SIMULATION OF GROUND-WATER FLOW IN THE ALBUQUERQUE BASIN, CENTRAL NEW MEXICO, 1901-1994, WITH PROJECTIONS TO 2020

By John Michael Kernodle, Douglas P. McAda, and Condé R. Thorn

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	2.54	centimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	0.4047	hectare
square foot	0.09290	square meter
square mile	2.590	square kilometer
gallon	3.785	liter
cubic foot	7.481	gallon
	0.02832	cubic meter
acre-foot	0.001233	cubic hectometer
	43,560.	cubic foot
acre-foot per acre	0.3048	cubic meter per square meter
acre-foot per year	0.001233	cubic hectometer per year
	0.0013803	cubic foot per second
	0.6184	gallon per minute
foot per day	0.3048	meter per day
foot per year	0.3048	meter per year
gallon per day	0.003785	cubic meter per day
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
cubic foot per second per mile	0.01760	cubic meter per second per kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the equation:

$$°F = 9/5\ (°C) + 32$$

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

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ABSTRACT

This report describes a three-dimensional finite-difference ground-water-flow model of the Santa Fe Group aquifer system in the Albuquerque Basin, which comprises the Santa Fe Group (late Oligocene to middle Pleistocene age) and overlying valley and basin-fill deposits (Pleistocene to Holocene age). The model is designed to be flexible and adaptive to new geologic and hydrologic information as it becomes available, by using a geographic information system as a data-base manager to interface with the model. The aquifer system was defined and quantified in the model consistent with the current (July 1994) understanding of the structural and geohydrologic framework of the basin. Rather than putting the model through a rigorous calibration process, discrepancies between simulated and measured responses in hydraulic head were taken to indicate that the understanding of a local part of the aquifer system was incomplete or incorrect.

The model simulates ground-water flow over an area of about 2,400 square miles to a depth of 1,730 to about 2,020 feet below the water table with 244 rows, 178 columns, and 11 layers. Of the 477,752 cells in the model, 310,376 are active. The top four model layers approximate the 80-foot thickness of alluvium in the incised and refilled valley of the Rio Grande to provide detail of the effect of ground-water withdrawals on the surface-water system. Away from the valley, these four layers represent the interval within the Santa Fe Group aquifer system between the computed predevelopment water table and a level 80 feet below the grade of the Rio Grande. The simulations include initial conditions (steady-state), the 1901-1994 historical period, and four possible ground-water withdrawal scenarios from 1994 to 2020.

The model indicates that for the year ending in March 1994, net surface-water loss in the basin resulting from the City of Albuquerque's ground-water withdrawal totaled about 53,000 acre-feet. The balance of the about 123,000 acre-feet of withdrawal came from aquifer storage depletion (about 67,800 acre-feet) and captured or salvaged evapotranspiration (about 2,500 acre-feet).

In the four scenarios projected from 1994 to 2020, City of Albuquerque annual withdrawals ranged from about 98,700 to about 177,000 acre-feet by the year 2020. The range of resulting surface-water loss was from about 62,000 to about 77,000 acre-feet. The range of aquifer storage depletion was from about 33,400 to about 95,900 acre-feet. Captured evapotranspiration and drain-return flow remained nearly constant for all scenarios. From 1994 to 2020, maximum projected declines in hydraulic head in the primary water-production zone of the aquifer (model layer 9) for the four scenarios ranged from 55 to 164 feet east of the Rio Grande and from 91 to 258 feet west of the river. Average declines in a 383.7-square-mile area around Albuquerque ranged from 28 to 65 feet in the production zone for the same period.

INTRODUCTION

Many hydrologic studies, both qualitative and quantitative, have been conducted in the Albuquerque Basin (fig. 1) dating back to the late 19th century. Recent (within the last 5 years) investigations of the Albuquerque Basin, in particular in the Albuquerque area, indicate that the zone of highly productive aquifer material is less extensive and thinner than previously thought (Hawley and Haase, 1992; Thorn and others, 1993). On the basis of these and other investigations, officials with the City of Albuquerque have decided that a better understanding of the hydrologic system of the Albuquerque Basin must be developed so that present and future water demands can be met for all basin residents. In July 1992, the U.S. Geological Survey in cooperation with the City of Albuquerque Public Works Department began an investigation designed to reevaluate the geohydrology of the Albuquerque Basin in central New Mexico, with emphasis on the Albuquerque area.

The study described in this report is the third of a three-phase study to quantify ground-water resources in the Albuquerque Basin. The first phase, conducted by the New Mexico Bureau of Mines and Mineral Resources in cooperation with the City, described the hydrogeologic framework of the Albuquerque Basin on the basis of recent data. The results of that study are presented in a report by Hawley and Haase (1992). The second phase of the study resulted in a description of the geohydrologic framework and hydrologic conditions in the Albuquerque Basin (Thorn and others, 1993). This report, a result of the third phase, describes ground-water-flow simulations of the Albuquerque Basin based on the concepts presented in Hawley and Haase (1992) and Thorn and others (1993), with minor revisions.

Purpose and Scope

This report describes a three-dimensional finite-difference ground-water-flow model of the Albuquerque Basin, with emphasis on the Albuquerque area. The model incorporates recent (July 1994) geologic and hydrologic data about the Albuquerque Basin. The model simulates initial conditions, historical responses to ground-water withdrawals for 1901-1994, and projected responses to selected possible future conditions to the year 2020. The hydrogeologic framework for the model is based on material presented in Hawley and Haase (1992). Geohydrologic characteristics of the basin are based on those presented in Thorn and others (1993). Recent revisions to the understanding of the hydrogeologic framework are not included in these simulations. The section Possible Model Revisions and Additional Data Needs focuses on adapting the model to those recent revisions as well as listing those additional data needs that would be of benefit in improving the model.

The Santa Fe Group aquifer system described in this report includes the Santa Fe Group (late Oligocene to middle Pleistocene age) and overlying valley and basin-fill deposits (Pleistocene to Holocene age). For a description of the properties of the Santa Fe Group and valley and basin-fill deposits, the reader is referred to Hawley and Haase (1992) and Thorn and others (1993). The modeling effort differs from previous modeling efforts in the Albuquerque Basin in that: (1) the data base and data extraction system can be dynamically updated and used for enhancements to the model as updated information on the geohydrologic system becomes available; (2) the model simulates detailed surface-water/ground-water interaction; and (3) disagreement between measured and simulated conditions is used to identify areas where more information is needed to improve the understanding of the geohydrologic system.

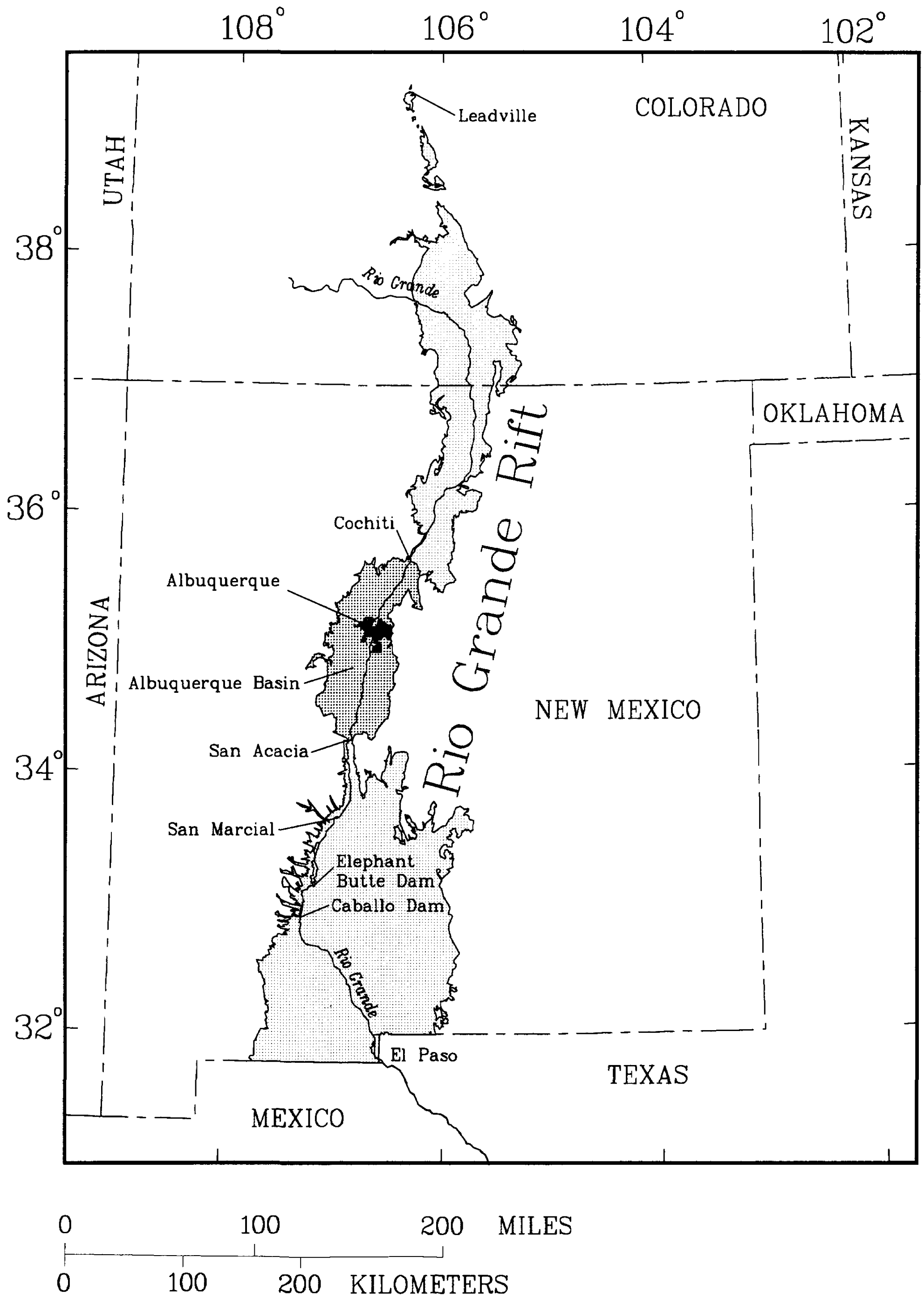

Figure 1.—Location of the Albuquerque Basin and the Rio Grande Rift, central New Mexico (modified from Thorn and others, 1993, fig. 1).

Plate 1 displays the boundary of the Albuquerque Basin and the modeled area described in this report. The boundary of the Albuquerque Basin is defined by the present extent of Cenozoic deposits, whereas the modeled area is further restricted on the basis of structure and lithologic constraints on the flow of ground water in the basin.

Previous Investigations

Previous investigations in the Albuquerque Basin are described in Thorn and others (1993). Ground-water-flow modeling investigations within the basin are few in number. One of the first ground-water modeling efforts performed in the Albuquerque area, completed by Reeder and others (1967), predicted drawdowns to the year 2000. Most of the basic data and hydrologic understanding for that report came from Bjorklund and Maxwell (1961). Kernodle and Scott (1986) developed a three-dimensional simulation of steady-state conditions in the Santa Fe Group aquifer system underlying the Albuquerque Basin. Transient ground-water flow, also in the Santa Fe Group aquifer system in the Albuquerque Basin, is discussed in Kernodle and others (1987). Kernodle (1992b) summarized all U.S. Geological Survey modeling efforts in the Rio Grande Rift up to 1990 and presented guidelines for preferred approaches to modeling alluvial-fill rift basins. Bibliographies that provide other useful references concerning the hydrogeology of the Albuquerque Basin can be found in Kelley (1977), Borton (1978; 1980; and 1983), Wright (1978), and Stone and Mizell (1979). The investigations of Hawley and Haase (1992) and Thorn and others (1993) are the basis for this modeling investigation.

Base Credits

All maps in this report are in the Lambert Conformal Conic projection with standard parallels 33° 00′ and 45° 00′, and central meridian -106° 00′. The base for figure 1 was compiled from U.S. Department of Commerce, Bureau of Census TIGER/line Precensus Files, 1990, scale 1:100,000.

The base for the page-size map (scale about 1:900,000) of the Albuquerque Basin was compiled from several sources. Hydrography is from 1977-1978 U.S. Geological Survey digital data, scale 1:100,000. Cultural features are from 1992 City of Albuquerque digital data, scale 1:2,400, and digitized from 1977-1978 U.S. Geological Survey maps, scale 1:100,000. For an example, see figure 3.

The base for the page-size maps (scale about 1:210,000) of the Albuquerque area was compiled from the following sources: hydrography is from 1977-1978 U.S. Geological Survey digital data, scale 1:100,000; roads are from 1992 City of Albuquerque digital data, scale 1:2,400, and 1977-1978 U.S. Geological Survey digital data, scale 1:100,000. Cultural features are from 1992 City of Albuquerque digital data, scale 1:2,400, and digitized from 1978, 1980, and 1983 Bureau of Land Management maps, scale 1:100,000, and 1977-1978 U.S. Geological Survey maps, scale 1:100,000. For an example, see figure 6.

Acknowledgments

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and Mineral Resources; William White, Bureau of Indian Affairs; and Steve Hansen, Bureau of Reclamation. Special appreciation is offered to neighboring communities and Pueblos who provided data that were essential to the modeling effort.The authors also extend appreciation to Steven Lewandowski, Pat Kincaid, and Presiliano Pino, U.S. Geological Survey, for gathering and compiling pumpage data.

MODEL DESCRIPTION

Movement of water through an aquifer may be expressed by differential equations (Pinder and Bredehoeft, 1968). Solving these equations analytically, however, usually is not possible because of the complexity of geohydrologic 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 technique is not unique in that any number of reasonable variations in the representation of the geohydrologic system used in the model may produce equally acceptable results. Nevertheless, the model is a tool that can be used to help understand an aquifer system, project aquifer responses to assumed stresses, and evaluate needs for additional information about the aquifer system that would improve the representation of the system. 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 geohydrologic system, and results of simulations made with the model need to be interpreted with this in mind.

Numerical Solution

Ground-water flow in the Santa Fe Group aquifer system in the Albuquerque Basin was simulated in three dimensions. By assuming that the Cartesian coordinate axes x, y, and z are aligned with the principal components of hydraulic conductivity, three-dimensional ground-water flow through a porous medium can be expressed as follows (McDonald and Harbaugh, 1988, p. 2-1):

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

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

The three-dimensional flow equation can be approximated by replacing the derivatives with finite differences. The aquifer is divided into a series of cells by a sequence of layers and a series of rows and columns that extend through each layer. Aquifer properties are assumed to be uniform within each individual cell. Hydraulic heads are assumed to be at the center of each model cell. The computer program used for this study was developed by McDonald and Harbaugh (1988). The preconditioned conjugate-gradient method (Hill, 1990) was used as the algorithm to solve the equations.

The Santa Fe Group aquifer system in the Albuquerque Basin is represented in the model by 11 layers (fig. 2). The top of layer 1 is the water table as defined by the initial-condition, steady-state simulation. The base of layer 4 was defined as 80 feet below the elevation of the Rio Grande. To form the elevation surface (fig. 3) for the base of layer 4, contour lines of the elevation level 80 feet below the river surface were extended to the basin margins orthogonally from the inner Rio Grande Valley. This elevation surface parallels the grade of the Rio Grande through the basin. The saturated thickness of the aquifer between the base of layer 4 and the simulated steady-state water-table surface was divided equally among the top four layers. Each of the top four layers was approximately 20 feet thick in the inner valley and became thicker toward the basin margins. The largest thickness of each of layers 1 through 4 is 92 feet in the far northeast part of the basin. The purpose of the relatively thin upper four layers in the inner valley is to simulate ground-water/surface-water interaction in the valley. The thicknesses of layers 5-11 range from 50 to 500 feet (fig. 2) and are consistent throughout the modeled area. On the basis of the predevelopment condition, the total saturated thickness of the simulated part of the aquifer ranges from 1,730 feet in the inner valley to about 2,020 feet at the far northeast part of the basin. This interval includes the entire saturated thickness of the upper part of the Santa Fe Group in the Albuquerque area, which contains the primary water-yielding zones in the aquifer system (Thorn and others, 1993, p. 30, 66).

The 11 layers in the model are divided into a series of cells by a horizontal grid with 244 rows and 178 columns (pl. 1). The grid spacing varies from 656 feet (200 meters) on a side in the Albuquerque area to a maximum of 3,281 feet (1 kilometer) on a side at the basin margins. Cell size ranges from about 10 to about 250 acres. The model has a total of 477,752 cells, of which 310,376 are active. Each active cell requires a minimum of seven parameters characterizing hydraulic properties.

For the steady-state condition, only the uppermost active cell in each row and column of the model is simulated as being unconfined (water-table condition). All other cells are simulated as being confined (artesian condition). If the hydraulic head in a cell in a confined condition falls below the elevation of the top of the cell during a transient simulation, that cell converts to an unconfined condition, and thus allows the simulated water table to transfer to the next lower layer in the model as water levels decline. In the simulations described in this report, layer 6 was the lowest layer that was allowed to convert to unconfined conditions.

The simulated predevelopment condition was assumed to exist prior to 1901. The 1901 to 1994 historical period was simulated using 59 stress periods. The historical period from 1901 through 1960 was simulated in 12 5-year stress periods, from 1961 through 1979 in 19 1-year stress periods, and from 1980 to 1994 in 28 summer and winter stress periods, with the first stress period in 1980 encompassing 9 months.

Use of a Geographic Information System to Construct the Model

The model is designed to be flexible and adaptive to new information. The use of a Geographic Information System (GIS) as a data-base manager is essential to assimilate the massive quantities of information needed for the current model and to meet the requirement that the model evolve as more information becomes available.

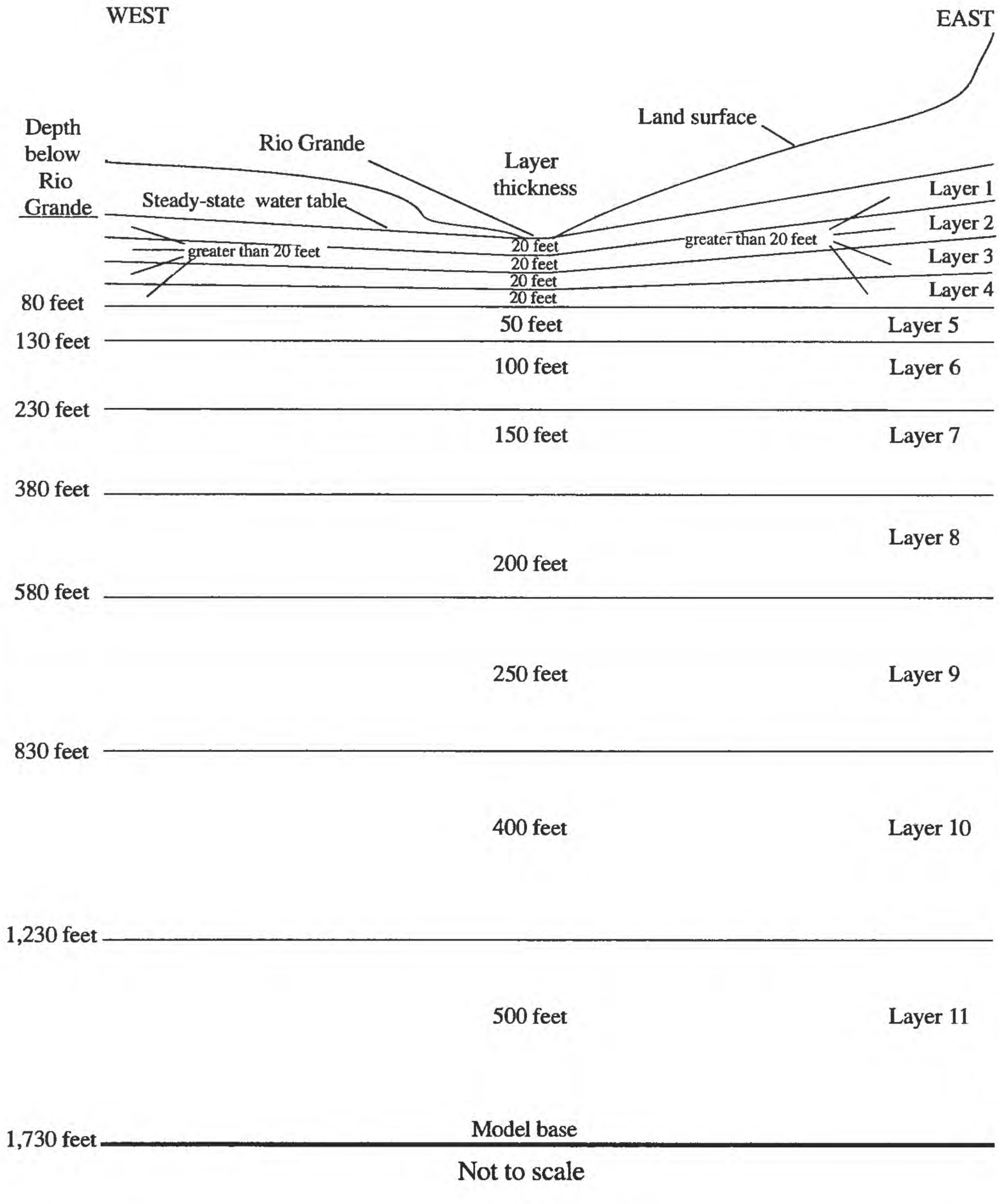
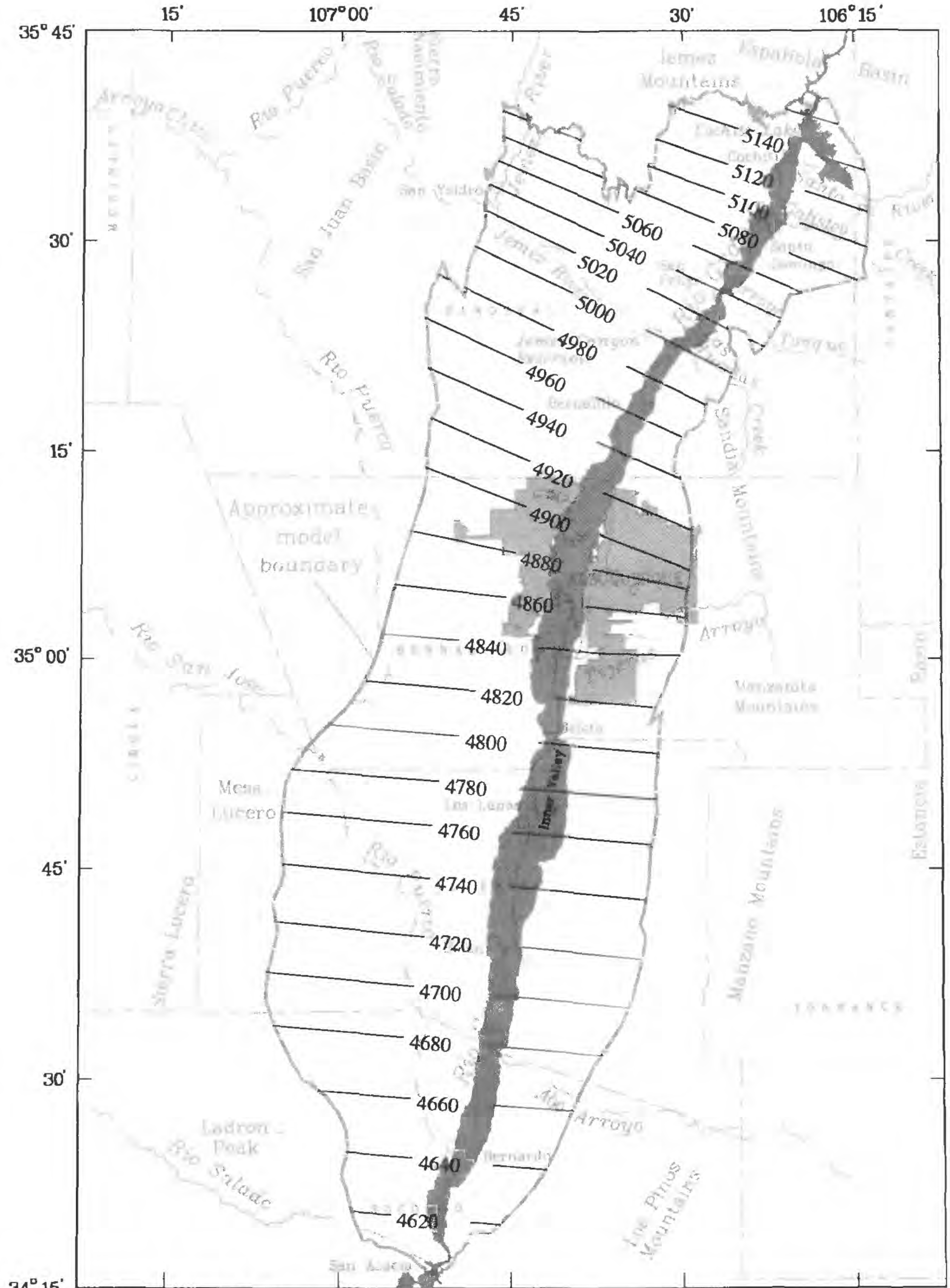


Figure 2.--Configuration of model layers.



Base credit is contained in the introduction section of the text

0 10 20 30 MILES

0 10 20 30 KILOMETERS

EXPLANATION

—4620— ALTITUDE OF BASE OF MODEL LAYER 4—Contour interval 20 feet. Datum is sea level

Figure 3.—Altitude of base of layer 4 in the ground-water flow model of the Albuquerque Basin.

As will be described in later sections, the GIS was used to prepare model input for model layer top and bottom elevations, horizontal hydraulic-conductivity and transmissivity values, vertical leakance (McDonald and Harbaugh, 1988, chap. 5, p. 12), and storage coefficients for each of the 11 model layers. Simulated underflow to and from the basin was distributed by the GIS along the basin margin, as was mountain-front and tributary recharge. Evapotranspiration estimates were constructed from riparian vegetation data provided by the National Biological Survey (formerly part of the U.S. Fish and Wildlife Service) and land-cover data provided by the Bureau of Reclamation for 1935, 1975, 1989, and 1992. These same agencies provided GIS data that were used to estimate agricultural irrigation-return flow to ground water for 1935, 1975, and 1992, and to locate and classify the channels of the Rio Grande, irrigation canals, laterals, ditches, and drains for 1935, 1975, 1989, and 1992. Topographic data that were needed in conjunction with the land-use/land-cover and hydrography data were obtained from U.S. Geological Survey 30-meter and 3-arc-second Digital Elevation Models. Population data from the U.S. Department of Commerce and GIS data for utility-service areas from the City of Albuquerque for 1970, 1980, and 1990 were used to compute volumes of privately supplied water, imported utility-service water, and septic returns. Finally, the GIS was used to organize the historical ground-water-withdrawal data provided by the City of Albuquerque and the New Mexico State Engineer Office and to format those data for model input. GIS data that were used directly by the model are itemized in table 1.

A GIS macro (a combination of GIS and relational-data-base command steps and Fortran programs) was used to generate GIS representations of the finite-difference model grid as geo-referenced point, line, and polygon topological features. The polygon and point (at the centroid of each polygon cell) representations are used to sample data layers and generate model input. The line representation is useful for rapid plotting of the grid. The macro reads a grid-specification file as input. The following grid-specification file was used to generate the grid for this model of the Albuquerque Basin. Length units are in meters and the angle of rotation is in degrees counterclockwise from local true north. The projection of the model grid is, as are all GIS data used in the model, a Lambert Conformal Conic projection based on the Clarke 1866 spheroid, 1927 horizontal datum, with principal parallels of 33 and 45 degrees north latitude, a central meridian of 106 degrees west longitude, a Y-coordinate origin of 30 degrees north latitude, and no linear X-coordinate or Y-coordinate offsets (false easting or northing). Free-format input in the specification file allows the use of multipliers for repeated dimensions of rows or columns. Explanations, which are not to be included in the file, begin with a backslash (\). Lines that are blank except for comments should not be included in the file.

```
244 178         \Number of rows and columns in the finite-difference grid
0.0             \Angle of rotation about the grid origin (upper left corner of row=1,
                \column=1)
-101171 629654  \Map-unit coordinates of the origin
47*1000,2*750,500,400,3*300,102*200,3*300,400,500,2*750,81*1000
                \Free-format dimensions of the rows (Y dimension)
END             \Required literal string used for error checking
31*1000,2*750,500,400,3*300,112*200,3*300,400,500,2*750,21*1000
                \Free-format dimensions of the columns (X dimension)
END             \Required literal string for error checking
```

Table 1.--Geographic information system data that were incorporated into the three-dimensional ground-water-flow model of the Albuquerque Basin

[USGS: U.S. Geological Survey; NMD: USGS National Mapping Division; DLG: digital line graph; NBS: National Biological Survey; BOR: Bureau of Reclamation; DEM: digital elevation model; GWSI: Ground Water Site Inventory data base; KAFB: Kirtland Air Force Base; SEO: New Mexico State Engineer Office; Census: U.S. Bureau of Census]

Data type	Source scale	Source
Finite-difference model grid	Computer generated	USGS
Hydrography	1:100,000	NMD DLG
River, canals, and drains	1:24,000	1935 NBS
	1:12,000	1975 BOR
	1:24,000	1989 NBS
	1:12,000	1992 BOR
Land cover	1:24,000	1935 NBS
	1:12,000	1975 BOR
	1:12,000	1992 BOR
Riparian vegetation	1:24,000	1935 NBS
	1:24,000	1989 NBS
Topography	1:250,000	NMD DEM
	1:24,000	NMD DEM
	1:24,000	USGS (digitized)
Faults	1:500,000	USGS (Dane and Bachman, 1965)
	1:190,000	USGS (from Kelley, 1977)
	1:62,500	USGS (from Titus, 1980)
	1:100,000	Hawley and Haase (1992)
Aquifer physical properties	1:100,000 (approximate)	USGS
Mountain-front and tributary recharge	1:100,000 (approximate)	USGS
Ground-water inflow	1:100,000 (approximate)	USGS
Water wells	1:24,000	USGS GWSI
City production wells	Various	City of Albuquerque
KAFB wells	Surveyed	KAFB
Rio Rancho wells	Surveyed	Rio Rancho Utilities
State-permitted withdrawal wells	Unknown	SEO
City monitor wells	Surveyed	City of Albuquerque
Population	1:100,000	1970,1980,1990 census
Albuquerque annexation history	1:2,400	City of Albuquerque
Water utility areas	Various	City of Albuquerque
Sewered areas	Various	City of Albuquerque
Septic systems	Various	Bernalillo County

The significance of the angle of rotation being relative to local true north can be seen on plate 1: the model rows and columns do not parallel graticule lines of either latitude or longitude. The model grid and all of the text and annotation are square with the plate edges while the edges of the base and graticule lines are not. The base map is distorted by the Lambert projection with respect to the grid and explanatory text. As long as the distortion of area remains relatively small (less than 0.1 percent per cell, in this case) and the cell otherwise is accurately geo-referenced, this error is far below the range of other errors encountered in the modeling process.

Interfaces between the GIS and the numerical model allow detailed spatial resolution on a regional scale. Many of the information layers used as model input have accurately mapped and classified features as small as 1 acre and a few have mapped features as small as a few tens of square feet. Although these small features are well beyond the resolution of the current model, they are easily reclassified by weighted averaging to the scale of the cell dimensions. Enhanced model detail and accuracy result from the ability of the GIS to manage information about small features.

A second GIS macro was used to extract data from the GIS data layers and format the data for input to the model. The macro can process polygon, line, or point features and can compute either totals or weighted averages for each model cell. For polygons the average is area-weighted; for lines the average is length-weighted; and for points the average is count-weighted. The output of the macro is an array of data in a user-defined format with an array header as required by the McDonald and Harbaugh (1988) model.

Boundary Conditions

Boundary types fall into three main categories: (1) boundaries that define flow conditions; (2) internal boundaries that affect flow; and (3) lateral or external boundaries. Boundaries that define flow in the Santa Fe Group aquifer system are represented in the model in two ways: specified flow or head-dependent flow. At a specified-flow boundary water is recharged or discharged independent of simulated hydraulic head. No flow is a special case of a specified-flow boundary. A no-flow boundary is implied at the base of the model (fig. 2). Ground-water withdrawal, septic-field return flow, irrigation seepage, ground-water inflow from adjacent basins, and mountain-front and tributary recharge are all simulated as specified-flow boundaries. 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 the stage of a river. Special types of head-dependent flow boundaries, where water is allowed only to discharge, are used for drains and evapotranspiration.

Surface-water boundaries are points of recharge to and/or discharge from the aquifer system. These boundaries include the Rio Grande, canals, drains, tributary streams, and reservoirs. The Rio Grande and canals in the inner valley are represented in the model as head-dependent flow boundaries. These boundaries allow leakage either to or from ground water, depending on the head in the aquifer. They simulate leakage between the river or canals and the aquifer as a function of hydraulic head in the aquifer, river or canal stage, altitude of the river or canal bed, and hydraulic conductance of the river or canal bed. These boundaries are discussed in detail in the River, Canal, and Reservoir Leakage section of this report. Drains in the inner Rio

Grande Valley are represented as head-dependent flow boundaries where leakage is allowed only from the aquifer to the drain. These boundaries simulate leakage as a function of hydraulic head in the aquifer, altitude of the drain, and hydraulic conductance of the drain/aquifer interface. They are discussed in detail in the Drain Seepage section. Recharge from tributary streams is simulated as specified-flow boundaries. Recharge specified for the tributary steams is discussed in the Mountain-Front and Tributary Recharge section.

Evapotranspiration is simulated in the model as a head-dependent flow boundary where flow is allowed only from the aquifer. These boundaries simulate evapotranspiration as a function of hydraulic head in the aquifer, altitude of land surface, and a maximum rate of evapotranspiration (Emery, 1970). The maximum evapotranspiration rate is achieved only when the simulated head in the aquifer is equal to or greater than land surface. The evapotranspiration rate is reduced linearly to zero at the specified extinction depth of 20 feet below land surface assumed for this model. The calculation of evapotranspiration used in the model is discussed in detail in the Riparian and Wetland Evapotranspiration section.

Internal geologic boundaries within the Santa Fe Group aquifer system affect ground-water flow within the aquifer. These boundaries include faults and contacts between basin-fill material of differing hydraulic characteristics. The simulation of these boundaries in the model is discussed in the Hydraulic Characteristics section of this report.

The lateral boundaries of the model are shown in figure 4. La Bajada Fault, which delineates an uplift of Santa Fe Group basin-fill material in the Española Basin relative to the Albuquerque Basin, forms the northeastern model boundary. This boundary is represented in the model as a specified flow to simulate ground-water inflow from the Española Basin. The boundary in the model between the northern end of the Sandia Uplift and La Bajada Fault follows a series of faults separating the Hagen Embayment from the remainder of the Albuquerque Basin. This boundary is represented in the model as a specified flow to simulate recharge from the Hagen Embayment. The Sandia, Manzano, and Los Pinos Uplifts form the central-eastern boundary of the model. Within the Albuquerque area, that boundary is formed by the Sandia Fault. South of Albuquerque, the eastern model boundary is along the Hubbell Springs and East Joyita Faults because of the relatively thin saturation of the Santa Fe Group sediments on the Joyita-Hubbell Bench. The Hubbell Springs and East Joyita Faults (referred to as the Ojuelas Fault by Titus, 1963) form a distinct hydrologic boundary, as shown by the water-table contours constructed by Titus (1963, pl. 3). The central-eastern boundary is represented in the model as a specified flow to simulate mountain-front recharge. The Joyita and Socorro Uplifts form the southern model boundary where the eastern and western structural boundaries of the Albuquerque Basin converge. This boundary is represented in the model as a no-flow boundary. The cells that have no flow along the southern boundary are shown on plate 1. Recharge along this boundary results from tributary recharge from the (southernmost) Rio Salado, rather than recharge from or discharge to adjacent areas. A line of faults within the Santa Fe Group on the west side of the basin forms the western model boundary. The Santa Fe and Coyote Faults form this boundary in the southern part of the basin and the Sand Hill Fault forms this boundary in the Albuquerque area. These faults are well cemented (front cover photograph) and restrict ground-water flow relative to the adjacent Santa Fe Group. Most of the western boundary is represented in the model as a specified flow to simulate ground-water inflow from adjacent areas to the west. Two intervals along this boundary are represented as no flow (pl. 1) because the majority of recharge is from the Rio Puerco, just inside the model boundary. The faults along the Nacimiento Uplift form the northwestern model boundary. The northwestern boundary is based on the faults shown by Kelley (1977, fig. 19); therefore it does not follow the extent of the Cenozoic basin-fill deposits (Dane and Bachman, 1965), which was used to define the boundary of the Albuquerque Basin shown on plate 1. This boundary is represented in the model as a specified flow to simulate ground-water inflow from adjacent basins. The surficial contact of Santa Fe Group material with Cenozoic volcanic rocks of the Jemez Uplift forms the northern model boundary. This boundary is represented in the model as a specified flow to simulate ground-water inflow from the Jemez Mountains. Recharge specified for the lateral model boundaries is discussed in the Mountain-Front and Tributary Recharge and the Ground-Water Inflow from Adjacent Basins sections of this report.

Mountain-Front and Tributary Recharge

Two types of peripheral and intrabasin recharge are simulated: mountain front and tributary. Mountain-front recharge is considered to be sheet runoff, shallow underflow, or minor surface inflow from adjacent highlands that infiltrates into piedmont-slope deposits and eventually becomes ground water in the Albuquerque Basin. Alluvium veneering rock pediments immediately adjacent to mountain fronts and thick fan deposits further basinward are the two major piedmont-slope components. Tributary recharge results from channel loss from major streams and arroyos that have flows extending considerable distances into the basin. Estimated rates of mountain-front and tributary recharge are shown in figure 5. The rates of peripheral and intrabasin recharge are similar to the estimates reported in Kernodle and others (1987), with several exceptions. The primary exception is that recharge is simulated to the Santo Domingo Basin (fig. 4), an area that was excluded from the earlier model. Other major changes are reductions of 50 percent in the estimated rates of tributary recharge from the Jemez River and southern Rio Salado.

Simulated mountain-front recharge and tributary recharge were varied for each simulated stress period in proportion to the departure from long-term mean annual precipitation for all reporting stations in and near the basin. Departures (table 2) were computed for 5-year intervals prior to 1961 and for 1-year intervals thereafter. Total mountain-front and tributary recharge uncorrected for departures was simulated to be about 110,000 acre-feet per year (152 cubic feet per second in fig. 5).

Mountain-front and tributary recharge is applied to the uppermost active layer of the model by using the recharge package of MODFLOW (McDonald and Harbaugh, 1988, chap. 6). It is horizontally distributed to the model cells in proportion to the length of each stream reach or boundary line segment within each model cell relative to the overall length of the boundary segments shown in figure 5. To simulate intermittent flow, tributary recharge per unit length from the Jemez River was linearly decreased from 0.85 cubic foot per second per mile at the confluence of the Rio Salado with the Jemez River to 0.10 cubic foot per second per mile at the confluence of the Jemez River with the Rio Grande.

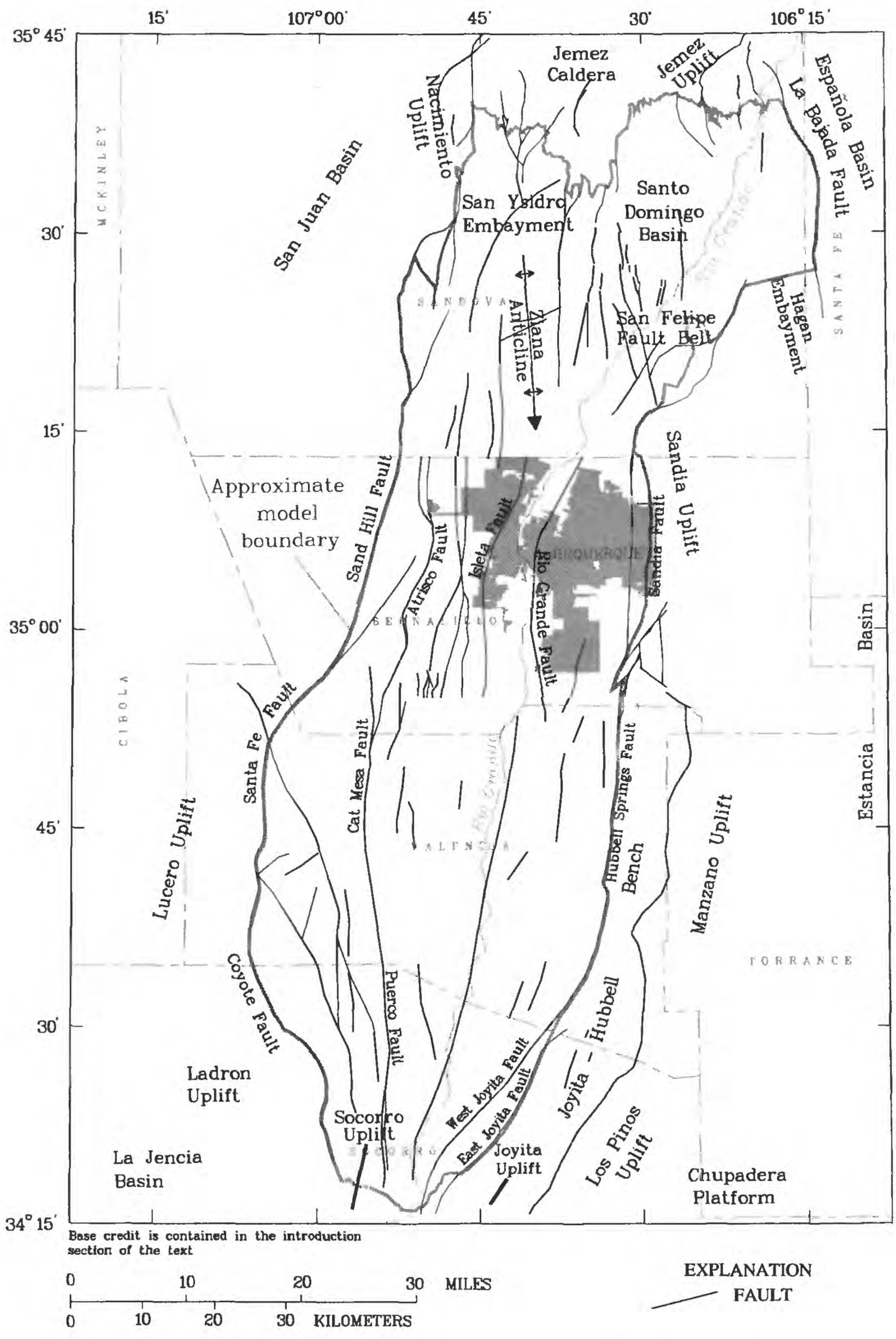
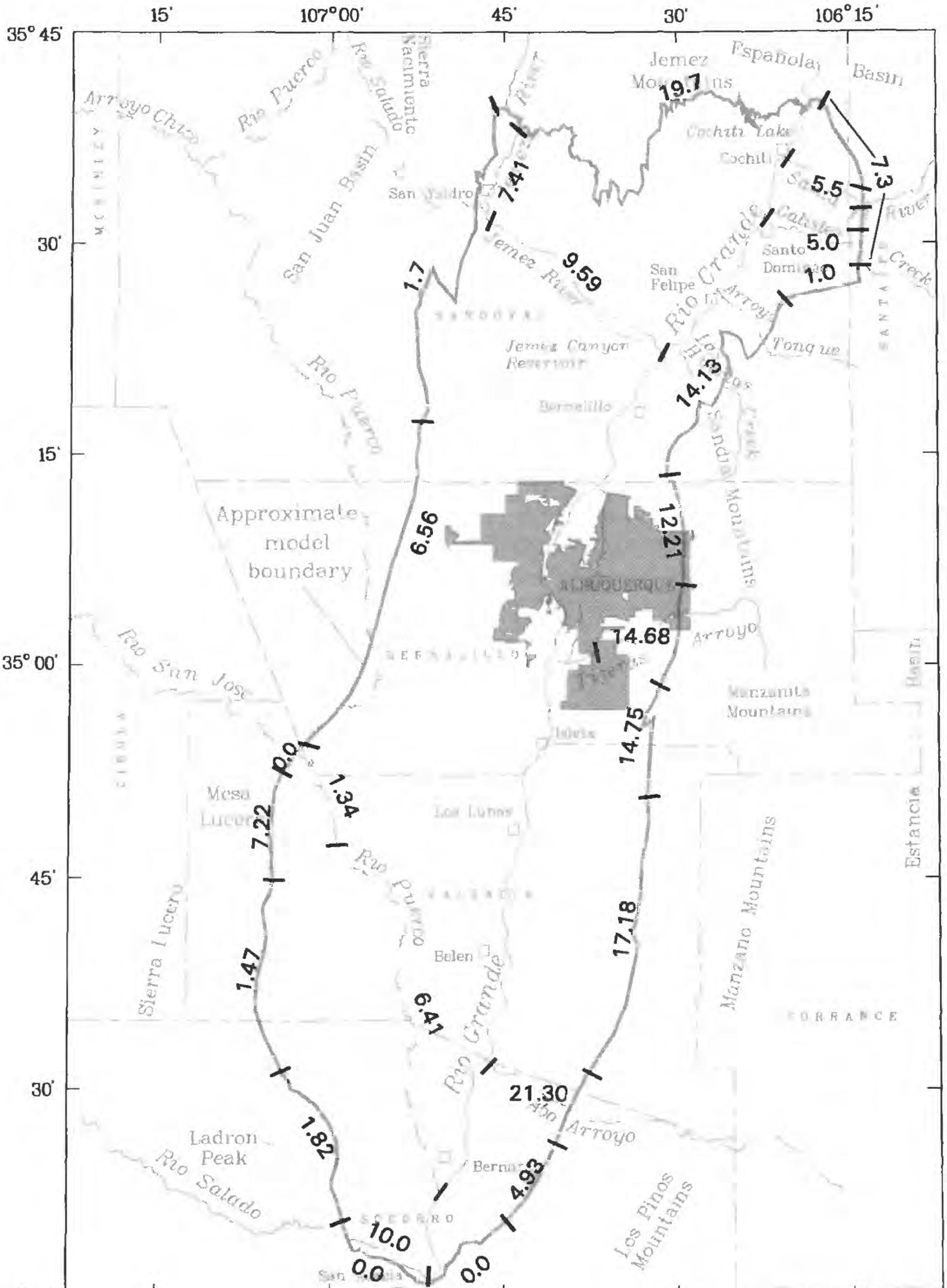


Figure 4.—Major tectonic features defining the Albuquerque Basin model boundary (geology modified from Kelley, 1977; Hawley and Haase, 1992).



Base credit is contained in the introduction section of the text

0 10 20 30 MILES

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EXPLANATION

/ 1.47 / MOUNTAIN–FRONT OR TRIBUTARY RECHARGE, OR INFLOW FROM ADJACENT BASINS, IN CUBIC FEET PER SECOND, WITHIN INDICATED REACH OR MODEL BOUNDARY—Values of mountain–front and tributary recharge are inside model boundary. Values of inflow from adjacent basins are outside model boundary

Figure 5.—Estimated mountain–front and tributary recharge to the Albuquerque Basin, and inflow from adjacent basins (modified from Thorn and others, 1993, fig. 38).

