

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

By John Michael Kernodle and William B. Scott

**U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 84-4353**

Albuquerque, New Mexico

1986



UNITED STATES DEPARTMENT OF INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
505 Marquette NW, Room 720
Albuquerque, New Mexico 87102

Copies of this report can
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CONVERSION FACTORS

In this report, all measurements except chemical concentrations are given in inch-pound units. When describing the results of previous investigations, the units of measurement in those works are retained. The following table contains factors for converting to metric units.

<u>Multiply inch-pound units</u>	<u>By</u>	<u>To obtain metric units</u>
foot	0.3048	meter
square foot per day	0.0929	square meter per day
cubic foot per second	0.02832	cubic meter per second
gallon per minute	0.06309	liter per second
gallon per minute per foot	0.2070	liter per second per meter
inch	25.4	millimeter
mile	1.609	kilometer
acre-foot	0.001233	cubic hectometer
ton	907.18	kilogram
square mile	2.590	square kilometer

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ABSTRACT

As part of the Southwest Alluvial Basins study, a three-dimensional ground-water flow model was constructed to simulate the alluvial-aquifer system underlying the Albuquerque-Belen Basin in New Mexico. The model was used to simulate the steady-state flow condition assumed to have existed prior to 1960. Until this time there apparently were no long-term ground-water level changes of a significant magnitude outside the immediate vicinity of Albuquerque. Therefore, the construction of a steady-state flow model of the aquifer system based on reported hydrologic data predating 1960 was justified.

During construction of the steady-state model, simulated hydraulic conductivity values were adjusted, within acceptable physical limits, until a best fit between measured or reported and computed heads at 34 control wells was achieved. The modeled area was divided into six subareas, or zones, within each of which hydraulic conductivity was assumed to be uniform. The model consisted of six layers for each of which simulated transmissivity was proportional to the layer thickness. Adjustments to simulated hydraulic conductivity values in the different zones resulted in final values that ranged from a low of 0.25 foot per day in the west to 50 feet per day in the eastern part of the basin. The error of the simulation, defined as the absolute difference between the computed and the measured or reported water level at the corresponding point in the physical system being modeled, ranged from 0.6 foot to 36 feet, with an average of 14.6 feet for the 34 control wells.

INTRODUCTION

In 1978 Congress appropriated funds to the U.S. Geological Survey, Water Resources Division, for the initiation of the Regional Aquifer-System Analysis (RASA) program. The RASA program is a systematic effort to study a number of significant regional ground-water systems that together cover much of the country and represent a major part of the national ground-water supply.

The RASA program began with the investigation of several regional aquifer systems in the western United States (Bennett, 1979). Included among these was the Southwest Alluvial Basins (SWAB) study. The SWAB study was divided into two parts. This study is the part of the SWAB investigation that includes about 70,000 square miles in Colorado, New Mexico, and Texas (fig. 1).

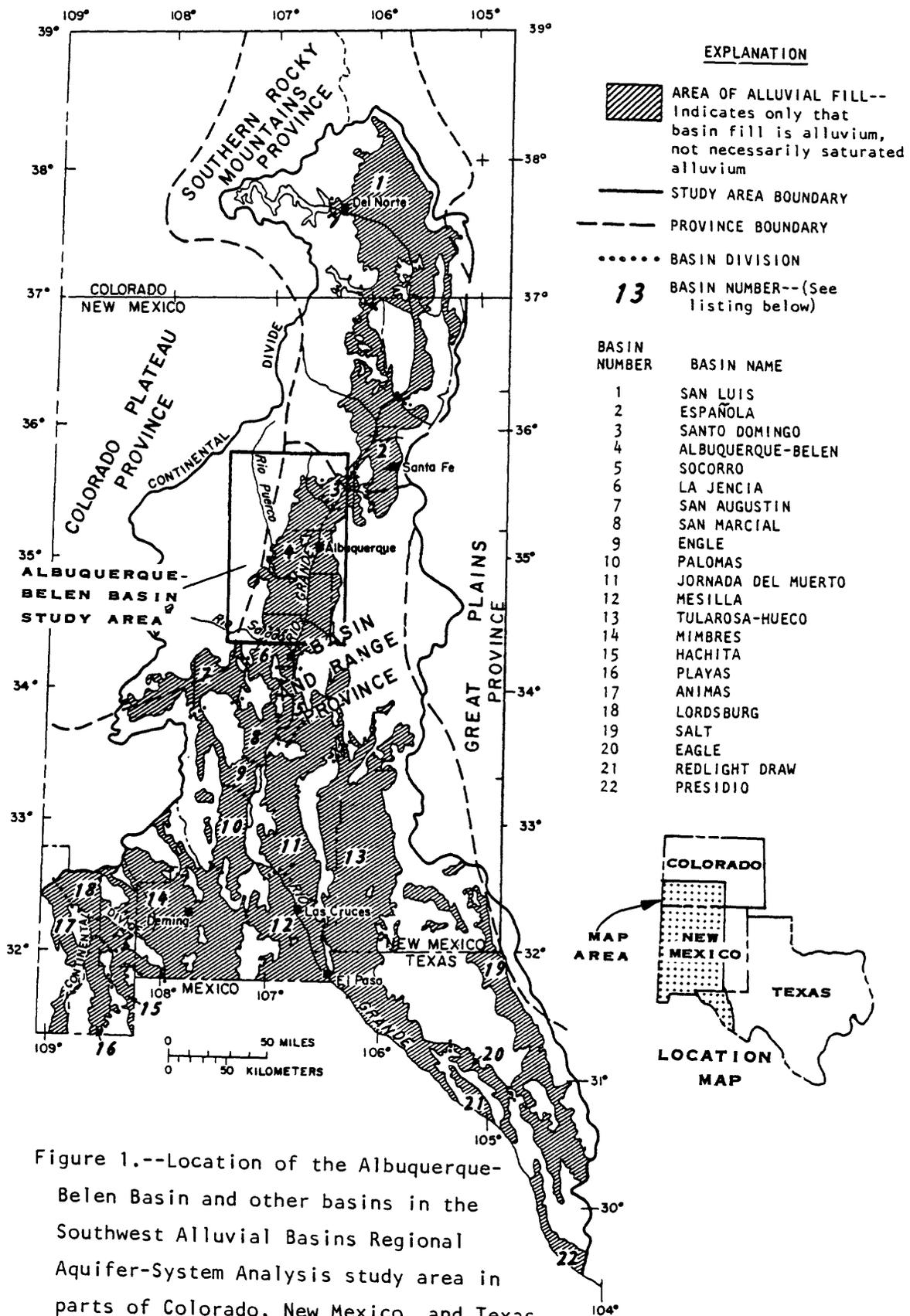
The principal objectives of the SWAB study are to assemble and evaluate hydrologic, geologic, and geochemical information and to evaluate the effects of stresses on the ground-water system. Within the framework of these objectives and this part of the study, 22 individual basins in Colorado, New Mexico, and Texas were investigated. Each basin study consists of data compilation and evaluation, limited data collection, and literature review of geologic and hydrologic information sources. Ground-water flow in selected basins was simulated depending on availability of data, extent of ground-water development, and the transferability of the simulation concepts to other similar basins. Basins of varied types were selected to broaden the transferability.

One of the basin aquifer systems chosen to be simulated was the ground-water flow system in the Albuquerque-Belen Basin. The objectives for the Albuquerque-Belen study are as follows: (1) To gain a better general understanding of the behavior of the hydrologic systems in the basin; (2) to construct a model capable of simulating the aquifer system and evaluating the response of the ground-water flow system to pumping stress; and (3) to test the feasibility of using a simplified simulation boundary type to represent the surface-water and ground-water interconnection in the Rio Grande valley.

In order to accomplish these objectives, the study involves three phases of activity: (1) Compiling and evaluating the geohydrologic data; (2) constructing a steady-state flow model of the basin aquifer system; and (3) adapting the steady-state model to simulate streamflow depletion (flood-plain depletion) and ground-water-level responses to pumpage stresses, and performing sensitivity analyses to determine the relative importance of individual hydrologic properties. This report documents the results of the first two phases.

Previous Investigations

The geology and physiography of the Albuquerque area and areas in and adjacent to the middle Rio Grande Rift, which includes the Albuquerque-Belen Basin, have been described by many investigators. The geologic reports most pertinent to the Albuquerque-Belen Basin study are those by Bryan (1909, 1938), Bryan and McCann (1936, 1937, 1938), Wright (1946), Baldwin (1956),



Northrop (1961), Lambert (1968, 1974), Galusha and Blick (1971), and Black and Hiss (1974). All of these reports describe the Tertiary and Quaternary geology of the middle Rio Grande Rift and vicinity. Detailed discussions of the Santa Fe Group, the most important aquifer unit, are also presented.

The description of pre-Tertiary stratigraphy and geologic history in the vicinity of the study area was reported by Sears and others (1936), Read and others (1944), Kelley and Wood (1946), Reiche (1949), Kelley (1952), Fitzsimmons (1961), and Smith (1961). The pre-Tertiary rocks include consolidated and unconsolidated sedimentary rocks and crystalline igneous and metamorphic rocks. These form the boundaries for aquifers of younger age and affect the runoff in the study area.

