THREE-DIMENSIONAL MODEL SIMULATION OF TRANSIENT GROUND-WATER FLOW IN THE ALBUQUERQUE-BELEN BASIN, NEW MEXICO

By John Michael Kernodle, Roger S. Miller, and William B. Scott

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U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS REPORT 86-4194

Albuquerque, New Mexico

1987

DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

In this report, figures for measurements 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
foot	0.3048	meter
foot squared per day	0.09294	meter squared per day
cubic foot	0.02832	cubic meter
	7.48	gallon
cubic foot per second	0.02832	cubic meter per second
	448.8	gallon per minute
inch	25.4	millimeter
mile	1.609	kilometer
acre-foot	0.001233	cubic hectometer
	43,560.	cubic foot
acre-foot per year	0.0013803	cubic foot per second
	0.6184	gallon per minute
square mile	2.590	square kilometer
acre-foot per year per square mile	0.0015625	cubic foot per year per square foot
	0.0004761	cubic hectometer per year per square kilometer

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ABSTRACT

A three-dimensional digital model that simulates transient flow in the alluvial aquifer system underlying the Albuquerque-Belen Basin, New Mexico, was constructed as part of a regional aquifer study of the southwest alluvial basins. The model simulates hydraulic heads and changes in hydraulic heads for 1907 to 1979. Hydraulic-conductivity values used in the accepted model range from 0.25 foot per day in part of the Santa Fe Group to 50 feet per day in the fluvial deposits in the Rio Grande flood plain. The majority of the basin-fill material of the Santa Fe Group of Tertiary and Quaternary age was modeled as having a horizontal hydraulic conductivity of either 30 or 40 feet per day. The simulated specific storage of the aquifer was 10^{-6} per foot and the simulated specific yield was 0.10. The aquifer was simulated as being vertically anisotropic with a ratio of vertical to horizontal hydraulic conductivity of 1:500.

Simulations for 1976-79 indicated that of the 100,000 acre-feet of ground water withdrawn annually from the basin-fill deposits outside of the Rio Grande flood plain, 68 percent was obtained from recharge around the basin margin, depletion of streams that are tributary to the Rio Grande, and the stream-aquifer system in the Rio Grande flood plain. Depletion of aquifer storage accounted for 25 percent of the ground-water supply to wells outside of the flood plain, and the remaining 7 percent was obtained by induced ground-water inflow from the Santo Domingo Basin.

The model displayed an acceptable performance throughout the period of simulation. However, by the end of the simulation period, 1979, the portrayal of the Rio Grande flood-plain system as a specified hydraulic-head boundary was having adverse effects on the simulation.

INTRODUCTION

The Albuquerque-Belen Basin (fig. 1) was one of four basins selected for simulation of ground-water flow as part of the U.S. Geological Survey's Southwest Alluvial Basins Regional Aquifer-System Analysis. Each of the models tested at least one approach to simulation of ground-water flow within a basin. The objectives and approaches for the investigation of ground-water flow and for the model of Albuquerque-Belen Basin were as follows:

(1) To gain a better understanding of the characteristics of the hydrologic systems in the basin;

(2) to simulate the three-dimensional response of the ground-water and surface-water flow systems to pumping stress; and

(3) to test the suitability of using specified hydraulic-head boundaries as a simplifying representation of a river and flood-plain hydrologic system in an alluvial-fill basin.

To accomplish these objectives, the study involved four phases of activity: (1) Compiling and evaluating geohydrologic data; (2) constructing a digital model to simulate steady-state flow in the alluvial aquifer system in the basin; (3) adapting the steady-state model to simulate ground-water-level changes and streamflow depletion (flood-plain depletion) under transient conditions; and (4) performing sensitivity analyses to determine the relative importance of individual hydrologic characteristics.

Purpose and Scope

This report emphasizes the results of the computer simulations of ground-water flow under transient conditions in the Albuquerque-Belen Basin (fig. 1) and the analysis of the sensitivity of the model to minor changes in values of simulated aquifer properties. The model described in this report is a direct descendent of the steady-state model that was documented by Kernodle and Scott (1986). Much of the introductory material presented by them has been omitted from this report; the emphasis of this report is on modifications, corrections, and additions to their work. For information on the background and scope of the regional aquifer studies, the reader is referred to the previous report by Kernodle and Scott (1986).

Other Investigations

A thorough description of previous investigations in the vicinity of the Albuquerque-Belen Basin and descriptions of the geology and geohydrology of the basin are given by Kernodle and Scott (1986). However, several previous works merit citation for their significant contributions or relevance to this investigation. Works by Bjorklund and Maxwell (1961); Reeder, Bjorklund, and Dinwiddie (1967); and Kelley (1977) provide descriptions of the hydrology and geology of the Albuquerque-Belen Basin. Guidebooks of the New Mexico Geological Society and the New Mexico Bureau of Mines and Mineral Resources also provide diverse geologic and hydrologic information, particularly those edited by Hawley (1978) and Callender (1982).

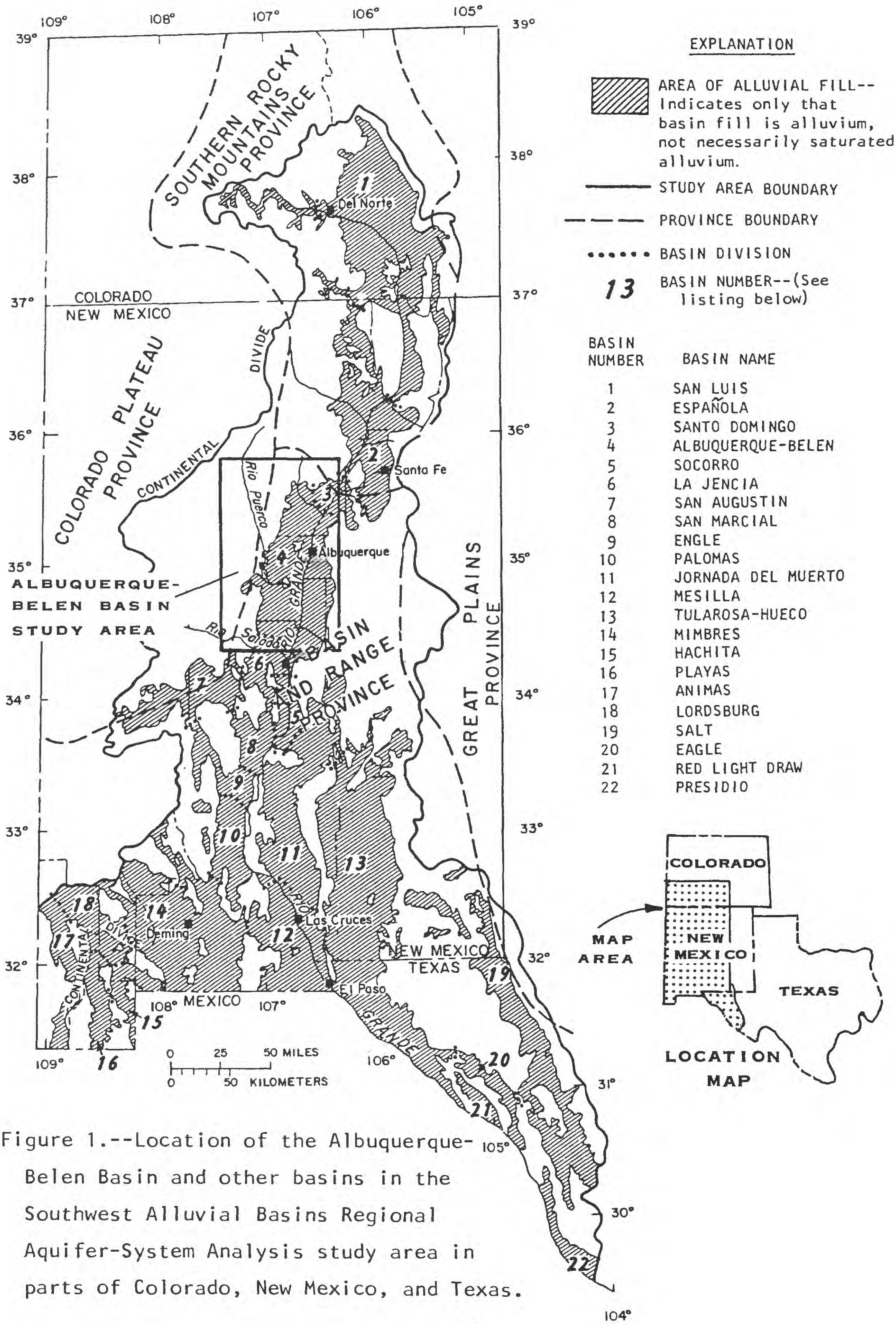


Figure 1.--Location of the Albuquerque-Belen Basin and other basins in the Southwest Alluvial Basins Regional Aquifer-System Analysis study area in parts of Colorado, New Mexico, and Texas.

LOCATION AND GENERAL FEATURES OF THE BASIN

The Albuquerque-Belen Basin is located in central New Mexico (basin 4, fig. 1). The total drainage area of streams that flow into the basin (excluding the upstream area of the Rio Grande) exceeds 10,000 square miles and includes the drainage areas of the Jemez River, Rio Puerco, Rio Salado, Tijeras Arroyo, and Abo Wash. Within this area are the Sandia, Manzanita, and Manzano Mountains (shown as uplifts in fig. 2) on the east side of the basin and Mesa Lucero and Sierra Ladron on the west side. The Nacimiento Uplift, Jemez caldera, and Santa Ana Mesa are prominent features at the north end of the basin.

Land-surface altitudes in the basin range from about 4,700 feet above sea level where the Rio Grande flows from the basin at the San Acacia constriction to more than 10,000 feet in the Sandia Mountains. At the lower altitudes are the flood plains or inner valleys of the Rio Puerco and Rio Grande that are incised into bordering mesas. The grade of the mesa east of the Rio Grande increases toward the steep west-facing slopes of the Sandia, Manzanita, and Manzano Mountains (see cover photograph). Alluvial fans coalesce at the base of the mountains and cover the mesa surface. Several arroyos drain the west slopes of the mountains. Two that also drain areas east of the mountains (Tijeras Arroyo and Abo Wash) incise the east mesa to the level of the Rio Grande flood plain. The mesa west of the Rio Puerco valley grades gradually upward to the Lucero Uplift. The mesa (Ceja and Wind Mesas) between the valleys of the Rio Puerco and Rio Grande is comparatively flat, aside from several small volcanic features and dune fields.

Precipitation quantity and distribution are orographically controlled in the basin. Average annual precipitation ranges from about 8 inches at low altitudes in the central part of the basin to about 24 inches in the Sandia and Manzano Mountains. Most precipitation in the central part of the basin occurs during summer thundershowers. Precipitation at high altitudes is mostly in the form of winter snow.

Vegetation type is dependent on altitude, aspect, and availability of water. Although precipitation quantities are small at the altitude of the Rio Grande flood plain, the shallow depth to ground water allows vigorous growth of riparian vegetation (cottonwood, grasses, and some tamarisk), whereas irrigation supports both riparian and agricultural vegetation. Vegetation is sparse on the mesas; those plants that are present include sage, tumbleweed, grass, and varieties of small cactus. Near the base of the mountains, at an altitude of about 7,000 feet, the vegetation includes juniper, prickly-pear and cholla cactus, piñon, grasses, and wildflowers. As altitude and precipitation increase, the forest types include ponderosa pine, aspen, and spruce. The east-facing slopes of the mountains are much more densely wooded than the west-facing slopes.

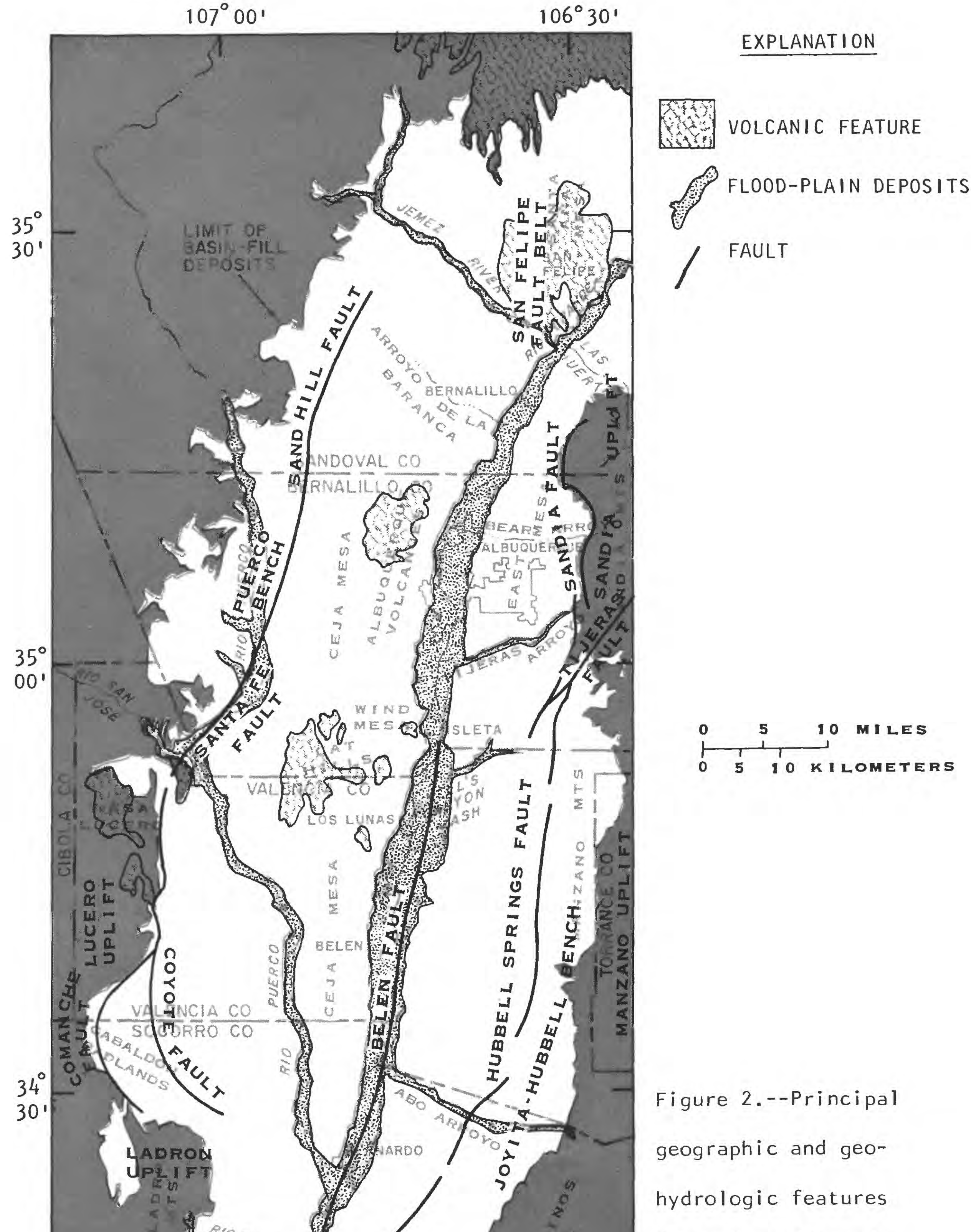


Figure 2.--Principal geographic and geohydrologic features (From Kernodle and Scott, 1986, fig. 3).

New Mexico's largest city, Albuquerque, is located near the Rio Grande approximately mid-latitude in the Albuquerque-Belen Basin (fig. 1). Albuquerque's population is increasing rapidly and the urban area has expanded to the foot of the Sandia Mountains on the east and to the base of the Albuquerque Volcanoes on the west. Expansion to the north or south is prevented by the presence of reservations of the Sandia and Isleta Pueblo Indians. The most likely direction of future expansion is westward, and accompanying that expansion will be new wells and well fields to provide municipal water.

HYDROLOGIC SETTING

Surface- and ground-water hydrologic interaction in an arid or semiarid region may be more complex than in a humid region. Quantities of water that would seem trivial in a more humid region can have a large effect on the availability and occurrence of both surface and ground water in an arid region. Usually, as is the case in the Albuquerque-Belen Basin, surface and ground water are inseparably related, both physically and legally.

The main components in the water budget are surface-water inflow and outflow in the Rio Grande, inflow from tributary streams, ground-water recharge from depletion of tributary streams, mountain-front recharge to ground water, ground-water inflow from the Santo Domingo Basin to the north, and ground-water outflow to the Socorro Basin on the south, pumped withdrawal of ground water, ground-water and surface-water discharge to the flood plain of the Rio Grande, and evapotranspiration. Pumped withdrawals and ground-water inflow and outflow between basins will be discussed in later sections of this report.

Surface-Water System

The surface-water system consists of the Rio Grande and its tributaries, irrigation canals, drainage ditches, and water that periodically flows in arroyos or washes, or is impounded in flood-retention reservoirs such as Jemez Reservoir (fig. 3). The components of this system are grouped into two subsystems: (1) A group of components that operate within the flood plain or inner valley of the Rio Grande; and (2) a group of components that operate independently in arroyos and rivers outside of the flood plain and disconnected from direct interaction with the ground-water flow system.

The Rio Grande is a through-flowing river that had an average inflow to the basin of 834,000 acre-feet per year and an average outflow of 669,000 acre-feet per year from 1948 to 1960. The difference of about 165,000 acre-feet of water per year is only a part of the water the river loses in its passage through the basin. Also lost from the surface-water system are the tributary inflows, described later, that totaled about 80,000 acre-feet per year for the same period. The majority of this total net loss of 245,000 acre-feet per year is to evapotranspiration in the flood plain (fig. 4) although an increasing proportion is being captured by the ground-water cone of depression associated with ground-water withdrawals in the Albuquerque area.

Figure 3.--Jemez Reservoir and adjacent Santa Ana Mesa at the northern end of the study area. The reservoir is operated primarily as a flood-retention impoundment although a small pool is maintained year-round as a trap for sediment. The mesa is comprised of Santa Fe sediments capped by fissure-flow basalts from the San Felipe field.

Figure 4.--Outwash bar at the mouth of Arroyo de la Baranca. View is upstream on the Rio Grande toward the north end of the basin. The river is flowing along the western edge of the inner flood plain, eroding older fluvial deposits. Riparian vegetation occupies the flood plain east of the river channel, whereas vegetation on the terrace above the river and flood plain is sparse and limited to desert species.

Water is diverted from the Rio Grande into irrigation canals and distributed for agricultural uses at facilities such as the Isleta Diversion and associated canals and drains (fig. 5). Most of the irrigation water is transpired by crops or evaporated, but some infiltrates to the water table in the flood plain. The water that infiltrates is prevented from mounding and waterlogging the soil by a network of lateral and riverside drains that usually are graded to a depth of 2 or more feet below the level of the Rio Grande. The slope of the drains is less than that of the Rio Grande so that the water that they intercept eventually is returned to the river.

Engineering and management practices can become very complicated in the effort to distribute water beneficially within the flood plain. Irrigation canals cross from one side of the river to the other through inverted siphons beneath the riverbed (figs. 6 and 7) and both canals and drains are routed beneath flood-diversion ditches from the bordering mesas. Such routing preserves the structural integrity and function of the drains and canals. Some drains serve dual functions. Water commonly is diverted from the Rio Grande to riverside drains to decrease conveyance losses by greatly decreasing the surface area of water that is exposed to evaporation (figs. 8 and 9). Use of the drains as conveyance channels at times of low river flow also minimizes riverbed infiltration, or loss to ground water and then to evapotranspiration.

Evaporation is about 5 feet per year in areas of exposed water. Evapotranspiration in the flood plain, whether from agricultural or riparian vegetation, is about 3 feet per year. About 0.5 foot of precipitation per year helps to slightly offset evapotranspiration, but the net loss for the flood plain is estimated to be 310,000 to 390,000 acre-feet per year (J.D. Dewey, U.S. Geological Survey, written commun., 1983). The difference between this loss and the surface-water loss reported previously (245,000 acre-feet per year) is made up by loss from ground water.

The second component of the surface-water system consists of tributary inflow and mountain-front runoff. None of the tributaries to the Rio Grande in the Albuquerque-Belen Basin are perennial, but several have a seasonal flow that reaches the Rio Grande. A significant percentage of the flow of the tributaries is lost to ground water in crossing basin-fill deposits. The three largest tributaries, the Jemez River, Rio Puerco, and Rio Salado, consistently have flows that reach the Rio Grande. Other tributaries (Tijeras Arroyo, Abo Wash, and Hell's Canyon Arroyo) often or occasionally have flows that reach the river, whereas the flow of innumerable small streams emanating from the bordering mountains infiltrates alluvial-fan deposits along the mountain fronts before reaching the Rio Grande except during extremely rare floods.

Ground-Water System

Because ground water and surface water are so interdependent in the Albuquerque-Belen Basin, the ground-water system is also divisible into two subsystems. The first subsystem is in and near the area of the Rio Grande flood plain, and the second is the broader regional-flow ground-water subsystem of the basin.

Figure 5.--Oblique aerial view of the Isleta Diversion. Both concrete-lined (1) and earthen (2) irrigation canals are shown, along with a stilling basin (3) for removal of canal-clogging sand. Riverside drains (4) also are shown, one of which (5) passes beneath several canals to reach the Rio Grande downstream from the diversion dam (6). Two wells (7) visible in the photograph are used to augment canal flow at times of low flow in the Rio Grande.

Figure 6.--Downstream end of the Corrales Main Canal siphon. Water in the canal is routed beneath the Rio Grande through the inverted siphon from the Albuquerque Main Canal on the opposite (eastern) side of the river (in the background).

Figure 7.--View southward of the Corrales Main Canal from near the siphon beneath the Rio Grande. The canal follows the western edge of the inner flood plain. A riverside drain (hidden by vegetation) begins just beyond the road fork.

Figure 8.--Albuquerque Riverside Drain entering an inverted siphon beneath the Albuquerque North Flood-Diversion Canal (shown in figure 9). This drain commonly is used as a conveyance channel for water diverted from the Rio Grande upstream from the junction with the Jemez River.

Figure 9.--Albuquerque North Flood-Diversion Canal at its junction with the Rio Grande (in the background). Near this location both the Albuquerque Main Canal and Riverside Drain are routed through inverted siphons beneath the floodway.

As with the surface-water system, the first ground-water subsystem is the closely interconnected set of elements that consist of the ground-water flow within flood-plain alluvium of the river valley, which interconnects the Rio Grande, canals, drains, and evapotranspiration. Ground-water flow within this subsystem takes place because of the hydraulic-head differentials imposed by the surface-water bodies, evapotranspiration, and recharge of excess irrigation water. Although there is a great volume of ground water that moves about in the flood-plain alluvium, both the hydraulic heads and gradients remain virtually unchanged from one year to the next, except in the vicinity of increasing ground-water withdrawals. Even seasonal hydraulic-head changes seldom exceed 5 feet.

The second ground-water subsystem is a regional system that operates outside of, but is hydraulically connected to, the flood-plain alluvium. Two forms of ground-water recharge occur outside of the flood plain: (1) Tributary recharge from streams as they traverse across basin fill; and (2) mountain-front recharge from flows that infiltrate almost immediately (figs. 10 and 11) after the streams flow from the virtually impervious bedrock that encircles the basin-fill deposits. Tributary and mountain-front recharge total about 130,000 acre-feet per year. Estimated tributary and mountain-front recharge for the Albuquerque-Belen Basin are summarized in figure 12. The mean annual surface inflow to the Rio Grande and the estimated tributary recharge for the major tributaries in the study area are summarized in table 1. Tributary and mountain-front recharge raise ground-water levels around most of the margin of the basin. Ground water then flows downgradient toward the axis of the basin, which does not necessarily coincide with the Rio Grande or its flood plain. As the flow approaches the axis of the basin, the flow paths curve and continue further downgradient (southward) to the lower end of the basin.

Ground water flows vertically as well as horizontally. In areas of recharge, some ground water descends into the aquifer and follows a deeper and generally more direct route to the basin's ground-water discharge area than shallow ground water. Although the shallow ground-water system includes and is substantially affected by the flood-plain alluvium of the Rio Grande, that effect decreases rapidly with depth.

Geologic Control of the Occurrence and Movement of Ground Water

The geologic structural basin is more restricted than the topographic basin. The dimensions of the structural basin are 35 to 40 miles in width by about 100 miles in length. The structural basin is one of the largest of a eries of grabens along the Rio Grande Rift. The central part of the basin has been downfaulted in relation to the bordering highlands. Material derived by erosion of the highlands and sediment transported into the basin by the Rio Grande and other streams has filled the graben to a thickness locally in excess of 18,000 feet. This basin-fill material, the Santa Fe Group of Tertiary and Quaternary age, is the principal aquifer in the Albuquerque-Belen Basin. Other hydraulically connected aquifers are the flood-plain alluvium in the valley of the Rio Grande and, to a much lesser degree, alluvial-fan deposits along the base of the Sandia, Manzanita, and Manzano Mountains.

Table 1. Mean annual inflow to the Rio Grande and estimated annual tributary recharge to ground water for the five major tributaries to the Rio Grande in the Albuquerque-Belen Basin, in acre-feet per year, for the period of record until 1960

Tributary	Inflow to Rio Grande	Tributary recharge
Jemez River	33,600	24,600
Rio Puerco	35,900	10,400
Rio San Jose[1/]	--	[2/]5,200
Rio Salado	9,060	13,100
Tijeras Arroyo	[3/]1,040	[2/]10,600
Abo Wash	not gaged	[2/]5,400
Total	79,600	79,300

1/ Tributary to Rio Puerco.
2/ Includes some mountain-front recharge.
3/ Period of record, 1975-82.

Figure 10.--View westward down Tijeras Arroyo from Four Hills Road. Infiltration of the flow, estimated to be about 1.5 cubic feet per second at the time, into basin-fill deposits occurs within 400 feet (arrow) of the basin-boundary fault. Larger flows travel further before infiltrating, and flood flows occasionally reach the Rio Grande about 12 miles away.

Figure 11.--View north along Four Hills Road showing weathered Sandia Granite (Kelley, 1977) of the Sandia uplift to the right (east) and downfaulted basin-fill deposits to the left (west) of the road. The trace of the Sandia Fault parallels the right side of the roadway. The photograph in figure 10 was taken to the left (west) from a bridge at the bottom of the arroyo crossing.