Table 2.--Departures from mean annual precipitation used in simulations of the Albuquerque Basin

Year(s)	Departure from mean annual precipi-tation, in percent	Year	Departure from mean annual precipi-tation, in percent	Year	Departure from mean annual precipi-tation, in percent
1901-05	-3	1964	-13	1979	5
1906-10	-10	1965	17	1980	-20
1911-15	11	1966	-30	1981	-12
1916-20	3	1967	-2	1982	-2
1921-25	-18	1968	6	1983	-7
1926-30	5	1969	26	1984	27
1931-35	20	1970	-14	1985	36
1936-40	4	1971	4	1986	50
1941-45	14	1972	21	1987	-7
1946-50	-20	1973	14	1988	34
1951-55	-22	1974	10	1989	-27
1956-60	-2	1975	-4	1990	27
1961	-11	1976	-37	1991	37
1962	-24	1977	-11	1992	18
1963	-12	1978	25	[1]1993-2020	0

[1]Annual precipitation data, from which departures are calculated, were not available for 1993 in time for inclusion in the historical simulations. Precipitation for 1993 and beyond were assumed not to depart from the mean annual.

Ground-Water Inflow from Adjacent Basins

Simulated ground-water inflow from basins adjacent to the Albuquerque Basin is shown in figure 5. As with the simulation of mountain-front and tributary recharge, simulated inflow from adjacent basins is horizontally distributed to the model cells in proportion to the length of each boundary line segment within each model cell relative to the overall length of the boundary segments shown in figure 5. The simulation of inflow from adjacent basins differs from the simulation of mountain-front recharge and tributary recharge in two ways. First, it enters the model in layers 5 through 9 rather than in the uppermost active layer. The simulated inflow is distributed to the layers in proportion to the layer thicknesses. Second, it is not adjusted for departures from long-term average precipitation because the inflow at depth probably is not significantly affected by short-term changes in climate or the surface-water system. Inflow from adjacent basins is simulated as constant flows using the well package of MODFLOW (McDonald and Harbaugh, 1988, chap. 8).

Estimated inflow from the Española Basin (McAda and Wasiolek, 1988, p. 36; Thorn and others, 1993, p. 85) of 12,600 acre-feet per year was divided into two components by apportioning it to either side of the Rio Grande. The amount to the east of the Rio Grande is 5,300 acre-feet per year (7.3 cubic feet per second in fig. 5). The remainder, 7,300 acre-feet per year, was included in the total amount of 14,300 acre-feet per year (19.7 cubic feet per second in fig. 5) entering the basin from the north in the vicinity of the Jemez Mountains. The inflow from the San Juan Basin was estimated to be 1,200 acre-feet per year (1.7 cubic feet per second in fig. 5; Frenzel and Lyford, 1982, figs. 9, 11; Thorn and others, 1993, p. 85). Estimated inflow in the vicinity of Mesa Lucero, Sierra Lucero, and Ladron Peak was estimated to be approximately 7,600 acre-feet per year (7.22, 1.47, and 1.82 cubic feet per second, respectively, in fig. 5; Kernodle and Scott, 1986, fig. 5).

Irrigation Seepage

The historical record of irrigated agriculture in the middle Rio Grande Valley is a complex function of social and economic pressures and environmental changes. A brief description of the history of irrigation in the middle Rio Grande Valley can be found in Thorn and others (1993, p. 4-7). Table 3 lists the total irrigated acres in the middle Rio Grande Valley within the Albuquerque Basin for 1935, 1955, 1975, 1982, and 1992.

Agriculture in the middle Rio Grande Valley is almost completely dependent on irrigation; surface-water diversions make up the deficit between summer rainfall (about 4 inches) and water requirements of the crop (about 40 inches). In addition, fields are routinely flooded each spring to leach out salts accumulated from the previous irrigation season. As a result of these practices, approximately one-third of the water applied to agricultural fields seeps through the soil profile and recharges shallow ground water in the flood-plain alluvial aquifer. Throughout the simulation period, this irrigation seepage rate was assumed to be 1 acre-foot per acre per year (Wilson, 1992, p. 32).

Model simulation of irrigation from 1901 to 1960 used 1935 land-cover information obtained from the National Biological Survey on the distribution and areal extent of riparian, wetland, urban, and agricultural land. These data were intended to be used in riparian and wetland studies. Because the mapped classification includes the category of agricultural land use, however, these data are suitable for use in the model. The data were compiled from aerial photographs and entered into the GIS at a scale of 1:24,000. The minimum mapped unit is 1 acre.

Table 3.--Irrigated acreage within the Rio Grande Valley in the Albuquerque Basin, 1935-1992

[NBS: National Biological Survey; BOR: Bureau of Reclamation; GIRAS: U.S. Geological Survey National Mapping Division's Geographic Information Retrieval and Analysis System]

Year	Acres	Source	Source scale	Crop type distinguished
1935	44,011	NBS	1:24,000	No
[1]1955	48,921	BOR	1:12,000	No
1975	56,468	BOR	1:12,000	Partially
[1]1982	59,500	GIRAS	1:250,000	Partially
1992	48,567	BOR	1:12,000	Yes

[1]Not used or not available for use in current model.

The period from 1901 to the late 1920's and early 1930's was characterized by increasing waterlogging and retirement of agricultural land. The Middle Rio Grande Conservancy District (MRGCD) was formed in 1925 to construct drains to lower the shallow water table, oversee a unified system of canals and laterals, and control flooding. Most of the MRGCD infrastructure was operational by 1935 when the aerial photographs used by the National Biological Survey were taken. However, land-use patterns and categories largely still reflected pre-MRGCD conditions.

Bureau of Reclamation land-cover data for 1975 were used to simulate irrigation seepage for 1960 to 1980. Similarly, Bureau land-cover data for 1992 were used to simulate irrigation seepage for 1980 to spring 1994. The Bureau mapped these data at 1:12,000 scale and transferred them to 1:24,000-scale maps for digitizing into the GIS. The minimum mapped unit is 1 acre in size.

Irrigation seepage to shallow ground water was simulated, along with mountain-front and tributary recharge and septic-system return flow, using the recharge module of the McDonald and Harbaugh (1988) model. No attempt was made to adjust the seepage rate for crop type. The model requires a rate (velocity) of recharge for each cell that received recharge. The rate of seepage was calculated for each cell by multiplying the irrigated acreage within each cell by the rate of seepage (1 acre-foot per acre per year; Wilson, 1992, p. 32) and then dividing by the total area of the cell and the number of days over which the recharge is applied. For stress periods of a year or longer, the number of days was 365.25. For stress periods that were seasonal, the summer recharge was based on 183 days and the winter recharge rate for irrigation seepage was set to zero.

Septic-Field Return Flow

Domestic water supply and disposal falls into four possible categories in current order of decreasing population (Neal Weinberg, City of Albuquerque, written commun., 1992; U.S. Bureau of Census, 1990): (1) public (utility) supply and public disposal; (2) private supply and private disposal; (3) public supply and private disposal; and (4) private supply and public disposal. The number of people in the basin in the fourth category was believed to be small in 1990 but may increase in response to recent (1994) trends in sewer-line expansion as well as City of Albuquerque and Bernalillo County joint legislation requiring sewer connection prior to or concurrent with water-supply connection. Estimates of the 1970, 1980, and 1990 populations in the second and third categories, along with total populations in the modeled area, are shown in table 4. Presently, two household categories have an effect on ground-water resources: (1) removal of water from a moderate depth (about 200 feet) and introduction of 75 percent of that water at the water table (category 2); and (2) importation of the household supply and introduction of 75 percent of that water at the water table (category 3).

Table 4.–Population by water supply and disposal categories: 1970, 1980, and 1990

Category	1970	1980	1990
Population within modeled area	334,007	455,550	551,586
Self-supplied private domestic on septic systems	103,906	49,741	65,480
Utility-supplied domestic on septic systems (Bernalillo County)	1,420	39,223	53,785

In areas not served by sewer systems, domestic wastewater is discharged to on-site septic systems. U.S. Department of Commerce census tract data were used to determine population densities throughout the Albuquerque Basin for 1970, 1980, and 1990. Digital population data for years prior to 1970 were not available. Areas served by sewer systems (table 1) and uninhabited areas such as the Rio Grande Floodway were excluded. For the remaining populated area, the population within each model cell was assumed to discharge 75 gallons per day per person (75 percent of estimated rural per capita domestic use) to the uppermost active model layer. Septic-return flow was simulated for the periods 1961-1974, 1975-1984, and 1985-1994 using 1970, 1980, and 1990 census data, respectively. Septic-return flow was not simulated prior to 1961. Septic fields prior to 1960 primarily were located in the inner Rio Grande Valley. Because the Rio Grande surface-water system is capable of maintaining ground-water levels near land surface in the inner valley, septic-return flow was assumed to have an insignificant effect on water levels for the early stress periods.

River, Canal, and Reservoir Leakage

The surface-water system in the inner valley of the Rio Grande includes the river itself as well as reservoirs, irrigation canals, laterals, ditches, and wasteways. These are simulated as head-dependent flow boundaries. The system also includes drains, which are discussed in the Drain Seepage section. The geometry and hydraulic properties of the surface-water system have changed over time. For example, the channel of the Rio Grande was substantially narrowed in the 1950's by the Bureau of Reclamation to increase flow velocity and prevent channel aggradation. The higher velocity and reduced sediment deposition probably resulted in a higher hydraulic conductivity of the streambed, although there is no record or direct evidence that this is true.

The system of ditches and community acequias that predated the MRGCD was local in scale and operation, but effective enough overall to support as much as 124,800 acres of irrigated land in the middle Rio Grande Valley in about 1880 (Stafford and others, 1938, p. 71). Each local acequia system had its own riverside diversion that required annual replacement or major overhaul. The ditches were maintained as well. The integrated MRGCD system, constructed in the early 1930's, that replaced the traditional acequia system was fed by four low-level diversion dams assisted by a few riverside diversions on the Rio Grande. One of these low-level dams (Cochiti) has since been inundated and replaced by a large flood-control dam and reservoir of the same name. In the 1960's, riverside diversions at Corrales and Atrisco (just south of the Interstate Highway 40 Rio Grande crossing; pl. 1) were replaced by inverted siphons running under the river from riverside drains that are converted seasonally into conveyance channels.

In the current (1994) system, each diversion feeds main and high-line canals that serve about 30 downstream miles of river valley on either side of the river. The river valley averages about 5 miles in width. In general, canals feed laterals that, in turn, feed ditches. Operation of the system is highly complex and operated much in the fashion of the older system of acequias and mayordomos (ditchmasters). Requests for irrigation water for a certain day are placed with the local "ditch rider" who coordinates diversions so that sufficient hydraulic head can be maintained in the ditches. Good records are kept at points of major diversion, but few operation records are kept thereafter within the system. In the middle Rio Grande Valley, irrigation diversions usually begin in mid- to late March and end in October or shortly after the first killing frost.

For 1901-1935, only the channel of the Rio Grande was simulated. National Biological Survey riparian and wetland digital data were used to determine the position of the river. For 1935-1960, the same data also were used to locate irrigation conveyance channels (no sub-classification was available for canals, laterals, and ditches).

Hydrography data for 1975 and 1992, obtained from the Bureau of Reclamation, were used to describe the channel of the Rio Grande and the irrigation distribution network for 1961-1980 and 1980-1994. These GIS data bases distinguish between canals, laterals, and ditches.

Values of streambed and canal-bed hydraulic conductivity were obtained from the Bureau of Reclamation (Steve Hansen, Bureau of Reclamation, written commun., 1993 and 1994). Tests conducted (and continuing) by the Bureau indicate an average hydraulic conductivity of 0.5 foot per day for the streambed. Controlled canal seepage tests conducted in the fall of 1993 indicate an average canal-bed hydraulic conductivity of 0.15 foot per day. These values of hydraulic conductivity were used in the model simulations. Thickness of the river and canal beds was assumed to be 1 foot.

The bed of the Rio Grande was simulated as being 3 feet below the water surface, beds of irrigation conveyance channels as being 2 feet below the water surface, and water elevation in irrigation conveyance channels as being 2 feet above land surface. When features could be identified (from 1975 and 1992 Bureau of Reclamation data used for 1961-1994 in the simulations), canals were simulated as 10 feet wide, laterals as 5 feet wide, and ditches as 2 feet wide; otherwise, all irrigation conveyance channels were simulated as 5 feet wide. The bed hydraulic conductance (length times width times hydraulic conductivity divided by bed thickness) was computed separately for the river and conveyance channels for each model cell so that elevation differences were preserved.

The model requires that leakage be calculated for an entire stress period. Because canals are in use only for half the year (during the summer season), the hydraulic conductances of the conveyance channel beds were adjusted to compensate for stress period lengths greater than one-half year. For stress periods of 1 or more years, the hydraulic conductances were multiplied by 0.50 (in use for 183 out of 365.25 days). For the three-quarters-year stress period (from January 1 to September 30, 1980), which included the summer season, the conductances were multiplied by 0.67 (in use for 183 out of 273.25 days). Values of conveyance-channel conductances were not adjusted for summer season stress periods. Conveyance-channel leakage was not simulated for winter season stress periods. Leakage from the Rio Grande was simulated throughout the year.

Leakage from Cochiti Lake, which began storing water in November 1973, is simulated in the model as a head-dependent flow boundary beginning in the 1974 stress period. The stage in Cochiti Lake was assumed to be the minimum pool elevation of 5,323 feet above sea level. Changes in pool elevation were not simulated. The hydraulic conductivity of the reservoir bottom was assumed to be 0.15 foot per day and the thickness of the reservoir-bottom material was assumed to be 1 foot. Jemez Canyon Reservoir was built for a 1-day detention of flows greater than 30 cubic feet per second for sediment control (Cruz and others, 1994, p. 158). Most of the time prior to 1979, no water was stored. Although the reservoir has had some major storage periods since 1979, the transient effects of Jemez Canyon Reservoir are not simulated in the current model.

Drain Seepage

A basinwide network of drains was constructed by the MRGCD in the middle Rio Grande Valley during the early 1930's to correct serious problems of waterlogged and alkaline soils (see back cover). The network was reconstructed by the Bureau of Reclamation in the mid-1950's to correct for channel aggradation of the Rio Grande. Riverside drains were constructed to intercept leakage from the Rio Grande toward lowland areas in the valley at altitudes less than that of the streambed. Interior drains removed water from swamps and saturated fields and discharged this water to riverside drains. With continued lowering of the water table in the Albuquerque area due to ground-water withdrawal, most interior drains in this area have become dysfunctional and serve only as conveyances for storm runoff or as wasteways for excess irrigation water.

Drains were added to the model simulations beginning in 1935. The National Biological Survey's 1935 riparian and wetland GIS data base was used to describe the drain network for 1935-1960. The Bureau of Reclamation's 1975 and 1992 hydrography GIS data bases were used to describe the network for 1960-1984 and 1985-1994, respectively.

All drains were simulated as being 5 feet wide and constructed at a grade elevation 5 feet below land surface. The GIS was used to determine the total length and average altitude of drains within each cell. Altitude data were obtained from U.S. Geological Survey National Mapping Division 30-meter and 3-arc-second Digital Elevation Models (DEM's). The hydraulic conductivity of the bed of the drains was simulated as 1 foot per day.

Riparian and Wetland Evapotranspiration

The riparian bosque (forest) in the middle Rio Grande Valley has undergone great changes during the last century. Photographs taken from the late 1880's to the early 1900's (inside back cover) show that the valley was mostly agricultural or barren with very few trees. In the late 1800's, irrigation diversions began to cause waterlogging of large areas of agricultural land (back cover). In addition, reduction of flow in the Rio Grande caused the channel to aggrade to a level higher than much of the adjacent valley. By the 1920's, much agricultural land had become either swamp or bosque. The process was reversed by the completion of riverside and interior drains by the MRGCD in the early 1930's. Wetlands and swampy land were drained and converted to agricultural or urban use. Completion of levees and channel-control structures in the mid-1950's created a protected and undisturbed bosque habitat bordering the Rio Grande.

Only riparian and wetland evapotranspiration was simulated by the model. Evapotranspiration from urban (such as golf courses, parks, and yards) and agricultural land comes from applied irrigation water, and therefore is not simulated. Except for swampy areas, evaporation from bodies of open water is assumed to come from the surface water, external to the ground-water-flow model. Riparian transpiration was limited to 2.6 feet per year (weighted average rate from Thorn and others, 1993, table 6, p. 88), decreasing linearly to zero at a depth to ground water of 20 feet or more. The maximum evapotranspiration rate was not adjusted for vegetation type or maturity. Evaporation from swampy land was limited to 5 feet per year.

National Biological Survey riparian and wetlands digital data for 1935 were used in the simulation of evapotranspiration in the valley for the period 1901-1960. For 1960-1980, National Biological Survey riparian and wetlands digital data for 1989 were used for the area within the Rio Grande Floodway and Bureau of Reclamation digital land-cover data for 1975 were used for the valley area outside of the floodway. Similarly, for 1980-1994, National Biological Survey riparian and wetlands digital data for 1989 were used for the area within the Rio Grande Floodway and Bureau of Reclamation digital land-cover data for 1992 were used for the valley area outside of the floodway.

In the simulations using seasonal stress periods, evapotranspiration is assumed to occur during only the summer season. The maximum rate of evapotranspiration for these stress periods is assumed to be 2.6 feet per stress period length (2.6 feet per one-half year or 0.014 foot per day) for the summer and zero for the winter. For stress periods greater than one-half year, the maximum rate of evapotranspiration is reduced to compensate for evapotranspiration occurring during only the summer season. For example, the maximum evapotranspiration rate for a 1-year stress period would be 2.6 feet per year or 0.0071 foot per day.

Captured or salvaged evapotranspiration (depending on individual perspective regarding riparian vegetation) is that amount of reduction in evapotranspiration that is caused by ground-water withdrawals. Ground-water withdrawals cause a lowering of the water table in the flood plain. This lowering is presumed to diminish the ability of phreatophytes to tap shallow ground water, thus reducing the amount that is consumed or evaporates. Amounts of salvaged evapotranspiration are discussed in the Initial Conditions and Historical Simulations and the Projected Simulations to 2020 sections of this report.

The evapotranspiration package of MODFLOW (McDonald and Harbaugh, 1988, chap. 10) applies the model-calculated evapotranspiration rate to the entire area of a model cell. In some cases, however, the area contributing to evapotranspiration does not cover an entire model cell. Therefore, the maximum evapotranspiration rate applied to each cell was adjusted by the proportion of the area of each model cell that contributes to evapotranspiration.

Ground-Water Withdrawals

Ground-water withdrawal in the Albuquerque Basin was simulated beginning in 1901. Initial withdrawal was simulated to be from the few wells documented by Lee (1907, p. 34-37). Many private domestic wells also existed at this time. These early domestic wells were assumed to be shallow and located primarily in the inner Rio Grande Valley. Because the Rio Grande surface-water system was capable of maintaining ground-water levels near land surface in the inner valley, domestic well withdrawal was assumed to have an insignificant effect on water levels for the early stress periods. However, this assumption does affect the water budget within the inner valley. Withdrawal by private domestic wells in the valley would be offset in the simulation by a nearly equivalent volume of flow depletion in the Rio Grande plus reduced evapotranspiration. Withdrawal by private domestic wells was simulated beginning in the 1961 stress period.

Simulated withdrawal by the City of Albuquerque was assumed to be 200 acre-feet in 1901 and to increase linearly to 1,970 acre-feet in 1933. Simulated withdrawal for the City from 1933 to 1960 was that reported by Bjorklund and Maxwell (1961, fig. 6). Because only total-withdrawal data were available for all City wells prior to 1960, the simulated withdrawal for each stress period was distributed to wells believed to have been in operation during that stress period. Locations of City of Albuquerque wells are shown in figure 6. Except for the 1956-1960 stress period, withdrawal was distributed to different model layers in proportion to the screened length (Thorn and others, 1993, table 2) in each well and the proportion of time each well was in existence during a stress period. Withdrawal for the 1956-1960 stress period was distributed to each well field in the same proportion as the 1960 withdrawal reported by Summers (1992, table 2). Simulated withdrawal by the City from 1961 through 1987 was that reported by Summers (1992, table 2 and app. 2) by well field on an annual basis. The withdrawal from each of the City's well fields for 1961 through 1979 was distributed to wells in existence within the well field in proportion to the screened length in each well. The annual withdrawal by well field from 1980 through 1987 was distributed to wells within each well field on a monthly basis in proportion to the rated production capacity of each well multiplied by the monthly time of operation of each well (City of Albuquerque files). Data for simulated withdrawal from 1988 through spring 1994 were provided by the City of Albuquerque on a monthly basis by well.

Several City of Albuquerque wells were renumbered within their respective well fields between the early 1970's and late 1980's. Every effort was made to assign the pumpage identified for each well name to the correct location in the model, but because only general time frames for the name changes were available, some simulated withdrawals may have been assigned to the wrong locations in the model. However, the effects of these possible errors in the model results are considered to be small because of the short time periods in which the well names could have been changed (generally a 1- to 2-year period) and because each well field as a whole would have been assigned the correct volume of withdrawal.

Data for withdrawals from wells other than City of Albuquerque or private domestic wells were obtained from files of the New Mexico State Engineer Office in Albuquerque and Santa Fe. The earliest withdrawal records found were for 1957; however, most records were for years beginning in the 1960's. Withdrawals for a few wells, described in the following paragraph, were estimated for years prior to the time for which records are available. Only the recorded rates of withdrawal were simulated for the remaining wells. Because data are missing in the records for some wells and because reporting withdrawals from all wells in the basin is not required, simulated withdrawal for this category is probably underestimated in the model.

Ground-water withdrawals for the University of New Mexico; Atchison, Topeka, and Santa Fe Railway yard near Belen (pl. 1); Kirtland Air Force Base; and two power plants were simulated for years prior to those for which records were available. In the early stress periods (prior to 1941), withdrawal from only two wells in addition to City of Albuquerque wells was simulated. Simulation of these wells in the model is based on information provided by Lee (1907, p. 34-37). One of these two wells was on the University of New Mexico campus (just north of the Yale well field; fig. 6) and the other was at the Atchison, Topeka, and Santa Fe Railway yard near Belen.

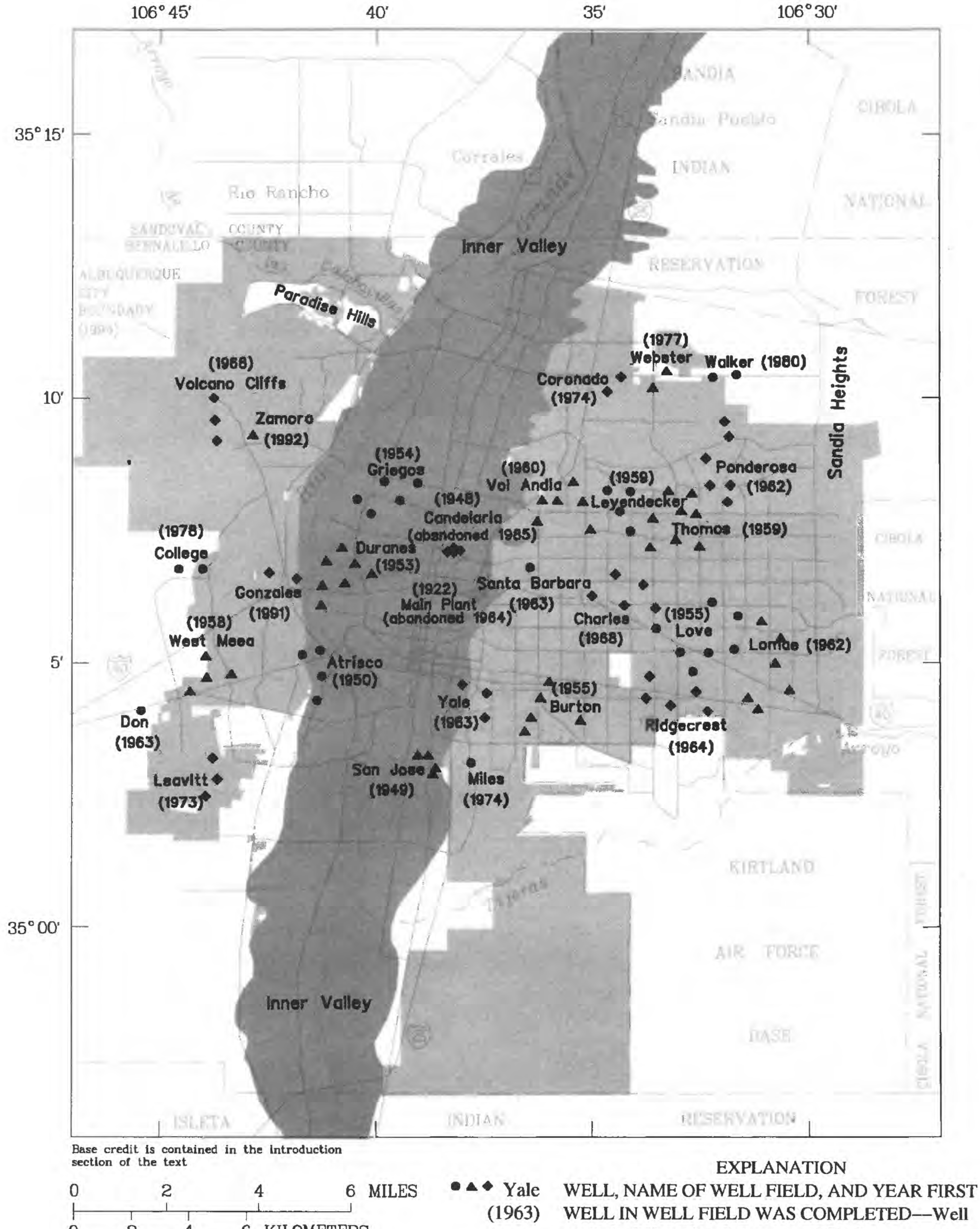


Figure 6.—Location of City of Albuquerque wells, 1993 (modified from Thorn and others, 1993, fig. 24).

Withdrawal for the University of New Mexico was assumed to be 68 acre-feet in 1901, increasing linearly to 1,063 acre-feet in 1957, the year for which the first withdrawal records for the University of New Mexico are available. Withdrawal for the Atchison, Topeka, and Santa Fe Railway yard near Belen was assumed to be 50 acre-feet per year from 1901 through 1950. The basis for simulating withdrawal from wells for Kirtland Air Force Base and the two power plants prior to the years for which records are available is the existence of depressions in the water table near some of those wells, as shown in Bjorklund and Maxwell's (1961, pl. 1a) 1960 water-table contour map. By extrapolating the earliest available records, withdrawal for Kirtland Air Force Base was assumed to begin at a rate of 3,490 acre-feet per year in 1948 and increase linearly to 4,620 acre-feet per year in 1960. Withdrawal from a local power plant north of the 1960 city boundary was assumed to be 1,000 acre-feet per year from 1957 to 1960 and from a second power plant south of the 1960 city boundary (see fig. 25 later in this report) was assumed to be about 1,200 acre-feet per year from 1955 to 1960.

Withdrawals from private domestic wells were simulated beginning in 1961. The population outside municipal water-system service areas (table 1) was assumed to be supplied water from private domestic wells. All simulated withdrawal from private domestic wells was applied to model layer 6, which represents a depth of 130 to 230 feet below the elevation of the Rio Grande. The rate of withdrawal applied to each cell outside water-system service areas was calculated by multiplying the area-weighted population density within each cell by the area of the cell times 100 gallons per person per day. Population density was calculated using Theisen polygons constructed around centroids of census tracts for Bureau of Census 1970, 1980, and 1990 data (U.S. Bureau of Census, 1970; 1980; and 1990). The population density for 1990 was shown by Thorn and others (1993, p. 11). Withdrawals for 1961 through 1974 were based on the 1970 population, withdrawals for 1975 through 1984 on the 1980 population, and withdrawals for 1985 and beyond on the 1990 population (table 4). Digital population data for years prior to 1970 were not available.

Hydraulic Characteristics

The general basis for assigning values of hydraulic conductivity in the model was table VI-1 from Hawley and Hasse (1992) and figure 21 from Thorn and others (1993). With the exception of the upper Santa Fe Group, generally uniform values of horizontal hydraulic conductivity, in feet per day (ft/d), were assigned for distinct mapped units. These units and values of horizontal hydraulic conductivity are the undivided lower Santa Fe Group (2 ft/d); the Zia Sand of the lower Santa Fe Group (4 or 10 ft/d); the Cochiti Formation of the middle Santa Fe Group and the undivided middle Santa Fe Group (4 ft/d); and the alluvial fill of the Rio Grande (40 and 0.5 ft/d), Rio Puerco (20 ft/d), and Jemez River (40 ft/d). The hydraulic conductivity of the upper Santa Fe Group was estimated to range from 10 to 70 ft/d. Piedmont-slope deposits against the Sandia Uplift were simulated as having a horizontal hydraulic conductivity of 10 ft/d. The areal distribution of horizontal hydraulic conductivity for the 11 model layers is shown in figures 7 through 17. The area-weighted mean horizontal hydraulic conductivity for each finite-difference cell was used in the ground-water-flow model.

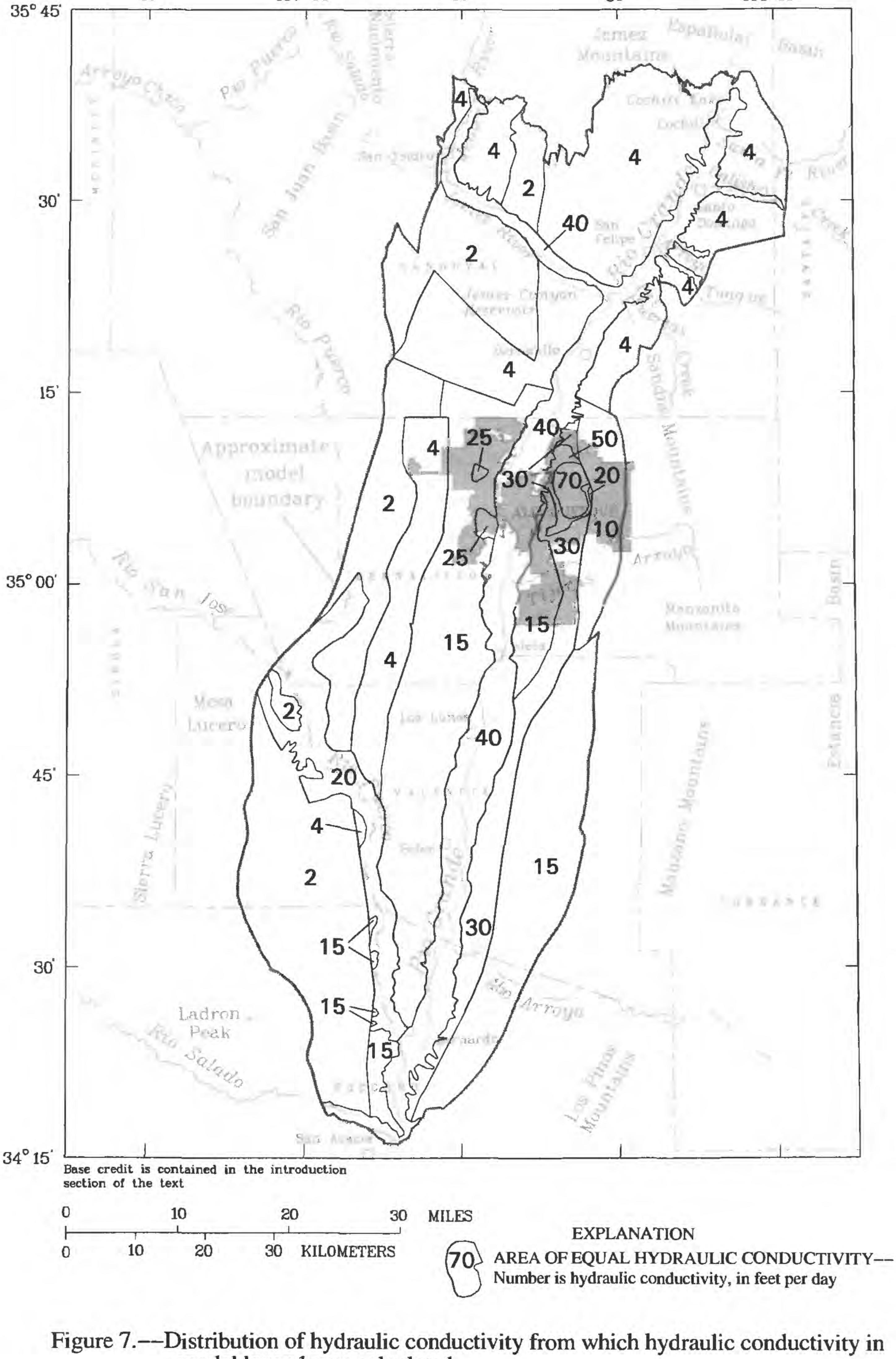


Figure 7.--Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 1 was calculated.

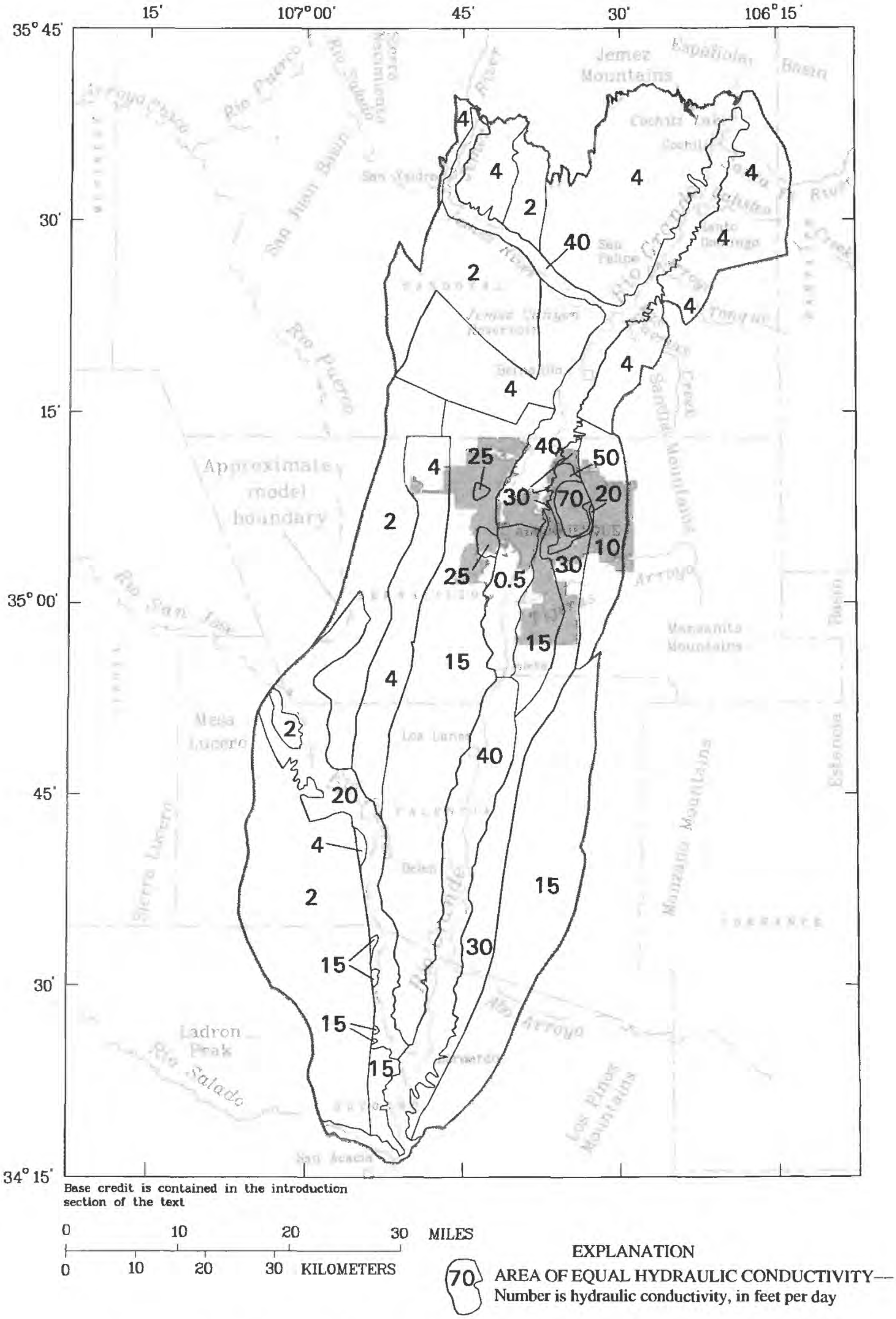


Figure 8.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 2 was calculated.

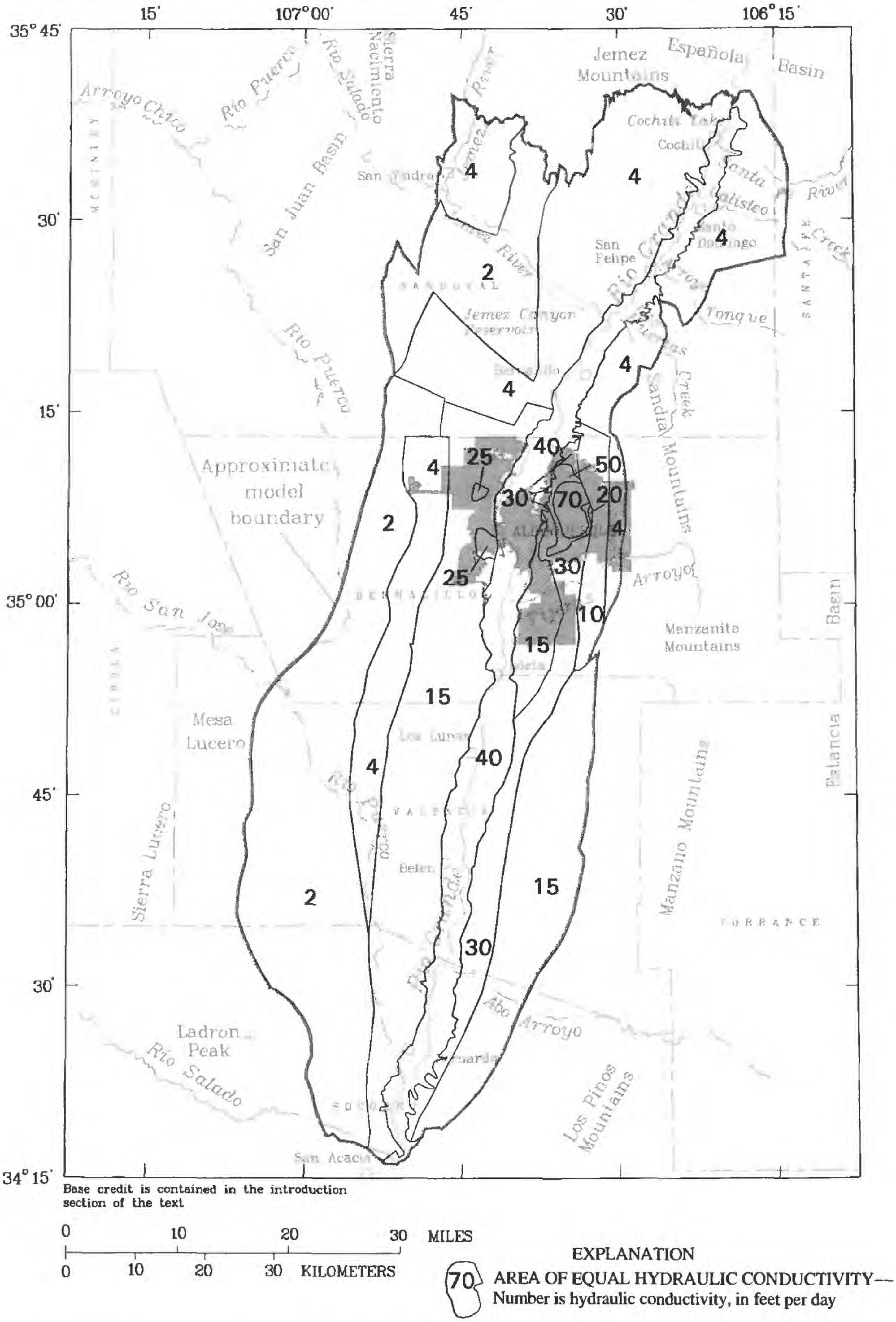


Figure 9.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 3 was calculated.

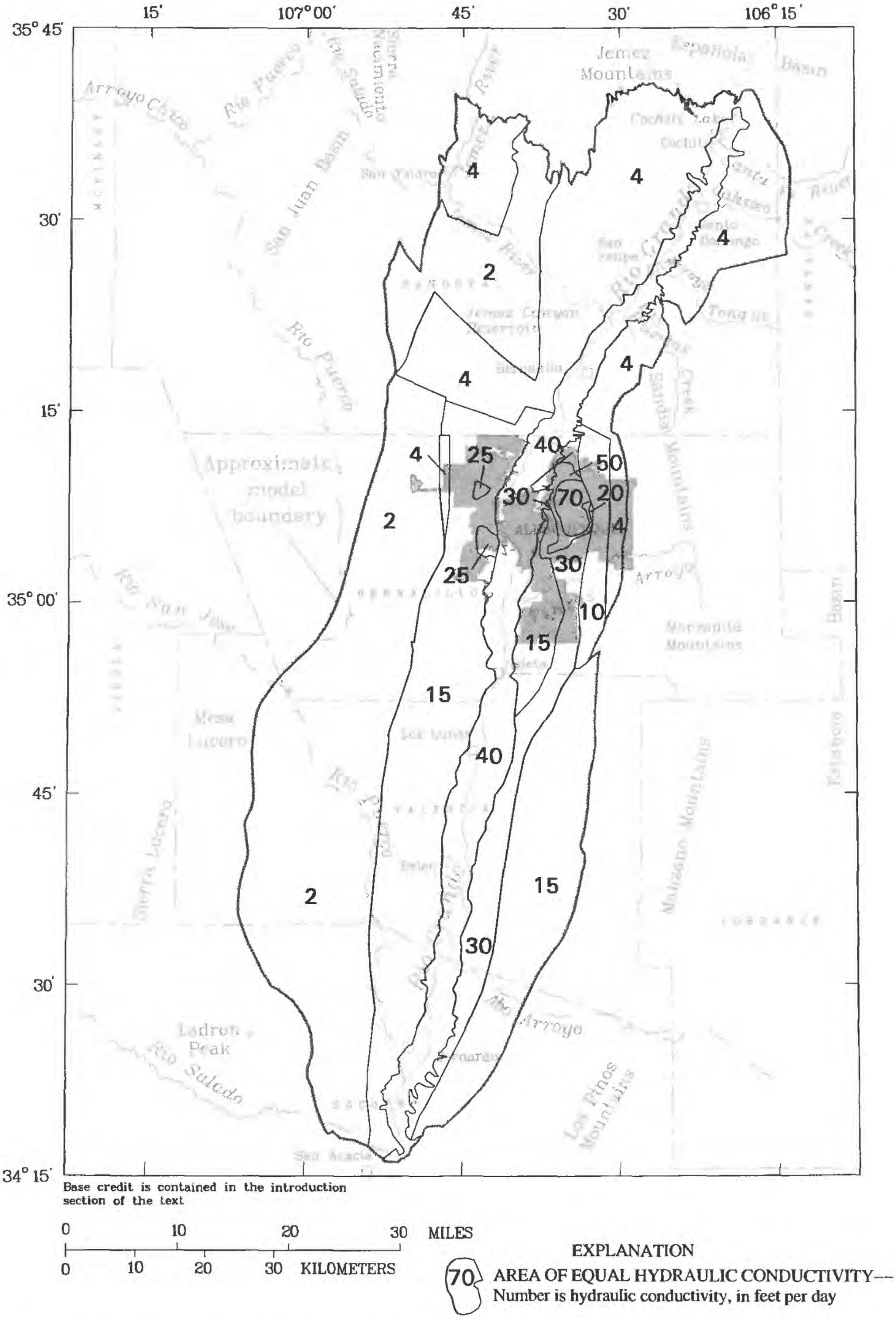


Figure 10.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 4 was calculated.

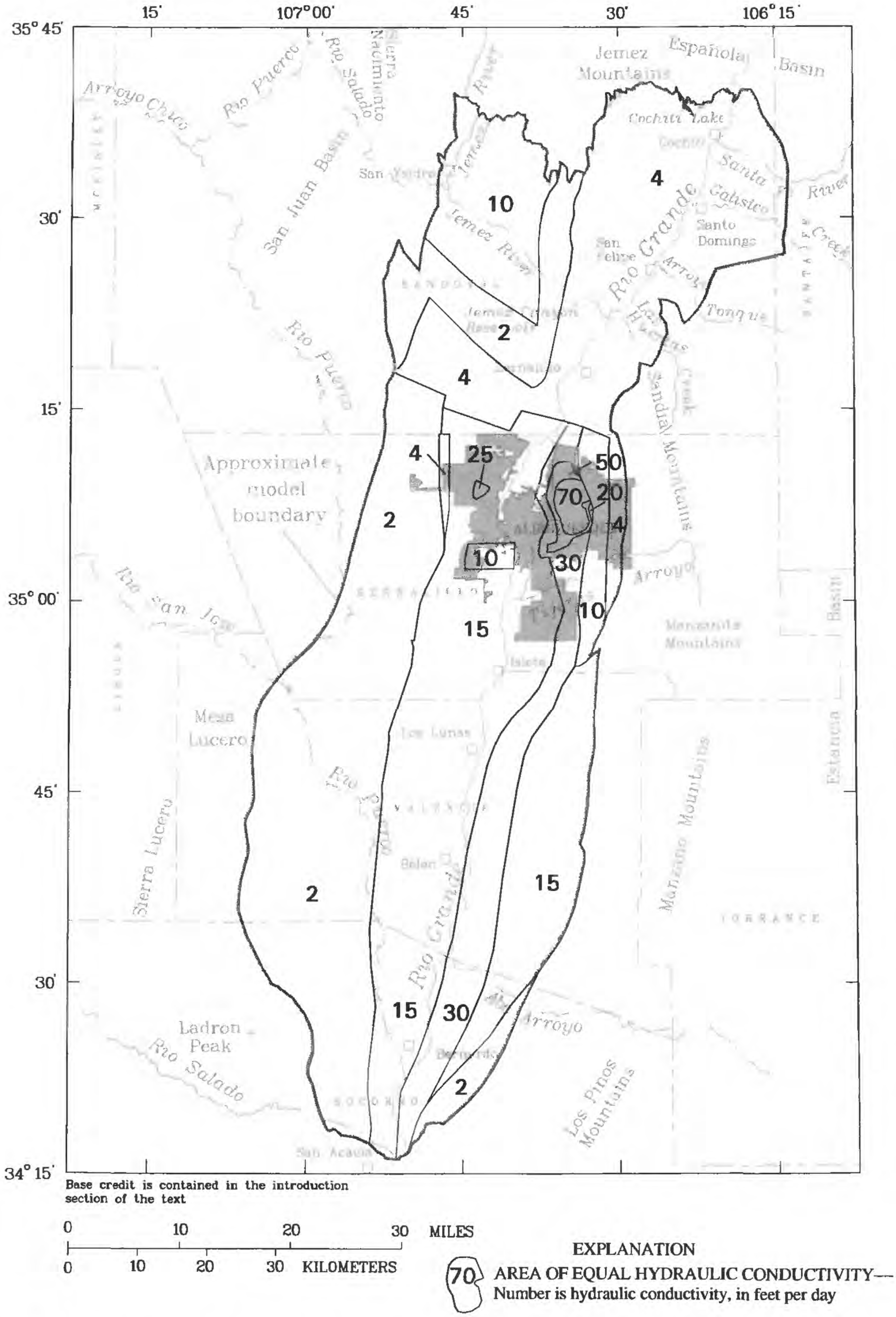


Figure 11.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 5 was calculated.