Detailed and site-specific studies of the geology in the vicinity of the Albuquerque-Belen Basin have been conducted by Joesting and others (1961), Lambert (1968), Cordell and others (1973), Kelley (1974, 1977), Kelley and Northrop (1975), Cordell (1976), Kelley and others (1976), and Kelley and Kudo (1978).

Several hydrologic studies of part of the Albuquerque-Belen Basin have been made. The first comprehensive ground-water study of the Albuquerque area was made by Bjorklund and Maxwell (1961). They presented detailed hydrologic data (aquifer boundaries, transmissivities, specific yield, recharge, chemical quality of ground water, and water-table altitudes) and records of wells (including locations, estimated yields, depths to water, and available well logs). Reeder and others (1967) presented a quantitative study that emphasized long-range water-level projections. A report by the U.S. Army Corps of Engineers (1979) updated the work by Reeder and others (1967), which was itself based mainly on data collected and published by Bjorklund and Maxwell (1961). The report by the Corps of Engineers is the most current water-resources evaluation of the study area and has provided information that was useful in this study.

Regional evaluations of the geology and hydrology of central New Mexico have also provided additional information concerning water supplies for the study area. Some of the earliest studies to evaluate the occurrence of ground water in the middle Rio Grande Rift were by Lee (1907), Bloodgood (1930), Bryan (1938), Theis (1938), and Theis and Taylor (1939). Studies to evaluate the geology and ground-water resources in this area were later conducted by Spiegel (1955), Titus (1963), Lansford and others (1973), Kelly and others (1974), Trainer (1974), Brutsaert and Gebhard (1975), Hiss and others (1975), and West and Broadhurst (1975). For more comprehensive bibliographies of the geology and hydrology in the vicinity of the Albuquerque-Belen Basin, the reader is referred to Wright (1978), Stone and others (1979), and Borton (1980).

Well-Numbering System

One system of numbering wells in New Mexico is based on the township and range subdivision of public lands. The well number, in addition to designating the well, locates its position in the land network. The number is divided by periods into four segments. The first segment denotes the township north or south of the New Mexico Base Line; the second denotes the range east or west of the New Mexico Principal Meridian; and the third denotes the section. The fourth segment of the number, which consists of three digits, denotes the 160-, 40-, and 10-acre tracts, respectively, in which the well is situated. The use of the numbering system is shown in figure 2.

The reader is referred to Bjorklund and Maxwell (1961) for a thorough explanation of the well-numbering system. Township and range identification numbers are given for wells that are referenced in this report. However, these identifications are not intended to be used as a means of location of the wells in the following figures.

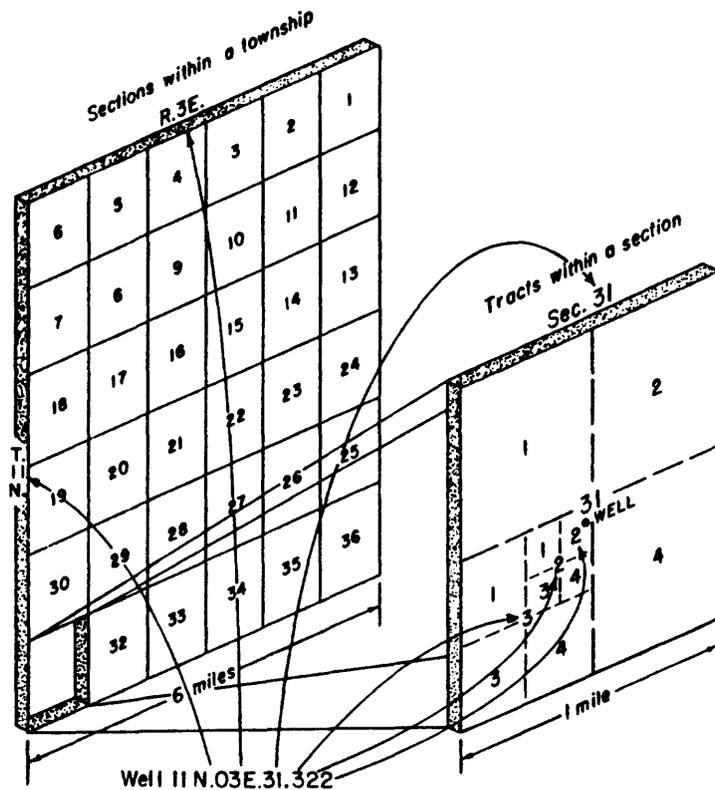


Figure 2.--A system used to number wells and springs in New Mexico.

LOCATION AND GENERAL FEATURES OF THE BASIN

The Albuquerque-Belen Basin is one of the largest of the south-trending series of grabens that form the Rio Grande Rift. The structural basin, which is located in the central part of New Mexico, is 25 to 40 miles wide, about 90 miles long, and covers approximately 2,700 square miles in parts of Sandoval, Bernalillo, Valencia, and Socorro Counties (fig. 3). The Albuquerque-Belen Basin extends from the Jemez caldera on the north to the San Acacia constriction on the south, and from the Lucero and Ladron Uplifts, the Rio Puerco bench and the San Juan Basin on the west to the Joyita-Hubbell bench and Sandia Uplift on the east.

The basin is bounded to the east by faults that separate it from the Sandia, Manzanita, and Manzano Uplifts (Black and Hiss, 1974, pl. 2). Kelley (1977, p. 52) postulated the concept of fault-bounded structural benches and steps within the Albuquerque-Belen Basin, with the most important of these being the Joyita-Hubbell bench (fig. 3). According to Kelley, the bench could be the principal eastern structural boundary of the Rio Grande Rift from the San Acacia constriction on the south to the Tijeras Fault and the Sandia Uplift on the north. For the purpose of this study, the Joyita-Hubbell bench is assumed to be the southeastern boundary of the ground-water basin. The Sandia Fault, a probable extension of the Hubbell Springs Fault, forms another bench that constitutes the eastern boundary of the basin. A short distance (usually less than 5 miles) east of these faults, Precambrian crystalline rocks and upper Paleozoic sedimentary rocks stand as much as 5,000 feet above the surface of the adjacent basin-fill deposits.

The basin is bounded to the west by a series of subparallel faults (only a few are shown in fig. 3) that extend south-southwest from near the Jemez caldera to near the Sierra Ladron, separating the basin from the Nacimiento Uplift, the Puerco bench, and the Lucero and Ladron Uplifts (Kelley, 1954, 1977; Slack, 1973). Precambrian, upper Paleozoic, and Mesozoic rocks are exposed in the uplifts west of the basin margin (fig. 4) but attain much lower altitudes than rocks of similar age east of the rift. Joesting and others (1961) estimated that stratigraphic displacement may be as great as 22,000 feet along the eastern margin of the basin and about 16,000 feet along the western margin.

The southern end of the basin is formed by convergence of side boundaries to a narrow and shallow structural trough and depositional channel that connects with the Socorro Basin to the south (Kelley, 1977, p. 7 and 43). The east side of the constriction is formed by the Joyita-Hubbell bench and the west side by the Ladron Uplift.

The northern end of the basin commonly is accepted to be at the southern flank of the Jemez caldera and the south and southwest flank of Santa Ana Mesa (Bryan, 1938; Spiegel, 1962). However, as will be discussed later, this delineation may be more topographic than structural or hydrologic. The Jemez caldera is the collapse remnant of a large extinct volcanic complex that formed at or near the edge of the rift, whereas Santa Ana Mesa is the erosional remnant of basaltic fissure flows of the San Felipe field. These flows originated from numerous north-trending fissures and small volcanic