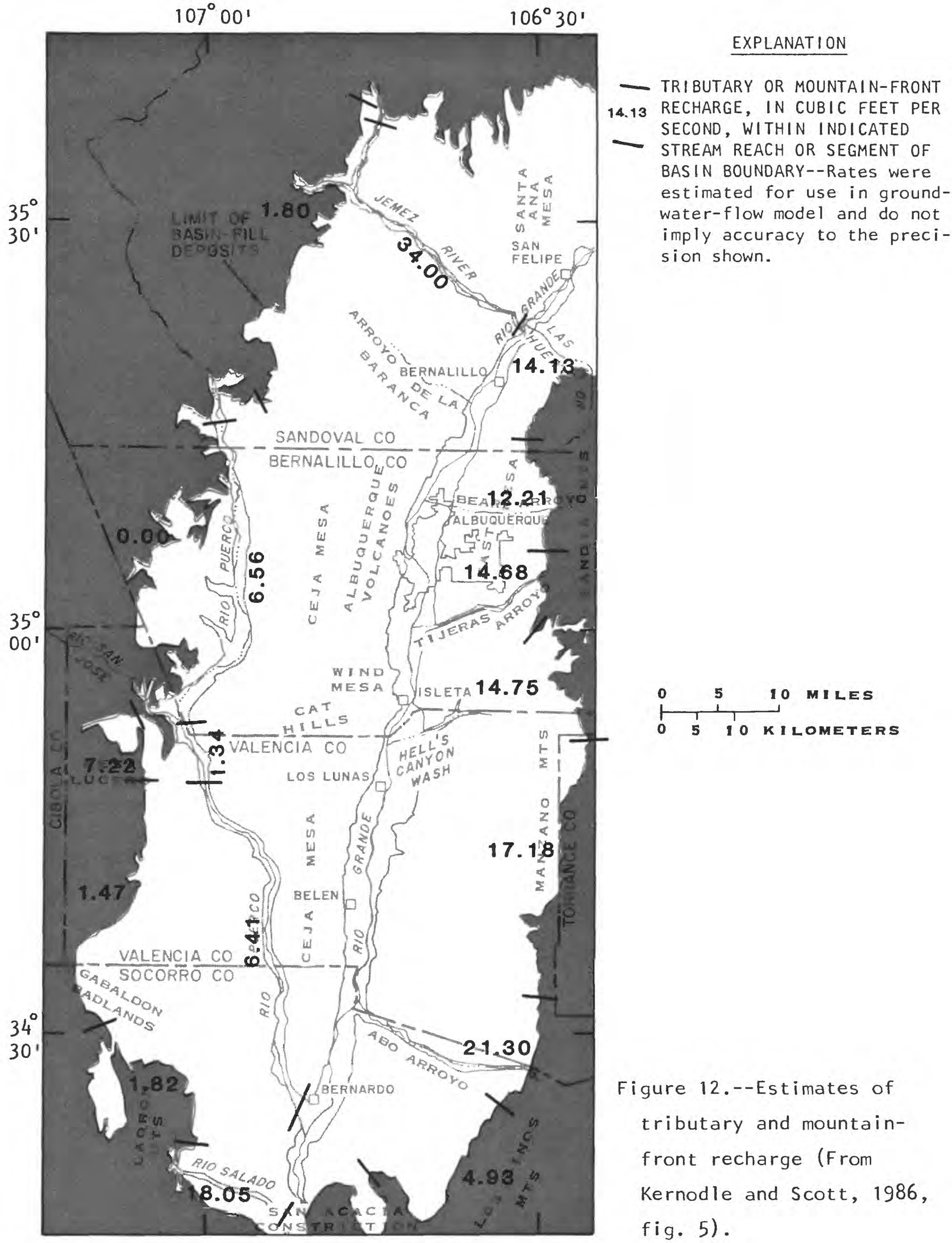


Figure 12.--Estimates of tributary and mountain-front recharge (From Kernodle and Scott, 1986, fig. 5).

The structural basin is bounded on the east and west sides by faults. The faults on the east are fewer in number but of greater displacement than the faults along the western margin of the basin. The total fault displacement along the east side of the rift is 5,000 to 6,000 feet greater than along the west side. Sandia and Hubbell Springs Faults (fig. 2) are the major faults that separate the basin from the Sandia, Manzanita, and Manzano Uplifts on the east, whereas numerous faults with less displacement separate the basin from Mesa Lucero, Sierra Ladron, and the San Juan Basin on the west. These faults have elevated benches of pre-Santa Fe bedrock to near or at land surface and, therefore, mark the east and west boundaries of the regional ground-water subsystem.

The Joyita-Hubbell bench on the east side of the basin (fig. 2) extends as much as 4 miles west of the base of the Manzanita and Manzano Mountains and is covered by a veneer of alluvial-fan outwash. Although ground water may occur in the veneer of basin-fill deposits on these benches, it is not a part of the regional flow system. Vertical discontinuities in ground-water altitude of as much as 700 feet between the perched and regional systems occur at the western edge of the Joyita-Hubbell bench.

The Puerco bench and Lucero Uplift are the major benches on the west side of the basin and are separated from the basin by the Sand Hill, Comanche, and Santa Fe Faults (fig. 2). Unlike the Joyita-Hubbell bench, however, a part of the Puerco bench is overlain by basin-fill material that is a part of the Albuquerque-Belen ground-water basin. Although ground-water gradients from the Puerco bench to the main body of the basin are steep, ground-water flow appears to be continuous rather than discontinuous or perched.

The southern end of the basin is terminated by converging faults and bedrock highs at the San Acacia constriction. Flood-plain alluvium and a thinner layer of Santa Fe deposits are present within the constriction, allowing some ground-water underflow to the Socorro Basin. Jiracek (1983) used electric-resistivity profiles to determine a basin-fill thickness at the San Acacia constriction of about 1,300 feet.

The northern end of the basin, as defined in this investigation, is at the southern and southeastern edge of the Jemez volcanic complex and along the southern and southwestern edge of Santa Ana Mesa. This location was selected as a boundary based primarily on the presence of the San Felipe fault belt and associated north- to northwest-trending fissure-flow volcanic rocks and also on the presence of faults within the area of the Jemez caldera.

Hydraulic Characteristics

Several properties define an aquifer's ability to convey and yield ground water: hydraulic conductivity, saturated thickness, anisotropy ratios, specific storage, and specific yield. These properties are briefly explained below. The reader is referred to Lohman and others (1972) for more rigorous definitions.

Hydraulic conductivity is the volume of water that passes through a unit cross-sectional area of aquifer under a unit hydraulic gradient in a specified time. In this report, hydraulic conductivity is reported in units of feet per day (a simplification of units of cubic feet per square foot per day).

The saturated thickness is the thickness of aquifer material that is saturated with water. In a confined aquifer this thickness is constant regardless of the hydraulic head, but in an unconfined (water-table) aquifer the saturated thickness varies with changes in water level. The product of this thickness and the hydraulic conductivity is the aquifer transmissivity.

An aquifer is anisotropic if hydraulic conductivity varies with direction. Variations may be caused by the existence of a fabric or grain in the aquifer material due to the environment of its deposition, or to fractures, solution openings, directional compaction, or other post-depositional changes.

Anisotropy also can be caused by bedded layering of aquifer materials. Each layer may or may not itself be isotropic and homogeneous, but because of the scale or dimension of the layering, the aquifer as a whole is anisotropic across the plane of the layering. The magnitude of observed anisotropy caused by layering is a function of the continuity of the beds and of the magnitude and direction of local and regional gradients. Hearne (1985) determined the anisotropy ratio (the ratio of vertical to horizontal hydraulic conductivity) for the Santa Fe Group at a site in the Española Basin (fig. 1) under undisturbed regional-flow conditions and stressed conditions during an aquifer test. He determined that under unstressed conditions, the regional ratio was 1:250, whereas during the aquifer test, the ratio was 1:20,000. In this instance the direction and magnitude of the hydraulic gradient were determined to affect the apparent anisotropy. Hearne ascribed the difference in apparent anisotropy to the tortuosity of flow paths due to local heterogeneities. In the regional flow system, gradients are low and nearly horizontal and water flows around rather than across individual lenticular beds (see Hearne, 1985, p. 22). When the system is stressed, the local gradients increase and become almost perpendicular to the plane of the layering. Under the stressed conditions, the calculated vertical hydraulic conductivity approached the harmonic mean of the vertical hydraulic conductivities of the individual beds.

Specific storage is the volume of water elastically released from or taken into storage per unit volume of aquifer per unit change in hydraulic head (Lohman and others, 1972). Specific storage is a function of the compressibility of the aquifer materials and water. The product of specific storage and saturated thickness is the storage coefficient of a confined aquifer.

Specific yield is the volume of water that will drain by gravity from a unit volume of aquifer material. Some water remains behind; therefore, specific yield also is equal to porosity minus specific retention (the percent of water that is retained after gravity drainage). In an unconfined aquifer the volume of water derived from storage by gravity drainage is vastly greater than that derived by elastic expansion (storage coefficient).

Bjorklund and Maxwell (1961, p. 24-25) reported the results of 24 aquifer tests in the Albuquerque-Belen Basin. Technical terminology was different at that time, but the results were transmissivities that ranged from 1,000 to 80,200 feet squared per day and that averaged 30,700 feet squared per day. The assumed saturated thicknesses in the tests ranged from 496 to 871 feet from which they derived hydraulic conductivities of 1.6 to 112 feet per day with an average of 45 feet per day. They also noted a tendency for the aquifer to be more transmissive east of the Rio Grande flood plain than to the west of it. None of the tests were conducted in such a manner that storage coefficients could be determined.

Wilkins (in press) reported the results of aquifer tests at two sites west of Albuquerque. One of the sites was on Ceja Mesa in the vicinity of the Albuquerque Volcanoes and the other was in the inner valley of the Rio Grande, northwest of Albuquerque. Both tests were single-well packer tests of multiple-completion intervals. The test at the Ceja Mesa site resulted in an estimated horizontal hydraulic conductivity in the range of 0.02 to 1.74 feet per day and a vertical to horizontal conductivity ratio (anisotropy) of 1:60 to 1:600. Horizontal hydraulic conductivity at the inner-valley site was estimated to range between 13 and 28 feet per day. The horizontal to vertical ratio could not be determined at this site. Because of the nature of the tests, storage coefficients could not be determined at either site.

Effects of Development

Diversion of surface water for irrigation was the earliest form of human disturbance of the natural water system in the Albuquerque-Belen Basin. Irrigation continued, and the volume of diverted water increased until drains became necessary to control waterlogging and salt accumulation in the soil in the 1930's. Domestic use of water was minimal compared with the volume of water used for irrigation.

Until the mid-1940's, Albuquerque's municipal water needs were met by ground-water withdrawals from wells completed in the flood-plain alluvium. The volume of withdrawal was small, and the effect on the natural water system was insignificant, especially in comparison to the effects of irrigation.

Dry weather and decreased streamflow in the 1950's forced an increased dependence on ground water for irrigation use. In addition, Albuquerque's population began to increase rapidly and municipal ground-water withdrawals increased in proportion to the population. New legal regulations imposed in 1959, prompted by the rapid increase in ground-water withdrawals, made construction of municipal wells outside of the flood plain increasingly attractive. The area of greatest ground-water stress began to shift away from the flood plain, the major potential source of aquifer recharge in the basin. In the area east of the flood plain, municipal withdrawals caused a decline in ground-water levels of about 20 feet by 1960 and an additional 60 to 80 feet from 1960 to 1980.

Albuquerque's municipal water needs have been met by ground-water withdrawals matched by the purchase and retirement of surface-water rights for water conveyed by the Rio Grande. An accounting system has been established whereby a percentage of the water that is withdrawn is credited as being returned by discharge of treated effluent to the surface-water ground-water system, and some is credited as having a delayed effect on the discharge of the Rio Grande. Other elements in the hydrologic system are being investigated to determine whether changes associated with urbanization lead to a savings or loss of water. Additional credits may be granted for water that can be shown to recharge the ground-water system as a result of changes in the watershed characteristics.

The effects of urbanization on the natural hydrologic system may be large although in some regards they are difficult to quantify. In addition to direct withdrawal of ground water, factors that affect the overall impact of urbanization on the surface-water ground-water system can be very subtle. For example, the U.S. Geological Survey, in cooperation with the city of Albuquerque, is conducting an investigation in which rates of recharge, runoff, and evapotranspiration for parcels of land with native landscaping are being compared to the rates for sprinkled or irrigated lawns. Also, impervious surfaces concentrate runoff into quantities that are large enough to recharge ground water after exceeding the soil capacity to retain water. Paving in an arid climate may have the effect of increasing recharge by collecting scant precipitation and concentrating runoff. Conversely, paving of arroyos and washes to alleviate flood damage prevents or redistributes recharge that would occur under natural conditions.

GROUND-WATER WITHDRAWAL

The trend of total ground-water withdrawal with time in the Albuquerque-Belen Basin is shown in figure 13. The earliest documented ground-water withdrawal began in 1907. Withdrawal remained at less than 120 acre-feet per year until 1932, when the city of Albuquerque constructed the Main Plant well field that supplied all of the city's ground-water needs until 1948. The city's rapid population increase after the late 1940's necessitated the construction of five new well fields from 1948 to 1956. Ground-water withdrawal for all uses increased from about 12,500 acre-feet per year during 1948 to 47,500 acre-feet per year during 1956. Prior to 1956, ground water was produced mostly from wells in or near the Rio Grande flood plain and only a small quantity was withdrawn from wells east of the flood plain.

Ground-water withdrawal from the area east of the flood plain did not become significant until after 1959 when the New Mexico State Engineer Office began regulating ground-water withdrawal in the Albuquerque-Belen Basin. The effect of the regulations was principally to minimize the effect of new ground-water withdrawal on surface water in the Rio Grande valley. The increase in ground-water withdrawal outside of the flood plain is illustrated in figures 14 and 15, which show the average withdrawal (in acre-feet per year per square mile) for 1956-59 and 1976-79, respectively, in the Albuquerque area. The change in the distribution is attributed to new production from wells east and west of the flood plain while withdrawal from wells in the Rio Grande valley (fig. 13) decreased.

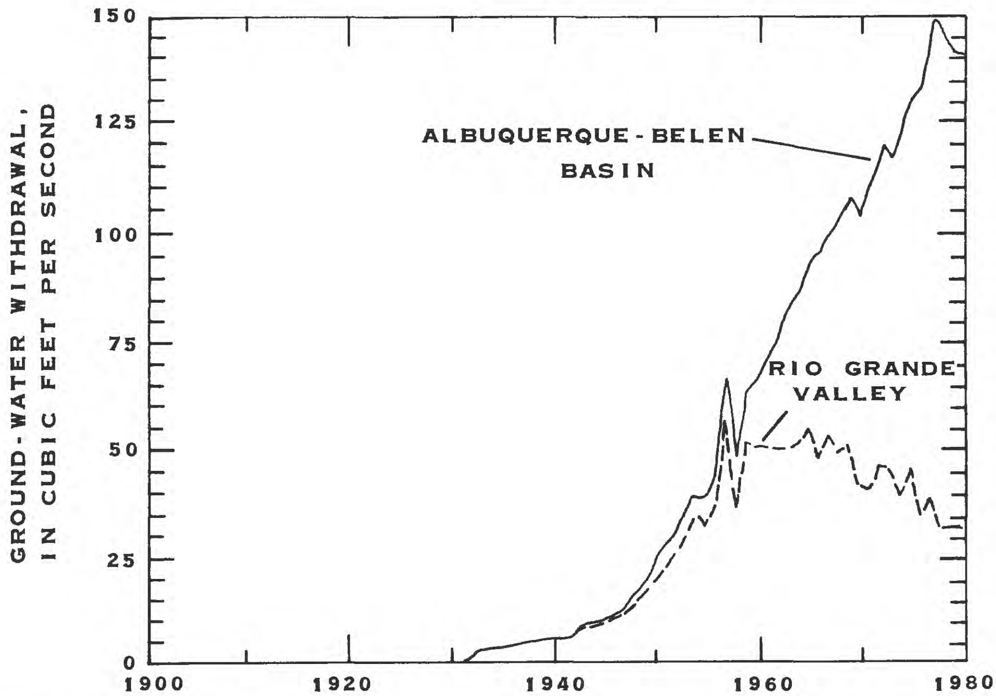


Figure 13.--Ground-water withdrawal in the Albuquerque-Belen Basin and ground-water withdrawal from the Rio Grande valley, 1907-79.

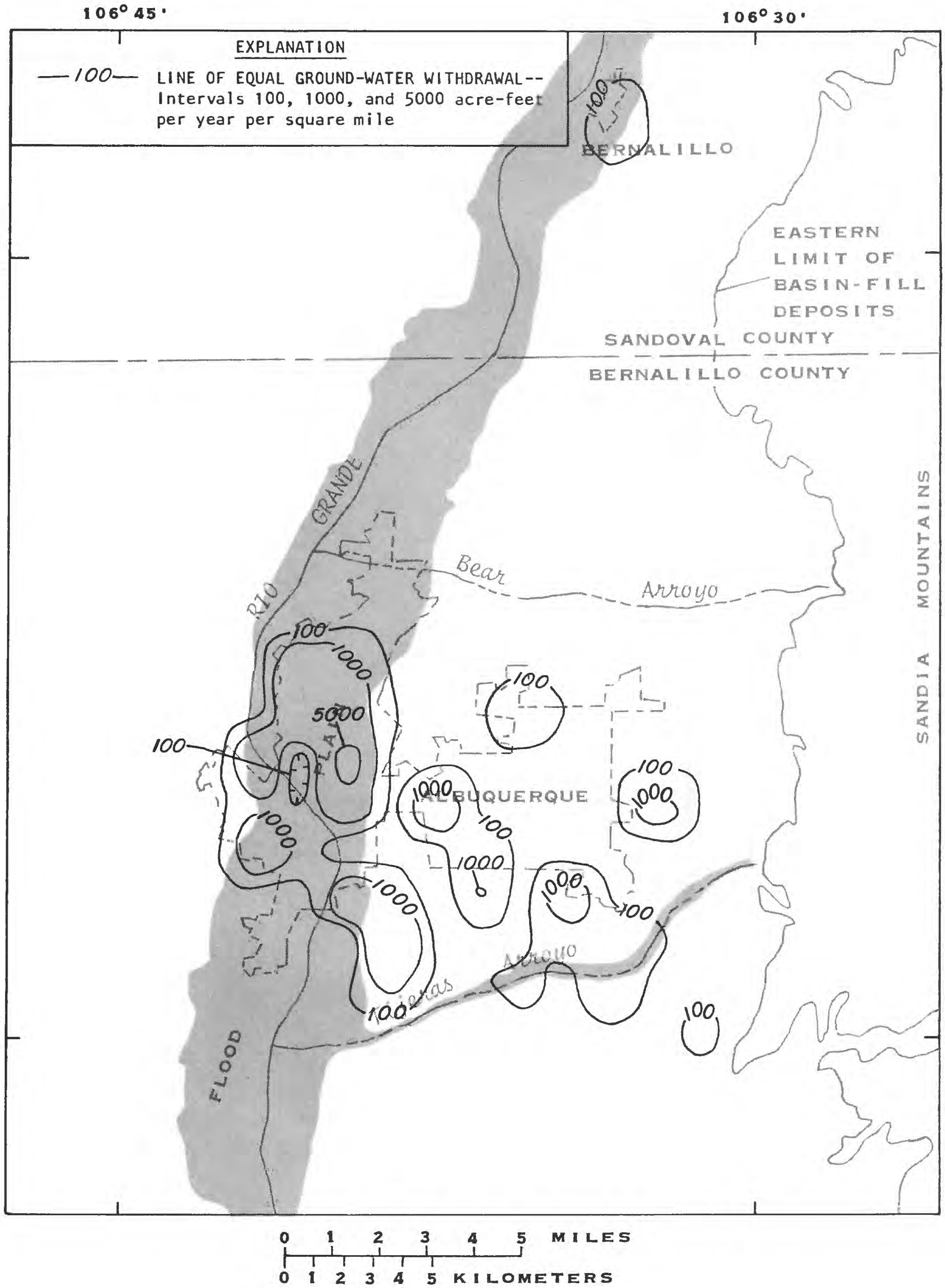


Figure 14.--Average ground-water withdrawal in the Albuquerque area, 1956-59.

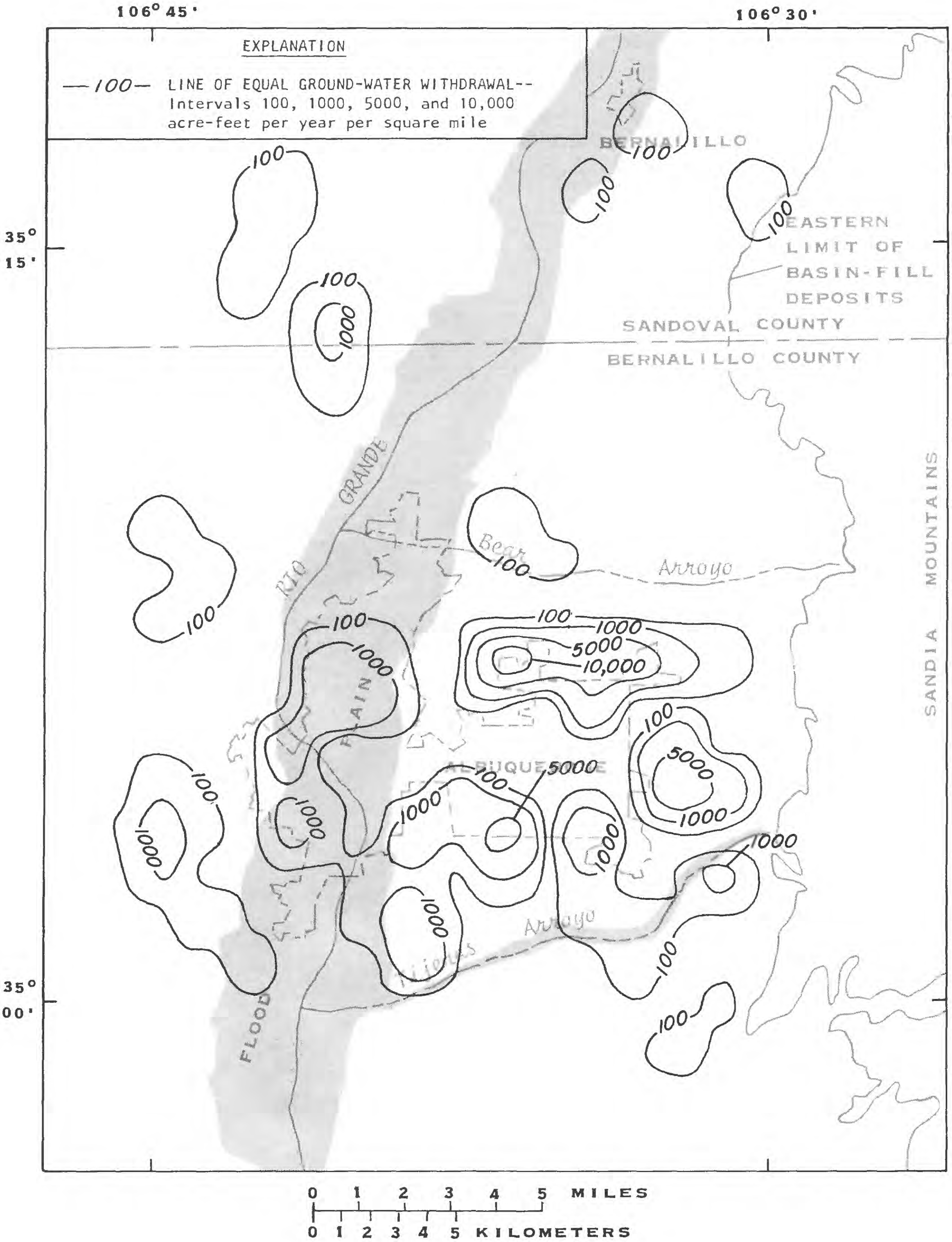


Figure 15.--Average ground-water withdrawal in the Albuquerque area, 1976-79.

The annual ground-water withdrawal in the Albuquerque-Belen Basin increased from about 44,200 acre-feet during 1959 to 76,500 acre-feet during 1969. The total ground-water withdrawal continued to increase at a nearly constant average rate after 1969. Although ground-water withdrawal from the East Mesa now supplies most of Albuquerque's ground-water needs, the current (1985) rapid expansion of the Albuquerque urban area on the west side of the Rio Grande is shifting the distribution of ground-water withdrawal in that direction.

The design and construction of the producing wells and well fields also have changed during the last 30 years. The development of more powerful pumps and the need to drill fewer, but more productive wells in areas where the depth to water generally exceeds 450 feet have led to greater well depths, longer perforated intervals, wider spacing between wells, and larger capacities. The principal result of these changes has been the withdrawal of more ground water from a larger area and greater thickness of the aquifer.

Source and Nature of Ground-Water-Withdrawal Data

Data on ground-water withdrawal in the Albuquerque-Belen Basin were assembled from records of the New Mexico State Engineer Office, District 1, Albuquerque, and from published technical papers, historical summaries, and legal notices. The State Engineer Office provided a list of water users, their allowed diversion, and metered ground-water withdrawal for 1978-81 and allowed use of documents on file at the Albuquerque office. The data contained in the documents consist of: (1) Records of metered wells for 1959-81; (2) well-location and completion data from driller's reports, lithologic logs, electric logs, and well-maintenance reports; and (3) historical water-use data for 1907-58, consisting of applications for water-use permits, documentation from water-rights cases, and from other legal and historical documents.

The 1978-81 list of ground-water users provided by the State Engineer Office served as a starting point for the compilation. The available data for each user were recorded and summarized. The information obtained generally included the items in the following list:

1. The State Engineer Office file number.
2. Location of well(s).
3. Metered annual ground-water withdrawal (1959-81).
4. Allowed diversions (throughout the period of record).
5. Dates drilled, permitted, abandoned, or maintained.
6. Well-construction information (total depth, casing diameter, perforated interval).

Information about specific capacity, reported initial water level, and pump capacity also was obtained where available. Historical references to established ground-water use and the origin of rights and permits also were obtained and were helpful in reconstructing estimates of ground-water withdrawals prior to 1959.

Records prior to 1959 generally were incomplete; ground-water withdrawal, well construction, and the dates drilled, abandoned, or repaired commonly required some estimation. Records for 1959-79 usually were complete; however, records for 1980-81 contained many omissions, probably because of the backlog of information to be processed.

Methods of Estimation

Data for 1959-79 served as the basis on which estimates and extrapolations of ground-water withdrawals for earlier times were made. The data were not extrapolated to provide estimates after 1979. Data on ground-water withdrawals for 1959-79 consisted of metered discharges. The records occasionally contain periods of unreported withdrawals, but the State Engineer Office personnel usually had already provided estimates for withdrawals for those periods. Additional estimates were completed by interpolation between periods of known withdrawals.

Occasionally, the available data were insufficient to allow interpolation. In these cases, ground-water withdrawal was estimated from the user's allowed diversion. The available information on allowed diversions and metered ground-water withdrawals by major users in the Albuquerque-Belen Basin in 1981 indicates that for municipal water systems, water cooperatives, and real-estate developments actual ground-water withdrawal can be estimated as 60 percent of the allowed diversion. Industrial ground-water withdrawal can be estimated as 25 percent of the allowed diversion. This method was rarely used in estimating ground-water withdrawals for 1959-79, but was of importance to estimates prior to 1959 when withdrawal data were incomplete.

A more common problem was that the user reported total well-field production rather than the withdrawal from individual wells. The withdrawal from individual wells in well fields was estimated by one of two methods. The more common method was to divide the well-field production by the number of producing wells in the field. Some well fields, however, that were developed during a number of years contained wells of significantly different construction and capacity and have records indicating different rates of withdrawal from different wells. The method of estimating withdrawal of individual wells in these cases was to divide the total well-field production between the producing wells in proportion to the capacity and operating history of the wells.

Well-construction data are available for many of the major water wells in the Albuquerque-Belen Basin. However, data commonly are not available for small wells and wells completed and abandoned prior to 1959. These data were needed to determine the distribution of stress to specific model layers. The information available from the State Engineer Office indicates that most wells drilled within an area for the same purpose tend to have similar construction. This is particularly true of wells drilled by the same contractor. These tendencies were used to estimate the well depth and perforated interval when necessary.

A water right is granted to a user for a specific beneficial use within the regulated basin. This right can be relocated from one well to another that may not necessarily be nearby or of similar construction. Therefore, well-completion data are very important. Unfortunately, the dates on which wells were placed in service, abandoned, or repaired are the most common omissions from the available records. Whereas the records are relatively complete regarding the date completed, the actual dates on which withdrawal began or stopped and the dates of any repairs or modifications are rarely included. These dates generally were estimated from the earliest and latest production records available, the time of development in the area of the well, or the dates on which water rights or permits were granted, transferred, or altered.