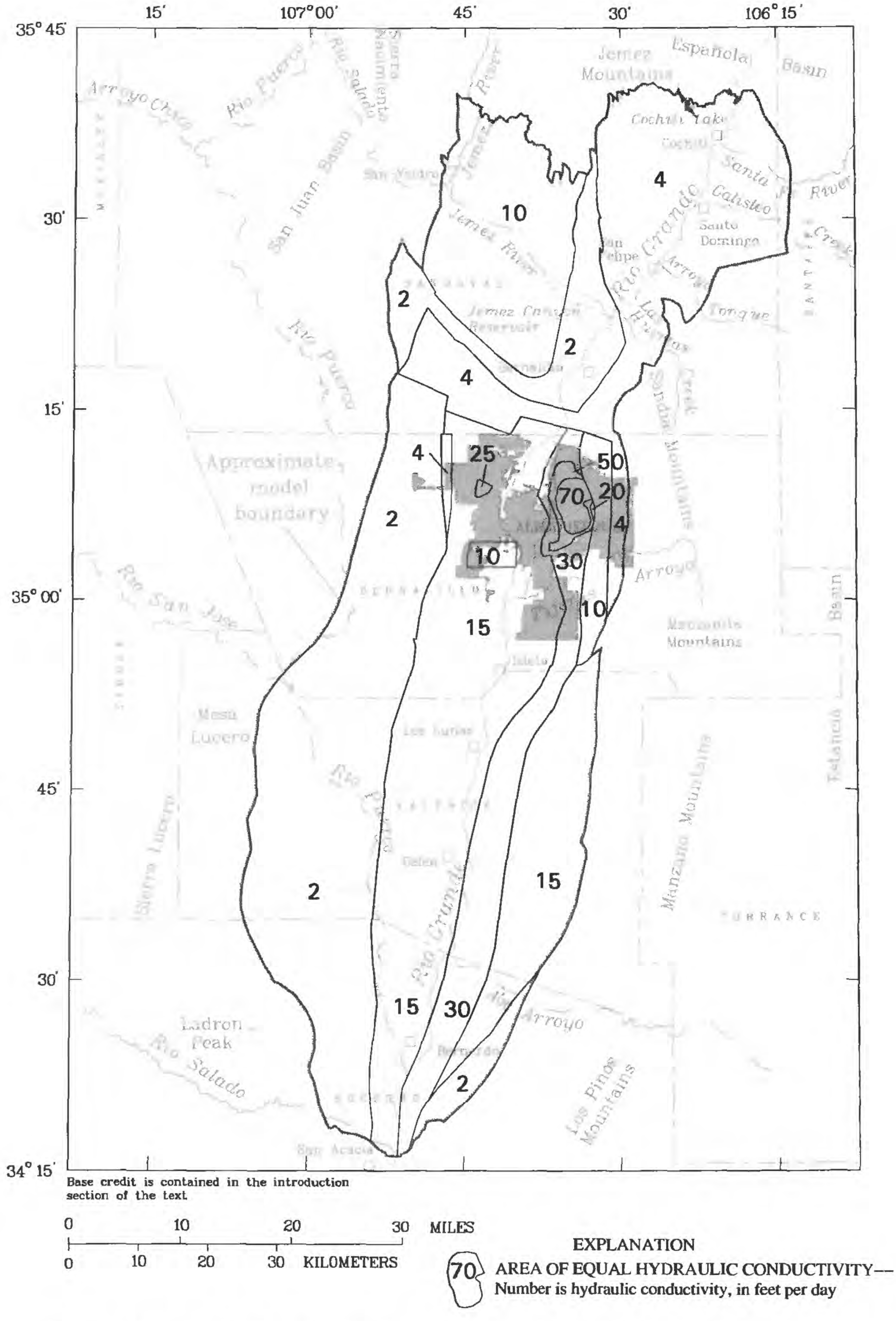


Figure 12.--Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 6 was calculated.

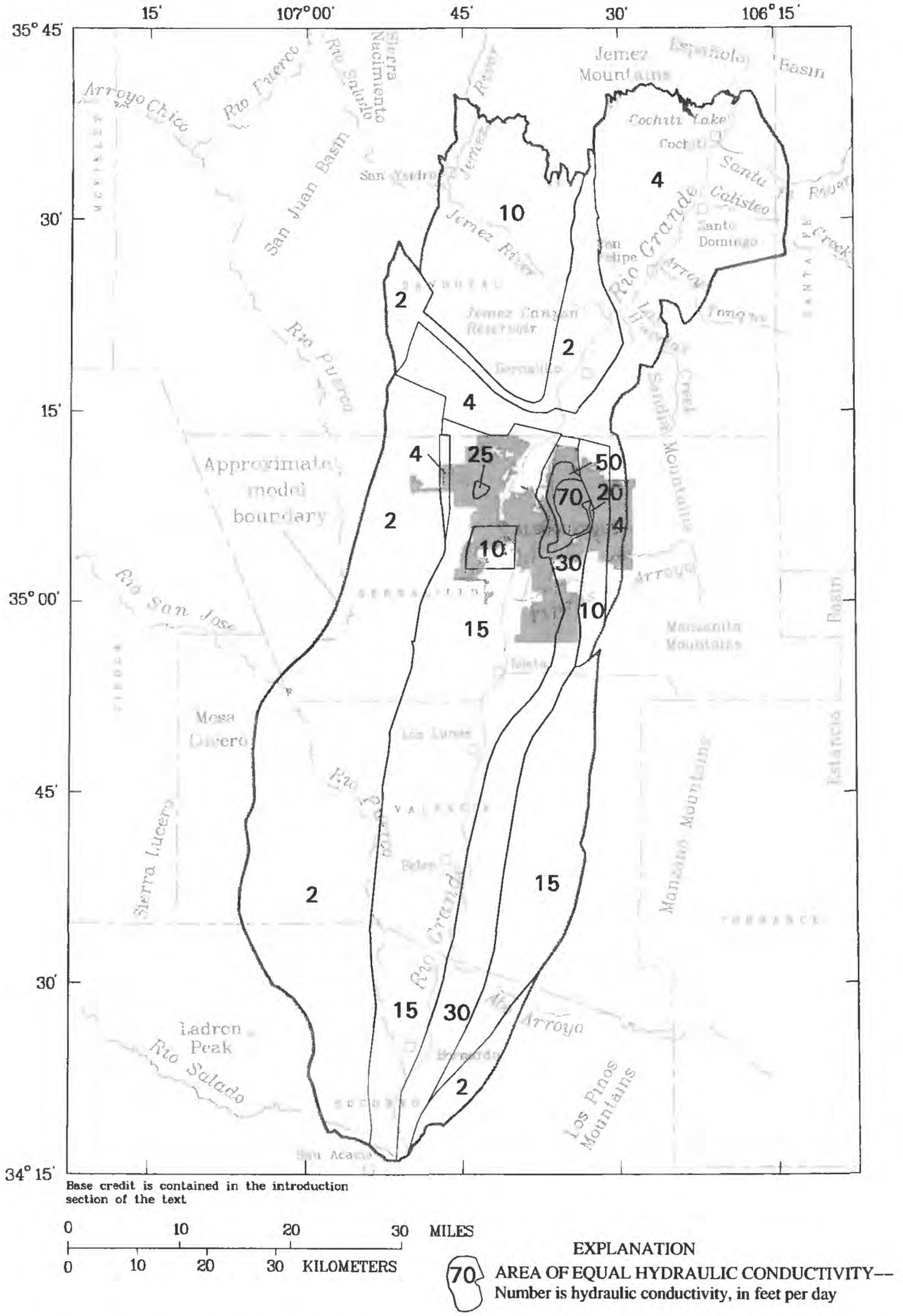


Figure 13.--Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 7 was calculated.

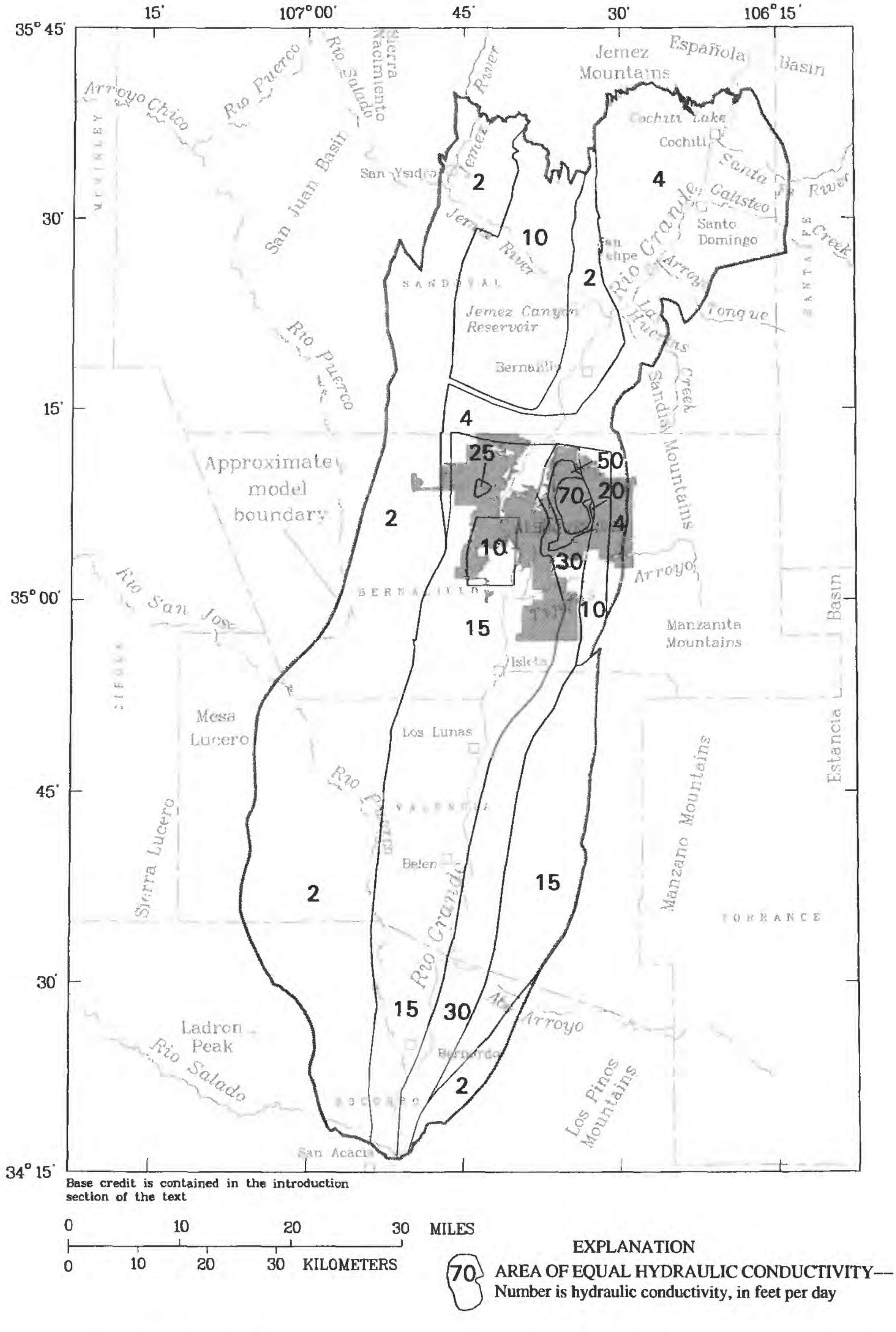
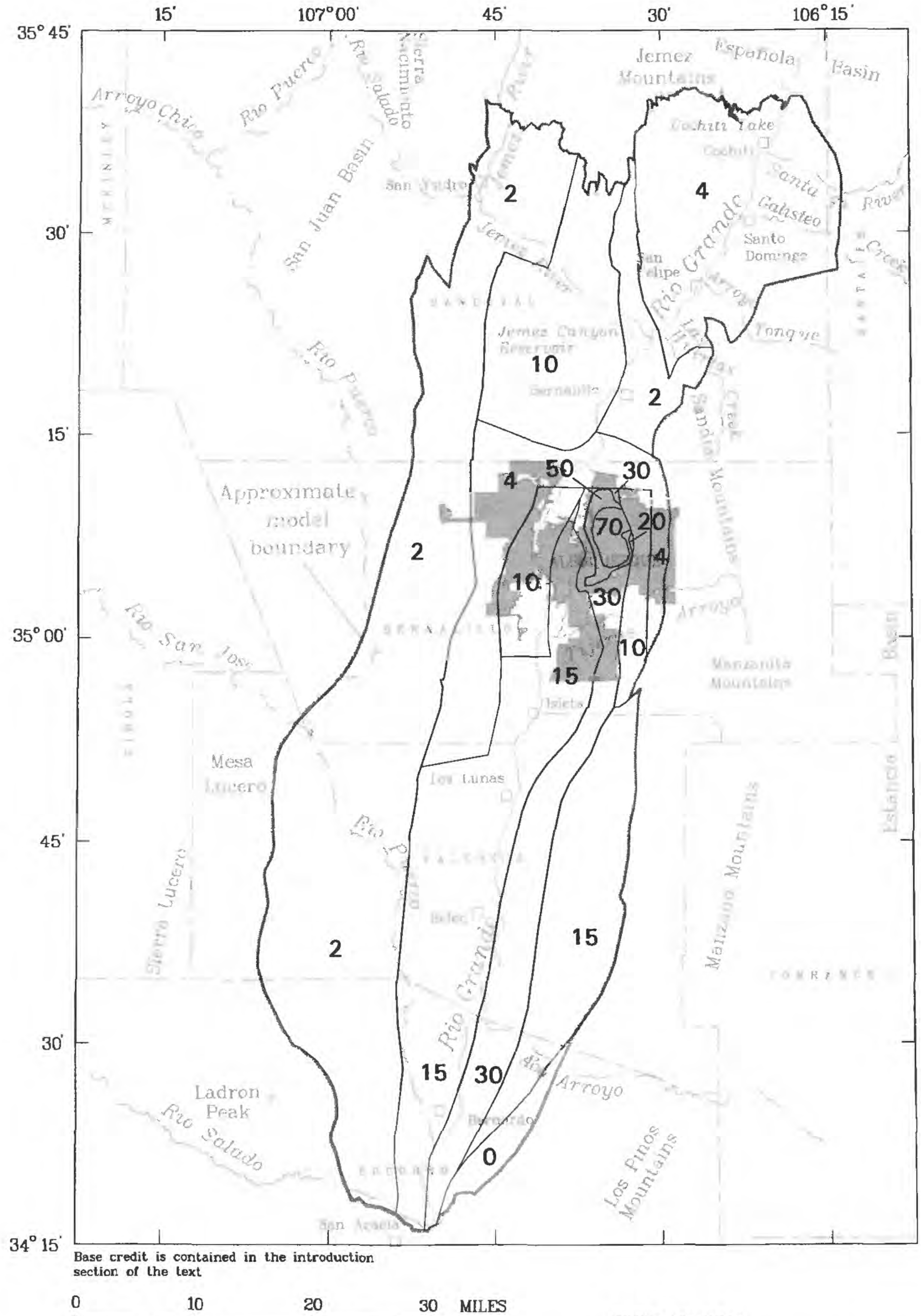


Figure 14.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 8 was calculated.



EXPLANATION

70 AREA OF EQUAL HYDRAULIC CONDUCTIVITY—Number is hydraulic conductivity, in feet per day

Figure 15.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 9 was calculated.

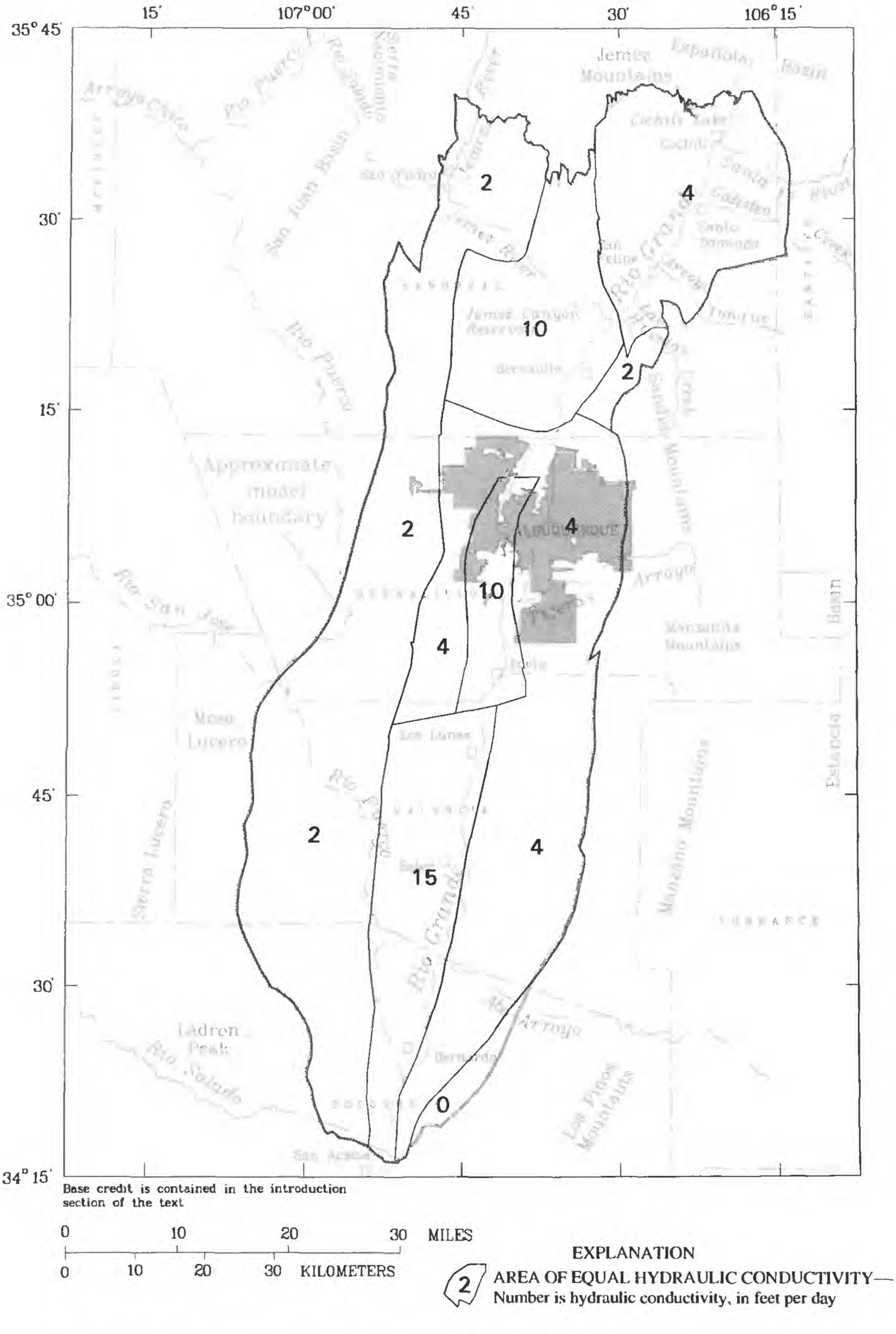


Figure 16.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 10 was calculated.

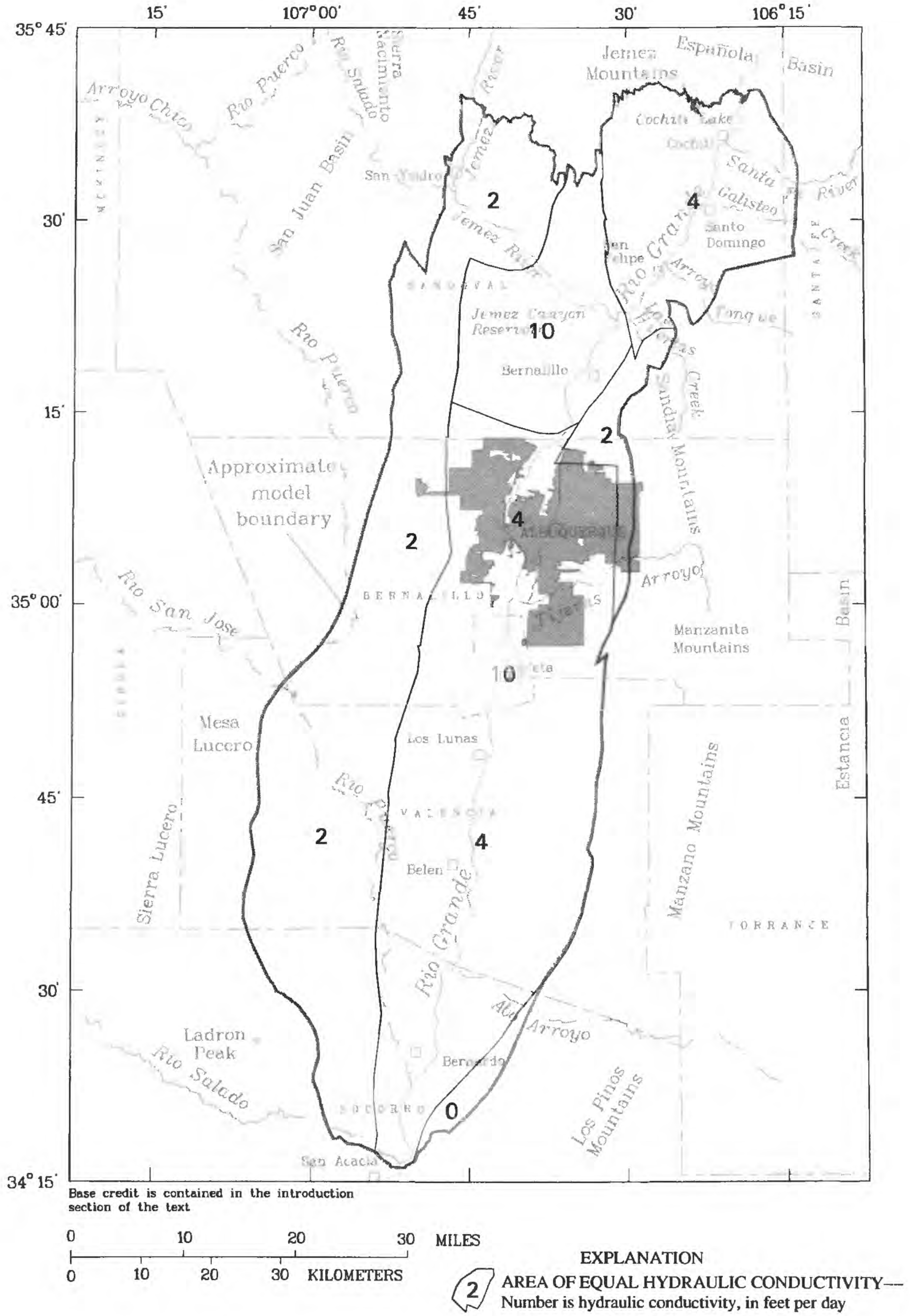


Figure 17.—Distribution of hydraulic conductivity from which hydraulic conductivity in model layer 11 was calculated.

With the exception of the Ziana Anticline in the northern part of the basin (fig. 4) and a simulated structural deformation on Sandia Indian Reservation (pl. 1), the near-horizontal beds in the Santa Fe Group map directly into the planar model layers. The Ziana Anticline plunges southward from outcrop areas in the Jemez Valley to a terminus just north of the Bernalillo-Sandoval County line. The Zia Sand within the Ziana Anticline is the primary aquifer for the City of Rio Rancho. The southward-plunging anticline was simulated as a series of downward-stepped model layers. The extension of the Zia Sand (simulated hydraulic conductivity of 10 ft/d) into the subsurface can be traced in figures 11 through 17.

An assumed structural deformation in the area of the Sandia Indian Reservation was simulated in the model. This 900-foot uplift of the entire Tertiary sequence was assumed because of the apparent outcrop of the middle part of the Santa Fe Group near Sandia Pueblo. Thus, in the model an area of low hydraulic conductivity (4 ft/d) is adjacent and just north of the high-conductivity (30 to 70 ft/d) axial-channel deposits of the upper part of the Santa Fe Group (figs. 7-15). Recent field mapping (Dr. John Hawley, New Mexico Bureau of Mines and Mineral Resources, oral commun., August 26, 1994) indicates that piedmont-slope deposits (misidentified as upper part of the Santa Fe Group) overlie axial-channel deposits and therefore the structural deformation is nonexistent.

The valley-fill alluvium of the Rio Puerco and Jemez River was simulated as being approximately 40 feet thick and the Rio Grande valley-fill alluvium was simulated as being about 80 feet thick. A low-conductivity (0.5 ft/d) zone from 20 to 40 feet in depth below the water table (fig. 8) was simulated in the Rio Grande valley-fill alluvium extending from just south of Interstate Highway 40 southward to Isleta Pueblo (Thorn and others, 1993).

Locations of the major faults also are shown in figure 4. The locations were obtained from Kelley (1977) and Hawley and Haase (1992). The faults shown in figure 3 are cemented and are a partial barrier to ground-water movement. Therefore, the area-weighted mean horizontal hydraulic conductivity was reduced by a factor of 0.2 for those finite-difference model cells that contain a fault. Faults may also affect ground-water flow by bringing into opposition geohydrologic units with different hydraulic properties.

Finally, the GIS was used to compute the vertical hydraulic conductance between model layers. In this calculation, the ratio of horizontal to vertical hydraulic conductivity was assumed to be 200:1 (Kernodle, 1992b, table 4). The presence of faults was assumed not to affect vertical hydraulic conductivity.

Values of storage coefficient, based on aquifer tests, are not known to be available for the Santa Fe Group aquifer system in the Albuquerque Basin. Storage coefficients for the model layers representing the confined portion of the aquifer were estimated by multiplying the assumed specific storage of 2×10^{-6} per foot (Lohman, 1979, p. 8) by the layer thickness.

No specific-yield data are available for the Santa Fe Group aquifer system in the Albuquerque Basin. Specific yields for the types of materials composing the Santa Fe Group aquifer system (gravelly sand, silts, and clays) typically average from about 0.1 to 0.25 (Johnson, 1967, p. 1). Specific yield was assumed to be 0.15.

INITIAL CONDITIONS AND HISTORICAL SIMULATIONS

The predevelopment condition of the aquifer, assumed to exist prior to 1901, was simulated by assuming a steady state between natural recharge to and discharge from the aquifer system. This simulated steady-state condition was used as the initial condition for the historical simulations. Evapotranspiration was simulated for all areas in the inner Rio Grande Valley (except the river channel) where simulated water levels were within 20 feet of land surface. No canals or drains were simulated.

The 1901 to 1994 historical period was simulated using 59 stress periods. All years in the simulations are assumed to be 365.25 days long to account for leap years. The length of the stress periods varied from 6 months to 5 years, based on the amount of detail available on ground-water withdrawal. The historical period from 1901 through 1960 was simulated in 12 5-year stress periods. For 1933 through 1959, the total amount of City of Albuquerque withdrawal is reasonably well known, but the distribution of ground-water withdrawal among City of Albuquerque well fields is not. City withdrawals prior to 1933 can only be estimated. Little information is available on withdrawals from other wells in the basin prior to 1960.

The period from 1961 through 1979 was simulated in 19 1-year stress periods. City of Albuquerque withdrawals are available by well field during this period and records of withdrawals from other wells in the basin were available primarily beginning during the 1960's.

The period from 1980 through 1994 was simulated in 28 semiannual (summer and winter) stress periods. Monthly withdrawal by well for City of Albuquerque wells is available or was estimated for this period. The first stress period in 1980 was three-quarters of a year long (273.25 days), from January 1 through September 30. This allowed subsequent stress periods to be divided into a summer season, when City withdrawals are relatively large (about 65 percent of the annual total), and a winter season, when withdrawals are relatively small (about 35 percent of the annual total). Summer seasons began April 1 and ended September 30 (183 days), and winter seasons began October 1 and ended March 31 (182.25 days). The end of the historical simulation was March 31, 1994. Evapotranspiration, seepage from irrigation canals, and agricultural irrigation-return flow was assumed to occur during only the summer seasons. Ground-water withdrawal rates for wells other than City of Albuquerque wells were not adjusted seasonally.

Model Adjustments

Initial estimates of mountain-front and tributary recharge, inflow from adjacent basins, hydraulic characteristics, and distribution of ground-water withdrawals for particular time periods were adjusted to simulate more reasonable hydraulic heads in parts of the model. However, simulated hydraulic characteristics were not adjusted beyond the constraints imposed by the information available on the hydrogeologic system. If a part of the model was thought to represent a particular geologic unit, the cells in that part of the model were assigned the hydraulic characteristics representative of that unit. Hydraulic conductivity was adjusted only for entire geologic units as described in the Hydraulic Characteristics section of this report. Specific yield and specific storage were adjusted only for the model as a whole. The characteristics of the model used for the simulations were described in the Model Description section.

Better matches between simulated and measured heads could have been achieved by arbitrarily adjusting the hydraulic characteristics. However, making adjustments without having appropriate data to support those adjustments only gives a false sense of model accuracy when, in fact, the predictive capability of the model for those areas cannot be verified (Konikow and Bredehoeft, 1992). An almost infinite number of variations in the modeled representation of an aquifer system will produce equally good agreement between simulated and measured hydraulic heads. Because the model described in this report is designed to be updated as more information and revised interpretations become available, the approach taken for this report is to identify the areas where simulated and measured hydraulic heads do not significantly agree. The disagreement in hydraulic heads is considered an indication that more information is needed to understand the hydrogeologic system in those areas. These areas are discussed in the Simulation Results and the Possible Model Revisions and Additional Data Needs sections.

Simulation Results

The three-dimensional ground-water-flow model computed basinwide hydraulic heads and head declines for each of the 11 model layers and ground-water budgets for the entire simulated volume. Heads and budgets are presented for the initial-condition simulation (steady state) as well as for 1960, 1979, and 1994. Head declines are presented for 1960-1994.

Hydraulic Heads

Simulated hydraulic heads for the steady-state simulation are shown in figures 18 and 19. The simulated water table (layer 1) is shown in figure 18, and the hydraulic heads at the depth of 580 to 830 feet below the Rio Grande, currently (1994) the main production zone (layer 9), are shown in figure 19. The water-table contours show the effects of the surface-water system in the inner Rio Grande Valley. Water moves from the basin margins and from the Rio Grande to the flood plain where it discharges by evapotranspiration. Hydraulic heads at depth are more isolated from the surface-water system (fig. 19). The contours for layer 9 show water moving from the basin margins toward the inner valley in a generally southerly direction. The water then moves upward toward the discharge areas in the inner valley. The water table and hydraulic head in layer 9 in the Albuquerque area are shown in figures 20 and 21, respectively. The contours with wider spacing in the eastern part of the Albuquerque area reflect the higher hydraulic conductivities (figs. 7 and 15) associated with the ancestral Rio Grande axial-channel deposits (Thorn and others, 1993, fig. 21).

Simulated hydraulic heads at the end of 1960 in the Albuquerque area are shown in figures 22-24 for layers 1, 5, and 9, respectively. These maps can be compared with figure 25, modified from Bjorklund and Maxwell's 1960 (1961) water-level contour map. Bjorklund and Maxwell's map represents a composite of heads from various levels within the aquifer system. The simulated heads in layer 5 (fig. 23), which represents the depth of 80 to 130 feet below the level of the Rio Grande, can be compared with contours in most of the inner valley area of Bjorklund and Maxwell's map. These depths are similar to those of many of the wells that were used to construct the water-level contours in that area. The simulated heads in layer 1 (fig. 22) are more appropriately compared with the contours immediately adjacent to the Rio Grande because of the direct influence of the Rio Grande on the contours. Likewise, simulated heads in layer 9 (fig. 24), which represents the depth of 580 to 830 feet below the level of the Rio Grande, are more appropriately compared with contours beyond the inner valley because many of the wells used to construct contours are production wells completed in intervals near those depths.

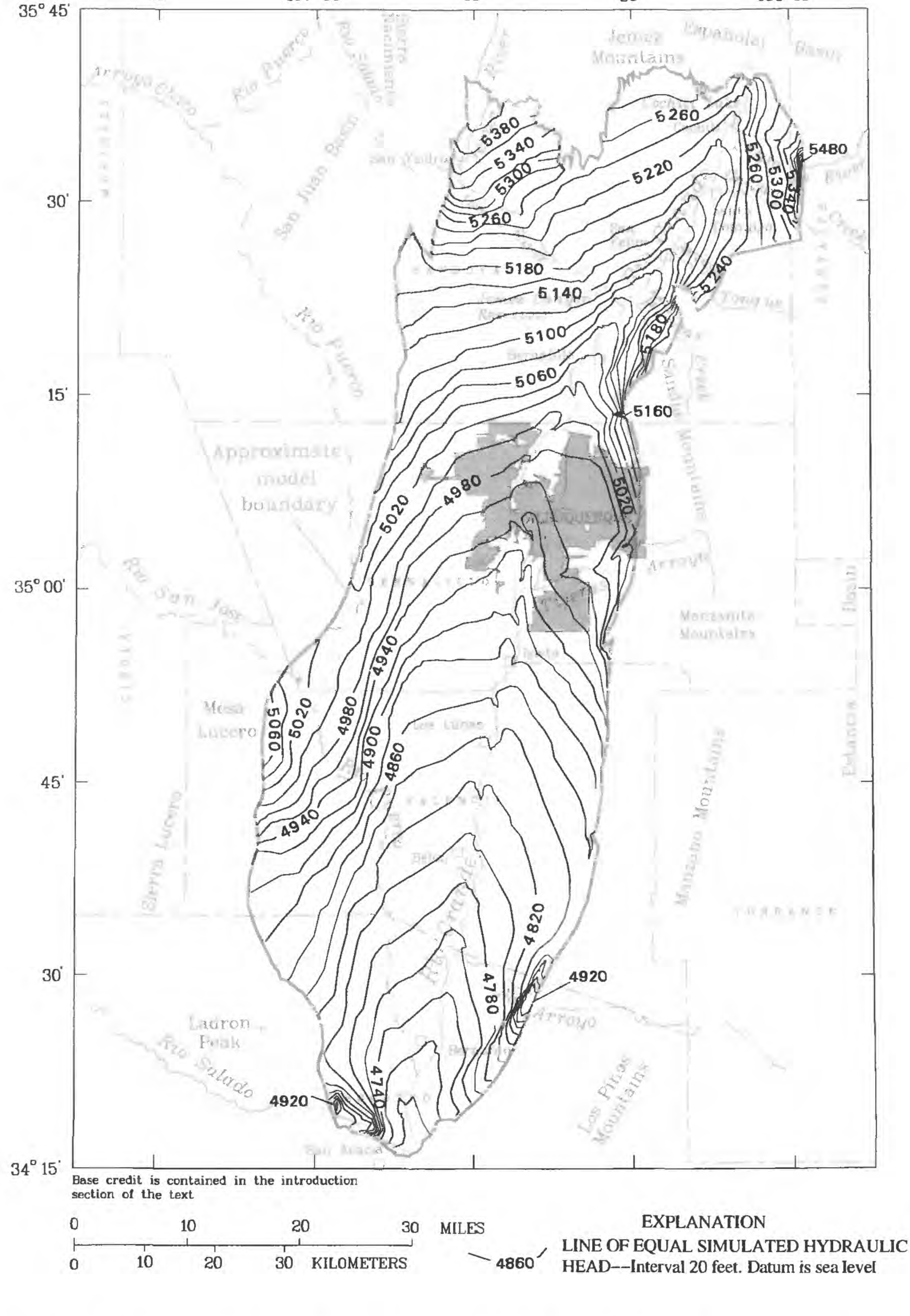


Figure 18.—Simulated steady–state hydraulic head in model layer 1 in the Albuquerque Basin.

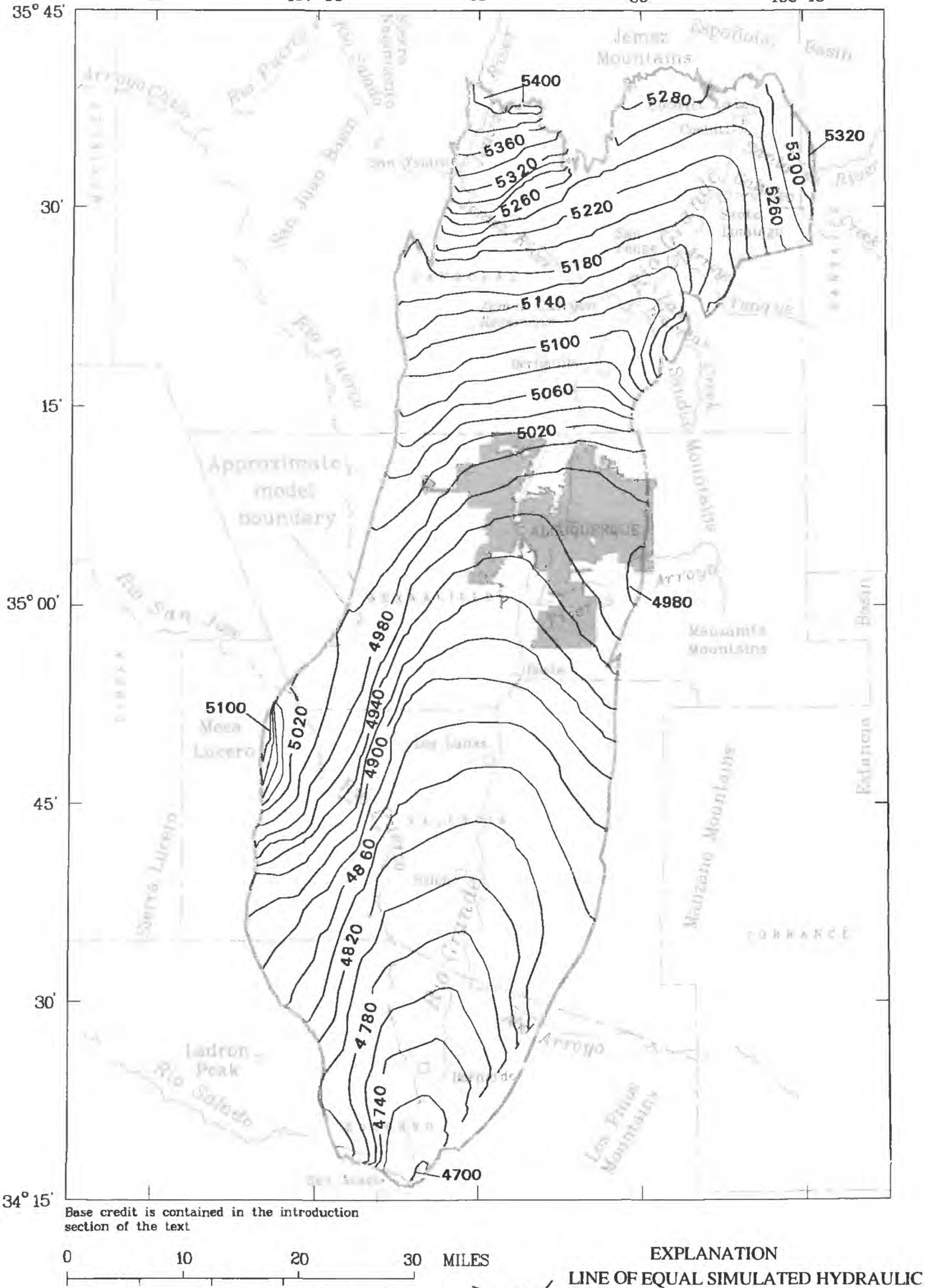


Figure 19.--Simulated steady-state hydraulic head in model layer 9 in the Albuquerque Basin.

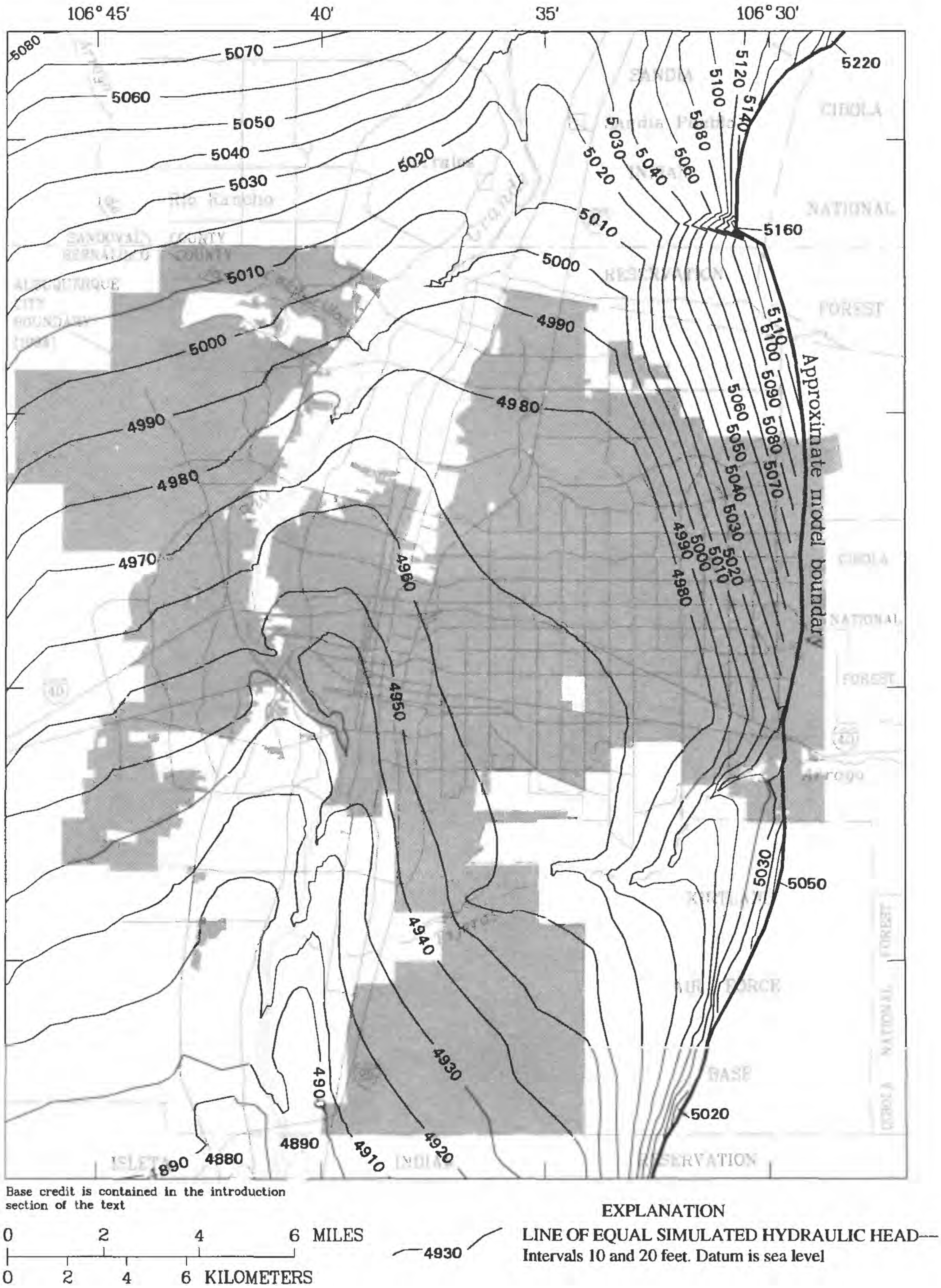
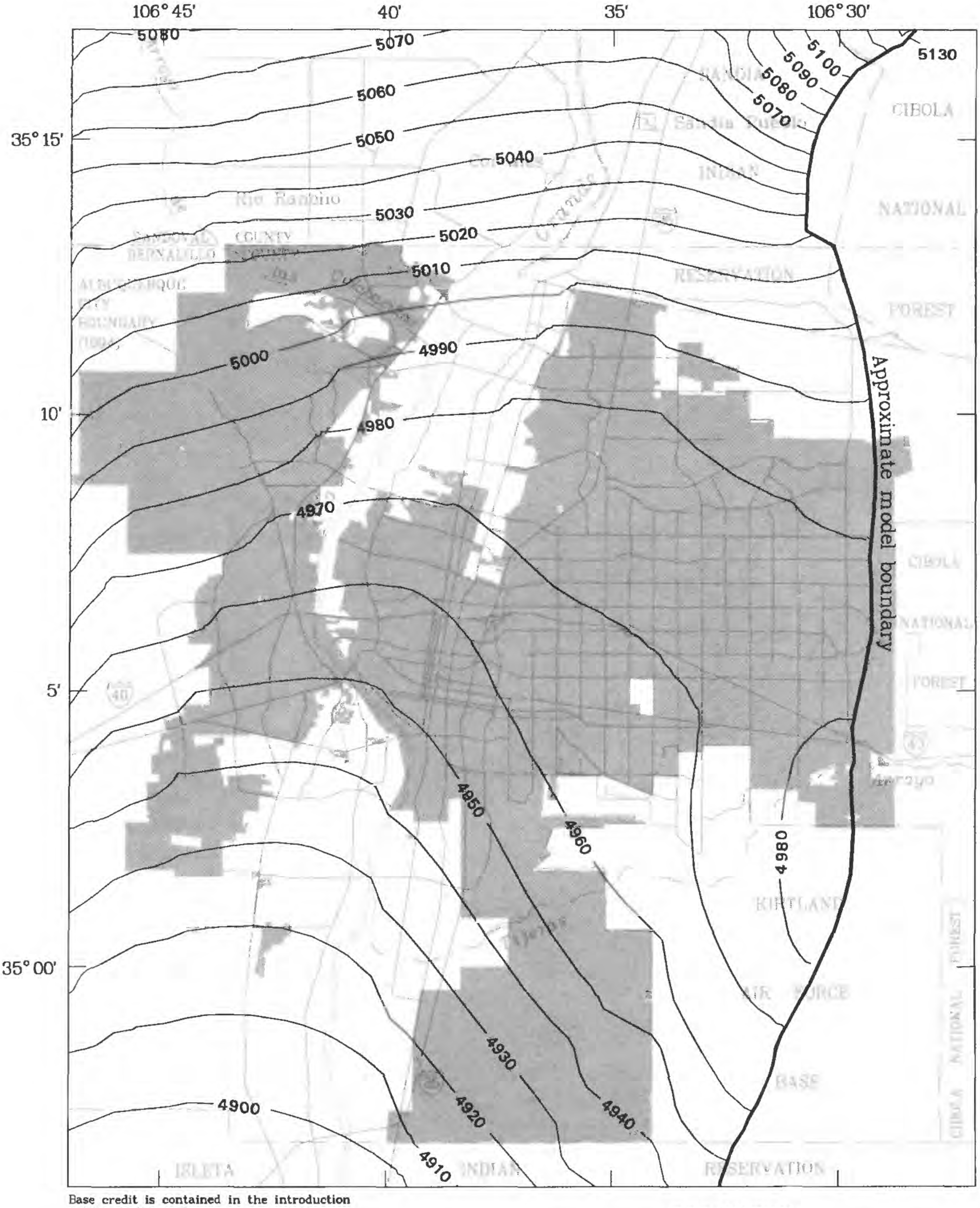


Figure 20.—Simulated steady–state hydraulic head in model layer 1 in the Albuquerque area.