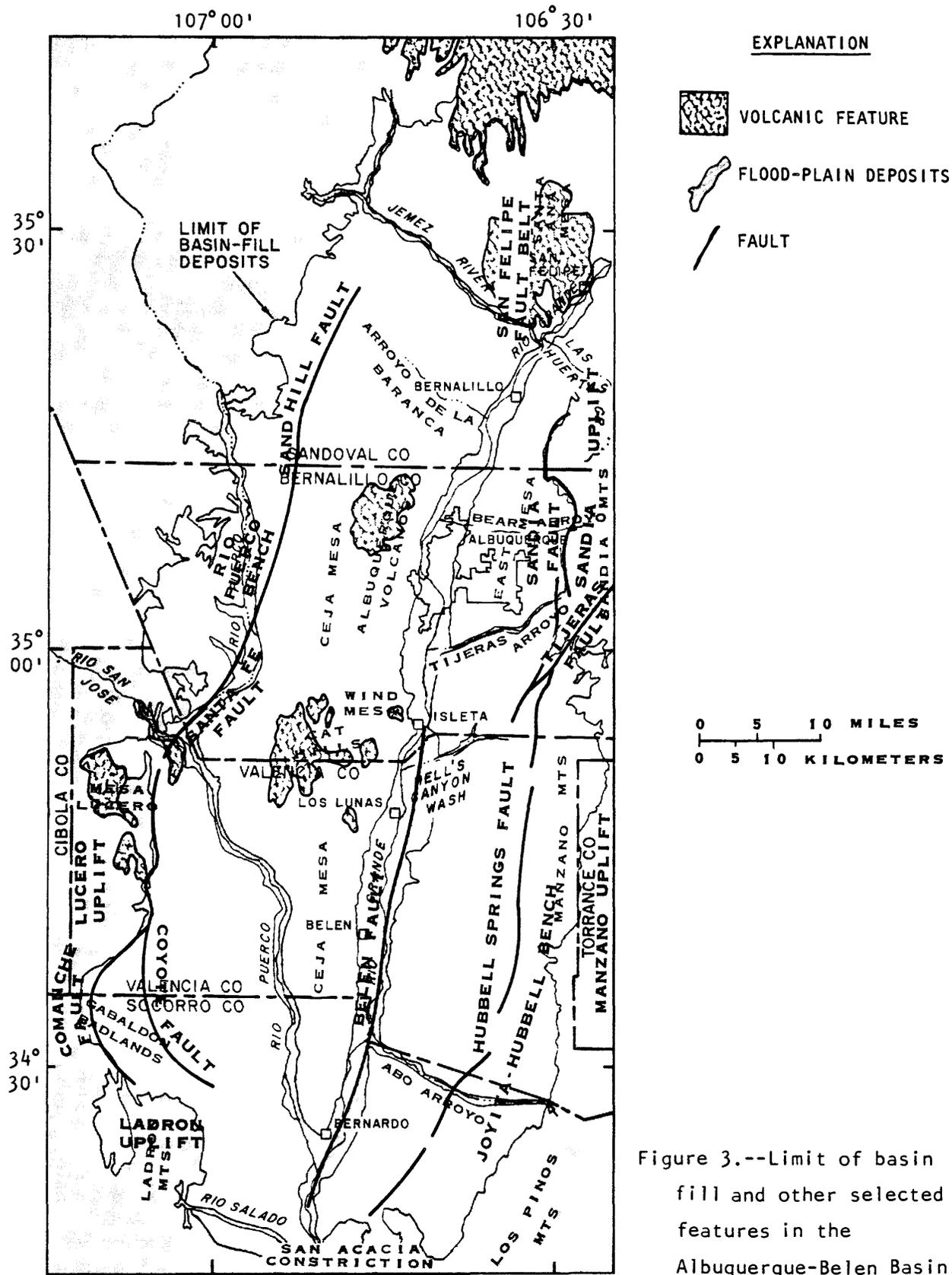


Figure 3.--Limit of basin fill and other selected features in the Albuquerque-Belen Basin.

cones approximately centered in the rift valley. Kelley (1977) placed the northern end of the basin at the northern end of La Bajada Fault, thereby including the Santo Domingo Basin and Santa Ana Mesa, whereas Bjorklund and Maxwell (1961) set the northern limit of their investigation at the southern edge of the mesa based on the presence of the San Felipe Fault belt. In this investigation the northern end of the basin is assumed to be at the southern flanks of the Jemez caldera and Santa Ana Mesa.

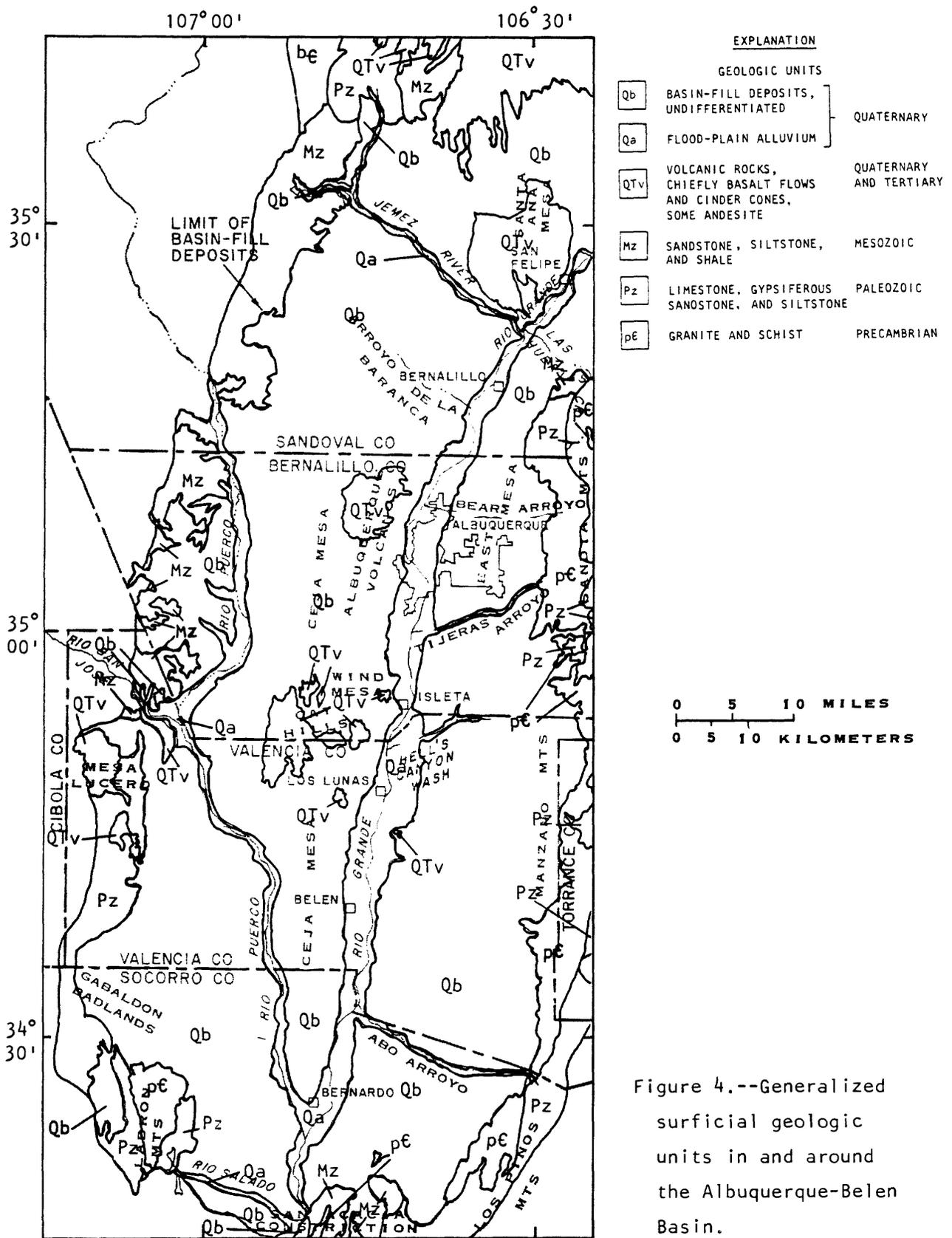
In addition to Santa Ana Mesa, small volcanic cones and fissure flows are surface features at several localities within the basin. The youngest among these are Cat Hills, a flow from Mesa Lucero into the western part of the basin, and the Albuquerque volcanoes. The flow from Mesa Lucero is only a surface feature in the basin, but Cat Hills and the Albuquerque volcanoes are both recent fissure-flow features with final-stage development of cinder cones. The fissures from which these flows emerged each extend approximately 5 miles in a north-south direction. These three flows have remained intact with only minor erosion on the edges. Older volcanic centers are located near Los Lunas and Isleta and on Wind Mesa. These have undergone more extensive erosion and some reburial. Although the Los Lunas volcanics are bounded by a fault swarm, none of the older volcanics appear to be associated with major linear structures.

The Albuquerque-Belen Basin is drained by two principal longitudinal streams, the Rio Grande in the east and the Rio Puerco in the west. Both streams are entrenched several hundred feet into older basin deposits. The Rio Puerco frequently is dry at its confluence with the Rio Grande downstream near Bernardo, about 50 miles south of Albuquerque. However, the Rio Puerco is subject to flooding and, at times of high discharge, sediment concentrations of over 200,000 milligrams per liter are common. The record daily sediment load is 2,240,000 tons. The inner valley of the Rio Puerco once supported irrigated agriculture, but, in recent history, severe entrenchment and bank erosion together with a steady decrease in dependable streamflow have discouraged agricultural development.

In sharp contrast with the inner valley of the Rio Puerco, the flood plain of the Rio Grande supports an extensive irrigated agriculture via a system of diversions, canals, and drains. Expanding urban areas are, however, removing an increasing area of the flood plain from agricultural use.

In this report the names "Rio Grande valley" and "Rio Puerco valley" are used in a restricted sense to identify only the incised inner valleys of these streams. The Rio Grande valley may also be referred to, in this report, simply as the flood plain. Other streams that will be discussed in more detail later are the Jemez River in the northern part of the basin and the Rio Salado in the southern part.

Between the Rio Grande and the Rio Puerco is Ceja Mesa (also known as the Llano de Albuquerque, or as the West Mesa), a remnant of high-level basin fill that extends from near the Jemez River on the north to Bernardo on the south. Except for volcanic features, the mesa is relatively flat and is veneered with windblown longitudinal dunes and thin alluvial sand and gravel of the Ortiz surface. At the top edge of the mesa bluff is a thin but almost



continuous caliche zone. The thin white line when viewed from a distance gave rise to the name Ceja (or eyebrow) Mesa.

A small area west of the valley of the Rio Puerco and a larger area east of the valley of the Rio Grande (East Mesa) are also remnants of high-level basin-fill deposits. East Mesa gains 800 to 1,000 feet altitude as it slopes from the edge of the inner valley of the Rio Grande toward the base of the Sandia and Manzano Mountains. At several locations the mesa is dissected to the level of the Rio Grande flood plain by arroyos and washes draining the mountains in the east. Some of its surface is, like Ceja Mesa, covered by northeast-trending longitudinal dunes.

