SIMULATION OF THE REGIONAL GEOHYDROLOGY OF THE TESUQUE AQUIFER SYSTEM NEAR SANTA FE, NEW MEXICO

By Douglas P. McAda and Maryann Wasiolek

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CONVERSION FACTORS

Figures for measurement in this report are given in inch-pound units only. The following table contains factors for converting to metric units.

Multiply inch-pound units	By	To obtain metric units
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
acre-foot per acre	0.003048	cubic hectometer per hectare
acre	0.4047	hectare
square mile	2.590	square kilometer
acre-foot	0.001233	cubic hectometer
million gallons	3,785	cubic meter
square foot per second	0.09290	square meter per second
gallon per day per foot squared	0.04075	meter per day
cubic foot per second	0.02832	cubic meter per second
gallon per minute	0.06309	liter per second
gallon per day	0.003785	cubic meter per day

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

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ABSTRACT

Declining ground-water levels resulting from ground-water withdrawals in the Santa Fe, New Mexico, area have caused concern about the future availability of water from the Tesuque aquifer system (includes the Tesuque, Puye, and Ancha Formations of Tertiary age). This report describes the geohydrology of the Tesuque aquifer system in the Santa Fe area and presents a three-dimensional regional ground-water flow model with which the effects of existing and possible future ground-water withdrawals on the regional aquifer system were assessed.

The model was calibrated using simulations of the predevelopment steady-state condition and the 1947-82 historical period. The response of the aquifer to two scenarios of future ground-water withdrawals from 1983 to 2020 was simulated.

The maximum projected decline in hydraulic head from 1983 to 2020 was 174 feet for both the large and small water-demand scenarios and occurred in the area of the Santa Fe well field. Simulated discharge to the Pojoaque River and its tributaries was 7.0 cubic feet per second at the end of the simulation with the small water demand and 6.9 cubic feet per second with the large water demand, compared to 7.3 cubic feet per second for the steady-state simulation and 7.1 cubic feet per second at the end of the historical transient simulation. Simulated discharge to the Rio Grande was 36.0 cubic feet per second at the end of the simulation with the small water demand and 34.3 cubic feet per second with the large water demand, compared to 39.3 cubic feet per second for the steady-state simulation and 37.2 cubic feet per second at the end of the historical transient simulation.

The sensitivity of the model to changes in aquifer thickness, hydraulic conductivity, specific yield, storage coefficient, and vertical anisotropy ratio was tested. The sensitivity analyses indicated that maximum simulated decline in hydraulic head is most sensitive to specific yield. Average change in hydraulic head is most sensitive to hydraulic conductivity. Simulated discharge to the rivers is most sensitive to the changes in hydraulic conductivity.

INTRODUCTION

The Santa Fe area has experienced a substantial increase in population since the 1930's. Accompanying this growth of the city and surrounding areas is an increasing demand for water. Since about 1946, public-supply wells have been drilled to supplement surface water for the city's water-supply system. In addition, many private wells have been drilled outside and inside the city of Santa Fe.

Declining ground-water levels resulting from ground-water withdrawals in the Santa Fe area have caused public concern about the future availability of water. As the population of the area continues to increase, additional stresses will be placed on the ground-water system.

Purpose and Scope

This study was done in cooperation with the New Mexico State Engineer Office and the Santa Fe Metropolitan Water Board to provide information to enhance the understanding of the geohydrologic system in the Santa Fe area. This information can be used in future planning and management of the water resources in the area. The specific objectives of the study were to: (1) Define components of the geohydrologic system in the Santa Fe area necessary for developing a regional ground-water flow model; (2) assess effects of existing ground-water withdrawals on the geohydrologic system; and (3) assess effects of possible future ground-water withdrawals on the geohydrologic system.

The scope of this study was limited to the Santa Fe Group of Tertiary and Quaternary age in the vicinity of Santa Fe, New Mexico. The ground water supplied to the city of Santa Fe is withdrawn from this group.

Location of the Study Area

The area of interest for this report is within Santa Fe County and extends from the Sangre de Cristo Mountains west to the Rio Grande and from La Cienega north to the Pojoaque River (fig. 1). Where it was practical, the model extends beyond the area of interest to include the natural boundaries of the geohydrologic system. The model described in this report simulates regional ground-water flow in an approximately 700-square-mile area of the Espanola Basin in north-central New Mexico that includes the northwestern part of Santa Fe County, the eastern part of Los Alamos County, and small parts of Rio Arriba and Sandoval Counties.

There are five major well fields in the model area (fig. 2). The Guaje, Los Alamos, and Pajarito well fields supply water to Los Alamos. The Buckman and Santa Fe well fields supply water to Santa Fe.

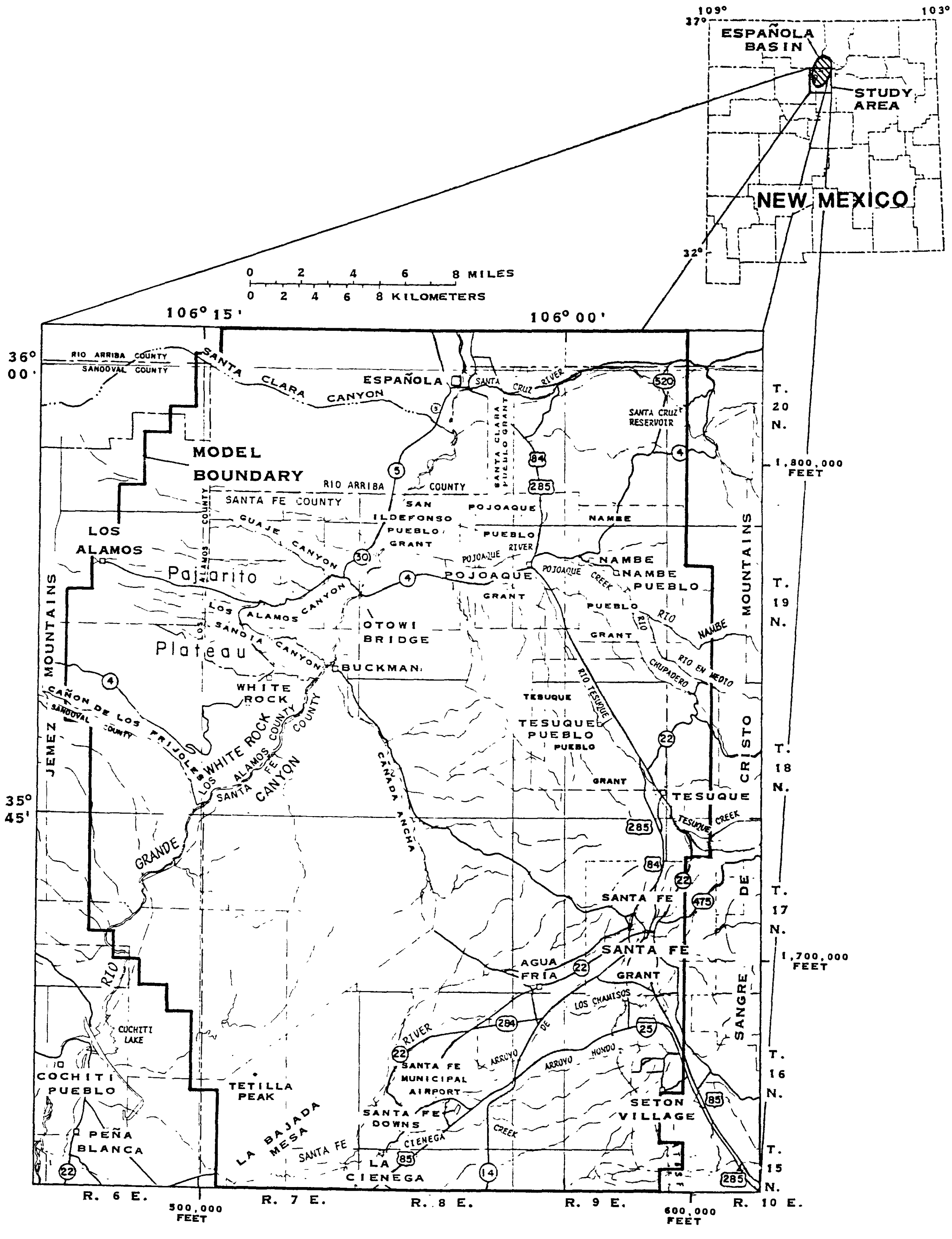


Figure 1.--Location of the study area.

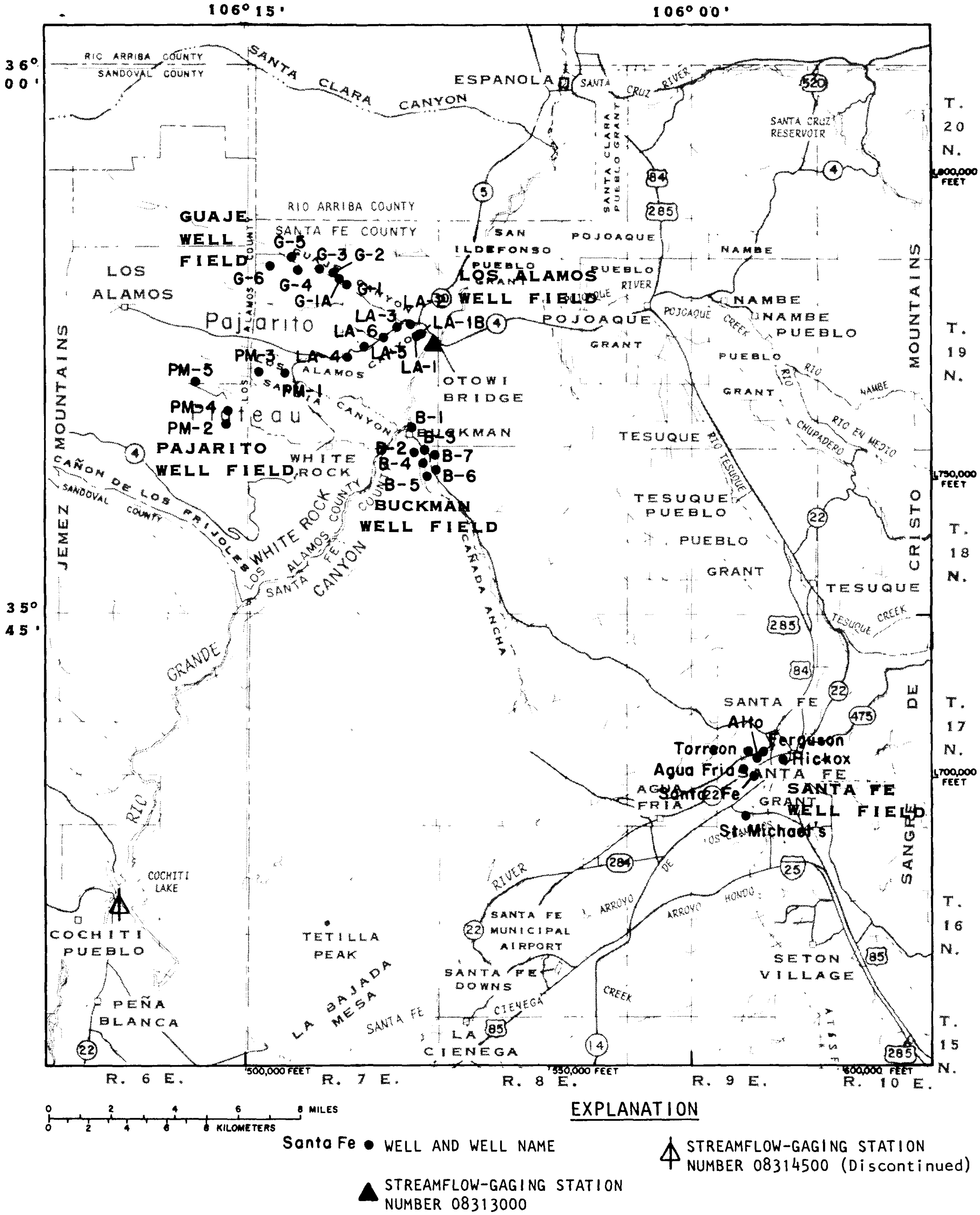


Figure 2.--Location of major well fields and selected streamflow-gaging stations.

Well-Numbering System

The system of numbering wells in this report is based on the common subdivision of land into townships, ranges, and sections in the Federal land-survey system. In land grants, well numbers are based on the New Mexico Coordinate System.

The well numbers based on townships, ranges, and sections consist of four parts separated by periods (fig. 3). The first part is the township number, the second part is the range number, and the third part is the section number. Since all the township blocks within the study area are north of the base line and east of the principal meridian, the letters N and E, indicating direction, are omitted as well as the letters T for township and R for range. Hence, the number 18.7.1 is assigned to any well located in sec. 1, T. 18 N., R. 7 E.

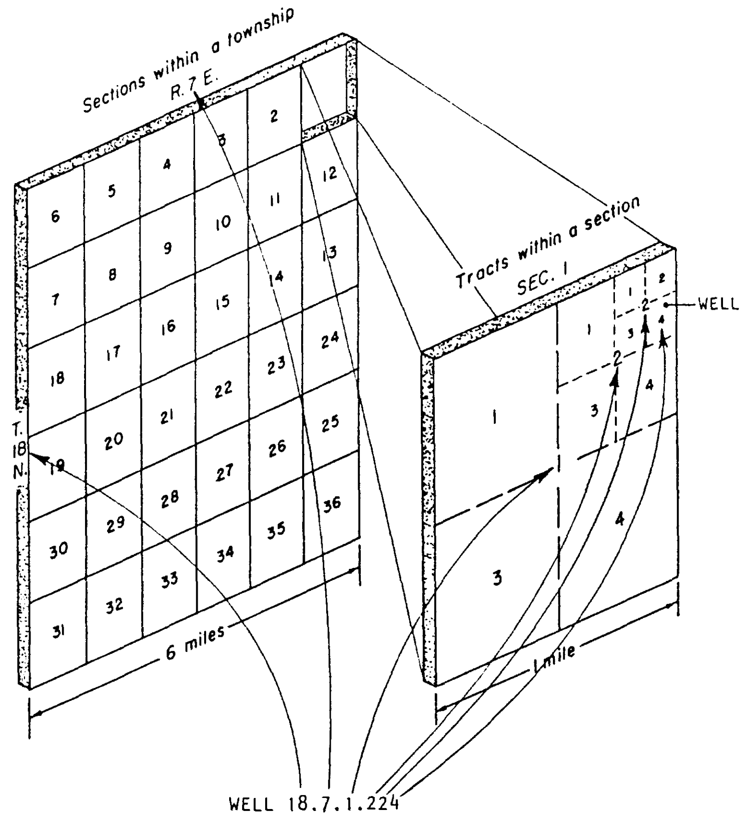


Figure 3.--System of numbering wells based on the Federal land-survey system.

The fourth part of the number consists of three digits that denote the particular 10-acre tract within the section in which the well is located. The method of numbering the tracts within the section is shown in figure 3. For this purpose, the section is divided into four quarters, numbered 1, 2, 3, and 4, in the normal reading order, for the northwest, northeast, southwest, and southeast quarters, respectively. The first digit of the fourth part gives the quarter section, which is a tract of 160 acres. Each quarter is subdivided in the same manner so that the first and second digits together define the 40-acre tract. Finally, the 40-acre tract is divided into four 10-acre tracts, and the third digit denotes the 10-acre tract. Thus, well 18.7.1.224 is in the SE$\frac{1}{4}$ of the NE$\frac{1}{4}$ of the NE$\frac{1}{4}$ of sec. 1, T. 18 N., R. 7 E.

The well numbers based on the New Mexico Coordinate System are used for land grants within the study area. This is a system of plane coordinates established by the U.S. Coast and Geodetic Survey. The well number is the geographic position designated by two distances expressed in feet. The X-coordinate gives the position in the east-west direction, and the Y-coordinate gives the position in the north-south direction. The State of New Mexico is divided into three north-trending zones of which the central zone contains the study area. In the central zone, distances are measured from 106°15'W. longitude (at which X = 500,000 feet) and from 31°N. latitude (at which Y = 0 feet).

Acknowledgments

This study was done in cooperation with the New Mexico State Engineer Office and the Santa Fe Metropolitan Water Board. The authors wish to thank Karol Nemick, graduate student at the University of New Mexico, for her help in preparing model-input data and plotting results of the many model runs. Pete Stewart, hydrologist with the Carson National Forest, and Allen Smart, hydrologist with the Santa Fe National Forest, provided valuable insight into the mechanisms governing mountain-front recharge and provided guidelines for quantifying such recharge for the Sangre de Cristo Mountains of New Mexico. Their assistance, as well as that of other State and Federal personnel and private individuals too numerous to mention, is gratefully acknowledged.

GEOHYDROLOGY

Geologic Setting

The area of this investigation is within the Espanola Basin in north-central New Mexico (fig. 4). Detailed descriptions of the geology of the Espanola Basin have been reported in previous studies (Spiegel and Baldwin, 1963; Griggs, 1964; Galusha and Blick, 1971; Baltz, 1978; Kelley, 1978; and Manley, 1978a, 1978b).

The Espanola Basin is a north- to northwest-trending and plunging, asymmetric faulted synclinal sag (Baltz, 1978, p. 213), filled to an unknown depth with semiconsolidated to unconsolidated Tertiary and Quaternary sediments. The Espanola Basin is one of a series of basins that constitute the Rio Grande depression of New Mexico and southern Colorado.

The basin is bounded on the west by the Pajarito fault zone. This fault zone is covered to a large degree by the Jemez Mountain volcanics, but where the fault can be seen, the basin sediments are downthrown mainly to the east, giving the formations a generally eastward dip in this area. The offset ranges up to several thousand feet at the juncture of the Espanola and Santo Domingo Basins. The eastern boundary of the basin is considered by Baltz (1978, p. 213) to be a faulted, west-facing anticlinal bend that merges with the westward-tilting Santa Fe block of the Sangre de Cristo uplift. To the northwest, the basin is bounded mainly by faults dropped down to the east, whereas the basin is limited to the northeast by bedrock highs of the Picuris block and the southern end of the Brazos uplift. The uplifts create a narrow, 11-mile-wide constriction in the bedrock called the Embudo channel through which the Rio Grande enters the Espanola Basin from the San Luis Basin to the north.

The southern margin of the Espanola Basin is defined by several physical features. To the south and southeast, the southeastern terminus of the northwest-plunging syncline of the basin is highest where only a thin section of semiconsolidated basin-fill sediments were either deposited or deeply eroded. To the south, the basin is bounded by the Cerrillos uplift. La Bajada fault trends northwest across the southwestern edge of the basin. La Bajada fault and the sequence of faults surrounding it (fig. 5) have uplifted the Espanola Basin relative to the Santo Domingo Basin to the south. Disbrow and Stoll (1957, p. 41) reported that to the south of the study area, the Rosario fault, which is a term used for La Bajada fault, has downthrown the Tertiary Galisteo Formation on the west against the Triassic Chinle Formation, with a vertical displacement of about 4,500 feet.

The Santa Fe Group in the Espanola Basin area is comprised of the Tesuque, Puye, and Ancha Formations of Tertiary age (Manley, 1978b, p. 202). The extent of the outcrops of these formations is shown in figure 5. These formations are unique to the Espanola Basin area, although the term Santa Fe Group is applied to basin-fill deposits throughout the Rio Grande depression in New Mexico. Hawley (1978, p. 239) presented a detailed chart correlating the nomenclature applied by various investigators to Espanola Basin sediments and the relation between these sediments and sediments of other basins along the Rio Grande rift zone.

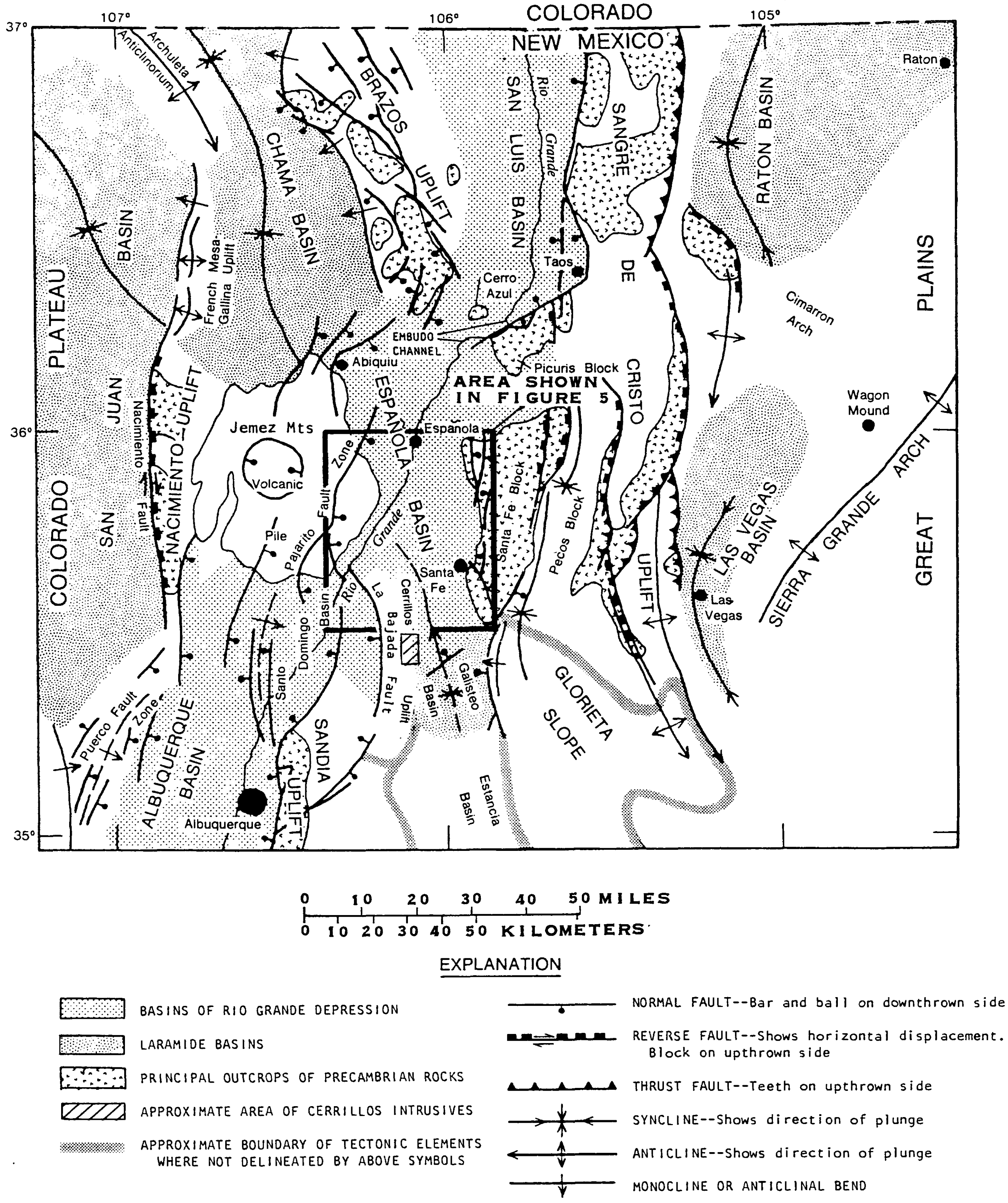


Figure 4.--Major tectonic features of north-central New Mexico (modified from Baltz, 1978, p. 121).

