWF1LPF1AL, GWF1LPF1FM, SGWF1LPF1B, SGWF1LPF1F, and SGWF1LPF1VCOND. The modifications in each subroutine and a brief description of the modifications are provided below. The changes made to the subroutines are listed in bold type.

Subroutine GWF1LPF1AL

Subroutine GWF1LPF1AL allocates array storage for the LPF package. The first 46 lines of the modified subroutine are listed below. The remaining lines of the subroutine contain no modifications and are not included in this listing. The two modified lines in subroutine GWF1LPF1AL serve to indicate within the code and in the GLOBAL output file that this is a modified version of the LPF package.

```
C  Modified to remove the vertical leakage correction for perched conditions
      SUBROUTINE GWF1LPF1AL(ISUM,LCHK,LCVKA,LCSC1,LCSC2,LCHANI,
     1  LCVKCB,IN,NCOL,NROW,NLAY,IOUT,ILPFCB,LCWETD,
     2  HDRY,NPLPF,NCNFBD,LCLAYF,IREWND,ISUMI,LAYHDT,ITRSS,LCSV,ISEN)
C
C-----VERSION 11JAN2000 GWF1LPF1AL
C     ******************************************************************
C     ALLOCATE ARRAY STORAGE FOR LAYER PROPERTY FLOW PACKAGE
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      INTEGER LAYHDT(NLAY)
      CHARACTER*14 LAYPRN(5),AVGNAM(3),TYPNAM(2),VKANAM(2),WETNAM(2),
     1            HANNAM
      COMMON /LPFCOM/LAYTYP(200),LAYAVG(200),CHANI(200),LAYVKA(200),
     1               LAYWET(200)
C
      DATA AVGNAM/'      HARMONIC','   LOGARITHMIC','     LOG-ARITH'/
      DATA TYPNAM/'      CONFINED','   CONVERTIBLE'/
      DATA VKANAM/'    VERTICAL K','    ANISOTROPY'/
      DATA WETNAM/'  NON-WETTABLE','      WETTABLE'/
      DATA HANNAM/'      VARIABLE'/
      CHARACTER*200 LINE
C     ------------------------------------------------------------------
      IREWND=0
      ZERO=0.
C
C1------IDENTIFY PACKAGE
      WRITE(IOUT,1) IN
    1 FORMAT(1X,/1X,'LPF1X -- LAYER PROPERTY FLOW PACKAGE, VERSION 1X',
     1', 1/11/2000',/,9X,'INPUT READ FROM UNIT ',I4)
C
C2------READ FIRST RECORD AND WRITE
      CALL URDCOM(IN,IOUT,LINE)
      LLOC=1
      CALL URWORD(LINE,LLOC,ISTART,ISTOP,2,ILPFCB,R,IOUT,IN)
      CALL URWORD(LINE,LLOC,ISTART,ISTOP,3,I,HDRY,IOUT,IN)
      CALL URWORD(LINE,LLOC,ISTART,ISTOP,2,NPLPF,R,IOUT,IN)
      IF(ILPFCB.LT.0) WRITE(IOUT,8)
    8 FORMAT(1X,'CONSTANT-HEAD CELL-BY-CELL FLOWS WILL BE PRINTED',
     1  ' WHEN ICLPFL IS NOT 0')
      IF(ILPFCB.GT.0) WRITE(IOUT,9) ILPFCB
    9 FORMAT(1X,'CELL-BY-CELL FLOWS WILL BE SAVED ON UNIT ',I4)
      WRITE(IOUT,11) HDRY
   11 FORMAT(1X,'HEAD AT CELLS THAT CONVERT TO DRY=',1PG13.5)
```