The climatic regime of the basin can be best characterized as arid-continental. Rainfall varies considerably from year to year and from place to place within the basin. Mean annual precipitation ranges from about 8 inches at lower altitudes along the river to about 24 inches at higher altitudes in the mountains bordering on the east. At lower altitudes most of the precipitation occurs as rainfall from thunderstorms during the summer months. In the mountains, a large percentage of the precipitation is snowfall during the winter. Snowmelt during the spring and summer months maintains high-altitude runoff in several of the larger westward-flowing tributaries to the Rio Grande, principally Tijeras Arroyo, Abo Wash, and Las Huertas Creek.

HYDROLOGIC SETTING

Surface water and ground water are closely interrelated in the Albuquerque-Belen Basin. Evidence of this may be found after rainfall by watching the flow in an arroyo being absorbed into the arroyo bed, perhaps disappearing completely. At the margins of the basin, streams may lose most or all of their flow to the ground as they cross onto the basin-fill deposits from less permeable soils and sediments on granite or consolidated rocks. Because of channel loss of flow, most arroyos exhibit a decrease in cross-sectional area and channel capacity in a downstream direction (Bjorklund and Maxwell, 1961, p. 50 and 51). Other examples of the interrelationship of ground and surface water include, at certain times of the year, dry reaches of the Rio Grande bracketed a short distance both upstream and downstream by flowing reaches. Finally, there are the riverside drains whose flow of clear water is often almost totally derived from the ground-water system. The hydrologic system in the basin is very complex. Changes in one part of the system eventually have an impact on the other parts.

Surface-Water System

The surface-water system consists of (1) The Rio Grande and its major tributaries; (2) arroyos, washes, and flood-runoff impoundments (which only temporarily contain water); (3) irrigation canals; and (4) drainage ditches.

The Rio Grande, the only perennial stream in the Albuquerque-Belen Basin, is the major source of surface water. The Rio Grande flows generally south-southwest through the Albuquerque-Belen Basin and gains approximately 10,670 square miles of drainage area as it passes through the basin.

The mean annual Rio Grande inflow and outflow for the Albuquerque-Belen Basin from 1948 to 1960 were 834,000 acre-feet and 669,000 acre-feet, respectively. The difference between mean inflow and mean outflow, a loss of 165,000 acre-feet per year, is only a part of the total loss of water to evapotranspiration in the flood plain. The mean annual surface flows, while perhaps useful for long-range planning purposes, are highly variable and cannot be depended on in any given year.

The Jemez River enters the Rio Grande from the west about 5 miles north of Bernalillo. It drains an area of about 1,030 square miles. The Rio Salado in the northern part of the basin (there are two; a northern and a southern river of the same name), the largest tributary of the Jemez River, brings drainage from the west front of the Nacimiento Uplift and from part of the San Juan Basin west of the mountains. The annual flow of the northern Rio Salado has not been gaged. The mean annual flow of the Jemez River at a station upstream from the confluence of the Rio Salado (drainage area of about 470 square miles) was 50,400 acre-feet for 33 years of record ending in 1981. In comparison, the flow of the Jemez River at its confluence with the Rio Grande averaged 40,100 acre-feet per year for 39 years of record ending in 1981. The inflow to the Rio Grande from the Jemez River is regulated by a dam a short distance upstream of its confluence with the Rio Grande. Mean annual surface-water inflow to the Rio Grande from the Jemez River from 1948 to 1960 was 33,600 acre-feet.

The Rio Puerco enters the Rio Grande about 50 miles south of Albuquerque and is one of the principal western tributaries in the basin. Its headwaters are in the San Juan structural basin, about 110 river miles upstream from its confluence with the Rio Grande. The Rio Puerco has a drainage area of approximately 7,350 square miles, including 1,130 square miles that do not contribute directly to surface runoff. Although usually dry, the Rio Puerco is subject to floods following summer and fall rainstorms. These floods transport large quantities of silt to the Rio Grande. Mean annual surface-water inflow to the Rio Grande from the Rio Puerco from 1948 to 1960 was 35,900 acre-feet. For 41 years of record ending in 1981, the mean annual flow was 33,400 acre-feet.

The Rio Salado (southern) enters the Rio Grande from the west downstream from the Rio Puerco. Although its drainage area, about 1,380 square miles, is roughly one-fifth that of the Rio Puerco, the mean annual surface-water inflow to the Rio Grande from the Rio Salado (southern) for the period of record ending in 1981 was 10,500 acre-feet, or almost one-third of the flow of the Rio Puerco. From 1948 to 1960 the mean annual flow was 9,060 acre-feet. Like the Rio Puerco, the Rio Salado (southern) has no flow throughout most of the year.

Arroyos are also part of the surface-water system. Few arroyos draining from the east discharge directly into the Rio Grande. Most either lose their flow by infiltration into alluvial fans at the base of the Sandia, Manzanita, and Manzano Mountains or empty into the numerous canals and drains paralleling the river. Las Huertas Creek, Abo Wash, and Tijeras Arroyo, the largest tributaries to enter the Rio Grande from the east, drain a part of the east slopes as well as the west slopes of the Sandia, Manzanita, and Manzano

Mountains. Between these three arroyos are numerous other washes and arroyos that originate on the west front of the mountains and flow westward across the East Mesa into the inner valley (Bjorklund and Maxwell, 1961, p. 10). In addition, the city of Albuquerque has two concrete-lined flood-control channels and many smaller lined washes that collect and redirect storm runoff to the river. The washes are lined as they pass through developed areas, but lining generally does not extend into undeveloped areas. Lining of arroyos and washes prevents local recharge of storm runoff to the aquifer. Of the numerous arroyos draining Ceja Mesa, Arroyo de la Baranca and those further north discharge directly to the river, whereas those to the south discharge into drains and canals.

Surface water that moves into the basin from bounding mountain ranges or from tributary basins and then, in a short distance, infiltrates into the aquifer within a short distance is defined in this report as boundary or mountain-front recharge. Using a technique documented in a report by Hearne and Dewey (in press) the flow of the tributaries from the mountain fronts bordering the Albuquerque-Belen Basin was estimated. The flow along the eastern boundary totals approximately 99 cubic feet per second (72,000 acre-feet per year). Flow along the southwestern boundary is considerably less. Boundary recharge along this margin of the basin is estimated to be about 11 cubic feet per second (8,000 acre-feet per year).

The estimated 1.8 cubic feet per second (1,300 acre-feet per year) of recharge along the northwestern margin of the basin (fig. 5) is ground-water underflow from the San Juan Basin. This recharge will be discussed later.

Some surface-water flows may extend far out into the basin, possibly even reaching the Rio Grande. Streambed infiltration along these reaches, termed tributary recharge, was determined by J.D. Dewey (U.S. Geological Survey, written commun., 1982). Approximately 32 cubic feet per second (23,200 acre-feet per year) is recharged by streambed infiltration along the Rio Puerco and Rio Salado (southern). An additional 34 cubic feet per second (25,000 acre-feet per year) is estimated to recharge along the Jemez River. The boundary or mountain-front recharge and streambed infiltration estimates for the basin are shown in figure 5.

An undetermined amount of recharge also occurs as a result of the retention of storm runoff in earth-lined flood-retention reservoirs on several of the larger arroyos (Bear Arroyo, for example). These reservoirs may increase recharge to the aquifer in two ways: first, by direct recharge through the bottom materials of the reservoir, and second, by controlling the rate of release of water, which allows more recharge to the aquifer and less runoff loss to the Rio Grande. This second process does not occur if the reservoir discharges directly into a lined channel.

Water diverted from the Rio Grande into the many irrigation canals is another part of the surface-water system. One of the major mechanisms of depletion of flow in the Rio Grande is diversion for irrigation. The Middle Rio Grande Conservancy District (MRGCD) originally constructed and now manages an extensive network of irrigation canals and drains to support irrigated land within the basin. Surface water is diverted by four main structures within

the basin: the Angostura and Atrisco Headings, and the Isleta and San Acacia Diversion Dams. The Angostura and Atrisco Headings are located on the Rio Grande just above the Jemez River and in south Albuquerque, respectively. The Isleta and San Acacia Diversion Dams are located at Isleta and at the San Acacia constriction. The MRGCD has divided the irrigation district into four general divisions; two of these are within the study basin. These are the Albuquerque Division, extending from Angostura Heading to the Isleta Diversion Dam, and the Belen Division, extending from the Isleta Diversion Dam to the San Acacia Diversion Dam. Annual surface-water diversions in the Albuquerque and Belen Divisions for 1967 to 1977 are shown in table 1. The actual amount of water that is diverted from the river is measured by MRGCD. Ultimately, all diverted surface water is evapotranspired, recharged to the aquifer system, or returned to the Rio Grande through the system of drains.