The Tertiary Tesuque Formation of the Santa Fe Group is the principal aquifer in the Santa Fe area. Tesuque sediments are composed of "several thousand feet of pinkish-tan soft arkosic, silty sandstone and minor conglomerate and siltstone" (Spiegel and Baldwin, 1963, p. 39). In the Santa Fe area, the Tesuque Formation is comprised of three distinct members: the Nambe, Skull Ridge, and Pojoaque Members (Galusha and Blick, 1971, p. 44-64; Kelley, 1978). The Tesuque Formation was deposited mainly as coalescing alluvial-fan deposits derived mainly from the highlands to the north and east. In the areas of the Pajarito Plateau and the Cerros del Rio (fig. 5), the Tesuque Formation is overlain by Tertiary and Quaternary volcanics. The thickness of Tesuque sediments is unknown. Estimates for thickness range between 4,000 and 10,000 feet for the deepest areas, thinning to zero at the eastern mountain front. Galusha and Blick (1971, p. 44) reported that more than 3,700 feet of Tesuque sediments fill the deepest parts of the basin. Kelley (1978) reported the thickness to be 8,000 to 9,000 or more feet near the Rio Grande.

The Tesuque sediments dip westward up to 25 degrees along the west flank of the Sangre de Cristo Mountains and have a general westward dip of between 4 and 10 degrees throughout the eastern half of the basin. Because of the westward dip, the three members of the Tesuque Formation crop out in north-south trending bands between the Sangre de Cristo Mountains and the Rio Grande, with the oldest unit being near the mountains. Although faulting has offset the strata of the Tesuque Formation on both sides of the Rio Grande, this gentle regional dip exposes a large section of the formation. Farthest to the east, the sediments of the Nambe Member lie in both fault and depositional contact with the bedrock of the Sangre de Cristo Mountains. The Nambe Member is composed predominantly of semiconsolidated to unconsolidated coarse-grained to conglomeratic arkosic sediments deposited in several sequences, each of which becomes finer grained toward the top. The Skull Ridge Member conformably overlies the Nambe and crops out farther to the west. The Skull Ridge Member is composed predominantly of cross-bedded, fine to medium-coarse sandstone interbedded with minor but numerous volcanic-ash and mudstone beds. The Pojoaque Member unconformably overlies the Skull Ridge and crops out closest to the Rio Grande. The Pojoaque Member is composed of buff to gray semiconsolidated fine- to medium-grained sandstones interbedded with considerable mudstone and some gravel.

The Tertiary Puye Formation of the Santa Fe Group (Griggs, 1964, p. 28; Purtymun and Johansen, 1974, p. 347-349) is younger than the Tesuque Formation and is present on the western side of the Rio Grande. The formation consists mainly of gray sand and small pebbles derived from rocks varying in composition from basaltic to rhyolitic that were associated with the volcanics of the Jemez Mountains. The deposits form high terraced escarpments deeply incised by east-west-trending washes extending from the Jemez Mountains to the Rio Grande. They range in thickness from over 700 feet near Santa Clara Canyon to 60 feet below the lava flow near Otowi Bridge (fig. 5). In the vicinity of Los Alamos, wells have penetrated water in the Puye Formation as well as in the underlying Tesuque Formation. The Puye Formation and Tesuque Formation are hydraulically connected. For the purpose of this study, the Puye Formation is included as part of the Tesuque aquifer system.

EXPLANATION

QUATERNARY AND TERTIARY VOLCANICS

TERTIARY (PLIOCENE) ANCHA FORMATION

TERTIARY (PLIOCENE) PUYE FORMATION

OTHER TERTIARY (MIOCENE) TESUQUE FORMATION

OTHER TERTIARY ROCKS

PENNSYVANIAN LIMESTONE

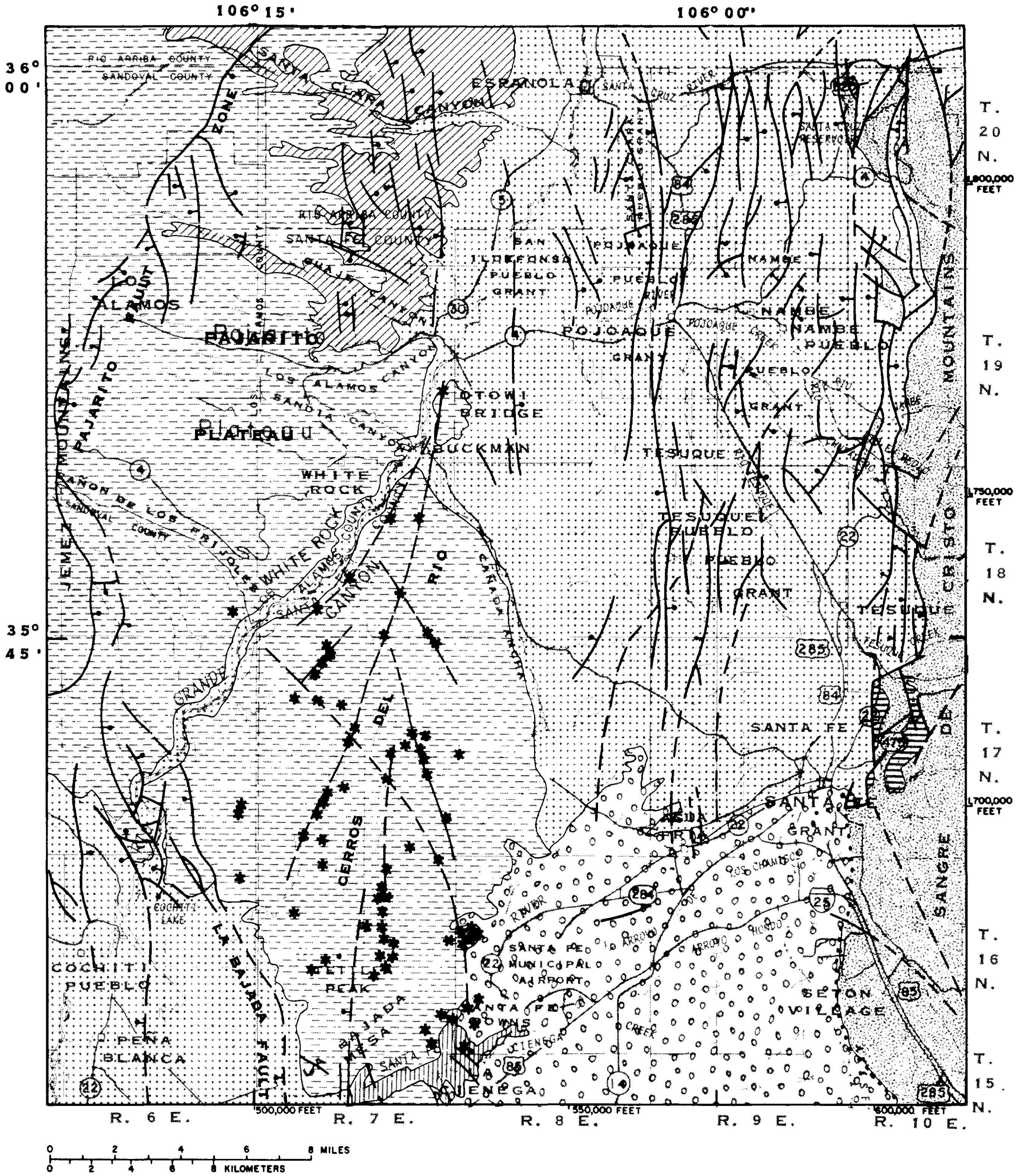
PRECAMBRIAN ROCK

FAULT--Dash where uncertain, dotted where buried, ball on downthrown side

* VOLCANIC CONE OR VENT

NOTE: Quaternary alluvial deposits not shown

Figure 5.--General geology (modified from Baltz, 1978, and Kelley, 1978).


106° 15'
106° 00'
36° 00'
35° 45'
RIO ARRIBA COUNTY
SANDOVAL COUNTY
SANTA CLARA CANYON
ESPANOLA
SANTA CRUZ RIVER
SANTA CRUZ RESERVOIR
ZONE
PAJARITO FAULT
LOS ALAMOS
PAJARITO PLATEAU
JEMEZ MOUNTAINS
SANTA FE COUNTY
GUAJE CANYON
SAN ILDEFONSO PUEBLO GRANT
POJOAQUE PUEBLO GRANT
NAMBE
NAMBE PUEBLO GRANT
POJOAQUE
LOS ALAMOS CANYON
SANDIA CANYON
OTOWI BRIDGE
BUCKMAN
WHITE ROCK
CANON DE LOS FRIJOLES
WHITE ROCK CANYON
TESUQUE
TESUQUE PUEBLO GRANT
RIO DEL CERROS
SANTA FE
SANTA FE GRANT
COCHITI LAKE
COCHITI PUEBLO
LA BAJADA FAULT
PENA BLANCA
LA BAJADA MESA
TETILLA PEAK
SANTA FE MUNICIPAL AIRPORT
SANTA FE DOWNS
LA CIENEGA
SETON VILLAGE
SANGRE DE CRISTO MOUNTAINS
T. 20 N.
T. 19 N.
T. 18 N.
T. 17 N.
T. 16 N.
T. 15 N.
1,800,000 FEET
1,750,000 FEET
1,700,000 FEET
500,000 FEET
550,000 FEET
600,000 FEET
R. 6 E.
R. 7 E.
R. 8 E.
R. 9 E.
R. 10 E.
0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS

The Ancha Formation of the Santa Fe Group (Spiegel and Baldwin, 1963, p. 45) is a Tertiary high pediment gravel deposited unconformably on the Tesuque Formation. The Ancha Formation is mainly south and west of Santa Fe as well as under the city itself. In general, the Ancha Formation can be described as pinkish-tan, angular and subangular fine to coarse pebble gravels that are mostly derived from granite and are interbedded with minor amounts of silt and sand. Well logs indicate that the Ancha Formation is as much as 300 feet thick.

The similarity between the natures of the Ancha and the Tesuque Formations was stressed by Spiegel and Baldwin (1963, p. 46) who noted that the two formations can be differentiated only with difficulty. Four distinctions can be made between the two formations: (1) The Ancha overlies the Tesuque; (2) the Ancha strata have a westward dip of only 2 to 4 degrees, whereas those of the Tesuque average 4 to 10 degrees; (3) the Ancha is unconsolidated everywhere except where cemented by caliche, whereas the Tesuque is semiconsolidated; and (4) the Ancha sediments are coarser, better sorted, and contain less silt than the underlying Tesuque sediments.

In most areas, the Ancha Formation is above the water table and supplies little water to wells, though where saturated, it is generally a more permeable aquifer than the Tesuque Formation because of the coarser, better sorted nature of the sediments. Exceptions occur in the La Cienega area, where Ancha-filled channels eroded in the Tesuque act as aquifers and in some areas within and south of Santa Fe. Where the Ancha Formation overlies impermeable beds of the Tesuque Formation, perched water of limited extent may occur. Because the Ancha is more permeable than the Tesuque, areas where the Ancha is present can be expected to allow more rapid infiltration of precipitation and to transmit slightly greater amounts of recharge to the underlying aquifer than in areas where the Tesuque crops out. For the purpose of this study, the Ancha Formation also is included as part of the Tesuque aquifer system.

Ground-Water Flow

Contours of the reconstructed predevelopment potentiometric surface of the upper part of the Tesuque aquifer system are shown in figure 6. This map was constructed based on the maps published by Spiegel and Baldwin (1963, pl. 6); Trauger (1967, fig. 1); Borton (1968); Purtymun and Johansen (1974, p. 348); Mourant (1980, fig. 3); and Purtymun and Adams (1980, p. 13). Assuming the aquifer is horizontally isotropic, the direction of ground-water flow is perpendicular to the potentiometric contours.

West of the Rio Grande, ground water enters the Tesuque aquifer system by infiltrating through the overlying volcanics of the Jemez Mountains and the Pajarito Plateau (figs. 4 and 5) and through the bottoms of deeply incised arroyos. The water flows east-southeast through the Puye Formation and Tesuque Formation toward the Rio Grande, where it discharges as springs and seepage (Griggs, 1964, p. 95; Purtymun and others, 1980, p. 8-10).

East of the Rio Grande and north of the Santa Fe River, ground water enters the aquifer system mainly as mountain-front recharge through fractured bedrock of the Sangre de Cristo Mountains, outcrops of the Tesuque Formation exposed along the edge of the mountains, and through permeable alluvium of streambeds draining those uplands. The water flows west-northwest through the Tesuque Formation to the Rio Grande. Most ground water discharges to the Rio Grande as springs and seepage. A smaller amount discharges to the Pojoaque River, Pojoaque Creek, and Rio Tesuque (Trauger, 1967, p. 18-20; Borton, 1968, p. 12).

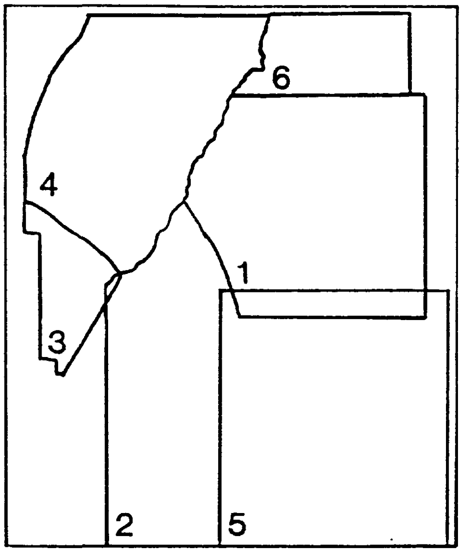
Because the Rio Grande is a major discharge area for the aquifer, a large vertical hydraulic gradient exists in that area. For this reason, ground water at depth near the Rio Grande is under artesian conditions. Deep wells that penetrate the Tesuque sediments at depths of as much as 1,900 feet near the Buckman well field on the east side of the Rio Grande penetrate warmer water with larger concentrations of dissolved solids than water from the shallow part of the aquifer. This and the upward vertical hydraulic-head gradient indicate that the older ground water is at depth and moving upward (Buckman well-field records, New Mexico State Engineer Office, Santa Fe; Buckman observation-well records, U.S. Geological Survey, Albuquerque).

East of the Rio Grande and south of the Santa Fe River, ground water flows west-southwest from recharge areas along the mountain front to discharge along the lower Santa Fe River and into Cienega Creek in La Cienega area. A small component of southward-moving ground water that does not discharge in La Cienega area probably passes into less permeable formations underlying the Tesuque Formation in this area and enters the Santo Domingo Basin (fig. 4). Some of the ground water may discharge as small springs at the base of the escarpment near La Bajada fault. A larger component passes into the Santo Domingo Basin to the west-southwest. Buried southwest-trending Ancha-filled channels that were cut into the Tesuque strata drain ground water from the southern end of the mountains across the plain south of Santa Fe to La Cienega area (Spiegel, 1975, p. 10, 11, 18-20). Water is discharged in this area because the channels terminate there, the Tesuque Formation thins over the uplifted southern block of the synclinal basin, and the underlying, less permeable formations are unable to transmit the same quantity of water.

EXPLANATION

—7100— WATER-LEVEL CONTOUR--Shows altitude of water level. Interval 100 feet. Datum is sea level.

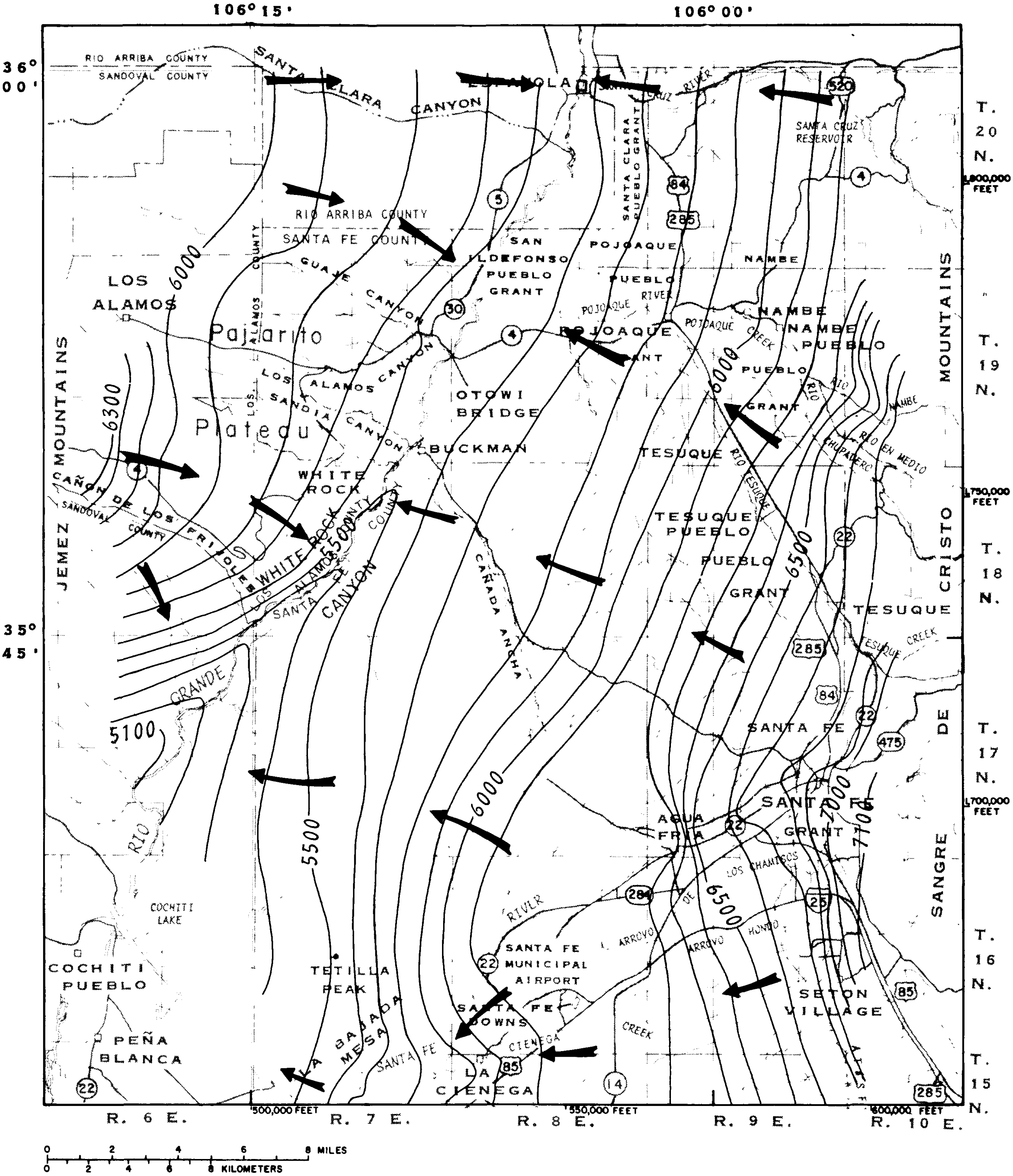
APPROXIMATE DIRECTION OF GROUND-WATER FLOW



Contours modified from:
1. Borton (1968)
2. Mourant (1980, fig. 3)
3. Purtymun and Adams (1980, p. 13)
4. Purtymun and Johansen (1974, p. 348)
5. Spiegel and Baldwin (1963, pl. 6)
6. Trauger (1967, fig. 1)

INDEX TO CONTOUR MAPPING

Figure 6.--Predevelopment potentiometric surface in the upper part of the Tesuque aquifer system.


106°15'
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RIO ARRIBA COUNTY
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SAN ILDEFONSO PUEBLO GRANT
POJOAQUE PUEBLO
NAMBE
LOS ALAMOS
Pajarito Plateau
POJOAQUE
NAMBE PUEBLO GRANT
OTOWI BRIDGE
BUCKMAN
WHITE ROCK
TESUQUE
TESUQUE PUEBLO GRANT
JEMEZ MOUNTAINS
SANGRE DE CRISTO MOUNTAINS
CAÑADA ANCHA
WHITE ROCK CANYON
RIO GRANDE
SANTA FE
SANTA FE GRANT
AGUA FRIA
COCHITI LAKE
COCHITI PUEBLO
PEÑA BLANCA
TETILLA PEAK
LA BAJADA MESA
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SANTA FE DOWNS
LA CIENEGA
SETON VILLAGE
6300
6000
5500
5100
6500
7000
7100
T. 20 N.
T. 19 N.
T. 18 N.
T. 17 N.
T. 16 N.
T. 15 N.
R. 6 E.
R. 7 E.
R. 8 E.
R. 9 E.
R. 10 E.
500,000 FEET
550,000 FEET
600,000 FEET
1,800,000 FEET
1,750,000 FEET
1,700,000 FEET
0 2 4 6 8 MILES
0 2 4 6 8 KILOMETERS

MODEL DESCRIPTION

Movement of water through an aquifer may be expressed by differential equations (Pinder and Bredehoeft, 1968). However, analytical solution of these differential equations usually is not possible because of complex boundary conditions and the heterogeneity and anisotropy of aquifer materials. A digital ground-water flow model may be used to solve the ground-water flow equations numerically with the aid of a computer. The resulting solution is not unique in that any number of reasonable variations to the characteristics of the geohydrologic system used in the model may produce equally good results. The model is a tool that may be used to help understand an aquifer system and to project aquifer responses to assumed stresses. Assumptions and simplifications are made during formulation and solution of the mathematical equations; therefore, the ground-water flow model is only an approximation, and simulated results need to be interpreted carefully.

Model Development

Ground-water flow in the Tesuque aquifer system was simulated in three dimensions. By assuming 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 may be expressed by the following equation (McDonald and Harbaugh, 1984, p. 7):

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = S_s \frac{\partial h}{\partial t}$$

where

K_x, K_y, K_z are the hydraulic-conductivity values in the x, y, and z directions, respectively;
h is the hydraulic head;
S_s is the specific storage of the aquifer material;
W is the volume of water recharged or withdrawn per unit volume per unit time; and
t is time.

The three-dimensional flow equation can be approximated by replacing the derivatives with finite differences. The aquifer is divided into a series of cube-shaped cells by a sequence of layers and a series of rows and columns that extend through each layer. Aquifer properties in each cell are assumed to be uniform. Hydraulic heads are assumed to be at the center of each model cell. For a model with N cells, N simultaneous equations are formulated with the hydraulic heads as unknowns. The finite-difference equations may then be solved simultaneously with the aid of a digital computer. The computer program used for this study was developed by McDonald and Harbaugh (1984). The strongly implicit procedure (SIP) was used as the algorithm to solve the finite-difference equations.

The Tesuque aquifer system in the study area is represented in the model by four layers. The layers do not represent specific units within the Tesuque aquifer system; they are used to discretize the aquifer into three dimensions in order to simulate the vertical component of flow. The layers were divided into a series of cells with uniformly spaced 1-mile-wide rows and columns. Rows were oriented east-west and columns oriented north-south (fig. 7). The orientation was assumed to align with the principal components of hydraulic conductivity. The lateral boundaries of the layers were based on well logs (Borton, 1974; files of the New Mexico State Engineer Office, Santa Fe) and on geology reported by various investigators (Disbrow and Stoll, 1957; Spiegel and Baldwin, 1963; Purtymun and Johansen, 1974; Geohydrology Associates, Inc., 1978; Kelley, 1978; and Manley, 1978a, 1978b).