Base credit is contained in the introduction section of the text

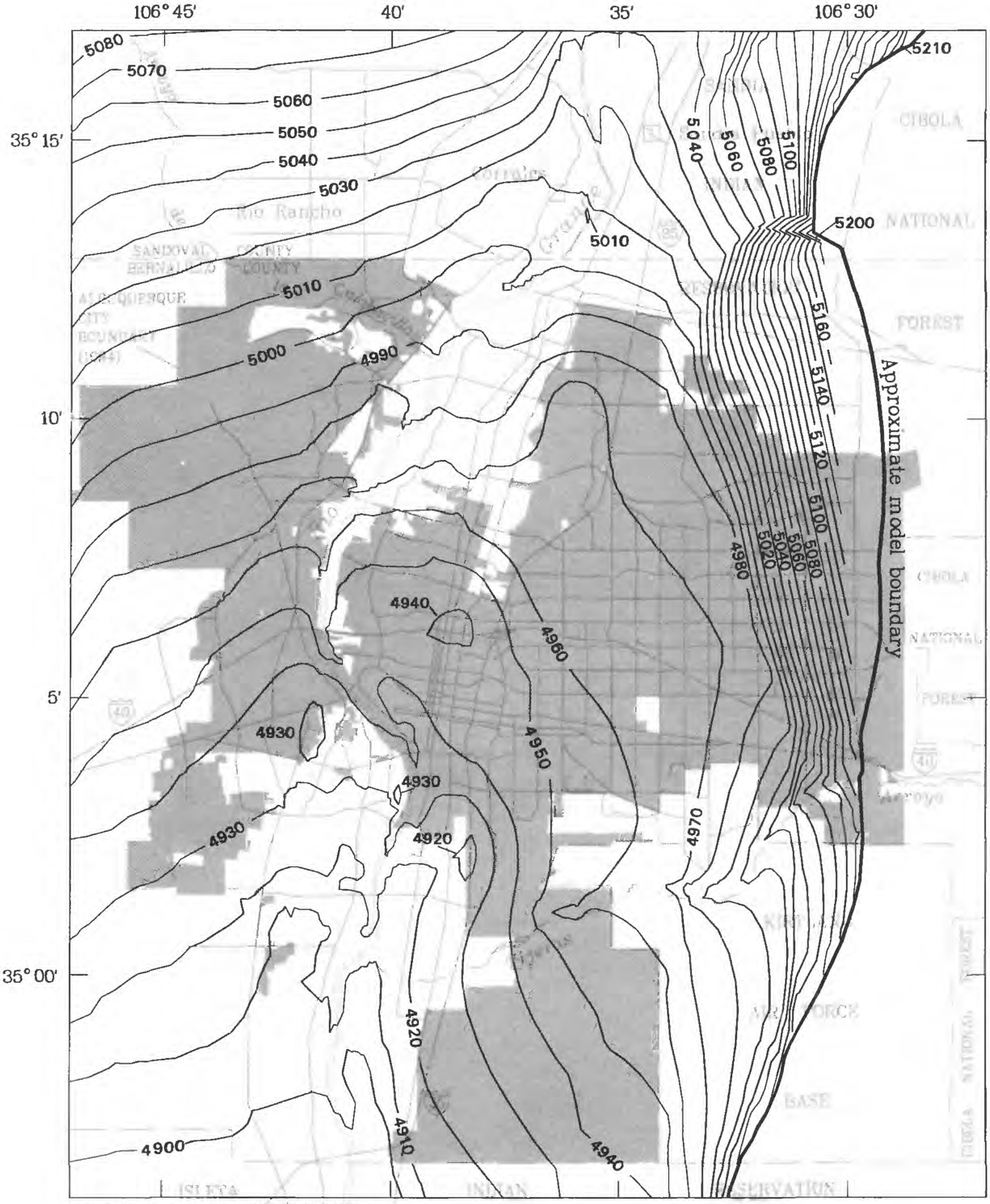
0 2 4 6 MILES

0 2 4 6 KILOMETERS

EXPLANATION

4930 LINE OF EQUAL SIMULATED HYDRAULIC HEAD-- Interval 10 feet. Datum is sea level

Figure 21.--Simulated steady-state hydraulic head in model layer 9 in the Albuquerque area.



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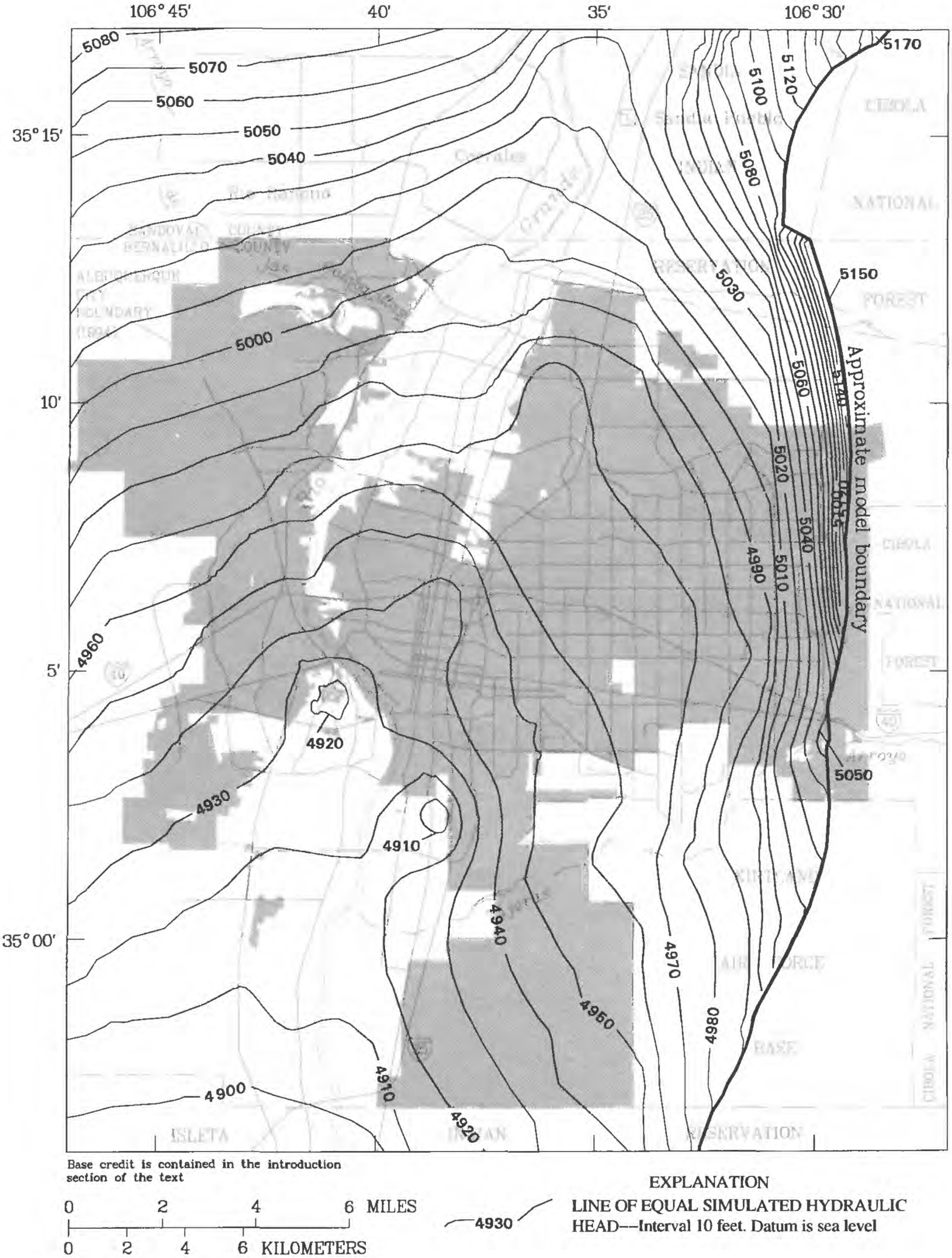
0 2 4 6 MILES

0 2 4 6 KILOMETERS

EXPLANATION

4930 LINE OF EQUAL SIMULATED HYDRAULIC HEAD—Intervals 10 and 20 feet. Datum is sea level

Figure 22.—Simulated 1960 hydraulic head in model layer 1 in the Albuquerque area.



EXPLANATION

4930 LINE OF EQUAL SIMULATED HYDRAULIC HEAD—Interval 10 feet. Datum is sea level

Figure 23.—Simulated 1960 hydraulic head in model layer 5 in the Albuquerque area.

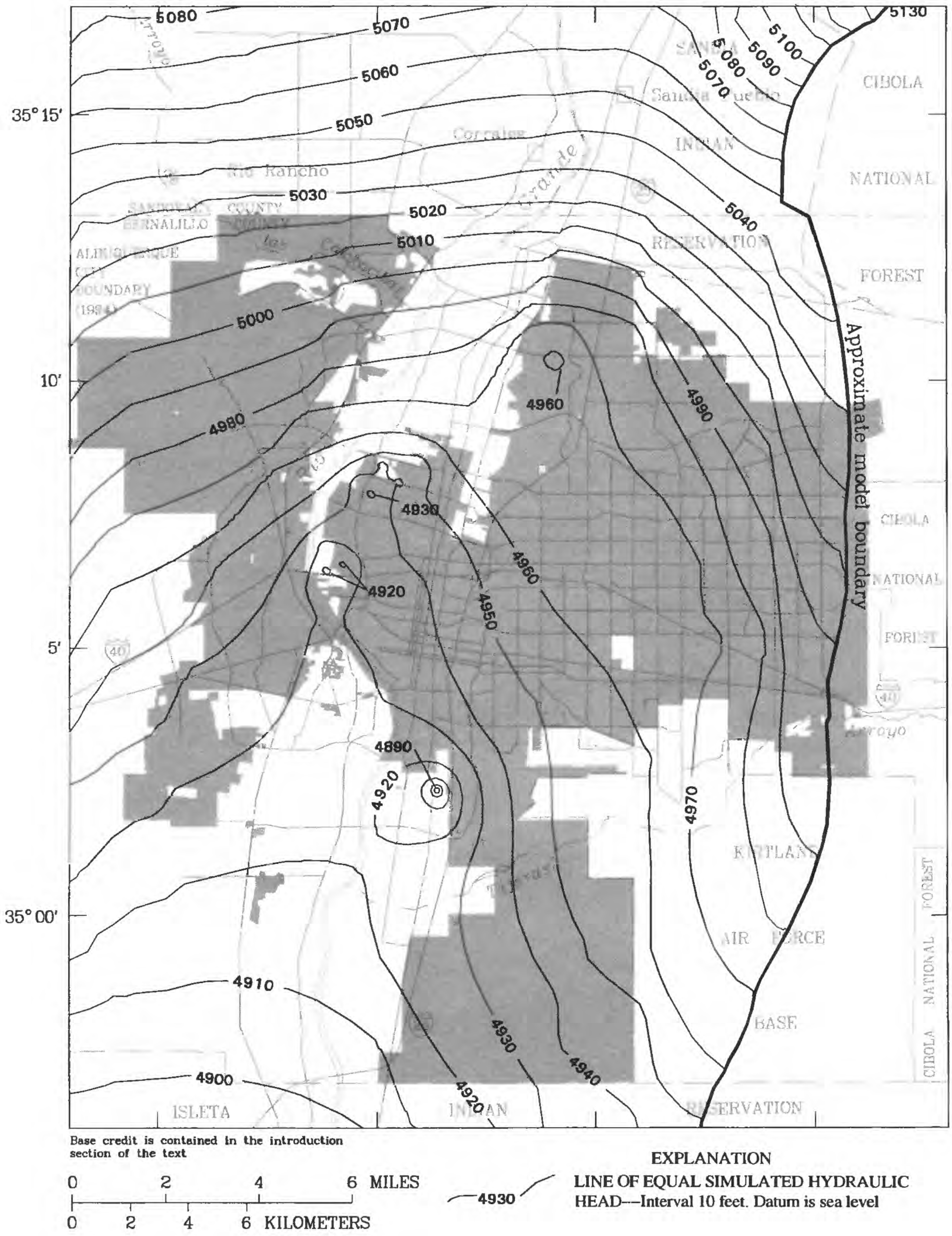
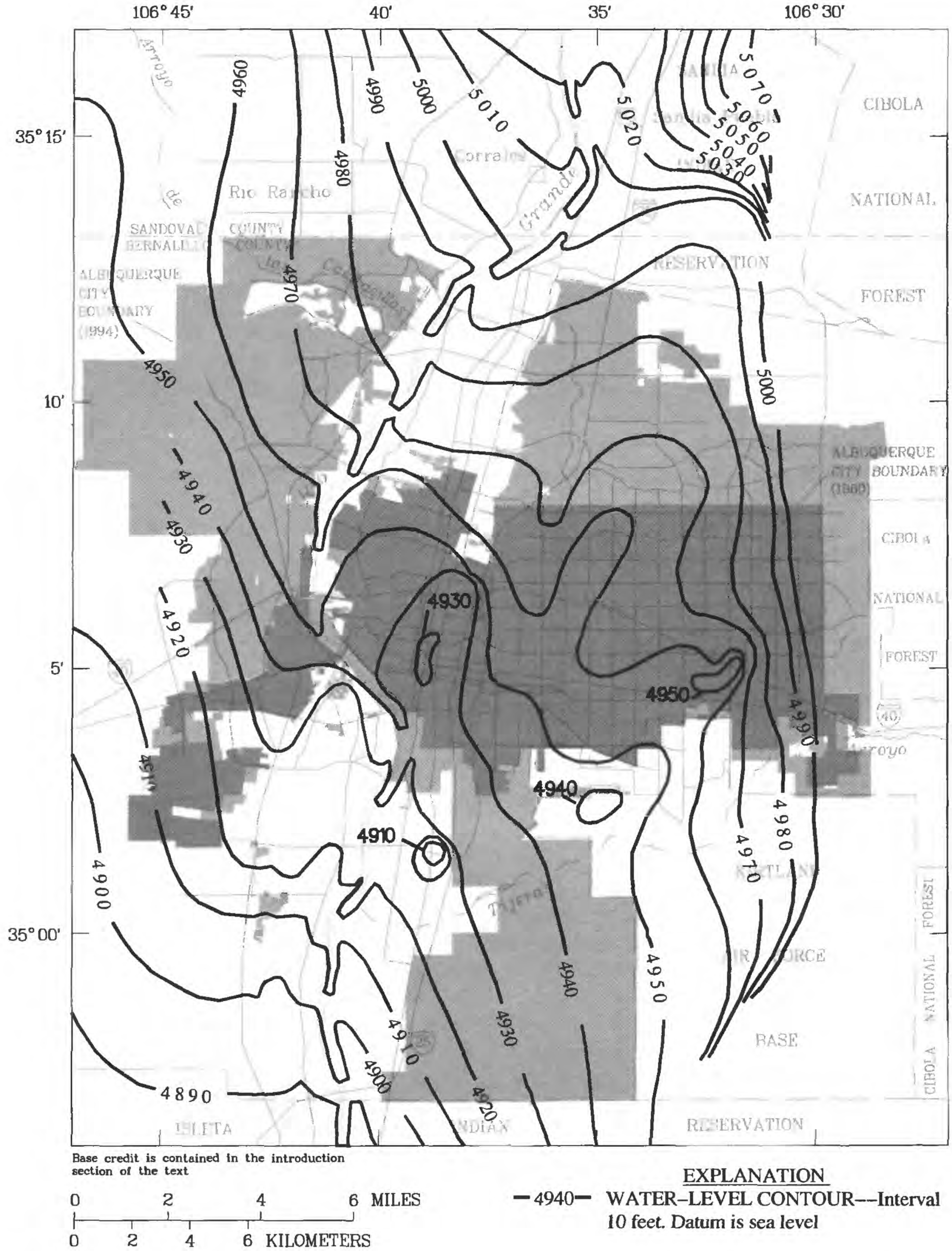


Figure 24.—Simulated 1960 hydraulic head in model layer 9 in the Albuquerque area.



EXPLANATION

—4940— WATER-LEVEL CONTOUR--Interval 10 feet. Datum is sea level

Figure 25.--Ground-water levels that represent 1960 conditions in the Santa Fe Group aquifer system in the Albuquerque area (modified from Bjorklund and Maxwell, 1961).

Hydrographs showing comparison between measured and simulated hydraulic heads for 21 wells in the Albuquerque Basin are shown in figure 26. The locations of these wells are shown in figure 27. Most of the 21 wells are those for which hydrographs were shown in Thorn and others (1993, fig. 35), and have the same letter designations in figure 26 as used by Thorn and others (1993). Two of the wells shown in Thorn and others (1993) are outside the modeled area and are therefore not shown in figure 26. An additional well (fig. 26W) was added in the area of Sandia Pueblo. The model layer selected for comparison was based on well depth or well completion interval if it was available.

Varying degrees of agreement between 1960 simulated and measured hydraulic heads are indicated in figures 22-25 as well as the hydrographs shown in figure 26. One reason the contours in figures 22-24 do not closely align in some areas with those constructed by Bjorklund and Maxwell (1961) is that the distribution of ground-water withdrawal prior to 1960 is not known. Although the 1956-1960 withdrawal distribution in the model was adjusted to some extent, it was concluded that the only adjustment to City of Albuquerque withdrawals that could be supported was to assume that the distribution of average 1956-1960 withdrawals was the same as that reported by Summers (1992, table 2) for 1960. The methods of distributing withdrawals were discussed in detail in the previous section on ground-water withdrawals.

Hydraulic-head contours in the western and northwestern parts of figures 22-24 do not match those of Bjorklund and Maxwell (1961; fig. 25). Bjorklund and Maxwell's (1961, pls. 1a and 1b) contours show a ground-water trough west of Albuquerque. Hydrographs for two wells in this area (figs. 26F and 26M) also show higher simulated than measured heads. Although in 1960 the existence of the ground-water trough was supported by few data, hydraulic-head data from test wells completed in the 1980's (Wilkins, 1987) support its existence. The trough in this area was not simulated on the basis of the geologic structure described by Hawley and Haase (1992) and the previously described values of hydraulic conductivity in the upper, middle, and lower parts of the Santa Fe Group. However, recent revisions to the conceptual model of this part of the basin (Dr. John Hawley, oral commun., October 5, 1994) may offer an explanation for the trough. The presence of the trough indicates that there could be a thicker sequence of more permeable material than the material on either side. Therefore, transmissivity within the trough would be greater than on either side, and thus could create the ground-water trough.

The contours in figures 22-24 from the northeast part of Albuquerque to Sandia Pueblo do not well match the contours of Bjorklund and Maxwell (1961). The two wells on Sandia Pueblo (fig. 26E and W) and the well northeast of Bernalillo (fig. 26D) also show the discrepancy between simulated and measured hydraulic heads. As described previously, the middle part of the Santa Fe Group was believed to crop out in the area of Sandia Pueblo. This area is simulated in the model as being the middle part of the Santa Fe Group in layers 1-8 and the lower part of the Santa Fe Group in layers 9-11. The model, therefore, uses a hydraulic conductivity of 4 ft/d (layers 1-8, figs. 7-14) or 2 ft/d (layers 9-11, figs. 15-17). This relatively low simulated hydraulic conductivity in comparison to the adjacent axial-channel deposits in the Albuquerque area does not allow simulated declines in hydraulic head to be as great as have actually occurred. However, recent field mapping in this area (Dr. John Hawley, oral commun., August 26, 1994) has identified the outcrops to actually be the upper part of the Santa Fe Group. With this new information, the model could be updated to reflect the higher hydraulic-conductivity values of the upper Santa Fe Group, thus allowing a more realistic simulation of hydraulic heads in this area. This new interpretation was not available in time to be included in the simulations described in this report.

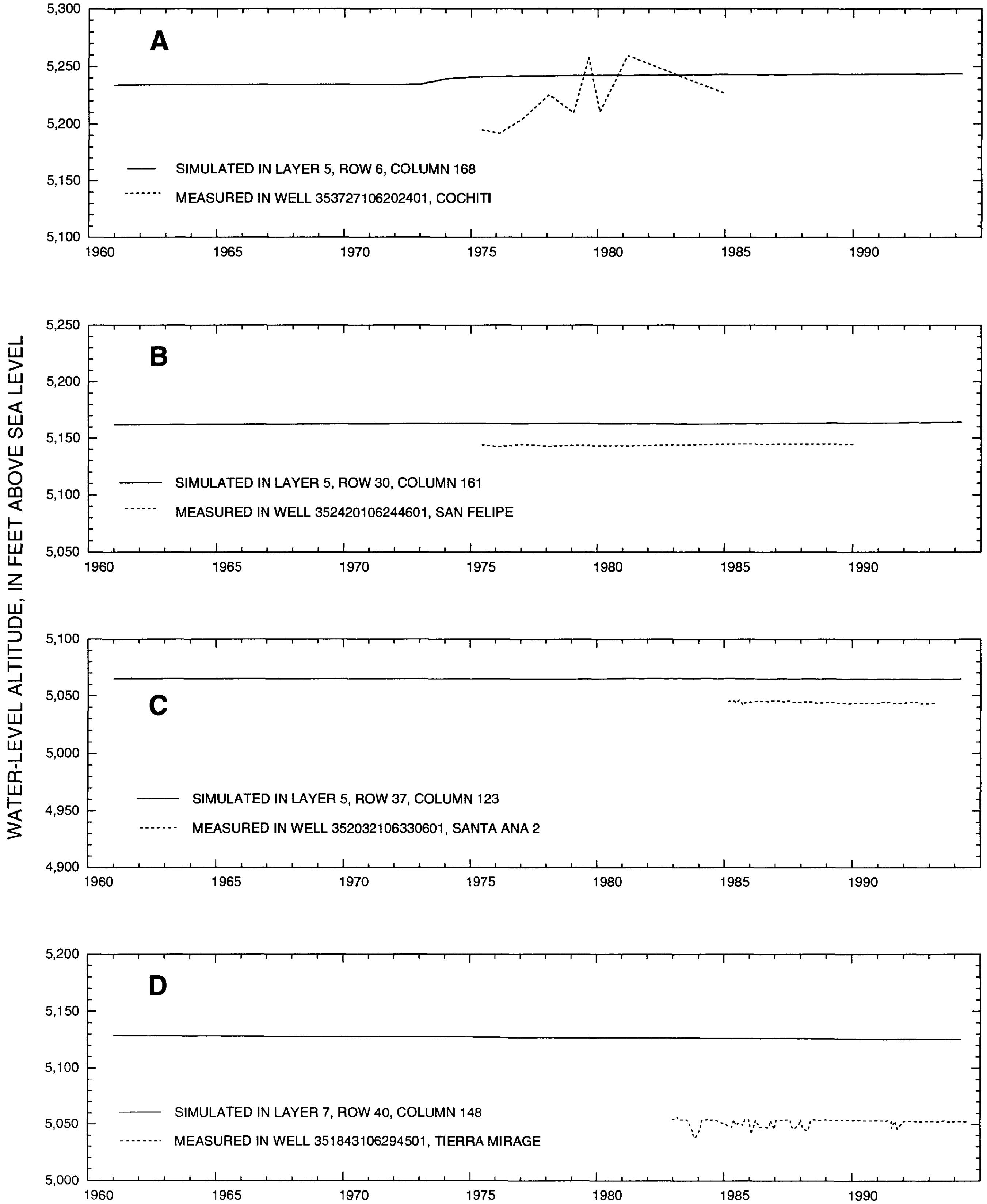


Figure 26.--Water levels measured in selected wells in the Albuquerque Basin and those simulated in corresponding model cells (location of wells shown in fig. 27).

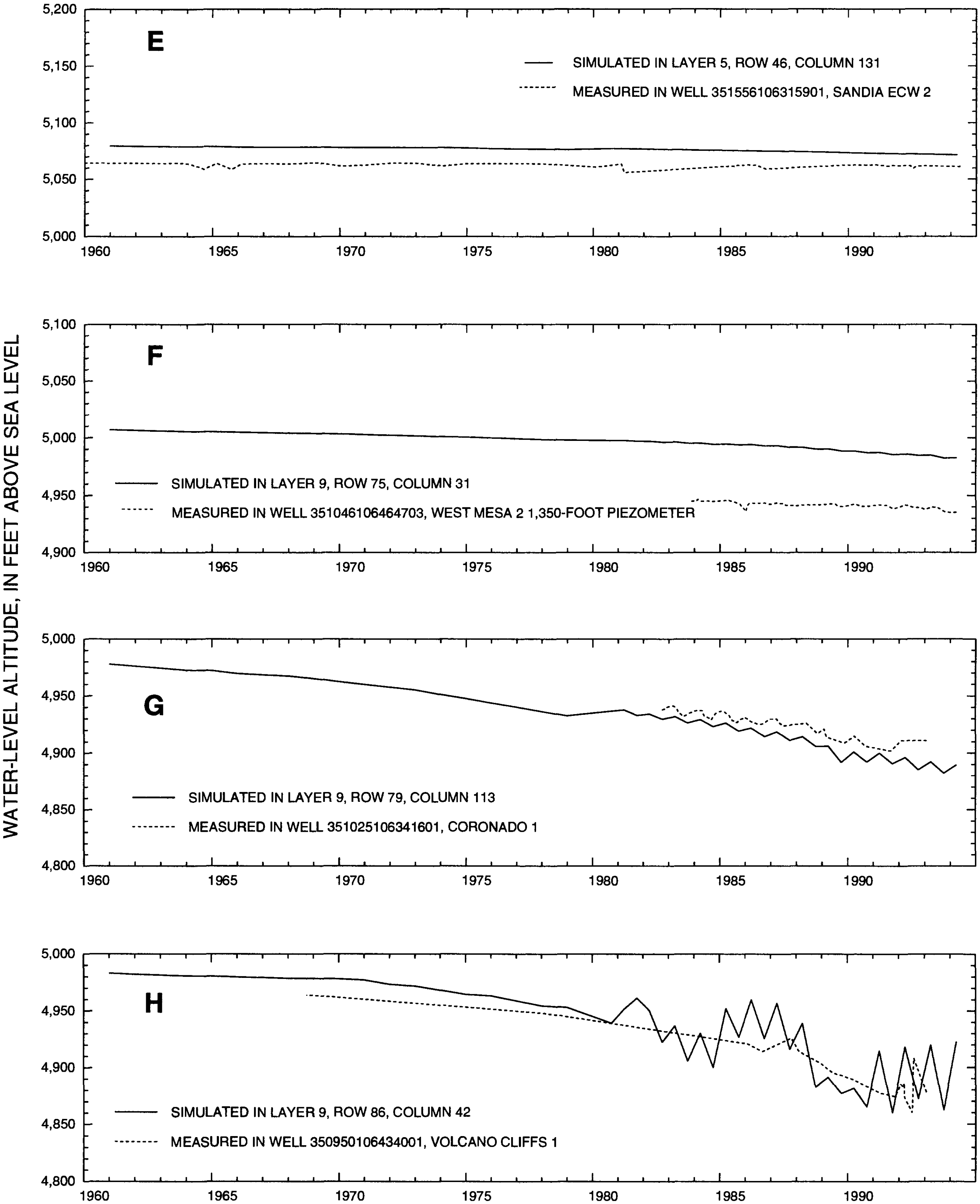


Figure 26.--Water levels measured in selected wells in the Albuquerque Basin and those simulated in corresponding model cells (location of wells shown in fig. 27)--Continued.

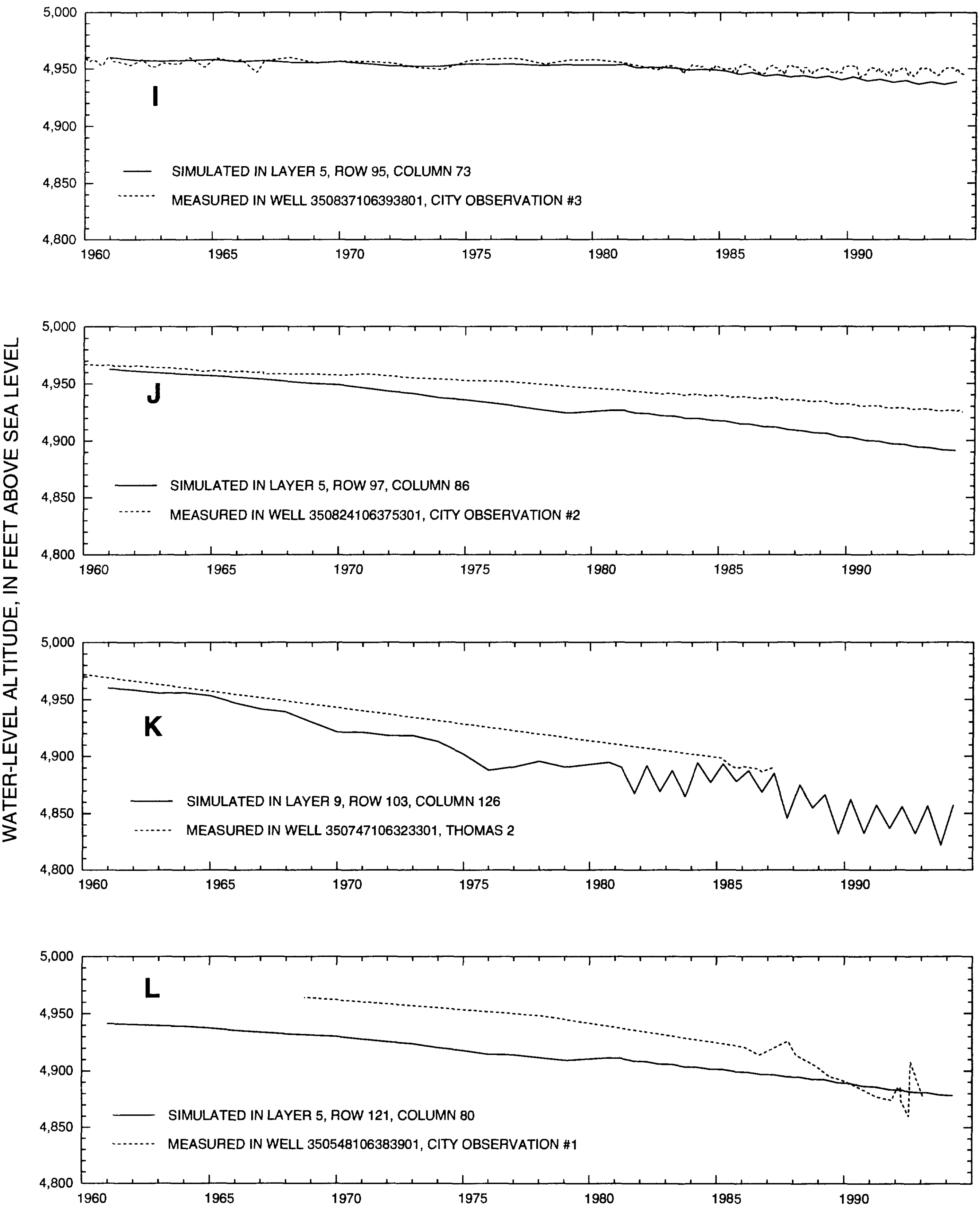


Figure 26.--Water levels measured in selected wells in the Albuquerque Basin and those simulated in corresponding model cells (location of wells shown in fig. 27)--Continued.

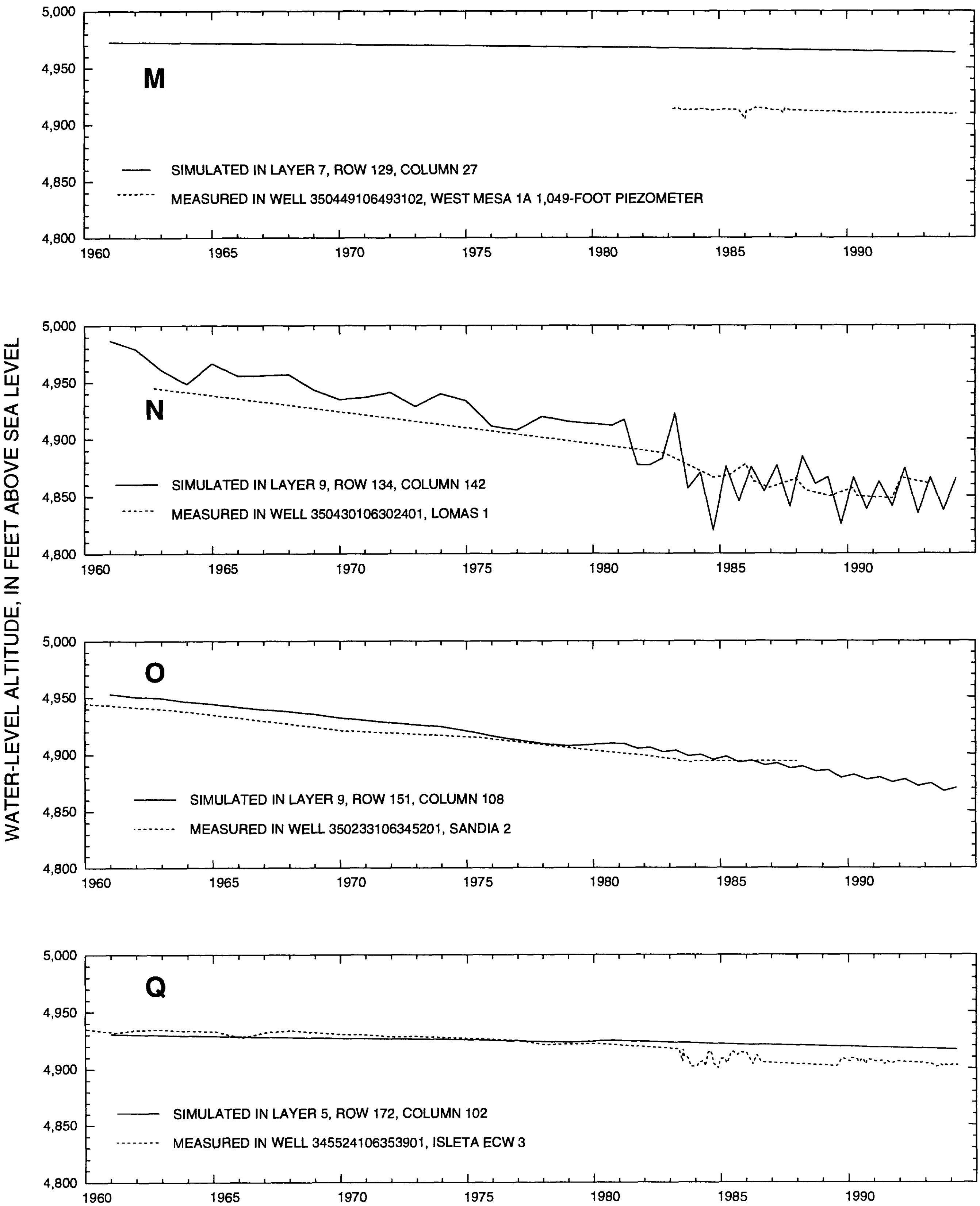


Figure 26.--Water levels measured in selected wells in the Albuquerque Basin and those simulated in corresponding model cells (location of wells shown in fig. 27)--Continued.

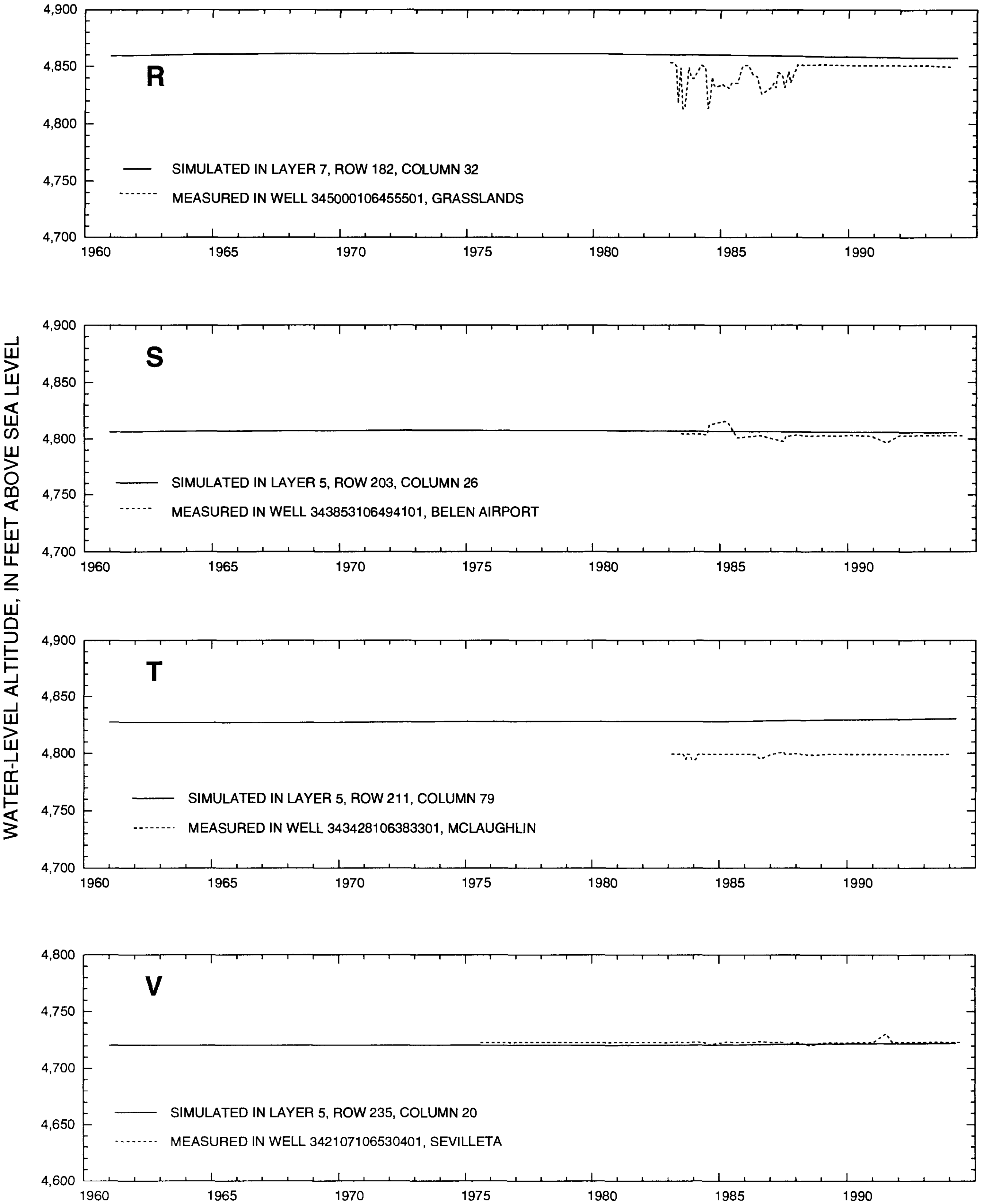


Figure 26.--Water levels measured in selected wells in the Albuquerque Basin and those simulated in corresponding model cells (location of wells shown in fig. 27)--Continued.

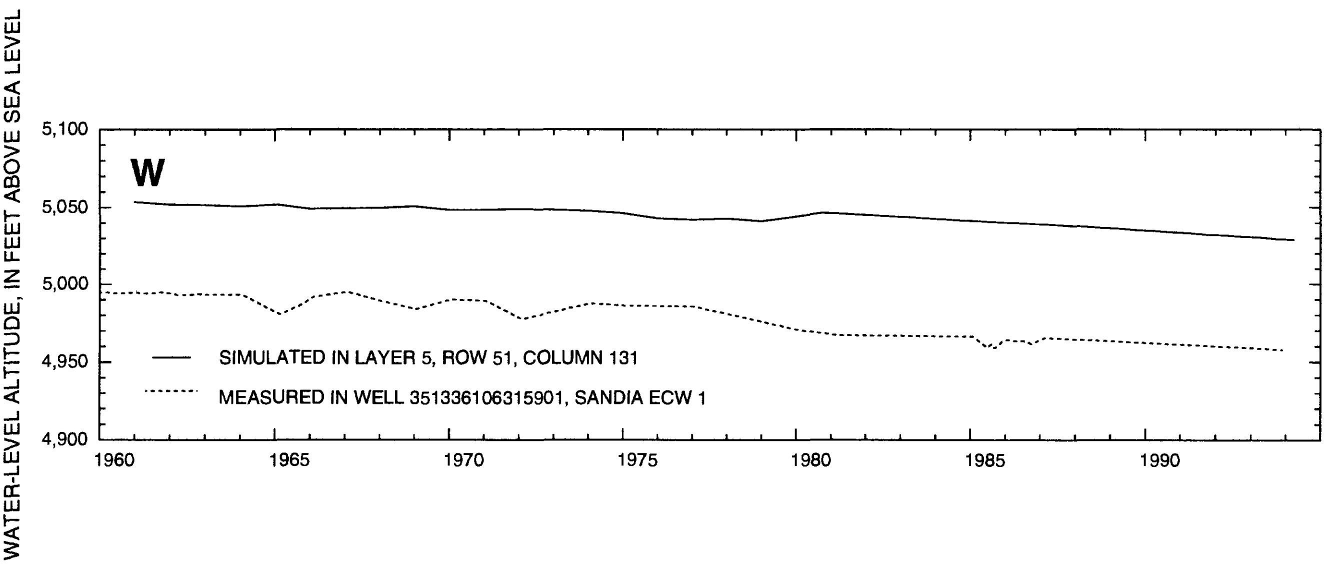


Figure 26.--Water levels measured in selected wells in the Albuquerque Basin and those simulated in corresponding model cells (location of wells shown in fig. 27)--Concluded.

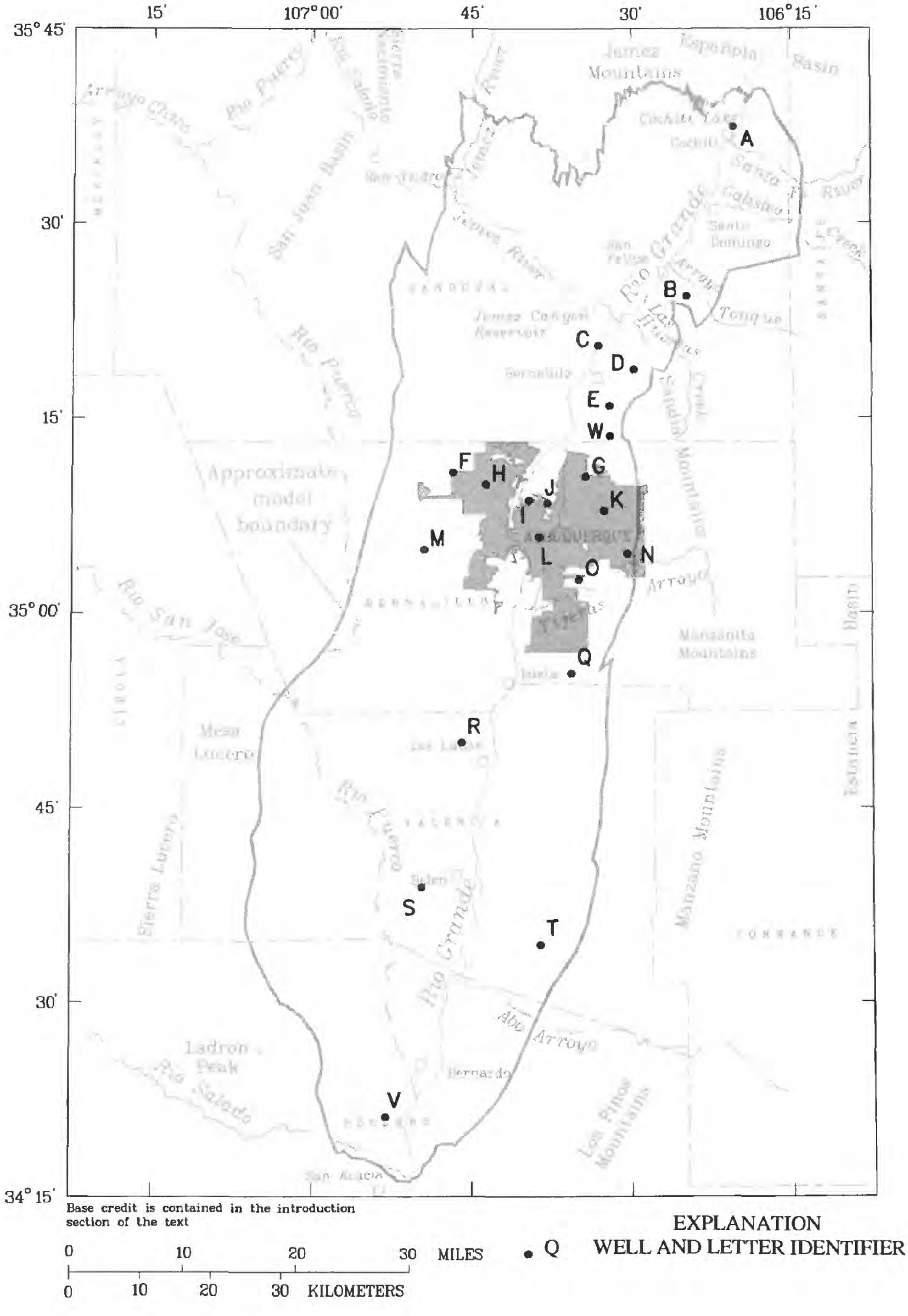


Figure 27.—Location of selected wells in the Albuquerque Basin (modified from Thorn and others, 1993).

Hydrographs for wells within the City of Albuquerque (fig. 26G-L, N, and O) show reasonable matches between simulated and measured hydraulic heads. The wells shown in figures 26I and J are on opposite sides of the mapped location of the Rio Grande Fault (fig. 4). Figure 26I, which represents the well on the west (Rio Grande) side of the fault, shows good agreement between simulated and measured hydraulic heads. Figure 26J, which represents the well on the east side of the fault, shows good agreement in the early 1960's but a divergence of simulated and measured hydraulic heads after the 1960's. This may be an indication that the fault, which may not even be present, is simulated as more of a barrier to ground-water flow in the vicinity of these wells (see Hydraulic Characteristics section) than it actually is, thus not allowing enough recharge water from the Rio Grande to the east side of the fault.