Table 1. Annual surface-water diversions for the Albuquerque and Belen Divisions of the Middle Rio Grande Conservancy District for 1967-77

Year	Net supply (acre-feet)
1967	285,620
1968	271,520
1969	315,560
1970	291,090
1971	232,730
1972	236,920
1973	374,170
1974	317,860
1975	356,690
1976	388,380
1977	317,520

Source: U.S. Army Corps of Engineers, 1979, tables 2-9

Drainage ditches, which were designed and constructed by the Middle Rio Grande Conservancy District from 1931 to 1935 to prevent waterlogging of irrigated lands, consist of two types: riverside and interior drains. The riverside drains are several feet lower than the bed of the Rio Grande. These drains collect water from interior drains and intercept leakage from the river that would otherwise move underground from the river channel to the flood plain and raise the water table. The intercepted water moves down the valley in the drain; downstream the drain level approaches river level, returning the water to the river by gravity flow at places where the water level in the

drain is equal to or greater than the stage of the river. The interior drains are located in the lower part of the flood plain on each side of the river. The purpose of these drains is to prevent the water table from rising in the alluvium because of recharge from irrigation, leakage from the canals, and recharge from the Santa Fe Group across the geologic contact with the flood-plain alluvium. The combined effect of the two types of drains is to maintain the water table under the flood plain at a depth that is not injurious to crops (Titus, 1963). They provide an equilibrium mechanism within the flood plain and control the water-table altitude.

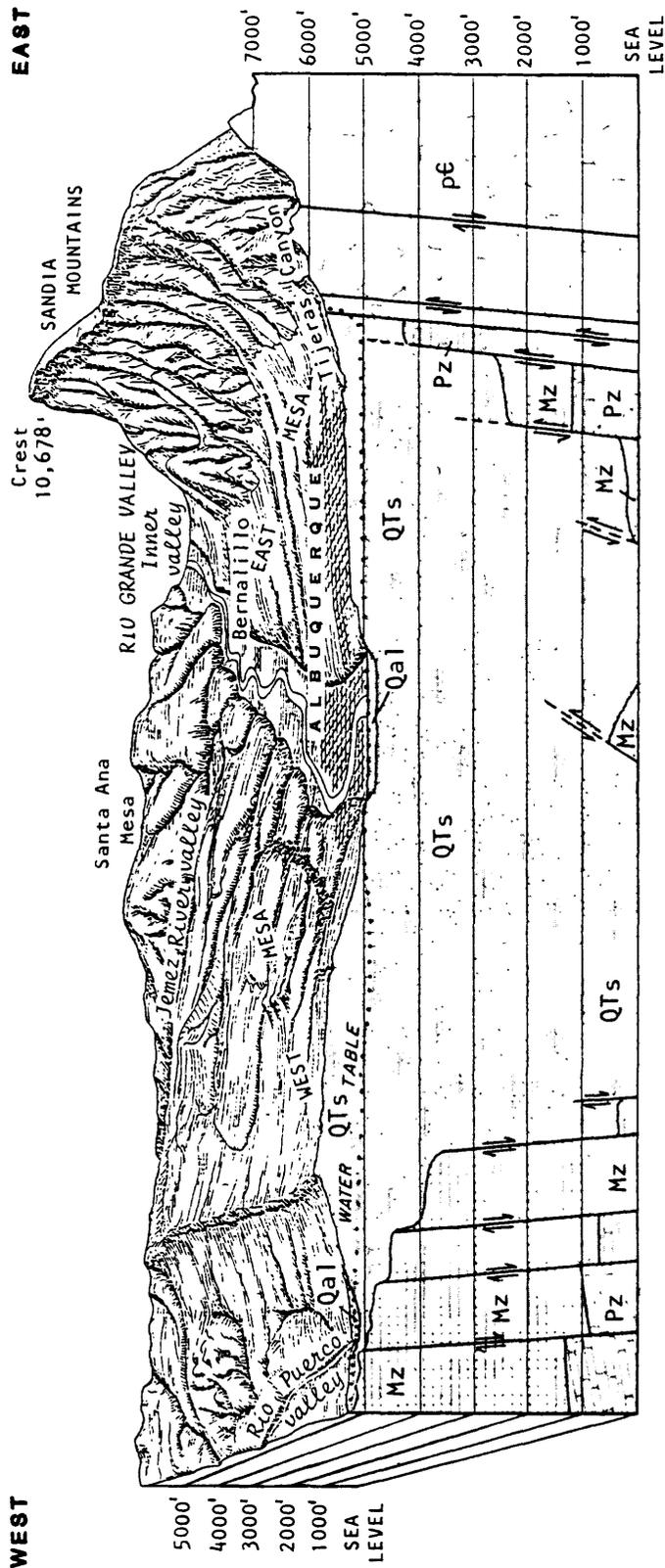
Ground-Water System

This part of the report presents a brief description of the ground-water flow system in the Albuquerque-Belen Basin. A detailed description of the geology and hydrology of the basin and vicinity can be found in Bjorklund and Maxwell (1961), Kelley (1977), and U.S. Army Corps of Engineers (1979). The following material is largely condensed from those reports.

Geologic Control of the Occurrence and Movement of Ground Water

The Albuquerque-Belen Basin is one of the largest grabens of the Rio Grande Rift. Rocks of pre-Tertiary age underlie the basin and crop out in bordering highlands. These rocks form the boundaries of the structural basin and typically yield little water to wells; therefore, they will not be discussed further. For purposes of this study, the basin-fill sediments of Tertiary and Quaternary age are of primary concern. These sediments crop out in most of the basin area. They unconformably overlie rocks of pre-Tertiary age, as stated by Bjorklund and Maxwell (1961), and generally are composed of unconsolidated to loosely consolidated gravel, sand, clay, and silt, and a few basalt flows and beds of tuff. Large-capacity water wells are completed in sediments of Tertiary and Quaternary age including the Santa Fe Group, alluvial fans, and valley alluvium. A generalized section through the basin, including the stratigraphy and general structure of the basin, is shown in figure 6.

The Santa Fe Group is a thick accumulation of sediments that were deposited in the basin during the late Tertiary and Quaternary time (Spiegel, 1955). It unconformably overlies earlier formations and is both the most areally extensive deposit in the study area and the most important aquifer in the basin. It consists of beds of unconsolidated to loosely consolidated sediments and interbedded volcanic rocks. The sediments range from boulders to clay and from well-sorted stream-channel deposits to poorly sorted slopewash deposits. These deposits vary abruptly both laterally and vertically from coarse conglomerate and gravel to sand, silt, and clay. The thickness of the Santa Fe Group varies widely in different parts of the basin.



EXPLANATION

Qa1

Alluvium
Mostly unconsolidated gravel, sand, silt, and clay. Yields large quantities of water to wells.

MZ

MESOZOIC
Sedimentary rocks, undivided
Mostly shale and sandstone. Yields small quantities of water to wells.

QTs

QUATERNARY and TERTIARY
Santa Fe Group
Mostly unconsolidated to loosely consolidated gravel, sand, silt, and clay, with some interbedded volcanic rocks. Includes bajada deposits of recent age. Yields large quantities of water to wells.

Pz

PALEOZOIC
Sedimentary rocks, undivided
Mostly limestone, sandstone, and shale. Yields small quantities of water to wells.

pE

PRECAMBRIAN
Granitic and metamorphic rocks, undivided
Yields small quantities of water to wells.

Figure 6.--Generalized geologic section of an area near Albuquerque (modified from Bjorklund and Maxwell, 1961, fig. 3).

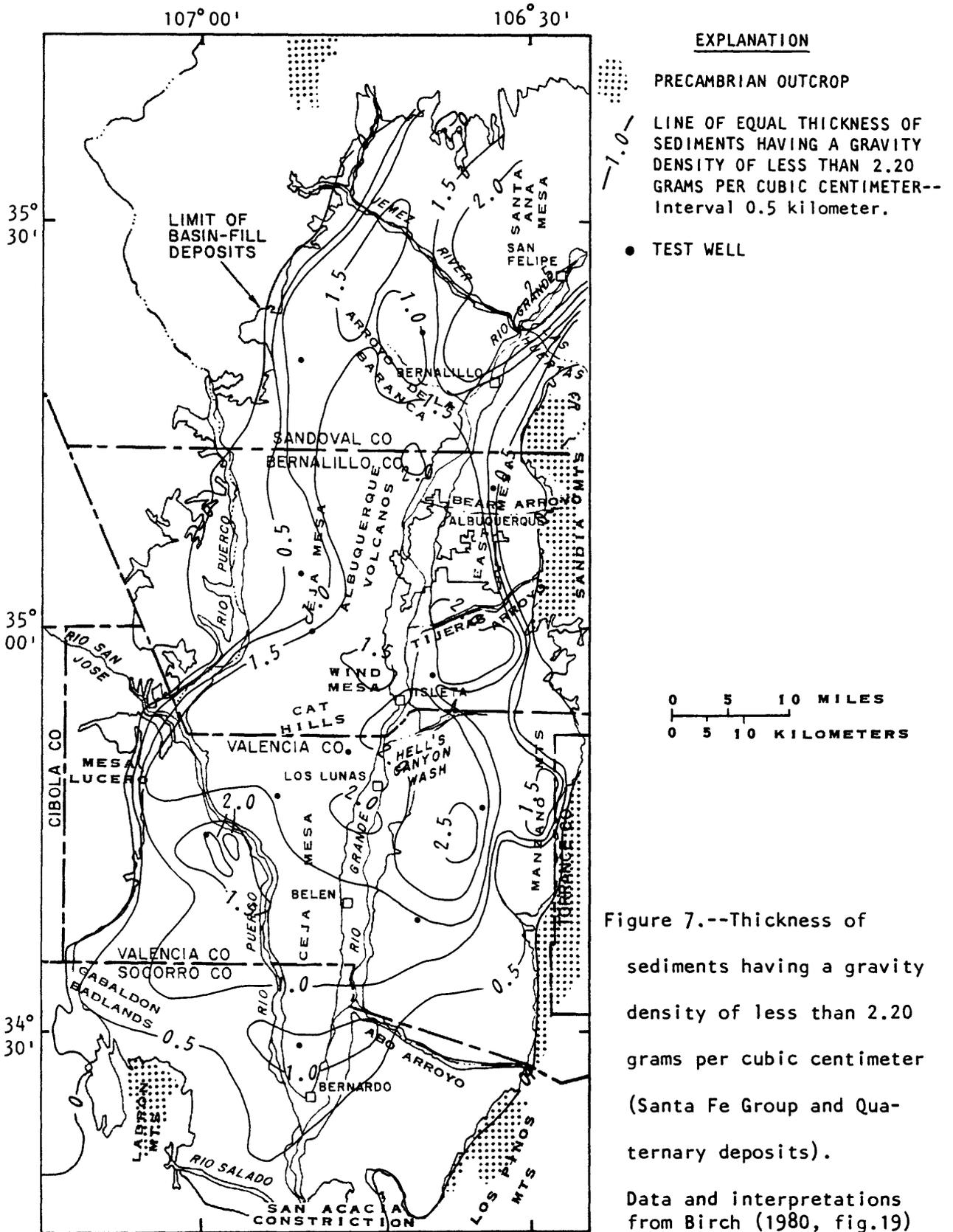
Birch (1980) interpreted gravity data over the Albuquerque-Belen Basin to determine the thickness of the major sedimentary units. The units were characterized according to density; those units that have a density of less than 2.20 grams per cubic centimeter correspond to the Santa Fe Group and Quaternary deposits. The less dense unit averages 1.5 kilometers in thickness (4,900 feet) and exceeds 2.5 kilometers (8,400 feet) in a north-south strip along the eastern side of the basin (fig. 7).