The upper layer of the model represents the upper, unconfined part of the aquifer. The thickness of the upper layer (layer 1) was established in the steady-state simulations to be a maximum of 800 feet, measured from the water-table surface, but was allowed to change with rise or decline in the altitude of the simulated water table. A major part of the pumpage in the aquifer is from the upper 800 feet. For the upper part of the aquifer to be represented by thinner layers, more specific information on the amount of pumpage for each layer, including pumpage proportioned from single wells, was necessary; however, this information was not available.

The lower layers of the model represent the lower, confined part of the aquifer. The thickness of the second layer is 1,200 feet, and the thicknesses of the third and fourth layers are each 1,800 feet.

A comparison of the model layers to a cross section adapted from Kelley (1978) is shown in figure 8. As discussed previously, various investigators (Galusha and Blick, 1971, p. 44; Baltz, 1978, p. 210) have estimated the thickness of Tesuque sediments to be thinner than that shown in figure 8. The sensitivity of the model to thickness is discussed in the section on model sensitivity.

This model was constructed to simulate the regional geohydrologic system in the Santa Fe area and is not intended to simulate hydraulic heads at particular well sites. The simulated results can at best represent an average condition in the model cells; therefore, simulated hydraulic heads may differ from those measured in wells.

Boundary Conditions

Aquifer boundaries can be represented in the model in four ways: constant head, specified flux, no flow, or head-dependent flux. At a constant-head boundary, the hydraulic head is maintained at a constant level throughout the simulation. At a specified-flux boundary, water is recharged or discharged independent of hydraulic head. At a no-flow boundary, no water is recharged or discharged and no water is allowed across that boundary. Head-dependent flux boundaries can be used to simulate flow between a river and the aquifer. These boundaries recharge or discharge water as a function of head in the river and head in the aquifer. Boundaries used in layer 1 of this model are shown in figure 9.

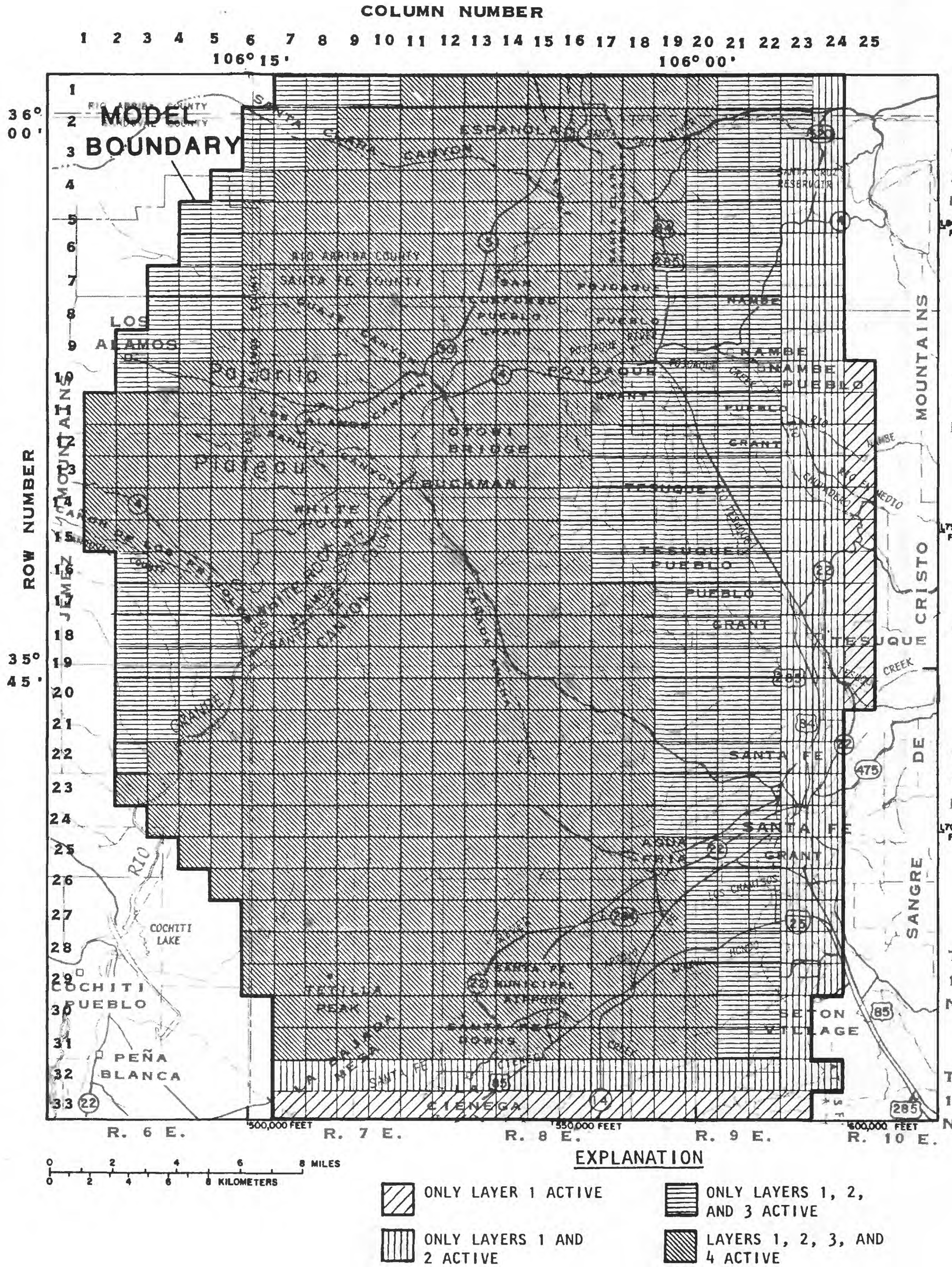


Figure 7.--Orientation of the model grid.

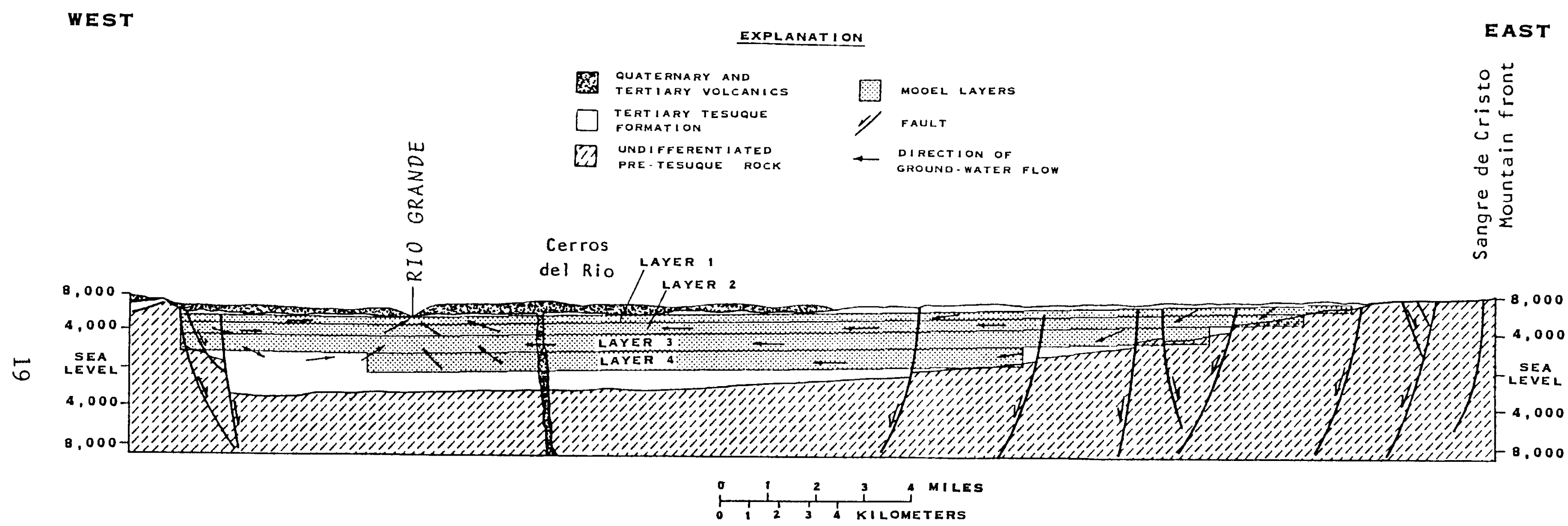


Figure 8.--Generalized geologic section showing direction of ground-water flow and configuration of model layers (modified from Kelley, 1978).

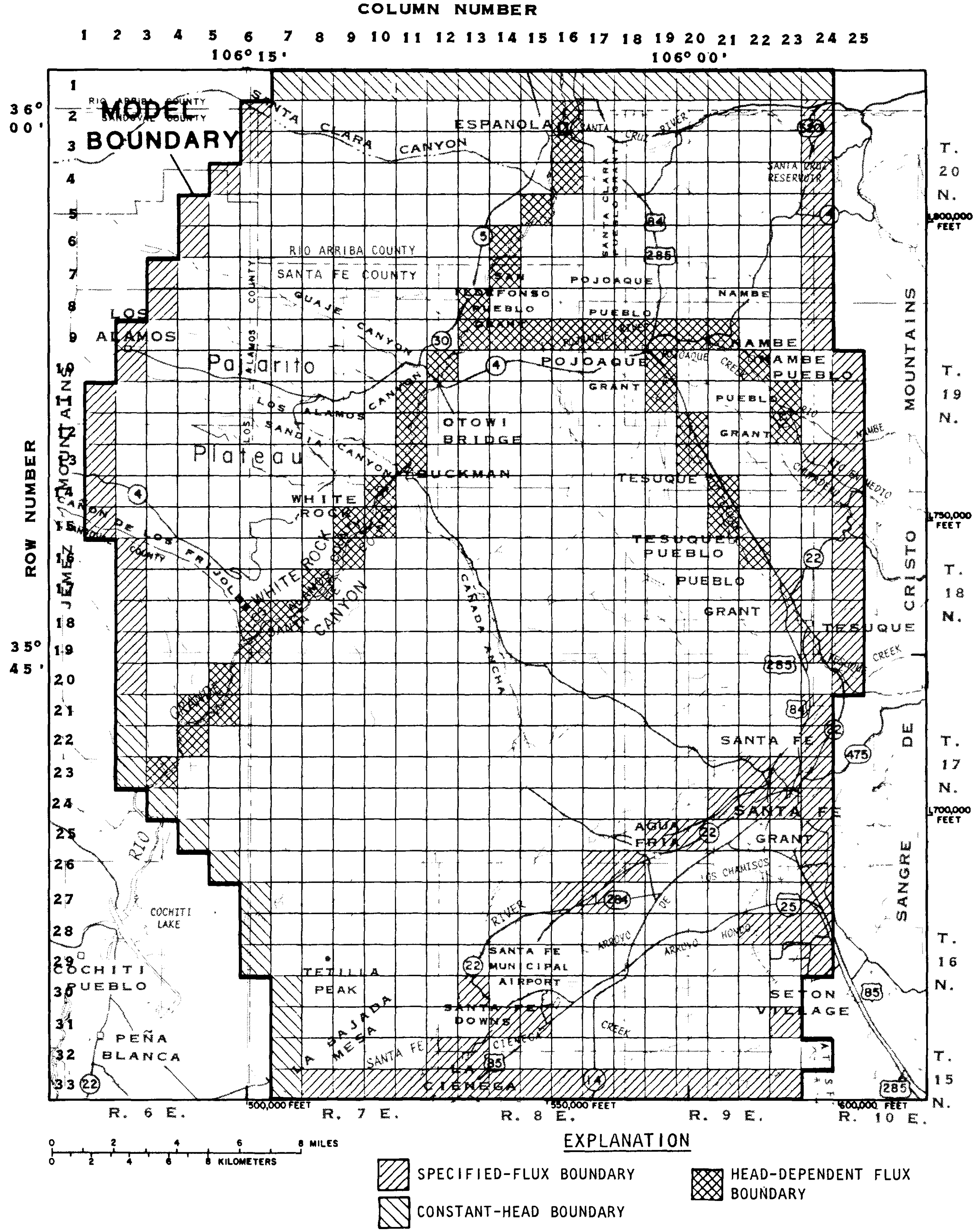


Figure 9.--Boundary conditions represented in layer 1 of the model.

The western boundary of the model is defined by the Pajarito fault zone (figs. 4 and 5). The effect of the Pajarito fault zone on ground-water flow between the Tesuque Formation and water-bearing formations to the west of the fault zone is not known. However, the Jemez Mountains to the west of the fault zone provide recharge across the fault zone to the Tesuque aquifer system. This is represented in the model as a specified-flux boundary in layer 1.

The eastern boundary of the model is defined by the contact of the Tesuque Formation with the Sangre de Cristo uplift. Ground water from alluvial channels and from fractures in the upper part of the Precambrian rocks of the Sangre de Cristo Mountains enters the Tesuque Formation by percolation and underflow at the eastern model boundary. This is represented in the model as a specified-flux boundary.

It was impractical to extend the model to the physical boundary of the Espanola Basin to the north; therefore, an artificial boundary was used. The northern boundary of the model is represented as a constant-head boundary in the upper three layers (fig. 9). The maximum difference in simulated inflow across the boundary between any of the simulations, including steady state and transient, was 0.19 cubic foot per second (9 percent difference), and the maximum difference in outflow was 0.08 cubic foot per second (3 percent difference). Since these amounted to less than two-tenths of 1 percent of the water budget, it was concluded that the artificial boundary was far enough from stresses in the model to have an insignificant effect in the area of interest around Santa Fe.

The southern extent of the model, where continuously saturated basin-fill sediments are truncated against older rocks, is represented by a specified-flux boundary for layer 1 and layer 2. The fluxes across the boundary represent leakage of ground water between the basin fill and older rocks. Few data are available that would provide a basis for estimating the flux rates across this boundary. Consequently, the rates were derived by using constant heads at the boundary for initial model simulations. The calculated fluxes were then used as the specified fluxes for the simulations described in this report.

The southwest boundary of the model represents the boundary between the Espanola Basin and the Santo Domingo Basin. Few data are available to provide a basis for estimating the amount of water that may move as underflow across this boundary into the Santo Domingo Basin. The boundary is represented in the model as constant head in the upper three layers. Since the maximum difference in simulated flow across the boundary between any of the steady-state and transient simulations was 0.07 cubic foot per second (0.4 percent difference), it was concluded that the boundary was far enough from stresses in the model to have an insignificant effect in the area of interest.

The Rio Grande and the Pojoaque River and its tributaries are represented in the model by head-dependent flux boundaries (fig. 9). The Rio Grande is perennial in the study area and has a mean annual flow of 1,500 cubic feet per second at the streamflow gage near Otowi Bridge (U.S. Geological Survey streamflow records for station number 08313000, 1896-1905, 1910-85). The Pojoaque River is perennial only in certain reaches, although it is thought to have been perennial under predevelopment conditions (Trauger, 1967, p. 17). The predevelopment flow at the mouth of the Pojoaque River was estimated by Reiland (1975, p. 19) to be 14.8 cubic feet per second.

These head-dependent flux boundaries simulate leakage between the rivers and the aquifers as a function of hydraulic head in the aquifer, river stage, altitude of the riverbed, and conductance of the riverbed (McDonald and Harbaugh, 1984, p. 209-217). Conductance of the riverbed is the hydraulic conductivity of the riverbed multiplied by the area of the riverbed in a model cell divided by the thickness of the riverbed. Initial values of riverbed conductance were estimated by assuming a hydraulic conductivity of 0.1 foot per day and a riverbed thickness of 1 foot. It was considered feasible that the conductance may be as much as half an order of magnitude smaller or larger than these initial estimates. The conductances were adjusted within these limits during the model calibration process. The resulting conductances are shown in table 1. The difference in the conductance values between cells is due to the different amount of area the riverbeds cover in each cell.

Table 1. Streambed conductances represented in the model at head-dependent flux boundaries

Layer	Row	Column	Conductance of riverbed, in square feet per second	Layer	Row	Column	Conductance of riverbed, in square feet per second
1	2	16	0.50	1	12	11	0.50
1	3	16	.50	1	12	20	.10
1	4	16	.55	1	12	23	.10
1	5	15	.74	1	13	11	.55
1	6	14	.69	1	13	20	.10
1	7	14	.46	1	14	10	.55
1	8	13	.50	1	14	21	.10
1	9	13	.60	1	15	9	.28
1	9	14	.10	1	15	10	.34
1	9	15	.10	1	15	21	.10
1	9	16	.10	1	16	9	.46
1	9	17	.10	1	16	22	.10
1	9	18	.10	1	17	8	.55
1	9	19	.10	1	18	6	.23
1	9	20	.10	1	18	7	.50
1	9	21	.10	1	19	6	.50
1	10	12	.55	1	20	5	.46
1	10	19	.10	1	21	4	.42
1	10	22	.10	1	21	5	.32
1	11	11	.55	1	22	4	.50
1	11	19	.10	1	23	3	.55
1	11	23	.10				

Flow in the Santa Fe River is not perennial over most of its length in the modeled area. Because the water table is below the level of the riverbed, a head-dependent flux boundary would not realistically represent the river. Recharge from the Santa Fe River was input as specified fluxes in the reaches upstream from the Santa Fe Municipal Airport (fig. 9). The amount and distribution of recharge were adjusted throughout the simulation periods, depending upon the available flow in the river. In La Cienega area, the Santa Fe River and Cienega Creek were estimated to gain about 6.5 cubic feet per second from ground water (Spiegel and Baldwin, 1963, p. 191). This ground-water discharge is represented as specified fluxes that remain constant throughout the simulation periods.

Aquifer Characteristics

Hydraulic Conductivity

Aquifer tests done on supply wells for Los Alamos in Guaje and Los Alamos Canyons indicate a hydraulic conductivity for the upper 2,000 feet of the aquifer to be between about 0.3 and 2 feet per day (Theis and Conover, 1962, p. 14-19; Griggs, 1964, p. 96-99; Cushman, 1965, p. 39-41). Purtymun (1977, p. 4) reported the coefficients of permeability for the Los Alamos Canyon wells, which are as much as 2,000 feet deep, to be between 8 and 37 gallons per day per foot squared (hydraulic conductivity between about 1 and 5 feet per day). Hearne (1980, p. 14) reported that aquifer tests done on wells penetrating 200 to 1,000 feet of saturated Tesuque Formation on the pueblo grants of San Ildefonso, Pojoaque, and Nambe indicate a range of hydraulic conductivity from 0.3 to 2.8 feet per day. Hearne (1980, p. 14) estimated that the average hydraulic conductivity of the Tesuque aquifer system in the zones that likely would be penetrated by wells probably is about 0.5 to 2.0 feet per day. Aquifer tests conducted by consultants and tests using the Public Service Company of New Mexico's supply wells indicate hydraulic conductivity in the range of 0.2 to 20 feet per day (files of the New Mexico State Engineer Office, Santa Fe).

The initial estimates of hydraulic conductivity were adjusted within this range during model calibration. The resulting distribution of hydraulic conductivity in layer 1 of the model is shown in figure 10. The average hydraulic conductivity for layer 1 was 1.1 feet per day.

In the vicinity of the Santa Fe Municipal Airport and Santa Fe Downs (fig. 10), aquifer tests indicate an average hydraulic conductivity in the range of 5 to 10 feet per day (Spiegel, 1975, p. 23, 28; files of the New Mexico State Engineer Office, Santa Fe). Drillers' logs for wells and lithologic descriptions of deep test holes drilled in the area for uranium exploration (files of the New Mexico State Engineer Office, Santa Fe) indicate that the Tesuque Formation is characterized by coarser materials than customarily observed near Santa Fe. Few beds of clay and silt were penetrated, and layers of sand, silty sand, and gravel tended to predominate.

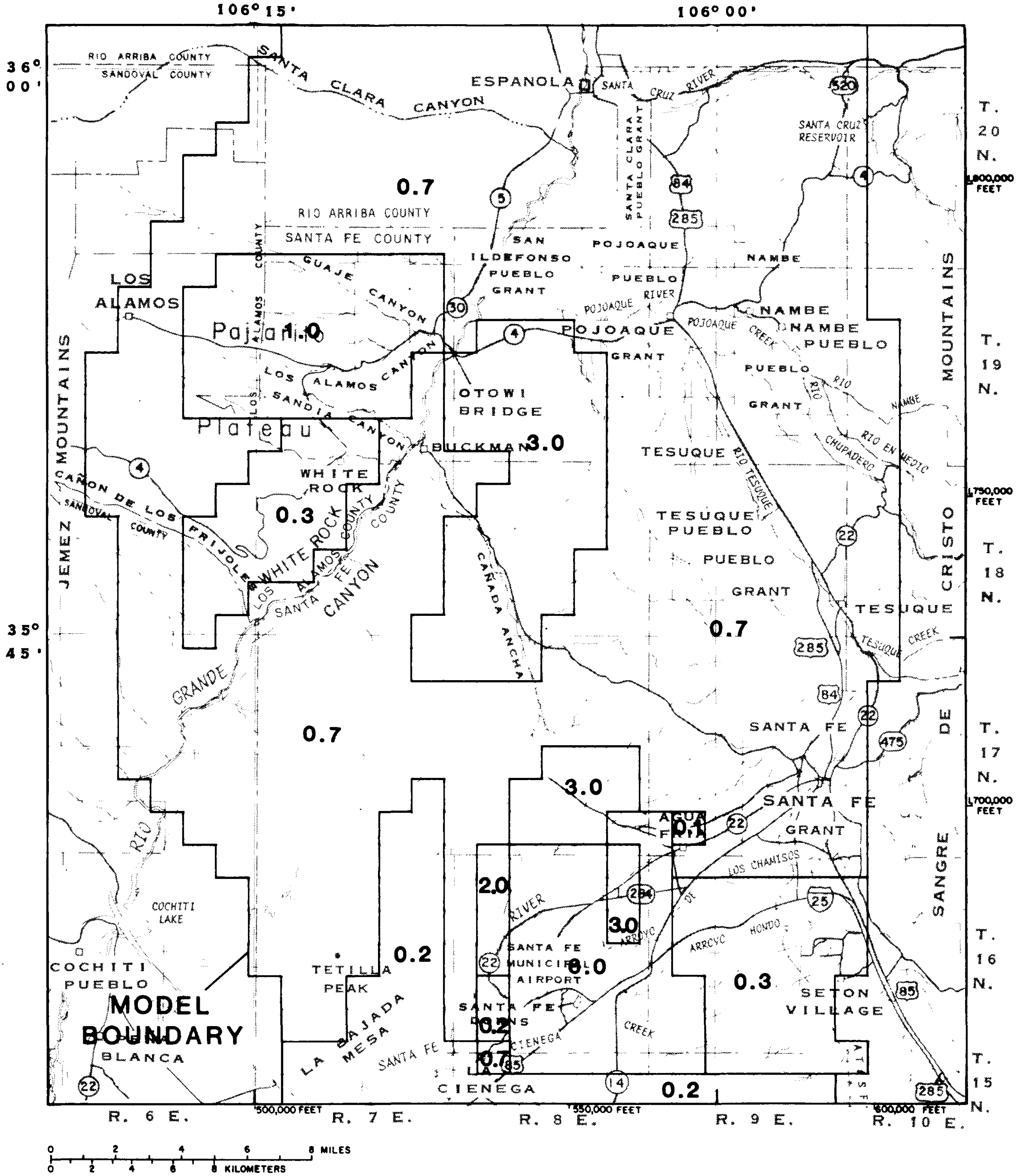


Figure 10.--Distribution of hydraulic conductivity in layer 1 of the model, in feet per day.