The hydrographs shown in figures 26A-C, Q-T, and V, which are for wells outside the Albuquerque area, show reasonable matches between simulated and measured hydraulic heads. The differences are generally within about 30 feet. Variation in measured hydraulic head in the well near Cochiti (fig. 26A) is a result of changes in stage in Cochiti Lake (Blanchard, 1993), which was not simulated in the model (see River, Canal, and Reservoir Leakage section).

A comparison of simulated and measured spring 1993 hydraulic heads was made for 186 wells located in the Albuquerque Basin (fig. 28). The mean difference (simulated minus measured head) is 2.7 feet using layer 5 for comparison and -3.9 feet using layer 9. The mean absolute difference is 20.0 feet using layer 5 for comparison and 22.8 feet using layer 9. A similar comparison of simulated and measured spring 1993 hydraulic heads was made only for those wells located in the Albuquerque area (fig. 29). The mean difference using only those wells is -3.2 feet using layer 5 for comparison and -11.6 feet using layer 9. The mean absolute difference is 17.2 feet using layer 5 for comparison and 20.4 feet using layer 9.

There are several reasons to suggest that these differences indicate an acceptable agreement between simulated and measured hydraulic heads. One is that the altitude of the Rio Grande, the base control for water levels, is simulated only to the accuracy limit of one contour interval on a 7.5-minute topographic map, which is usually 20 feet but often 50 feet in the basin. It is likely that this potential source of error is local and not systematic, and that regionally within the basin the error induced in the simulated heads approaches zero. However, the error may also be present wherever the land-surface altitude of a well is determined from a topographic map, as is usually the case. This potential error is compounded by the possibility that the actual location of the well on the map may be incorrect due to lack of distinguishing field control or inappropriate spatial coordinate conversions (direct township and range cadastral-survey coordinate conversions to geographic coordinates). Water-level altitudes in wells, whose land-surface altitudes (hence measuring-point altitudes) were determined from a topographic map, could be in error by as much as 20 feet.

Another reason that the differences are acceptable is that many of the wells, especially in the Albuquerque area, used in this comparison are designed and serve as production wells and not observation wells. These wells are completed over intervals of at least 500 feet and water levels measured in them represent a composite head in areas where steep vertical gradients almost always exist (see fig. 53). Comparisons of differences based on simulated heads in layers 5 and 9 were a first attempt to demonstrate and bracket this effect. The eventual solution to this source of error would be the construction and monitoring of specifically designed observation wells in areas of high vertical gradients.

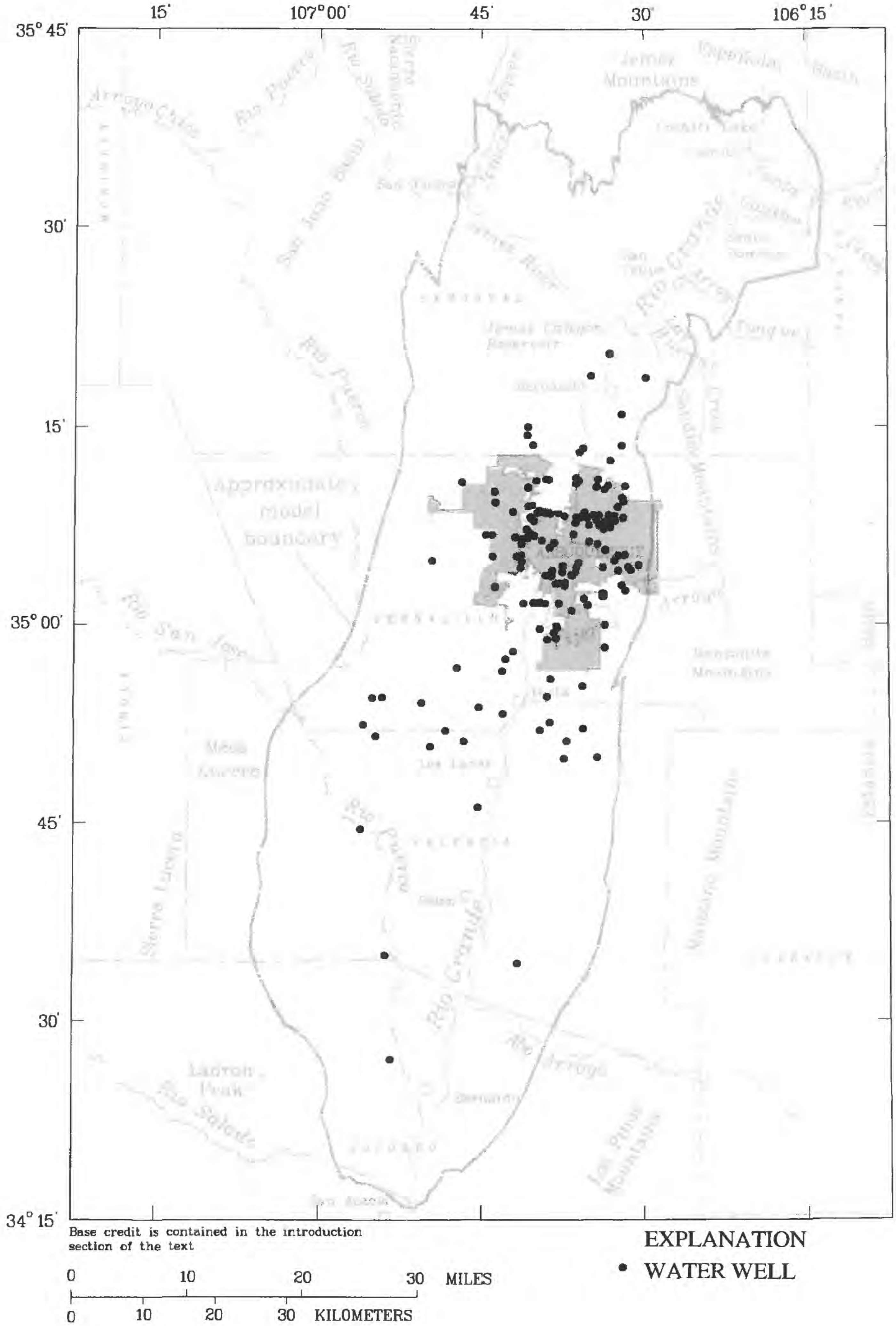


Figure 28.--Location of wells used to compute differences between computed and measured water levels in the Albuquerque Basin.

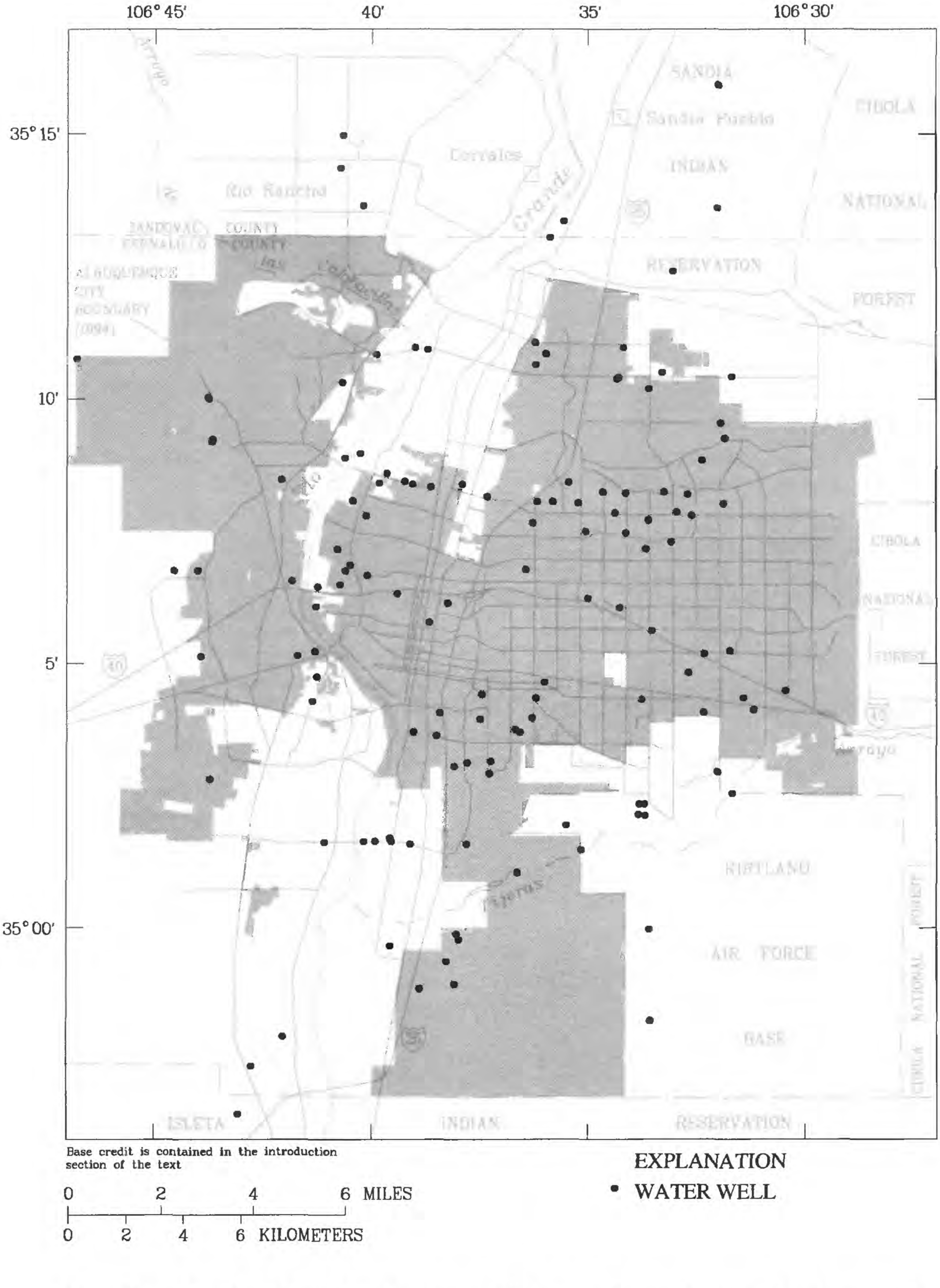


Figure 29.—Location of wells used to compute differences between computed and measured water levels in the Albuquerque area.

Simulated hydraulic heads at the end of the historical simulation (spring 1994) are shown in figure 30 for layer 5 and in figure 31 for layer 9. Layer 5 represents the upper part of the aquifer system (80-130 feet below river level) and layer 9 represents the production zone for the majority of City of Albuquerque wells (580-830 feet below river level). Detailed contours of simulated hydraulic heads for layers 5 and 9 in the Albuquerque area are shown in figures 32 and 33, respectively. As shown in figure 32, the simulation produced perched water tables or zones of hydraulic disconnection near the Rio Grande in the southern part of Albuquerque. Unrealistic results may be generated in cases where a simulated perched water table is created, a dry cell between the two water tables exists, and recharge is applied to the perched water table. Under these conditions, recharge water is not allowed to pass through the dry cell, the hydraulic head in the perched zone will increase to a greater extent than would otherwise be simulated, and the hydraulic head in the lower zone will decrease to a greater extent than would otherwise be simulated. These conditions were created in some of the simulations.

The simulated change in hydraulic head from 1960 to 1994 is shown for layer 5 in figure 34 and for layer 9 in figure 35. The pattern of declines in simulated hydraulic head is similar to the calculated declines shown by Thorn and others (1993, fig. 33) for 1960 to 1992. The greatest simulated declines in layers 5 and 9 were in the eastern part of Albuquerque beyond the limit of the axial-channel deposits (Thorn and others, 1993, fig. 21).

Water Budgets

The steady-state, 1960, and 1994 water budgets for the initial condition and historical simulations are shown in table 5. The discrepancies in the budgets are due to rounding errors during model simulations. Because the errors are small (0.2 percent), the effect on the simulations is insignificant. In the predevelopment steady-state simulation, about 53 percent of inflow to the aquifer system is leakage from the river, canals, and reservoirs, about 37 percent is from mountain-front and tributary recharge, and about 11 percent is from ground-water inflow from adjacent basins. The major outflow of water from the basin, 97 percent, is by riparian and wetland evapotranspiration in the inner valley.

The water budgets for 1960 and 1994 (table 5) reflect the changes simulated as a result of water development in the basin. In addition to inflows and outflows in the steady-state simulation, the influence of canals, drains, irrigation seepage, septic-field return flow, and ground-water withdrawal is simulated. Changes in the net water-budget values in the historical simulations are shown in figures 36 and 37. The values of water-budget terms that were input to the model are shown in figure 36 and the net model-derived flow rates are shown in figure 37. Depletion of aquifer storage (fig. 37A) is to a large extent the result of changes in mountain-front and tributary recharge (fig. 36C) and ground-water withdrawal by wells (fig. 36A). The abrupt periodic changes in Rio Grande, canal, and reservoir leakage, drain seepage, and riparian and wetland evapotranspiration (figs. 37B-D) are a result of differences in the GIS data bases that were used to define the features of the inner valley for different periods during the historical simulation (see the Model Description section of this report). Because of the many changes simulated simultaneously in the model, it is difficult to isolate the quantitative effects of some influences on the water budgets as presented in table 5 and figures 36 and 37.

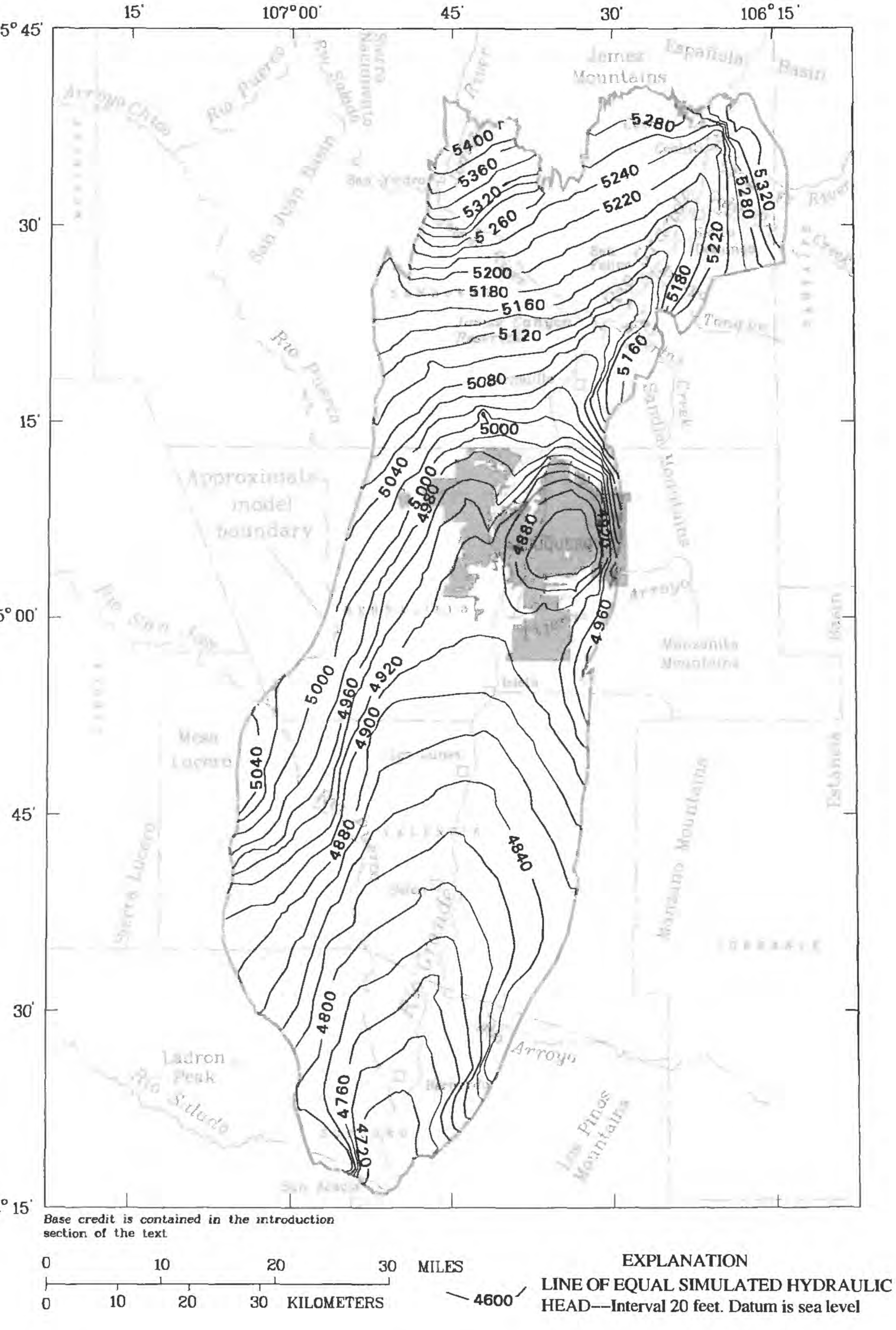


Figure 30.--Simulated 1994 hydraulic head in model layer 5 in the Albuquerque Basin.

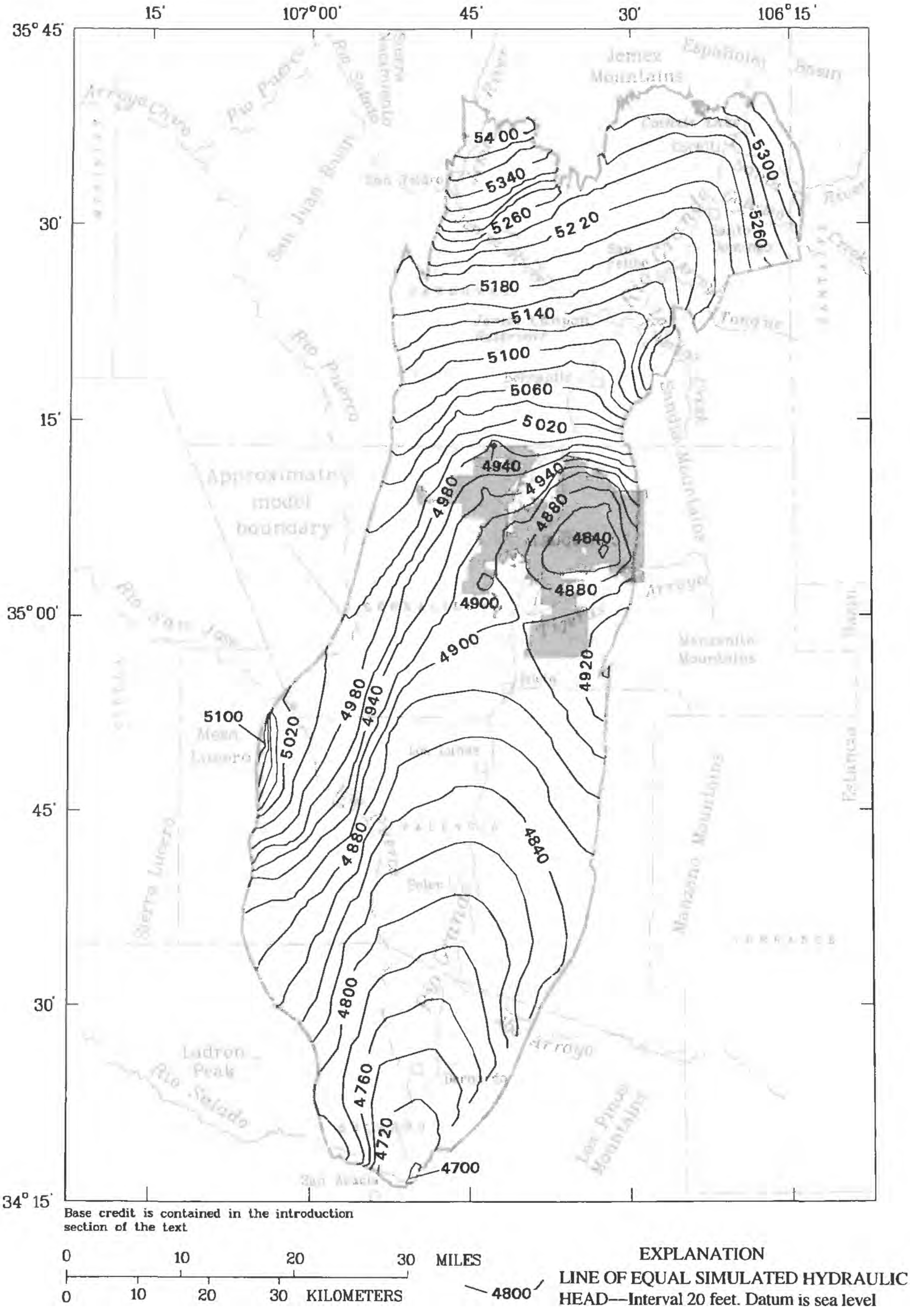


Figure 31.--Simulated 1994 hydraulic head in model layer 9 in the Albuquerque Basin.

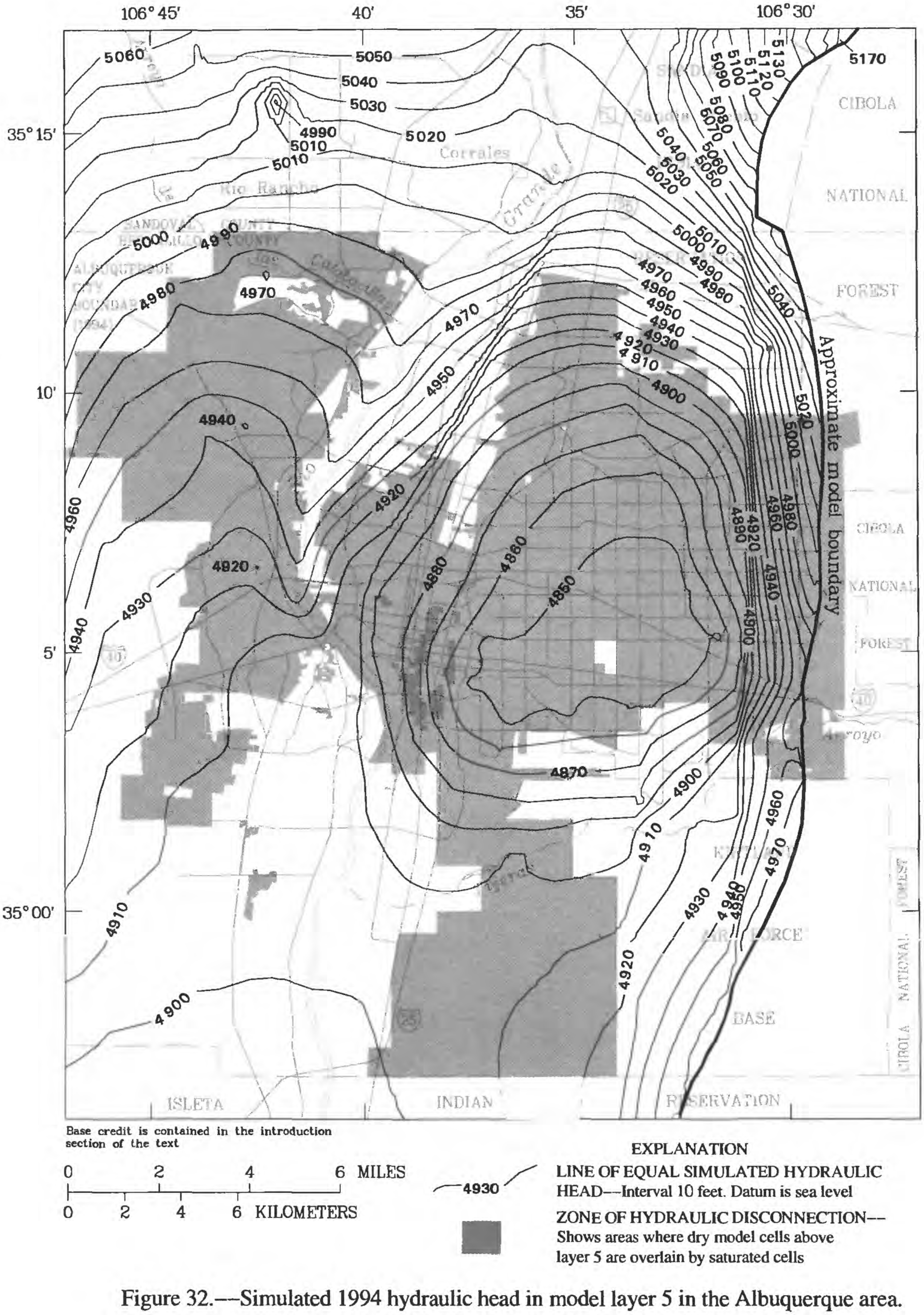


Figure 32.--Simulated 1994 hydraulic head in model layer 5 in the Albuquerque area.

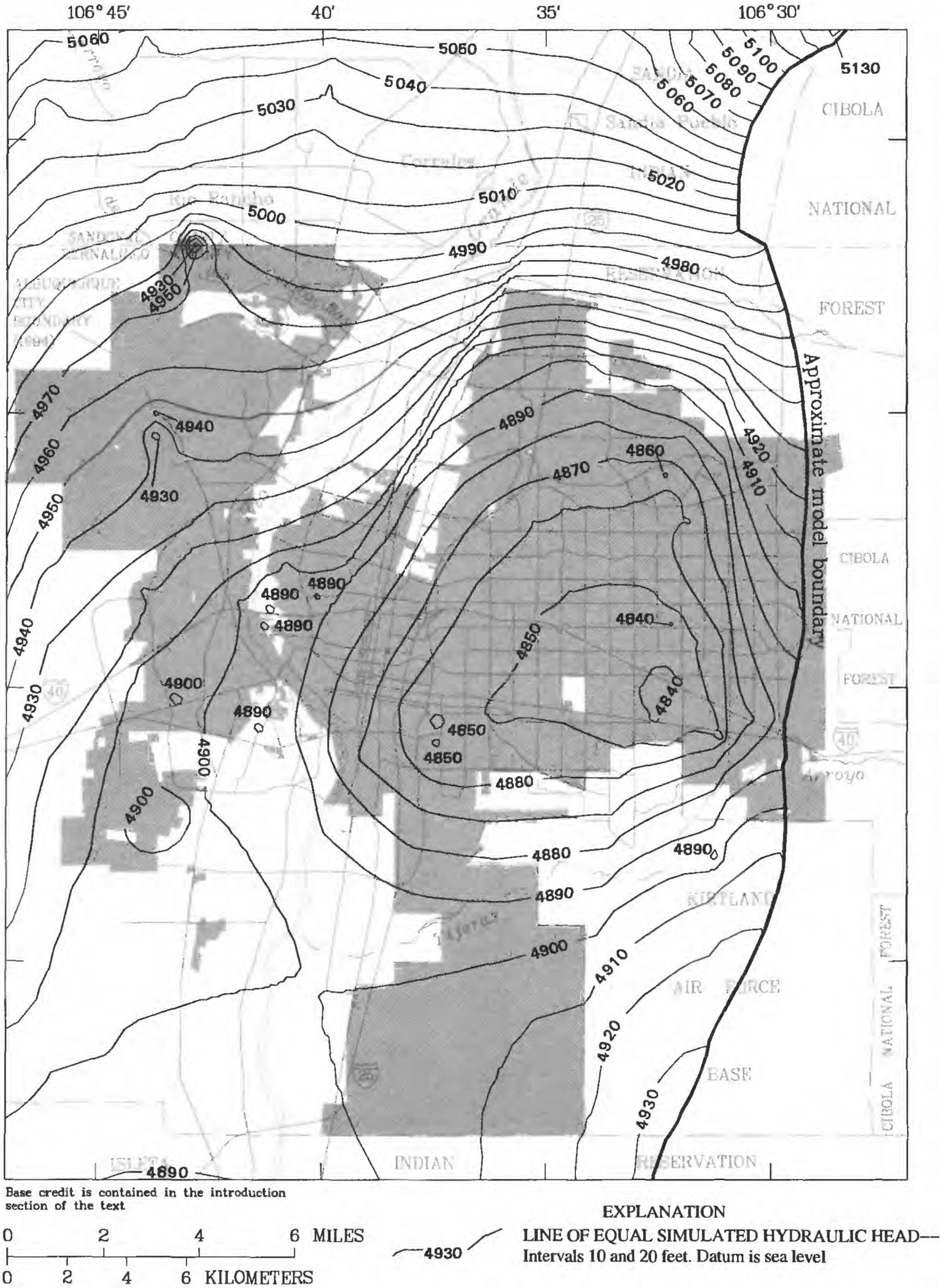


Figure 33.—Simulated 1994 hydraulic head in model layer 9 in the Albuquerque area.

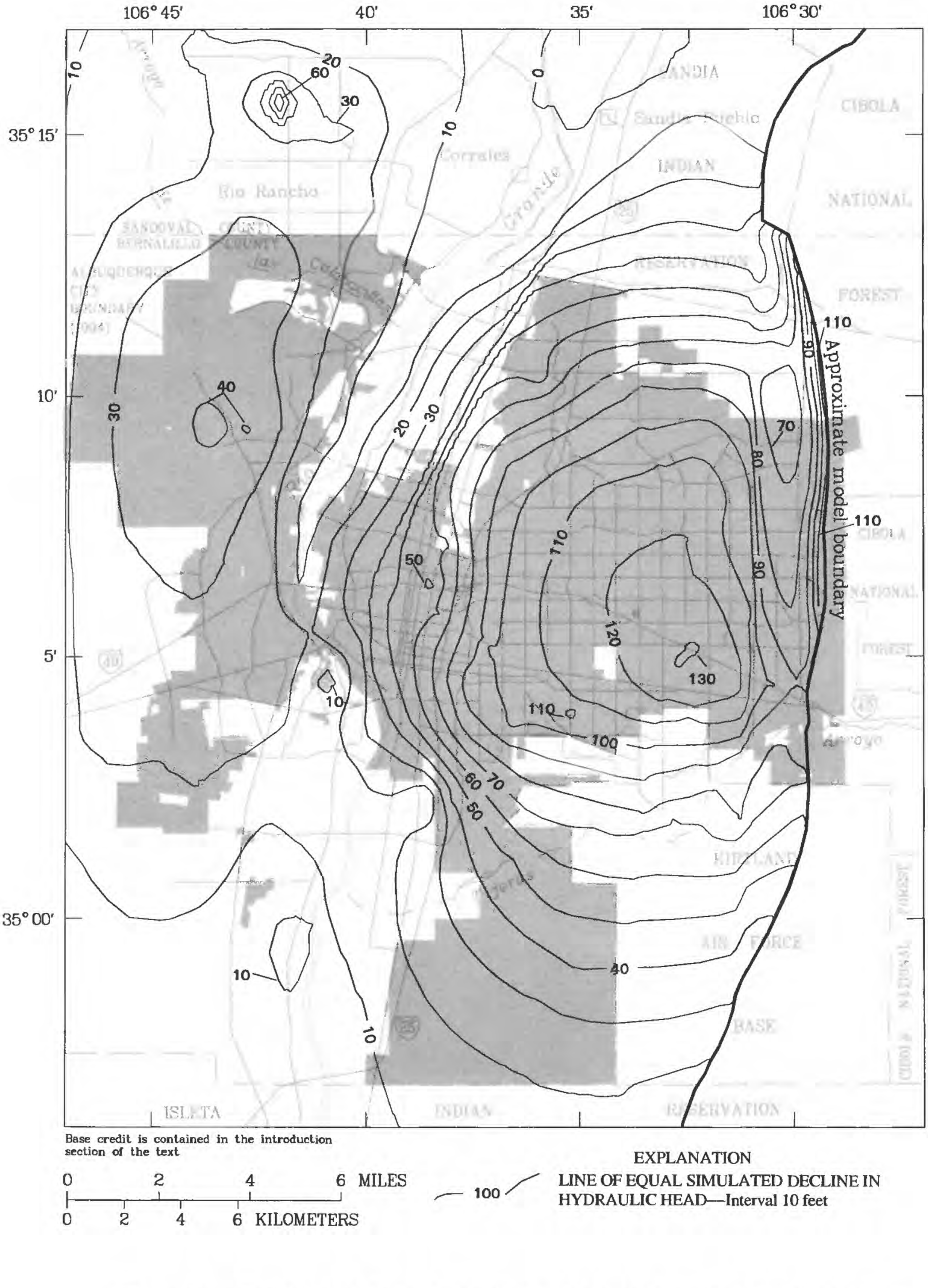


Figure 34.—Simulated decline in hydraulic head in model layer 5 in the Albuquerque area, 1960–1994.

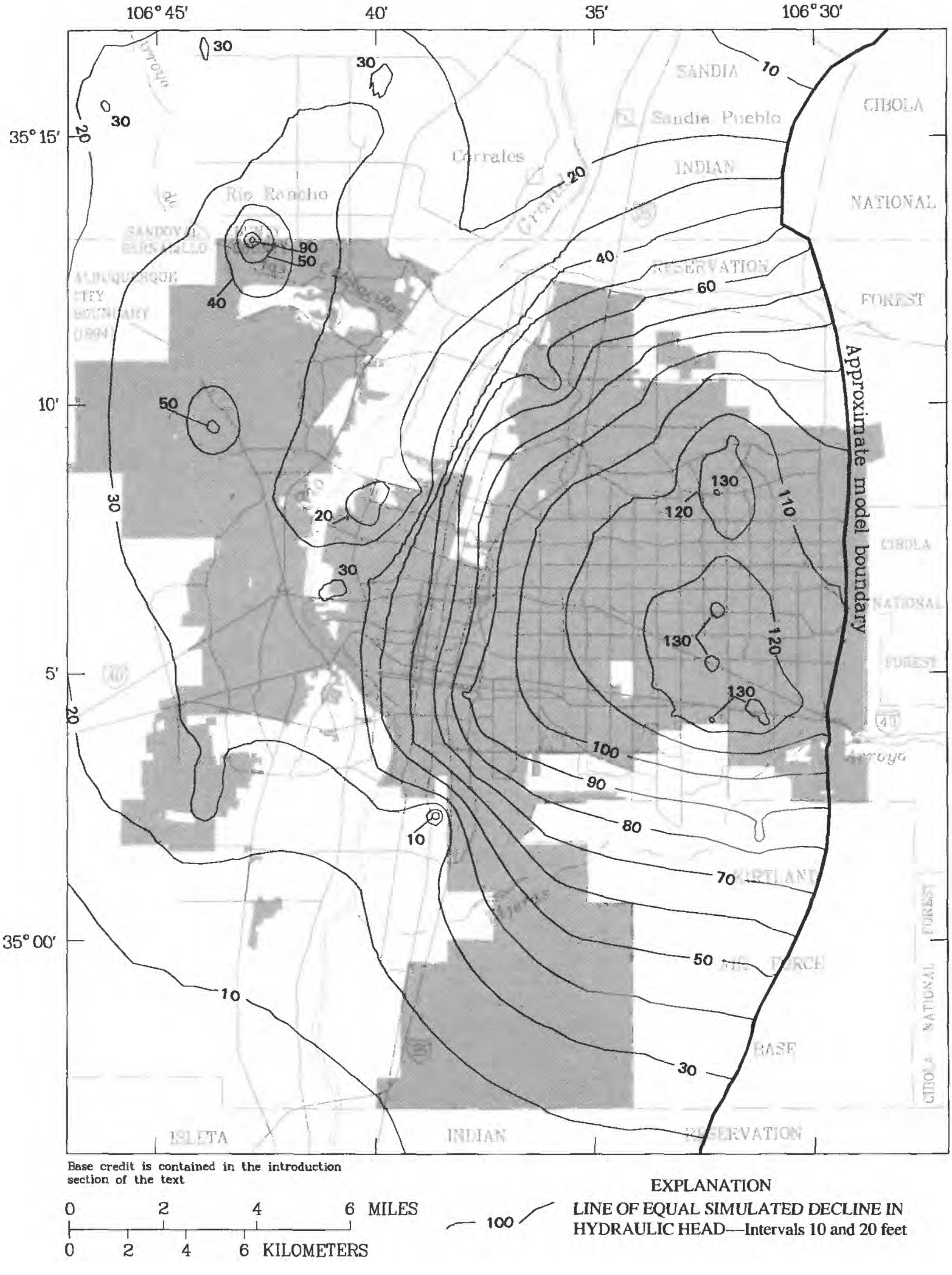


Figure 35.—Simulated decline in hydraulic head in model layer 9 in the Albuquerque area, 1960–1994.

Table 5.--Simulated annual water budgets for the Albuquerque Basin: steady state, 1960, and 1994

[All values are in acre-feet per year]

	Steady state (predevelopment)			1960			1994		
Mechanism	Inflow	Outflow	Net (inflow minus outflow)	Inflow	Outflow	Net (inflow minus outflow)	Inflow	Outflow	Net (inflow minus outflow)
Mountain-front and tributary recharge	99,100	0	99,100	107,000	0	107,000	131,000	0	131,000
Ground-water inflow from adjacent basins	28,400	0	28,400	28,400	0	28,400	28,400	0	28,400
River, canal, and reservoir leakage	[1]141,000	[1]8,170	[1]133,000	233,000	7,150	226,000	247,000	44,400	203,000
Drain seepage	0	0	0	0	98,900	-98,900	0	219,000	-219,000
Riparian and wetland evapotranspiration	0	261,000	-261,000	0	271,000	-271,000	0	89,200	-89,200
Irrigation seepage	0	0	0	44,000	0	44,000	28,300	0	28,300
Ground-water withdrawal	0	0	0	0	61,500	-61,500	0	171,000	-171,000
Septic-field return flow	0	0	0	0	0	0	8,220	0	8,220
Aquifer storage	0	0	0	29,700	4,400	25,300	109,000	27,800	81,200
Total	268,000	269,000	-500	442,000	443,000	-700	552,000	551,000	920
Percent discrepancy			0.2			0.2			0.2

[1]Represents flows to and from the Rio Grande. Canals were not simulated for predevelopment.

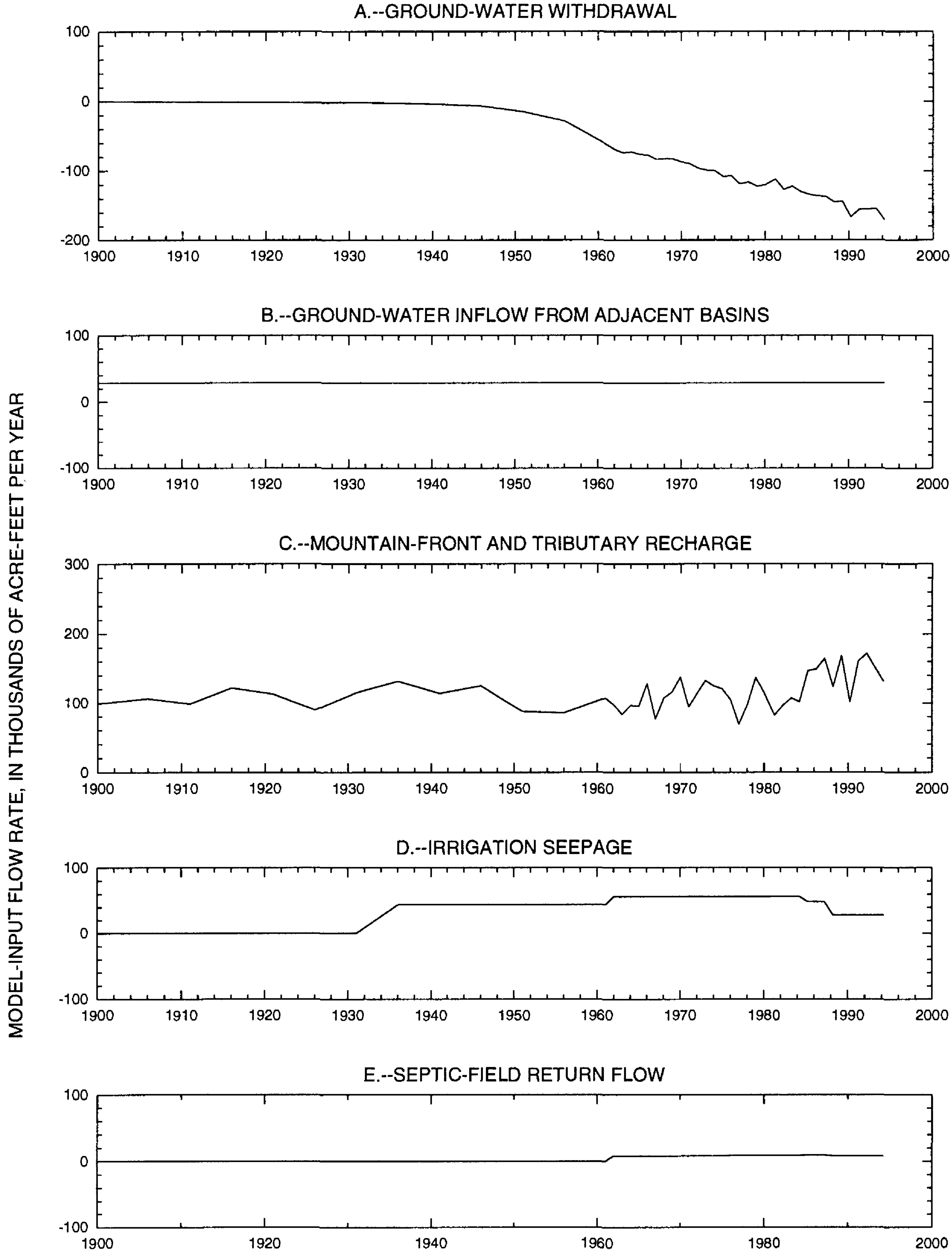


Figure 36.--Model-input flow rates for the 1901-1994 historical simulation of the Albuquerque Basin. Positive numbers indicate a source of water and negative numbers indicate a discharge of water.

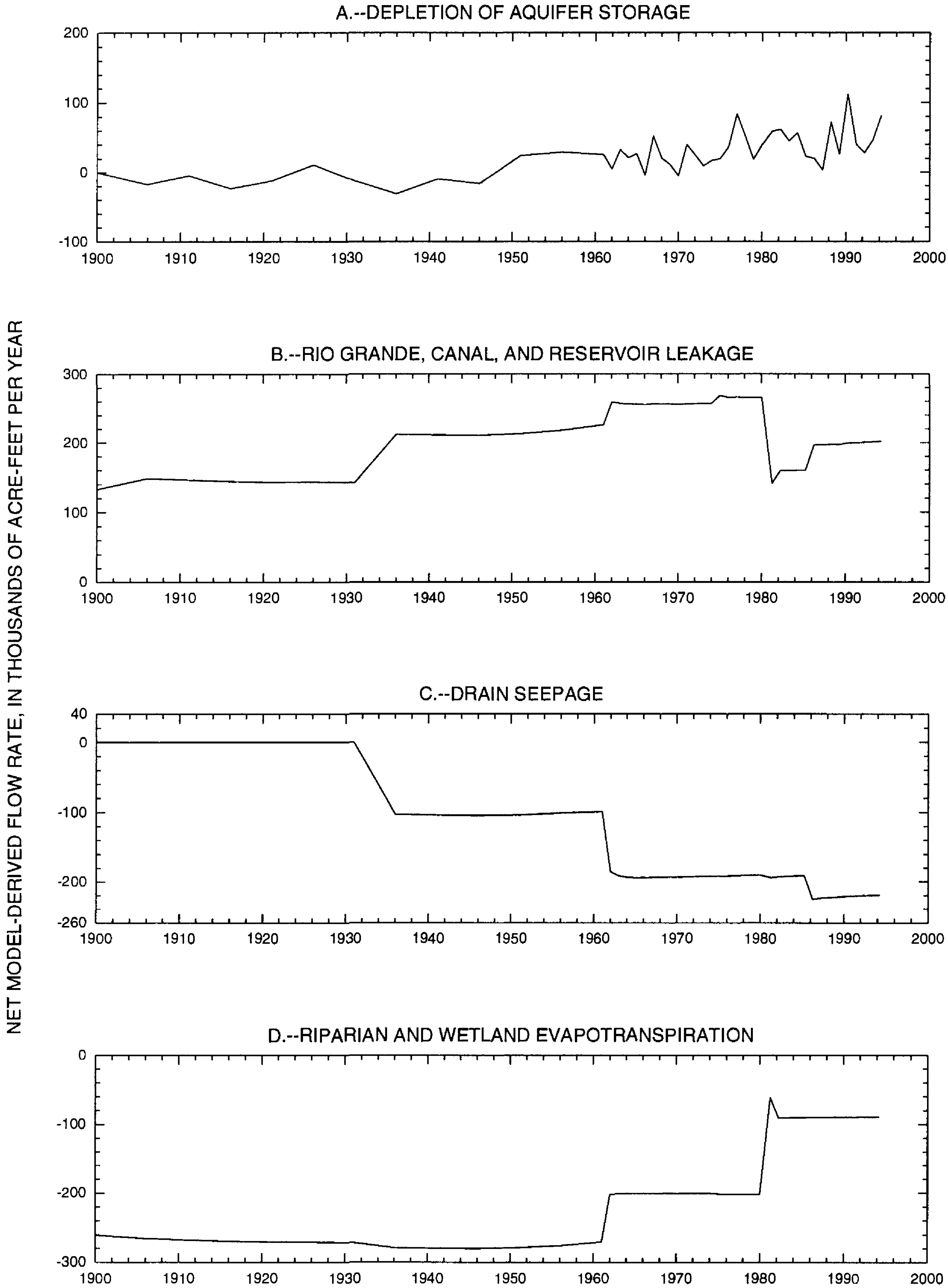


Figure 37.--Net model-derived flow rates for the 1901-1994 historical simulation of the Albuquerque Basin. Positive numbers indicate a source of water and negative numbers indicate a discharge of water.

To evaluate the influence of ground-water withdrawal by the City of Albuquerque on the aquifer system, a modified simulation of the historical period was done. The modified simulation is the same as the standard historical simulation except that withdrawals by the City of Albuquerque are not simulated. By comparing the net water budgets of the two simulations, the simulated sources of water to compensate for ground-water withdrawal by the City can be estimated. The sources of the City of Albuquerque withdrawals for the 1901-1994 simulation period are shown in figure 38. Flow rates plotted for stress periods of 1 or more years are those at the end of each stress period. Flow rates plotted for the part of the simulation where seasonal stress periods are used are the weighted-average rates for each pair of summer and winter seasons. River and canal seepage and reduced drain flow are net losses in surface water, which reduce the flow of the Rio Grande; therefore, they are combined. The abrupt changes at the end of 1960 shown in figure 38 are a result of two changes in the simulation. The increase in simulated City withdrawal is relatively rapid because the stress period changes from 5 years, where the simulated withdrawal is the average of 1956-1960, to 1 year, where the 1961 withdrawal is simulated. As a result, the change in withdrawal that appears to be from 1960 to 1961, a 1-year change, is more representative of the change from 1958 to 1961, a 3-year change. The rapid reduction in the volume of salvaged evapotranspiration and rapid increase in the depletion of flow in the Rio Grande are a result of the revitalization of the drain system in the inner valley during the 1950's. The revitalized drain system, which was simulated beginning in the 1961 stress period, is more efficient than the previously existing system. Thus, the revitalized drains salvage water that otherwise would have discharged as evapotranspiration and deliver it to the Rio Grande. Therefore, lowering of the water table as a result of City withdrawals, which would have reduced evapotranspiration prior to drain revitalization, depletes flow in the Rio Grande by reducing ground-water discharge to the drains.