Omissions and Data Accuracy

Some ground-water withdrawal data that were omitted from this compilation are: (1) Withdrawal from wells on Indian pueblos, (2) withdrawal from areas of the basin south of Bernardo, and (3) withdrawal by users with rights or permits of 3 acre-feet per year or less. Ground-water withdrawals on Indian pueblos and south of Bernardo were not reported in the State Engineer Office records. However, the volume of ground-water withdrawal in these areas is thought to be small, and its omission is not likely to introduce significant error in the simulation.

Ground-water withdrawals by users with rights or permits of 3 acre-feet per year or less, generally from domestic and small irrigation wells, also were omitted. Although the number of users with rights or permits of 3 acre-feet per year or less comprised 38 percent of the active ground-water users in the Albuquerque-Belen Basin in 1980, the total withdrawal by those users was only 0.07 percent of the total ground-water withdrawal of about 104,000 acre-feet. Five percent of the ground-water users in the Albuquerque-Belen Basin withdrew more than 93 percent of the total. One user, the city of Albuquerque, accounted for 87 percent of the total. The omission of withdrawals by users with rights or permits of 3 acre-feet per year or less has only a minor effect on the magnitude and distribution of ground-water withdrawal in the basin. However, this omission does create a systematically smaller estimate of ground-water withdrawal, with an error that is insignificant in estimates for 1959-79, but may be much more significant in estimates of early withdrawal particularly prior to 1947.

The omission of some users from the compilation may represent only a small part of the error that occurs in the process of estimating ground-water withdrawal. The major sources of error in the reported data are expected to be in the accuracy of user-supplied estimates and in the accuracy of flowmeters. The minimum error is established by the accuracy of a typical flowmeter, or probably about plus or minus 20 percent. The overall error of the reported data is estimated to range from 0 to plus 100 percent prior to 1947, from plus 60 percent to minus 40 percent for 1948-58, and plus or minus 30 percent for 1959-79. Although the actual errors only can be subjectively estimated, the following generalizations can be made from the analysis of pumpage data:

1. Well-maintained records for 1959-79 provide the most accurate information.
2. Records and estimates from users closely monitored by the State Engineer Office are likely to be more accurate than those from users not monitored. (Major municipal producers were closely monitored, whereas government and industrial users commonly were not monitored.)
3. The omission of some users creates a systematically smaller estimate of total ground-water withdrawal that may be significant in older records.

DESCRIPTION OF THE MODEL

Flow Equation and Computer Programs

Two ground-water-flow model programs were used during the course of this investigation. The first program, written and documented by Posson and others (1980), was used to complete a steady-state simulation (Kernodle and Scott, 1986) and also was used in early simulations of transient ground-water flow. The second program, written by McDonald and Harbaugh (1983), was used to complete the transient simulations and to perform sensitivity analyses. Although the programs are quite different, the basic equation of ground-water flow is the same, as is the solution algorithm. The conversion from one program to the other was made for two reasons: (1) Greater public access to the McDonald and Harbaugh (1983) model, and (2) a decrease in processing time and a consequent decrease in cost. The equation that was solved for three-dimensional flow of ground water in a porous medium by the McDonald and Harbaugh model (1983) is:

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

where

K_{xx}, K_{yy}, and K_{zz} are the hydraulic conductivities in the x, y, and z directions (L/T);

h is the hydraulic head (L);

S_s is the specific storage (1/L);

$W(x,y,z,t)$ is the volume of water released from or taken into storage per unit volume of the porous medium per unit time, and is a source-sink term (1/T); and

t is time (T).

The strongly implicit procedure (SIP) was used in both programs to solve the matrix of equations that describe flow and hydraulic head at each of the model cells. A comparison run was made at the time of the conversion to verify that the two programs produced identical results.

Assumptions for Simulation of Transient Conditions

A model that simulates transient conditions in an aquifer system commonly uses a steady-state solution as an initial condition. Three additional variables (time, aquifer storage, and, most importantly, a change in applied stress) are introduced in the transient simulations. A change in applied stress, usually but not necessarily pumped withdrawals, is required to disrupt the equilibrium of the steady-state simulation and produce transient conditions in simulated ground-water flow and hydraulic head. The simulated response may be compared with reported or measured responses, and simulated aquifer properties altered to improve the comparison. Depending on which simulated properties are altered, the steady-state or initial-condition simulation may evolve along with the transient simulation during the calibration process.

The assumptions that were made for simulations of transient ground-water flow in the Albuquerque-Belen Basin include most of the assumptions that were made for the steady-state model (Kernodle and Scott, 1986). They are as follows:

(1) The surface-water system and the ground-water system within the Rio Grande flood plain are hydraulically connected such that depletion from the flood-plain alluvium is compensated by approximately equal depletion from the Rio Grande, and the time lag is considered negligible.

(2) The average stage of the Rio Grande and grade levels in the drains remain constant with time, and the river flows continuously throughout the basin.

(3) Ground-water underflow does not occur across the east and west boundaries, and only a small volume of underflow occurs from the San Juan Basin across the northwest boundary.

(4) Hydraulic conductivity is not affected by compaction of the aquifer and increase in temperature at depth.

Model Grid

The area to be simulated by a finite-difference ground-water-flow model must be subdivided into a grid of rectilinear cells defined by rows, columns and, for a three-dimensional model, layers. The surface expression of the model grid used for simulation of transient ground-water flow in the

Albuquerque-Belen Basin is shown in figure 16. The grid within the flow region is identical to the one used in the steady-state simulation of Kernodle and Scott (1986). The model grid has 41 rows, 65 columns, and 6 layers, and the cell size is smallest in areas of greatest information and concern. The smallest cells, 0.5 mile on a side, represent the aquifer in the vicinity of Albuquerque. The largest cells, 3 by 6 miles, represent undeveloped areas where little data are available. Layer thickness increases from 200 feet in the top layer (layer 1) to 2,250 feet in the bottom layer (layer 6) of the model. The total thickness of simulated aquifer is 6,075 feet. With the exception of an eastward-dipping zone of low hydraulic conductivity, the model layers are not intended to represent vertically zoned aquifer properties, but are intended to allow simulation of vertical flow within a homogeneous but anisotropic aquifer.

Analysis with the previous steady-state model (Kernodle and Scott, 1986) indicated that the deep part of the basin (layer 6 of the model) had little influence on the upper flow system. The lower layers were maintained for the transient analysis because the storage in those layers may affect long-term simulations discussed later in this report.

Representation of Boundaries

The model is capable of simulating several types of boundaries: specified flux (including no flow), specified hydraulic head (or simply specified head), and hydraulic-head-dependent flux. With these three general boundary types, a considerable range of conditions can be simulated: recharge and discharge wells, tributary and mountain-front recharge, impermeable barriers, interaction with lakes and perennial streams hydraulically connected with an aquifer, evapotranspiration, interaction with surface-water bodies with clogged beds or channels, and ephemeral streams or drains.

The model of the Albuquerque-Belen ground-water basin uses specified-flux and specified-head boundaries. The location and type of boundaries used in the topmost layer of the ground-water-flow model are shown in figure 16. The remaining modeled area is enclosed by no-flow boundaries whose locations were described earlier as the limits of the ground-water basin. No-flow boundaries also are located within the modeled area. These internal no-flow boundaries represent fissure-flow volcanic rocks of the Cat Hills, Los Lunas, and Albuquerque volcanic centers.

Within the exterior no-flow boundaries are specified-flux boundaries that represent the estimated tributary and mountain-front recharge (fig. 12). This recharge is estimated for segments of a tributary reach or basin boundary and distributed to the flux-boundary cells in proportion to the length of reach or basin boundary defined by the cell.

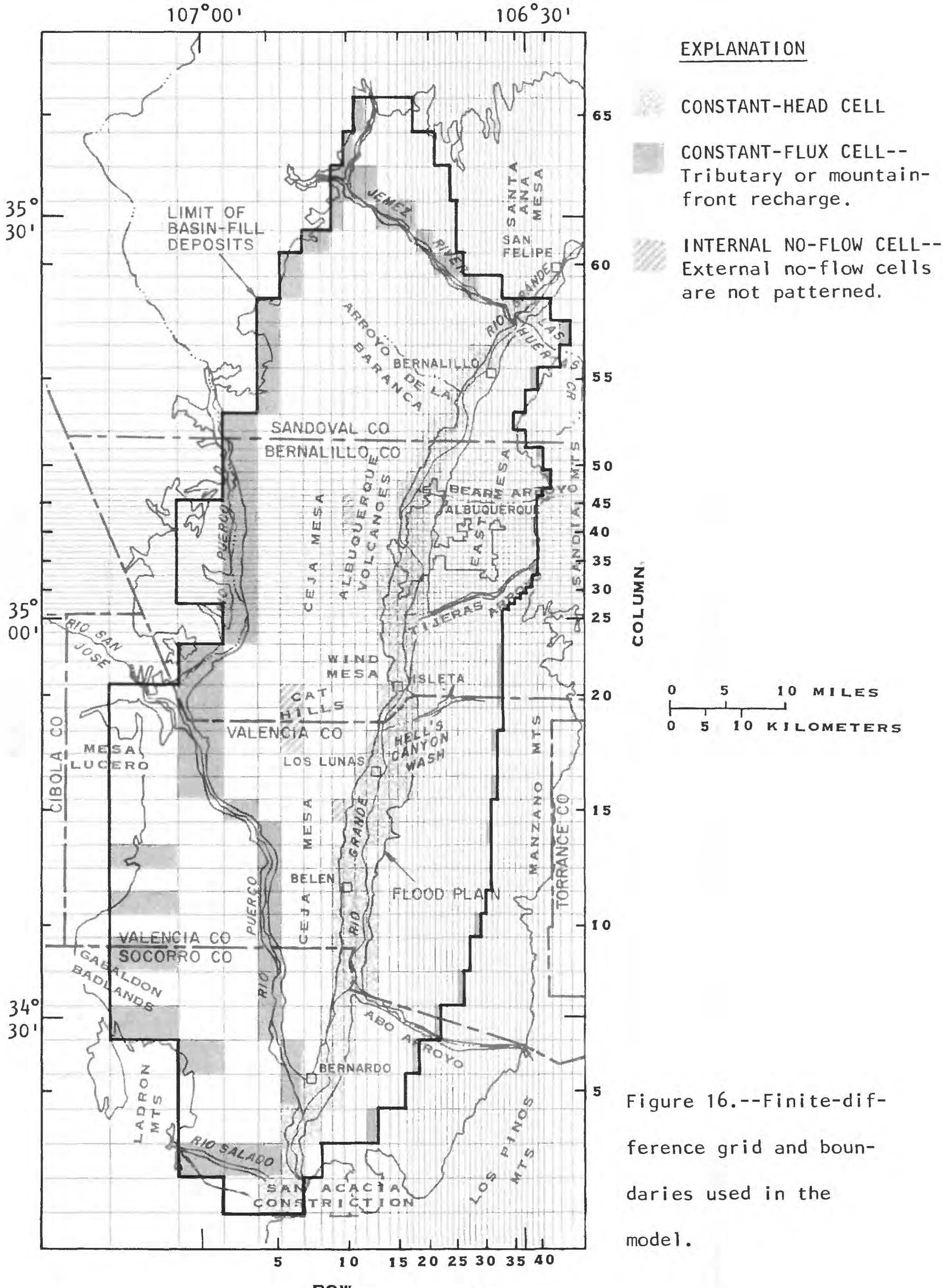


Figure 16.--Finite-difference grid and boundaries used in the model.

Specified-head cells are used to represent the stream and aquifer subsystems of the Rio Grande, its flood plain and flood-plain alluvium. Use of specified-head boundaries in the simulation is appropriate for 1907-61 for the following reasons: (1) Although the stream-aquifer subsystem in the flood plain is dynamic, the hydraulic heads were virtually unchanged from one year to the next; and (2) the surface-water system had ample water to maintain these hydraulic heads and meet the demands of evapotranspiration and seepage loss to ground water. Use of specified-head boundaries to represent the stream-aquifer subsystem within the flood plain has the advantage of simplifying the data requirements of the model; evapotranspiration and routing of surface flows are eliminated from the simulations. The use of specified-head boundaries to represent flood-plain alluvium and interaction of surface and ground water in the flood plain has the disadvantage of not allowing the simulation to quantify relationships between components of the surface-water and ground-water systems.

Model Parameters

In addition to hydrologic variables included as parameters in the steady-state model, the additional parameters of time, aquifer storage, and changing stress are included in transient simulations. Aquifer systems do not adjust instantly to a change in stress; rather, aquifer storage serves as a buffer that moderates and delays the responding change in hydraulic head. Time and aquifer storage are components of one term in the equation of ground-water flow. Once there is a stress on the aquifer system, time and aquifer storage become essential in the description of transient-flow conditions in the aquifer.

Time needs to be discretized for the model, just as space is discretized into cells. Each time interval represents a period in which changing stresses may be approximated by a single average value. Rapidly changing stress may dictate the use of many short time intervals and, conversely, a period of slow change in stress may be approximated by relatively few long time intervals. The end of a time interval also may be defined to correspond with a time of known water-level conditions in order to allow comparison between simulated and reported or measured hydraulic heads.

Model parameters are grouped into three categories: those that describe aquifer properties (including boundaries), those that quantify external influences (stresses) on the aquifer, and those that satisfy the operational or numerical requirements of the computer program. Among the simulation parameters that describe aquifer properties are vertical and horizontal hydraulic conductivity, anisotropy, specific storage, and specific yield. The density and viscosity of the water also affect flow, but are assumed to be uniform in space and constant in time. Aquifer properties in the basin, other than storage, were discussed at length in Kernodle and Scott (1986).

The second category, external stresses, was described in the sections on ground-water withdrawal and ground-water movement. The stresses include pumped withdrawals from wells, tributary and mountain-front recharge, and evapotranspiration. Recharge is assumed to be constant, and evapotranspiration from the flood plain is assumed to have no time-dependent effect on ground-water levels in the flood-plain alluvium. Changing pumped withdrawals are the external stresses that cause changes in ground-water flow in the flow model of the Albuquerque-Belen Basin.

The most significant requirement of the numerical solution is the discretization of space and time. The orientation of the model grid and the size of the cells of a finite-difference model affect the accuracy of the location of simulated boundaries and the degree of correspondence between cell-centered, simulated hydraulic heads and the actual location of wells with reported or measured hydraulic heads. Likewise, the choice of thicknesses of model layers in a three-dimensional system has an effect on the correlation between simulated and reported or measured hydraulic heads. Although the most accurate simulations are obtained by using a fine grid and short time intervals, concessions are made to computer capability and the geometric increase in processing time and expense needed for increased model refinement.

Adaptation of Historical Ground-Water-Withdrawal Data to the Transient Model

The completed compilation of ground-water-withdrawal data for the Albuquerque-Belen Basin consisted of the location, producing intervals, and measured or estimated annual withdrawal for 234 wells from 1907 through 1979. These data were adapted to the three-dimensional, finite-difference grid of the Albuquerque-Belen Basin model, and a discretized time frame was selected to allow simulation of ground-water withdrawal as it changed in distribution and magnitude.

The first step in the adaptation was to locate each well by the row, column, and layer indices of the model. These indices and information available on the construction and use of the wells were used to construct a table of the time and locations of withdrawals. Withdrawal cells in the top layer of the model grid within the Rio Grande flood plain (which is simulated as a specified-head boundary) were omitted. The entry for each well contained the proportion of the perforated interval in the cell and the proportion of the allowed diversion used (where necessary) to estimate the well's total production.

The second step in the adaptation was to construct a table of time-dependent data. The table contained a list of periods (in calendar years) during which a single value for annual ground-water withdrawal could be applied for each well and within each period the measured ground-water withdrawal, the estimated ground-water withdrawal, or the allowed diversion.

The third step in the adaptation was to define a set of stress periods during which ground-water withdrawal could be reasonably approximated as being constant. The divisions between stress periods were chosen to coincide with times of major changes in the volume or location of ground-water withdrawal. Thus, the duration of a stress period was shortest when those changes were most frequent. Ten stress periods were defined from 1907 through 1979 (fig. 17). The data available for comparison to the model results did not justify a more detailed breakdown. The stress periods are:

1. 1907-31
2. 1932-47
3. 1948-50
4. 1951-55
5. 1956-59
6. 1960-61
7. 1962-65
8. 1966-69
9. 1970-75
10. 1976-79

The tables and stress periods were combined to construct computer files in appropriate units and formats for direct entry to the model code. Values used in the model are listed in tables 6 and 7 (Supplemental Information at the back of report). Total withdrawals, as used in the model, are compared to actual values in figure 17.

Calibration Process

Calibration of a ground-water-flow model is, in the strictest sense, impossible to obtain. The following paragraph from Bredehoeft, Neuzil, and Milly (1983, p. 30), a good description of the process and problems of calibration, illustrates that calibration is a function of the degree of understanding of the system.

> "We have presented numerical flow simulations which reproduce the regional potentiometric head distribution in the aquifers reasonably well. The fact that one can reproduce the observed hydraulic data using a conceptual model of the ground-water flow system does not prove that the model is correct; it merely shows that it is consistent with the data. In many, if not most, ground-water systems, sufficient degrees of freedom exist so that a unique solution cannot be determined. A potential means of eliminating one or more of the feasible models is to impose more constraints; that is, one must make use of additional information in testing for feasibility. Depending on the extent to which a model is consistent with the new observed data, it may be retained, modified, or discarded."

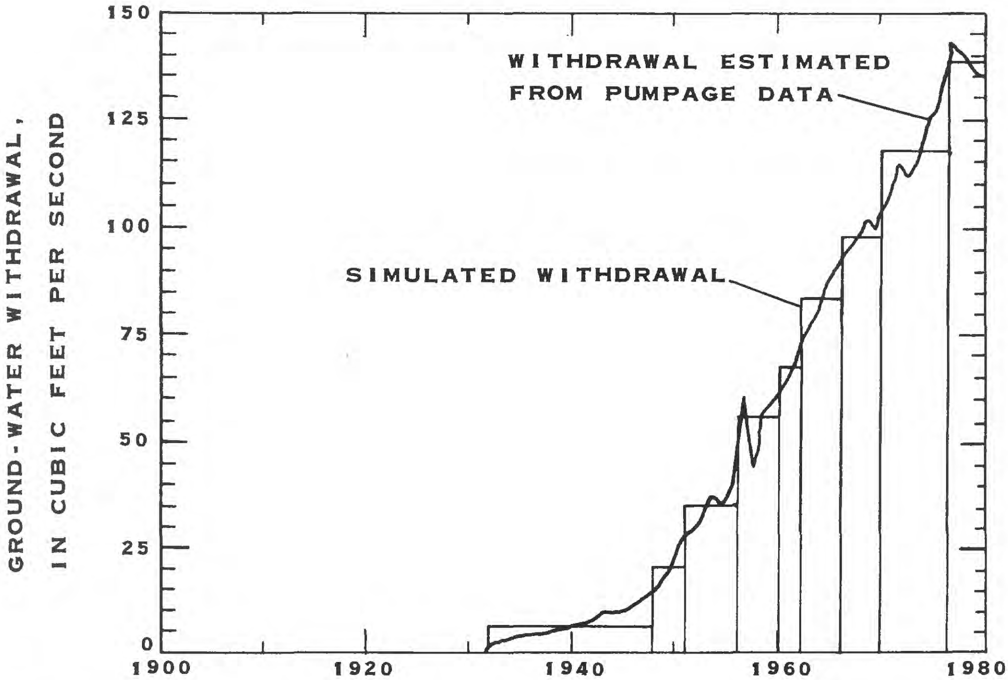
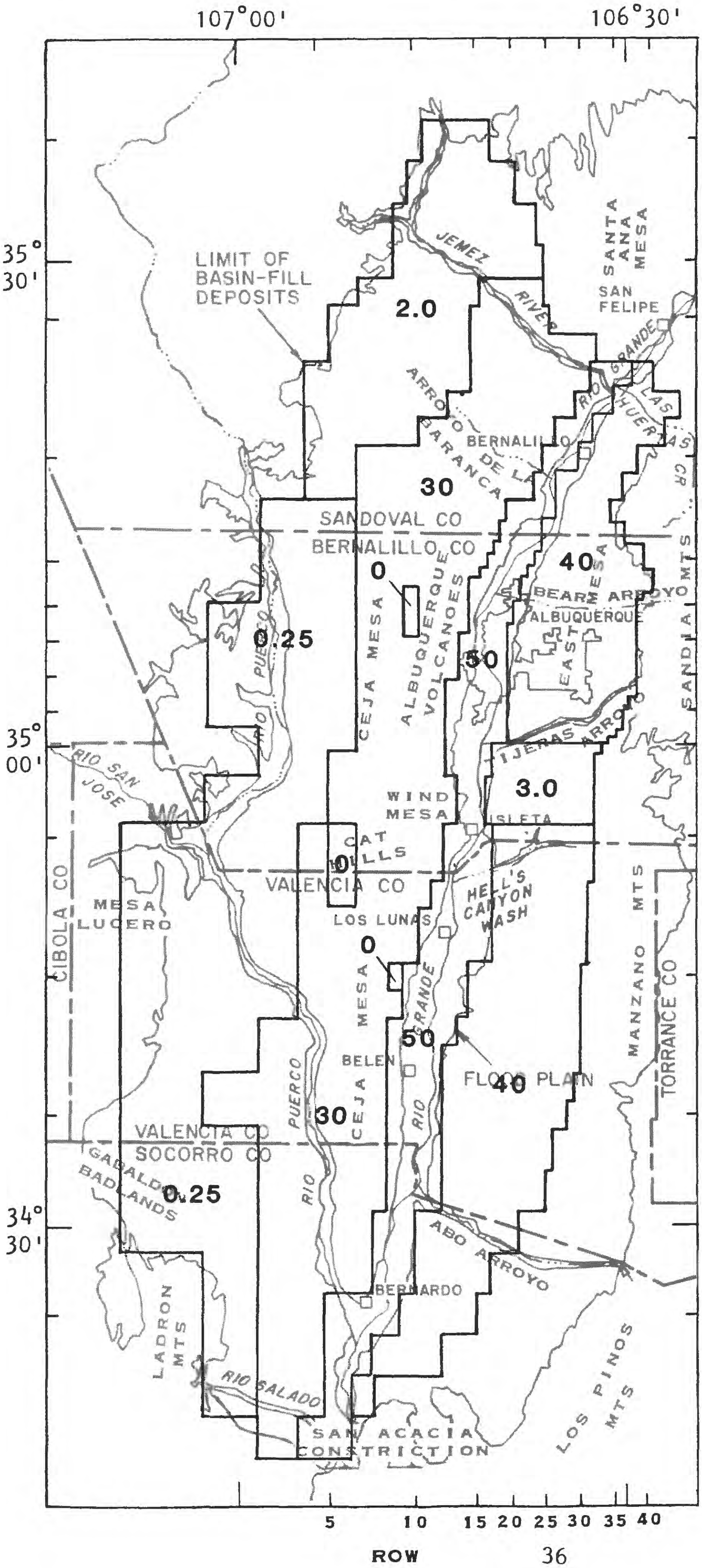


Figure 17.--Discretized ground-water withdrawals as simulated in the transient model and actual ground-water withdrawals, 1907-79.

The additional information incorporated in the model of transient ground-water flow (time-dependent ground-water withdrawals and aquifer storage) forced minor modification of the steady-state ground-water-flow model of the Albuquerque-Belen Basin. The conceptual model of the overall system remained unchanged, and only the values of hydraulic conductivity in two areas of the model required modification. The simulated values of hydraulic conductivity assigned to each of the six model layers are shown in figures 18 through 23. The changes from the steady-state model are a decrease in simulated hydraulic conductivity in all model layers from 50 to 40 feet per day in the area east of and beneath the flood plain and an increase in simulated hydraulic conductivity from 20 to 30 feet per day west of the flood plain. The ratio of vertical to horizontal hydraulic conductivity remained at 1:500. Initial estimates of aquifer storage proved to be acceptable; the top layer was assigned a specific yield of 0.10 and the lower five layers were assigned storage coefficients based on their individual thickness multiplied by an estimated specific storage of 10^{-6} per foot.

During calibration, simulated hydraulic heads were compared with reported or measured hyraulic heads for 34 wells (with 37 data values) for 1961. The reported or measured hydraulic heads were the same as those used for the steady-state analysis. Calibration of the transient model was an iterative process consisting of a steady-state simulation with modified simulation parameters followed by a transient simulation to 1961. The steady-state part of the simulation used a constant value of transmissivity in the top layer and zero storage in all layers; in the transient part of the simulation, transmissivity in the top layer was allowed to vary as a function of saturated thickness. Storage in the top layer was treated as being due to water-table gravity drainage (specific yield), whereas the other layers were simulated as having artesian storage that varied as a function of the thickness of aquifer represented by each layer. A comparison of the altitude of simulated and reported or measured hydraulic heads is presented in table 2.

For 1960-61 the accepted model resulted in a mean absolute error of 14.1 feet for the 34 wells that had reported or measured hydraulic heads. In the urban Albuquerque area, which was the area of the greatest transient stress and had the most dense and reliable information, the mean absolute error was only 8.9 feet. Changes performed during the calibration process were made with the intent to preserve that match. The area with the greatest mean absolute error (25.1 feet) was the northwest quadrant of the basin. Some of the error in the western part of the modeled area, where there are steep gradients, may be caused by discretization error due to large grid cells. Because of minimal hydraulic-head data and lack of significant transient stress in this area, the model is still accepted as reasonable.

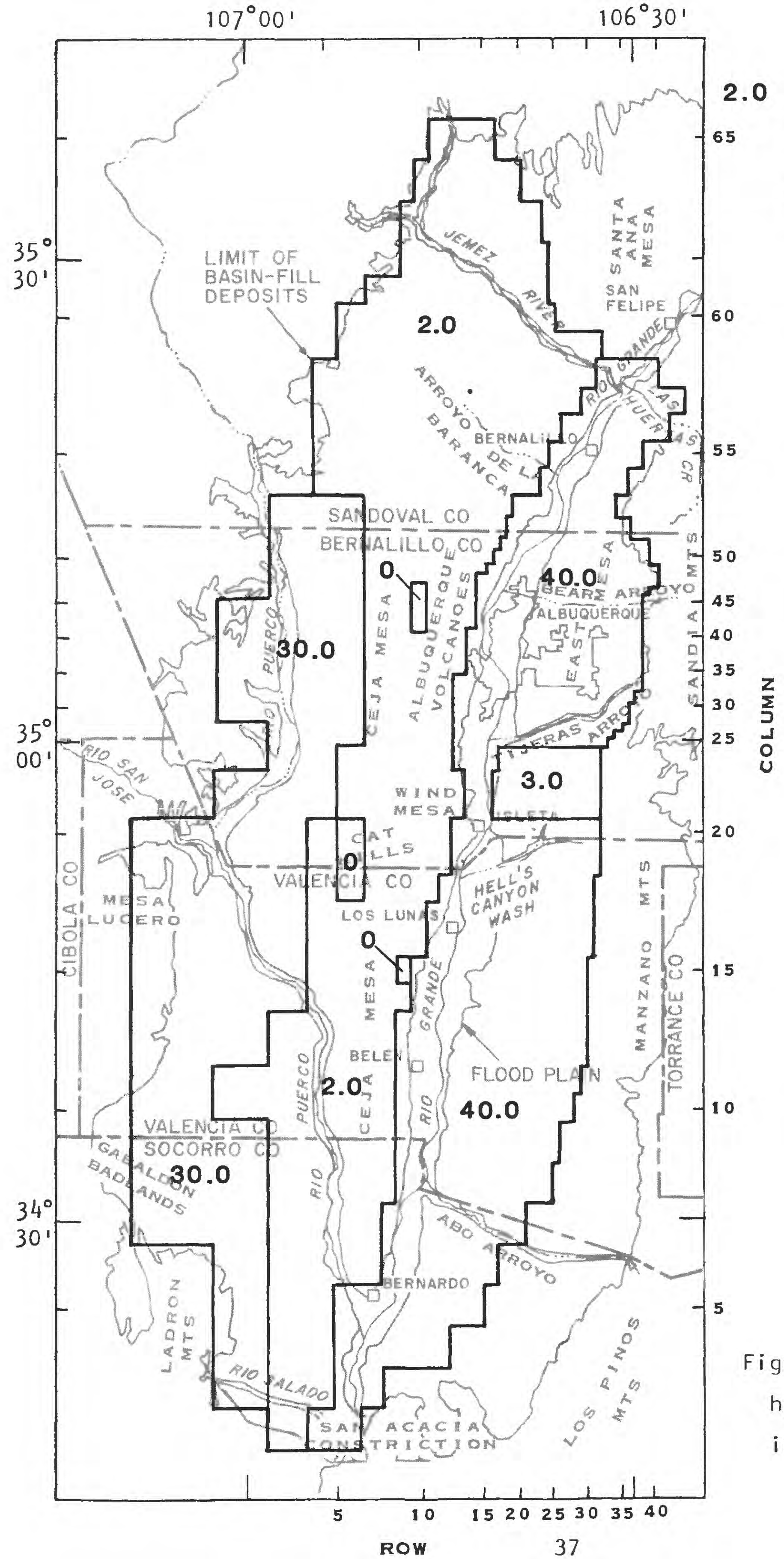


EXPLANATION

2.0 VALUE OF SIMULATED HYDRAULIC CONDUCTIVITY FOR DESIGNATED BLOCK, IN FEET PER DAY--Thickness of layer is 200 feet.

0 5 10 MILES
0 5 10 KILOMETERS

Figure 18.--Simulated hydraulic conductivity in layer 1 (top layer) of the model.