A localized but significant fault apparently disrupts the smooth gradient of the potentiometric surface in the area of the village of Agua Fria (figs. 5 and 6). Its presence is reflected by a zone of small permeability, as indicated by the close spacing of the potentiometric-surface contours in figure 6. Movement of the fault may have smeared clays and silts of the Tesuque Formation in that area into gouge, less permeable than the surrounding formation, which partially blocks water movement. Although faults are numerous throughout the basin, most faults seem to have little effect on the regional hydraulic gradient.

The series of roughly north-south-trending faults east of La Bajada fault in the southwest part of the study area (fig. 5) have uplifted the Tertiary rocks underlying the Santa Fe Group. Although some ground water is diverted around this area (fig. 6), some moves though the Tertiary rocks. Therefore, the uplifted Tertiary rocks were included as an active part of the model in this area. The uplifted older Tertiary rocks, which are less permeable than the Santa Fe sediments, and the intrusives, which produced the many volcanic cones (fig. 5), result in a smaller hydraulic conductivity in that area. This area of small hydraulic conductivity is shown in figure 10 as a north-south-trending band near the lower Santa Fe River, west of La Cienega, extending north about 11 miles.

The information on hydraulic conductivity described previously was obtained from wells 2,000 feet deep or less. Over most of the model area, hydraulic conductivity was assumed to decrease with depth in the Tesuque aquifer system. This assumption is based on the characteristics of the three members of the Tesuque Formation. The permeable Nambe Member probably is present only within a few miles of the Sangre de Cristo Mountains. The Skull Ridge Member, which contains a larger percentage of fine-grained material than the Nambe Member, is present at depth throughout most of the basin (Galusha and Blick, 1971). The moderately permeable Pojoaque Member comprises the uppermost part of the aquifer in the central part of the basin. The exception is in the area of Los Alamos Canyon, where hydraulic conductivity has been shown to increase with depth to approximately 1,800 feet (Purtymun, 1977, p. 20). The distribution of hydraulic conductivity assigned to layer 2 is shown in figure 11. The average hydraulic conductivity in this layer was 0.56 foot per day. Layers 3 and 4 were assigned uniform values of hydraulic conductivity on the basis of lithology. The hydraulic conductivity was 0.1 foot per day in layer 3 and 0.02 foot per day in layer 4.

Specific Yield

Few specific-yield data are available for the Tesuque aquifer system; however, values of specific yield for the types of materials composing the Tesuque Formation (sands, silts, and clays) generally average from 0.10 to 0.20, although values outside this range are common (Johnson, 1967, p. 1). The value of specific yield used over most of the model area was 0.15, which is consistent with the value used by Hearne (1980, p. 18) in his simulation of the Tesuque aquifer system in the Pojoaque River basin and with the laboratory analyses of samples from the Tesuque Pueblo Grant (Hearne, 1980, p. 17-18). Specific yield is applicable only to the unconfined part of the aquifer, which is represented by layer 1.

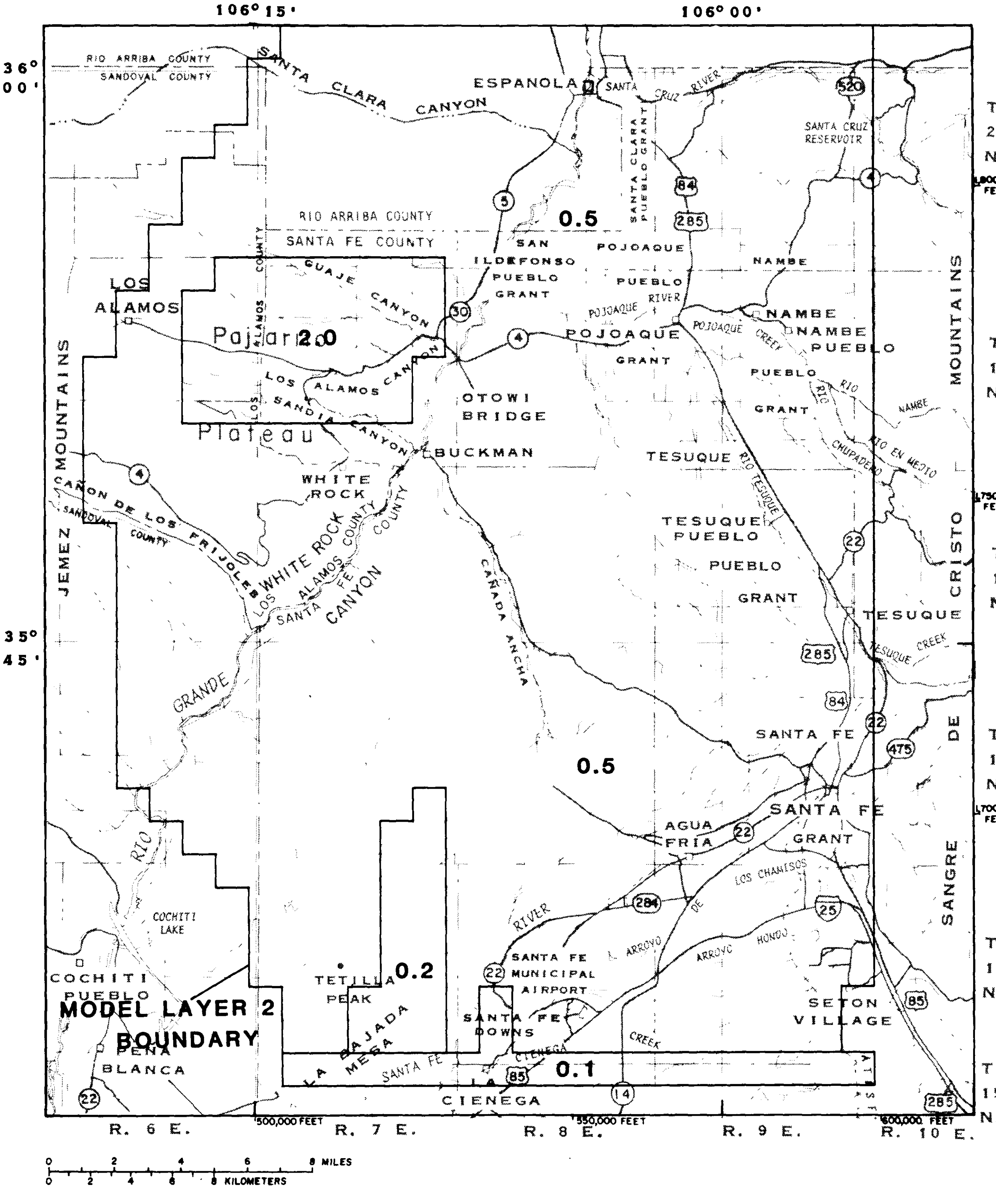


Figure 11.--Distribution of hydraulic conductivity in layer 2 of the model, in feet per day.

Measured water levels from the Guaje Canyon well field could not be simulated using specific-yield values within this range because declines in hydraulic head were greater than those simulated. This area is outside the area of interest, and redefinition of the model based on the limited information from this area was not practical. Therefore, the specific yield in the vicinity of this well field was reduced to 0.05 to more closely simulate the declines (fig. 12). A larger proportion of pumpage may be coming from confined storage in the aquifer than was simulated by equally proportioning the pumpage between layer 1 (unconfined layer) and layer 2 (confined layer). Part of the aquifer represented by layer 1 may be confined or a larger proportion of the pumpage may be coming from the part of the aquifer that is represented by layer 2. Therefore, the lower specific-yield value used for this area may represent a combination of specific yield and a confined storage coefficient. The sensitivity of the model to changes in specific yield is discussed in the section on model sensitivity. The average specific yield used in the model was 0.15.

Storage Coefficient

Little information on the storage coefficient is available for the confined model layers (layers 2 through 4). Storage coefficients for these layers were estimated by multiplying the assumed specific storage of 10^{-6} per foot (Lohman, 1972, p. 8) by the thickness of the layers. The lower layer thicknesses range from 1,200 to 1,800 feet, resulting in storage coefficients that range from 1×10^{-3} to 2×10^{-3}. The estimated plausible range of the storage coefficient is 1×10^{-4} to 5×10^{-3}. Because storage coefficients are not known with certainty, 1×10^{-3} was used for all lower layers in the model. The sensitivity of the model to changes in the storage coefficients is addressed in the section on model sensitivity.

Anisotropy

Vertical leakage between model layers was simulated as a function of the hydraulic heads in two contiguous layers and the vertical conductance between the layers. The vertical conductance is the vertical hydraulic conductivity divided by the distance between nodes (McDonald and Harbaugh, 1984, p. 138-147). The vertical hydraulic conductivities were calculated on the basis of the average horizontal hydraulic conductivity for each layer using the vertical to horizontal anisotropy ratio (ratio of vertical to horizontal hydraulic conductivity). The vertical conductances between layers were then calculated using equation 49 of McDonald and Harbaugh (1984, p. 142).

Koopman (1975, p. 11) estimated that the vertical to horizontal anisotropy ratio for the Tesuque Formation is 1:25 or 0.04. Hearne (1980, p. 15) concluded that 0.003 is a reasonable average anisotropy ratio for the aquifer and estimated the range to be 0.001 to 0.01. Based on these estimates, the anisotropy ratio may range from 0.001 to 0.04. Because little additional information on anisotropy is available, an anisotropy ratio of 0.01 was assumed for the model. The sensitivity of the model to changes in the anisotropy ratio is discussed in the section on model sensitivity. Because no data are available to estimate the horizontal anisotropy, no attempt was made to simulate horizontal anisotropy in the aquifer. Therefore, it was assumed to be 1.

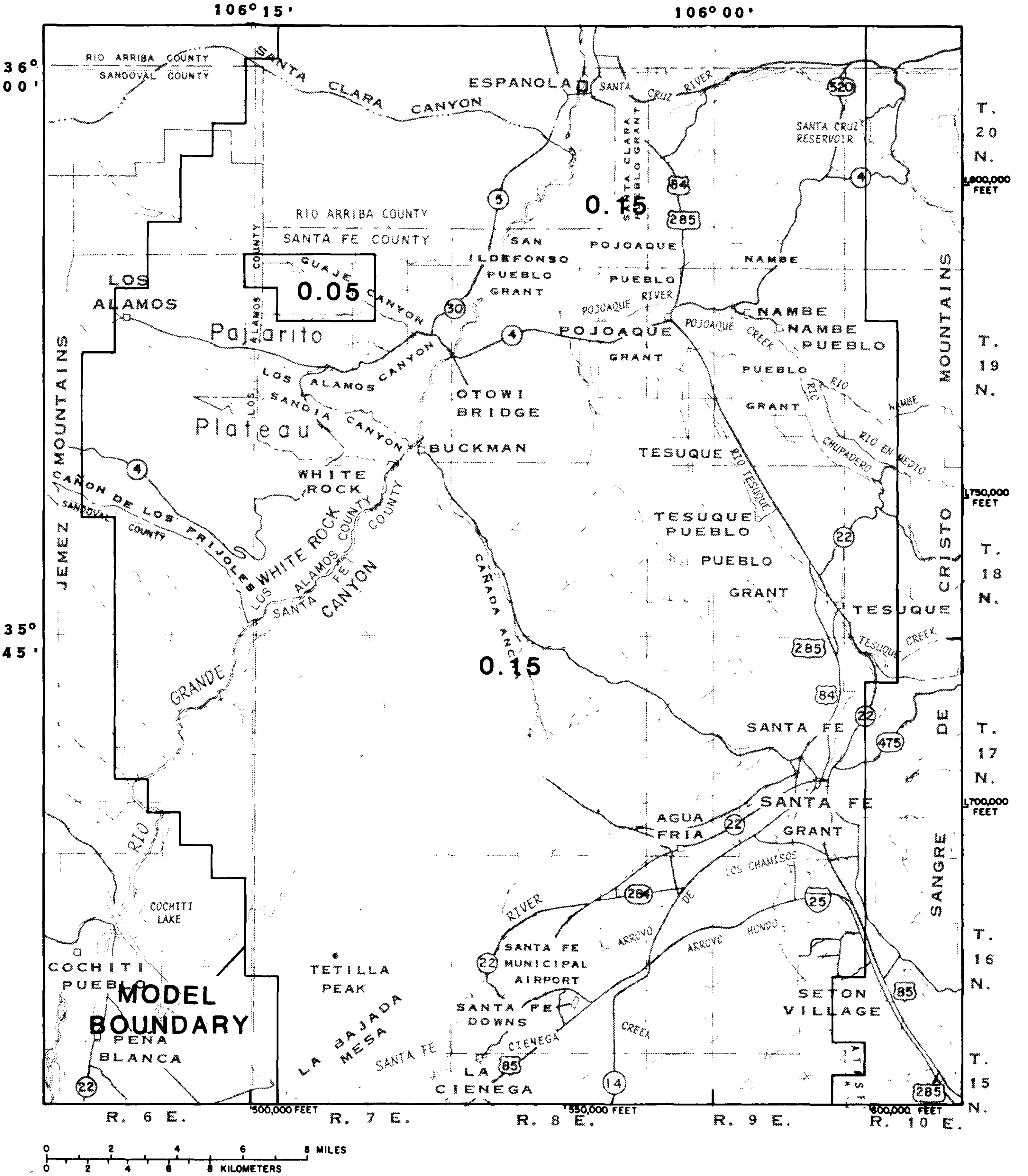


Figure 12.--Distribution of specific yield in layer 1 of the model.

Recharge

Mountain-Front and Stream-Channel Recharge

The Sangre de Cristo and Jemez Mountains provide a significant amount of recharge to the Tesuque aquifer system. This occurs because much of the area of both ranges is at altitudes that receive large amounts of precipitation, and much of this mountain precipitation falls in the winter as snow, when evapotranspiration is small. In addition, extensive deposits of permeable glacial material at high altitudes in the Sangre de Cristo range allow rapid infiltration and percolation of water into the underlying fractured rocks and alluvium of mountain-stream canyons.

The quantity of water entering the aquifer as subsurface flow from the mountain blocks cannot be directly measured. The quantity of this recharge can be estimated as follows:

ground-water recharge = precipitation - evapotranspiration - runoff

It was assumed that the ground-water recharge in the mountain drainages eventually becomes recharge to the Tesuque aquifer system. Because there are few precipitation gages with long-term records in the Sangre de Cristo Mountains, precipitation was estimated for various altitude ranges using the altitude-precipitation relation developed by Spiegel and Baldwin (1963, p. 149) and a relation derived by the U.S. Forest Service (Pete Stewart, written commun., 1984). The U.S. Forest Service relation was used to generate precipitation values for altitudes above 9,600 feet. Evapotranspiration for the mountain area was estimated by apportioning the area of the mountains into altitude ranges and using pan-evaporation data and a relation developed by the U.S. Forest Service between seasonal rainfall and evapotranspiration for those altitudes in the Rocky Mountains, as outlined by Troendle and Leaf (1980, p. 62-96). Yields of major surface-water basins draining the mountains have been previously calculated by Reiland (1975) and by Reiland and Koopman (1975, p. 9-27) from U.S. Geological Survey streamflow data. The mountain-front recharge was estimated to be in the range of 0.7 to 3 cubic feet per second per mile of mountain front. This recharge enters the upper part of the Tesuque aquifer system, which is represented by layer 1 in the model.

Initial steady-state model simulations used constant-head boundaries to represent subsurface flow at the mountain fronts. This allowed mountain-front recharge to change during initial model calibration. The previously estimated range of recharge was used to provide the limits in which mountain-front recharge was allowed to vary. When reasonable simulation results were obtained and recharge was within the estimated range, the fluxes across these boundaries were used as specified fluxes for subsequent simulations.

Runoff from the Sangre de Cristo Mountains recharges the Tesuque aquifer system by infiltration into the alluvium of stream channels and into the underlying Tesuque sediments as the streams flow from the mountain front. Spiegel and Baldwin (1963, p. 250) calculated the mean natural discharge of the Santa Fe River near the mountain front to be about 9.3 cubic feet per second and the median to be about 8.0 cubic feet per second. The loss rate of discharge from the river may be about 1 cubic foot per second per mile of stream (Spiegel and Baldwin, 1963, p. 173-175). Natural discharge of tributaries to the Pojoaque River near the mountain front has been reported by Reiland (1975) and by Reiland and Koopman (1975, p. 9-27).

Mountain-front and stream-channel recharge were input to the model as specified fluxes. The specified-flux rates for the steady-state model are shown in table 2. Except for four cells in layer 1 (14, 25; 20, 25; 24, 24; 25, 24), the specified fluxes for the cells adjacent to the model boundary (fig. 9) represent subsurface flow, and the others represent stream-channel recharge.

Areal Recharge

It is difficult to estimate rates of areal recharge in the Espanola Basin, but certainly they are much lower than in the mountain area. It is recognized that the distribution of areal recharge is influenced by topography, land disturbance, and other factors that are too numerous and whose interactions are too complex to account for, and that locally, recharge rates may vary from regional estimates. However, the amount and distribution of precipitation, permeability of the bedrock and soil cover, and evapotranspiration rate can be accounted for. Since little is known about the recharge rates, uniform values were assumed for areas of similar altitude and surface geology. Lee Wilson and Associates (1978, p. 1.62) estimated that 0.28 inch per year is a low estimate for recharge to the aquifer from the area covered by the Santa Fe Group. A range of recharge rates, using this estimate as a guide, was tried and adjusted during model calibration. The distribution of annual areal recharge used in the model is shown in figure 13.

The main area of the basin where the Tesuque Formation or soil derived from it is at land surface was assumed to allow precipitation to infiltrate at a rate of 0.2 inch per year. The recharge rate for the flood plains of the lower drainages, which presumably are covered with more permeable alluvial sediments, was estimated to be 0.4 inch per year. The recharge rate south of Santa Fe, where the permeable sediments of the Ancha Formation crop out, was assumed to be 0.5 inch per year. The areas of the Cerros del Rio and Tetilla Peak, which are covered with basalt flows, were assumed to permit only 0.05 inch of precipitation per year to infiltrate to the ground-water surface hundreds of feet below land surface. The Pajarito Plateau-Los Alamos region, where tuffs of late Tertiary and early Quaternary age and other volcanics crop out, was estimated to have a recharge rate of 0.15 inch per year. The area around La Cienega, where Tertiary rocks less permeable than the Tesuque Formation crop out, was assumed to have a recharge rate of 0.15 inch per year.

Table 2. Simulated steady-state flow rates at specified-flux boundaries

[Negative numbers represent discharge from the aquifer]

Layer	Row	Column	Flow to aquifer, in cubic feet per second	Layer	Row	Column	Flow to aquifer, in cubic feet per second
1	2	6	0.67	1	17	25	0.70
1	2	24	.60	1	18	2	.76
1	3	6	.88	1	18	23	1.00
1	3	24	.60	1	18	25	.50
1	4	5	1.34	1	19	2	.61
1	4	24	.60	1	19	24	1.20
1	5	4	.69	1	19	25	.40
1	5	24	.60	1	20	2	.18
1	6	4	1.05	1	20	25	[a]1.50
1	6	24	.60	1	20	25	.40
1	7	3	.91	1	21	24	.80
1	7	24	.60	1	22	24	.80
1	8	3	.69	1	23	22	.50
1	8	24	.60	1	23	23	.50
1	9	2	1.07	1	23	24	1.40
1	9	24	.60	1	24	21	1.00
1	10	2	1.38	1	24	22	.50
1	10	25	1.00	1	24	23	.50
1	11	1	1.24	1	24	24	[a]1.00
1	11	25	1.00	1	24	24	1.40
1	12	1	1.25	1	25	19	.70
1	12	25	.70	1	25	20	.70
1	13	1	1.36	1	25	24	[a]1.40
1	13	24	2.00	1	25	24	1.40
1	13	25	.70	1	26	17	.35
1	14	1	1.45	1	26	18	.70
1	14	24	.40	1	26	24	.50
1	14	25	[a]1.40	1	27	16	.70
1	14	25	.70	1	27	17	.35
1	15	1	1.32	1	27	24	.15
1	15	25	.70	1	28	22	.30
1	16	2	.76	1	28	23	.40
1	16	25	.70	1	28	24	.50
1	17	2	.94	1	29	24	.50
1	17	23	.50	1	30	13	-.90

Table 2. Simulated steady-state flow rates at specified-flux boundaries - Concluded

Layer	Row	Column	Flow to aquifer, in cubic feet per second	Layer	Row	Column	Flow to aquifer, in cubic feet per second
1	31	14	-1.40	1	33	21	-0.05
1	31	15	-1.40	1	33	22	-.07
1	31	23	1.10	1	33	23	-.09
1	32	12	-1.40	2	32	8	.06
1	32	13	-1.40	2	32	9	.01
1	33	8	.06	2	32	10	.09
1	33	9	.11	2	32	11	.04
1	33	10	.06	2	32	12	.31
1	33	11	.08	2	32	13	.06
1	33	12	.26	2	32	14	-.03
1	33	13	.17	2	32	15	.07
1	33	14	-.01	2	32	16	.05
1	33	15	.07	2	32	17	.04
1	33	16	.06	2	32	19	.07
1	33	17	.07	2	32	20	-.03
1	33	18	.07	2	32	22	-.06
1	33	19	.17	2	32	23	.15
1	33	20	.01	2	32	24	.09

[a]Two entries for these cells. The first entry represents flow from surface water to the aquifer, and the second entry represents subsurface flow at the mountain front.