The net water budgets for the modified (without City withdrawals) and standard (with City withdrawals) simulations and the differences are listed in table 6 for 1960, 1979, and 1994. All sources of recharge (mountain-front and tributary recharge, ground-water inflow from adjacent basins, irrigation seepage, and septic-field return flow) are combined in table 6. The simulated withdrawal by the City of Albuquerque for 1960, which is the 1956-1960 average withdrawal over the 5-year stress period, was 34,300 acre-feet. About 40 percent of the water to compensate for this withdrawal (13,600 acre-feet) came from net storage; 26 percent (9,000 acre-feet) from river, canal, and reservoir leakage; about 12 percent (4,100 acre-feet) from drain seepage; and about 20 percent (7,000 acre-feet) from riparian and wetland evapotranspiration (percentages sum to 98 percent because of rounding). The net loss from surface water (river, canal, and reservoir leakage and drain seepage) was 31 percent (13,100 acre-feet).

For 1979 the simulated withdrawal by the City was 86,400 acre-feet. About 56 percent of the water to compensate for this withdrawal (48,100 acre-feet) came from net storage; about 19 percent (16,000 acre-feet) from river, canal, and reservoir leakage; about 25 percent (22,000 acre-feet) from drain seepage; and about 1 percent (1,000 acre-feet) from riparian and wetland evapotranspiration (percentages sum to 101 percent because of rounding). The net loss from surface water was about 44 percent (38,000 acre-feet).

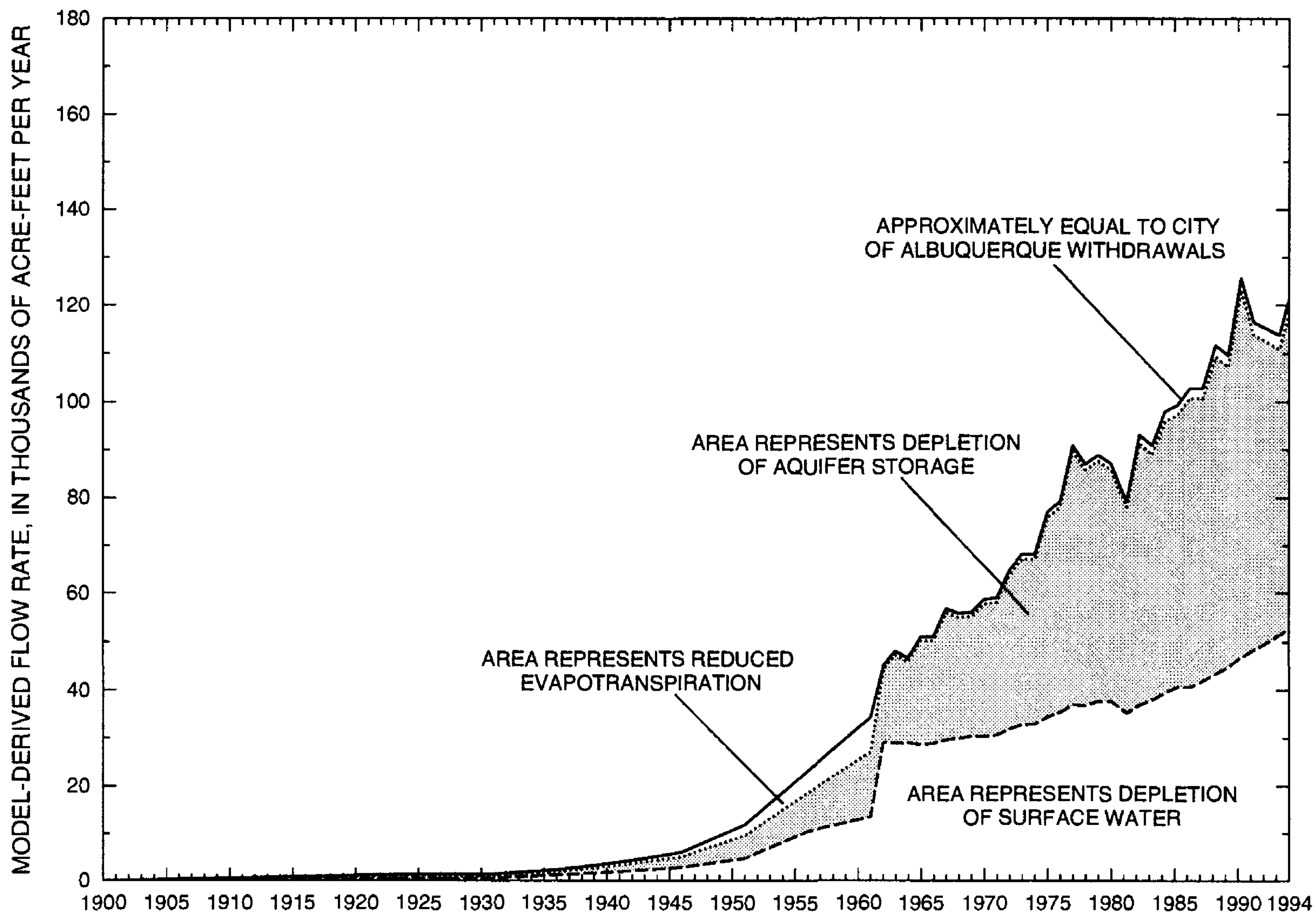


Figure 38.--Sources of City of Albuquerque withdrawals, 1901-1994.

Table 6.--Simulated water budget without and with City of Albuquerque ground-water withdrawals: 1960, 1979, and 1994

[All values are in acre-feet per year]

Mechanism	1960			1979			1994		
	Simulation without City withdrawal	Simulation with City withdrawal	Difference	Simulation without City withdrawal	Simulation with City withdrawal	Difference	Simulation without City withdrawal	Simulation with City withdrawal	Difference
Net storage	11,700	25,300	13,600	-9,160	38,900	48,100	13,400	81,200	67,800
River, canal, and reservoir leakage	217,000	226,000	9,000	250,000	266,000	16,000	178,000	202,000	24,000
Drain seepage	-103,000	-98,900	4,100	-212,000	-190,000	22,000	-248,000	-219,000	29,000
Riparian and wetland evapo-transpiration	-278,000	-271,000	7,000	-203,000	-202,000	1,000	-91,700	-89,200	2,500
Recharge[1]	180,000	180,000	0	209,000	209,000	0	196,000	196,000	0
Ground-water withdrawal	27,200	61,500	34,300	34,600	121,000	86,400	47,500	171,000	123,000
Net surface-water loss			13,100			38,000			53,000

[1]Mountain-front and tributary recharge, ground-water inflow from adjacent basins, irrigation seepage, and septic-field return flow.

The simulated withdrawal by the City for spring 1993 to spring 1994 was 123,000 acre-feet. About 55 percent of the water to compensate for this withdrawal (67,800 acre-feet) came from net storage; about 20 percent (24,000 acre-feet) from river, canal, and reservoir leakage; about 24 percent (29,000 acre-feet) from drain seepage; and about 2 percent (2,500 acre-feet) from riparian and wetland evapotranspiration (percentages sum to 101 percent because of rounding). The net loss from surface water was about 43 percent (53,000 acre-feet).

PROJECTED SIMULATIONS TO 2020

Four projections of possible future ground-water withdrawals by the City of Albuquerque were simulated to provide estimates of the effects of these future City withdrawals on hydraulic heads within the aquifer and on flow in the Rio Grande. The future withdrawal scenarios (Tom Shoemaker, City of Albuquerque, written commun., June 17, 1994) are: (1) a medium growth rate (Bureau of Business and Economic Research, 1993) and a 30-percent reduction in ground-water withdrawals by conservation implemented over 5 years; (2) the medium growth rate with new wells located only near the Rio Grande; (3) the medium growth rate with new wells located in accordance with the City's Decade Plan Update, FY95-FY08 (Roy Robinson, City of Albuquerque, Water Utility Division, written commun., 1994), hereafter referred to as the Decade Plan Update; and (4) a nearly straight line continuation of the current historical trend (current trend) with new wells located as in the Decade Plan Update. A fifth projection was run without City withdrawals to determine by superposition the City's incremental impacts on the basinwide water budget for the four scenarios. All projections begin in the spring of 1994 and end in the spring of 2020. The City of Albuquerque's historical ground-water withdrawals and projected withdrawals to the year 2020 for the three projected withdrawal rates are shown in figures 39-41.

The City of Albuquerque's ground-water withdrawal rates and distribution are the only differences among the scenarios. The growth rate for public-supply systems other than Albuquerque's was simulated to follow the Bureau of Business and Economic Research (1993) medium growth rate by county. Irrigation seepage loss and self-supplied commercial and private domestic withdrawals and returns were kept constant at the 1990 rates. Simulated mountain-front recharge and tributary recharge were held constant at the long-term mean (the base value upon which departures were imposed for the historical simulations).

Except for the current trend projection, population growth projections for 1995-2012 for the City of Albuquerque are based on the Decade Plan Update. Thereafter, the growth rate is based on the Bureau of Business and Economic Research (1993) medium rate for Bernalillo County. The projected rates of population growth for the current trend were increased until an approximate straight-line continuation of the current trend of ground-water withdrawal was obtained.

The City of Albuquerque water-service area was divided into seven different areas (fig. 42) of anticipated growth. The growth divisions were delineated by aggregating 37 trunk and zone areas as shown in the Decade Plan Update. Each well field in the city water system was assigned to a particular division; therefore, the projected increase in withdrawal from each well field is in proportion to the projected increase in population served within each division. Table 7 lists the growth rate from 1994 to 2020 for each division. In addition, the planned completion of and production from new wells as described in the Decade Plan Update were simulated.

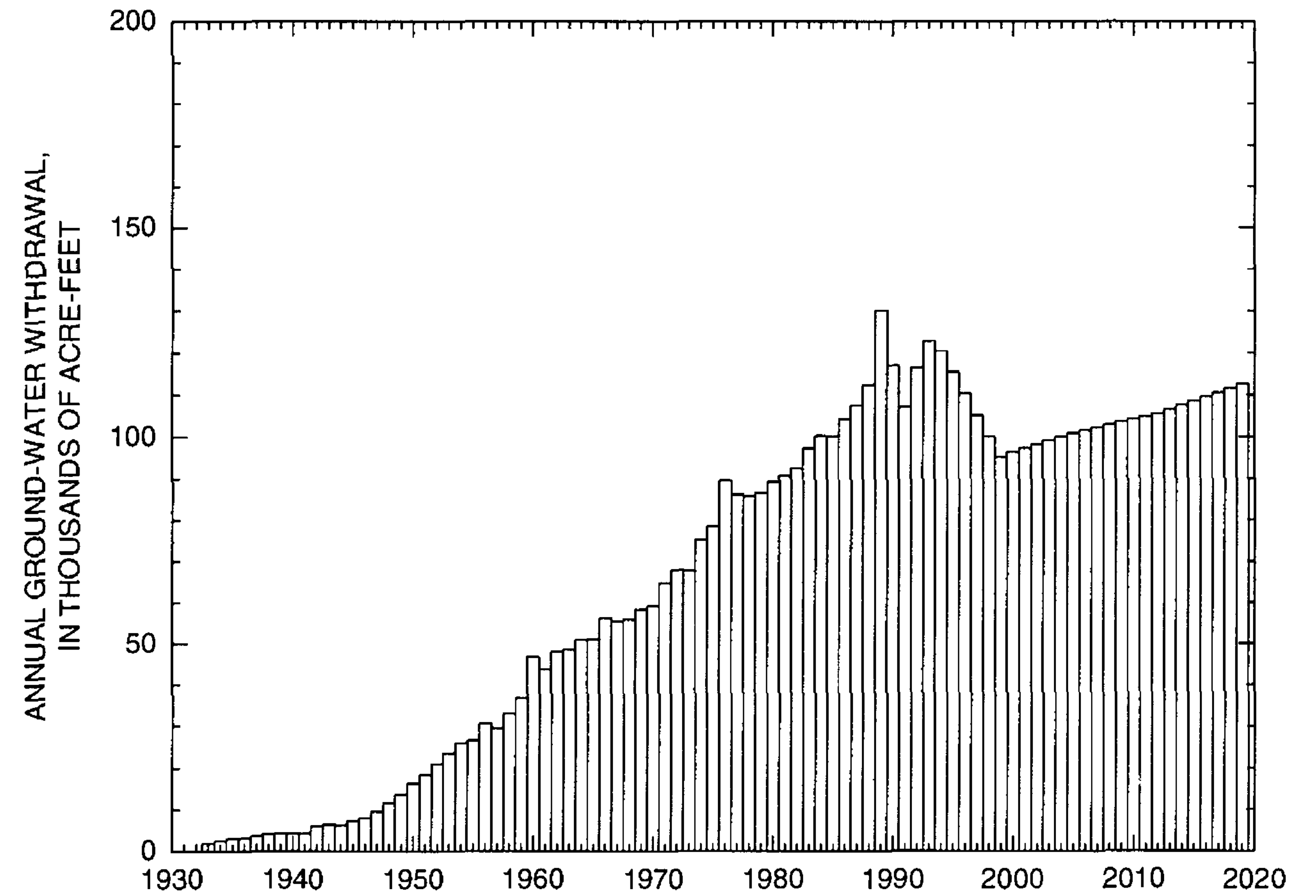


Figure 39.--Historical (1933-1994) and projected (1994-2020) ground-water withdrawal by the City of Albuquerque assuming medium growth and 30-percent conservation (data from Bjorklund and Maxwell, 1961; Sorensen, 1982; Wilson, 1992; files of the City of Albuquerque; and files of New Mexico State Engineer Office, Albuquerque).

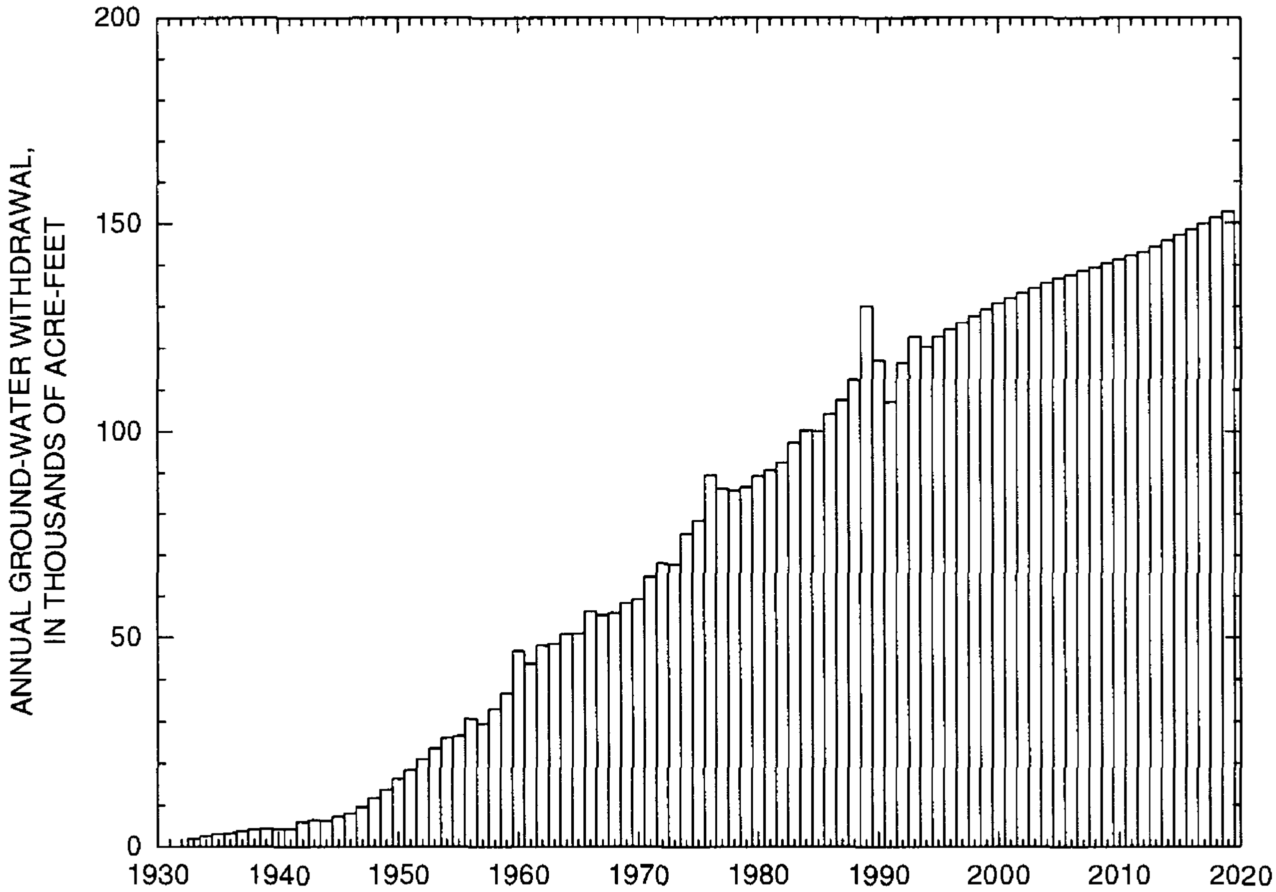


Figure 40.--Historical (1933-1994) and projected (1994-2020) ground-water withdrawal by the City of Albuquerque assuming medium growth (data from Bjorklund and Maxwell, 1961; Sorensen, 1982; Wilson, 1992; files of the City of Albuquerque; and files of New Mexico State Engineer Office, Albuquerque).

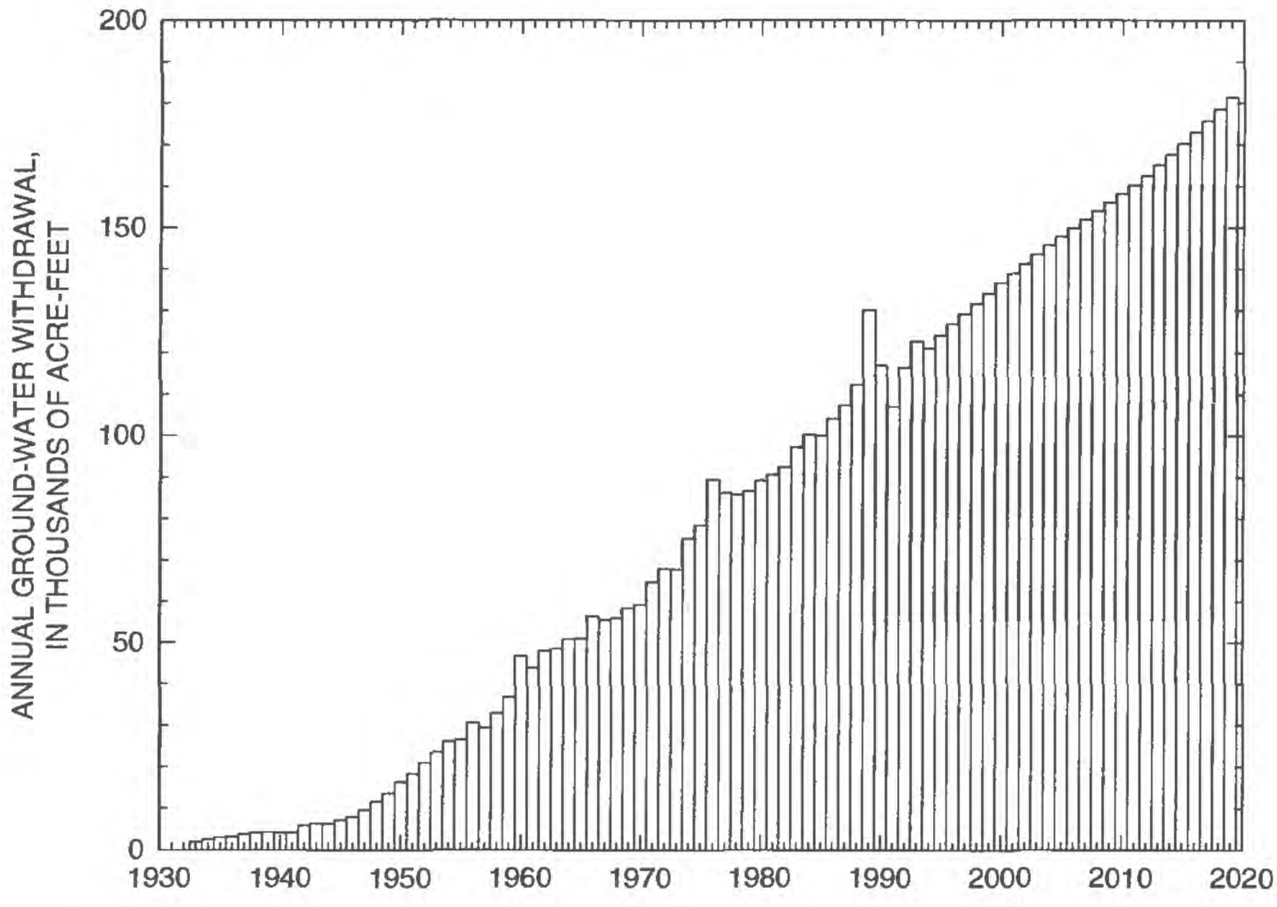


Figure 41.--Historical (1933-1994) and projected (1994-2020) ground-water withdrawal by the City of Albuquerque assuming the current growth trend (data from Bjorklund and Maxwell, 1961; Sorensen, 1982; Wilson, 1992; files of the City of Albuquerque; and files of New Mexico State Engineer Office, Albuquerque).

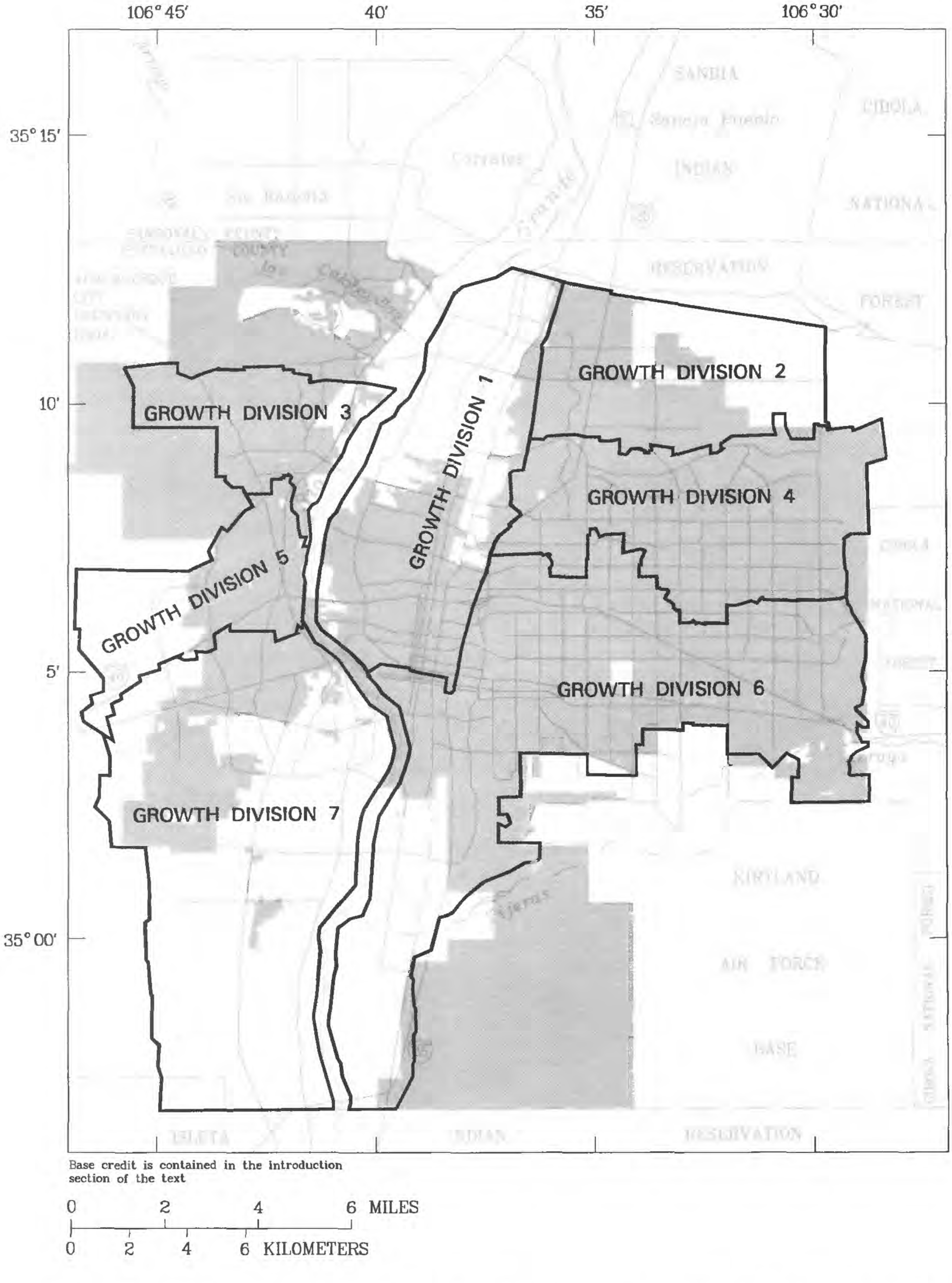


Figure 42.—Projected growth divisions in the Albuquerque area used for the 1994–2020 simulations (modified from City of Albuquerque digital data; projected medium growth for the divisions is shown in table 7).

Table 7.--Projected medium growth by division for the City of Albuquerque water-service area

[Values are annual growth, in percent; growth divisions are shown in figure 42; 1994-2012 values from Roy Robinson, City of Albuquerque, Water Utility Division, written commun., 1994; 2013-2020 values from Bureau of Business and Economic Research, 1993]

Growth division	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013 to 2020
1	0.67	0.69	0.58	0.65	0.65	0.68	0.67	0.65	0.64	0.68	0.68	0.72	0.63	0.71	0.70	0.73	0.72	0.75	0.74	0.94
2	4.37	4.21	3.94	3.87	3.73	3.60	3.48	0.42	0.42	0.43	0.43	0.43	0.59	0.65	0.64	0.66	0.65	0.57	0.56	0.94
3	4.48	4.29	4.04	3.95	3.80	3.68	3.55	2.61	2.55	2.50	2.44	2.38	1.95	1.97	1.93	1.91	1.87	1.77	1.74	0.94
4	0.49	3.82	2.11	1.20	1.19	1.12	1.11	0.87	0.86	0.77	0.76	0.41	0.39	0.19	0.19	0.12	0.12	0.06	0.06	0.94
5	2.52	2.48	2.32	2.34	2.29	2.26	2.21	1.37	1.35	1.37	1.35	1.33	1.24	1.28	1.26	1.26	1.25	1.16	1.14	0.94
6	0.34	0.36	0.30	0.33	0.33	0.34	0.34	0.49	0.49	0.50	0.50	0.51	0.35	0.38	0.38	0.39	0.39	0.35	0.35	0.94
7	2.80	2.75	2.54	2.59	2.52	2.49	2.43	2.85	2.78	2.73	2.66	2.61	2.24	2.27	2.22	2.19	2.14	2.12	2.08	0.94

A computer program was written that assigned the incremental annual increase in withdrawal from each well field to the most undercapacity well in the field. However, if the incremental change was a decrease (as in the 30-percent conservation scenario), the decrease in withdrawal was simulated to be from the well that was nearest to full capacity. In the scenario of new wells constructed only near the Rio Grande, the new wells often were associated with well fields located at higher pressure zones. It was assumed that an appropriate infrastructure would be in place to raise water from the valley to the higher zones.

Although the pumpage-distributing program emulates an operation of individual well fields, two system-operation decisions are not emulated. First, system-operation decisions such as whether an overcapacity field can be assisted by nearby, less utilized well fields are not emulated. Therefore, situations of large drawdown arose in some projections, particularly in the current trend simulation, that probably would not be allowed to happen under actual circumstances. Second, the failure or abandonment of an existing well and its possible replacement with a new well not in the current decade plan (this is currently happening at a rate of one or two wells per year) cannot be predicted and is not emulated.

The basinwide computed hydraulic head in layer 5 (assumed to represent the water table) and hydraulic head in the primary production interval (layer 9) in 2020 for the medium growth rate of projected increase in ground-water withdrawal are shown in figures 43 and 44. Except in the immediate Albuquerque area, computed water-table altitudes for the other scenarios are similar to the medium growth projection. Computed water-table altitudes (layer 5) in the Albuquerque area for 2020 for each of the scenarios are shown in figures 45-48; the potentiometric heads in the primary production interval (layer 9) are shown in figures 49-52. Computed potentiometric heads for predevelopment steady state, spring 1994, and each of the scenarios along a west-to-east section through central Albuquerque (row 110, pl. 1; figs. 45-52) are shown in figure 53. Finally, drawdown in the Albuquerque area in the water table (layer 5) and in the primary production interval (layer 9) from 1994 to 2020 is shown for each of the scenarios in figures 54-57 and 58-61, respectively. The hydraulic-head and drawdown maps show a wide range of response to the different projected withdrawals. The effect of 30-percent conservation can be noted by comparing the hydraulic heads for the various scenarios in figure 53.

Figures 45-48 all show an area in the Albuquerque south valley where hydraulic disconnection between a perched water table and the fully saturated zone is simulated to develop by 2020. This disconnection is largely due to the presence of a low hydraulic-conductivity zone in the shallow alluvial aquifer (fig. 8). Because of the numerical approximation of this condition, all vertical connection is simulated to be broken between the perched water table and the regional aquifer system (horizontal connection still exists). In reality, some vertical movement of water across the unsaturated zone would still occur. The west-to-east sections shown in figure 53 are north of this perched water-table area.

Table 8 lists the water budgets and local changes in potentiometric head in 2020 for the four scenarios both without and with the effect of the City of Albuquerque's projected pumpage. The area (383.7 square miles) for which the average drawdown was computed is the modeled area within the basin shown in all figures of the immediate Albuquerque area. Changes in the water budgets attributable to Albuquerque's pumpage are also listed.

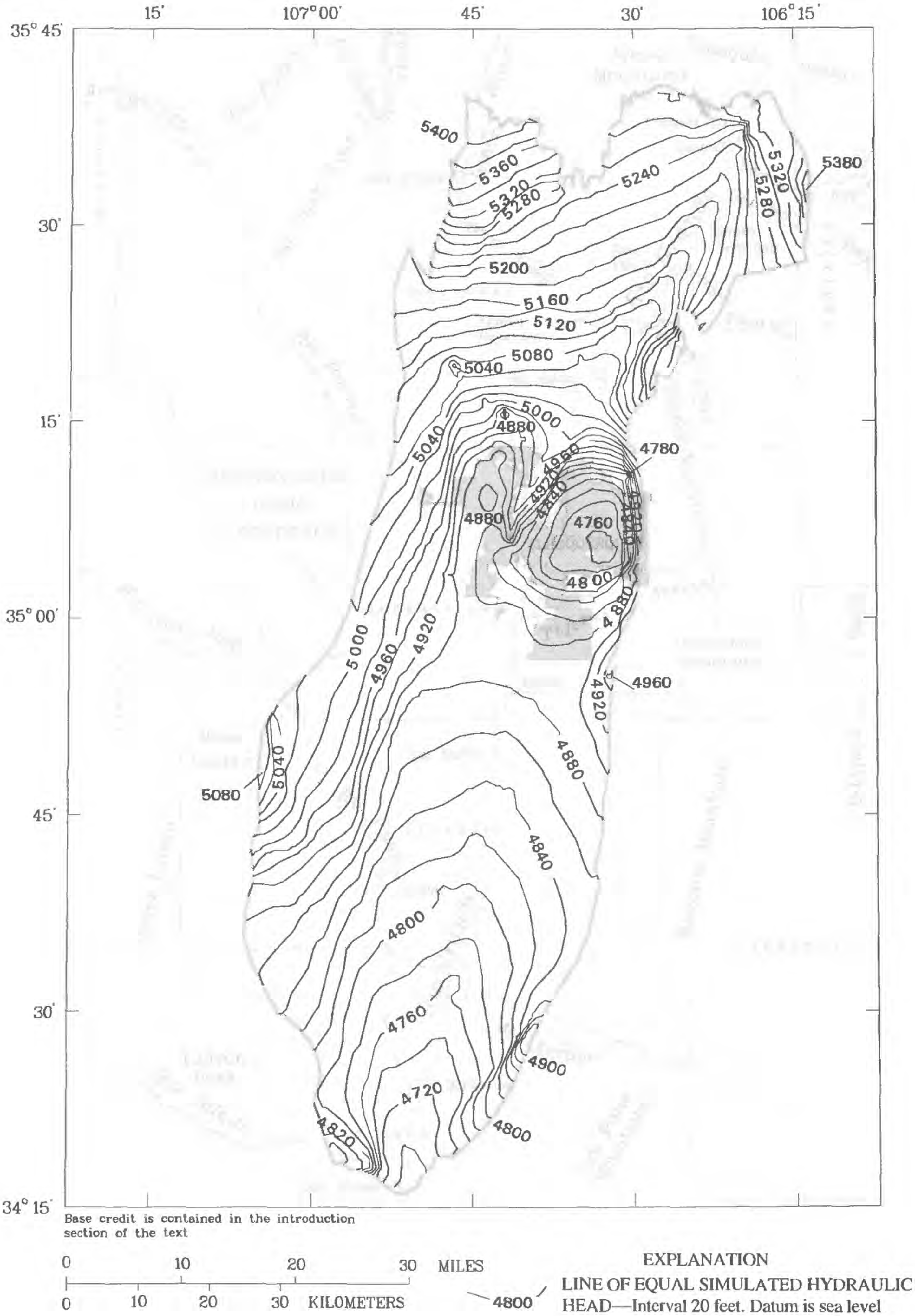


Figure 43.—Simulated 2020 hydraulic head in model layer 5 in the Albuquerque Basin assuming medium growth.

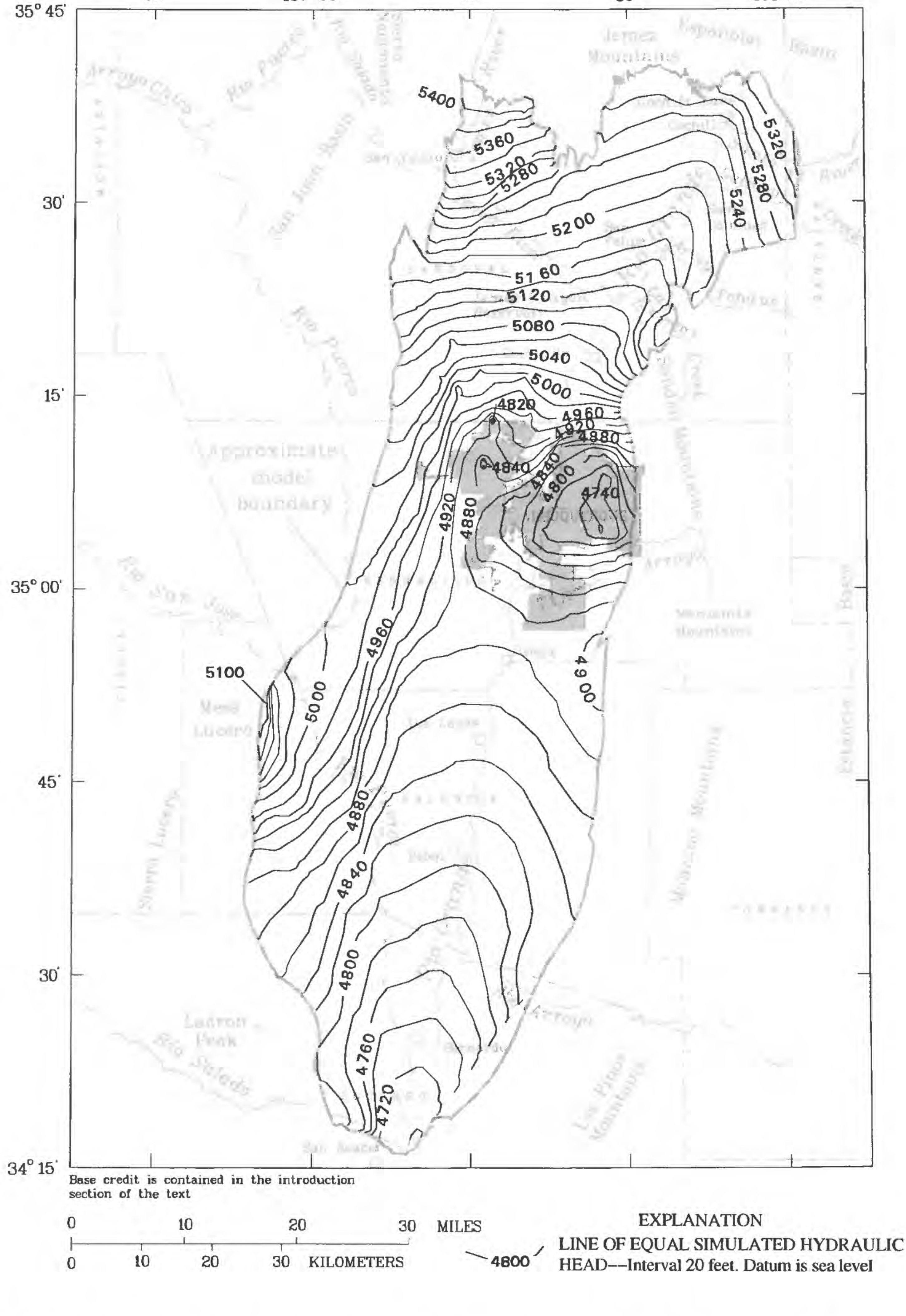
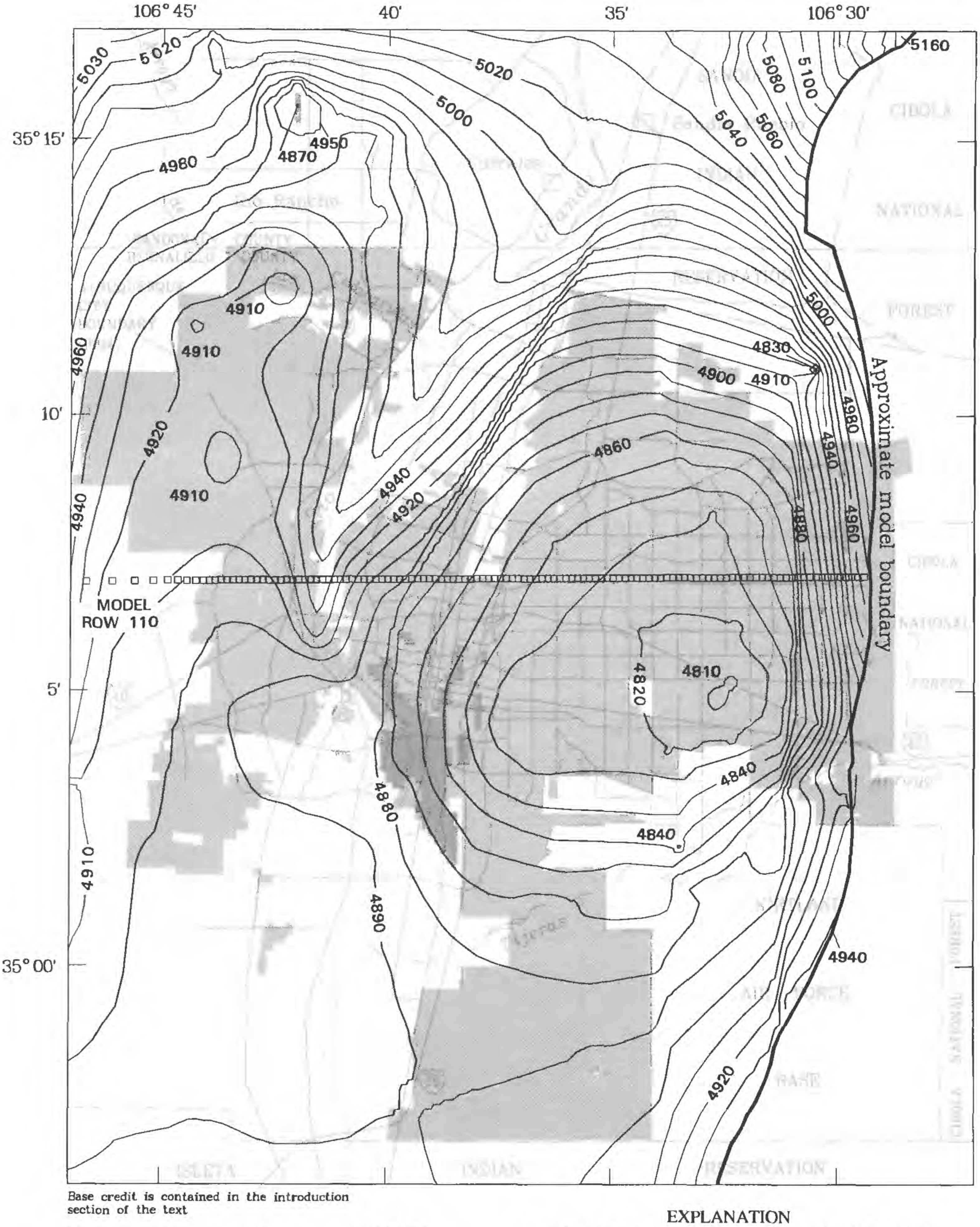


Figure 44.—Simulated 2020 hydraulic head in model layer 9 in the Albuquerque Basin assuming medium growth.



EXPLANATION

4920 LINE OF EQUAL SIMULATED HYDRAULIC HEAD--Interval 10 feet. Datum is sea level

ZONE OF HYDRAULIC DISCONNECTION--Shows areas where dry model cells above layer 5 are overlain by saturated cells

Figure 45.--Simulated 2020 hydraulic head in model layer 5 in the Albuquerque area assuming medium growth and 30-percent conservation.

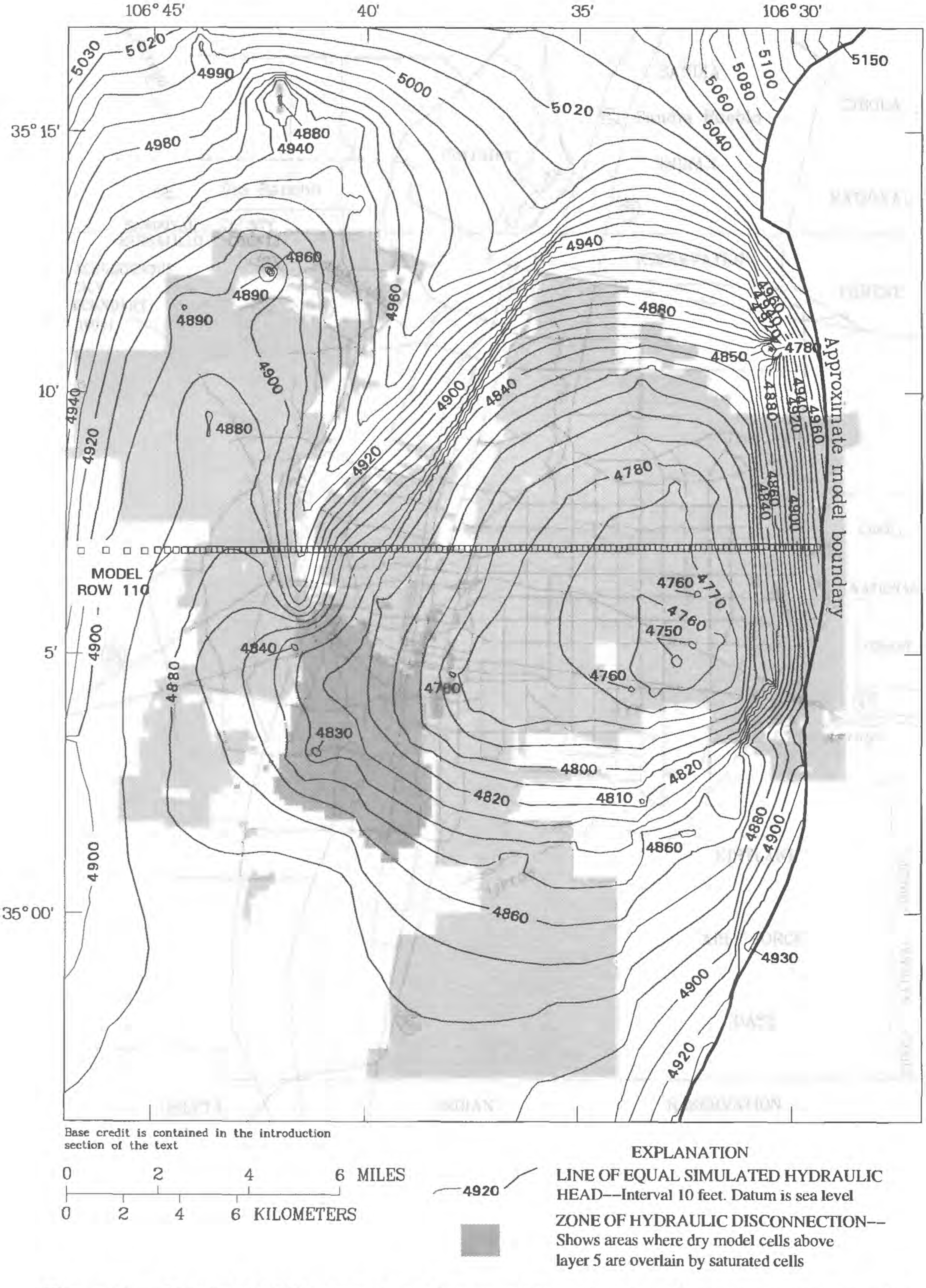


Figure 46.--Simulated 2020 hydraulic head in model layer 5 in the Albuquerque area assuming medium growth and new well locations near the Rio Grande.