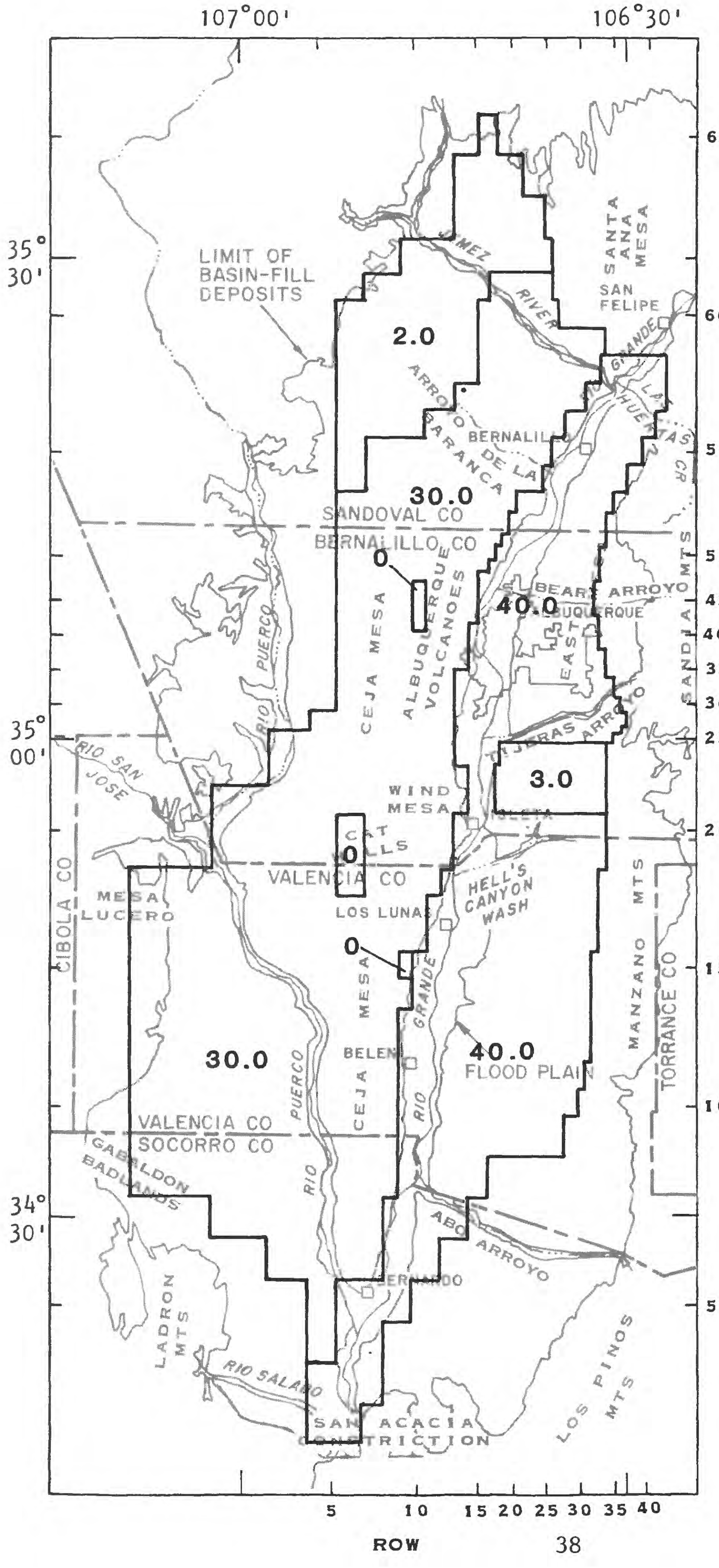
EXPLANATION

2.0 VALUE OF SIMULATED HYDRAULIC CONDUCTIVITY FOR DESIGNATED BLOCK, IN FEET PER DAY--Thickness of layer is 450 feet.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 19.--Simulated hydraulic conductivity in layer 2 of the model.



EXPLANATION

2.0 VALUE OF SIMULATED HYDRAULIC CONDUCTIVITY FOR DESIGNATED BLOCK, IN FEET PER DAY--Thickness of layer is 675 feet.

0 5 10 MILES
0 5 10 KILOMETERS

Figure 20.--Simulated hydraulic conductivity in layer 3 of the model.

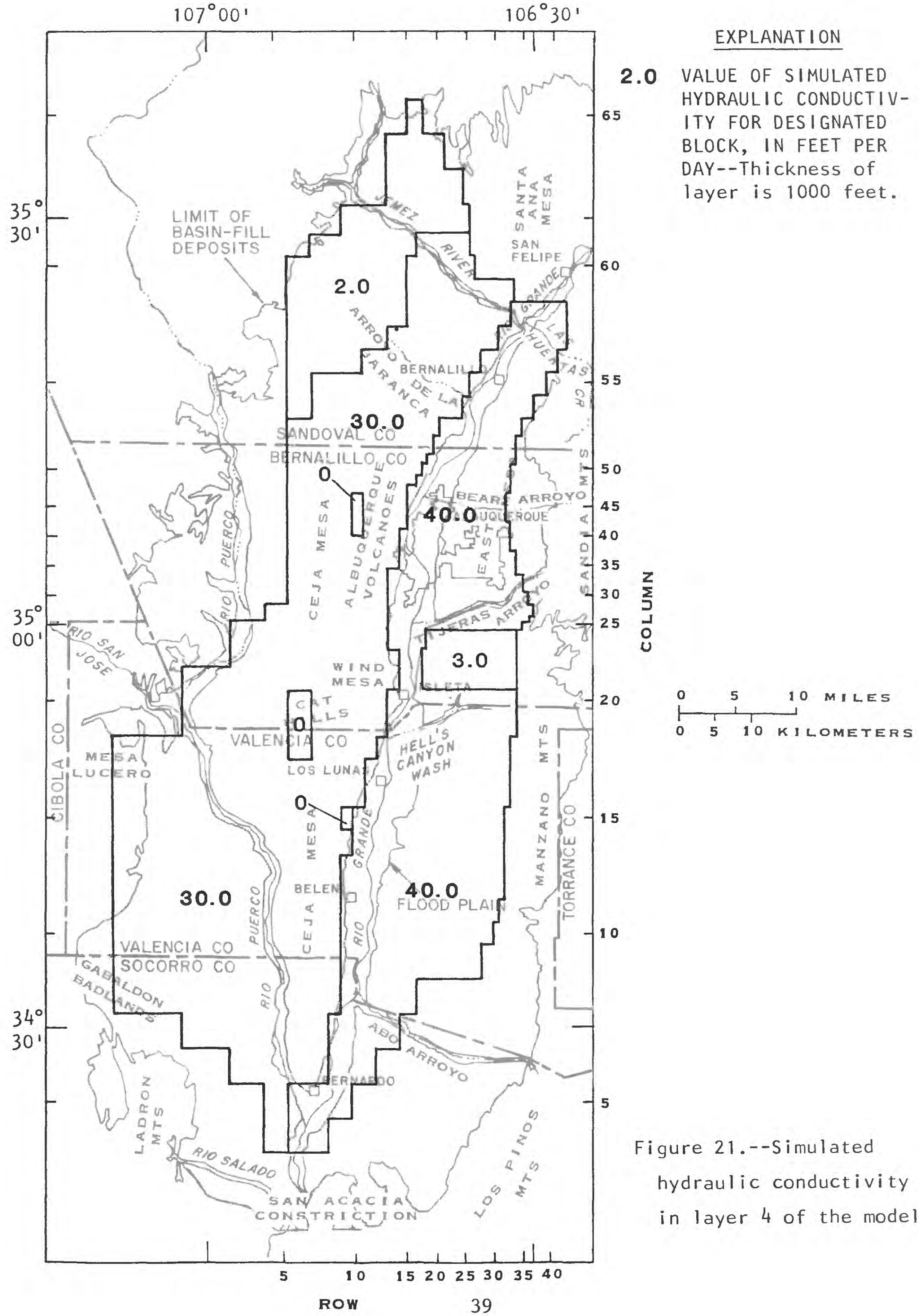


Figure 21.--Simulated hydraulic conductivity in layer 4 of the model.

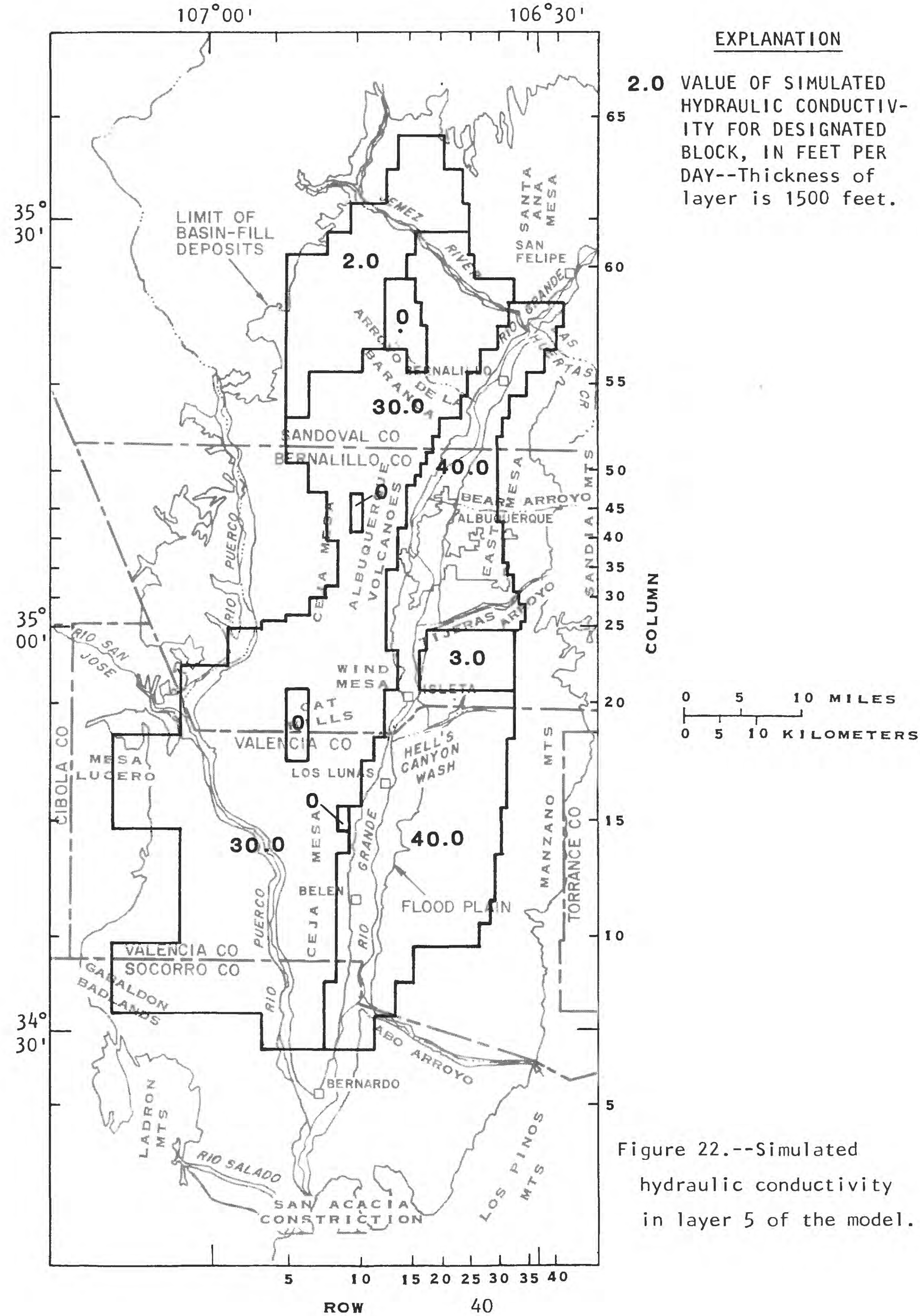
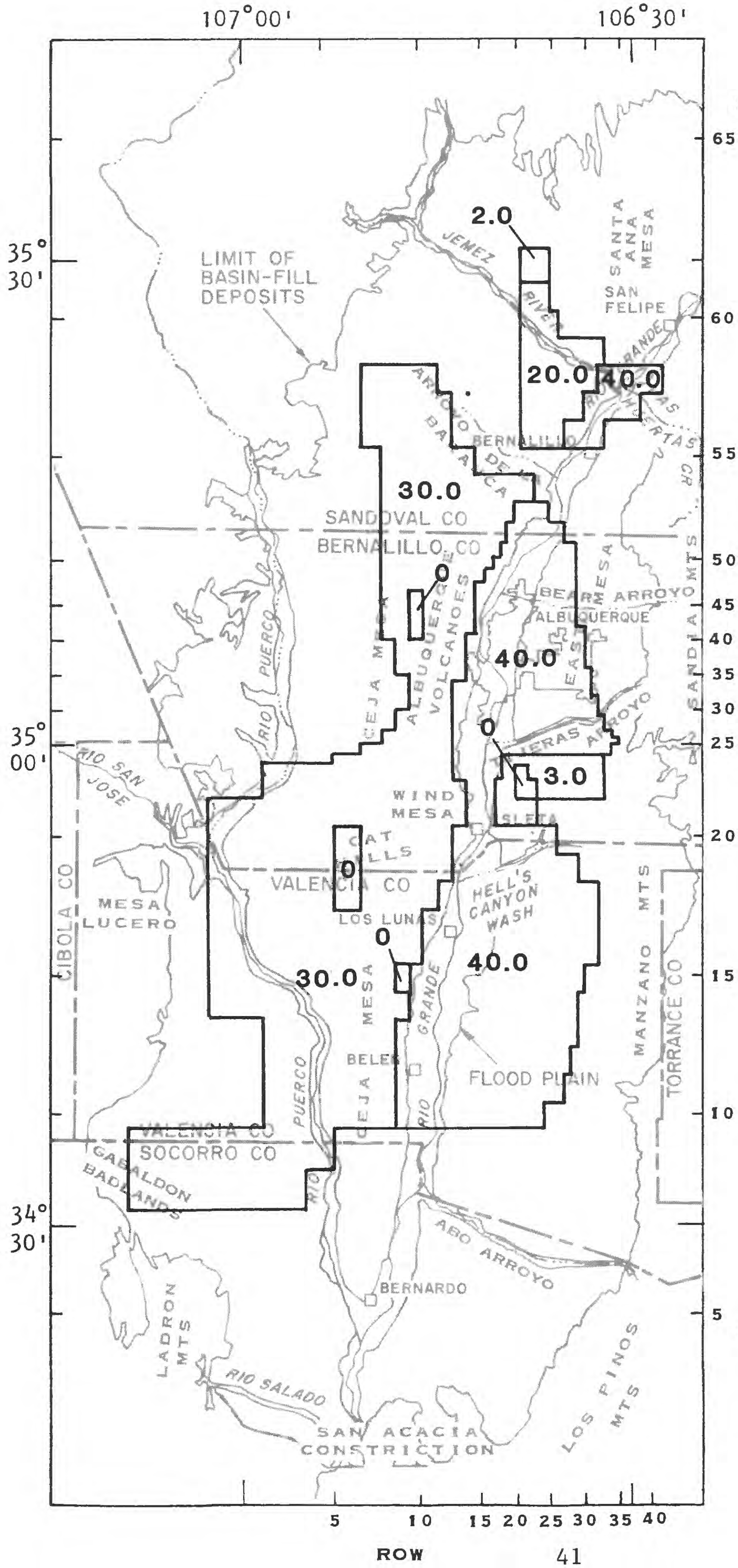


Figure 22.--Simulated hydraulic conductivity in layer 5 of the model.



EXPLANATION

2.0 VALUE OF SIMULATED HYDRAULIC CONDUCTIVITY FOR DESIGNATED BLOCK, IN FEET PER DAY--Thickness of layer is 2250 feet.

0 5 10 MILES
0 5 10 KILOMETERS

Figure 23.--Simulated hydraulic conductivity in layer 6 (bottom layer) of the model.

Table 2. Altitude of simulated and reported or measured hydraulic heads at the 34 control wells

[Altitudes are in feet above sea level. The difference listed is the difference, in feet, between simulated and reported or measured hydraulic heads]

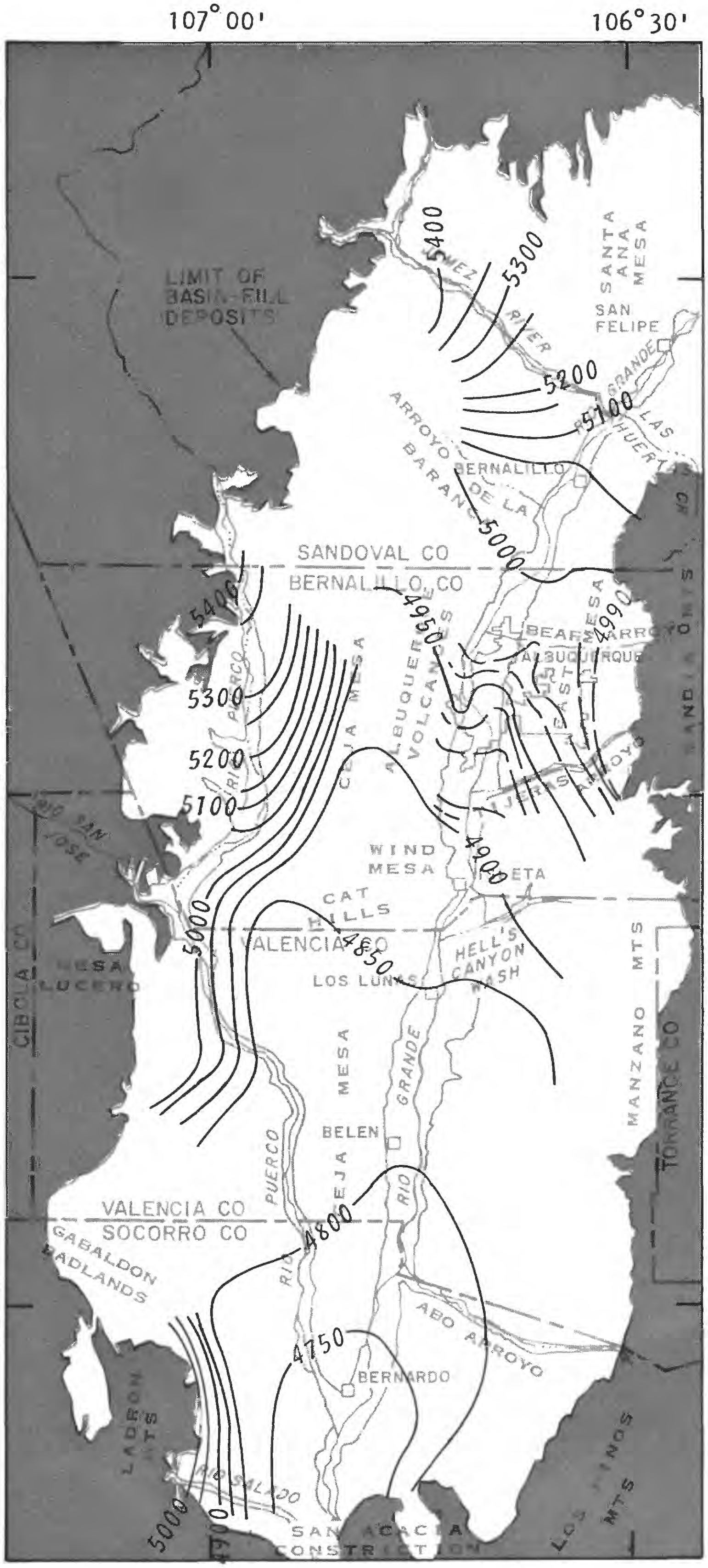
Land-net location	Node location (row, column)	Altitude of simulated hydraulic head	Altitude of reported or measured hydraulic head	Difference (feet)
Layer 1				
3N.1W.35.430	4, 6	4774	4765	9
4N.1E.9.324	6, 9	4796	4798	-2
6N.1E.5.412	6,16	4846	4832	14
10N.1E.22.322	7,38	4938	4907	31
12N.1E.22.222	7,54	4988	4955	33
10N.1E.26.343	8,36	4933	4899	34
11N.1E.26.424	8,48	4962	4942	20
8N.1E.1.342	9,22	4892	4888	4
9N.1E.25.241	9,25	4905	4871	34
11N.2E.18.313	9,50	4971	4962	9
11N.2E.22.441	13,49	4975	4967	8
3N.2E.26.330	14, 6	4767	4765	2
5N.3E.19.212	18,12	4825	4798	27
14N.3E.6.423	18,62	5273	5298	-25
8N.3E.32.412	20,20	4872	4864	8
12N.3E.8.233	20,55	5029	5008	21
10N.3E.21.223	22,39	4942	4952	-10
10N.3E.3.412	24,44	4960	4969	-9
13N.3E.3.223	24,59	5133	5141	-8
8N.3E.14.231	26,21	4922	4936	-14
10N.3E.1.114	27,45	4969	4956	13
9N.3E.36.211	29,24	4958	4944	14
12N.4E.32.242	33,53	5017	4987	30
9N.4E.15.311	35,28	4961	4964	-3
Layer 2				
11N.2E.18.313	9,50	4967	4946	21
11N.3E.18.411	17,50	4977	4967	10
10N.3E.27.243	24,36	4940	4945	-5
14N.3E.3.434	24,61	5130	5145	-15
10N.3E.35.111	25,35	4940	4954	-14
10N.3E.36.132	27,34	4942	4942	0
9N.3E.1.222	29,33	4945	4948	-3
10N.4E.32.433	32,33	4952	4955	-3
10N.4E.34.214	36,35	4972	4984	-12
10N.4E.5.122	36,45	4989	4965	24
Layer 3				
11N.2E.18.313	9,50	4964	4946	18
11N.3E.18.411	17,50	4973	4960	13
10N.4E.20.111	31,39	4951	4954	-3

Water-level contour maps representing 1960-61 conditions in the basin, which were compiled by combining data from Spiegel (1955), Bjorklund and Maxwell (1961, figs. 1a and 1b), and Titus (1963), are presented for the upper 200 feet of saturated thickness in figure 24 and for depths between 200 and 650 feet below the water-level surface in figure 25. These maps may be used for comparison with simulated hydraulic heads for 1960-61 for model layers 1 and 2 (figs. 27 and 28). The location of wells used to construct the water-level contour maps and the location of the wells also used to compare simulated and reported or measured hydraulic heads are shown in figure 26. The contours show one possible configuration and slope of the water table in 1960-61 for shallow wells (completed in the upper 200 feet of saturated thickness (model layer 1), fig. 24) and of the potentiometric surface for deep wells (completed between 200 and 650 feet below the water-level surface (model layer 2), fig. 25). Simulated water-level contours for the top three model layers for 1960-61 are shown in figures 27-29, and the simulated declines in hydraulic head between predevelopment conditions (steady state) and 1960-61 are shown in figures 30-32.

Sensitivity Analysis

A sensitivity analysis is a formalization of the process of model calibration in that during the calibration process the modeler gains insight into expected model responses to modifications in the simulation parameters. However, some model components usually are not challenged during calibration. These include estimates or measurements of pumped withdrawal or simulated boundary location and type. For this model, tributary and mountain-front recharge also were assumed to be accurately defined, and changes in them during calibration to improve the model were not considered.

Because there remained a slight systematic tendency for simulated hydraulic heads to be higher than those reported or measured, the sensitivity analysis consisted of a series of changes in simulation parameters to attempt to cause a decline in the simulated hydraulic heads and, perhaps therefore, a decrease in the error. A change in simulated hydraulic conductivity of the aquifer has offsetting effects during steady-state and transient parts of the simulation; therefore, simulated horizontal hydraulic conductivity and the ratio of horizontal to vertical hydraulic conductivity were both increased and decreased. Simulated storage and recharge were decreased. Simulated pumped withdrawals were increased. Changes were made by either multiplying or dividing the accepted value of the parameter by 1.1. An analysis of this model's sensitivity to boundary type and location was not performed (except as noted later). Also, there was no attempt to test the model's sensitivity to alterations of the simulated properties of individual cells or groups of cells. The table on page 53 summarizes the results of the sensitivity analysis.