The stratigraphic subdivision of the Santa Fe Group, as well as the classification of the Santa Fe as a group or as a formation, has been a subject of debate for years. A history of this debate can be found in Kelley (1977), who preferred to classify the Santa Fe as a formation consisting of three members (which do not conform with U.S. Geological Survey usage): the Zia, middle red, and Ceja. These members are roughly the equivalents of the lower gray, middle red, and upper buff of Bryan and McCann (1937). Kelley's (1977) identification of the members is largely based on color but, in a very general sense, the Zia is sand or sandstone of eolian origin, the middle red is typical of a playa deposit with more clay and silt than the Zia, and the Ceja Member has fluvial facies of alluvial fill deposited by the Rio Grande and ancestral rivers.

The hydraulic properties of the basin-fill deposits are of great importance to the occurrence and movement of ground water. The playa deposits are of major importance to the ground-water hydrology of the basin because their low hydraulic conductivity restricts both the vertical and horizontal flow of water. Extensive playa deposits consisting of mudstones and fine sand occur in the western part of the basin from south of the Jemez River valley along the Rio Puerco valley (Bjorklund and Maxwell, 1961) southward to the Gabaldon Badlands, which are adjacent to the Lucero and Ladron Uplifts (Kelley, 1977). Through step faulting, in particular, the playa deposits in the west-central part of the basin decrease in elevation toward the axis of the basin; other possible causes for the decrease in elevation are rotation during faulting or remnant depositional dip.

Deposited unconformably on the Santa Fe Group is a series of coalescing alluvial fans of Holocene age. They extend westward from the base of the Sandia and Manzano Mountains to the bluffs along the east side of the Rio Grande flood plain. East of the Hubbell Springs and Sandia Faults, the fans rest on eroded pediment slopes. The fan deposits thicken to as much as 200 feet toward the mountains and contain both poorly sorted mudflow materials and well-sorted stream gravels. The beds are discontinuous and consist of channel-fill and lenticular interchannel deposits.

The deposits generally are above the water table; however, along the mountain front, they may be saturated and may yield small amounts of water. Much of the flood flow and mountain runoff carried in arroyos is absorbed by these deposits; a large part of the absorbed water flows across the less permeable buried pediment, then percolates downward as recharge to the Santa Fe Group (Bjorklund and Maxwell, 1961).



The valley alluvium of Holocene age is limited to the flood plain of the Rio Grande and its tributaries. It consists, generally, of unconsolidated sand, silt, gravel, and clay. It is not easily distinguishable from the underlying Santa Fe Group, especially in borehole-geophysical logs, because the alluvium is largely reworked material derived from the Santa Fe Group. However, the alluvium does contain more coarse-grained and organic material than the Santa Fe Group. The alluvium is 100-200 feet thick along the Rio Grande and thinner in the tributary valleys. Faults and folds are not apparent in the alluvium, and the bedding, where present, is more nearly horizontal than in the Santa Fe Group.

Hydraulic Characteristics

The capacity of an aquifer to transmit and store water is determined by its hydraulic properties. The ability to transmit water is determined by the hydraulic conductivity and saturated thickness, or transmissivity, of the aquifer. Hydraulic conductivity, a measurable property of the aquifer, represents the volume of water transmitted per unit time through a unit cross-sectional area under a unit hydraulic gradient. Transmissivity is the product of the average hydraulic conductivity and the saturated thickness of the aquifer. Saturated thickness is the vertical distance from the water table or definable top of an aquifer to the base of the aquifer.

Under most of the Rio Grande valley, the alluvium has a high hydraulic conductivity and readily yields water to wells. According to Bjorklund and Maxwell (1961), most of the early irrigation and domestic wells along the Rio Grande were completed in the alluvium; some wells were reported to yield as much as 3,000 gallons per minute. The alluvium in the tributary valleys generally is not saturated; however, it may be saturated in some arroyos that are tributary to the Rio Puerco and in arroyos along the mountain front. Wells completed in the thin alluvium underlain by relatively impermeable rocks, as in arroyos near the mountain front, have small sustained yields.

The sediments of the Santa Fe Group form the thickest and most extensive aquifer in the basin. Shallow ground water in the Santa Fe Group generally occurs under unconfined conditions. However, clays and silts interbedded with more permeable sand and gravel cause semiconfined responses in wells that are completed below the water table. The hydraulic conductivity of the Santa Fe Group in the basin generally is high (20 feet per day or in the range of a medium sand) except in areas of fine-grained sediments or where secondary cementation has occurred along fault zones. Wells that are properly constructed in the Santa Fe Group typically yield several hundred to several thousand gallons of water per minute.

Bjorklund and Maxwell (1961) reported the apparent transmissibility (transmissivity) of the Santa Fe Group determined at 24 wells by measuring the drawdown and recovery of water levels during and after pumping at measured rates and by applying the Theis recovery formula as described by Ferris and Knowles (1955, p. 31-32). The reported transmissivity ranged from 50,000 to 600,000 gallons per day per foot (6,700 to 80,200 feet squared per day) at 23 of the wells and was 7,500 gallons per day per foot (1,000 feet squared per day) at the other well. The average of the 24 wells was about 221,000 gallons

per day per foot (29,500 feet squared per day). The average apparent hydraulic conductivity at the 24 wells was determined by dividing the reported transmissivity by the penetrated thickness of the saturated material (Bjorklund and Maxwell, 1961, p. 24). Values of hydraulic conductivity ranged from 1.6 to 112 feet per day and averaged 45 feet per day.

On the basis of these tests and the specific capacities of other wells, Reeder and others (1967, p. 11) determined an average transmissivity of about 26,700 feet squared per day east of the Rio Grande and about 13,400 feet squared per day west of the Rio Grande. If these transmissivity values are assumed to represent the upper 650 feet of saturated thickness (this interval is typical of most large-capacity wells), they are equivalent to an average hydraulic conductivity of about 40 feet per day east of the Rio Grande and 20 feet per day west of the Rio Grande.

The storage coefficient of an aquifer is a measure of the capability of the aquifer to store water. The storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In a confined aquifer, the storage coefficient is a function of the compressibility of water and of the aquifer matrix. In an unconfined aquifer, the storage coefficient is virtually equal to the specific yield. The specific yield is the volume of water per unit volume of saturated aquifer that can be released from storage by gravity drainage. There were no known tests conducted in the Albuquerque-Belen Basin to determine aquifer storage properties of the basin-fill deposits. However, these data are not required for steady-state simulations because steady state is defined as a condition of equilibrium in which changes in aquifer storage do not take place.

Physical Boundaries

The saturated zone in the basin fill has definite natural bounds at all sides, at the bottom, and at the top. Boundaries are assumed to be at locations where aquifer properties, particularly hydraulic conductivity, change appreciably. The side boundaries are the same as those described previously as the basin boundaries. The bottom boundary, whose depth is determined from gravity data, is formed by beds of consolidated rock, probably of Mesozoic age, that were down faulted to form the depression in which the basin fill was deposited. The top boundary is coincident with the free water surface or water table. The north and south boundaries of the basin are partially constricted; parts of the basin fill are continuous northeastward into the Santo Domingo Basin and southward into the Socorro Basin. The Albuquerque-Belen Basin is only a segment of the ground-water surface-water system that extends the length of the Rio Grande.