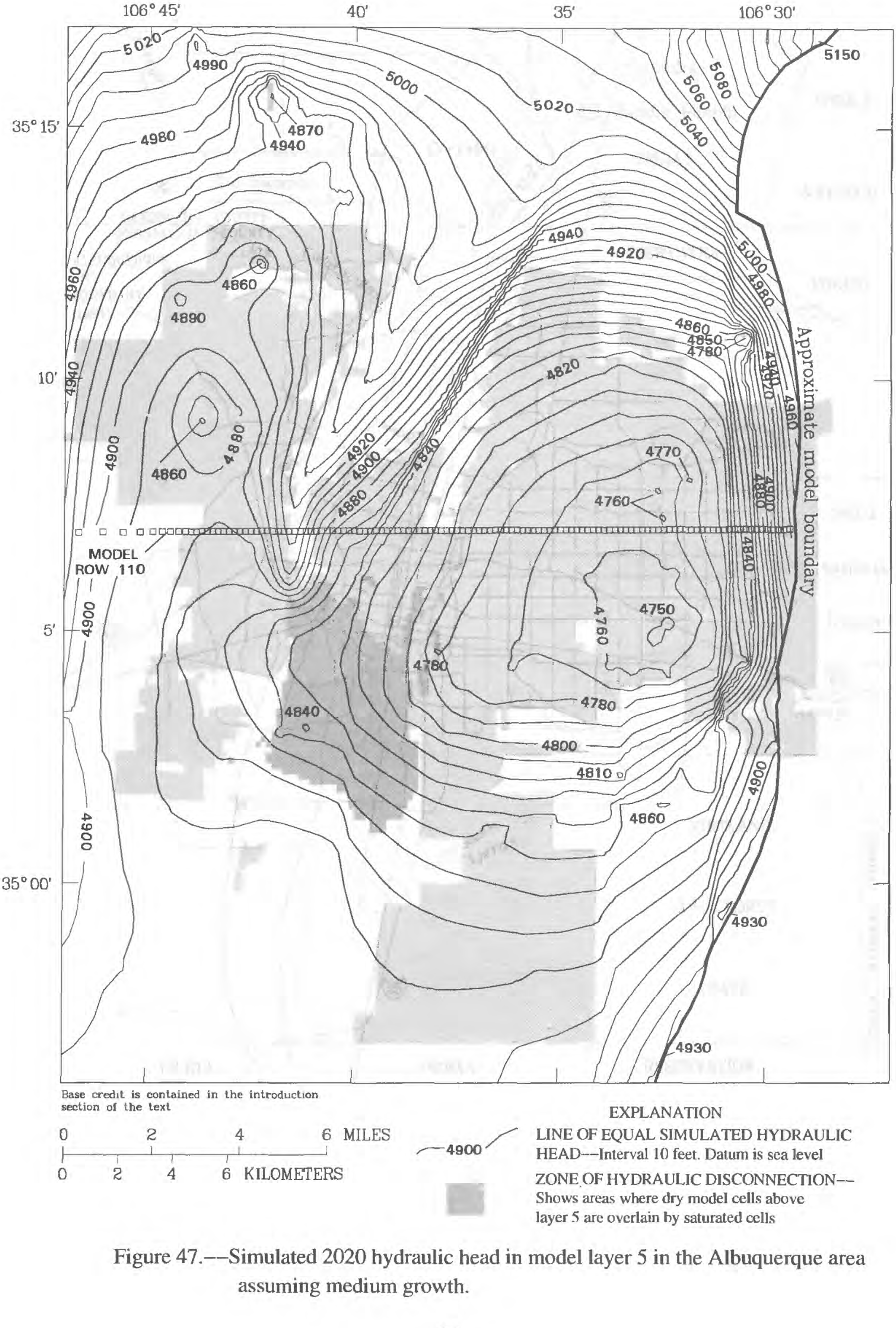
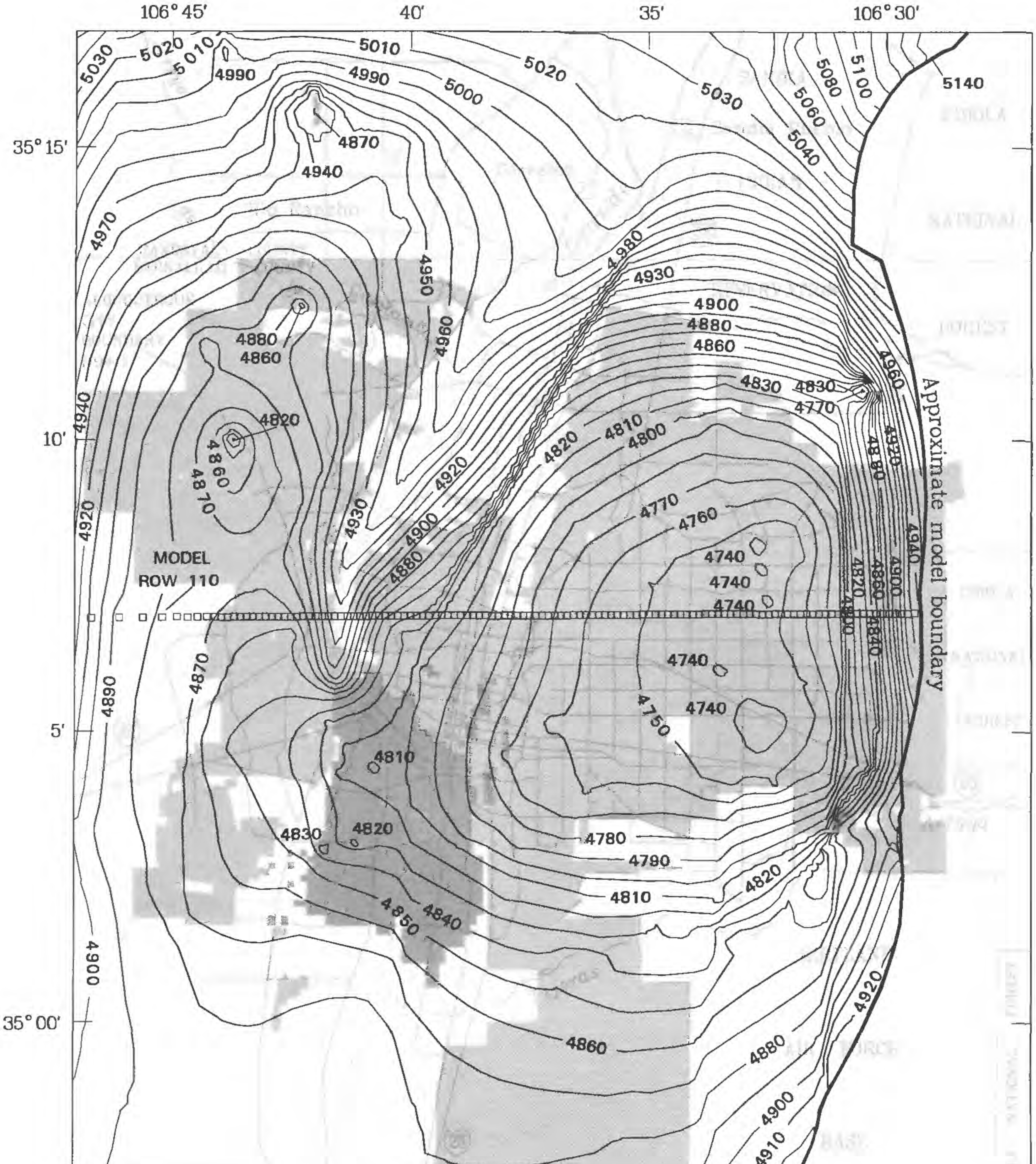


Figure 47.--Simulated 2020 hydraulic head in model layer 5 in the Albuquerque area assuming medium growth.



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0 2 4 6 MILES
0 2 4 6 KILOMETERS

EXPLANATION

4920 LINE OF EQUAL SIMULATED HYDRAULIC HEAD—Interval 10 feet. Datum is sea level

ZONE OF HYDRAULIC DISCONNECTION—Shows areas where dry model cells above layer 5 are overlain by saturated cells

Figure 48.—Simulated 2020 hydraulic head in model layer 5 in the Albuquerque area assuming the current growth trend.

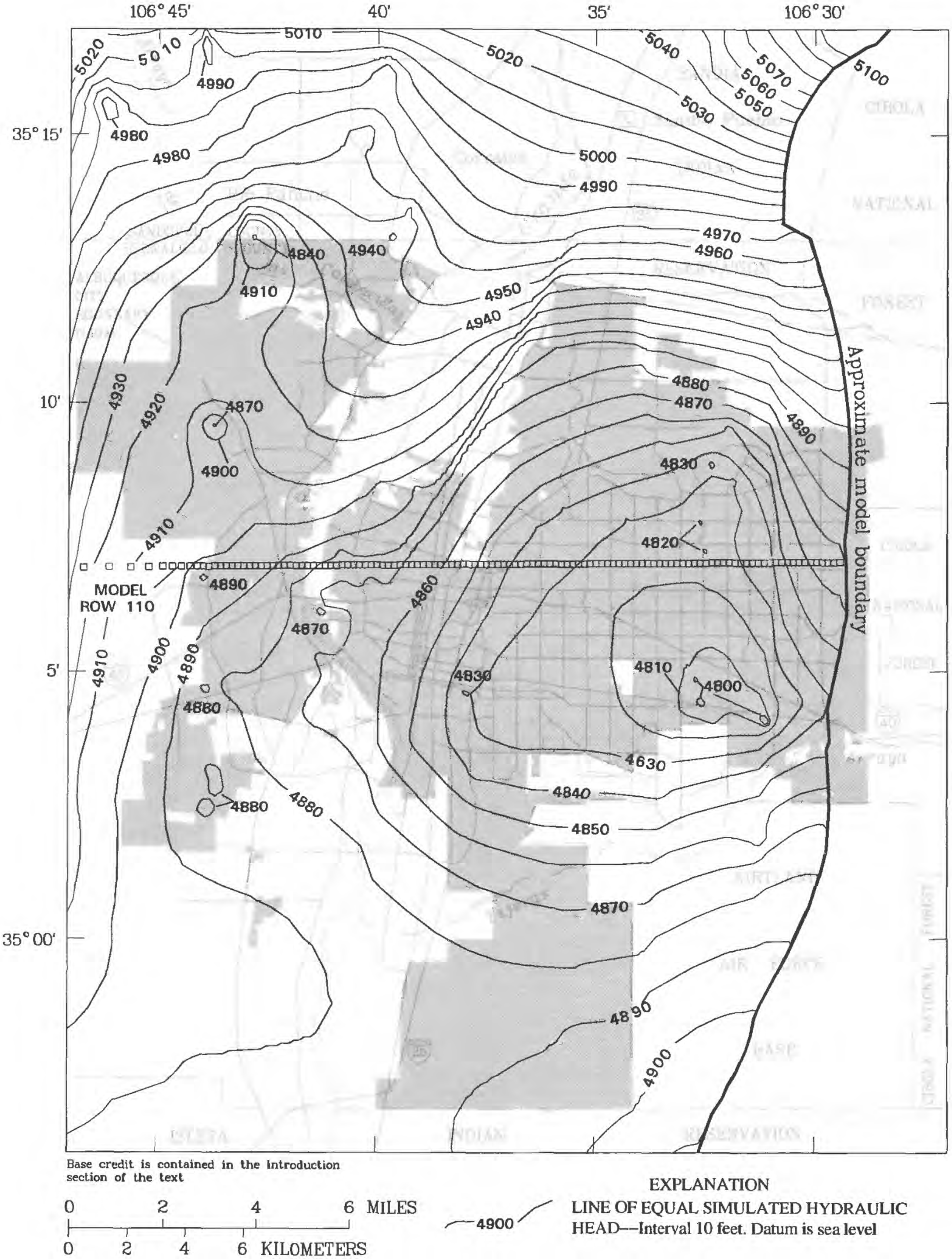


Figure 49.—Simulated 2020 hydraulic head in model layer 9 in the Albuquerque area assuming medium growth and 30–percent conservation.

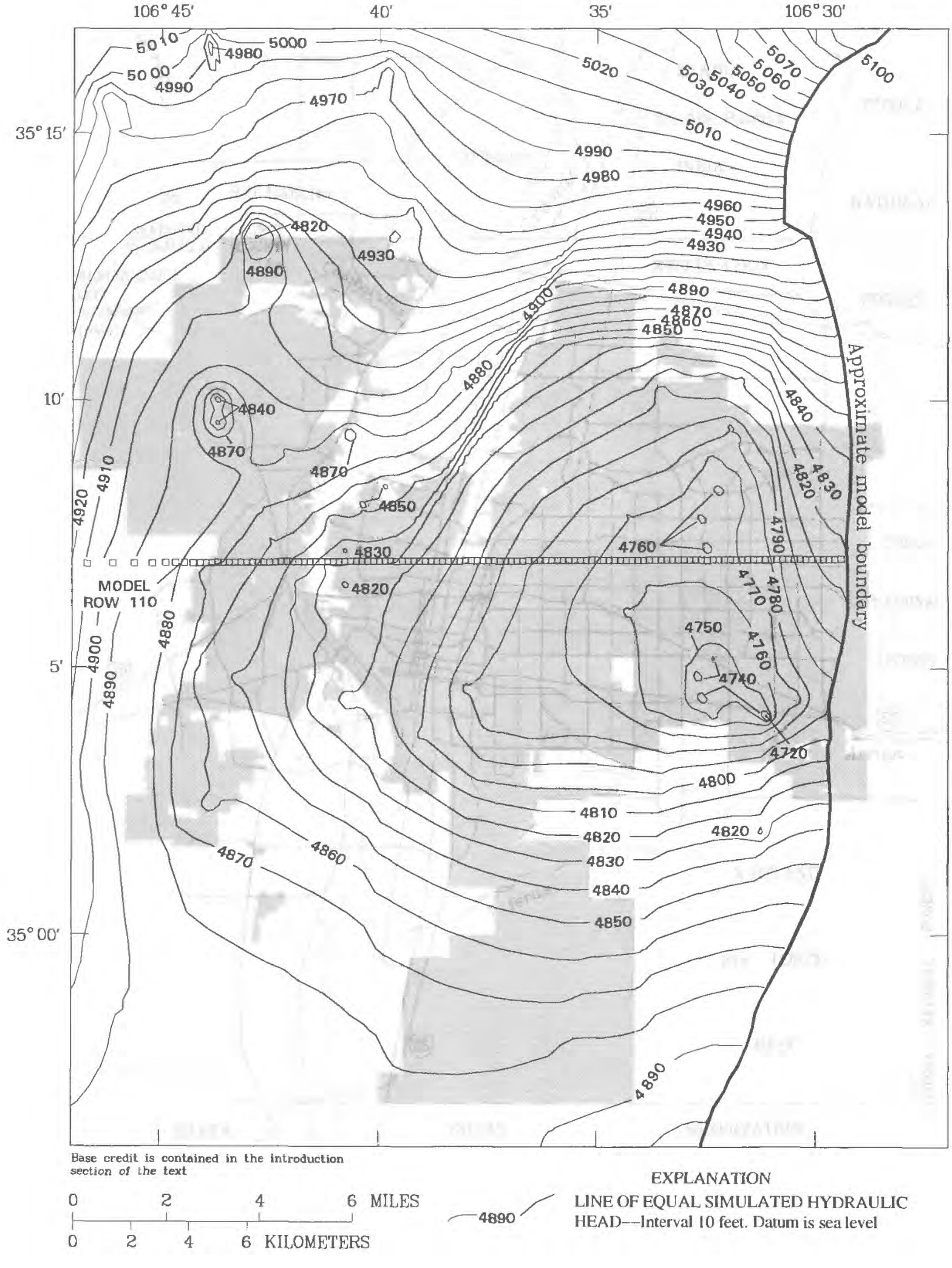


Figure 50.--Simulated 2020 hydraulic head in model layer 9 in the Albuquerque area assuming medium growth and new well locations near the Rio Grande.

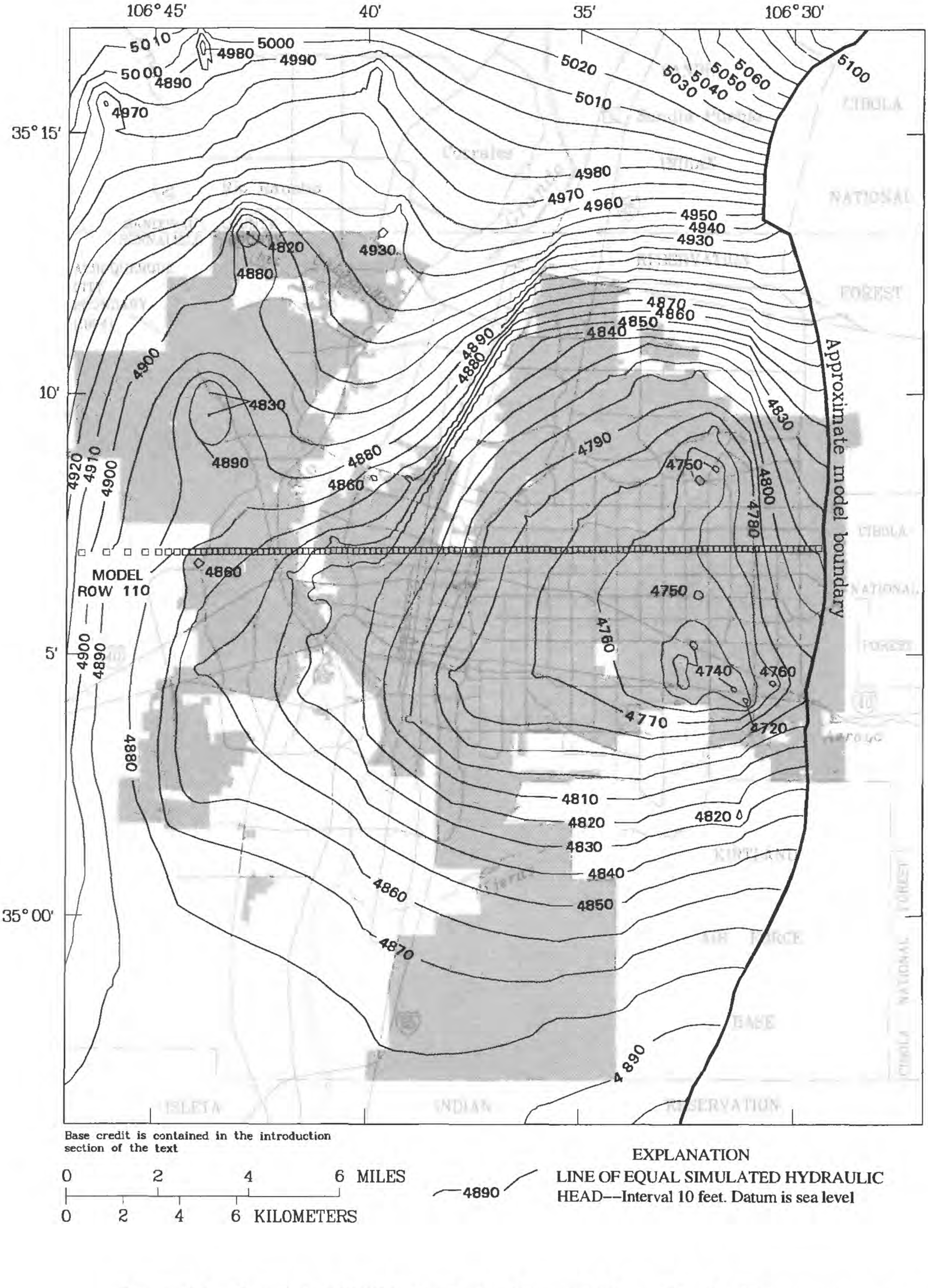


Figure 51.—Simulated 2020 hydraulic head in model layer 9 in the Albuquerque area assuming medium growth.

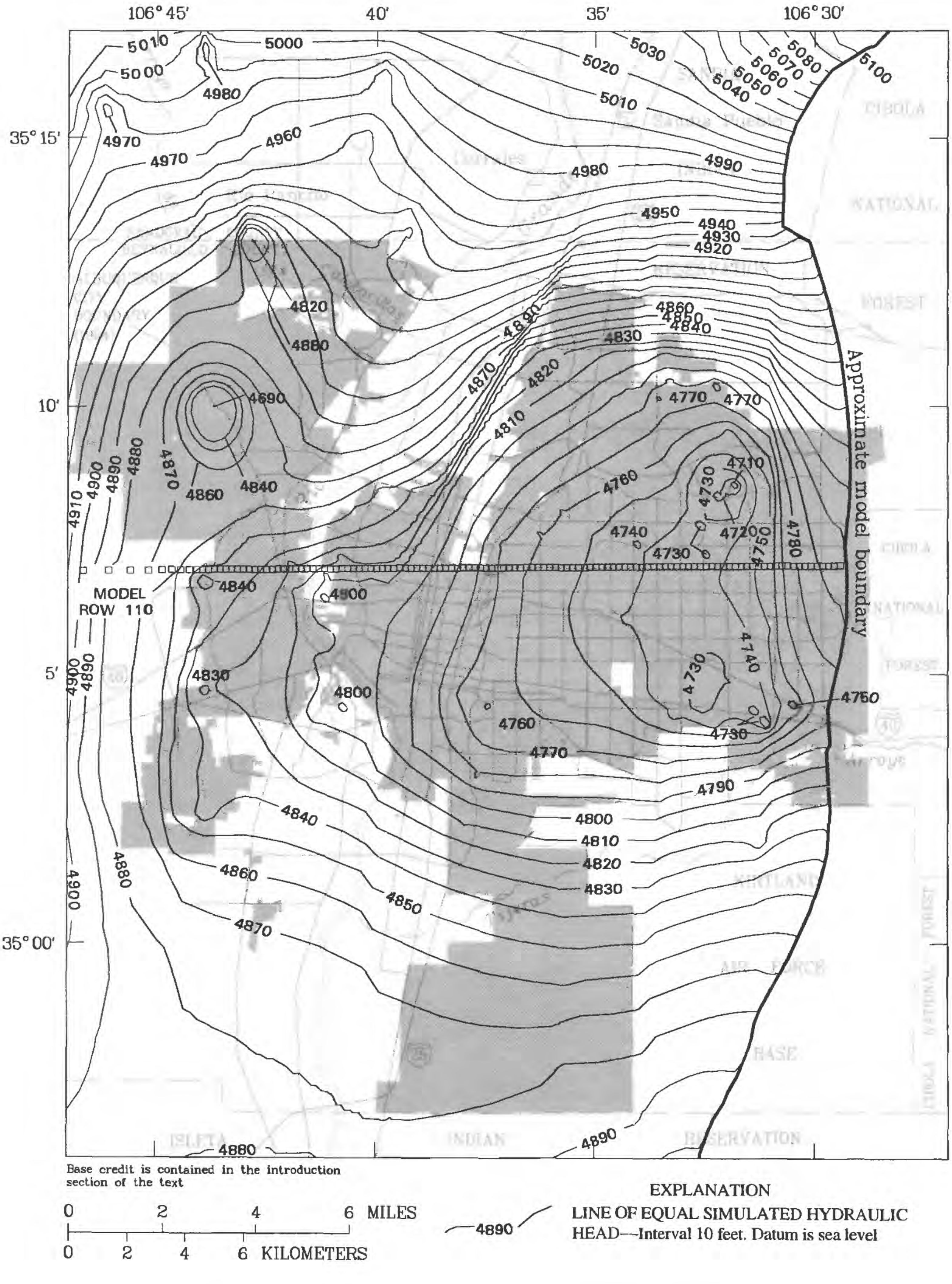


Figure 52.—Simulated 2020 hydraulic head in model layer 9 in the Albuquerque area assuming the current growth trend.

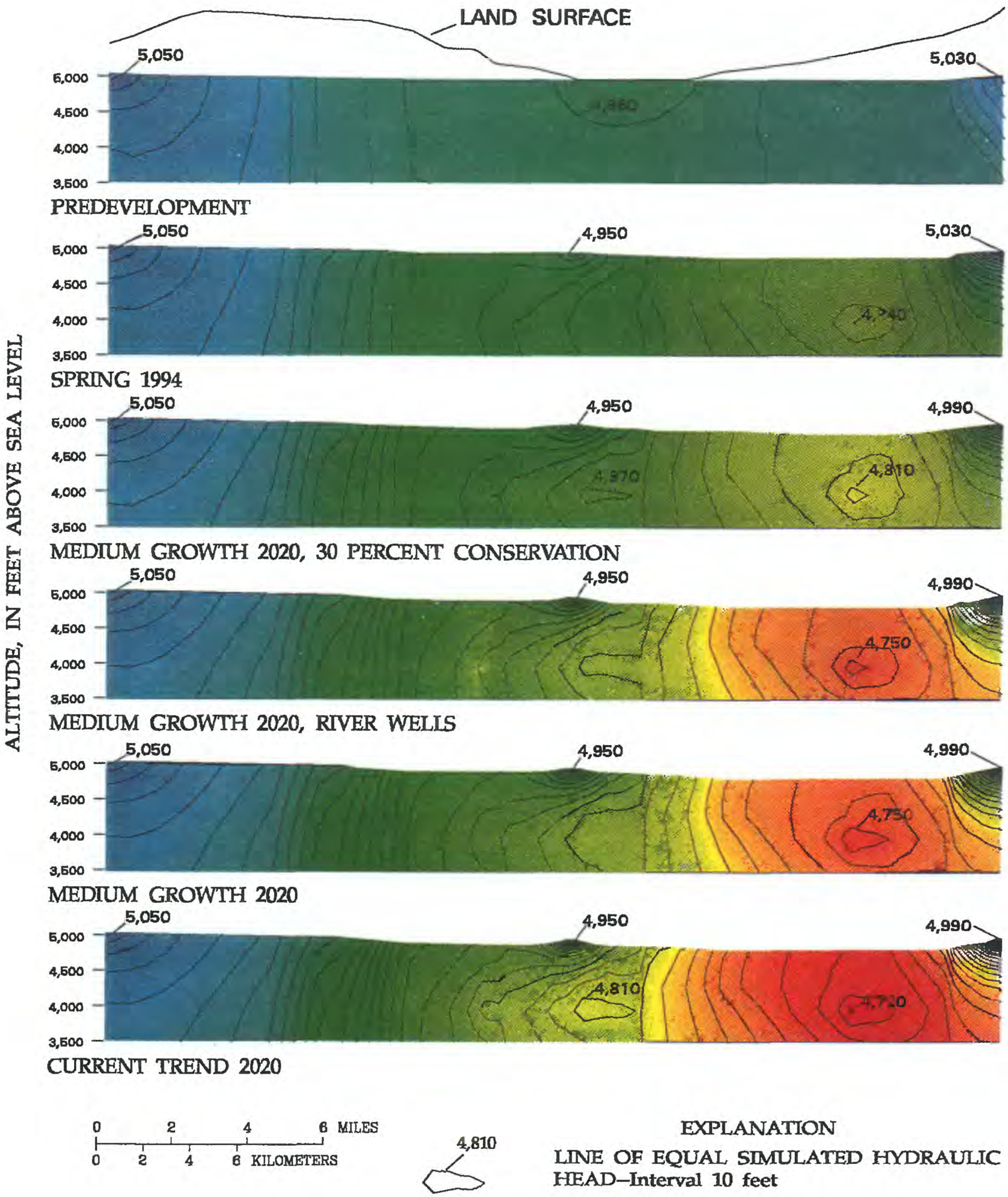


Figure 53.–Sections along model row 110 showing hydraulic head for various simulations (rows shown on plate 1).

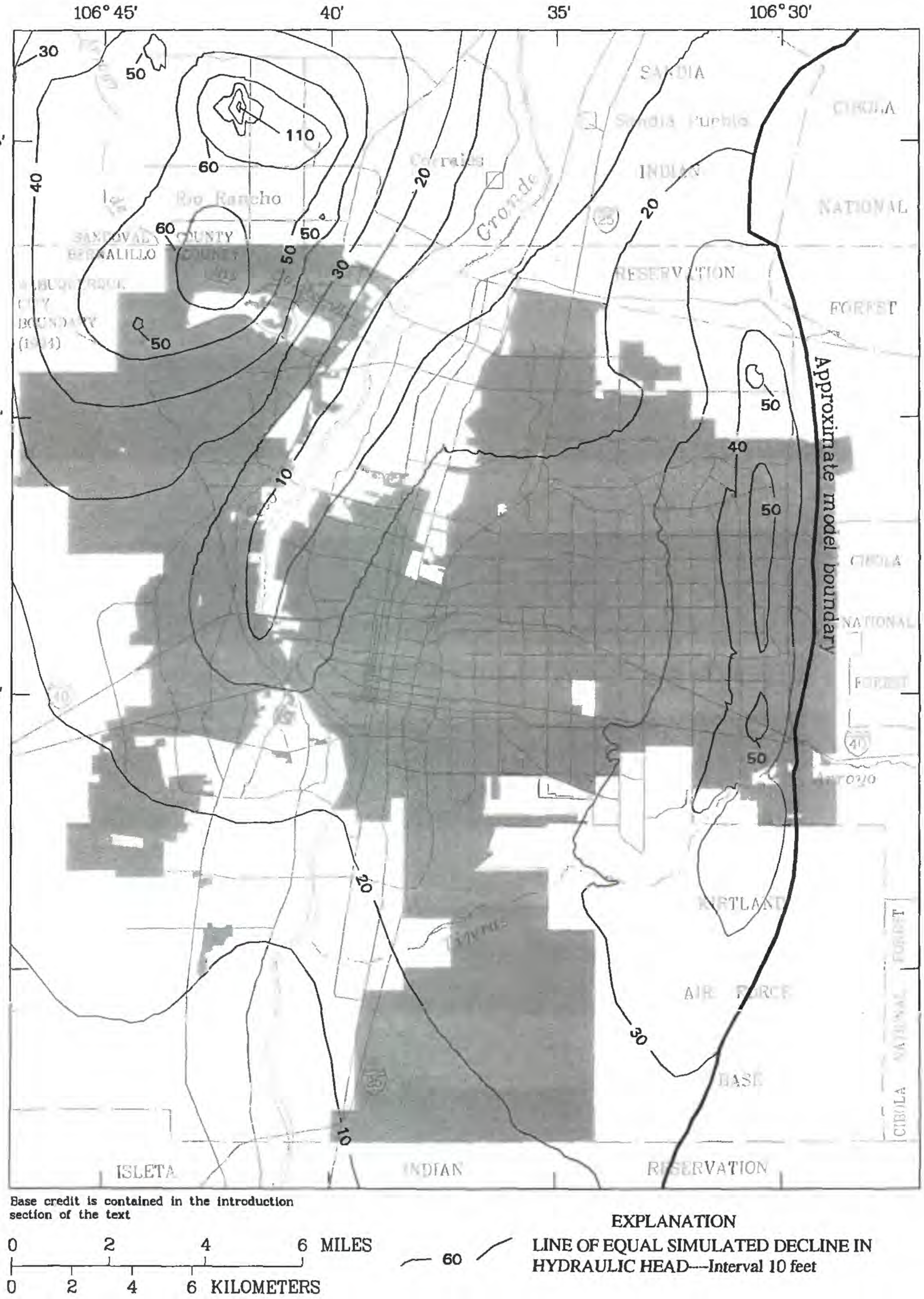


Figure 54.—Simulated decline in hydraulic head in model layer 5 in the Albuquerque area assuming medium growth and 30–percent conservation, 1994–2020.

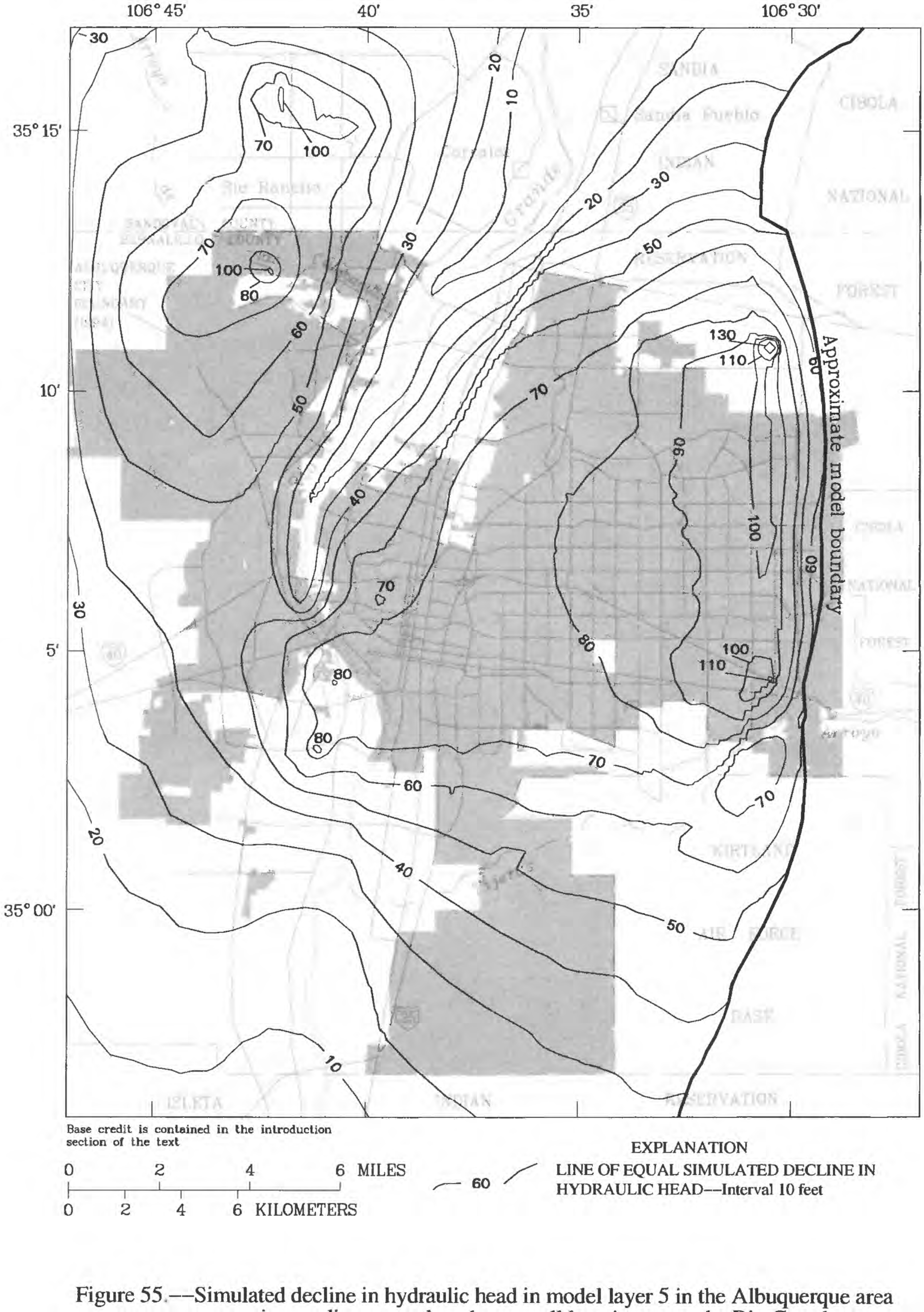
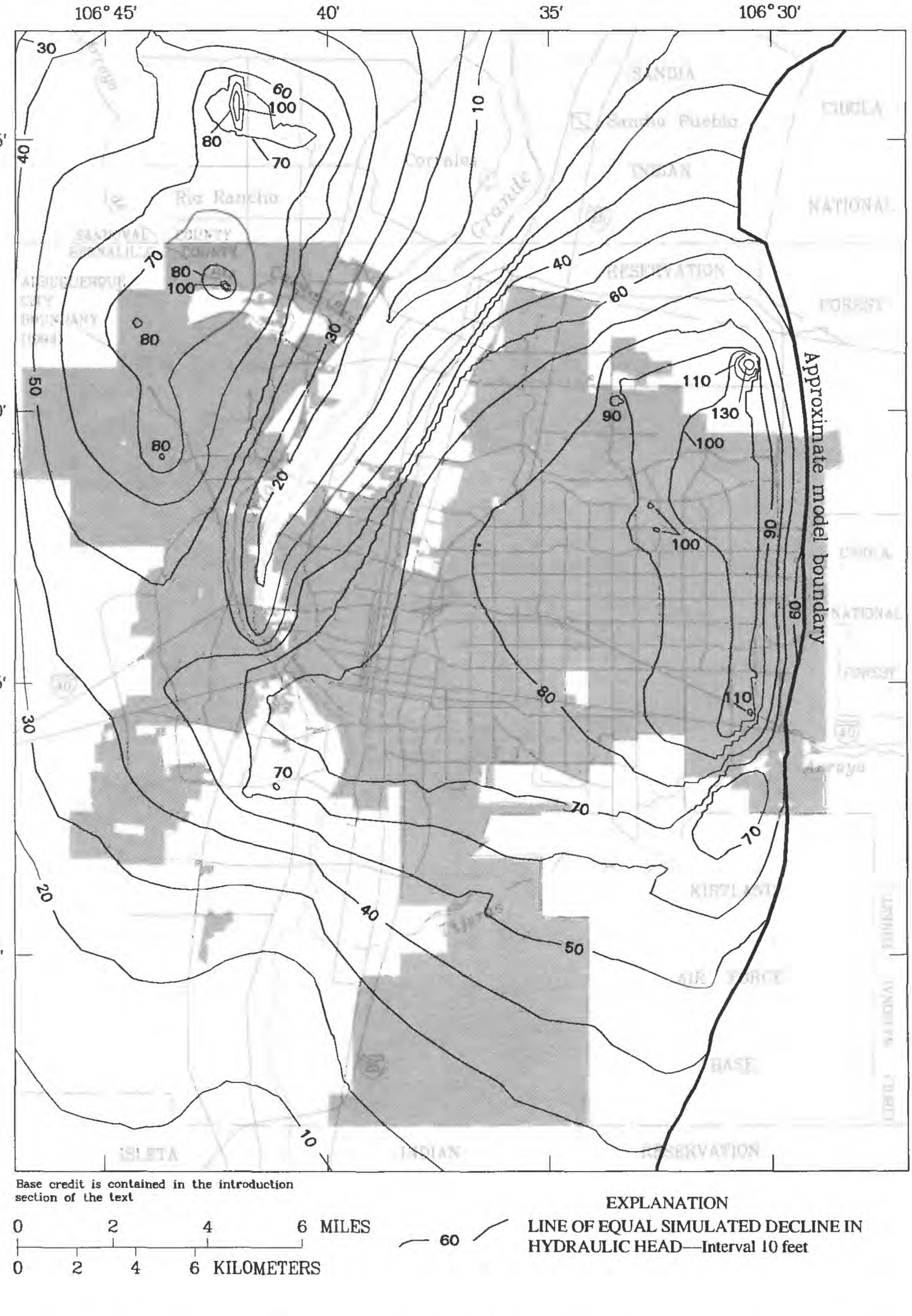


Figure 55.--Simulated decline in hydraulic head in model layer 5 in the Albuquerque area assuming medium growth and new well locations near the Rio Grande, 1994–2020.



EXPLANATION

60 LINE OF EQUAL SIMULATED DECLINE IN HYDRAULIC HEAD—Interval 10 feet

Figure 56.—Simulated decline in hydraulic head in model layer 5 in the Albuquerque area assuming medium growth, 1994–2020.

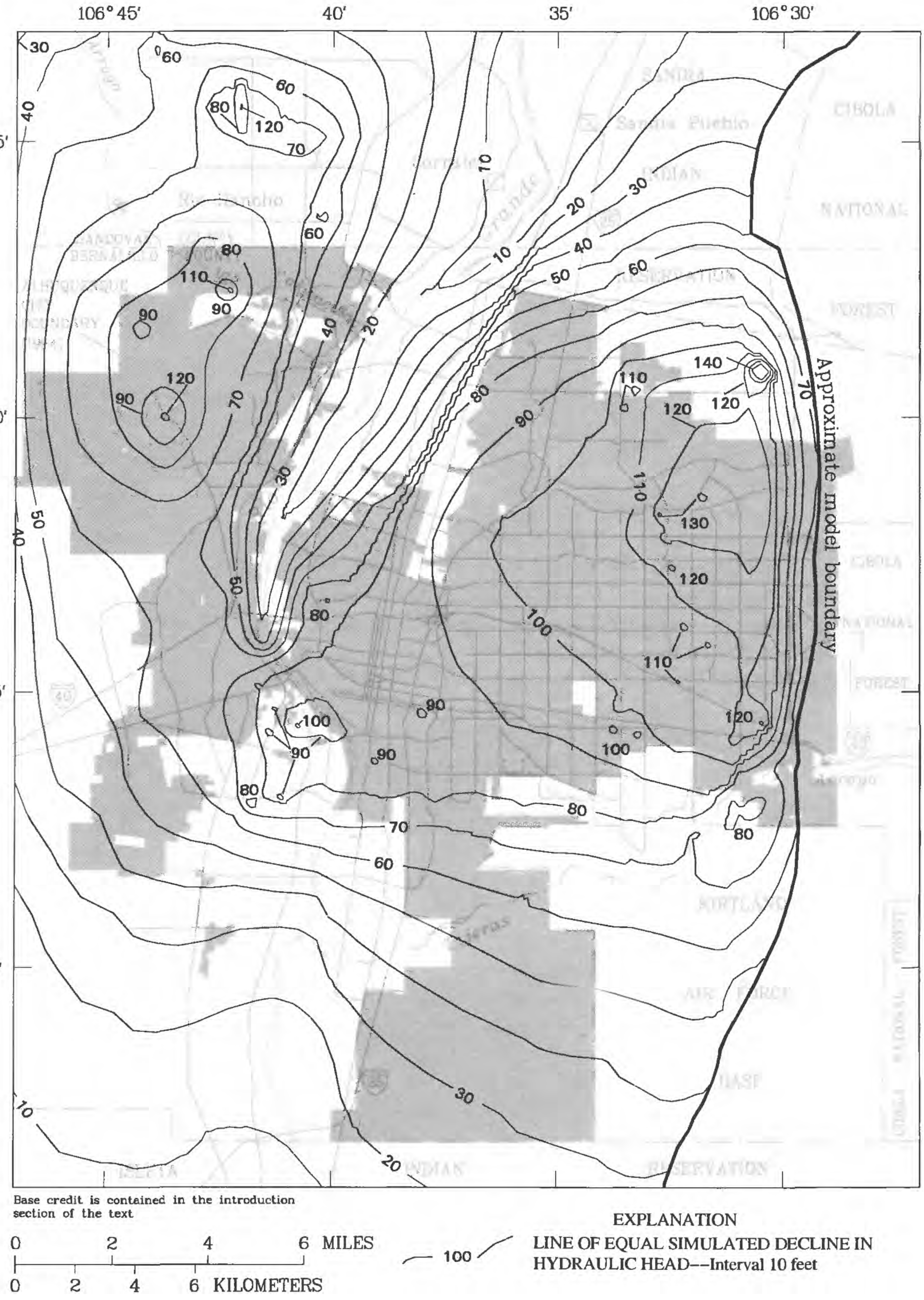


Figure 57.--Simulated decline in hydraulic head in model layer 5 in the Albuquerque area assuming the current growth trend, 1994–2020.

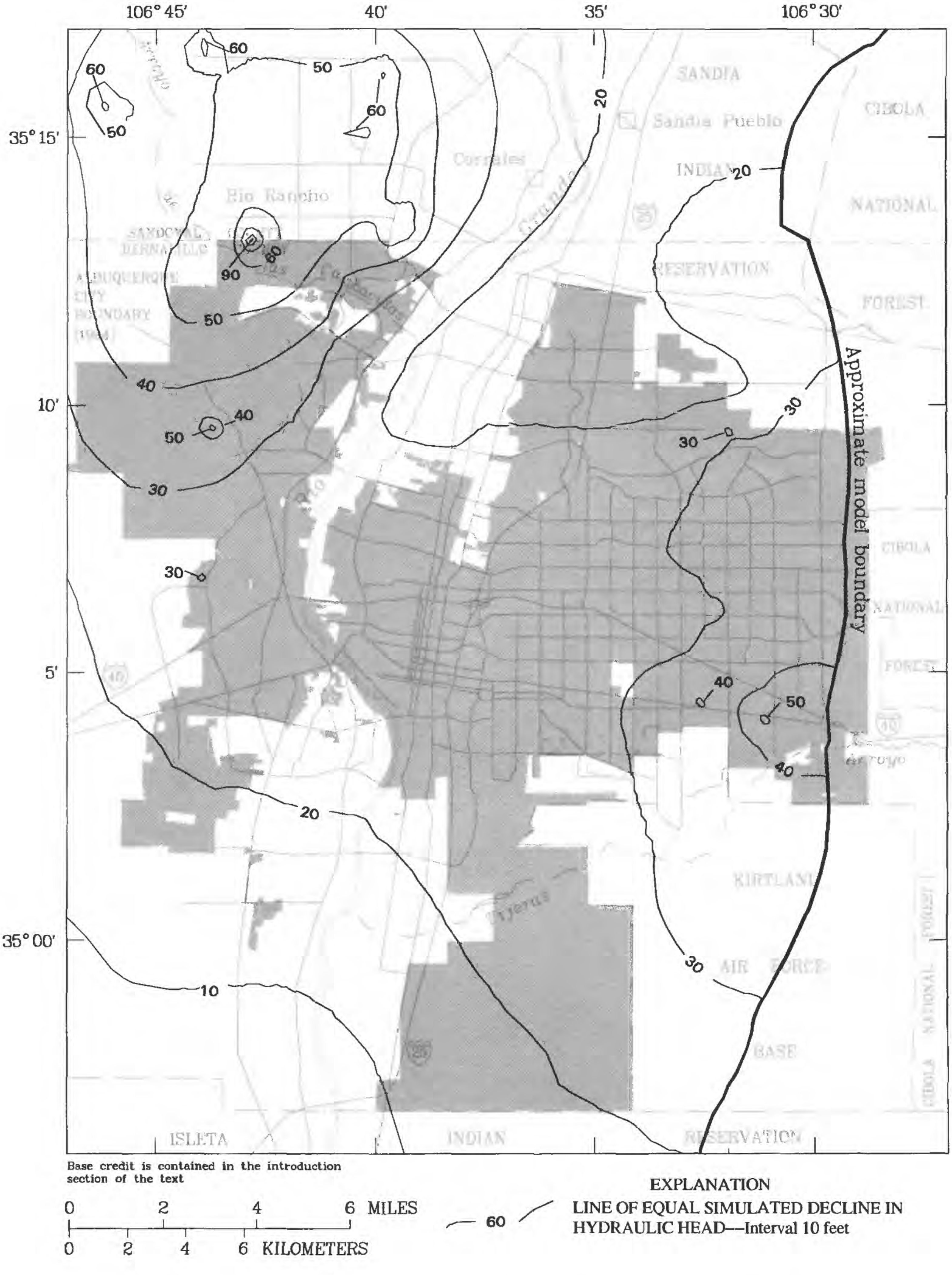


Figure 58.—Simulated decline in hydraulic head in model layer 9 in the Albuquerque area assuming medium growth and 30–percent conservation, 1994–2020.