EXPLANATION

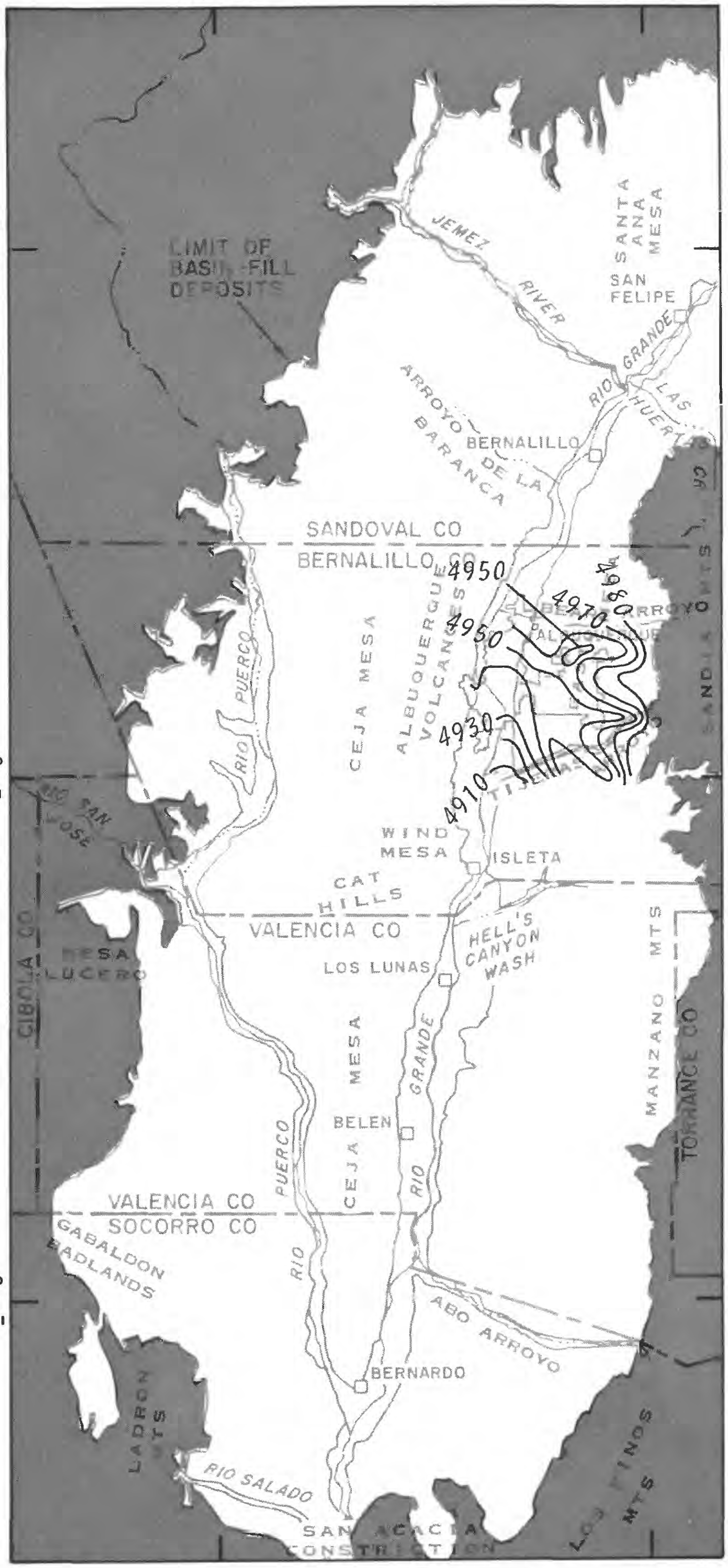
WATER-LEVEL CONTOUR--Shows altitude of water level. Contour interval 50 feet with dashed 10-foot supplemental contours in the Albuquerque area. Datum is sea level.

5300

0 5 10 MILES

0 5 10 KILOMETERS

Figure 24.--Water-level contours that represent 1960 conditions in the upper 200 feet of saturated thickness (From Kernodle and Scott, 1986, fig. 8).

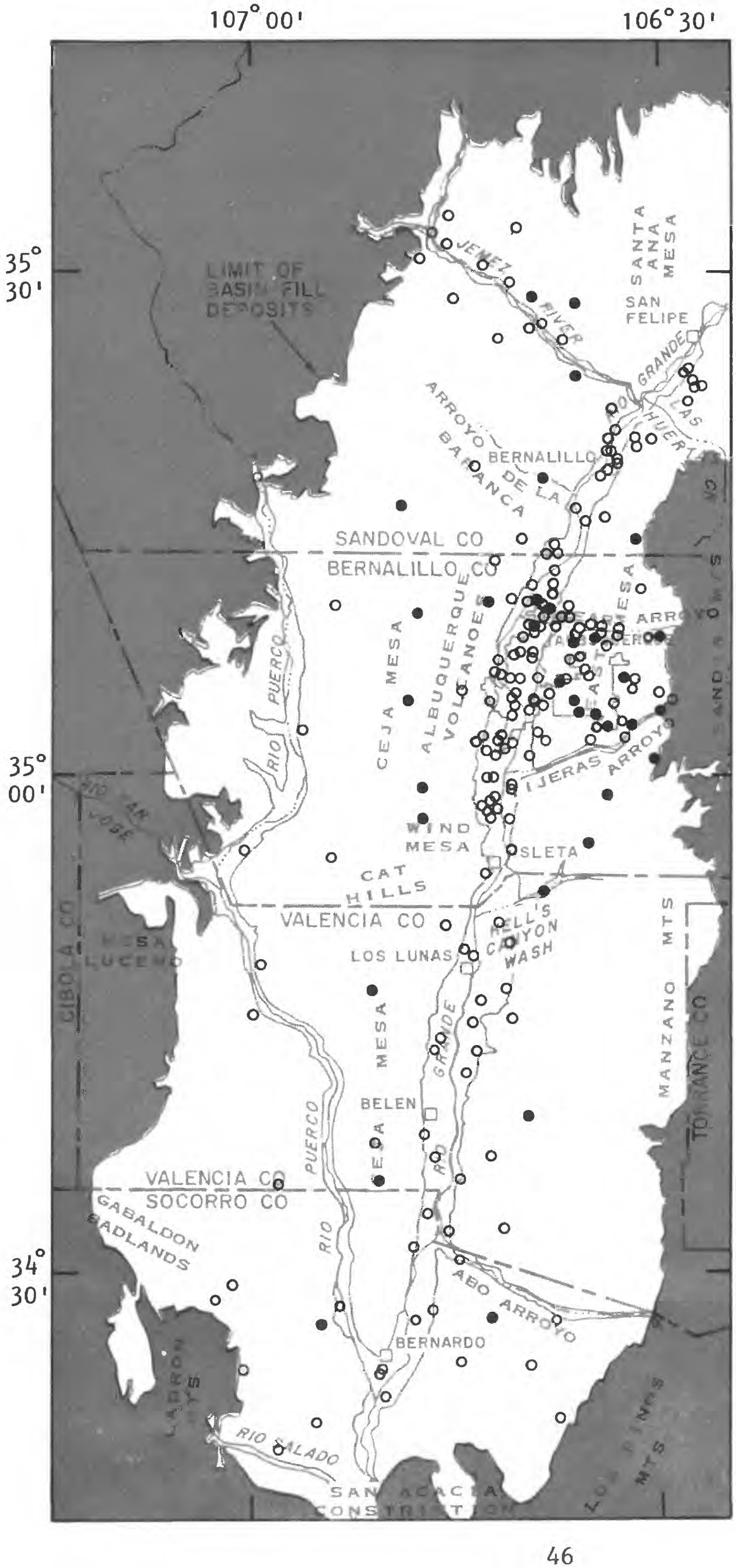


EXPLANATION

4950 WATER-LEVEL CONTOUR--Shows altitude of water level. Contour interval 10 feet. Datum is sea level.

0 5 10 MILES
0 5 10 KILOMETERS

Figure 25.--Water-level contours that represent 1960 conditions at depths of from 200 to 650 feet below the water-level surface (From Kernodle and Scott, 1986, fig. 9).



EXPLANATION

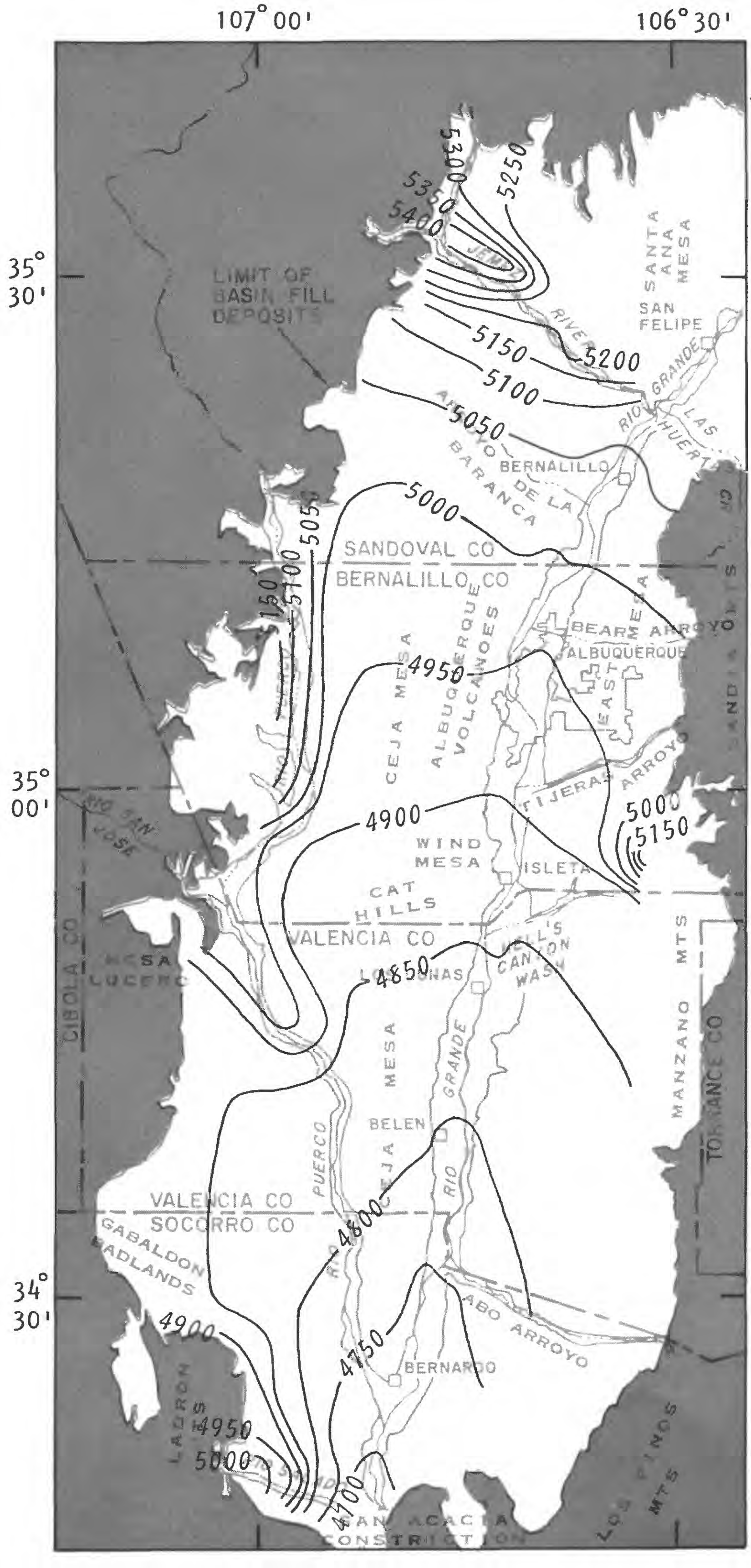
o WELL USED TO CONSTRUCT WATER-LEVEL CONTOUR MAPS

● WELL USED TO CONSTRUCT WATER-LEVEL CONTOUR MAPS AND TO COMPARE SIMULATED AND REPORTED OR MEASURED HYDRAULIC HEADS

0 5 10 MILES

0 5 10 KILOMETERS

Figure 26.--Location of wells that were used to construct the water-level contour maps (figs. 24 and 25) and the wells that were also used in the statistical comparison of simulated and reported or measured hydraulic heads (table 2) (From Kernodle and Scott, 1986, fig. 10).



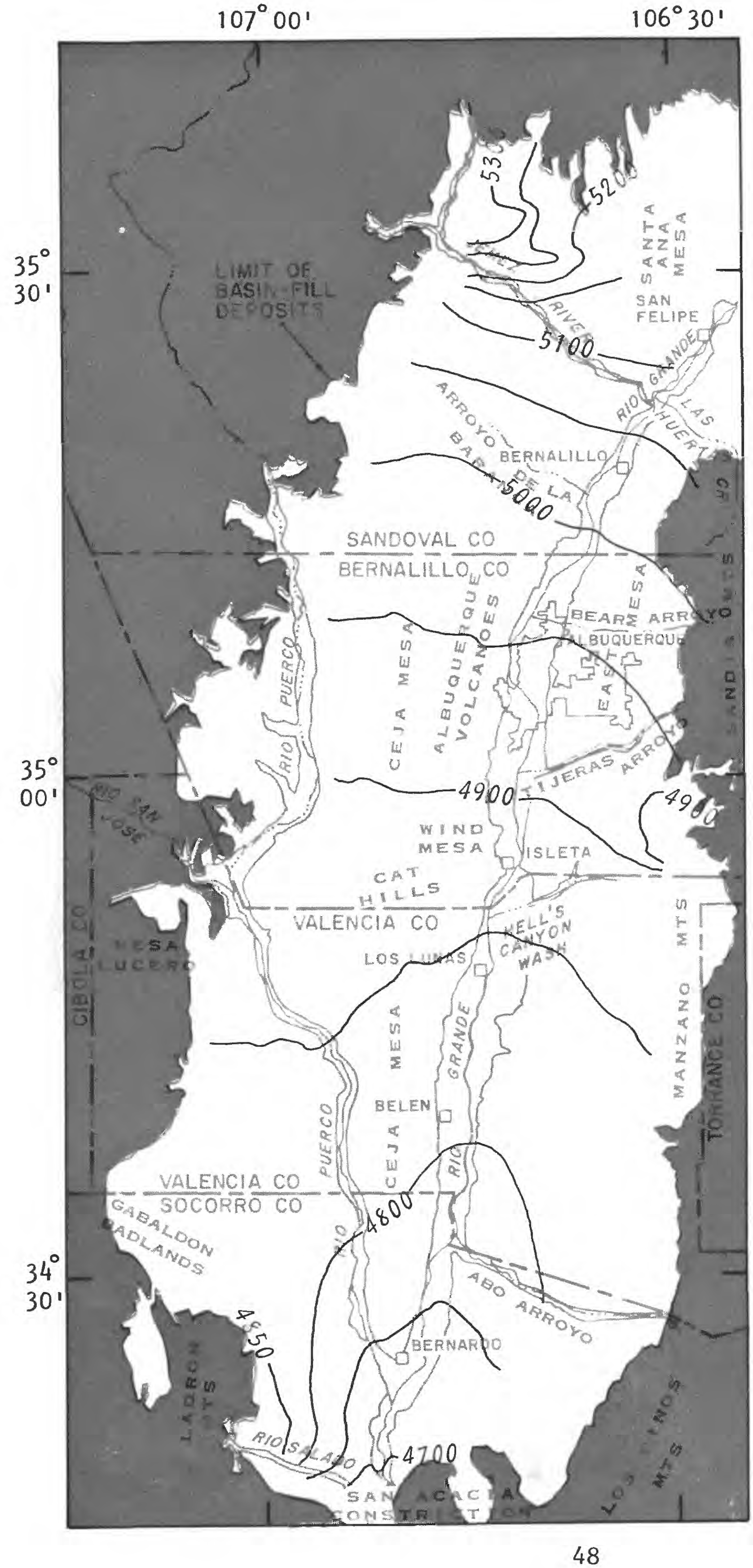
EXPLANATION

— 5000 — SIMULATED WATER-LEVEL CONTOUR--Shows simulated altitude of water level. Contour interval 50 feet. Datum is sea level.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 27.--Simulated water-level contours in layer 1 of the model for 1960-61 (From Kernodle and Scott, 1986, fig. 17).



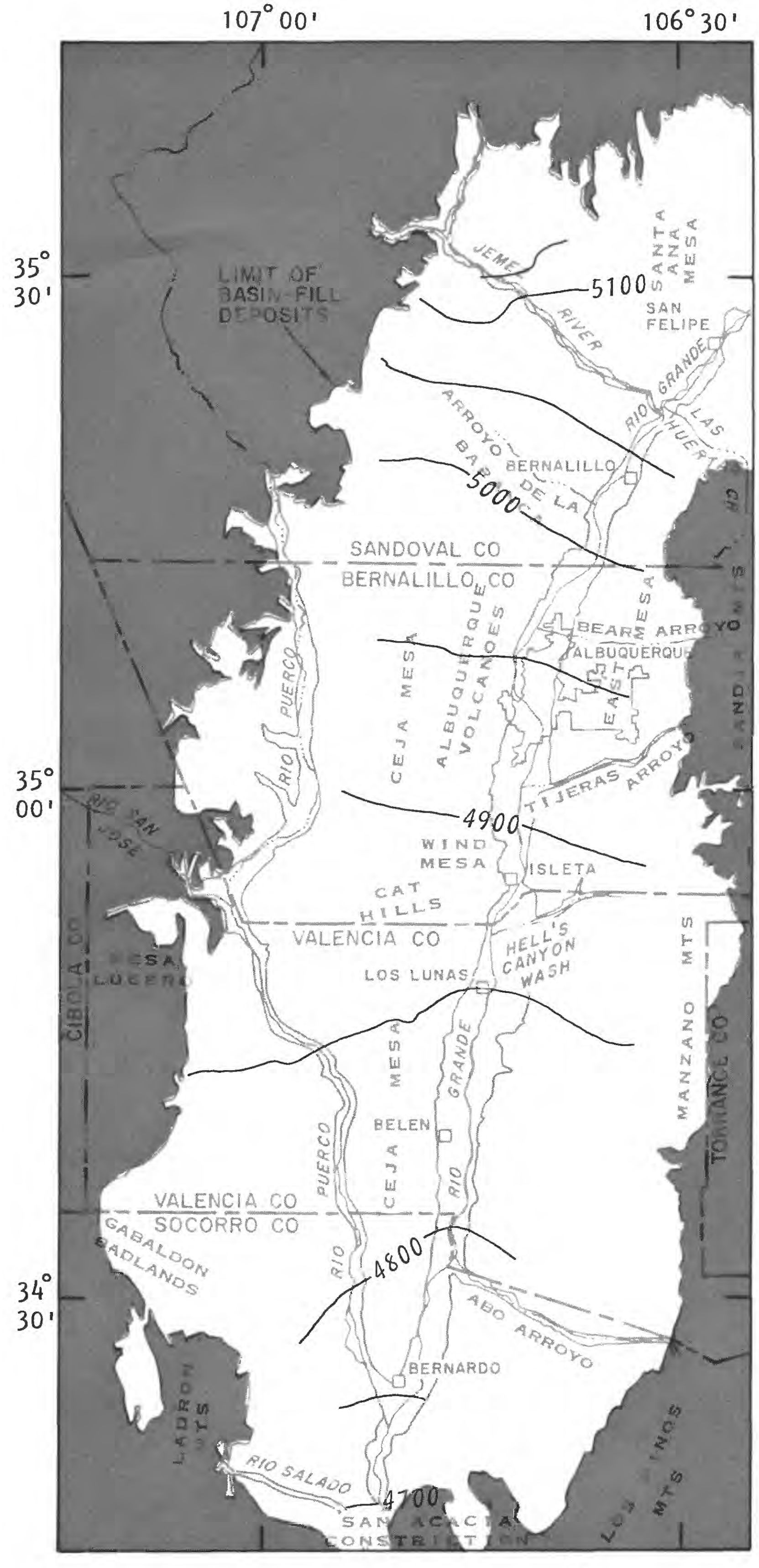
EXPLANATION

5200 — SIMULATED WATER-LEVEL CONTOUR--Shows simulated altitude of water level. Contour interval 50 feet. Datum is sea level.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 28.--Simulated water-level contours in layer 2 of the model for 1960-61.



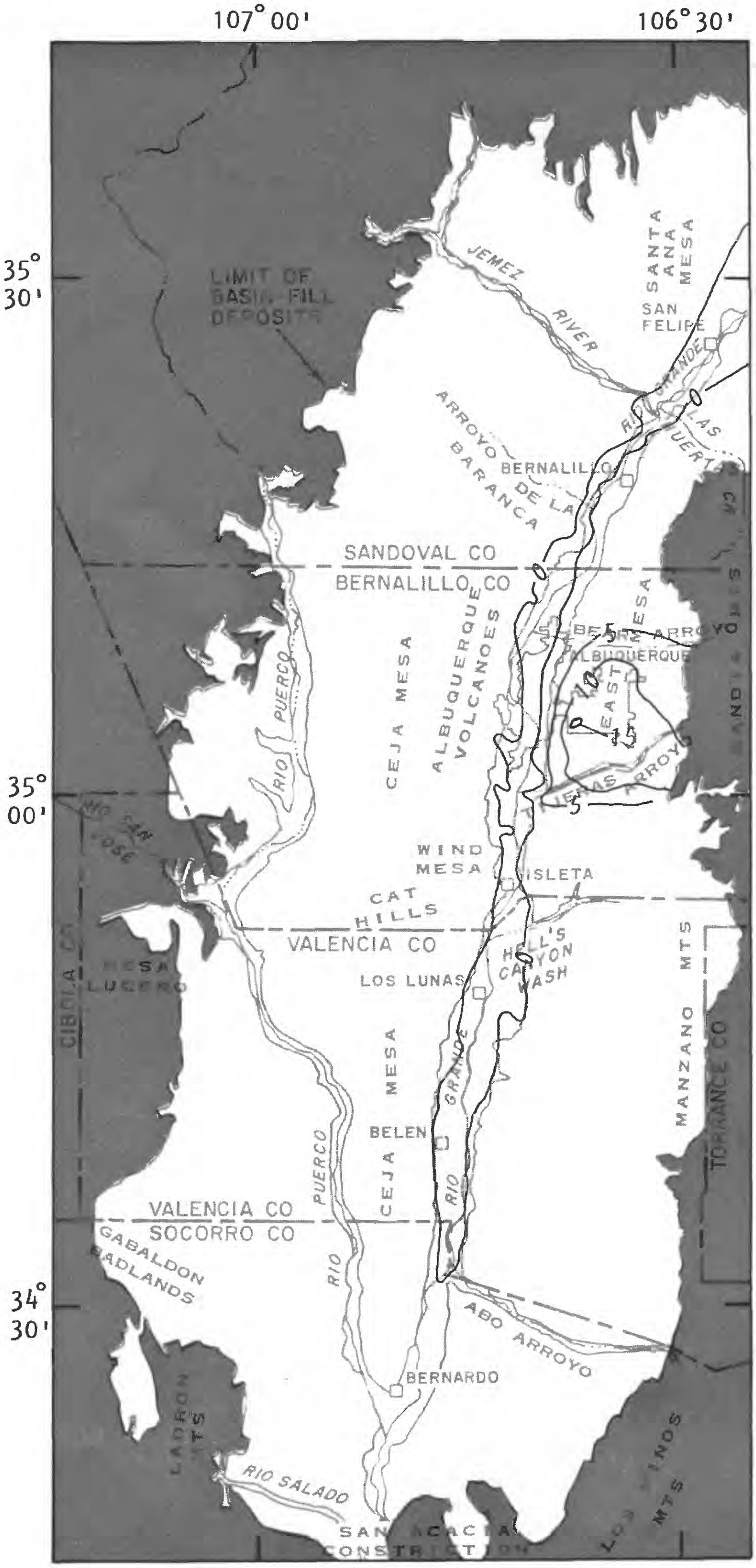
EXPLANATION

SIMULATED WATER-LEVEL CONTOUR--Shows simulated altitude of water level. Contour interval 50 feet. Datum is sea level.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 29.--Simulated water-level contours in layer 3 of the model for 1960-61.



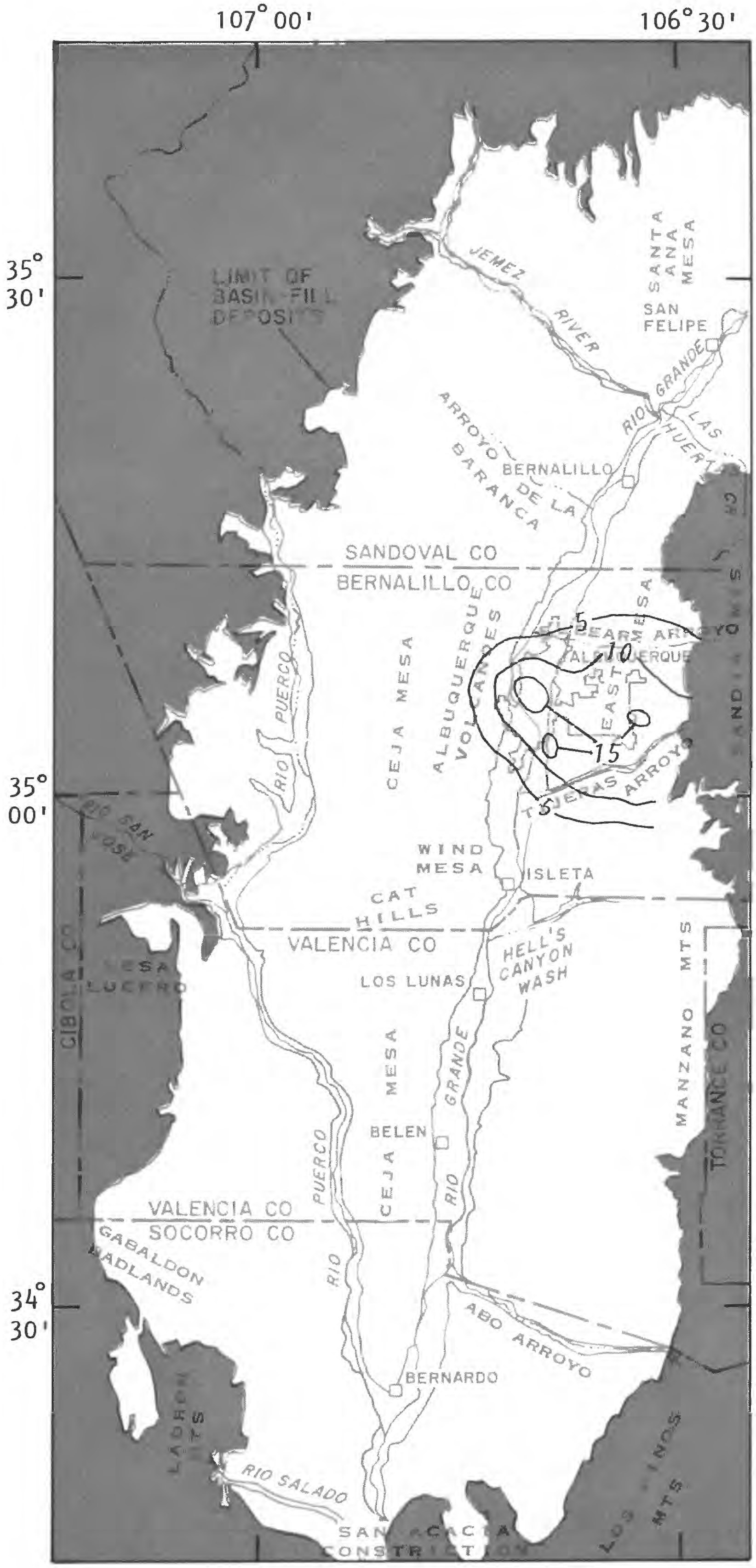
EXPLANATION

—5— LINE OF EQUAL DECLINE IN HYDRAULIC HEAD--Interval 5 feet.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 30.--Simulated hydraulic-head decline in layer 1 of the model from 1907 to 1960-61.