Physical boundaries also exist within the basin. Among these are fissure volcanics and cemented fault zones that primarily impede horizontal movement of ground water. Buried playa deposits and volcanic flows impede vertical movement of ground water. Examples of the fissure volcanics are the Albuquerque, Cat Hills and San Felipe volcanic fields. Bjorklund and Maxwell (1961) described secondary mineralization and cementation along north-south

trending faults on and west of Ceja Mesa. Playa deposits and volcanic flows have been mapped on the surface (as discussed earlier) and in the subsurface as reported in well logs.

The Rio Grande and its flood plain form another internal boundary. Unlike the other boundaries, the Rio Grande is a boundary that prevents head changes in the immediately underlying alluvial aquifer.

Ground-water inflow to the basin primarily occurs along the northern boundary from the Santo Domingo Basin in the vicinity of the Rio Grande flood plain. Smaller contributions are from the rocks forming the east, west, and northwest boundaries. With the exception of eastward flow from the San Juan Basin, these are assumed to be negligible. Ground-water outflow from the basin occurs along the southern boundary in the vicinity of the San Acacia constriction through both the Santa Fe Group and the Rio Grande flood plain. Gravity data indicate that the depth of basin-fill deposits is shallower at the southern boundary than at the northern boundary.

Movement of Ground Water

The Santa Fe Group, alluvial-fan deposits, and valley alluvium, collectively termed the basin fill in this report, are interconnected hydraulically and together constitute the principal aquifer in the Albuquerque-Belen Basin. Movement of ground water within the basin fill is governed by the hydraulic properties of the aquifer and by head differences within the saturated zone.

The head in a ground-water flow system is a measure of the potential energy of the ground water above a common datum. The head difference between two points indicates, by the direction of the gradient, a vector component of the direction of ground-water flow. Flow usually is vertical as well as horizontal within the basin-fill aquifer because heads vary with depth beneath the water table. The terms water-table elevation and potentiometric head, which are comparable but not identical in meaning, are defined below.

Potentiometric surface: The potentiometric surface...is a surface that represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells. Where the head varies appreciably with depth in the aquifer, a potentiometric surface is meaningful only if it describes the static head along a specified surface or stratum in that aquifer. More than one potentiometric surface is then required to describe the distribution of head. The water table is a particular potentiometric surface (Lohman and others, 1972, p. 11).

Water table: The water table is that surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists (Lohman and others, 1972, p. 14).

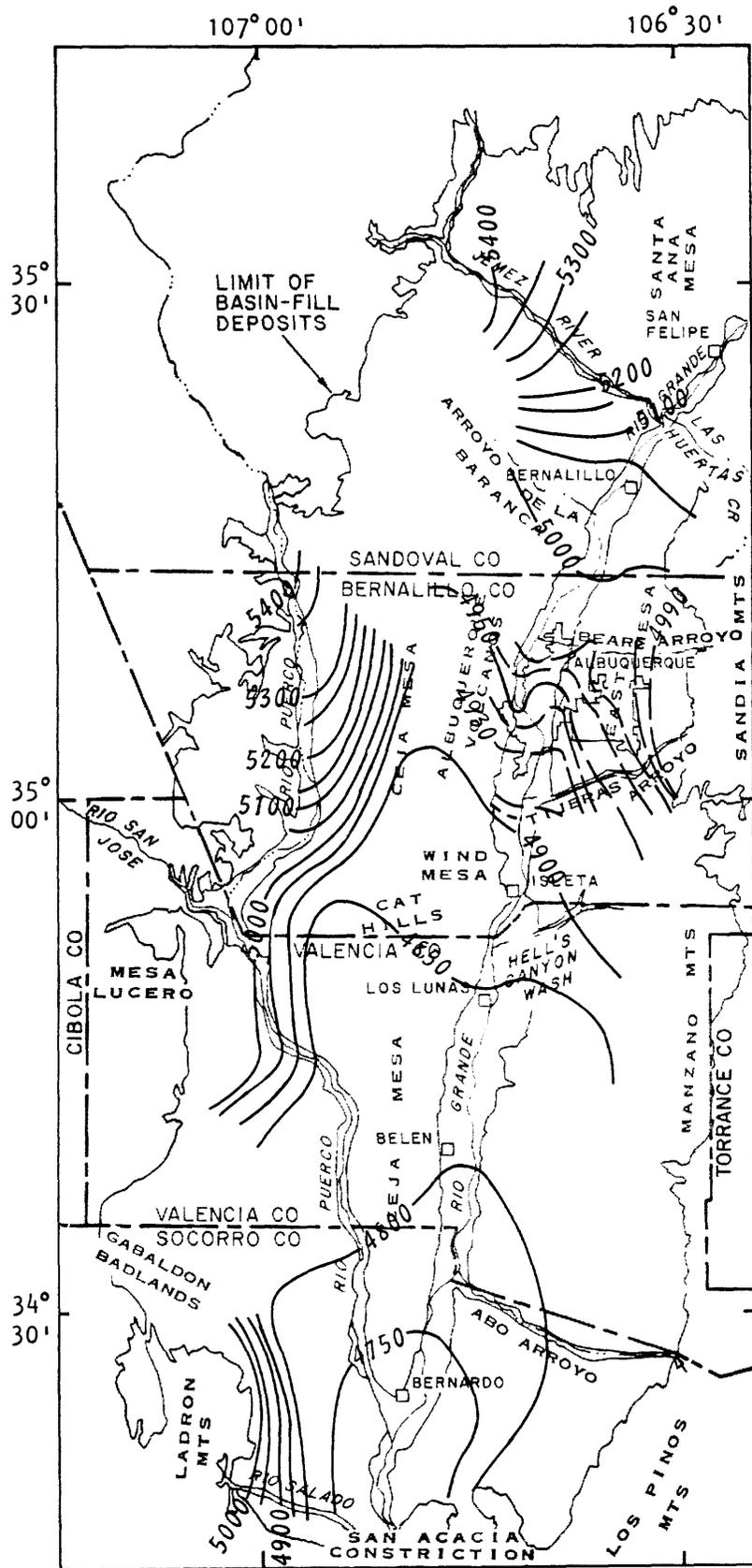
Water-level contour maps for the basin that were compiled by combining data from Spiegel (1955), Bjorklund and Maxwell (1961, figs. 1a and 1b), and Titus (1963) are shown in figures 8 and 9. The location of wells used to construct the contour maps is shown in figure 10. The contour lines in figures 8 and 9 show possible configurations and slopes of the water table in 1960 for shallow wells (completed in the upper 200 feet of saturated aquifer, fig. 8) and for deep wells (completed between 200 and 650 feet below the water-table surface, fig. 9).

The general direction of horizontal ground-water movement within the basin can be determined from the slope of the water table or potentiometric surface. Ground water of a uniform density moves down a water-table slope, or gradient, at right angles to water-level contours, toward water-table depressions and away from water-table mounds. Because of minor deflections caused by local differences in hydraulic conductivity of the basin fill, evapotranspiration, withdrawal from wells, local recharge from irrigation water, and arroyo runoff, only the general direction of movement can be determined.

The potentiometric gradients in figures 8 and 9 show that the general direction of horizontal ground-water flow is toward the flood plain of the Rio Grande. The flood plain, which encompasses the Rio Grande surface-water system, acts as a drain for ground water in much of the basin. Presumably, even water moving through the Santa Fe Group at great depth eventually rises and discharges to the flood plain at the lower end of the basin.

According to Bjorklund and Maxwell (1961) and Titus (1963), the water table slopes at a low gradient diagonally downvalley from the bases of the Sandia and Manzano Mountains on the east and from the Rio Puerco on the west toward a generally southward-trending zone about 8 miles west of the Rio Grande. This southward-trending zone is shown in figure 8, which is based largely on data reported by these investigators. The water table along this zone is reported to be 30 to 40 feet lower than the water table beneath the Rio Grande. This depression in the water table, a ground-water trough, is reported to extend from north to south through most of the study area and coincides with the location of the Rio Grande flood plain at a point downstream in Valencia County.

Evidence from gravity and ground-water level data is presented by Bjorklund and Maxwell (1961) and Titus (1963) supporting the existence of this ground-water trough. In the area of the trough, water-level data are very sparse and the values used in the construction of the contours for that area are mainly reported and not actually measured. However, data collected from recently completed test wells west of the Albuquerque volcanoes (Wilkins, in press) tend to verify the existence of the trough. In addition, these data indicate a decrease in potentiometric head with increasing depth. The trough apparently does exist but, as stated earlier, the configuration of the trough is poorly defined because the meager data presented as evidence for its existence are reported rather than measured.



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.

0 5 10 MILES
0 5 10 KILOMETERS

Figure 8.--Water-level contours that represent 1960 conditions in the upper 200 feet of the saturated aquifer.

Ground water in the basin flows vertically as well as horizontally. This flow includes mountain-front recharge to the shallow part of the basin fill, creating a water-level mound (or potentiometric high), which must dissipate both horizontally and downward into lower zones in the aquifer. Elsewhere, it is likely that there are upward gradients to the Rio Grande and flood-plain drain system. Firm evidence that there are vertical differences in potentiometric head (vertical gradients) can be seen by comparing figures 8 and 9. Only in the earlier mentioned test wells and in the immediate area of Albuquerque are there enough data to conclusively show differences in head at different depths in the aquifer.