Subroutine GWF1LPF1FM

The unmodified subroutine GWF1LPF1FM adds the flow-correction term (Harbaugh and others, 2000, p. 31-33) for partially unsaturated cells to the flow equation. The last 50 lines of the modified subroutine are listed below. The first 91 lines of the subroutine contain no modifications and are not included in this listing. The two lines added to subroutine GWF1LPF1FM avoid adding flow-correction terms for partially unsaturated cells to the right-hand side (RHS) of the flow equation.

```
C6------FOR EACH LAYER DETERMINE IF CORRECTION TERMS ARE NEEDED FOR
C6------FLOW DOWN INTO PARTIALLY SATURATED LAYERS.
            go to 301
      DO 300 K=1,NLAY
C
C7------SEE IF CORRECTION IS NEEDED FOR LEAKAGE FROM ABOVE.
      IF(LAYTYP(K).NE.0 .AND. K.NE.1) THEN
C
C7A-----FOR EACH CELL MAKE THE CORRECTION IF NEEDED.
         DO 220 I=1,NROW
         DO 220 J=1,NCOL
C
C7B-----IF THE CELL IS EXTERNAL(IBOUND<=0) THEN SKIP IT.
         IF(IBOUND(J,I,K).LE.0) GO TO 220
         HTMP=HNEW(J,I,K)
C
C7C-----IF HEAD IS ABOVE TOP THEN CORRECTION NOT NEEDED
         TOP=BOTM(J,I,LBOTM(K)-1)
         IF(HTMP.GE.TOP) GO TO 220
C
C7D-----WITH HEAD BELOW TOP ADD CORRECTION TERMS TO RHS.
         RHS(J,I,K)=RHS(J,I,K) + CV(J,I,K-1)*(TOP-HTMP)
  220    CONTINUE
      END IF
C
C8------SEE IF THIS LAYER MAY NEED CORRECTION FOR LEAKAGE TO BELOW.
      IF(K.EQ.NLAY) GO TO 300
      IF(LAYTYP(K+1).NE.0) THEN
C
C8A-----FOR EACH CELL MAKE THE CORRECTION IF NEEDED.
         DO 280 I=1,NROW
         DO 280 J=1,NCOL
C
C8B-----IF CELL IS EXTERNAL (IBOUND<=0) THEN SKIP IT.
         IF(IBOUND(J,I,K).LE.0) GO TO 280
C
C8C-----IF HEAD IN THE LOWER CELL IS LESS THAN TOP ADD CORRECTION
C8C-----TERM TO RHS.
         HTMP=HNEW(J,I,K+1)
         TOP=BOTM(J,I,LBOTM(K+1)-1)
         IF(HTMP.LT.TOP) RHS(J,I,K)=RHS(J,I,K)- CV(J,I,K)*(TOP-HTMP)
  280    CONTINUE
      END IF
C
  300 CONTINUE
  301     continue
C
C9------RETURN
      RETURN
      END
```

Subroutine SGWF1LPF1B

Subroutine SGWF1LPF1B computes flow between adjacent cells. The last 45 lines of the modified subroutine are listed below. The first 135 lines of the subroutine SGWF1LPF1B contain no modifications and are not included in this listing. Three lines are commented out of the subroutine by beginning the lines with “c” so that the head difference used to calculate flow between an active cell and the next lower cell is the difference between the simulated heads in the cells, even when the lower cell is partially unsaturated.

```
C5A-----CALCULATE FLOW ACROSS LAYERS (THROUGH LOWER FACE).  IF NOT
C5A-----SAVING IN A FILE, SET THE SUBREGION.  CLEAR THE BUFFER.
      IF(IBD.EQ.0) THEN
         K1=IL1-1
         IF(K1.LT.1) K1=1
         K2=IL2
         I1=IR1
         I2=IR2
         J1=IC1
         J2=IC2
      END IF
      DO 510 K=K1,K2
      DO 510 I=I1,I2
      DO 510 J=J1,J2
      BUFF(J,I,K)=ZERO
  510 CONTINUE
C
C5B-----FOR EACH CELL CALCULATE FLOW THRU LOWER FACE & STORE IN BUFFER.
      IF(K2.EQ.NLAY) K2=K2-1
      DO 600 K=1,K2
      IF(K.LT.K1) GO TO 600
      DO 590 I=I1,I2
      DO 590 J=J1,J2
      IF(ICHFLG.EQ.0) THEN
         IF((IBOUND(J,I,K).LE.0) .AND. (IBOUND(J,I,K+1).LE.0)) GO TO 590
      ELSE
         IF((IBOUND(J,I,K).EQ.0) .OR. (IBOUND(J,I,K+1).EQ.0)) GO TO 590
      END IF
      HD=HNEW(J,I,K+1)
      IF(LAYTYP(K+1).EQ.0) GO TO 580
c      TMP=HD
c      TOP=BOTM(J,I,LBOTM(K+1)-1)
c      IF(TMP.LT.TOP) HD=TOP
  580 HDIFF=HNEW(J,I,K)-HD
      BUFF(J,I,K)=HDIFF*CV(J,I,K)
  590 CONTINUE
  600 CONTINUE
C
C5C-----RECORD CONTENTS OF BUFFER AND RETURN.
      IF(IBD.EQ.1)
     1   CALL UBUDSV(KSTP,KPER,TEXT(3),ILPFCB,BUFF,NCOL,NROW,NLAY,IOUT)
      IF(IBD.EQ.2) CALL UBDSV1(KSTP,KPER,TEXT(3),ILPFCB,BUFF,NCOL,NROW,
     1     NLAY,IOUT,DELT,PERTIM,TOTIM,IBOUND)
      RETURN
      END
```