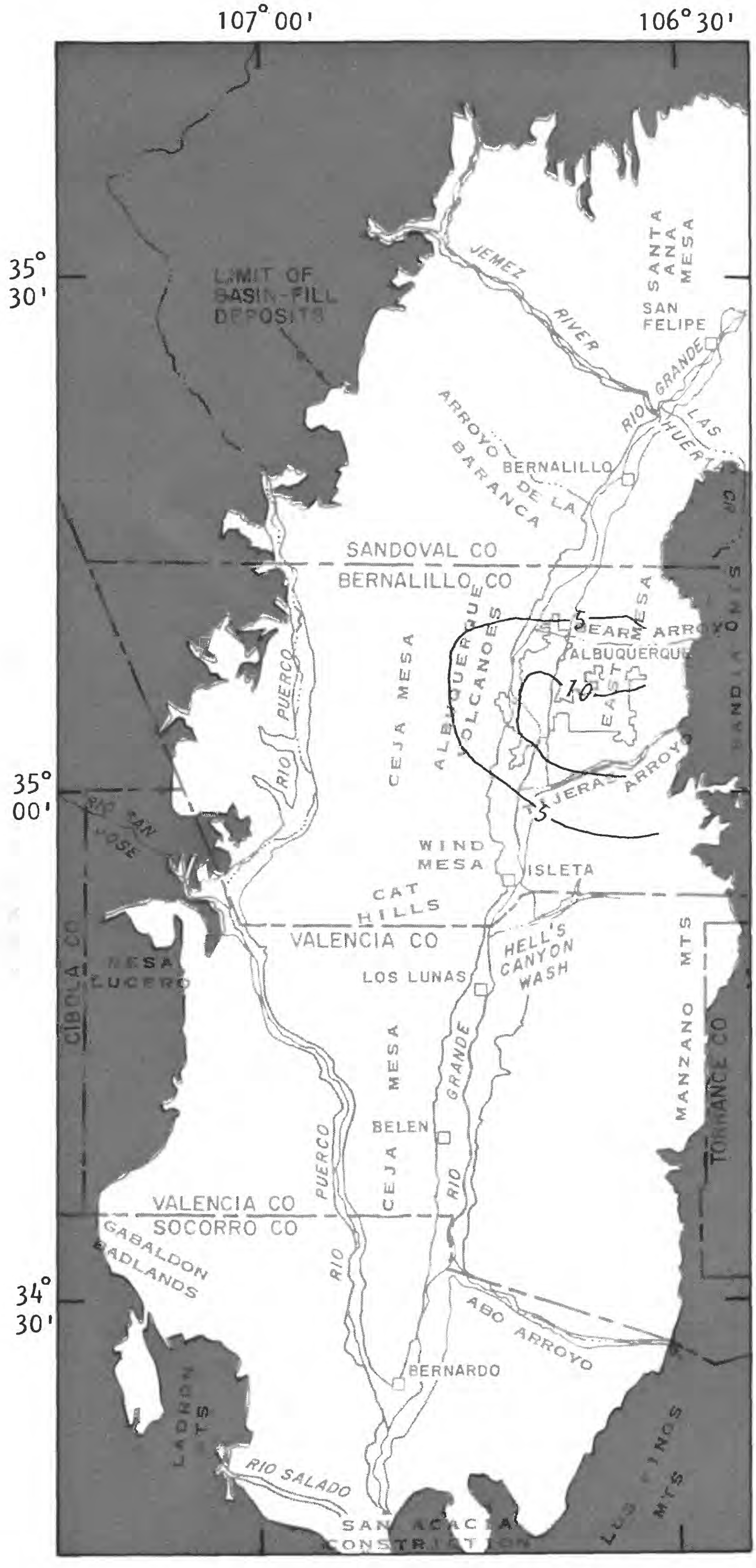
EXPLANATION

—5— LINE OF EQUAL DECLINE IN HYDRAULIC HEAD--Interval 5 feet.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 31.--Simulated hydraulic-head decline in layer 2 of the model from 1907 to 1960-61.



EXPLANATION

—5— LINE OF EQUAL DECLINE IN HYDRAULIC HEAD--Interval 5 feet.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 32.--Simulated hydraulic-head decline in layer 3 of the model from 1907 to 1960-61.

Model version or parameter changed	Error (feet)			
	Mean total	Mean absolute	Median	Root-mean square
Accepted model	7.3	14.1	7.7	17.3
Pumpage (+)	6.9	14.3	7.6	17.3
Storage (-)	7.2	14.1	7.7	17.3
Horizontal hydraulic conductivity (+)	6.6	15.4	8.3	19.0
(-)	11.1	14.2	10.2	18.2
Vertical hydraulic conductivity (+)	7.8	14.8	8.5	18.3
(-)	9.8	14.5	9.9	18.1
Recharge (-)	6.4	15.4	8.3	18.8

(+) Increase in the parameter.
(-) Decrease in the parameter.

Minimizing the mean absolute error was the primary but not the sole objective of the calibration process. Other factors and criteria that were considered include the assurance that the value of the simulated hydrologic parameter was reasonable. The sensitivity analysis indicated that only one change, a 10-percent decrease in simulated aquifer storage, would result in a slightly improved model. However, aquifer storage in the accepted model was already at or near the minimum commonly accepted (Lohman, 1972, p. 53) for both specific yield (0.1) and specific storage (10^{-6} per foot). Depending on the weight given the various statistical indicators, an increase in simulated pumpage also might improve the model. Because storage and pumped withdrawals are interrelated in their effect on hydraulic heads in the area of stress, a reasonable expectation is that the simulated ground-water withdrawal was underestimated rather than that aquifer storage is actually less than modeled. The apparent underestimation probably is due to the treatment of the flood-plain alluvium as a specified-head boundary; shallow production wells completed in the flood-plain alluvium, and, therefore, not simulated, must cause some drawdown both in the flood-plain alluvium and in the hydraulically connected Santa Fe sediments. Among these wells are a large percentage of the early municipal-supply wells for the city of Albuquerque.

Initial or starting conditions also affect the transient comparisons for 1960-61. Initial steady-state hydraulic heads are affected by horizontal and vertical hydraulic conductivities and by the volume of tributary and mountain-front recharge. In the sensitivity analysis, each of these parameters was altered in the prestress and transient parts of the simulation. However, unlike hydraulic conductivity, tributary and mountain-front recharge are a function of climate and are, therefore, variable in time. Because the climate is variable, steady state becomes a theoretical concept rather than an actual prestress condition. Paleoclimatic conditions were not included in the simulations, but the effect of historical climatic differences on simulated hydraulic heads was investigated as a form of sensitivity analysis.

Simulated hydraulic-head changes at selected locations in response to 400 years of wetter climate (20 percent more recharge than estimated for current climatic conditions) followed by 800 years of current climatic conditions are shown in figures 33-36. The hydraulic-head changes are plotted to end at the present time (1984) but do not include any changes in stress other than climatic. The results of the simulations indicate that the aquifer system responds very slowly to a change in recharge, thereby justifying the omission of short-term changes in recharge from the transient simulations. However, significant residual effects are likely to remain for at least as many as 200 but probably not more than 800 years after a marked change in recharge. A large and long-term departure from current recharge rates within the last 800 years would have a finite effect on current hydraulic heads and ground-water flow. A similar change ending 200 or fewer years ago might have a detectable residual effect on the historical hydraulic heads used in the development of this model, perhaps accounting for some of the error remaining in the model in remote areas of the basin.

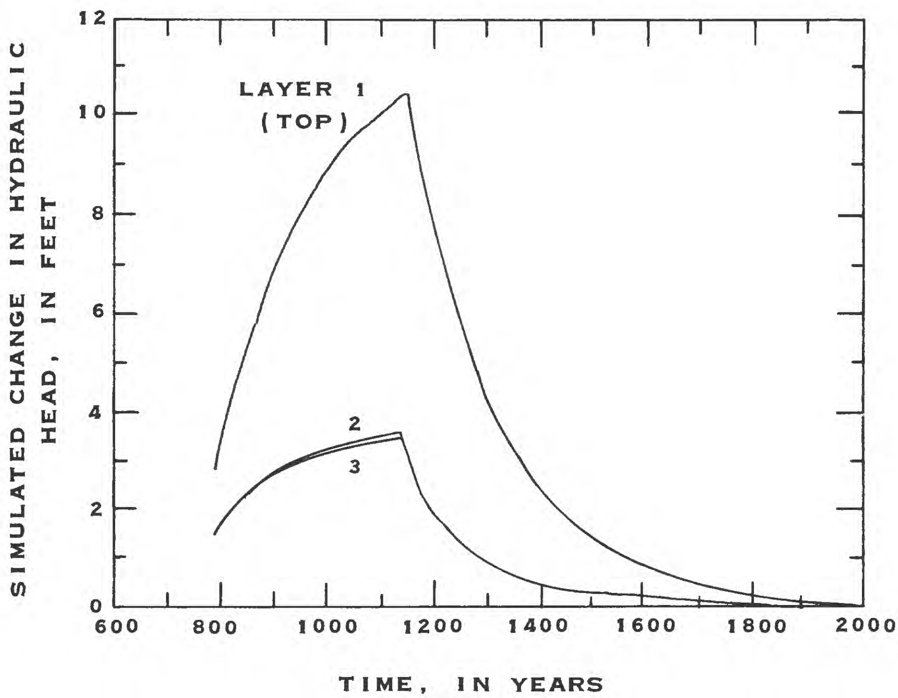


Figure 33.--Simulated changes in hydraulic head in the southwestern part of the basin (model row 1, column 10, layers 1-3) in response to 400 years of wetter climate (20 percent more recharge than estimated for current climatic conditions) followed by 800 years of current climatic conditions.

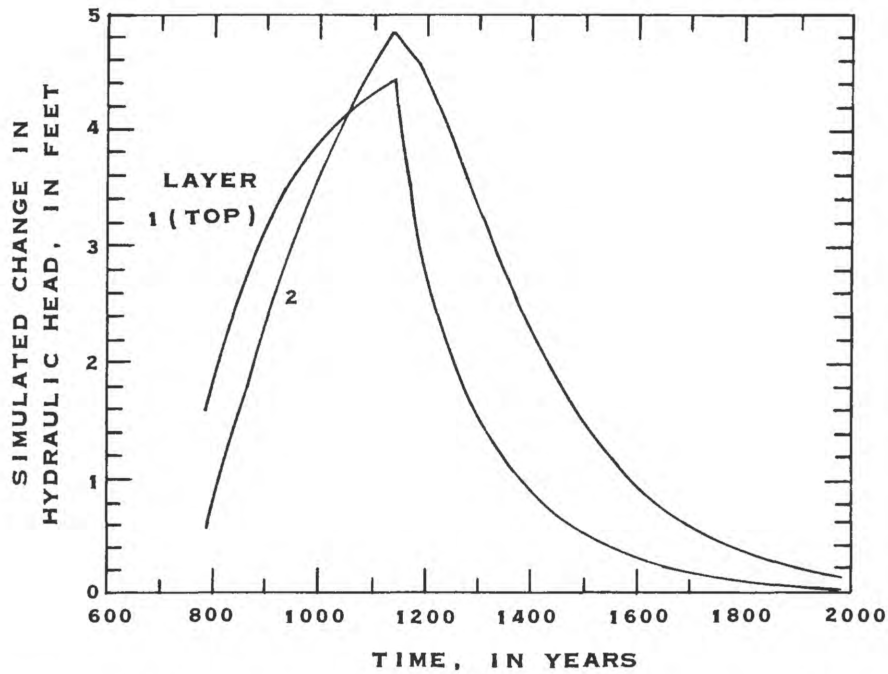


Figure 34.--Simulated changes in hydraulic head in the western part of the basin (model row 2, column 35, layers 1 and 2) in response to 400 years of wetter climate (20 percent more recharge than estimated for current climatic conditions) followed by 800 years of current climatic conditions.

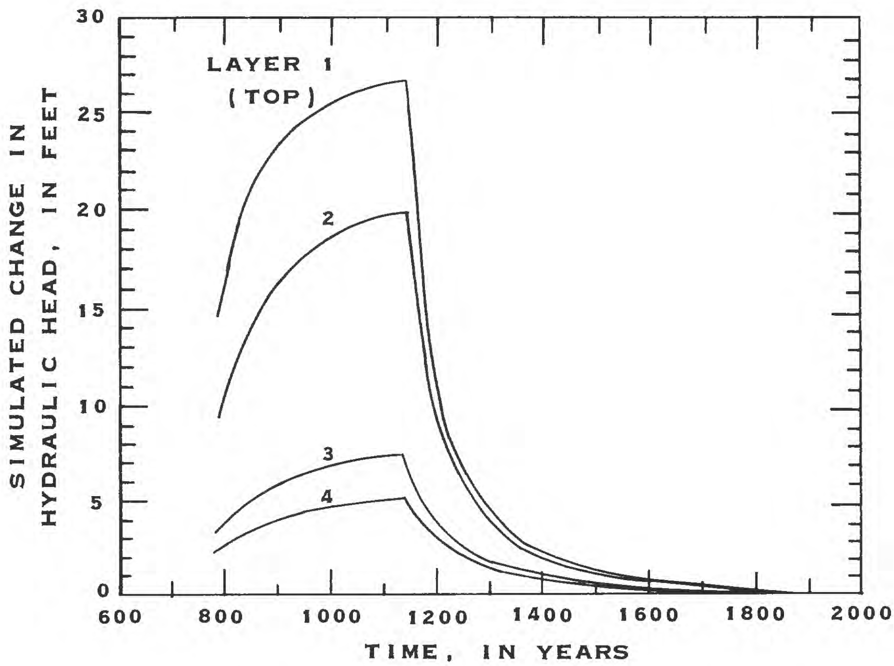


Figure 35.--Simulated changes in hydraulic head in the northern part of the basin (model row 15, column 60, layers 1-4) in response to 400 years of wetter climate (20 percent more recharge than estimated for current climatic conditions) followed by 800 years of current climatic conditions.

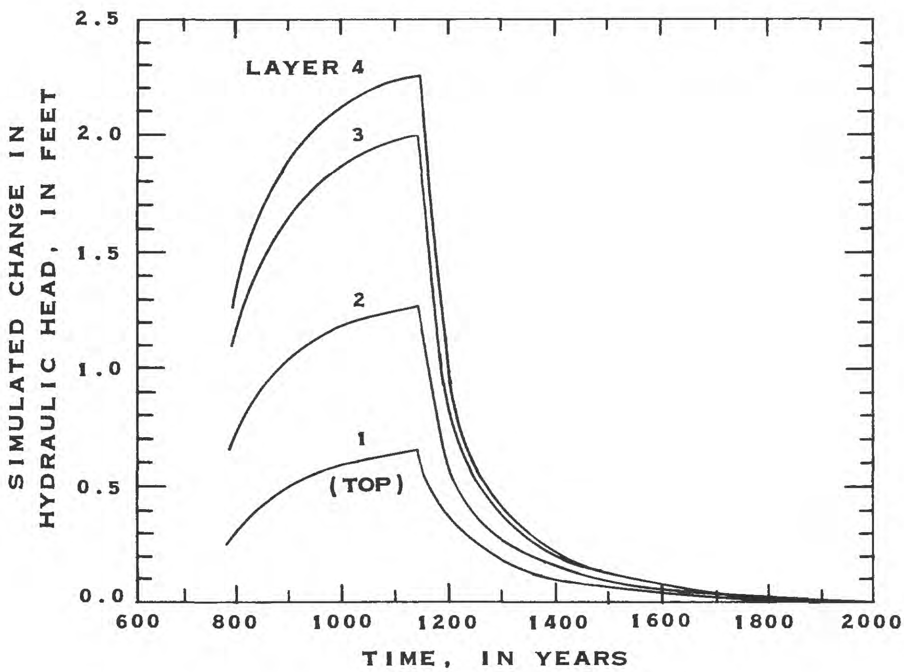
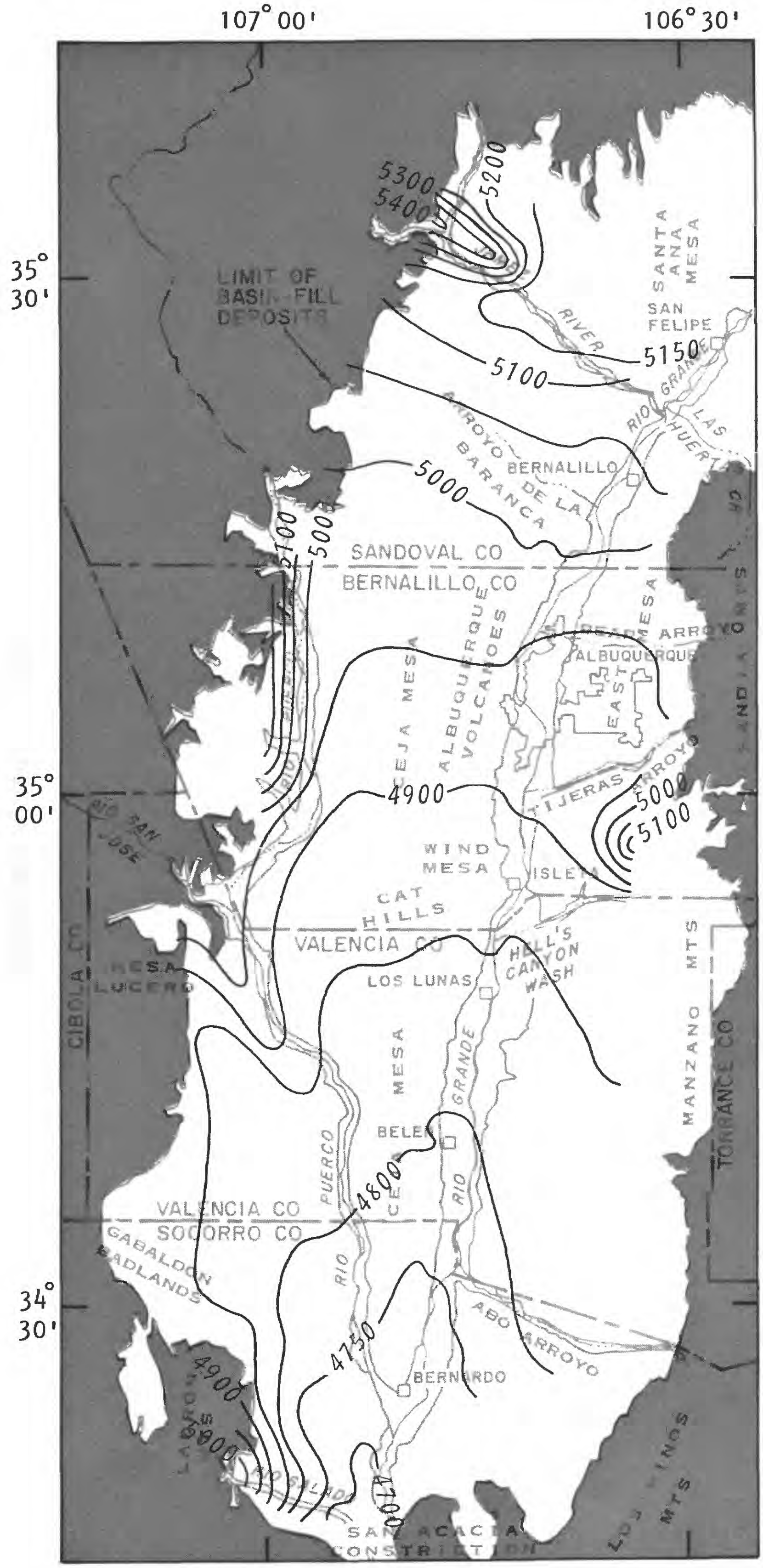


Figure 36.--Simulated changes in hydraulic head in the central part of the basin (model row 10, column 25, layers 1-4) in response to 400 years of wetter climate (20 percent more recharge than estimated for current climatic conditions) followed by 800 years of current climatic conditions.

Extension of the Simulation through 1979 and Discussion of Results

Records of ground-water withdrawals are complete and available, but post-1960 ground-water levels are not available until 1984. There is no overlap of water-level and withdrawal data and, therefore, no basis for using data more recent than 1960-61 to refine the ground-water model. Simulations extended to 1979 probably are generally correct, but simulated and measured hydraulic heads cannot be compared. Simulated water-level contours for the top three model layers for 1979 are shown in figures 37-39. Simulated hydraulic head declines from 1907 (predevelopment) to 1979 are shown in figures 40-42. Hydrographs of simulated hydraulic heads at selected locations in the basin are shown in figures 43-46.

One of the objectives of the investigation was to assess the effects of ground-water withdrawals on the combined ground-water and surface-water system in the Rio Grande flood plain (hereafter, flood-plain system). The volumes of water that are computed to be obtained from aquifer storage, from induced recharge from the Rio Grande flood-plain system, and from captured ground-water discharge to the flood-plain system as a result of ground-water withdrawals from 1907 to 1979 are listed in table 3. The data in the table indicate that at any selected time after 1950 about 25 percent of all water withdrawn from the aquifer outside of the flood plain is derived from aquifer storage. The remaining 75 percent is obtained by depletion of flow in the Rio Grande, salvage of evapotranspiration loss, or is induced inflow from the Santo Domingo Basin.

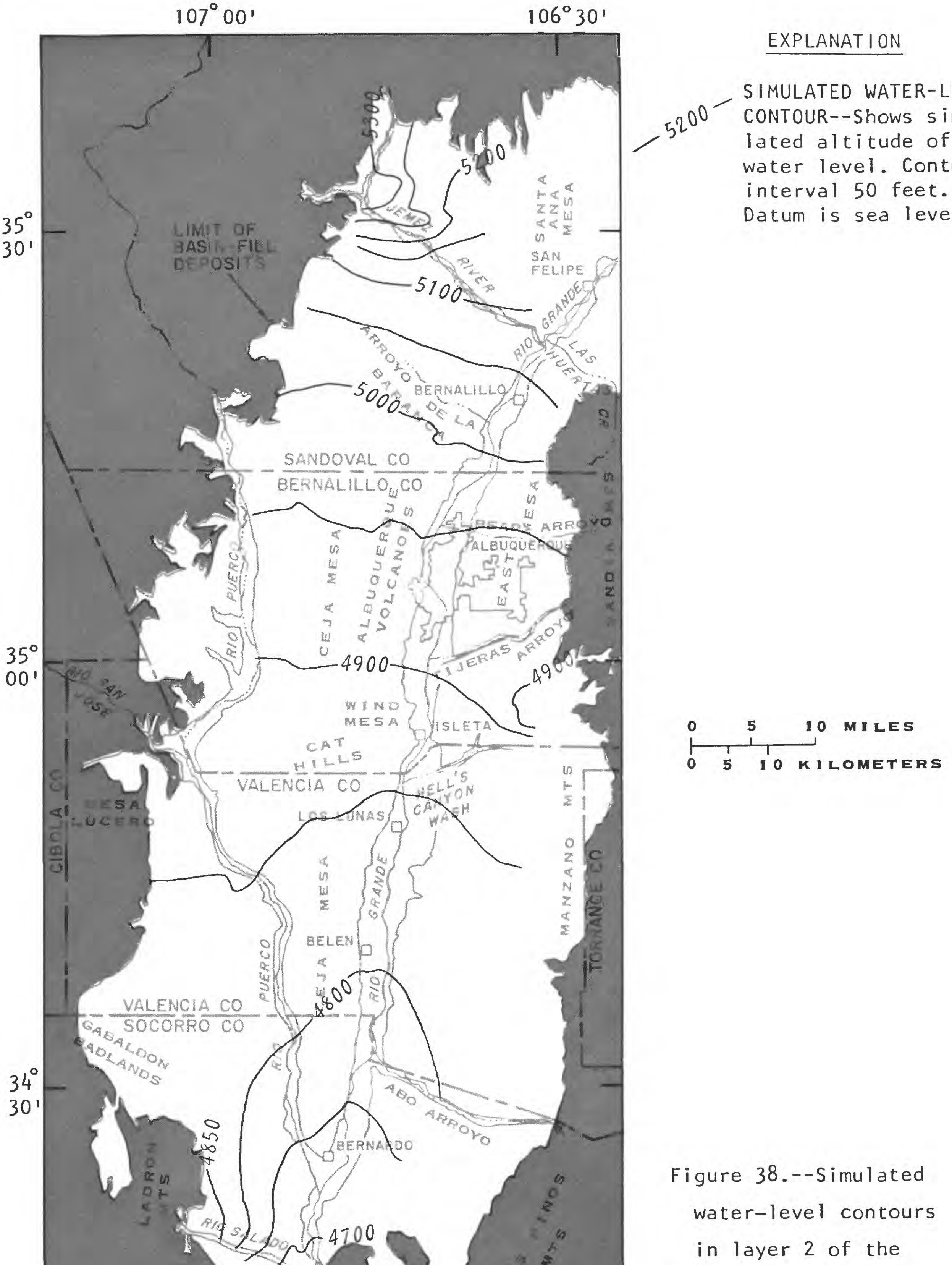


EXPLANATION

—5400— SIMULATED WATER-LEVEL CONTOUR--Shows simulated altitude of water level. Contour interval 50 feet. Datum is sea level.

0 5 10 MILES
0 5 10 KILOMETERS

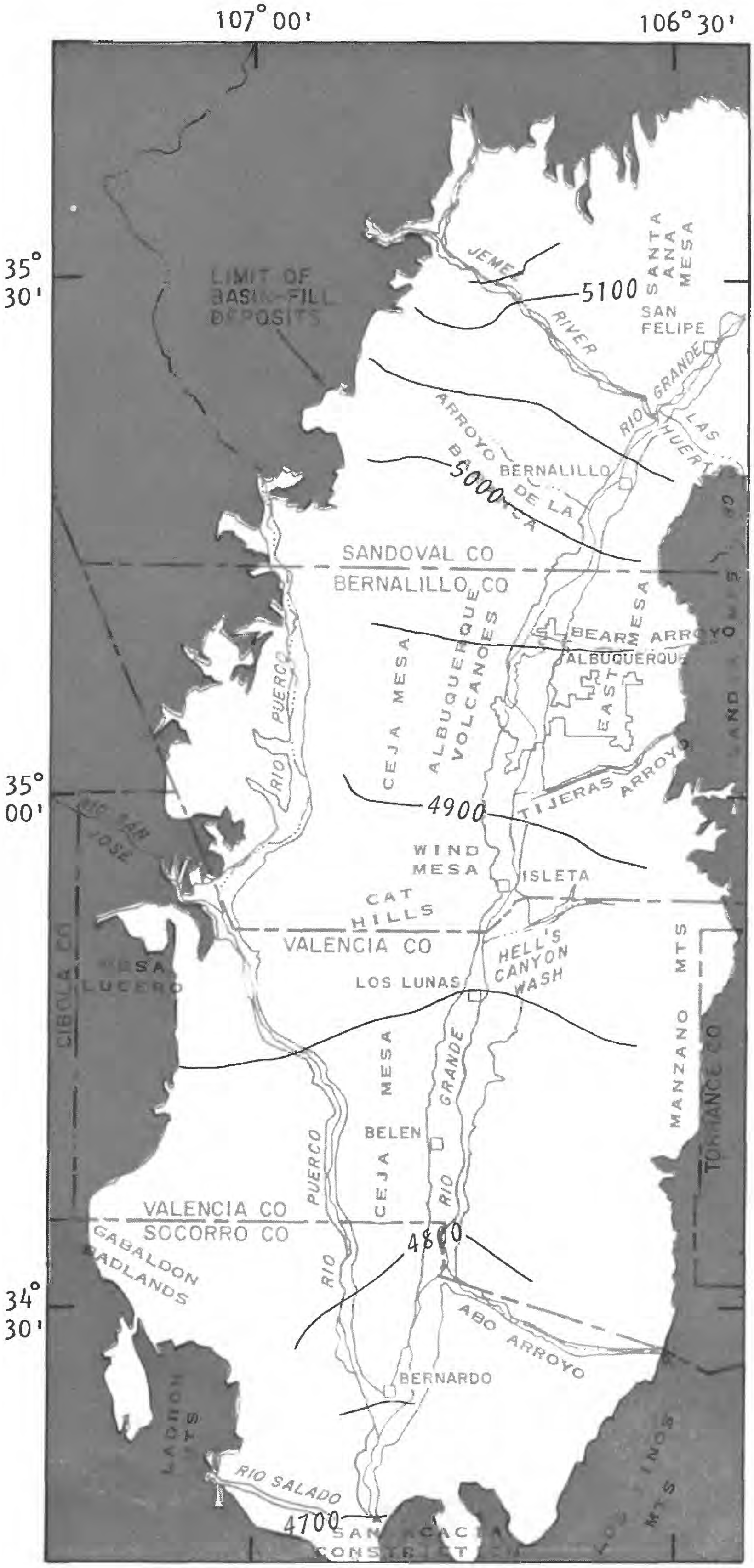
Figure 37.--Simulated water-level contours in layer 1 of the model for 1979.