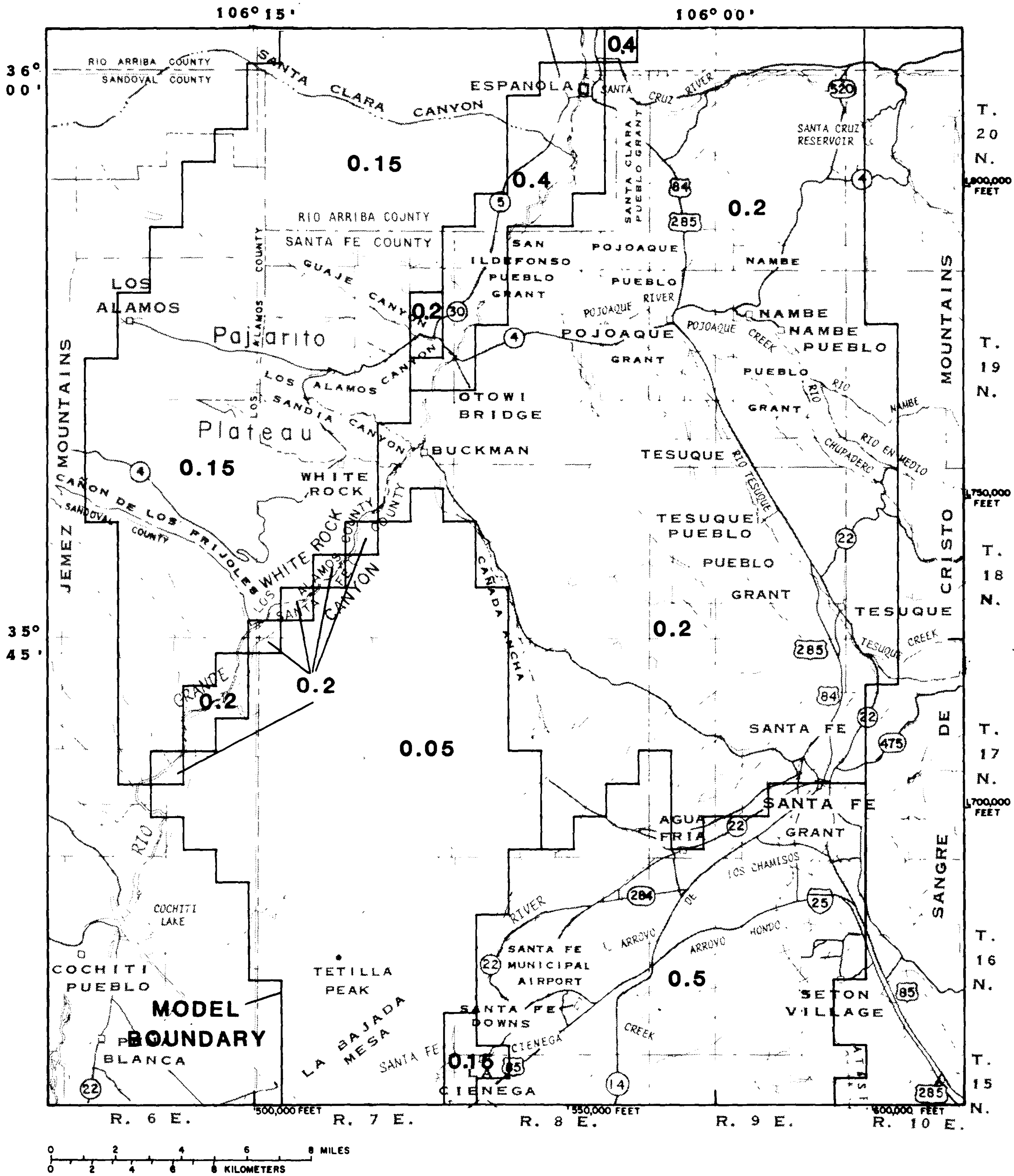


Figure 13.--Distribution of areal recharge in the model, in inches per year.

STEADY-STATE SIMULATION

The predevelopment condition of the aquifer was simulated by assuming a steady state between natural recharge to and discharge from the aquifer. Although ground- and surface-water resources had been developed in the Santa Fe area prior to 1947, large-scale development of ground water in the basin began about this time (Spiegel and Baldwin, 1963, p. 97-99). For this study, it was assumed that a steady-state condition existed prior to 1947.

Initial estimates of hydraulic head were taken from water-level measurements in wells. In areas where little development had occurred, water levels measured after 1947 were used if earlier data were unavailable. These initial estimates may differ somewhat from actual predevelopment water levels; however, considering the grid size, these differences probably are insignificant. In areas where actual water-level measurements were unavailable, water levels interpolated from the predevelopment potentiometric-surface contours shown in figure 6 were used. Because little control was available for hydraulic heads in the lower three layers of the model, hydraulic heads in those layers were determined by the model based on the recharges, discharges, and aquifer characteristics in the model.

Model Adjustments

Recharge and aquifer characteristics in the steady-state model were adjusted by a judgmental trial-and-error procedure. Adjustments were made to enable the model to duplicate the geohydrologic system as accurately as possible. This was accomplished by minimizing the difference in measured and simulated hydraulic heads and by matching simulated fluxes between the aquifer and rivers to established ranges. Aquifer characteristics were adjusted within their plausible ranges based on data from previous investigations. Because the steady-state solution to the ground-water flow equation is independent of the storage coefficient and specific yield, these values were not adjusted in the steady-state simulations.

The accepted model is as described in the previous sections. The representation of the physical geohydrologic system in the model is substantiated by available data. However, distributions of aquifer characteristics in the model do not constitute a unique solution. Sensitivity of the model to the uncertainty of these characteristics is addressed in the section on model sensitivity.

Simulation Results

Water Budget

The water budget for the predevelopment steady-state simulation is shown in table 3. The major source of water, 52 percent, is mountain-front and stream-channel recharge along the Sangre de Cristo Mountains on the east side of the basin. The major discharge, 53 percent, is along the Rio Grande. The southwest constant-head boundary, which represents underflow to the Santo Domingo Basin, discharged 17.4 cubic feet per second (12,600 acre-feet per year) from the model. A relatively small amount of water is recharged and discharged at the north constant-head boundary (table 3). This is illustrated in figure 6. The direction of flow generally is parallel to that boundary. Flow rates for the constant-head boundaries are listed in table 4, and those for the head-dependent flux boundaries are listed in table 5.

Hydraulic Head

The simulated hydraulic-head distribution in layer 1 of the steady-state model is shown in figure 14, and the distribution in layer 2 is shown in figure 15. Only layers 1 and 2 have measured hydraulic heads for comparison. The mean difference between measured and simulated hydraulic heads for a total of 176 wells was 17.2 feet, and the standard deviation was 57.5 feet. The frequency distribution of the differences between measured and simulated steady-state hydraulic heads is shown in figure 16. Some of the error shown in figure 16 may be attributed to the inability of the model to represent the detailed geology in the area and to heads being simulated at the center of each cell rather than at a particular well site. Some of the error shown in figure 16 may also be due to the measured heads representing a composite head from the entire screened interval of the well, which may not coincide with the center of the three-dimensional cell.

Table 3. **Water budget for the predevelopment steady-state simulation**

Description	Flow: Cubic feet per second	Flow: Acre-feet per year
Sources		
Areal recharge	10.6	7,700
East mountain-front and stream-channel recharge	38.5	27,900
West mountain-front recharge	18.6	13,500
Recharge from Rio Grande	1.9	1,400
Subsurface inflow at south specified-flux boundary	2.2	1,600
Subsurface inflow at north constant-head boundary	2.0	1,400
Total	73.8	53,500
Discharges		
Discharge to Pojoaque River and tributaries	7.3	5,300
Discharge to Rio Grande	39.3	28,500
Discharge to Santa Fe River	6.5	4,700
Subsurface outflow at south specified-flux boundary	.3	200
Subsurface outflow at north constant-head boundary	3.0	2,200
Subsurface outflow at southwest constant-head boundary	17.4	12,600
Total	73.8	53,500

Table 4. **Simulated steady-state flow rates at constant-head boundaries**

[Negative numbers represent discharge from the aquifer]

Layer	Row	Column	Flow to aquifer, in cubic feet per second	Layer	Row	Column	Flow to aquifer, in cubic feet per second
1	1	7	-0.03	2	1	11	0.10
1	1	8	-.02	2	1	12	.06
1	1	9	.06	2	1	13	.02
1	1	10	.06	2	1	14	-.13
1	1	11	.09	2	1	15	-.23
1	1	12	.06	2	1	16	-.30
1	1	13	.05	2	1	17	-.26
1	1	14	-.06	2	1	18	-.16
1	1	15	-.09	2	1	19	-.16
1	1	16	.05	2	1	20	-.13
1	1	17	-.13	2	1	21	-.09
1	1	18	-.12	2	1	22	-.02
1	1	19	-.15	2	1	23	.12
1	1	20	-.14	2	1	24	.46
1	1	21	-.11	2	21	2	-1.33
1	1	22	-.08	2	22	2	-1.01
1	1	23	-.01	2	23	2	-.90
1	1	24	.10	2	24	3	-.94
1	21	2	-1.40	2	25	4	-.51
1	22	2	-1.05	2	26	5	-.38
1	23	2	-1.17	2	27	6	-.43
1	24	3	-1.02	2	28	6	-.50
1	25	4	-.39	2	29	6	-.43
1	26	5	-.39	2	30	7	-.42
1	27	6	-.39	2	31	7	-.34
1	28	6	-.46	2	32	7	-.09
1	29	6	-.39	3	1	7	.10
1	30	7	-.35	3	1	8	.04
1	31	7	-.30	3	1	9	.04
1	32	7	-.12	3	1	10	.03
1	33	7	-.17	3	1	11	.03
2	1	7	.17	3	1	12	.004
2	1	8	.05	3	1	13	-.02
2	1	9	.09	3	1	14	-.07
2	1	10	.08	3	1	15	-.12

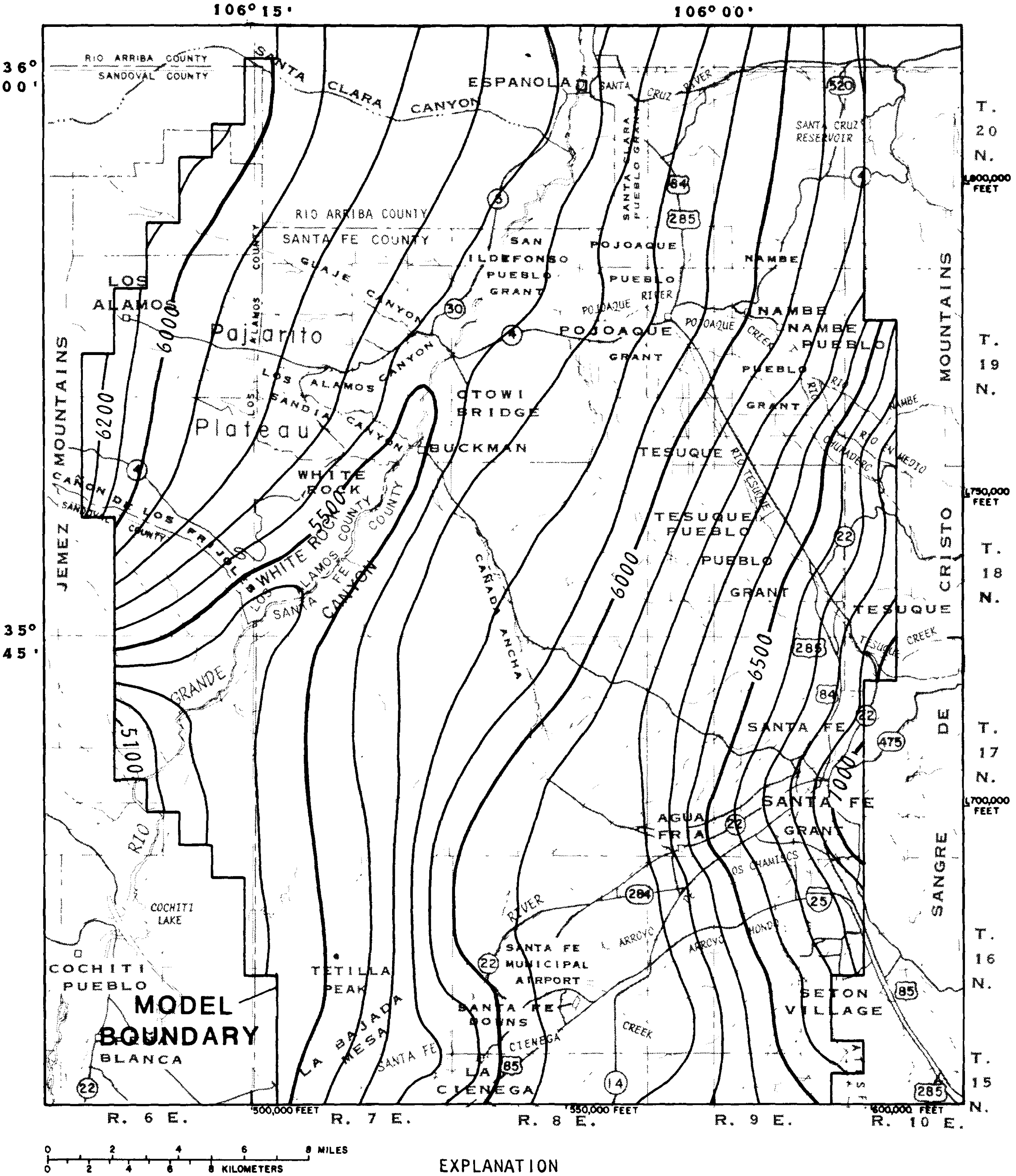
Table 4. **Simulated steady-state flow rates at constant-head boundaries** - Concluded

Layer	Row	Column	Flow to aquifer, in cubic feet per second	Layer	Row	Column	Flow to aquifer, in cubic feet per second
3	1	16	-0.14	3	23	2	-0.28
3	1	17	-.11	3	24	3	-.30
3	1	18	-.06	3	25	4	-.18
3	1	19	-.05	3	26	5	-.15
3	1	20	-.02	3	27	6	-.18
3	1	21	.01	3	28	6	-.19
3	1	22	.05	3	29	6	-.16
3	1	23	.11	3	30	7	-.22
3	21	2	-.39	3	31	7	-.16
3	22	2	-.31				

Table 5. **Simulated steady-state flow rates at head-dependent flux boundaries**

[Negative numbers represent discharge from the aquifer]

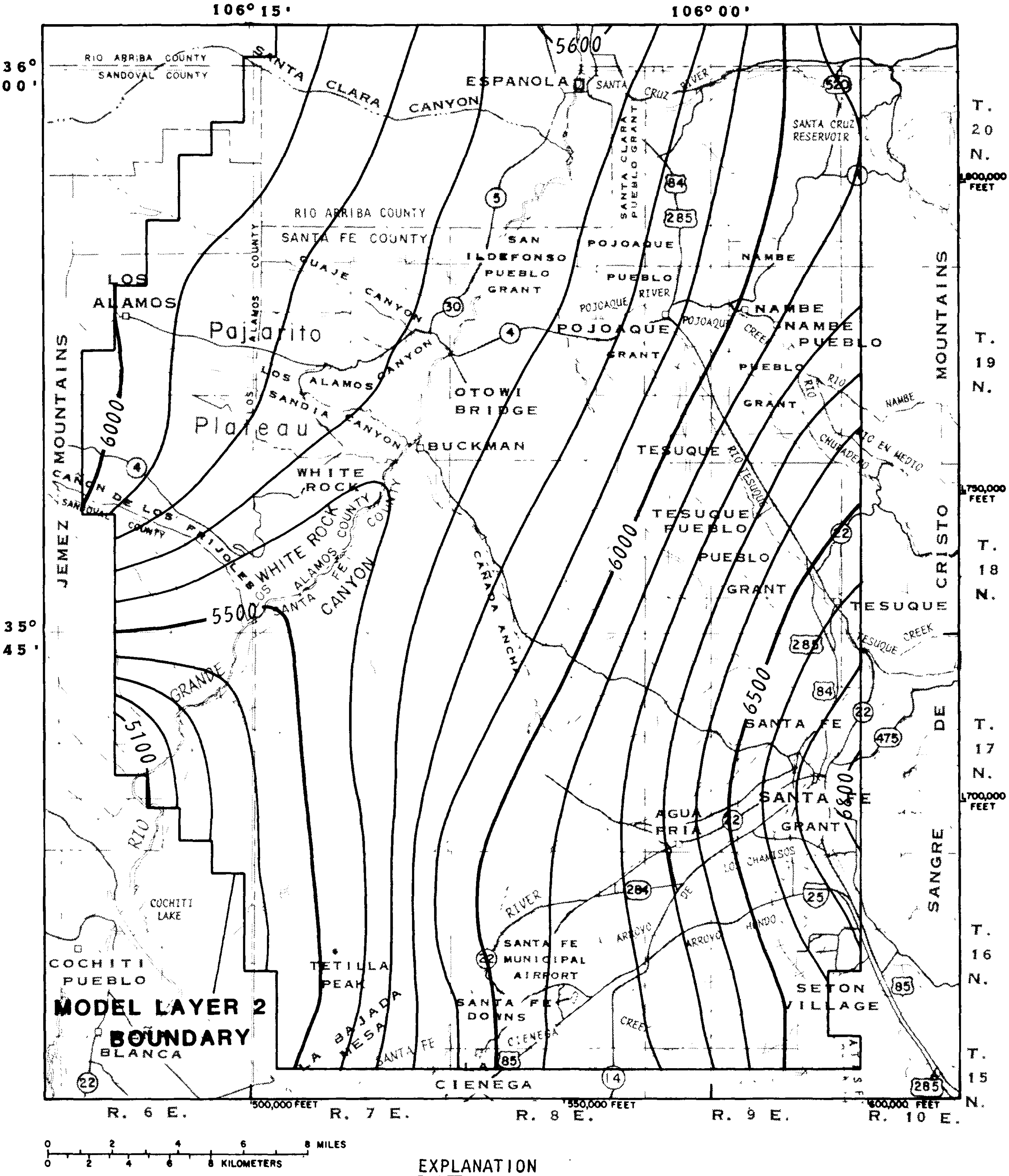
Layer	Row	Col-umn	Flow to aquifer, in cubic feet per second	Layer	Row	Col-umn	Flow to aquifer, in cubic feet per second
1	2	16	-0.79	1	12	11	-2.51
1	3	16	-1.05	1	12	20	-.14
1	4	16	-1.67	1	12	23	-.71
1	5	15	-1.66	1	13	11	-2.99
1	6	14	-1.38	1	13	20	.10
1	7	14	-1.55	1	14	10	-1.90
1	8	13	-1.63	1	14	21	-.27
1	9	13	-2.12	1	15	9	-1.18
1	9	14	-.45	1	15	10	-2.05
1	9	15	-.98	1	15	21	-.03
1	9	16	-.48	1	16	9	-2.00
1	9	17	-.40	1	16	22	-.18
1	9	18	-.51	1	17	8	-2.05
1	9	19	-.33	1	18	6	-1.15
1	9	20	-.30	1	18	7	-1.52
1	9	21	-.59	1	19	6	-1.40
1	10	12	-3.16	1	20	5	-1.09
1	10	19	-.31	1	21	4	-.43
1	10	22	-.37	1	21	5	-.88
1	11	11	-3.14	1	22	4	.26
1	11	19	.39	1	23	3	1.65
1	11	23	-.84				



EXPLANATION

—5500— SIMULATED WATER-LEVEL CONTOUR--Shows altitude of simulated steady-state water level in layer 1 of the model. Interval 100 feet. Datum is sea level

Figure 14.--Steady-state hydraulic heads simulated by the model in layer 1.



EXPLANATION

—5500— SIMULATED WATER-LEVEL CONTOUR--Shows altitude of simulated steady-state water level in layer 2 of the model. Interval 100 feet. Datum is sea level

Figure 15.--Steady-state hydraulic heads simulated by the model in layer 2.

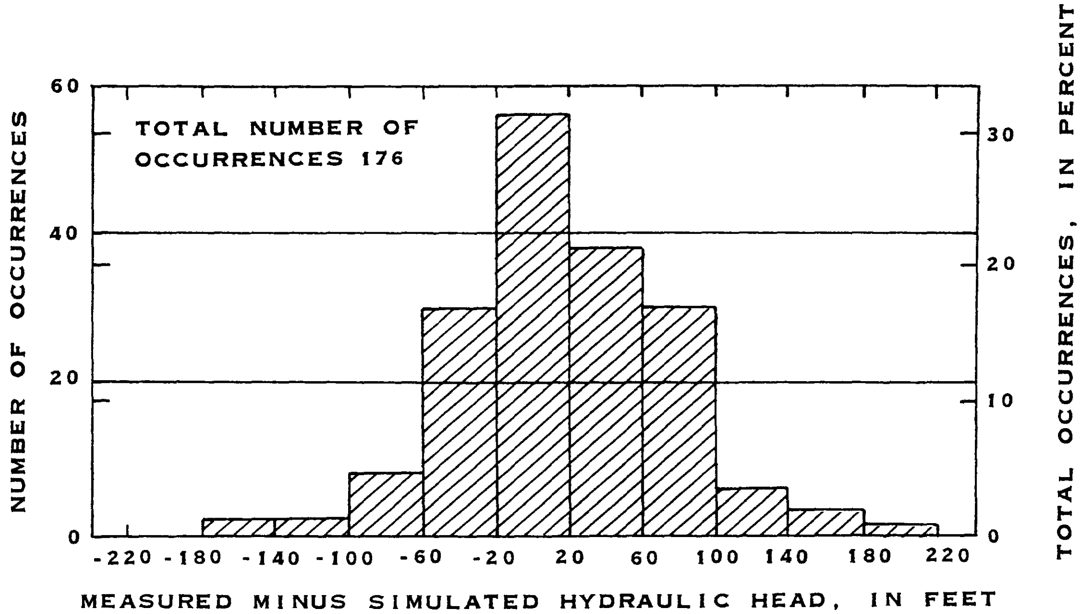


Figure 16.--Histogram of hydraulic-head differences during the steady-state simulation for model cells in which measured heads were available.

Pojoaque River and Tributaries

The water budget for the Pojoaque River and its tributaries is shown in table 6. Surface-water inflow to tributaries of the Pojoaque River from outside the modeled area was estimated to be 17.7 cubic feet per second by summing the discharges calculated by Reiland (1975, discharges of sites 1, 3, 4, and gaging stations 8-3025 and 8-3050). Reiland (1975, p. 19) estimated runoff from a 33-square-mile area in the lower part of the Pojoaque River basin to be 700 acre-feet per year (0.97 cubic foot per second). The same proportionate runoff over the 100-square-mile area of the Pojoaque River basin within the modeled area resulted in an estimated 2.9 cubic feet per second of surface runoff to the river. Hearne (1980, p. 24) estimated consumption by native vegetation in the Pojoaque River and its tributaries to be about 1.1 cubic feet per second and evaporation from the river and exposed channel beds to be about 3.3 cubic feet per second. Simulated inflow to the Pojoaque River and its tributaries from ground water was 7.3 cubic feet per second in the upper reaches, and simulated outflow to ground water was 8.1 cubic feet per second along the lower reaches. Based on these discharges, the calculated predevelopment discharge at the mouth of the Pojoaque River was 15.4 cubic feet per second (table 6). This is comparable to the 10,700 acre-feet per year (14.8 cubic feet per second) calculated by Reiland (1975, p. 19).