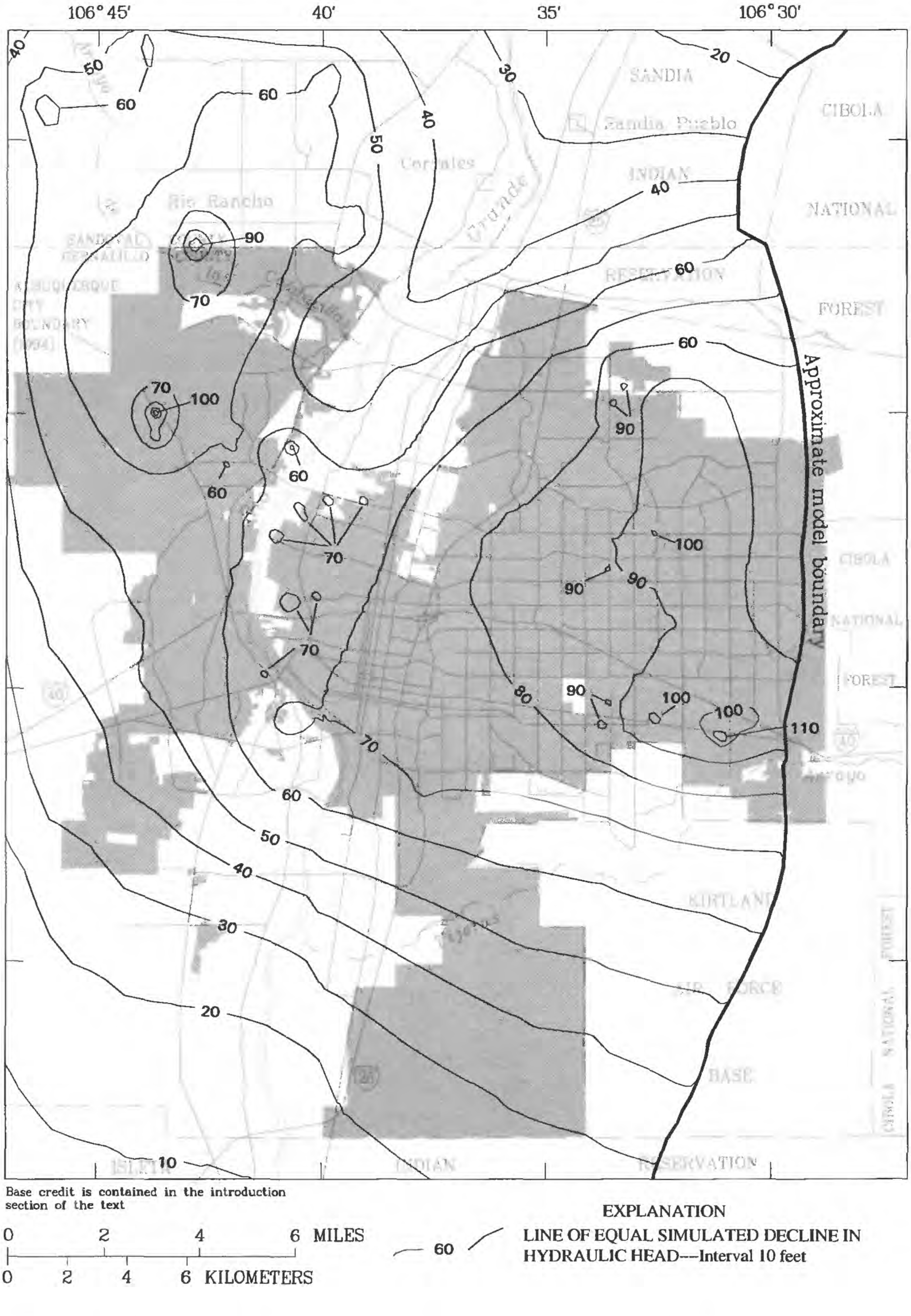


Figure 59.--Simulated decline in hydraulic head in model layer 9 in the Albuquerque area assuming medium growth and new well locations near the Rio Grande, 1994–2020.

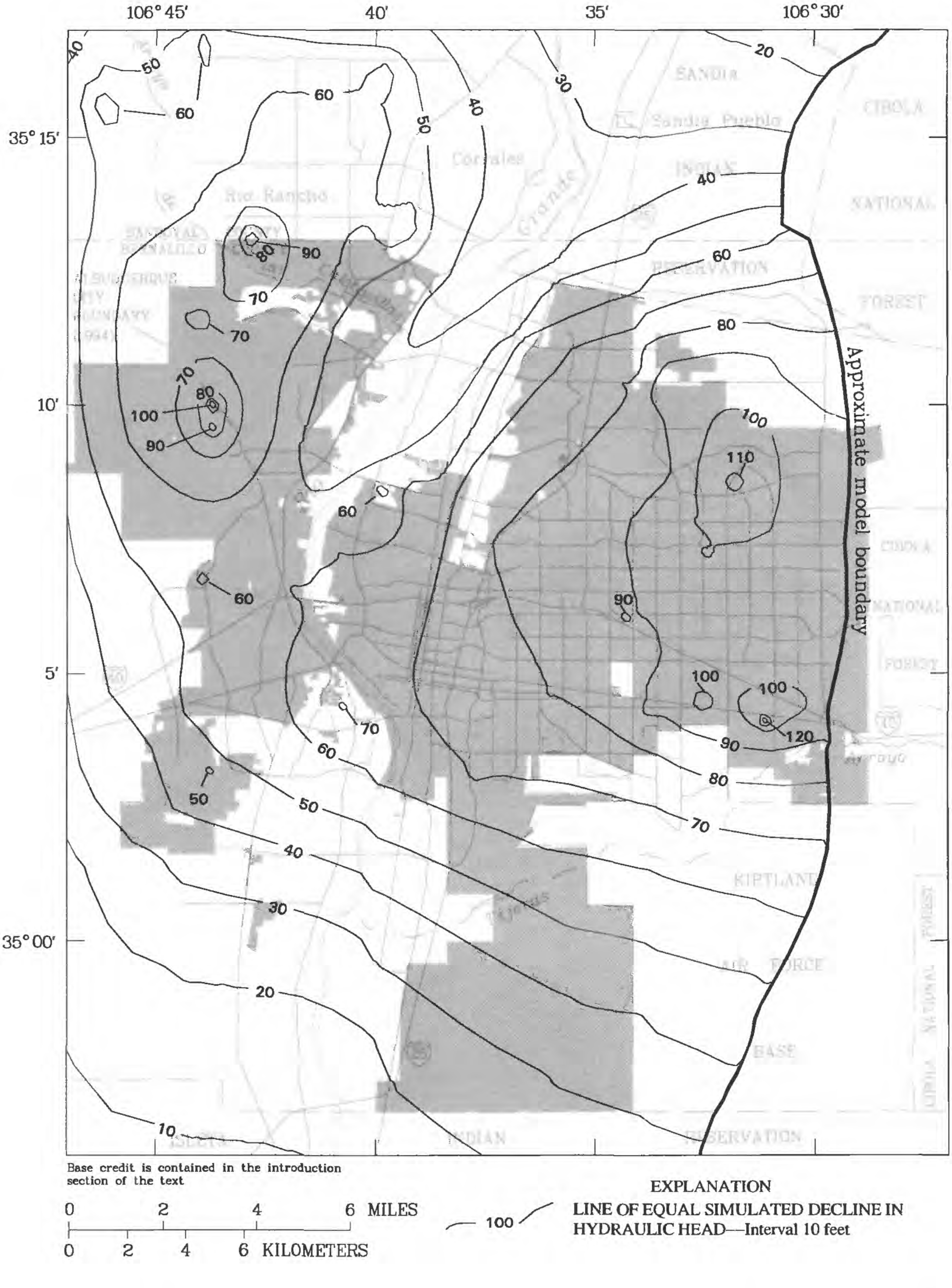
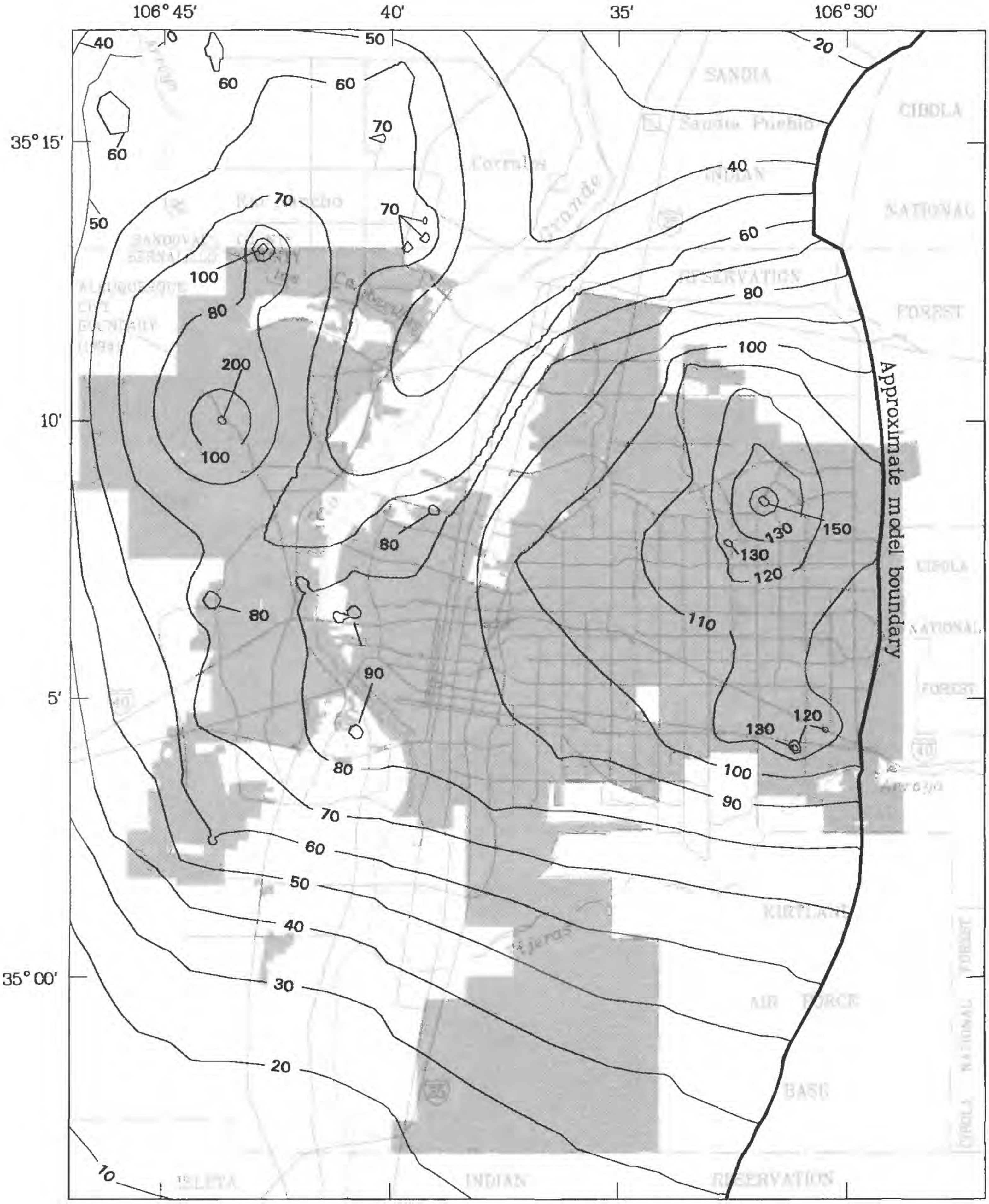


Figure 60.—Simulated decline in hydraulic head in model layer 9 in the Albuquerque area assuming medium growth, 1994–2020.



Base credit is contained in the introduction section of the text

Figure 61.—Simulated decline in hydraulic head in model layer 9 in the Albuquerque area assuming the current growth trend, 1994–2020.

Table 8.--Simulated water budget without and with City of Albuquerque ground-water withdrawals and drawdown with City of Albuquerque ground-water withdrawals for current trend, medium growth, river wells, and 30-percent conservation scenarios, 2020

[All values are in acre-feet per year]

		Current trend		Medium growth		River wells		30-percent conservation	
Mechanism	Simulation without City withdrawal	Simulation with City withdrawal	Difference	Simulation with City withdrawal	Difference	Simulation with City withdrawal	Difference	Simulation with City withdrawal	Difference
Net storage	27,100	123,000	95,900	99,800	72,700	98,000	71,000	60,500	33,400
River, canal, and reservoir leakage	182,000	229,000	47,000	225,000	43,000	227,000	45,000	215,000	33,000
Drain seepage	-238,000	-208,000	30,000	-208,000	30,000	-208,000	30,000	-209,000	29,000
Riparian and wetland evapo-transpiration	-93,100	-88,400	4,700	-88,600	4,500	-88,500	4,600	-89,000	4,100
Recharge[1]	196,000	196,000	0	196,000	0	196,000	0	196,000	0
Ground-water withdrawal	74,300	251,000	177,000	224,000	150,000	224,000	150,000	173,000	98,700
Net surface loss[2]			77,000		73,000		75,000		62,000
		1994-2020 drawdown in model layer 9, in feet							
Maximum drawdown (west/east of the Rio Grande)			258/164		112/131		96/62		91/55
Average drawdown in Albuquerque area (383.7 square miles)			65		56		34		28

[1]Mountain-front and tributary recharge, ground-water inflow from adjacent basins, irrigation seepage, and septic-field return flow.
[2]Increased river, canal, and reservoir seepage plus decreased drain seepage.

The source of water to Albuquerque's production wells for each of the scenarios from 1995 to 2020 is shown in figures 62 to 65. Figure 62 (30-percent conservation) in particular shows the virtual immunity of the surface-water system to changes in ground-water withdrawal. Table 8 and figures 62-65 indicate that induced recharge from the river and decreased drain seepage (net surface loss) is little affected by scenario conditions, whereas aquifer storage depletion is very responsive to the volume of ground-water withdrawal. Net surface loss is the cumulative result of almost a century of ground-water withdrawal and responds slowly to a change in withdrawal. The slight difference in water budgets for the two medium-growth scenarios without conservation contrasted with the large difference in production-zone drawdown may indicate that flow between the Rio Grande and the Santa Fe Group across the valley-fill alluvium has, at least locally, reached a maximum. The apparent anomaly between drawdown and depletion of storage is due to partial desaturation of model layers beneath the flood plain, giving rise to multiple layers with specific yield storage values. The effective disconnection from some of the surface-water system is further evidenced by the almost constant volume of captured drain flow and salvaged evapotranspiration for all scenarios: at the end of the simulations, virtually all drain flow and riparian evapotranspiration are projected to have been captured by 2020 in the Albuquerque area.

POSSIBLE MODEL REVISIONS AND ADDITIONAL DATA NEEDS

Although some changes to the model were made to correct highly improbable simulated water-table and potentiometric heads, the model was not subjected to a rigorous calibration process. The working assumption was that if the model incorporated all that is known about the hydrogeologic system and about historical changes in any water-related process that could affect that system, then any discrepancy between simulated and measured hydraulic heads or water budgets signaled a failure to understand some part of the system.

The following sections list possible revisions to and improvements in the present model. Revisions known to be needed that can be accomplished without change to either the computer model or the GIS interface are described in the Changes to the Geohydrologic Conceptual Framework section. Recently acquired spatial data that will fill in missing historical changes or will allow the model to be updated are described in the Incorporation of Additional Data section. Revisions that may improve the model but would require either a change in the computer model or a change in the GIS interface are described in the Numerical Enhancements section. Finally, several data-collection activities that would enhance the understanding of the system and would ultimately improve the model are listed in the Data Needs section.

Changes to the Geohydrologic Conceptual Framework

Knowledge of the geohydrologic framework of the basin is being updated and improved at a remarkable rate (Dr. John Hawley, oral commun., August 26, 1994, October 11, 1994, and October 26, 1994) but, for practical reasons, the model representation of the system was not updated after late August 1994. Field surveys and geophysical interpretations since then have made obsolete some of the tectonic interpretations of Lozinsky (1988), Russell and Snelson (1990), Hawley and Hasse (1992), and Thorn and others (1993).

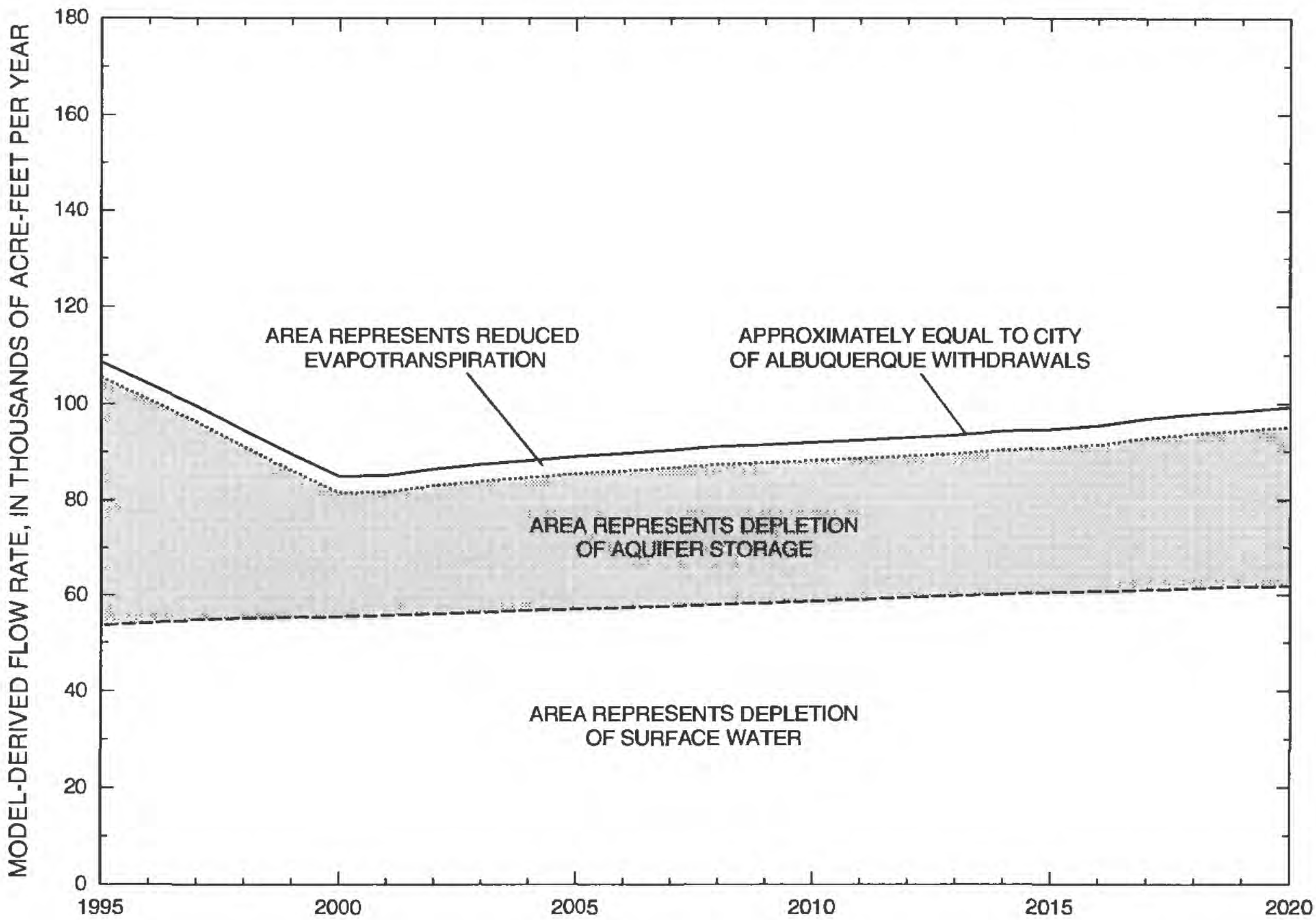


Figure 62.--Sources of City of Albuquerque withdrawals assuming medium growth and 30-percent conservation, 1995-2020.

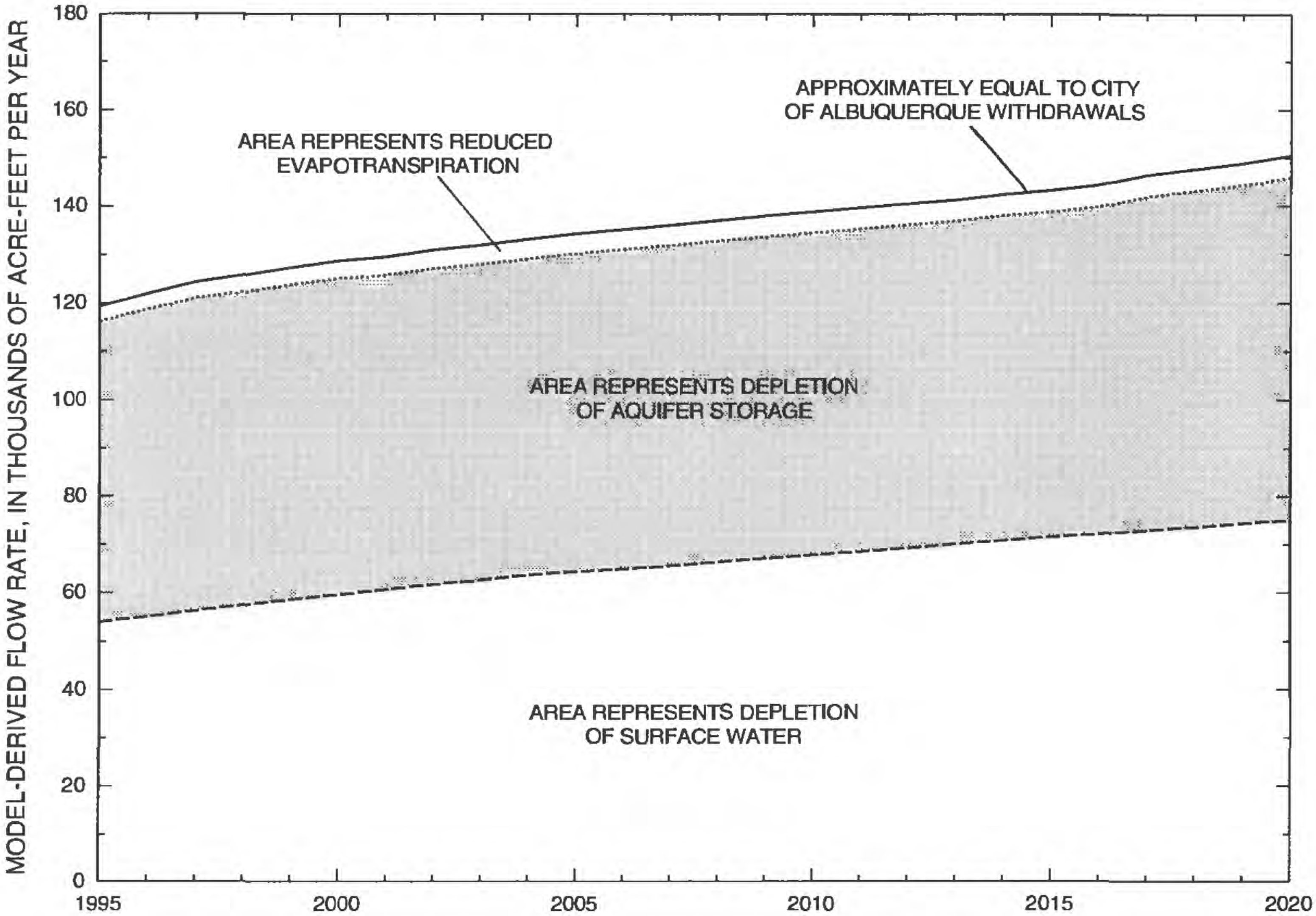


Figure 63.--Sources of City of Albuquerque withdrawals assuming medium growth and new well locations near the Rio Grande, 1995-2020.

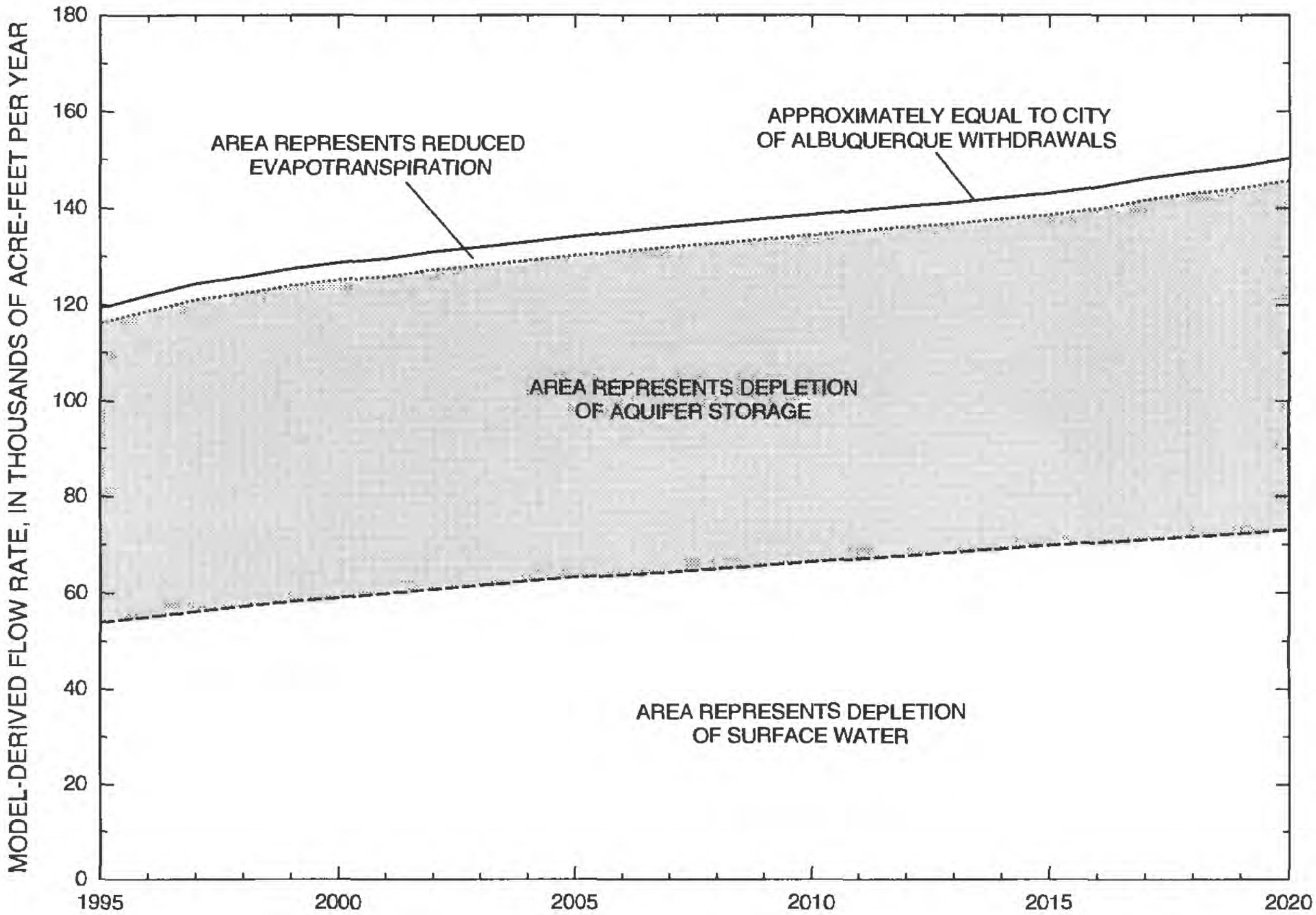


Figure 64.--Sources of City of Albuquerque withdrawals assuming medium growth, 1995-2020.

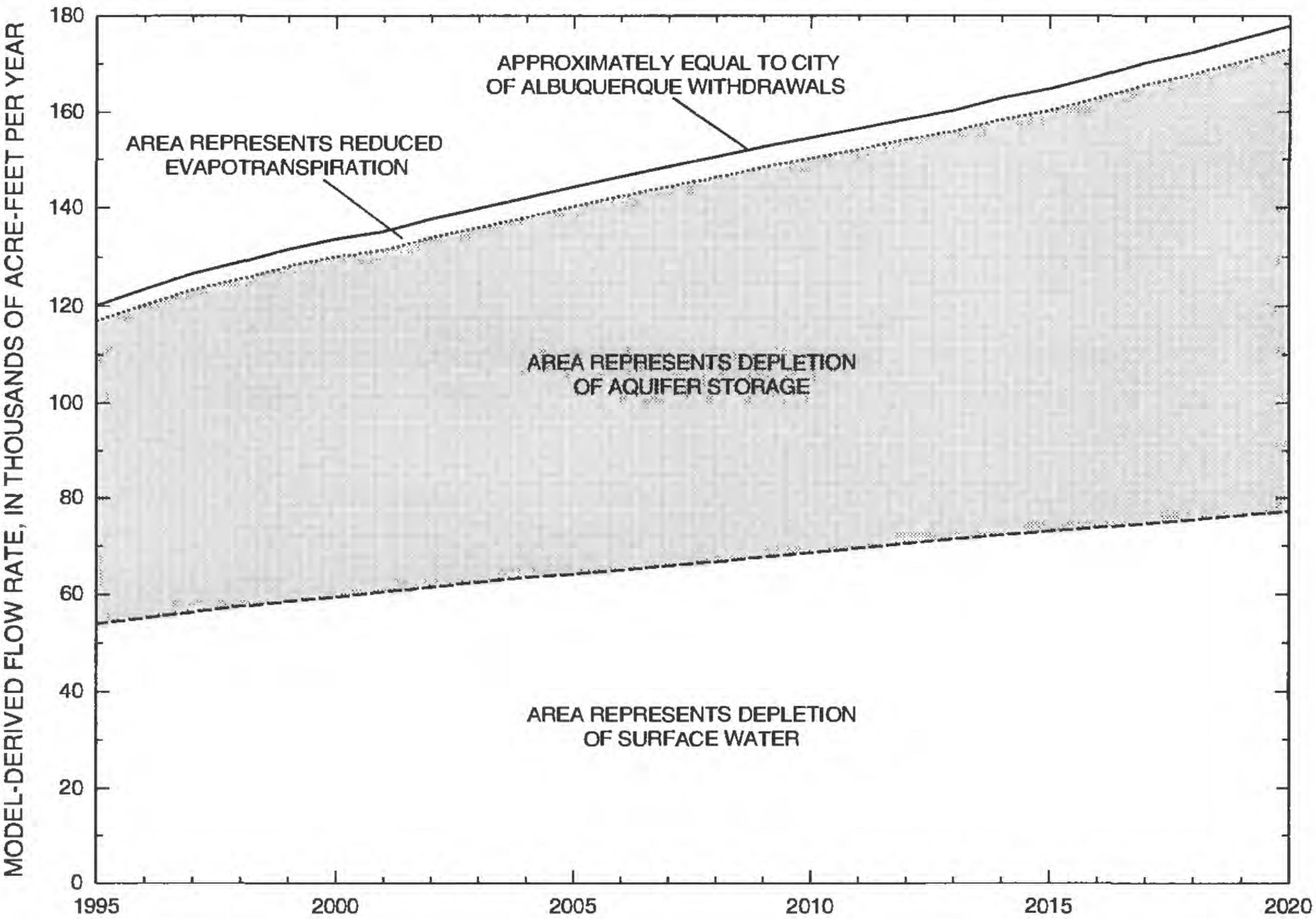


Figure 65.--Sources of City of Albuquerque withdrawals assuming the current growth trend, 1995-2020.

Extent of the Axial-Channel Deposits

One revision that could be made to the conceptual model is based on a change in the interpretation of outcrops in the area north of Albuquerque and east of the Rio Grande (Dr. John Hawley, oral commun., August 26, 1994). A northwest-trending line where the upper Santa Fe Group axial-channel deposits are truncated against lower hydraulic conductivity middle Santa Fe Group deposits is shown in figures 7-16. The recent revision will allow extension of the axial-channel deposits further to the east and northeast around the northern flank of the Sandia Mountains. The higher hydraulic conductivity could cause simulated water levels in the area to be in the range of measured water levels (figs. 26E and W).

The latest revision (Dr. John Hawley, written commun., December 14, 1994) extends the western limit of axial-channel deposits to a distance of about 2 miles west of the inner valley in the Rio Rancho area. This revised western limit is based on samples and geophysical logs from several large-capacity wells recently completed in that area. This change probably would have little effect on simulations of the historical period but could influence results of the projections to 2020.

Reinterpretation of the Isleta and Rio Grande Faults

A more substantial revision to the conceptual model based on recent inspection of geophysical logs would be the replacement of the north-trending Rio Grande and Isleta Faults (fig. 4) with a series of northwest-trending benches that step down from a horst near southwest Albuquerque to a low in southeastern Rio Rancho. The structural block beneath eastern Albuquerque hinges along a line where the Rio Grande Fault was previously mapped and is rotated down to the east. In southwest Albuquerque, clays in the middle Santa Fe are fairly shallow (about 600 feet below the water table). The same beds are found at a depth below water of about 1,600 feet near southeast Rio Rancho. On the southwest side of the horst other benches descend into the southern Albuquerque Basin. Removal of the Rio Grande Fault as a partial barrier to ground-water flow could improve the match between simulated and measured heads just east of the former fault trace. Otherwise, very little change in simulated heads is likely because the distribution of aquifer material is not greatly changed by the new structural interpretation. West and southwest of the horst, however, the simulation of more permeable aquifer material, inferred to be present, could cause water to drain from behind the less permeable deposits in the horst, thereby offering the possibility that the ground-water trough first reported by Bjorklund and Maxwell (1961) could be simulated.

Holes Through the Alluvial Clay Unit

Recent and ongoing geohydrologic investigations in Albuquerque's south valley area indicate that the clay layer in the valley-fill alluvium simulated to exist from Interstate Highway 40 south to Isleta is not continuous. It may have been deposited as broad lenses rather than a continuous sheet, or it has holes and thin areas carved out by post-depositional erosion. These higher conductivity passageways were implicitly recognized in the current investigation by raising the simulated horizontal hydraulic conductivity and vertical leakance to higher average values than normally would be associated with lacustrine clay. Because of a small area of vertical hydraulic disconnection that developed in the historical simulation to 1994 and grew to a significant area in all of the projections to 2020 some other approach to simulating the passageway-riddled clay may be necessary and more appropriate. The present approach completely cuts off vertical movement of water from surface sources to the deep ground-water system. The objective of seeking another simulation approach would be to maintain some small, and as yet unknown, amount of vertical flow.

Two approaches are feasible. One approach would be to convert a hydraulically disconnected cell location to a specified vertical flux. However, estimates of the amount of this flux would be unsupported by field evidence and could only be bounded by zero as a lower limit and the maximum flux before disconnection as an upper limit. Another approach would be to actually simulate the passageways as randomly placed, high horizontal hydraulic-conductivity and vertical leakance cells within a matrix of cells that have lower hydraulic conductivities and leakances than presently simulated. Presumably, this would allow some cell locations in the area to maintain top-to-bottom connection through the alluvial aquifer. The second approach, which is a better approximation of the conceptual system, is preferred.

Incorporation of Additional Data

The model documented in this report was designed to assimilate new information with relative ease despite its great numerical complexity and detail. All data are maintained as "layers" of information in a GIS. Corrections made to the model in the future can be accomplished using interactive graphic procedures, and the revised GIS data layer can then be interfaced to the ground-water-flow model. As simple as this process sounds and actually is, it is still very time consuming because of the magnitude of the computational task of completing the interface and running the model.

Land-Cover and Hydrography Data

The Bureau of Reclamation recently (summer 1994) completed GIS "layers" of land cover and hydrography for the Albuquerque Basin for the mid-1930's, mid-1950's, and 1993. These data could be blended into existing time-series land-cover data to provide more even transitions over time in the simulations.

The mid-1950's data would be particularly useful because they immediately postdate a major revision of the diversion and drainage networks. By the 1950's, sediment accumulation in the channel of the Rio Grande began to cause the drains constructed by the MRGCD to cease to function. In the mid-1950's, the Bureau of Reclamation, on the MRGCD's behalf, deepened the channel and reconstructed the drain system. The Bureau of Reclamation also constructed flood-control levees to restrict the floodway. Bureau of Reclamation 1955 land-cover data (not available in time for use in the present model) would be a valuable addition to later versions of this model.

Extension of Utility Services

The City of Albuquerque Public Works Department maintains GIS data bases of sewer and water-utility service areas. When the data bases were recently constructed, historical records of expansion dates of these infrastructures were incomplete. However, careful records of current changes and additions are kept and could be used to correctly simulate decreased areas of private supply and disposal systems.

For the present model, the extent of service areas for sewer and water systems other than Albuquerque's was estimated rather than accurately mapped. The actual extent of these smaller systems could be added to the model input.

Ground-Water Withdrawals

Revisions to the model need to include updated information on ground-water withdrawals. Current daily records of withdrawal for each production well are monitored by telemetry and stored in computer files by the City of Albuquerque. Records for other users may be as much as a year out of date and present problems for keeping model historical simulations accurate and current.

Numerical Enhancements

The following are two possible revisions to the model. The revisions would require either a modification of the computer model or the development of a complicated new interface between the GIS and the model.

Interbed Compaction

The current model does not simulate interbed compaction and inelastic release of water from aquifer storage. The original intent was to include interbed compaction in the simulation; however, the existing computer code (Leake and Prudic, 1988) is intended for use in artesian conditions with constant overburden load. A more appropriate computer code written for water-table aquifers and variable loading (Leake, 1991; 1992) is being documented; when it is available, the current ground-water-flow model could be revised to include interbed compaction and land subsidence.

The confined storage coefficient of an aquifer has elastic and inelastic components. The elastic component is recoverable but the inelastic component is not because it is due to a permanent deformation of the structural matrix of the aquifer-system material. For clays, the material most likely to compress, the clay platelets first orient into a common plane; finally, given enough pressure, structure-supporting intermolecular water is pressed out. In the process, not only is storage capacity lost but low-permeability clay can become virtually impermeable, increasing the ratio of horizontal to vertical hydraulic conductivity and reducing vertical flow in the system. The inelastic component of the storage coefficient is larger than the elastic by at least an order of magnitude. The inelastic component does not come into effect until a threshold stress, called the preconsolidation stress, is exceeded. Every time this threshold is exceeded the system permanently loses storage capacity. Hence, a hysteresis loop in both interbed compaction and storage recovery is established as hydraulic heads are cyclically lowered. The cycle period may be locally as short as the daily operation cycle of a well or regionally as long as the seasonal peak of water-system demands.

Water is released from aquifer storage when interbeds of fine-grained material are compressed and compacted either by a reduction in interstitial pore pressure or by an increase in overburden loading. The effects of compaction propagate and accumulate upward, resulting in land subsidence that is often accompanied by the development of tensional fissures.

Land subsidence resulting from lowering of the water table and dehydration of shallow beds of clay- and organic-rich material is known to be occurring in the Rio Grande flood plain near Albuquerque. Locally, land subsidence has been observed to be as much as 2 feet in the center of broad depressions that extend as much as several hundred feet in diameter. Most of these depressed areas correlate with swampy or transitional wetlands mapped from 1935 aerial photography by the National Biological Survey. A similar situation in the El Paso, Texas, area was reported by Land and Armstrong (1985) and simulated by Kernodle (1992a).

In addition to localized subsidence features in the flood plain, preliminary indications based on repeated first-order leveling are that broad areas outside of the flood plain may be subsiding as well. Subsidence outside of the flood plain results from compaction of beds at a considerable depth below land surface and would therefore be much less focused than subsidence in the valley.

Anisotropy Proportional to Stress

Measured horizontal to vertical hydraulic-conductivity anisotropy can be related to the amount of stress applied to an aquifer system. Ratios of horizontal to vertical hydraulic conductivity for an aquifer test conducted and analyzed in the Tesuque Formation of the Santa Fe Group by Hearne (1985) ranged from 250:1 for regional unstressed conditions to 20,000:1 during the aquifer test (Hearne, 1985; Kernodle, 1992b, table 4). Hearne (1985) attributed the apparent discrepancy to the differences in the tortuosity of the flow path of water around low-conductivity aquifer material under unstressed versus stressed (pumped) conditions.

The present model of the Albuquerque Basin simulates the ratio of horizontal to vertical hydraulic conductivity as uniformly 200:1, a relatively low anisotropy ratio for a highly stressed area such as the immediate Albuquerque area (Kernodle, 1992b, table 4). It would be difficult but probably not prohibitively so, using the GIS, to simulate the anisotropy ratio as a function of the local amount of stress on the aquifer system--that is, to simulate the anisotropy ratio as a function of the distance from large-capacity production wells. As significant as this change probably would be to simulated vertical head gradients in the historical simulations and projections to 2020, presently there are virtually no measured vertical head gradients in highly stressed areas against which simulated values could be compared. A network of nested piezometers in the Albuquerque area would be needed to determine vertical head gradients and thereby allow simulation refinement of the estimate of this hydraulic property.

Data Needs

The following information would either eliminate sources of error in simulated stresses and boundary conditions or provide more accurate and reliable field data against which the model can be calibrated. Most of these needs were discussed in previous sections of the report. The list of data needs is restricted to those that would be of immediate beneficial use in model improvement.

Dedicated Observation Wells in the Albuquerque Area

A network of multicompletion piezometers is needed in the main area of ground-water withdrawal in Albuquerque to accurately determine the water table, vertical hydraulic-head gradients, and changes in hydraulic heads with time. Improved head data will allow model refinement and, in conjunction with microgravity surveys described below, determination of aquifer specific yield. The Albuquerque area in the basin is singled out because ground-water withdrawals have caused steep vertical hydraulic-head gradients (fig. 53) and no wells are appropriately constructed to measure them. Piezometers in other parts of the basin would be useful but less critical. Completion of the wells would also allow geophysical tests, collection of aquifer samples, and sampling for isotope and trace- and common-element analyses of formation water.

Direct Measurement of Surface-Water Losses

During 1992-1994 the Bureau of Reclamation has conducted a surface-flow measurement program at Bernalillo and Isleta (pl. 1). By using preliminary statistical analyses of paired-flow measurements, winter losses in the reach were found to be about 33,000 acre-feet per year (Steve Hansen, written commun., May 1994) although the number of samples was so low that the uncertainty in the estimate was about the same magnitude as the estimate itself. These measurements are scheduled to continue until the spring of 1995.

Direct Measurement of Change in Aquifer Storage

The amount of change in the volume of water in storage can be calculated using repeated microgravity surveys. These surveys, in conjunction with a good network of water-table measurements, would then allow direct computation of local values of specific yield.

Better Vertical Control on the River, Canals, and Drains

Lack of accurate vertical control for surface-water features probably is the greatest cause of differences between measured and simulated hydraulic heads. At least in the Albuquerque area, surface altitudes for water in the Rio Grande, canals, and drains need to be determined to within 1 or 2 feet. The riverside drains, which probably exert the greatest control on shallow ground-water levels in the valley, need to be given priority for accurate altitude determination.

SUMMARY

The study described in this report is the third of a three-phase study to quantify ground-water resources in the Albuquerque Basin. The first phase, conducted by the New Mexico Bureau of Mines and Mineral Resources in cooperation with the City, described the hydrogeologic framework of the Albuquerque Basin on the basis of recent data. The second phase of the study resulted in a description of the geohydrologic framework and hydrologic conditions in the Albuquerque Basin. This report, a result of the third phase, describes ground-water-flow simulations of the Albuquerque Basin based on the concepts developed in the earlier study phases.

The model simulates ground-water flow in the Pleistocene to Holocene valley-fill alluvium and the late Oligocene to middle Pleistocene Santa Fe Group basin-fill deposits in the Albuquerque Basin, and underflow from adjacent basins. The simulations include predevelopment (steady state), the 1901-1994 historical period, and four possible scenarios of ground-water withdrawal from 1994 to 2020.

The model simulates ground-water flow over an area of about 2,400 square miles to a depth of 1,730 to about 2,020 feet below the water table. Because one of the major objectives of the simulations is to define the effect of ground-water withdrawals on the surface-water system, emphasis is placed on the shallow-aquifer system. The top four layers of the 11-layer model represent the 80-foot thickness of alluvium in the incised and refilled valley of the Rio Grande. Away from the valley, these four layers represent the interval within the Santa Fe Group aquifer system between the water table and a level 80 feet below the grade of the Rio Grande. Most ground-water withdrawals from the system are from the upper Santa Fe Group (the top nine model layers) in the Albuquerque area east of the Rio Grande.

The model is designed to be flexible and adaptive to new information. The use of a Geographic Information System (GIS) as a data-base manager is essential to assimilate the massive quantities of information needed for the current model and to meet the requirement that the model evolve as more information becomes available. The GIS was used to prepare model input for model layer top and bottom elevations, hydraulic-conductivity and transmissivity values, vertical harmonic conductivity, and storage coefficients for each of the 11 model layers. The GIS also was used to process simulated underflow to the basin, mountain-front and tributary recharge, evapotranspiration estimates for riparian vegetation, agricultural irrigation-return flow to ground water, and leakage to and from the river, irrigation canals, laterals, ditches, and drains. Population data from the U.S. Department of Commerce and GIS data for utility-service areas from the City of Albuquerque were used to compute volumes of privately supplied water, imported utility-service water, and septic returns. Finally, the GIS was used to organize the historical ground-water-withdrawal data provided by the City of Albuquerque and the New Mexico State Engineer Office and to format those data for model input.

The model did not undergo a rigorous calibration process. The aquifer system was defined and quantified in a manner consistent with the current understanding of the structural and geohydrologic framework of the basin. Assigned aquifer and boundary properties were kept as simple and uniform as possible. Discrepancies between simulated and measured responses in hydraulic head were assumed to indicate that the understanding of a local part of the system was incomplete or incorrect. In general, the historical comparisons of simulated and measured

hydraulic head were good in the Albuquerque area because the lithology and hydraulic properties of the aquifer system are well understood. Properties simulated in the model are listed below.

Storage coefficients	
Specific yield	0.15
Specific storage	$2x10^{-6}$ per foot
Hydraulic conductivity[1]	
Rio Grande and Jemez River alluvium	40 ft/d (0.5 ft/d for clay zone along Rio Grande from Central Avenue to Isleta Pueblo)
Rio Puerco alluvium	20 ft/d
Rio Grande bed	0.5 ft/d
Cochiti Lake bed, canals, laterals, ditches	0.15 ft/d
Drains	1 ft/d
Lower Santa Fe, undifferentiated	2 ft/d
Zia Sand	4 or 10 ft/d
Middle Santa Fe and Cochiti Formation	4 ft/d
Main body, upper Santa Fe Group	10 or 15 ft/d
Piedmont-slope deposits	10 ft/d
Axial-channel deposits	30 to 70 ft/d
Vertical hydraulic conductivity	1/200th of the harmonic mean between layers[1]
Riparian and agricultural	
Wetland evaporation	5 ft/yr
Maximum riparian transpiration	2.6 ft/yr (20-ft extinction depth)
Irrigation seepage	1 ft/yr
Private domestic	
Per capita withdrawal	100 gallons per day (gal/d)
Septic-field return flow	75 gal/d

[1]Because of cementation, faults are simulated to reduce the horizontal hydraulic conductivity to 20 percent of the assigned cell value. Vertical hydraulic conductivity is unaffected.

The model simulations indicate that for the year ending in March 1994, net surface-water loss in the basin resulting from the City of Albuquerque's ground-water withdrawal totaled about 53,000 acre-feet. The balance of the approximately 123,000 acre-feet of withdrawal came from net storage depletion (about 67,800 acre-feet) and riparian and wetland evapotranspiration (about 2,500 acre-feet). In the four projected scenarios from 1994 to 2020, City of Albuquerque withdrawals ranged from about 98,700 to about 177,000 acre-feet by the year 2020. Resulting surface-water loss ranged from about 62,000 to about 77,000 acre-feet. The net storage depletion ranged from about 33,400 to about 95,900 acre-feet. Riparian and wetland evapotranspiration and drain seepage remained nearly constant for all scenarios. Maximum projected water-level declines from 1994 to 2020 ranged from 55 to 164 feet east of the Rio Grande and from 91 to 258 feet west of the river in model layer 9. Average production-level declines in a 383.7-square-mile area around Albuquerque ranged from 28 to 65 feet for the same time period.

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