EXPLANATION

—5200— SIMULATED WATER-LEVEL CONTOUR--Shows simulated altitude of water level. Contour interval 50 feet. Datum is sea level.

Figure 38.--Simulated water-level contours in layer 2 of the model for 1979.



EXPLANATION

—5100— SIMULATED WATER-LEVEL CONTOUR--Shows simulated altitude of water level. Contour interval 50 feet. Datum is sea level.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 39.--Simulated water-level contours in layer 3 of the model for 1979.

EXPLANATION

—5— LINE OF EQUAL DECLINE IN HYDRAULIC HEAD--Interval 5 feet.

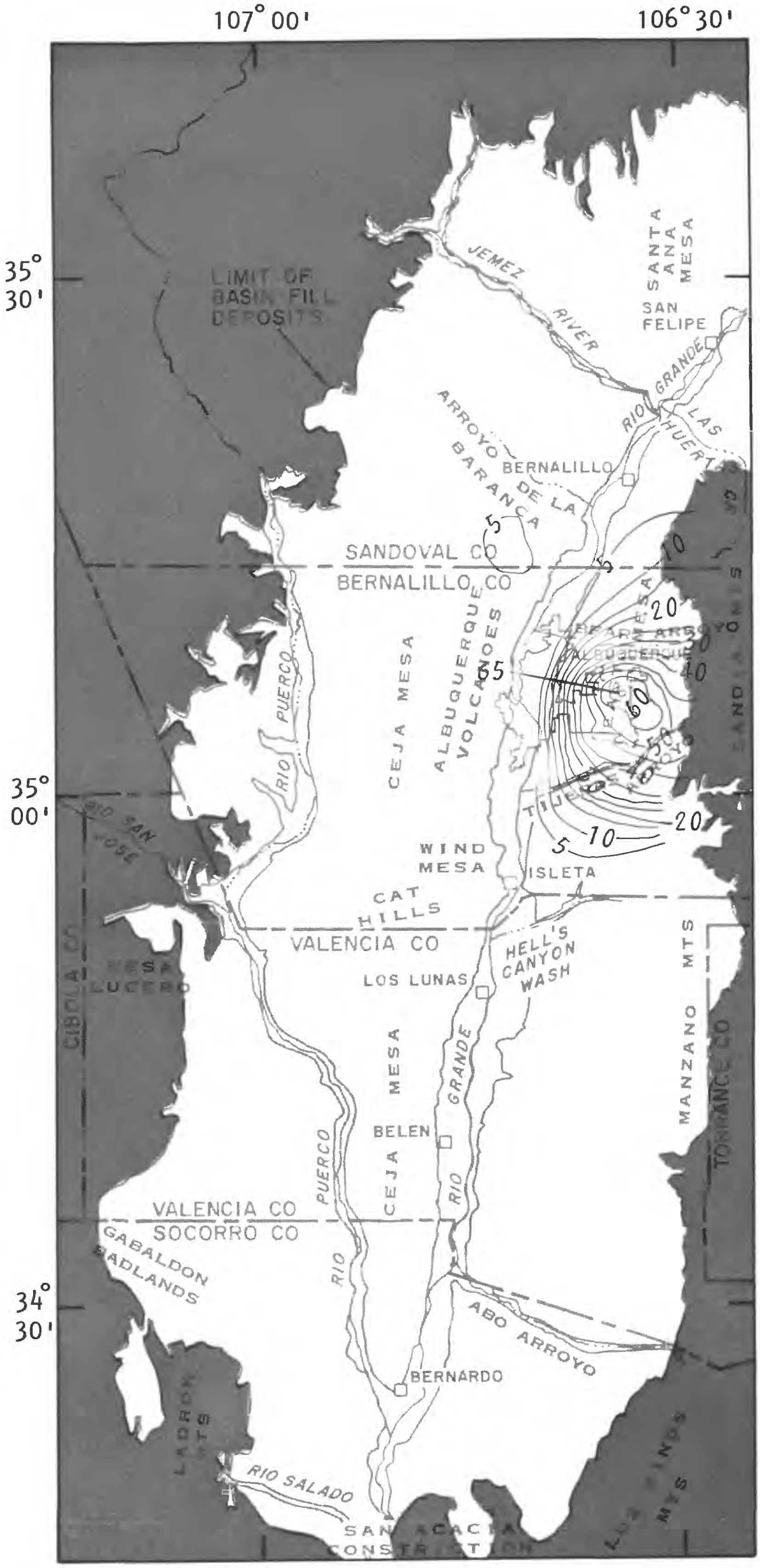
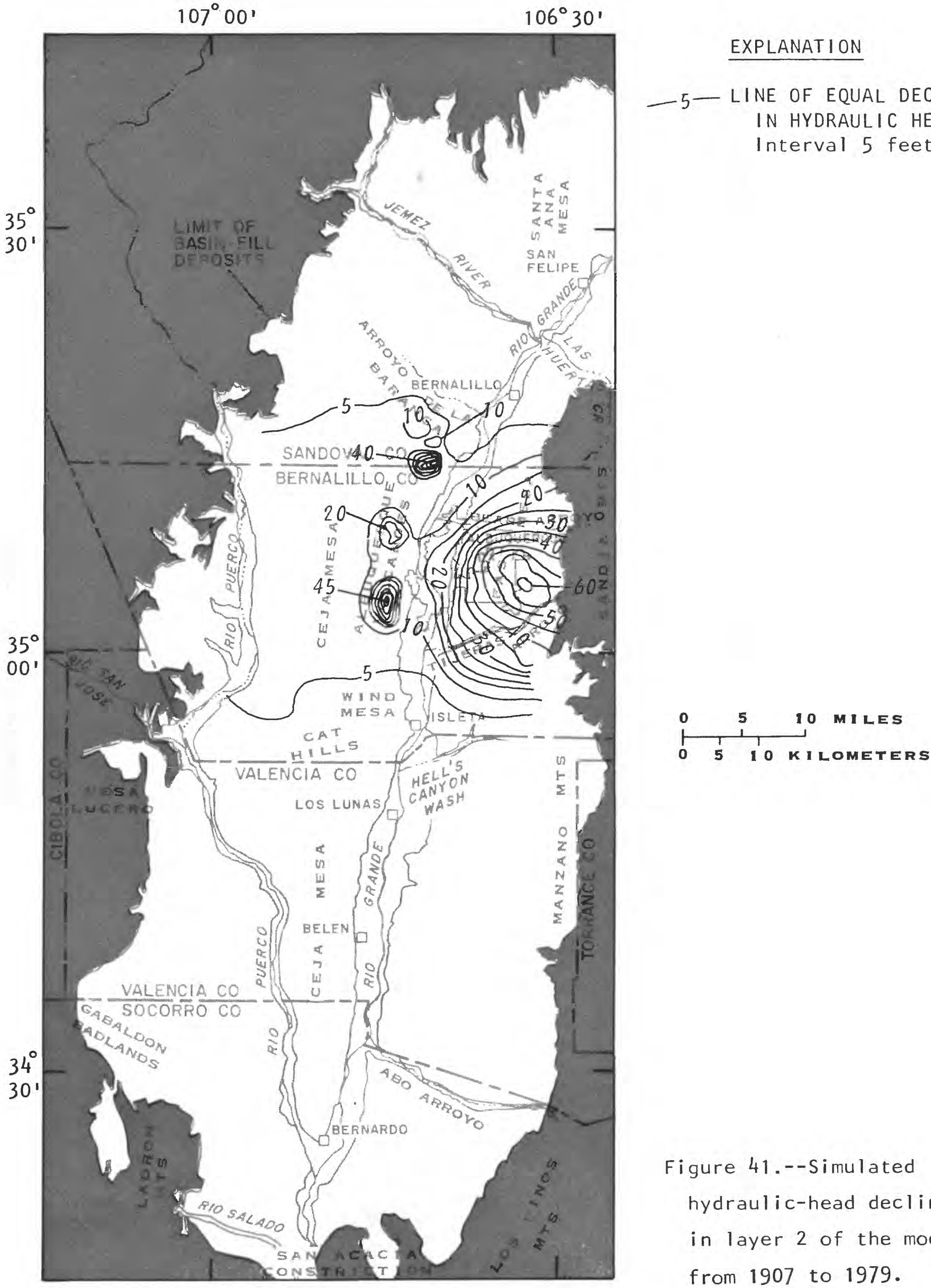


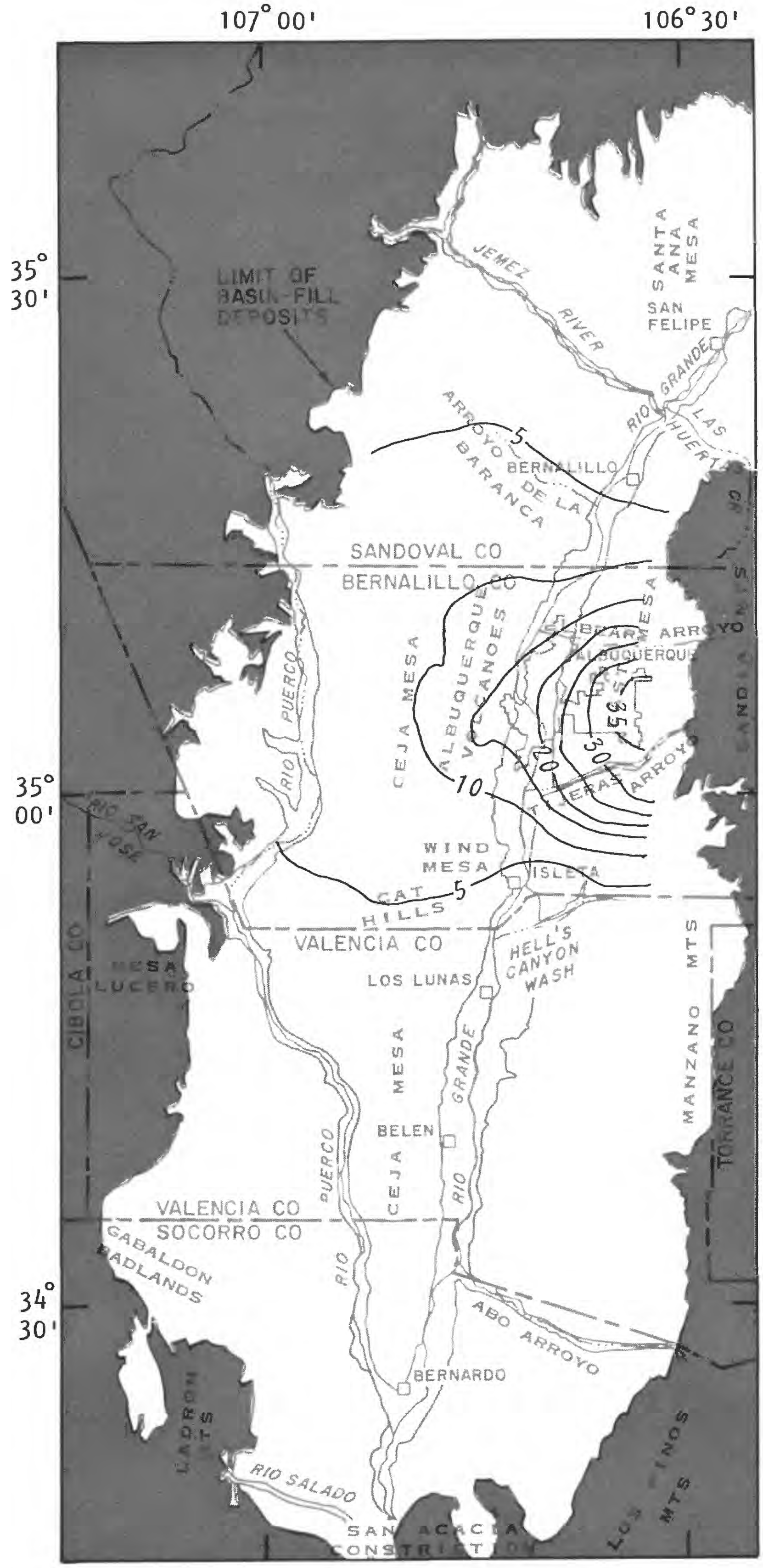
Figure 40.--Simulated hydraulic-head decline in layer 1 of the model from 1907 to 1979.



EXPLANATION

—5— LINE OF EQUAL DECLINE IN HYDRAULIC HEAD--Interval 5 feet.

Figure 41.--Simulated hydraulic-head decline in layer 2 of the model from 1907 to 1979.



EXPLANATION

—5— LINE OF EQUAL DECLINE IN HYDRAULIC HEAD--Interval 5 feet.

0 5 10 MILES

0 5 10 KILOMETERS

Figure 42.--Simulated hydraulic-head decline in layer 3 of the model from 1907 to 1979.

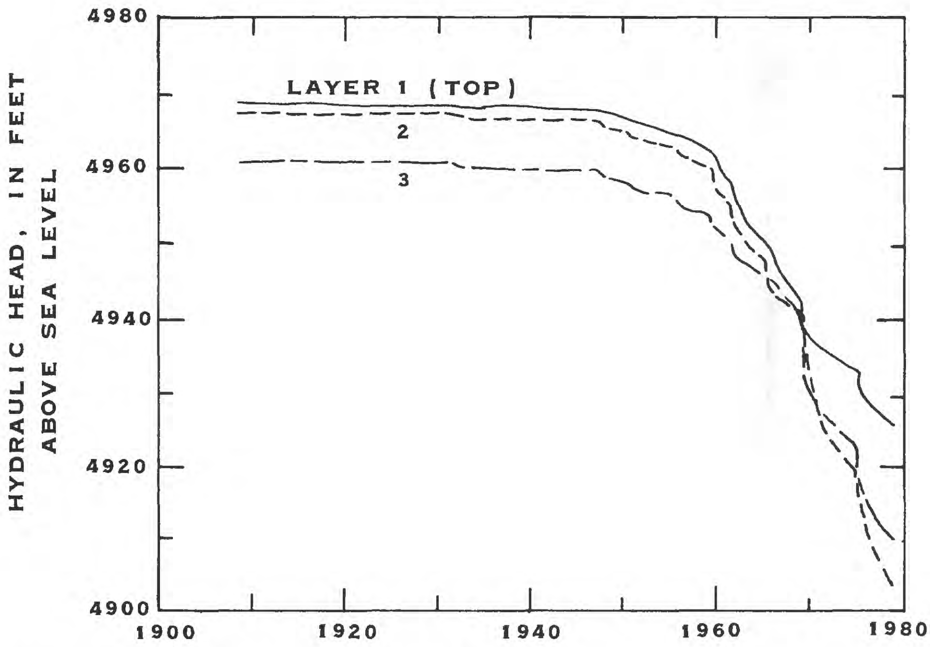


Figure 43.--Simulated hydraulic heads for 1907-79 at a site in Albuquerque (model row 28, column 38, layers 1-3).

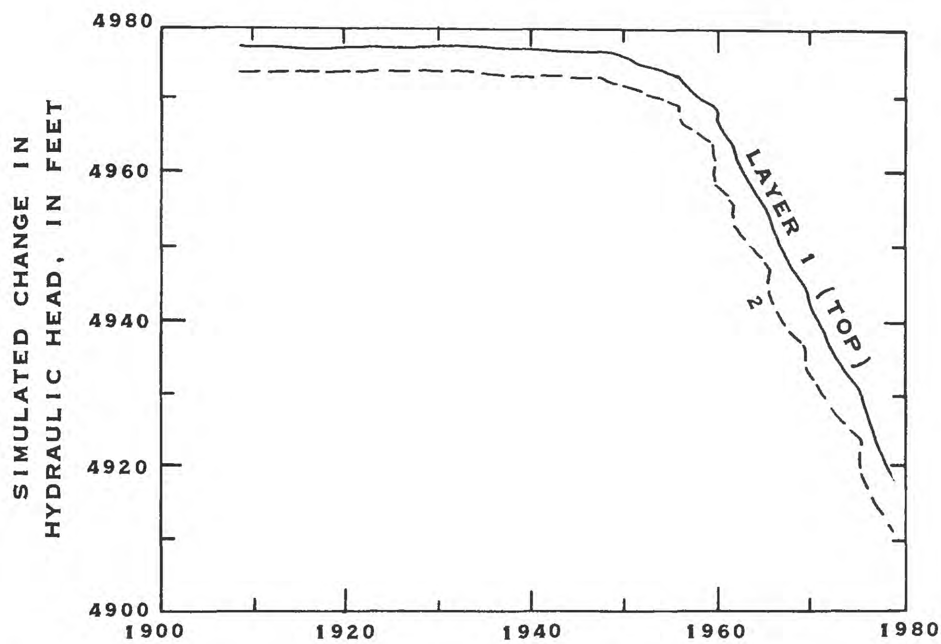


Figure 44.--Simulated hydraulic heads for 1907-79 at a site in Albuquerque (model row 32, column 34, layers 1 and 2).

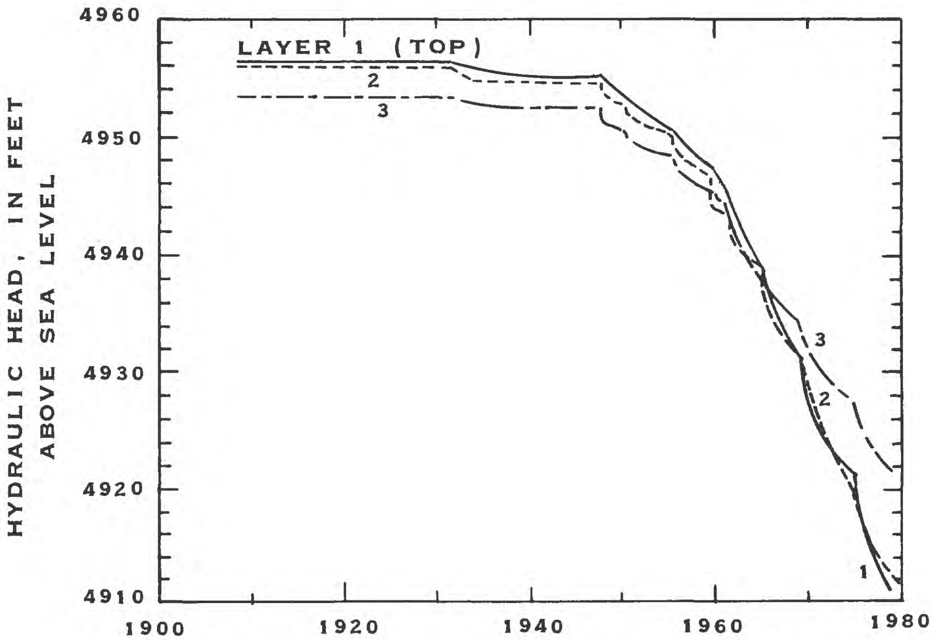


Figure 45.--Simulated hydraulic heads for 1907-79 at a site in Albuquerque (model row 25, column 35, layers 1-3).

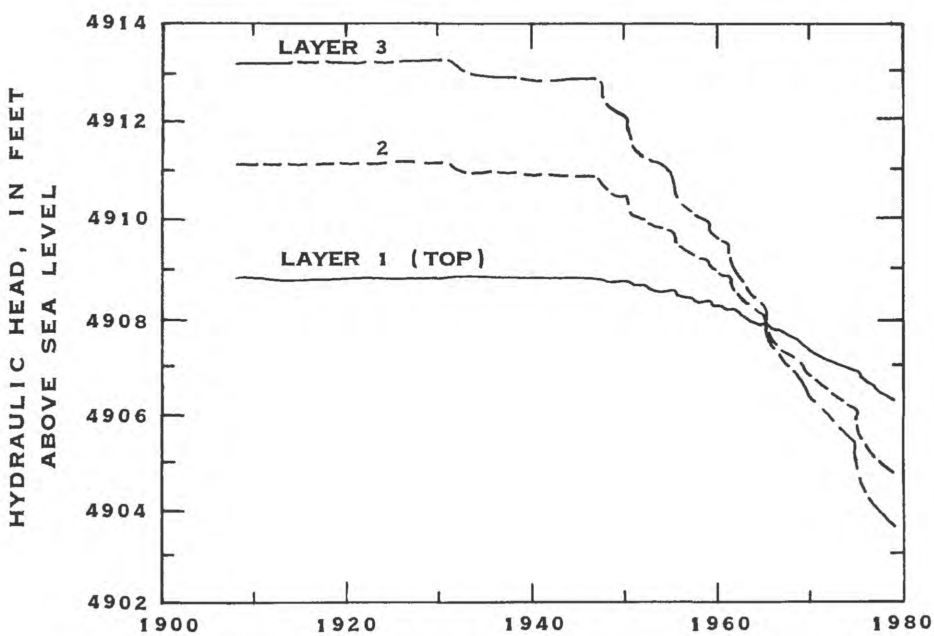


Figure 46.--Simulated hydraulic heads for 1907-79 at a site near the center of the basin (model row 9, column 25, layers 1-3).

Table 3. Total ground-water withdrawal (excluding withdrawal from the shallow flood-plain alluvium) and the sources of withdrawn water

[All values in cubic feet per second]

		Source of pumped water		
			Rio Grande flood-plain system	
Time	Average total pumpage	Depletion of aquifer storage	Captured ground-water discharge	Induced recharge[1/]
1907-31	0.093	0.035	0.058	0.00
1932-47	6.74	1.00	4.48	1.26
1948-50	20.79	6.50	11.49	2.80
1951-55	34.63	8.04	19.76	6.83
1956-59	55.17	12.89	27.70	14.58
1960-61	66.93	18.52	30.79	17.62
1962-65	83.51	23.41	35.55	24.55
1966-69	98.39	25.36	40.38	32.65
1970-75	117.35	27.96	45.45	43.94
1976-79	138.28	34.43	50.13	53.72

1/ Includes induced flow from the Santo Domingo Basin.

Water budgets for the Albuquerque-Belen Basin are presented in table 4 for 1960-61 and 1976-79. The data in table 4 indicate that for 1976-79, 68 percent of all ground-water withdrawals from outside the flood plain is supplied by streamflow depletion or salvaged evapotranspiration in the flood plain; 25 percent is from aquifer storage; 7 percent is induced ground-water underflow from the Santo Domingo Basin. Comparison of the two periods indicates an increase in the relative importance of induced flow from the flood-plain systems. Of lesser magnitude but also increasing significantly is the proportion of induced ground-water flow from the Santo Domingo Basin.

For the simulations after 1960-61, the greatest shortcoming of the model is its inability to simulate drawdown in and near the flood-plain alluvium of the Rio Grande where hydraulic-head declines of more than 20 feet have been measured throughout most of the urbanized area of Albuquerque. Simulation of the flood-plain alluvial aquifer as a specified-head boundary causes simulated hydraulic-head declines to be too small in the adjacent (both horizontally and vertically) Santa Fe sediments, particularly in the simulations after 1960-61. The areal extent of this effect is large because pumping effects that pass beneath the flood plain extend great distances into the western part of the basin. In the simulations, these effects are diminished beneath the overlying specified-head boundary, but nevertheless reach the western edge of the modeled area (figs. 41 and 42). The increasingly adverse effect of the specified-head boundary on simulated ground-water levels is one of the reasons that simulations were not projected beyond 1979. The model is acceptable for times from prestress to about 1960-61, but thereafter the modeled system progressively complies less with the true Rio Grande flood-plain system. To simulate periods after 1979 will require that a more appropriate boundary type replace the specified-head representation of surface-water and ground-water systems in the Rio Grande flood plain.

Another possible misrepresentation of the basin aquifer system is the exclusion of the Santo Domingo Basin, the Santa Ana Mesa area, and the southeastern flank of the Jemez caldera from the modeled area. Inclusion of these areas might not enhance the accuracy of the results of the current model, but the true hydrologic system would be represented more faithfully. Data are few, however, and the ground-water interconnection with these areas is not known. One purpose of ground-water modeling is to develop and refine concepts of the ground-water system and reveal areas where additional information is needed, or where the conceptual model of the ground-water system may be in error or inadequate. The hydrologic relationship between the Albuquerque-Belen and Santo Domingo Basins remains to be defined.

Table 4. Water budget for the basin, 1960-61 and 1976-79

[All values in thousands of acre-feet per year. Total ground-water withdrawal (46,000 acre-feet per year for 1960-61, 100,000 acre-feet per year for 1976-79) has been itemized as to source of withdrawn water]

	1960-61		1976-79	
Mechanism	Inflow	Outflow or loss	Inflow	Outflow or loss
Rio Grande main stem.....	834	669	885	753
Rio Grande tributaries (surface flow)........	80	--	80	--
Ground water............	58	13	62	13
Tributary and mountain-front recharge........	129	--	129	--
Evapotranspiration......	--	310-390	--	310-390
Ground-water withdrawal:				
Intercepted ground-water discharge to the flood-plain system	--	22	--	36
Induced recharge from the flood-plain system...........	--	11	--	32
Induced inflow from Santo Domingo Basin1/	--	2	--	7
Depletion in aquifer storage2/	--	11	--	25
TOTAL	1,101	1,027-1,107	1,156	1,151-1,231

1/ Included also with ground-water inflow.
2/ Not included in totals.

Similarly, information on the volume of ground-water underflow into the western part of the basin from the Mesa Lucero area could be used to enhance the model. The volume of this flow is thought to be small, and its inclusion would have little effect on the model simulations. However, inclusion of the underflow would make the model consistent with the interpretations by other investigators in this area (Anderholm, in press). An investigation of the Mesa Lucero area is just beginning and will include a ground-water-flow model that may provide this information. A similar investigation by Frenzel and Lyford (1982) supplied an estimate of ground-water inflow from the San Juan Basin to the Albuquerque-Belen Basin. These other models are able to provide estimated inflow because the volume of flow is proportionately large in terms of the total water budgets of those areas, whereas the same volumes are almost insignificant in the water budget of the Albuquerque-Belen Basin.

The ground-water-flow model of the Albuquerque-Belen Basin persistently failed (using reasonable simulation parameters) to reproduce the ground-water trough reported by Bjorklund and Maxwell (1961). An attempt was made to generate the trough in the simulations by assuming and simulating a zone with greater hydraulic conductivity west of the Albuquerque Volcanoes and in the lower four model layers. This attempt resulted in a moderate trough expressed in each of the top three layers but also resulted in an unwanted decrease in simulated drawdown in the Albuquerque area. Another attempt at generating a simulated trough was through the investigation of the effects of paleoclimates on historic ground-water levels. According to this hypothesis, a prolonged drier climate many centuries ago might cause residually lower ground-water levels in the center of the basin. The results were not encouraging because of the small magnitude of the residual effects. However, this hypothesis was not given a fair test because under the conditions of an assumed drought, the Rio Grande might not have been a perennial source of water to the ground-water system and hydraulic heads in the aquifer might have declined much more rapidly than simulated.

The trough may be due to drawdown in response to ground-water withdrawal in the Albuquerque area, or it may be the result of differences in observation depths in wells used to construct Bjorklund and Maxwell's (1961) contours. The model illustrates that either explanation is possible, especially in view of the fact that simulated drawdown west of the flood plain is diminished by the specified-head boundary used to portray the Rio Grande flood-plain system. Again, it is more appropriate to change the boundary type in subsequent models than to appeal to an unknown or unproven mechanism to force the generation of the trough.

The preceding comments are expressions of the gain in knowledge of the hydrologic processes operating in the basin. The comments point to ways of improving this or other models of the Albuquerque-Belen Basin or other similar basins.