Table 6. Water budget for the Pojoaque River and tributaries using simulated steady-state flows

Description	Flow: Cubic feet per second	Flow: Acre-feet per year
Surface-water inflow from upstream of modeled area	17.7	12,800
Inflow from surface runoff in modeled area	2.9	2,100
Simulated inflow from ground water to Pojoaque River and tributaries	7.3	5,300
Simulated outflow to ground water from Pojoaque River and tributaries	-8.1	-5,900
Consumption of surface water by native vegetation	-1.1	-800
Evaporation from stream channels	-3.3	-2,400
Calculated streamflow at mouth of Pojoaque River	15.4	11,100

Rio Grande

As simulated by the model, the net loss of water from the aquifer to the Rio Grande was 37.4 (39.3 - 1.9, table 3) cubic feet per second for steady-state conditions. However, this number does not represent the net increase in discharge of the Rio Grande through the modeled area because evaporation from the river channel and transpiration by native vegetation were not simulated by the model. Blaney and others (1938, p. 416-417) reported 772 acres of water and riverbed surfaces in the 22-mile reach of the Rio Grande through what was Santa Fe County prior to the creation of Los Alamos County in 1949. Approximately 28 miles of the Rio Grande is in the modeled area. By assuming the same proportion of water and riverbed surfaces per mile of the Rio Grande in the modeled area as in pre-1949 Santa Fe County, there is an estimated 980 acres of water and riverbed surfaces in the modeled area. By assuming an evaporation rate of 2.5 feet per year from this area (Blaney and others, 1938, p. 423), the estimated evaporation from the Rio Grande water and riverbed surfaces was 3.4 cubic feet per second. Blaney and others (1938, p. 416-417) reported 1,058 acres of trees along the Rio Grande in pre-1949 Santa Fe County. Only a small amount of water is consumed by native vegetation along the Rio Grande in White Rock Canyon (fig. 5) compared to reaches upstream and downstream from the canyon (Spiegel and Baldwin, 1963, p. 200). Therefore, it was assumed that natural vegetation in White Rock Canyon does not significantly increase consumption of water along the Rio Grande. By assuming that trees consume 2.5 feet of water per year (Blaney and others, 1938, p. 423), the estimated consumption was 3.7 cubic feet per second. Based on the above estimates of loss of water from the river by evaporation and transpiration and the simulated net loss of water from the aquifer to the river, the net increase in discharge of the Rio Grande through the modeled area was estimated to be 30.3 (37.4 - 3.4 - 3.7) cubic feet per second.

The average gain in discharge of 1.1 cubic feet per second per river mile is consistent with estimates by Spiegel and Baldwin (1963, p. 200-201) of 25 cubic feet per second over a 26-mile reach (0.96 cubic foot per second per mile) between the streamflow gages at Otowi Bridge (station number 08313000) and near Cochiti Pueblo (station number 08314500) (fig. 2) and with estimates by Griggs (1964, p. 95) of 500 to 600 gallons per minute per mile (1.1 to 1.3 cubic feet per second per mile) in a 21-mile reach downstream from Otowi Bridge. French (1913, p. 83) reported a gain of 47.7 cubic feet per second in a 26.5-mile reach (1.8 cubic feet per second per mile) downstream from Buckman. Gordon (1982, p. 73) calculated a gain of 15 cubic feet per second over the 26-mile reach between the Otowi and Cochiti Pueblo streamflow gages (0.58 cubic foot per second per mile) for 1955 to 1973.

Gains in discharge between the Otowi streamflow gage and Canon de los Frijoles were reported to range from 6 to 29 cubic feet per second and to average 15 cubic feet per second (W.D. Purtymun, U.S. Geological Survey, written commun., 1966). The simulated ground-water discharge to the Rio Grande in that reach is consistent with those reported. The simulated discharge of 20.5 cubic feet per second includes nodes in layer 1 between and including 11, 11 and 18, 6 (fig. 9 and table 5). By comparison to stream-channel evaporation and consumption of water by native vegetation over the entire modeled reach of the Rio Grande, the loss over this reach probably is not more than about 3 cubic feet per second. Therefore, the increase in streamflow in that reach based on the simulation is about 18 cubic feet per second.

HISTORICAL TRANSIENT SIMULATION

Changes in the predevelopment condition of the Tesuque aquifer system have occurred because of ground water being withdrawn from storage within the aquifer and changes in the amount and location of recharge from surface water. Reported ground-water withdrawals from 1947 through 1982 and calculated changes in recharge were used to simulate changes in hydraulic head and in flow between ground water and surface water in the Rio Grande and Pojoaque River basin. The simulated predevelopment condition was assumed to exist prior to 1947.

Ground-Water Withdrawals

The major ground-water withdrawals have occurred in the well fields that supply water to Los Alamos and Santa Fe (fig. 2). Ground-water withdrawals used in the model for the Los Alamos, Guaje, and Pajarito well fields were reported by Purtymun, Becker, and Maes (1985, p. 14-31). Ground-water withdrawals from the Buckman and Santa Fe well fields were reported by the Sangre de Cristo Water Company and the New Mexico State Engineer Office.

Pumping records for individual wells in the Buckman well field were not available for all years in the simulation. For years when only total withdrawal from the well field was available, it was assumed that the withdrawal was distributed equally among the pumping wells.

Several production wells produce water from parts of the aquifer that are represented by layer 1 and layer 2 in the model. If a well was determined to be open to the aquifer at depths represented by both layers, it was assumed that the well produces equal amounts of water from each layer.

Each domestic well in the Santa Fe area identified from files of the New Mexico State Engineer Office was assumed to have a net withdrawal of 0.2 acre-foot per year, based on a rural usage of 60 gallons per day per person (Lee Wilson and Associates, 1978, p. 2.4) and 3.4 persons per household. Ground-water withdrawals for commercial uses and community water systems in the Santa Fe area were determined from records of the Santa Fe River Hydrographic Survey (New Mexico State Engineer Office, 1976 and 1978).

It was estimated that in 1978, only 236 acres of cropland were irrigated with ground water in the modeled area in Santa Fe County (New Mexico State Engineer Office, written commun., 1979). Ground-water withdrawals for irrigation were considered to be insignificant in the model simulations because of the scattered nature and small amount of area irrigated.

Ground-water withdrawals in the model represent the average annual amounts. No effort was made to simulate seasonal variations.

Changes in Recharge

The amount and location of recharge of surface water to the Tesuque aquifer system in the Santa Fe area have changed from predevelopment conditions. Diversion of surface water in the Santa Fe River for municipal supply, return of sewage effluent to the Santa Fe River, and use of sewage effluent for irrigation were incorporated into the transient simulations.

Predevelopment recharge from the Santa Fe River near the mountain front was reduced for the transient simulations by the average amount of surface water that was diverted for municipal use over each 5-year period of the simulation. The amount of these diversions was provided by the Sangre de Cristo Water Company. The amount of water from the Santa Fe River that was calculated to be available for recharge is given in table 7.

The history of use of sewage effluent for irrigation in the Santa Fe area was described by Scanlon and Associates (1984, p. 1-2, 4-7). It was estimated that in 1951 about 400 acres were irrigated by sewage effluent (Spiegel and Baldwin, 1963, p. 174-176). The areas irrigated are in the northeast corner of T. 16 N., R. 8 E. and the northwest corner of T. 16 N., R. 9 E. The 1977 Santa Fe River Hydrographic Survey (New Mexico State Engineer Office, 1978, p. xix) identified 139 acres irrigated by sewage effluent in approximately the same area. Because the area irrigated with effluent is not known for other years in the transient simulation, it was assumed that 400 acres were irrigated through 1967 and 139 acres were irrigated after 1967. The distribution of irrigated areas used in the model was given by Spiegel and Baldwin (1963, p. 174). It was estimated that 1.5 acre-feet of sewage effluent per acre is applied each year and that 0.5 to 0.75 acre-foot per acre per year recharges the aquifer.

Table 7. Recharge from the Santa Fe River represented in the model

Location			Flow, in cubic feet per second							
Layer	Row	Column	1947-52	53-57	58-62	63-67	68-72	73-77	78-82	Steady state
1	24	24	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	23	23	.50	.50	.50	.50	.50	.50	.50	.50
1	24	23	.50	.50	.50	.50	.50	.50	.50	.50
1	23	22	.50	.50	.20	-	.10	.30	.10	.50
1	24	22	.50	.50	.30	-	.20	.30	.10	.50
1	24	21	1.00	1.00	-	-	-	-	-	1.00
1	25	20	.50	.70	-	-	-	-	-	.70
1	25	19	-	.30	-	-	-	-	-	.70
1	26	18	-	-	-	-	-	-	-	.70
1	26	17	-	-	-	-	-	-	-	.35
1	27	17	-	-	-	-	-	-	-	.35
1	27	16	-	-	-	-	-	-	-	.70

The Siler Road sewage treatment plant (in sec. 33, T. 17 N., R. 9 E.) was in operation over the entire time of the historical transient simulation. Effluent from the plant was discharged through a pipeline to an unlined ditch in sec. 12, T. 16 N., R. 8 E. The effluent that was not used for irrigation was discharged to the Santa Fe River in sec. 1, T. 16 N., R. 8 E. The Airport Road treatment plant (in sec. 10, T. 16 N., R. 8 E.) was constructed in 1963, and both plants operated until 1984, when the Siler Road plant was closed. The Airport Road plant discharges effluent to the Santa Fe River near the plant.

The amount of sewage effluent discharged from the sewage treatment plants for all the years in the simulation is not known. Discharge from both plants was estimated to be 1,303, 1,318, 1,358, 1,490, and 1,526 million gallons per year 1980 through 1984 (B.R. Siler, City of Santa Fe, written commun., 1984). The amount of effluent discharged in previous years was estimated on the basis of census figures for Santa Fe and usage of 80 gallons per day per capita (Woodward-Clyde Consultants, 1980, p. 1.13). When both treatment plants were in operation, it was assumed that each plant discharged 50 percent of the effluent. For simulation purposes, the amount of effluent from each plant used for irrigation is based on information given by Scanlon and Associates (1984, p. 1-2, 4-7) and the City of Santa Fe (B.R. Siler, written commun., 1984).

Spiegel and Baldwin (1963, p. 176) estimated that about 30 to 50 percent of Santa Fe's sewage effluent recharges the aquifer through irrigation during the growing season and that almost 100 percent recharges the ground water by infiltration in the Santa Fe River downstream from Agua Fria in the winter. On the basis of these estimates, probably about 80 percent of the sewage effluent recharges the aquifer over a year. Spiegel and Baldwin (1963, p. 176) reported that at maximum flow, sewage effluent discharged into the Santa Fe River infiltrates within 1½ miles of the discharge point. The distribution of recharge in the model from sewage effluent is given in table 8.

Table 8. Distribution of recharge from sewage effluent represented in the model

Location			Flow, in cubic feet per second						
Layer	Row	Column	1947-52	53-57	58-62	63-67	68-72	73-77	78-82
1	27	18	1.00	1.00	1.10	0.60	0.60	0.90	1.10
1	27	17	1.00	1.20	1.30	.90	1.20	1.20	1.30
1	26	17	.70	.80	.80	.40	.40	.40	.40
1	26	19	.14	.14	.14	.14	.01	.01	.01
1	26	18	.04	.04	.04	.04	.03	.03	.03
1	27	15	-	-	-	.20	.30	.30	.30
1	28	14	-	-	-	.70	.80	.80	.80
1	28	13	-	-	-	.70	.80	.80	.80

Model Adjustments

All aquifer characteristics except specific yield and storage were adjusted in the steady-state simulations. Only specific yield was adjusted in the historical transient simulations. Little information on the storage coefficients are available for the lower layers of the model but were estimated by multiplying the assumed specific storage of 10^{-6} per foot (Lohman, 1972, p. 8) by the thickness of each layer. Storage coefficients were not adjusted during the historical transient simulations.

Specific yield in layer 1 was adjusted, within the plausible ranges previously discussed, by a judgmental trial-and-error procedure to minimize the difference between measured and simulated hydraulic heads and to match simulated fluxes between the aquifer and the rivers to established ranges. However, the aquifer characteristics used in the model do not constitute a unique solution. Sensitivity of the model to the uncertainty of these characteristics is addressed in the section on model sensitivity.

Simulation Results

Water Budget

When withdrawal of water by wells is superimposed on a steady-state condition, the withdrawals need to be balanced by a decrease in natural discharge, an increase in recharge, a decrease in the amount of water stored within the aquifer, or a combination of these, so that total discharge equals total recharge plus change in storage. A detailed discussion of this was given by Theis (1940) and Bredehoeft, Papadopulos, and Cooper (1982).

The water budget at the end of the historical transient simulation is shown in table 9. The total discharge (including pumping) from the aquifer increased from 73.8 cubic feet per second in the simulated predevelopment condition (table 3) to 83.5 cubic feet per second at the end of the transient simulation, whereas recharge decreased from 73.8 to 73.3 cubic feet per second. The amount of discharge that is greater than recharge comes from storage. In this simulation, the 12.0 cubic feet per second of pumpage plus the 0.5-cubic-foot-per-second decrease in recharge from predevelopment was balanced by a 2.3-cubic-foot-per-second decrease in natural discharge and a 10.1-cubic-foot-per-second decrease in storage (tables 3 and 9). The imbalance between the total sources and total discharges is a result of round-off errors during the model simulation. Because the 0.1-percent difference is small, the effect on the simulation results is insignificant.

A simulation excluding withdrawals from the wells in the Buckman, Los Alamos, Guaje, and Pajarito well fields showed only a 0.2-cubic-foot-per-second reduction in natural discharge from predevelopment conditions. In this simulation, the 4.1 cubic feet per second of pumpage plus the 0.6-cubic-foot-per-second decrease in recharge was balanced by a 0.2-cubic-foot-per-second decrease in natural discharge and a 4.6-cubic-foot-per-second decrease in storage. This indicates that the 2.3-cubic-foot-per-second reduction of natural discharge in the historical transient simulation primarily results from wells near the Rio Grande intercepting some water that would otherwise discharge to the river and that water withdrawal in the immediate area of Santa Fe nearly all comes from storage.

Table 9. Water budget at the end of the historical transient simulation

Description	Flow: Cubic feet per second	Flow: Acre-feet per year
Sources		
Storage	10.1	7,300
Areal recharge	10.6	7,700
East mountain-front and stream-channel recharge	33.2	24,000
West mountain-front recharge	18.6	13,500
Recharge from Rio Grande	1.9	1,400
Subsurface inflow at south specified-flux boundary	2.2	1,600
Subsurface inflow at north constant-head boundary	2.1	1,500
Recharge from sewage effluent	4.7	3,400
Total	83.4	60,400
Discharges		
Pumpage	12.0	8,700
Discharge to Pojoaque River and tributaries	7.1	5,100
Discharge to Rio Grande	37.2	26,900
Discharge to Santa Fe River	6.5	4,700
Subsurface outflow at south specified-flux boundary	.3	200
Subsurface outflow at north constant-head boundary	3.0	2,200
Subsurface outflow at southwest constant-head boundary	17.4	12,600
Total	83.5	60,400

Flow rates at the constant-head boundaries in the historical transient simulation were virtually unchanged from the steady-state rates (tables 3 and 9). Flow rates at the end of the historical transient simulation for the head-dependent flux boundaries representing the Rio Grande and Pojoaque River are listed in table 10.

Table 10. Simulated flow rates at head-dependent flux boundaries at the end of the historical transient simulation

[Negative numbers represent discharge from the aquifer]

Layer	Row	Column	Flow to aquifer, in cubic feet per second	Layer	Row	Column	Flow to aquifer, in cubic feet per second
1	2	16	-0.79	1	12	11	-2.34
1	3	16	-1.04	1	12	20	-.13
1	4	16	-1.66	1	12	23	-.70
1	5	15	-1.64	1	13	11	-2.61
1	6	14	-1.36	1	13	20	.10
1	7	14	-1.52	1	14	10	-1.57
1	8	13	-1.56	1	14	21	-.27
1	9	13	-2.03	1	15	9	-1.13
1	9	14	-.42	1	15	10	-1.94
1	9	15	-.96	1	15	21	-.02
1	9	16	-.46	1	16	9	-1.96
1	9	17	-.39	1	16	22	-.17
1	9	18	-.50	1	17	8	-2.02
1	9	19	-.32	1	18	6	-1.14
1	9	20	-.29	1	18	7	-1.51
1	9	21	-.58	1	19	6	-1.40
1	10	12	-2.85	1	20	5	-1.09
1	10	19	-.30	1	21	4	-.43
1	10	22	-.37	1	21	5	-.88
1	11	11	-2.71	1	22	4	.26
1	11	19	-.38	1	23	3	1.65
1	11	23	-.83				

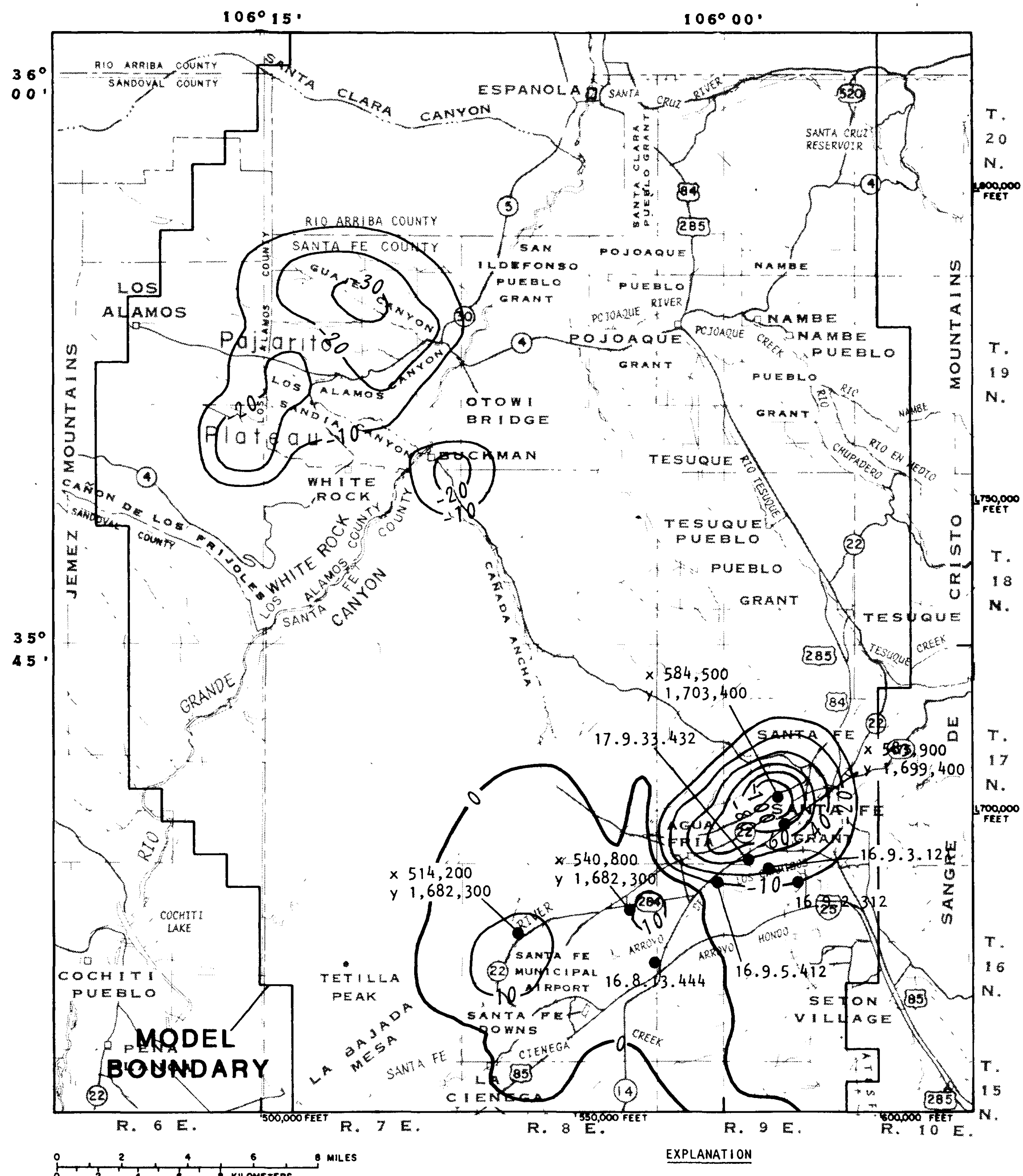
Hydraulic Head

The simulated change in hydraulic head from 1947 to 1982 for layer 1 is shown in figure 17 and for layer 2 in figure 18. The major drawdown is concentrated in the areas of the well fields that supply water to Santa Fe and Los Alamos. An increase in hydraulic head occurred in the area where sewage effluent is used for irrigation and where the effluent is discharged to the Santa Fe River.

The frequency distribution of the differences between measured and simulated 1982 hydraulic heads at 109 wells is shown in figure 19. Some of the error shown in figure 19 may be attributed to the inability of the model to represent the detailed geology in the area and to heads being simulated at the center of each cell rather than at well sites. Some of the error may also be due to the measured heads representing a composite head from the entire screened interval of the well, which may not coincide with the center of the three-dimensional cell. The mean difference between measured and simulated hydraulic heads was 16.1 feet and the standard deviation was 82.4 feet. The head differences in the range of 200 feet (fig. 19) occur near the Sangre de Cristo Mountain front, where heads change rapidly with the distance from the mountain front. All of these measured heads are from wells in the eastern edge of the model cells, where the measured heads are expected to be higher than simulated heads.

Hydrographs showing comparison between measured and simulated hydraulic-head changes for 10 wells in the Santa Fe area are shown in figure 20. The measured change in hydraulic head is shown as the change from the earliest measured head in the well. A negative change indicates a decline in hydraulic head. Considering that the simulated hydraulic heads represent an average condition in each cell, the simulated hydrographs are considered to represent the trend of water-level change in the area represented by the cell. Drawdown measured in production wells, such as shown in figure 20F, may be more than would be representative of the aquifer due to the hydraulic head in the well not being fully recovered from previous pumping.

The measured decline in hydraulic head in well 18.7.1.224 (Buckman well number 7) is substantially greater than that simulated (fig. 20A). Some of the difference in the two hydrographs may be due to production wells 18.7.1.212 and 18.7.1.233 (Buckman wells number 3 and 4, fig. 2) being closer to well 18.7.1.224 than can be simulated by the model. These production wells are in an adjacent cell to well 18.7.1.224. Because the model assumes that the wells are at the center of the cell, the model simulates wells 18.7.1.212 and 18.7.1.233 as being about twice as far from well 18.7.1.224 as they actually are.