Subroutine SGWF1LPF1F

Subroutine SGWF1LPF1F computes flow between constant-head cells and adjacent cells. The 37 lines of the modified subroutine SGWF1LPF1F, beginning with comment line C11 and ending with statement number 170, are listed below. The first 145 lines and the last 39 of subroutine SGWF1LPF1F contain no modifications and are not included in this listing. Six lines are commented out of the subroutine so that the head difference used to calculate flow between a constant-head cell and a vertically adjacent cell is the difference between the simulated heads in the cells, even when the constant-head cell or the lower cell is partially unsaturated.

```
C11-----CALCULATE FLOW THROUGH THE UPPER FACE.
  120 IF(K.EQ.1) GO TO 150
      IF (IBOUND(J,I,K-1).EQ.0) GO TO 150
      IF (IBOUND(J,I,K-1).LT.0 .AND. ICHFLG.EQ.0) GO TO 150
      HD=HNEW(J,I,K)
      IF(LAYTYP(K).EQ.0) GO TO 122
c      TMP=HD
c      TOP=BOTM(J,I,LBOTM(K)-1)
c      IF(TMP.LT.TOP) HD=TOP
  122 HDIFF=HD-HNEW(J,I,K-1)
      CHCH5=HDIFF*CV(J,I,K-1)
      IF(IBOUND(J,I,K-1).LT.0) GO TO 150
      X5=CHCH5
      XX5=X5
      IF(X5) 130,150,140
  130 CHOUT=CHOUT-XX5
      GO TO 150
  140 CHIN=CHIN+XX5
C
C12-----CALCULATE FLOW THROUGH THE LOWER FACE.
  150 IF(K.EQ.NLAY) GO TO 180
      IF(IBOUND(J,I,K+1).EQ.0) GO TO 180
      IF(IBOUND(J,I,K+1).LT.0 .AND. ICHFLG.EQ.0) GO TO 180
      HD=HNEW(J,I,K+1)
      IF(LAYTYP(K+1).EQ.0) GO TO 152
c      TMP=HD
c      TOP=BOTM(J,I,LBOTM(K+1)-1)
c      IF(TMP.LT.TOP) HD=TOP
  152 HDIFF=HNEW(J,I,K)-HD
      CHCH6=HDIFF*CV(J,I,K)
      IF(IBOUND(J,I,K+1).LT.0) GO TO 180
      X6=CHCH6
      XX6=X6
      IF(X6) 160,180,170
  160 CHOUT=CHOUT-XX6
      GO TO 180
  170 CHIN=CHIN+XX6
```

Subroutine SGWF1LPF1VCOND

Subroutine SGWF1LPF1VCOND calculates the vertical conductance between a cell and the next lower cell (Harbaugh and others, 2000, p. 28-33). The last 48 lines of the modified subroutine are listed below. The first 48 lines of subroutine SGWF1LPF1VCOND contain no modifications and are not included in this listing. Four lines are commented out of the subroutine so that the contribution to vertical conductance from a lower, partially unsaturated cell is not set to zero.

```
C4------CALCULATE INVERSE LEAKANCE FOR CELL.
               BBOT=BOTM(J,I,LBOTM(K))
               TTOP=BOTM(J,I,LBOTM(K)-1)
               IF(LAYTYP(K).NE.0) THEN
                  HHD=HNEW(J,I,K)
                  IF(HHD.LT.TTOP) TTOP=HHD
               END IF
               BOVK1=(TTOP-BBOT)*HALF/HYC1
C
C5------CALCULATE INVERSE LEAKANCE FOR CELL BELOW.
               BBOT=BOTM(J,I,LBOTM(K+1))
               TTOP=BOTM(J,I,LBOTM(K+1)-1)
               B=(TTOP-BBOT)*HALF
c               IF(LAYTYP(K+1).NE.0) THEN
c                  HHD=HNEW(J,I,K+1)
c                  IF(HHD.LT.TTOP) B=ZERO
c               END IF
               BOVK2=B/HYC2
C
               IF(LAYCBD(K).NE.0) THEN
C6------CALCULATE VERTICAL HYDRAULIC CONDUCTIVITY FOR CONFINING BED.
                  IF(VKCB(J,I,LAYCBD(K)).GT.ZERO) THEN
C
C7------CALCULATE INVERSE LEAKANCE FOR CONFINING BED.
                     B=BOTM(J,I,LBOTM(K))-BOTM(J,I,LBOTM(K)+1)
                     IF(B.LT.ZERO) THEN
                        WRITE(IOUT,45) K,I,J
   45                   FORMAT(1X,/1X,
     1  'Negative confining bed thickness below cell (Layer,row,col)',
     2                  I4,',',I5,',',I5)
            WRITE(IOUT,46) BOTM(J,I,LBOTM(K)),BOTM(J,I,LBOTM(K)+1)
   46       FORMAT(1X,'Top elevation, bottom elevation:',1P,2G13.5)
                        STOP
                     END IF
                     CBBOVK=B/VKCB(J,I,LAYCBD(K))
                     CV(J,I,K)=DELR(J)*DELC(I)/(BOVK1+CBBOVK+BOVK2)
                  END IF
               ELSE
                  CV(J,I,K)=DELR(J)*DELC(I)/(BOVK1+BOVK2)
               END IF
            END IF
         END IF
      END IF
  100 CONTINUE
C
C8------RETURN.
      RETURN
      END
```

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BOOK RATE

D.P. McAda and P. Barroll—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