SUMMARY AND CONCLUSIONS

A three-dimensional, ground-water-flow model of the Albuquerque-Belen Basin, New Mexico, was constructed as part of a regional aquifer study of the southwest alluvial basins. The model was used to simulate hydraulic heads and changes in hydraulic heads in the alluvial aquifer from 1907 to 1979. Simulated hydraulic heads for 1960-61 were compared with reported or measured hydraulic heads and the discrepancies were minimized. The part of the simulation from 1961 to 1979 used reported ground-water withdrawals; however, no measured hydraulic-head data were available, and thus there is no way to verify the performance of the model for this period. No projections were made beyond 1979.

The basin was assumed to be bounded on all sides by impermeable rocks, except near the inflow and outflow areas of the Rio Grande and along the border with the San Juan Basin. The flood-plain alluvium was simulated as a specified-head boundary. Internal no-flow boundaries that represent fissure-flow volcanic rocks were included in the model, as was an eastward-dipping zone of low hydraulic conductivity. Recharge from tributaries and along mountain fronts was included as specified fluxes into the topmost of the model's six layers.

The accepted fit between simulated and reported or measured hydraulic heads was obtained using simulated hydraulic conductivities that ranged from 0.25 foot per day in the eastward-dipping zone of low hydraulic conductivity in the western part of the basin to 50 feet per day in the fluvial deposits in the Rio Grande flood plain. The hydraulic conductivities for the Santa Fe Group were simulated to be 2 feet per day in the northern part of the basin, 3 feet per day in an area just south of Albuquerque, 30 feet per day west of the Rio Grande flood plain, and 40 feet per day beneath and east of the fluvial deposits in the Rio Grande flood plain. Specific storage was simulated as being 10^{-6} per foot and specific yield as 0.10. A ratio of vertical to horizontal hydraulic conductivity of 1:500 was simulated and assumed to be constant regardless of the modeled horizontal conductivity.

Hydraulic heads simulated by the model for 1960-61 were compared with reported or measured hydraulic heads at 34 locations in the basin. The mean absolute difference between the simulated and reported or measured hydraulic heads was 14.1 feet. A sensitivity analysis showed that the model is most responsive to an increase in horizontal hydraulic conductivity and least responsive to a decrease in aquifer storage.

The smallest error (difference between simulated and reported or measured hydraulic head) was in the immediate vicinity of Albuquerque (8.9 feet). The largest error was in the northwest quadrant of the basin (25.1 feet). The model performed acceptably for the period of simulation to 1960-61 but thereafter was adversely affected by the portrayal of the flood-plain alluvium and its contained surface-water system as a specified-head boundary.

Throughout the simulation period (1907-79), about three-quarters of all ground water withdrawn from outside of the Rio Grande flood plain was derived from that source, representing depletion of flow in the surface-water system or salvage of water that would otherwise be lost to evapotranspiration. Simulations for 1976-79 indicated that of the total of 100,000 acre-feet of ground water withdrawn annually from outside of the Rio Grande flood plain, 68 percent was obtained from the flood-plain system; depletion of aquifer storage accounted for 25 percent, and the remaining 7 percent was obtained by induced ground-water inflow from the Santo Domingo Basin.

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SUPPLEMENTAL INFORMATION

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second

			Stress period									
Layer	Row	Column	1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
1	9	22	--	--	--	--	0.007	0.012	0.015	0.030	0.063	0.060
1	10	32	--	--	--	--	--	--	--	0.052	0.042	0.023
1	11	30	--	--	--	--	--	--	--	--	0.013	0.118
1	11	32	--	--	--	--	--	--	--	--	--	0.023
1	12	21	--	--	--	--	0.010	0.006	0.008	--	--	--
1	12	41	--	--	--	--	--	--	--	0.042	0.056	0.028
1	13	10	--	--	--	--	--	--	0.123	0.185	0.911	1.340
1	13	41	--	0.012	0.095	0.095	0.095	0.035	0.074	0.074	0.074	0.045
1	13	52	--	--	--	--	--	--	--	--	0.554	0.538
1	13	53	--	--	--	--	--	--	--	--	--	0.042
1	14	53	--	--	--	--	--	--	--	--	--	0.289
1	15	7	--	--	--	--	--	--	0.153	0.158	0.156	0.119
1	15	52	--	--	--	--	--	--	--	--	0.231	0.210
1	16	50	--	--	--	--	--	--	0.084	0.187	0.546	0.148
1	16	51	--	--	--	--	--	--	0.004	0.086	0.472	0.505
1	17	20	--	--	--	0.006	0.010	0.010	0.010	0.010	0.016	0.040
1	17	23	--	--	--	--	--	0.021	0.025	0.011	0.007	0.019
1	18	24	--	--	--	--	0.073	0.108	0.122	0.050	0.050	0.036
1	19	24	--	0.072	0.201	0.147	0.147	--	--	--	--	--
1	19	27	--	--	--	0.263	0.263	0.263	0.263	0.288	0.353	0.457
1	19	28	--	--	--	--	0.001	0.001	0.008	0.011	0.011	0.011
1	19	29	--	--	0.258	0.387	0.393	0.360	0.337	0.245	0.204	0.170
1	19	30	--	--	0.258	0.387	0.393	0.360	0.337	0.245	0.204	0.170
1	19	35	--	--	--	--	--	--	0.014	0.033	0.047	0.070
1	20	26	--	--	--	0.152	0.485	0.485	0.485	0.533	0.657	0.852
1	20	29	--	--	0.129	0.194	0.197	0.180	0.169	0.123	0.102	0.085
1	20	32	--	--	--	--	--	--	--	0.197	0.276	0.108
1	20	33	--	--	--	--	--	--	--	--	0.076	0.201
1	20	38	--	--	0.011	0.011	0.011	0.011	--	--	--	--
1	21	28	--	--	--	--	--	--	0.001	0.301	0.286	0.274
1	21	30	--	--	--	--	--	--	--	--	--	0.063
1	21	32	--	--	--	--	--	--	--	--	0.076	0.201

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

Layer	Row	Column	Stress period 1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
1	21	34	0.093	0.194	0.258	0.258	0.222	0.221	0.223	0.081	--	--
1	22	33	--	--	--	--	--	--	--	0.197	0.276	0.108
1	22	34	--	0.141	0.451	0.451	0.395	0.407	0.390	0.141	0.059	0.212
1	22	35	--	0.030	0.665	1.029	0.901	0.928	0.719	0.865	0.868	0.532
1	23	30	--	--	--	--	0.169	0.313	0.438	0.403	0.595	0.380
1	23	32	--	--	--	--	0.700	0.700	0.711	0.624	0.551	0.853
1	23	38	--	--	--	--	--	--	--	0.152	0.264	0.436
1	23	42	--	--	0.001	0.002	0.002	0.003	0.150	0.095	0.199	0.271
1	23	43	--	--	--	--	--	--	--	0.001	0.034	0.013
1	23	46	--	--	--	--	--	--	--	--	0.012	0.055
1	23	47	--	0.009	0.012	0.012	0.012	0.012	0.012	0.012	0.010	--
1	24	30	--	--	--	0.139	0.253	0.313	0.438	0.403	0.595	0.380
1	24	33	--	--	--	--	--	--	0.648	1.248	1.101	1.706
1	24	34	--	--	--	--	--	--	0.172	0.457	0.504	0.529
1	24	40	--	--	--	--	--	--	0.316	0.299	0.530	0.758
1	24	41	--	--	--	--	--	--	0.632	0.597	1.059	1.517
1	24	46	--	--	--	--	--	0.042	0.247	0.194	0.162	0.071
1	24	48	--	0.001	0.009	0.009	0.009	0.009	0.008	0.008	0.012	0.018
1	25	26	--	--	--	0.311	0.861	0.749	0.676	0.031	0.036	0.022
1	25	42	--	--	--	--	--	--	0.316	0.299	0.530	0.758
1	25	46	--	--	--	--	--	0.020	0.056	0.079	0.080	0.041
1	26	38	--	--	0.036	0.073	0.073	0.073	0.073	0.073	0.024	--
1	26	40	--	--	--	--	--	--	0.316	0.299	0.530	0.758
1	26	41	--	--	--	--	--	--	0.316	0.299	0.530	0.758
1	26	44	--	--	--	--	--	0.036	0.215	0.168	0.141	0.061
1	26	47	--	--	--	0.002	0.010	0.010	0.010	0.027	0.067	0.091
1	27	33	--	--	--	--	--	--	--	--	--	0.057
1	27	37	--	--	--	--	--	--	--	--	0.824	1.134
1	27	38	--	--	--	--	--	--	--	--	0.824	1.134
1	27	41	--	--	--	--	--	0.720	0.720	0.720	0.758	0.941
1	27	49	--	--	--	--	--	--	0.040	0.040	0.040	0.061
1	28	31	--	--	--	0.168	0.201	0.088	0.125	0.211	0.250	0.184
1	28	32	--	--	--	--	--	--	--	--	--	0.338

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

			Stress period									
Layer	Row	Column	1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
1	28	38	--	--	--	--	--	--	--	--	0.824	1.134
1	28	40	--	--	--	--	--	0.360	0.360	0.360	0.379	0.471
1	28	41	--	--	--	--	--	0.360	0.360	0.360	0.379	0.471
1	28	50	--	--	--	--	--	--	0.081	0.150	0.017	0.014
1	28	53	--	--	--	--	--	0.114	0.078	0.078	0.121	0.112
1	29	28	--	--	--	0.084	0.100	0.044	0.062	0.106	0.125	0.092
1	29	30	--	--	0.140	0.084	0.100	0.044	0.062	0.106	0.125	0.092
1	29	37	--	--	--	--	--	--	--	--	0.824	1.134
1	29	41	--	--	--	--	--	0.130	0.261	0.428	0.606	0.605
1	29	54	--	0.005	0.080	0.124	0.158	0.090	0.062	0.062	0.096	0.089
1	30	27	--	--	--	--	0.100	0.044	0.062	0.106	0.125	0.092
1	30	29	--	--	--	--	0.100	0.044	0.062	0.106	0.125	0.092
1	30	40	--	--	--	--	--	0.130	0.261	0.428	0.606	0.605
1	30	41	--	--	--	--	--	0.260	0.521	0.855	1.211	1.211
1	31	23	--	--	--	--	--	0.021	0.062	0.106	0.125	0.092
1	31	29	--	--	--	0.034	0.100	0.044	0.062	0.106	0.125	0.092
1	31	32	--	--	--	--	--	--	--	0.352	0.361	0.412
1	31	34	--	--	--	--	0.106	0.425	0.459	0.529	0.556	0.557
1	31	37	--	--	--	--	--	--	--	--	--	0.278
1	31	54	--	--	--	--	--	--	--	--	--	0.040
1	32	34	--	--	--	--	0.106	0.423	0.458	0.529	0.556	0.557
1	32	35	--	--	--	--	--	--	0.070	0.265	0.278	0.278
1	32	36	--	--	--	--	--	--	--	--	--	0.278
1	32	41	--	--	--	--	--	--	0.018	0.069	0.047	0.182
1	33	25	--	--	--	0.084	0.100	0.044	0.062	0.106	0.125	0.092
1	33	30	--	--	--	--	--	--	--	--	0.016	0.056
1	33	36	--	--	--	--	--	--	--	--	--	0.171
1	33	41	--	--	--	--	--	--	--	--	--	0.182
1	34	30	--	--	--	--	--	0.181	0.219	0.257	0.257	0.235
1	34	34	--	--	--	--	--	--	0.173	0.230	0.310	0.343
1	34	35	--	--	--	--	--	--	--	--	--	0.171
1	35	53	--	--	--	--	--	--	--	0.052	0.453	0.511
1	36	56	--	--	--	--	--	--	--	0.002	0.016	0.044

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

			Stress period									
Layer	Row	Column	1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
1	37	42	--	--	--	--	--	--	--	--	--	0.007
1	37	54	--	--	--	--	--	--	--	0.001	0.002	0.006
2	8	10	--	--	--	0.341	1.659	1.739	1.572	1.376	0.786	0.786
2	9	10	--	0.047	0.251	0.368	0.671	0.640	0.651	0.651	0.651	0.651
2	10	16	--	--	--	--	--	0.076	0.048	0.080	0.185	0.305
2	10	32	--	--	--	--	--	--	--	0.471	0.379	0.207
2	11	16	--	--	--	0.019	0.023	0.061	0.099	0.112	0.054	0.089
2	11	30	--	--	--	--	--	--	--	--	0.073	0.671
2	11	32	--	--	--	--	--	--	--	--	--	0.206
2	11	33	--	--	--	--	--	--	0.219	0.340	0.299	0.977
2	11	34	--	--	--	--	--	--	--	0.304	0.299	0.521
2	11	43	--	--	--	--	--	--	--	--	0.152	0.388
2	11	46	--	--	--	--	--	--	--	--	0.055	0.388
2	12	29	--	--	--	--	--	--	--	--	0.125	1.151
2	12	33	--	--	--	--	--	--	--	--	--	0.267
2	12	44	--	--	--	--	--	--	--	--	0.152	0.388
2	13	26	--	--	--	--	--	--	--	0.003	0.056	0.085
2	13	53	--	--	--	--	--	--	--	--	--	0.125
2	14	32	--	--	--	0.478	0.447	0.418	0.417	0.444	0.394	0.329
2	14	33	--	--	0.159	0.955	0.895	0.836	0.835	0.887	0.787	0.658
2	14	34	--	--	--	0.478	0.671	0.836	0.835	0.887	0.787	0.658
2	14	36	--	--	--	0.191	1.135	1.098	1.058	1.054	0.888	0.795
2	14	37	--	--	--	0.382	2.270	2.196	2.116	2.108	1.775	1.590
2	14	53	--	--	--	--	--	--	--	--	--	0.381
2	15	7	--	--	--	--	--	--	0.076	0.078	0.077	0.058
2	15	32	--	--	--	0.955	0.895	0.836	0.835	0.887	0.787	0.658
2	15	33	--	--	0.478	1.910	1.790	1.672	1.670	1.775	1.574	1.315
2	15	34	--	--	--	0.955	0.895	0.836	0.835	0.887	0.787	0.658
2	15	38	--	--	--	0.191	1.135	1.098	1.058	1.054	0.888	0.795
2	15	39	--	--	--	--	0.583	1.056	1.017	1.013	0.853	0.713
2	15	51	--	--	--	--	--	--	--	--	0.524	0.476
2	16	38	--	--	--	0.191	1.820	2.968	2.847	2.746	2.349	2.059
2	16	41	--	--	--	--	1.989	1.910	1.814	1.626	1.443	1.204

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

Layer	Row	Column	Stress period 1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
2	16	51	--	--	--	--	--	--	0.010	0.164	0.792	0.984
2	17	35	--	0.740	0.407	0.389	0.476	0.461	0.461	0.461	0.384	--
2	17	37	--	--	0.640	0.624	0.816	0.809	0.809	0.727	0.613	0.012
2	17	42	--	--	--	--	0.994	0.955	0.907	0.813	0.721	0.602
2	18	29	--	--	--	--	--	--	0.603	0.598	0.497	0.415
2	18	31	--	--	0.726	1.089	1.106	1.013	0.949	0.690	0.573	0.479
2	18	34	--	0.740	0.407	0.389	0.476	0.461	0.461	0.461	0.384	--
2	18	35	--	2.723	2.036	1.611	1.427	1.382	1.382	1.382	1.152	--
2	18	36	--	0.449	0.728	0.695	0.850	0.823	0.823	0.823	0.686	--
2	18	37	--	1.110	2.503	2.391	2.664	2.468	2.468	2.468	2.057	--
2	18	38	--	--	0.567	0.567	0.490	0.499	0.498	0.527	0.468	0.390
2	18	39	--	--	1.134	1.134	0.981	0.999	0.996	1.055	0.935	0.781
2	18	41	--	--	--	--	0.994	0.955	0.907	0.813	0.721	0.602
2	19	24	--	--	0.027	0.082	0.082	--	--	--	--	--
2	19	25	--	--	--	--	--	0.003	0.006	0.006	0.004	0.005
2	19	27	--	--	--	0.496	0.496	0.496	0.496	0.552	0.675	0.875
2	19	29	--	--	1.452	2.177	2.212	2.026	2.666	2.577	2.141	1.788
2	19	30	--	--	1.452	2.177	2.212	2.026	1.899	1.380	1.147	0.958
2	19	37	--	0.378	0.407	0.222	--	--	--	--	--	--
2	19	39	--	--	0.567	0.567	0.490	0.499	0.498	0.527	0.468	0.390
2	20	26	--	--	--	--	0.239	0.239	0.239	0.256	0.323	0.419
2	20	29	--	--	0.726	1.089	1.106	1.013	0.949	0.690	0.573	0.479
2	20	31	--	--	--	--	0.220	0.879	0.823	0.598	0.497	0.415
2	20	32	--	--	--	--	--	--	--	0.887	1.241	0.485
2	20	33	--	--	--	--	--	--	--	--	0.340	0.485
2	21	28	--	--	--	--	--	--	0.002	0.678	0.644	0.616
2	21	30	--	--	--	--	--	--	--	--	--	0.875
2	21	32	--	--	--	--	--	--	--	--	0.340	0.905
2	22	33	--	--	--	--	--	--	--	0.887	1.241	0.485
2	22	34	--	--	--	--	--	--	--	--	0.088	0.318
2	23	30	--	--	--	--	0.253	0.470	0.657	0.605	0.893	0.570
2	23	32	--	--	--	--	1.049	1.049	1.066	0.936	0.826	1.279
2	23	38	--	--	--	--	--	--	--	1.231	2.133	3.525

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

			Stress period									
Layer	Row	Column	1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
2	23	42	--	--	--	--	--	--	0.014	0.007	0.038	0.064
2	24	30	--	--	--	0.208	0.379	0.470	0.657	0.605	0.893	0.570
2	24	33	--	--	--	--	--	--	0.971	1.871	1.652	2.559
2	24	40	--	--	--	--	--	--	0.737	0.697	1.236	1.770
2	24	41	--	--	--	--	--	--	1.474	1.394	2.472	3.539
2	24	46	--	--	--	--	--	0.091	0.539	0.423	0.354	0.154
2	24	48	--	--	--	--	--	--	0.008	0.019	0.027	0.040
2	25	26	--	--	--	--	0.037	0.150	0.135	0.017	0.026	0.013
2	25	42	--	--	--	--	--	--	0.737	0.697	1.236	1.770
2	25	54	--	--	--	--	--	--	--	0.003	0.019	0.103
2	26	38	--	--	0.146	0.291	0.291	0.291	0.291	0.291	0.097	--
2	26	40	--	--	--	--	--	--	0.737	0.697	1.236	1.770
2	26	41	--	--	--	--	--	--	0.737	0.697	1.236	1.770
2	26	44	--	--	--	--	--	0.081	0.482	0.378	0.317	0.138
2	26	47	--	--	--	0.001	0.006	0.006	0.006	0.018	0.043	0.059
2	27	33	--	--	--	--	--	--	--	--	--	1.139
2	27	37	--	--	--	--	--	--	--	--	1.237	1.700
2	27	38	--	--	--	--	--	--	--	--	1.237	1.700
2	27	41	--	--	--	--	--	1.441	1.441	1.441	1.515	1.883
2	27	49	--	--	--	--	--	--	0.029	0.029	0.029	0.045
2	28	28	--	--	--	0.336	0.402	0.177	0.250	0.422	0.500	0.367
2	28	31	--	--	--	0.471	0.803	0.354	0.500	0.844	1.001	0.734
2	28	32	--	--	--	--	--	--	--	--	--	1.170
2	28	38	--	--	--	--	--	--	--	--	1.237	1.700
2	28	40	--	--	--	--	--	0.720	0.720	0.720	0.758	0.941
2	28	41	--	--	--	--	--	0.720	0.720	0.720	0.758	0.941
2	28	53	--	--	--	--	--	0.229	0.157	0.158	0.243	0.226
2	29	30	--	--	0.558	0.336	0.402	0.177	0.250	0.422	0.500	0.367
2	29	37	--	--	--	--	--	--	--	--	1.237	1.700
2	29	41	--	--	--	--	--	0.301	0.602	0.988	1.400	1.399
2	29	54	--	0.015	0.224	0.349	0.443	0.253	0.173	0.174	0.268	0.249
2	30	27	--	--	--	--	0.402	0.177	0.250	0.422	0.500	0.367
2	30	29	--	--	--	--	0.402	0.177	0.250	0.422	0.500	0.367

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

			Stress period									
Layer	Row	Column	1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
2	30	40	--	--	--	--	--	0.301	0.602	0.988	1.400	1.399
2	30	41	--	--	--	--	--	0.602	1.205	1.977	2.800	2.798
2	31	23	--	--	--	--	--	0.084	0.250	0.422	0.500	0.367
2	31	29	--	--	--	0.135	0.402	0.177	0.250	0.422	0.500	0.367
2	31	32	--	--	--	--	--	--	--	1.583	1.620	1.850
2	31	34	--	--	--	--	0.477	1.910	2.064	2.379	2.497	2.503
2	31	37	--	--	--	--	--	--	--	--	--	1.251
2	31	54	--	--	--	--	--	--	--	--	--	0.298
2	32	34	--	--	--	--	0.475	1.900	2.057	2.379	2.497	2.503
2	32	35	--	--	--	--	--	--	0.316	1.190	1.249	1.251
2	32	36	--	--	--	--	--	--	--	--	--	2.106
2	32	41	--	--	--	--	--	--	0.143	0.539	0.365	1.414
2	33	25	--	--	--	0.336	0.402	0.177	0.250	0.422	0.500	0.367
2	33	41	--	--	--	--	--	--	--	--	--	1.414
2	34	30	--	--	--	--	--	0.408	0.493	0.578	0.579	0.529
2	34	34	--	--	--	--	--	--	0.862	1.150	1.544	1.709
2	34	35	--	--	--	--	--	--	--	--	--	0.855
2	37	54	--	--	--	--	--	--	0.001	0.004	0.011	0.014
3	10	32	--	--	--	--	--	--	--	0.524	0.421	0.231
3	11	30	--	--	--	--	--	--	--	--	0.060	0.553
3	11	32	--	--	--	--	--	--	--	--	--	0.229
3	11	33	--	--	--	--	--	--	0.195	0.303	0.266	0.870
3	11	34	--	--	--	--	--	--	--	0.270	0.266	0.464
3	11	43	--	--	--	--	--	--	--	--	0.025	0.065
3	11	46	--	--	--	--	--	--	--	--	0.009	0.065
3	12	33	--	--	--	--	--	--	--	--	--	0.238
3	12	44	--	--	--	--	--	--	--	--	0.025	0.065
3	13	53	--	--	--	--	--	--	--	--	--	0.142
3	14	32	--	--	--	0.132	0.124	0.115	0.115	0.122	0.109	0.091
3	14	33	--	--	0.044	0.264	0.247	0.231	0.230	0.245	0.217	0.181
3	14	34	--	--	--	0.132	0.185	0.231	0.230	0.245	0.217	0.181
3	15	32	--	--	--	0.264	0.247	0.231	0.230	0.245	0.217	0.181
3	15	33	--	--	0.132	0.527	0.494	0.461	0.461	0.490	0.435	0.363

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Continued

Layer	Row	Column	Stress period 1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
3	15	34	--	--	--	0.264	0.247	0.231	0.230	0.245	0.217	0.181
3	15	39	--	--	--	--	0.187	0.338	0.326	0.325	0.273	0.229
3	16	38	--	--	--	--	0.260	0.801	0.768	0.740	0.633	0.555
3	16	41	--	--	--	--	0.549	0.527	0.501	0.449	0.398	0.332
3	17	37	--	--	0.177	0.169	0.206	0.200	0.200	0.200	0.167	--
3	17	42	--	--	--	--	0.274	0.264	0.250	0.224	0.199	0.166
3	18	29	--	--	--	--	--	--	0.402	0.399	0.331	0.277
3	18	31	--	--	0.194	0.291	0.296	0.271	0.254	0.185	0.153	0.128
3	18	36	--	0.020	0.088	0.084	0.103	0.100	0.100	0.100	0.083	--
3	18	37	--	0.050	0.354	0.338	0.341	0.300	0.300	0.300	0.250	--
3	18	38	--	--	0.157	0.157	0.135	0.138	0.138	0.146	0.129	0.108
3	18	39	--	--	0.313	0.313	0.271	0.276	0.275	0.291	0.258	0.216
3	18	41	--	--	--	--	0.274	0.264	0.250	0.224	0.199	0.166
3	19	29	--	--	0.388	0.582	0.591	0.542	1.019	1.167	0.969	0.810
3	19	30	--	--	0.388	0.582	0.591	0.542	0.508	0.369	0.307	0.256
3	19	39	--	--	0.157	0.157	0.135	0.138	0.138	0.146	0.129	0.108
3	20	26	--	--	--	--	0.035	0.035	0.035	0.038	0.048	0.062
3	20	29	--	--	0.194	0.291	0.296	0.271	0.254	0.185	0.153	0.128
3	20	31	--	--	--	--	0.146	0.586	0.549	0.399	0.331	0.277
3	20	32	--	--	--	--	--	--	--	0.295	0.413	0.161
3	20	33	--	--	--	--	--	--	--	--	0.113	0.161
3	21	28	--	--	--	--	--	--	--	0.184	0.175	0.167
3	21	30	--	--	--	--	--	--	--	--	--	0.625
3	21	32	--	--	--	--	--	--	--	--	0.113	0.301
3	22	33	--	--	--	--	--	--	--	0.295	0.413	0.161
3	24	46	--	--	--	--	--	0.015	0.089	0.070	0.058	0.025
3	24	48	--	--	--	--	--	--	0.002	0.005	0.008	0.012
3	27	33	--	--	--	--	--	--	--	--	--	0.930
3	27	41	--	--	--	--	--	0.240	0.240	0.240	0.253	0.314
3	28	32	--	--	--	--	--	--	--	--	--	0.616
3	28	40	--	--	--	--	--	0.120	0.120	0.120	0.126	0.157
3	28	41	--	--	--	--	--	0.120	0.120	0.120	0.126	0.157
3	30	37	--	--	--	--	--	--	--	--	--	0.278

Table 5. Ground-water withdrawal rates in the basin, in cubic feet per second - Concluded

			Stress period									
Layer	Row	Column	1907 to 1931	1932 to 1947	1948 to 1950	1951 to 1955	1956 to 1959	1960 to 1961	1962 to 1965	1966 to 1969	1970 to 1975	1976 to 1979
3	31	32	--	--	--	--	--	--	--	0.352	0.361	0.412
3	31	34	--	--	--	--	0.212	0.848	0.917	1.059	1.112	1.114
3	31	35	--	--	--	--	--	--	0.070	0.265	0.278	0.278
3	31	36	--	--	--	--	--	--	--	--	--	0.278
3	33	29	--	--	--	--	--	0.014	0.018	0.021	0.021	0.019
TOTAL (rounded)			0.093	6.735	20.79	34.63	55.17	66.93	83.51	98.39	117.4	138.3

Table 6.--Total ground-water withdrawal (excluding withdrawal from the shallow flood-plain alluvium) and the interval below the water-table surface from which the water was withdrawn

[Interval withdrawals may not add to total due to rounding]

Time	Average total withdrawal in cubic feet per second	Withdrawal in cubic feet per second by interval		
		0-200 feet	200-650 feet	650-1275 feet
1907-31	0.093	0.093	0.0	0.0
1932-47	6.74	0.46	6.20	0.07
1948-50	20.79	2.61	15.59	2.58
1951-55	34.63	4.51	25.58	4.55
1956-59	55.17	6.90	41.83	6.45
1960-61	66.93	9.31	49.18	8.45
1962-65	83.51	14.04	59.94	9.53
1966-69	98.39	16.60	70.19	11.60
1970-75	117.35	25.68	80.60	11.07
1976-79	138.28	31.20	93.00	14.08