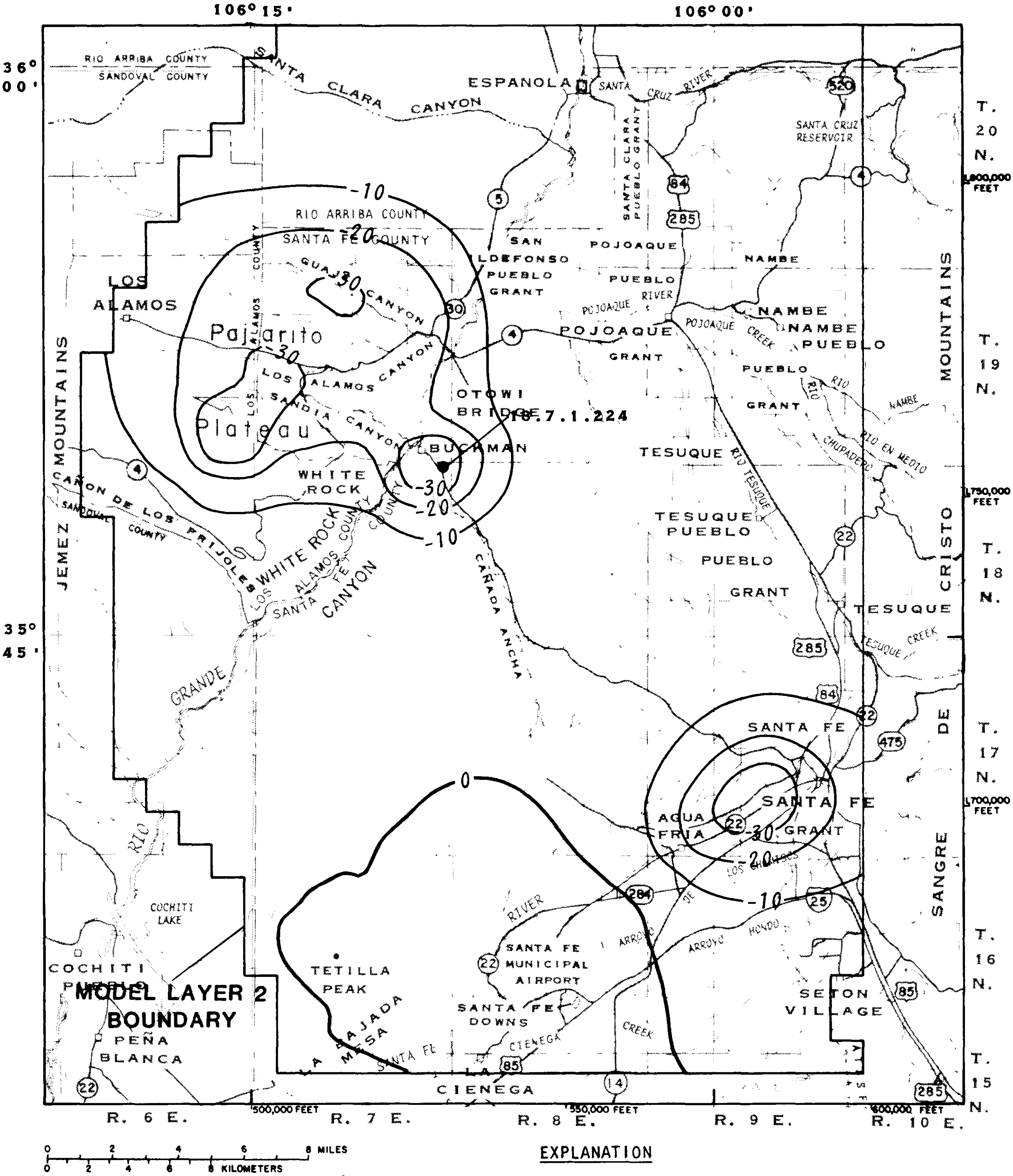


EXPLANATION

—10— LINE OF EQUAL SIMULATED CHANGE IN HYDRAULIC HEAD--Intervals 10 and 20 feet. Negative numbers indicate decline

16.8.13.444 ● LOCATION AND NUMBER OF WELL WITH HYDROGRAPH--Hydrographs shown in figure 20

Figure 17.--Simulated change in hydraulic head in layer 1 for the historical transient simulation, 1947-82.



EXPLANATION

—-10— LINE OF EQUAL SIMULATED CHANGE IN HYDRAULIC HEAD--Interval 10 feet. Negative numbers indicate decline

● 18.7.1.224 LOCATION AND NUMBER OF WELL WITH HYDROGRAPH--Hydrographs shown in figure 20

Figure 18.--Simulated change in hydraulic head in layer 2 for the historical transient simulation, 1947-82.

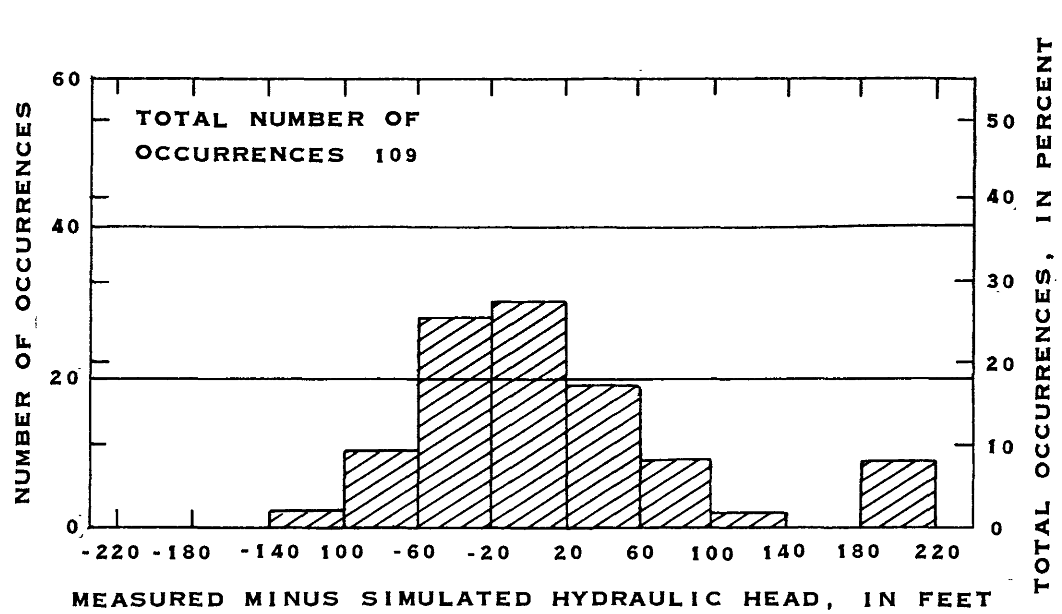


Figure 19.--Histogram of hydraulic-head differences at the end of the historical transient simulation for model cells in which measured heads were available.

Pojoaque River and Tributaries

Simulated outflow from the Pojoaque River and its tributaries to ground water, 8.1 cubic feet per second, remained the same in the transient simulation as in steady state (table 6). Simulated ground-water inflow to the Pojoaque River and its tributaries decreased from 7.3 cubic feet per second in the steady-state simulation (table 6) to 7.1 cubic feet per second at the end of the historical transient simulation. In addition to the 12.5-cubic-foot-per-second loss of flow in the Pojoaque River shown in table 6, an estimated 7.7 cubic feet per second of water is consumed by irrigation (Hearne, 1980, p. 22). Simulation of return flow from irrigation and diversion of water from the river for irrigation in the Pojoaque River basin was not attempted. The flow in the Pojoaque River during the period of the historical transient simulation was sufficient to maintain the hydraulic head in the aquifer at or near the riverbed elevation (Hearne, 1980, p. 22). Therefore, the diversions and return flow were assumed to have an insignificant effect on the regional ground-water flow system.

Rio Grande

The recharge from the Rio Grande at the end of the transient simulation remained the same as in the steady-state simulation, 1.9 cubic feet per second. The discharge to the Rio Grande decreased from 39.3 cubic feet per second in the steady-state simulation to 37.2 cubic feet per second at the end of the historical transient simulation (tables 3 and 9). The reduction in discharge to the Rio Grande primarily is the result of pumpage from the Buckman well field.

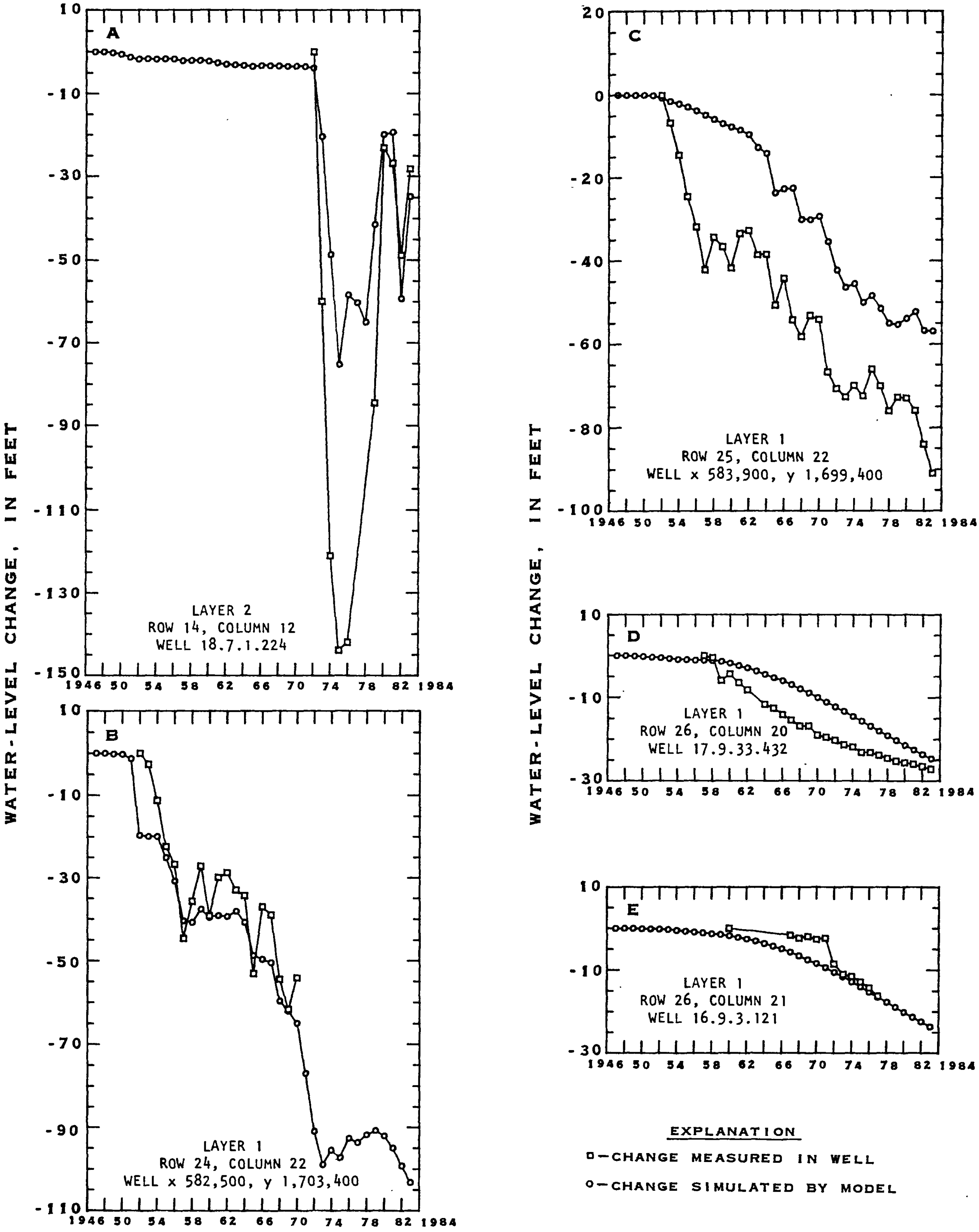


Figure 20.--Comparison between water-level changes measured in selected wells and simulated in corresponding model cells, 1947-82.

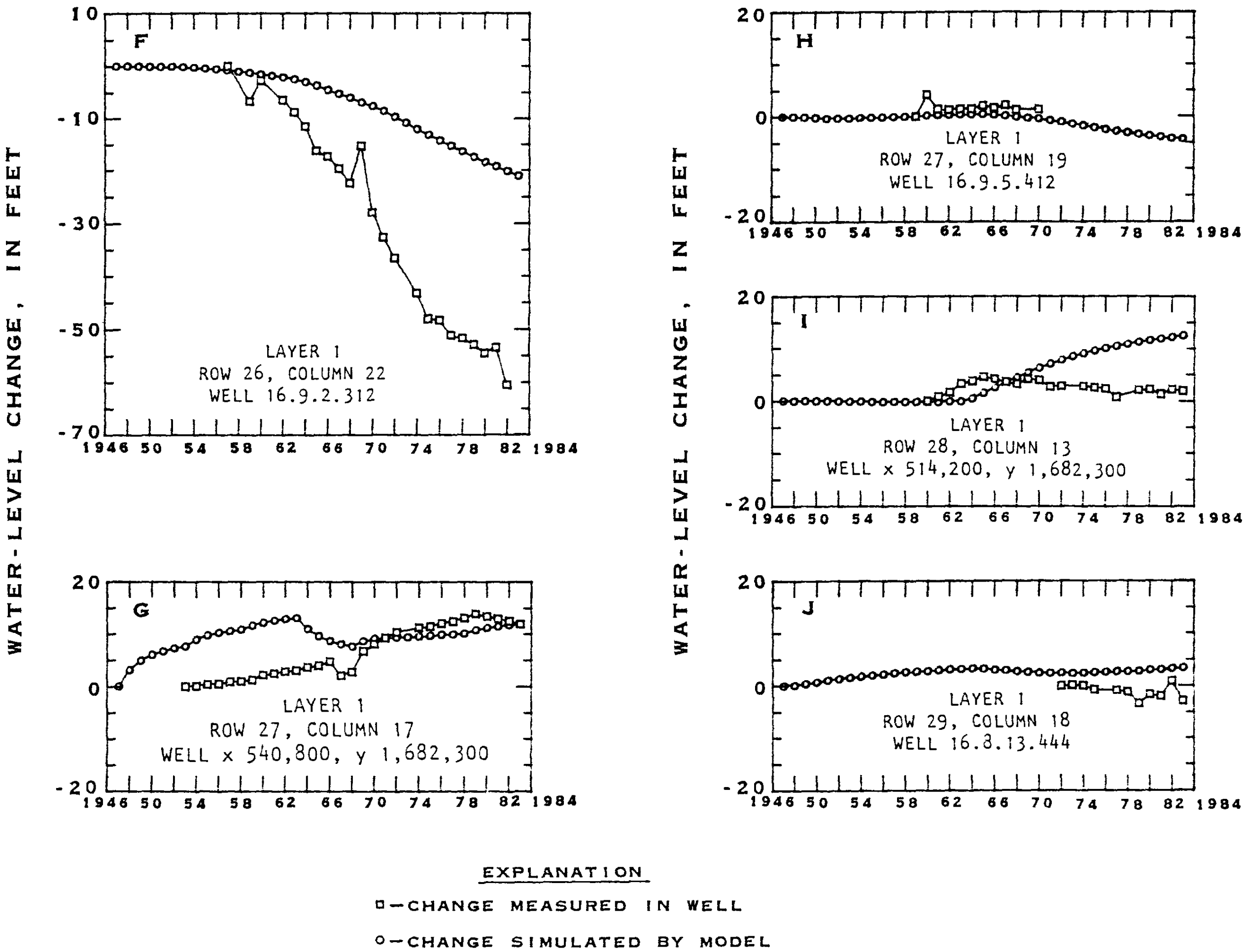


Figure 20.--Comparison between water-level changes measured in selected wells and simulated in corresponding model cells, 1947-82 - Concluded.

SIMULATED RESPONSE TO PROJECTED WITHDRAWALS

The response of the aquifer to future ground-water withdrawals in the Santa Fe area was simulated to the year 2020. The two scenarios simulated used the large and small future water demands for the Santa Fe and Buckman well fields reported by the Santa Fe Metropolitan Water Board (1984, table 4-2). Projected demand for water in Los Alamos was assumed to increase at an average rate of 77 acre-feet per year (Purtymun and others, 1985, p. 4). The projected withdrawal in the Santa Fe well field was distributed among the wells in the same proportion of the total as each well's average withdrawal from 1981 to 1983. Withdrawal from the Buckman wells was assumed to be evenly distributed to wells B-3, B-4, and B-6 (fig. 2). The increased withdrawal of water for Los Alamos was assumed to come from the Pajarito well field, where two large-capacity wells (PM-4 and PM-5, fig. 2) have recently been drilled (Purtymun and others, 1983 and 1984). The other wells supplying Los Alamos were assumed to continue to pump at the 1983 rates, as were all other withdrawals and recharge.

For both the small and large water demands, the maximum pumpage in the Santa Fe well field increased 1.3 percent from the maximum during the historical transient simulation. In the Buckman well field, the maximum pumpage decreased 25 percent from the maximum during the historical transient simulation for the small water demand and increased 53 percent for the large water demand. In the well fields supplying Los Alamos, the maximum pumpage increased 36 percent from the maximum during the historical transient simulation for both the small and large water demands.

Although the pumpage used in the model projections is not the same as was used during calibration, the projections were made because the changes were at most an increase of 53 percent. It is unlikely that future ground-water withdrawals will match either of the scenarios; therefore, the simulated response of the aquifer to future withdrawals cannot be considered a prediction of the future condition of the aquifer. However, if the withdrawals are similar to the scenarios, these simulations may give an indication of the approximate range of aquifer response that can be expected.

Water Budget

The water budget for the model projections for the small and large water demands is shown in table 11. The recharge, 73.4 cubic feet per second, remained the same for the two projections. At the end of the projection with the large water demand, pumpage was 23.9 cubic feet per second compared to 20.3 cubic feet per second for the small demand. All increased pumpage was from the Buckman well field. The larger pumpage resulted in an 18.7-cubic-foot-per-second decrease in storage compared to a 17.0-cubic-foot-per-second decrease with the small demand and a 1.8-cubic-foot-per-second decrease in natural discharge from the small demand. The decrease in natural discharge between the two projections resulted primarily from a reduction of discharge to the Rio Grande (table 11). About half of the increased pumpage from the Buckman wells came from storage and about half came from intercepted discharge to the Rio Grande. The imbalance between the total sources and total discharges for the small water demand is a result of round-off errors during the model simulation. Because the 0.1-percent difference is small, the effect on the simulation results is insignificant.

Table 11. **Water budget at the end of the model projections**

Description	Flow: Small demand: Cubic feet per second	Flow: Small demand: Acre-feet per year	Flow: Large demand: Cubic feet per second	Flow: Large demand: Acre-feet per year
Sources				
Storage	17.0	12,300	18.7	13,500
Areal recharge	10.6	7,700	10.6	7,700
East mountain-front and stream-channel recharge	33.2	24,000	33.2	24,000
West mountain-front recharge	18.6	13,500	18.6	13,500
Recharge from Rio Grande	1.9	1,400	1.9	1,400
Subsurface inflow at south specified-flux boundary	2.2	1,600	2.2	1,600
Subsurface inflow at north constant-head boundary	2.2	1,600	2.2	1,600
Recharge from sewage effluent	4.7	3,400	4.7	3,400
Total	90.4	65,500	92.1	66,700
Discharges				
Pumpage	20.3	14,700	23.9	17,300
Discharge to Pojoaque River and tributaries	7.0	5,100	6.9	5,000
Discharge to Rio Grande	36.0	26,100	34.3	24,800
Discharge to Santa Fe River	6.5	4,700	6.5	4,700
Subsurface outflow at south specified-flux boundary	.3	200	.3	200
Subsurface outflow at north constant-head boundary	2.9	2,100	2.9	2,100
Subsurface outflow at southwest constant-head boundary	17.3	12,500	17.3	12,500
Total	90.3	65,400	92.1	66,600

Hydraulic Head

The simulated change in hydraulic head from 1983 to 2020 for the small water demand is shown in figure 21 for layer 1 and in figure 22 for layer 2. The simulated change in hydraulic head for the large water demand is shown in figure 23 for layer 1 and in figure 24 for layer 2. For both simulations, the decline in hydraulic head is centered around the Santa Fe, Buckman, Los Alamos, Guaje, and Pajarito well fields. The simulation with the small water demand produced declines greater than 10 feet in layer 1 and 30 feet in layer 2 in the Buckman area, whereas the simulation with the large water demand produced declines greater than 50 feet in layer 1 and 90 feet in layer 2. The greatest declines in hydraulic head occurred at the Santa Fe well field, where maximum declines were greater than 160 feet in layer 1. A maximum decline in layer 1 of 174 feet occurred at cell 24, 21 in the area of the Santa Fe well field for both simulations. The decline in layer 2 at that location was 60 feet for both simulations. The maximum decline in layer 2 of 74 feet for the small water-demand simulation occurred in cell 13, 5 in the area of the Pajarito well field. The maximum decline in layer 2 of 123 feet for the large water-demand simulation occurred in cell 14, 11 in the area of the Buckman well field. Increases in hydraulic head in both simulations occurred southwest of Santa Fe in the area where recharge from sewage effluent occurs, as indicated by the line of zero change (figs. 21-24). However, the increases in head were less than 10 feet.

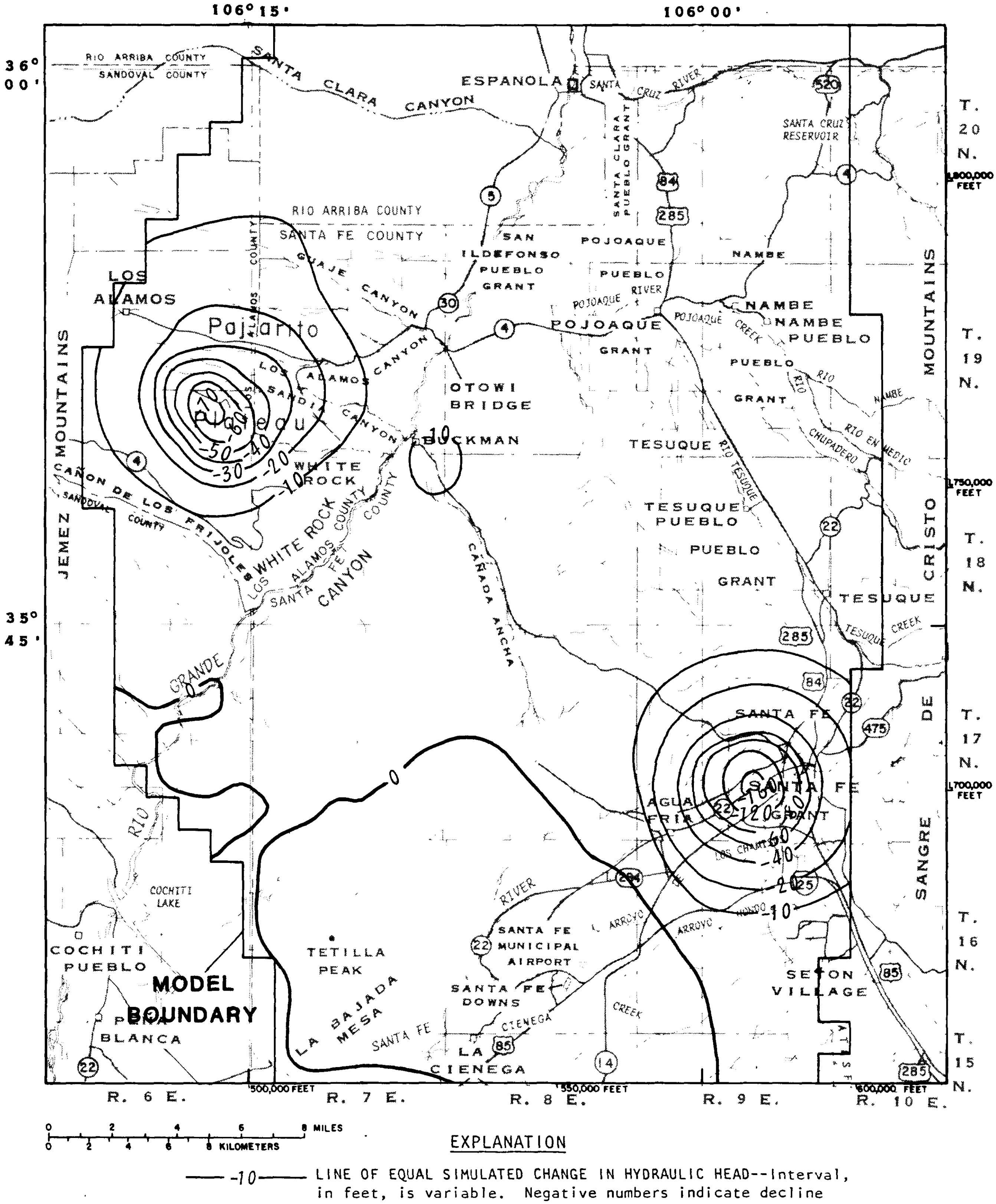
The apparent flattening of the lines of equal change to the north of the Buckman well field in figure 23 is not an effect of a boundary in that area but rather a result of the decline propagating farther out in the other directions. The bulge in the lines of equal change to the northwest is a result of the declines in the area of the Los Alamos well fields. The extension of the lines to the east, southeast, and south is a result of the area of relatively larger hydraulic conductivity (3.0 feet per day) near Buckman in layer 1 (fig. 10).

Pojoaque River and Tributaries

As in the historical transient simulation, simulated recharge from the Pojoaque River and its tributaries, 8.1 cubic feet per second, remained the same for both demand projections. The simulated discharge to the Pojoaque River and its tributaries decreased from 7.1 cubic feet per second in the historical transient simulation to 7.0 cubic feet per second in the small water-demand projection and 6.9 cubic feet per second in the large water-demand projection (tables 9 and 11).

Rio Grande

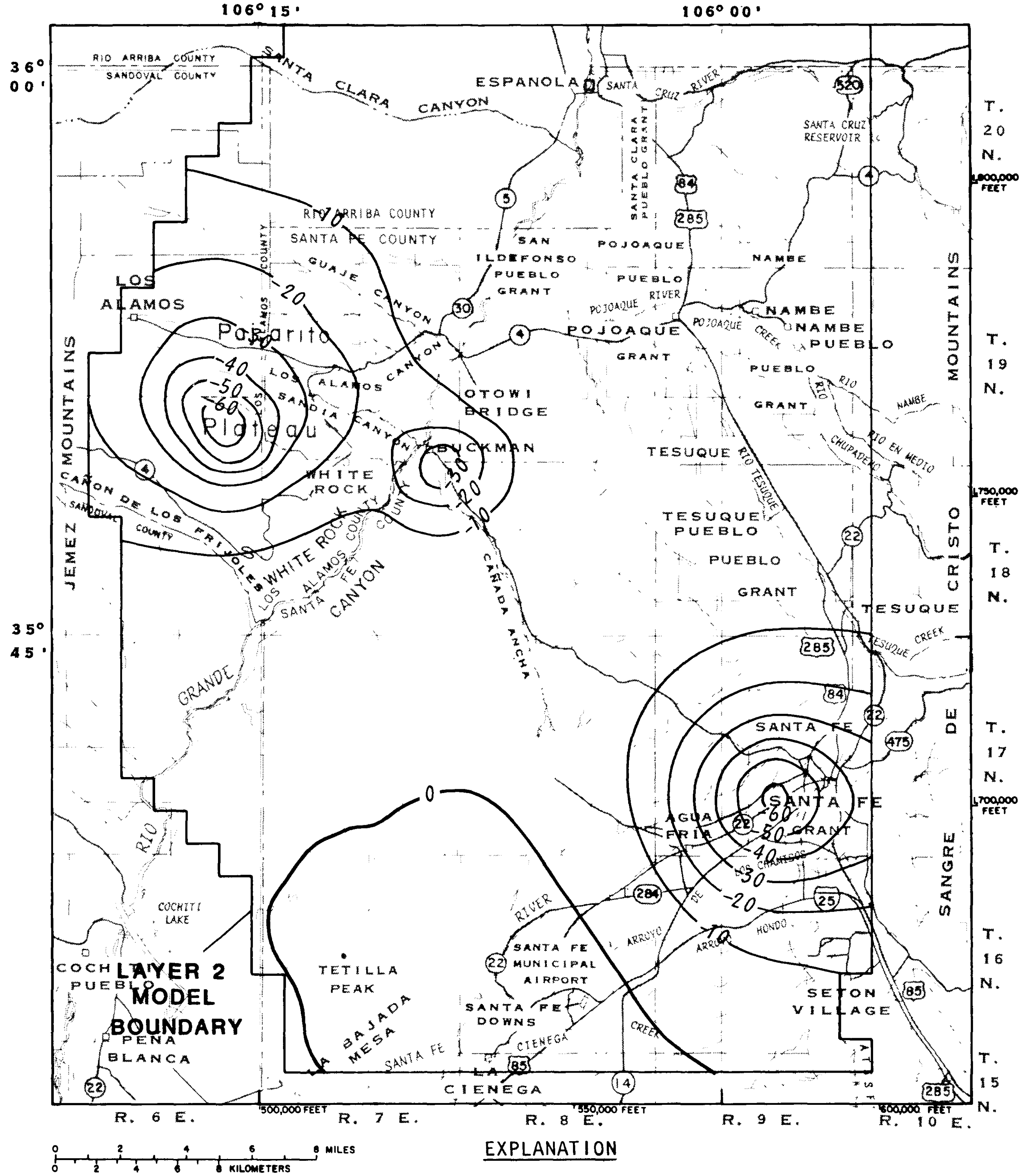
Simulated recharge from the Rio Grande, 1.9 cubic feet per second, remained the same in both water-demand projections, as in the historical-transient simulation. The simulated discharge to the Rio Grande decreased from 37.2 cubic feet per second in the historical transient simulation to 36.0 cubic feet per second in the small water-demand projection and 34.3 cubic feet per second in the large water-demand projection (tables 9 and 11).



EXPLANATION

—— -10 —— LINE OF EQUAL SIMULATED CHANGE IN HYDRAULIC HEAD--Interval, in feet, is variable. Negative numbers indicate decline

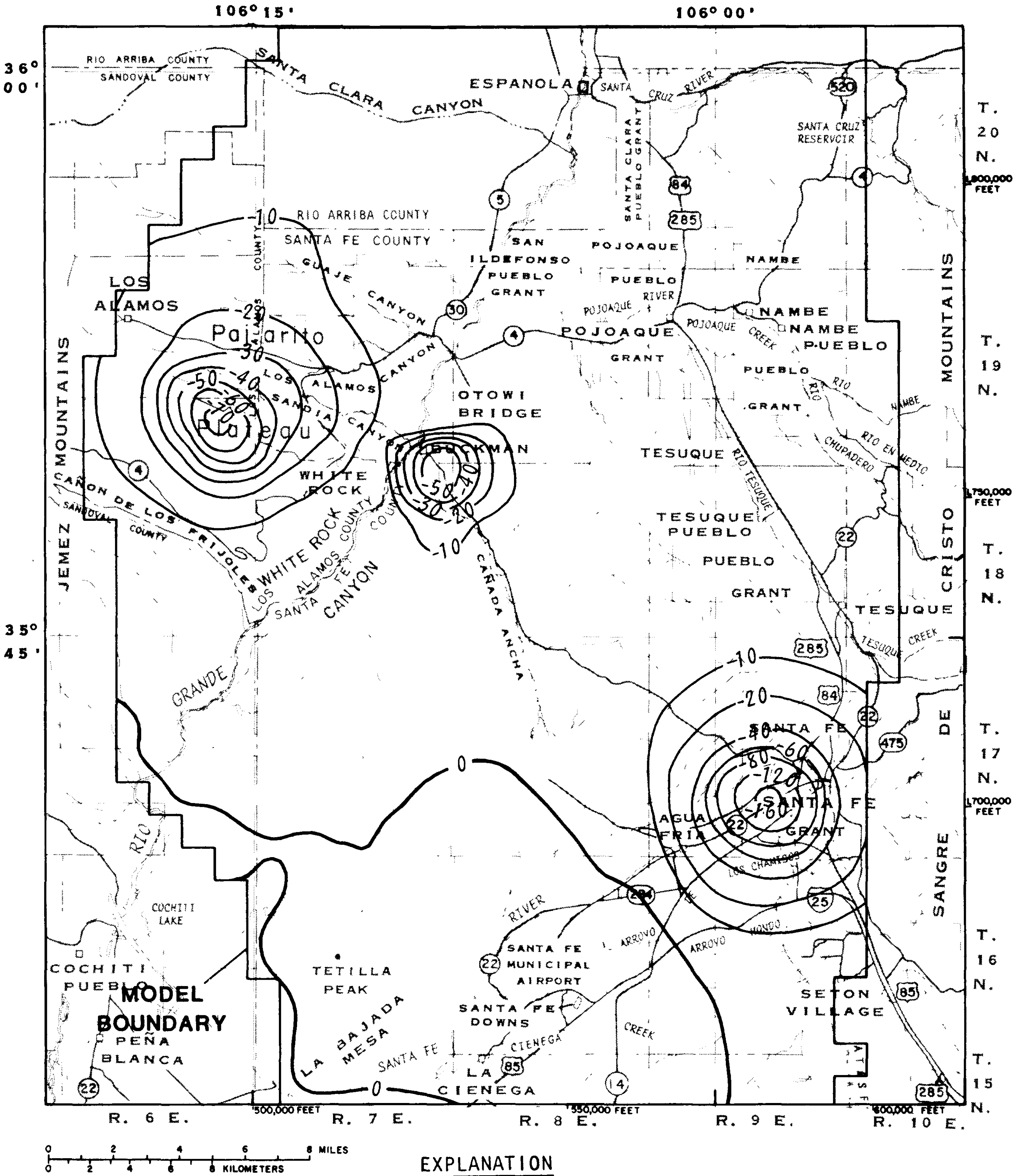
Figure 21.--Simulated change in hydraulic head in layer 1 assuming the small projected water demand, 1983-2020.



EXPLANATION

—— -10 —— LINE OF EQUAL SIMULATED CHANGE IN HYDRAULIC HEAD--Interval 10 feet. Negative numbers indicate decline

Figure 22.--Simulated change in hydraulic head in layer 2 assuming the small projected water demand, 1983-2020.



EXPLANATION

——*-160*—— LINE OF EQUAL SIMULATED CHANGE IN HYDRAULIC HEAD--Interval, in feet, is variable. Negative numbers indicate decline

Figure 23.--Simulated change in hydraulic head in layer 1 assuming the large projected water demand, 1983-2020.

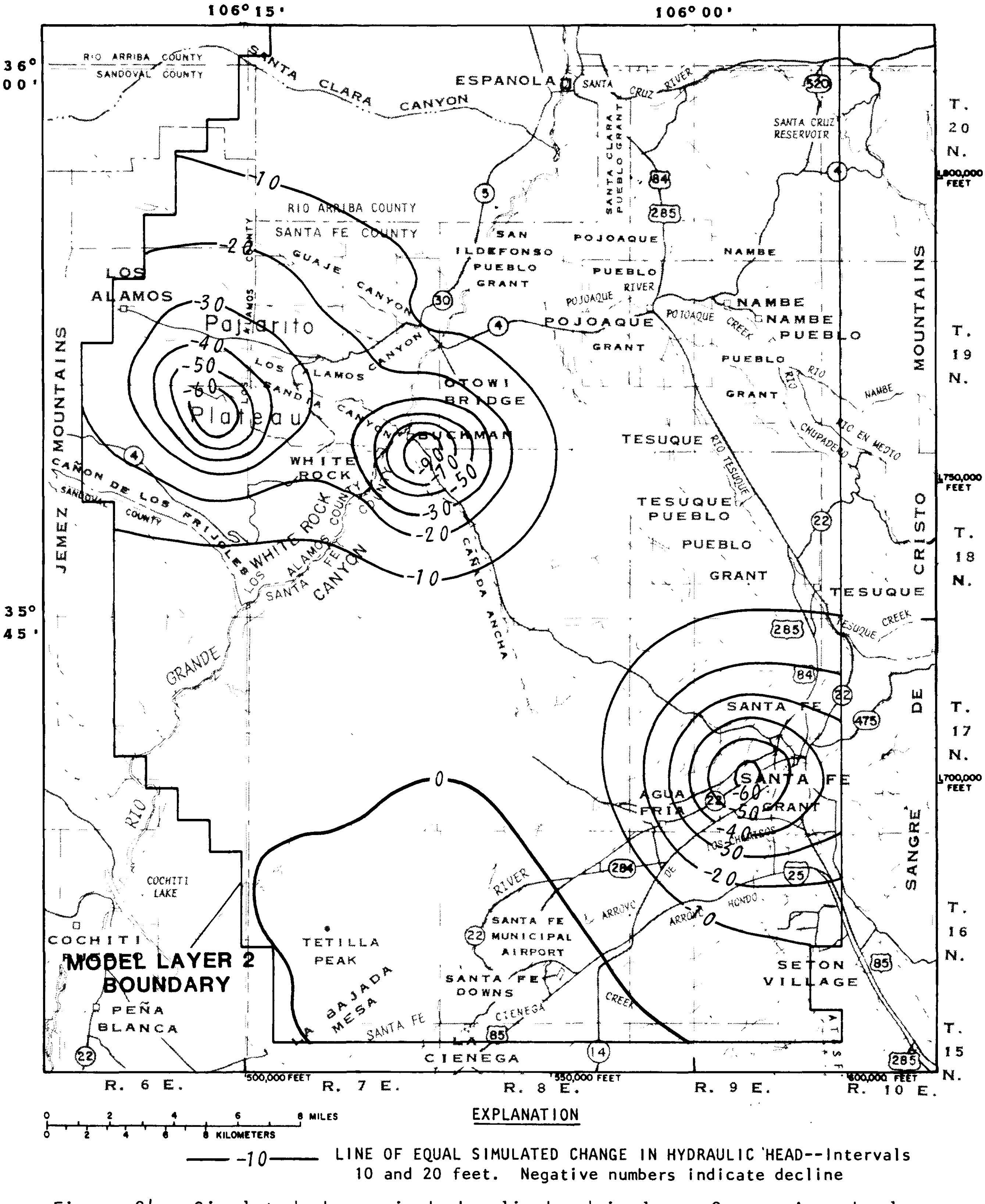


Figure 24.--Simulated change in hydraulic head in layer 2 assuming the large projected water demand, 1983-2020.

MODEL SENSITIVITY

Simulated responses of the aquifer need to be used with caution because aquifer characteristics in the model are assumed to approximate those in the aquifer, but those characteristics are not known with certainty. Therefore, sensitivity of the model to variations in selected aquifer characteristics was tested. Model sensitivity was tested for the steady-state and the historical-transient conditions.

The sensitivity of the model to each characteristic was tested by varying that characteristic while holding the others constant. Each characteristic was varied so that the maximum and minimum values approximated the plausible values of that characteristic. These sensitivity tests give a subjective measure of the uncertainty of the simulated response in relation to the uncertainty of values assigned to each characteristic.

Aquifer Thickness

The maximum saturated thickness simulated in the model was 5,600 feet. Galusha and Blick (1971, p. 44) reported the Tesuque Formation to be more than 3,700 feet thick. The sensitivity of the model to a smaller saturated thickness was tested by eliminating layer 4 to make the maximum saturated thickness 3,800 feet. The results of these sensitivity tests are shown in table 12.

Because of the small changes in hydraulic head and flow to the Rio Grande and Pojoaque River, the model is considered to be insensitive to the change in aquifer thickness. Therefore, whether the Tesuque Formation is about 3,700 feet thick or as much as 9,000 feet thick (Kelley, 1978) is not critical to the model simulations of this report.

Hydraulic Conductivity

The average hydraulic conductivity used in the calibrated model simulations was 1.1 feet per day in layer 1. The estimated plausible range of average hydraulic conductivity was 0.5 to 2.0 feet per day. Sensitivity of the model to changes in hydraulic conductivity was tested using a 50-percent increase and a 50-percent decrease in the hydraulic conductivities in all layers. Results of these sensitivity tests are shown in table 12.

Changes in hydraulic conductivity resulted in the largest average changes in hydraulic head for any of the sensitivity tests. Simulated discharge to rivers was most sensitive to hydraulic conductivity. Simulated steady-state discharge to the Pojoaque River and its tributaries increased by 108 percent over the calibrated simulation with the smaller hydraulic conductivity. Changes to hydraulic conductivity resulted in changes in the simulated transient discharge to the Rio Grande of about 40 percent from the calibrated simulation. The model is therefore sensitive to the changes in hydraulic conductivity.

Table 12. Comparison of simulated responses of the model with variations in aquifer characteristics

Adjustment made to model	Average difference in simulated hydraulic head from calibrated simulation, in feet		Maximum difference in simulated hydraulic head from calibrated simulation, in feet		Simulated decline in hydraulic head at cell [a]1,24,21, in feet	Simulated discharge to rivers, in cubic feet per second	
	Layer 1	Layer 2	Cell layer, row, column			Pojoaque River and tributaries	Rio Grande
Steady state							
Calibrated simulation	-	-	-	-	-	7.3	39.3
Maximum aquifer thickess of 3,800 feet	1.9	1.9	3,30,19 and 3,31,19	16.8	-	7.4	39.4
Hydraulic conductivity X 1.5	-90.6	-87.8	2,25,24	-312	-	2.9	44.7
Hydraulic conductivity X 0.5	195	189	2,25,24	703	-	15.2	32.2
Anisotropy ratio of 0.04	-25.3	-20.5	4,23,2	-159	-	6.1	43.6
Anisotropy ratio of 0.002	40.7	12.7	4,29,20	-272	-	9.2	34.3
Transient							
Calibrated simulation					137	7.1	37.2
Maximum aquifer thickness of 3,800 feet	.08	.2	3,27,18	11.3	137	7.1	37.1
Hydraulic conductivity X 1.5	-9.0	-10.7	2,24,24	-110	153	7.7	51.5
Hydraulic conductivity X 0.5	10.1	11.5	2,24,24	186	131	5.0	21.0
Specific yield X 1.33	.7	.7	1,24,21	16.6	121	7.1	37.4
Specific yield X 0.67	-1.3	-1.3	1,24,21	-24.2	162	7.1	36.8
Storage coefficient X 5	.2	.4	4,10,6	8.1	137	7.1	37.2
Storage coefficient X 0.1	-.05	-.08	4,11,1 and 4,11,2	-6.2	138	7.1	37.2
Anisotropy ratio of 0.04	-2.7	2.7	3,23,22	152	139	7.6	43.4
Anisotropy ratio of 0.002	3.3	-27.8	3,24,22	-297	125	6.6	29.7

[a]Cell in which maximum decline occurred during the historical-transient simulation.

Specific Yield

The average specific yield used in the calibrated model simulations was 0.15, and the plausible range was estimated to be 0.10 to 0.20. Sensitivity of the model to specific yield was tested using a 33-percent increase and a 33-percent decrease in specific yield in layer 1. The steady-state simulation is independent of specific yield; therefore, sensitivity was tested only for the transient simulation. Results of these sensitivity tests are shown in table 12.

The maximum decline in hydraulic head was most sensitive to specific yield. A 33-percent increase in specific yield resulted in a 12-percent reduction in the maximum head decline (cell 1,24,21), and a 33-percent decrease resulted in an 18-percent increase in maximum head decline.

Changes in specific yield resulted in as much as a 1-percent change in discharge to the Rio Grande and Pojoaque River. Discharge to the rivers is relatively insensitive to changes in specific yield, possibly due to there being relatively little ground-water withdrawal and subsequent change in water-table altitude near these rivers at the end of the historical transient simulation.

Storage Coefficient

The storage coefficient used in the calibrated model simulations was 1×10^{-3}. The plausible range was estimated to be from 1×10^{-4} to 5×10^{-3}. Sensitivity of the model to the storage coefficient was tested by increasing the storage coefficient in layers 2, 3, and 4 by a factor of 5 and decreasing it by a factor of 10 to correspond to the plausible range of values. The steady-state simulation is independent of the storage coefficient; therefore, the sensitivity was tested only for the transient simulation. Results of these tests are shown in table 12.

Changes in storage coefficient resulted in small changes in hydraulic head and discharge to the rivers. Therefore, simulated results are relatively insensitive to the changes in storage coefficient in layers 2, 3, and 4.

Vertical Anisotropy Ratio

The vertical anisotropy ratio used in the calibrated model simulations was 0.01. The sensitivity of the model to changes in the anisotropy ratio was tested using the plausible range of values, 0.002 to 0.04. Results of the sensitivity tests are shown in table 12.

Changes in anisotropy ratio resulted in significant changes in simulated hydraulic heads and a 7- to 26-percent change in simulated discharge to the rivers. Therefore, the model is considered to be sensitive to changes in the anisotropy ratio.

SUMMARY

Declining ground-water levels resulting from ground-water withdrawals in the Santa Fe, New Mexico, area have caused concern about the future availability of water from the Tesuque aquifer system (includes the Tesuque, Puye, and Ancha Formations of Tertiary age). This report describes the geohydrology of the Tesuque aquifer system in the Santa Fe area and presents a three-dimensional regional ground-water flow model that assesses the effects of existing and possible future ground-water withdrawals on the regional aquifer system.

The model was calibrated using simulations of the predevelopment steady-state condition and the 1947-82 historical period. The model was adjusted in an effort to match simulated hydraulic heads to those measured in wells and to match simulated river fluxes to those calculated by previous investigators. The mean difference in measured and simulated hydraulic heads was 17.2 feet for the steady-state simulation, and the standard deviation was 57.5 feet. For the 1947-82 period, the mean difference in measured and simulated hydraulic heads was 16.1 feet, and the standard deviation was 82.4 feet. Simulated discharge from the aquifer to the Pojoaque River and its tributaries was 7.3 cubic feet per second for steady state and 7.1 cubic feet per second at the end of the 1947-82 period. Simulated discharge to the Rio Grande was 39.3 cubic feet per second for steady state and 37.2 cubic feet per second at the end of the 1947-82 period.

Response of the aquifer to two scenarios of future ground-water withdrawals from 1983 to 2020 was simulated. The two scenarios used large and small future water demands. The maximum projected decline in hydraulic head was 174 feet for both water-demand scenarios and occurred in the area of the Santa Fe well field. Simulated discharge from the aquifer to the Pojoaque River and its tributaries was 7.0 cubic feet per second at the end of the simulation with the small water demand and 6.9 cubic feet per second with the large water demand. Simulated discharge to the Rio Grande was 36.0 cubic feet per second at the end of the simulation with the small water demand and 34.3 cubic feet per second with the large water demand.

Sensitivity tests indicate that maximum decline in hydraulic head is most sensitive to specific yield. A 33-percent increase in specific yield resulted in a 12-percent reduction in maximum head decline, and a 33-percent decrease resulted in an 18-percent increase in maximum head decline. The average change in hydraulic head is most sensitive to hydraulic conductivity. Simulated discharge to rivers is most sensitive to the changes in hydraulic conductivity. The 50-percent changes in hydraulic conductivity resulted in changes in simulated discharge to the Rio Grande of about 40 percent. Simulated steady-state discharge to the Pojoaque River and its tributaries increased by 108 percent with the 50-percent reduction in hydraulic conductivity.

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