Effects of Development

Under ideal natural conditions the ground-water flow system is in an equilibrium or steady-state condition: recharges equal discharges and water levels in the aquifer system remain virtually unchanged with time. (Seasonal and climatic changes are the greatest natural cause for nonequilibrium in an otherwise steady-state system.) Prior to the influences of man, principally early irrigation beginning in the 13th century, the ground-water system in the Albuquerque-Belen Basin was in this natural near-equilibrium condition. With the settlement of western Europeans came the rapid development of the water resources in the basin. Some of the early settlements were in the flood-plain area near the Rio Grande. The proximity of these settlements to the Rio Grande allowed for the diversion of water from the river to irrigate crops, and the digging of shallow wells to provide water for domestic purposes.

Development of the water resources in the basin upset the existing equilibrium condition, causing the water table in the flood plain to fluctuate in response to modifications in aquifer recharge and discharge patterns. Excess irrigation water infiltrated the alluvium and caused a slight rise in the water table. Because the flood-plain alluvial aquifer and the Rio Grande are hydraulically connected, the recharge from excess application of irrigation water eventually returned to the river through the aquifer. As long as the extent of irrigation remained relatively small, the ground-water levels in the flood plain remained at a distance below the root zone not harmful to plants. However, by the 1930's a network of drains was required to keep ground-water levels below the root zone.

Prior to expansion of the city of Albuquerque municipal water-well system in 1959, most municipal supply wells were located in the flood plain. The higher mesa areas outside the flood plain were used primarily as range land with springs and scattered stock wells serving as water supplies. Major expansion onto the adjacent mesas began in 1959 with the development of several new municipal well fields. The average pumping rate in the Albuquerque municipal system increased from about 2 million gallons per day in 1930 to 33 million gallons per day in 1959 (Bjorklund & Maxwell, 1961, p. 29). According to Reeder and others (1967, p. 20), about 80 percent of the ground water pumped during 1920 to 1960 was derived by induced recharge from the Rio Grande. The average flow of the Rio Grande at Albuquerque from 1942 to 1959 was 1,000 cubic feet per second or about 650 million gallons per day

(U.S. Geological Survey, 1960, p. 414). These figures indicate that the average flow of the Rio Grande was sufficiently large to supply the city's needs and still maintain flow in the Rio Grande through the basin.

Historically, the water table in the flood plain maintained a relatively constant elevation despite the increased stresses because of the discharging effects of the drains and the recharging effects of the river and irrigation seepage. In both 1936 and 1960, the depth to the water table was generally less than 8 feet throughout the flood plain, which again illustrates that the ground-water surface-water system of streamflow, irrigation, and drains does tend to maintain a stable ground-water level. The greatest decline in the water table in the Albuquerque area from 1936 to 1960, as shown in figure 11, was approximately 20 feet (U.S. Army Corps of Engineers, 1979, p. 4-10). Except for the immediate Albuquerque area, water-level conditions that existed in 1960 were assumed, for the purpose of this study, to represent a steady-state condition because of the relatively minor and localized declines in the water level. In addition, 1960 was chosen as being representative of steady-state conditions because earlier, areally extensive water-level data do not exist.

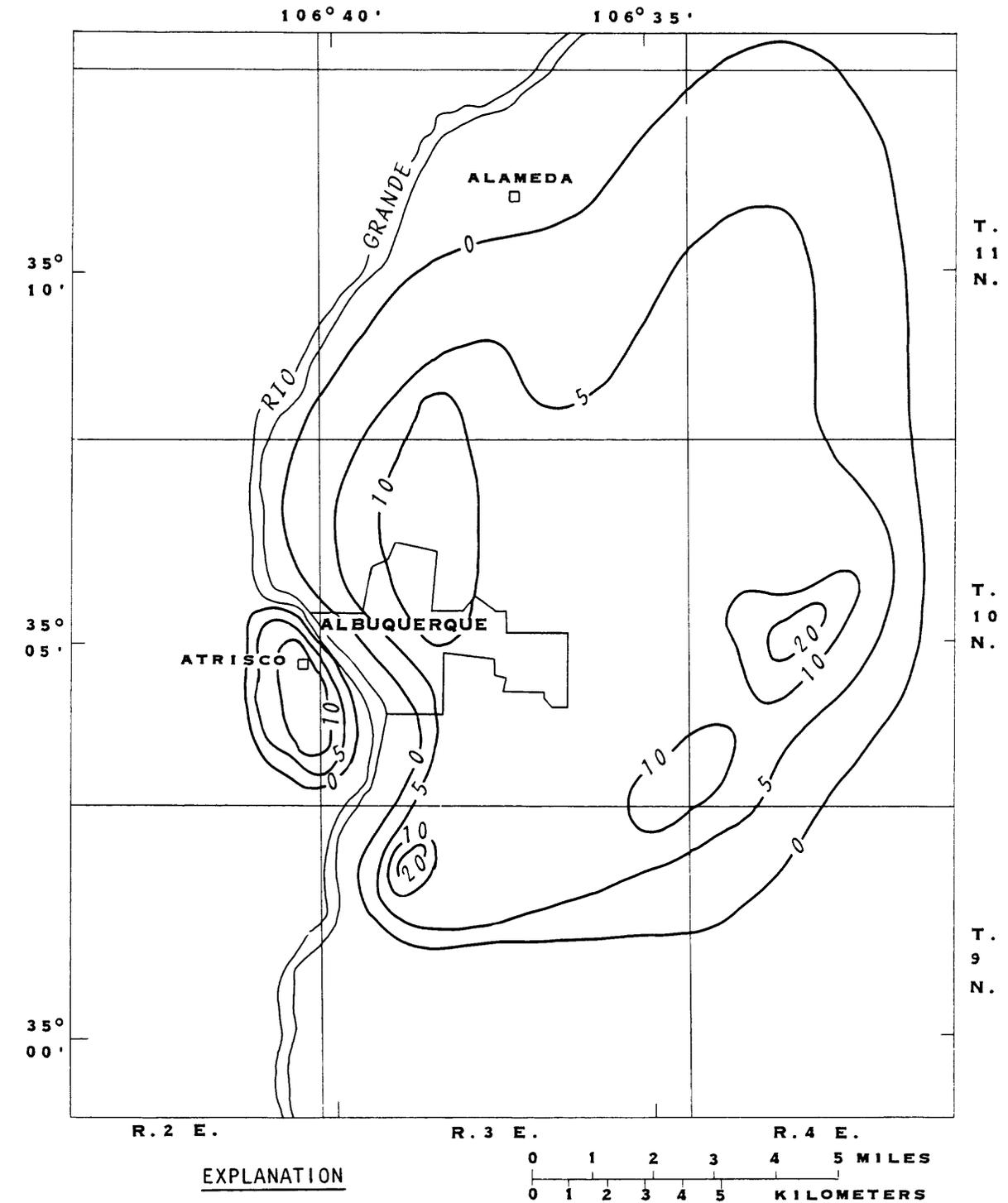


Figure 11.--Water-table decline in the Albuquerque area from 1936 to 1960
(modified from U.S. Army Corps of Engineers, 1979, fig. 4.3).

DESCRIPTION OF THE MODEL

An extensive review of existing publications and data indicated that the representation of certain elements of the ground-water flow system was essential in the ground-water flow model and that other elements might be simplified or omitted. The composite of these elements resulted in a conceptual model of the ground-water flow system of the basin-fill aquifer. The extent of the modeled area, the decision to simulate the aquifer in three dimensions, and the location and type of external and internal boundaries were the primary products of the conceptual model.

Assumptions

Although a conceptual model ideally represents all the hydrologic characteristics of the actual flow system, the conceptualization must be simplified to the extent that an operational mathematical model can be constructed. The modeling of the Albuquerque-Belen ground-water basin was initiated by developing a simplified conceptual model of the actual ground-water surface-water system. This model necessarily includes some simplifying assumptions that make it possible to simulate the system. These assumptions are:

(1) The surface-water system and the ground-water system within the Rio Grande flood plain are hydraulically connected.

(2) Depletion of ground water from the flood-plain alluvium is immediately compensated by approximately equal depletion of surface water from the Rio Grande.

(3) The stage of the Rio Grande remains constant with time and the river flows continuously throughout the basin.

(4) There is no ground-water flow across the east and west basin boundaries, and only a small amount of underflow from the San Juan Basin across the northwest boundary.

(5) The ground-water system is assumed to be a single, confined aquifer (including the top layer of the model). This assumption is valid for steady-state conditions and also for transient conditions if water-level changes are but a fraction of the total saturated thickness.

(6) Near-steady-state conditions existed in the basin until 1960.

(7) Hydraulic conductivity is not affected by possible compaction of the aquifer or increase in temperature at depth.

Flow Equation and Computer Program

Flow of ground water in the aquifer system is three dimensional. The equation that describes three-dimensional flow of ground water in a porous medium can be written similarly to Trescott (1975) and is quoted directly from Hearne (1980, p. 9) as:

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

where

K_x , K_y , and K_z are hydraulic conductivities in the x, y, and z directions (L/T);

h is hydraulic head (L);

S_s is specific storage (1/L);

$W(x,y,z,t)$ is 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).

To simulate a three-dimensional flow system, the description of the aquifer system is subdivided into a large number of orthorhombic (brick-shaped) cells. Continuous spatial distributions of physical and hydraulic properties of the porous medium (that is, the ability to store and transmit water) are represented as discrete functions of space by assuming them to be uniform within each cell. The properties may, however, vary from cell to cell. The hydraulic head and other data associated with each cell are considered to be a cell-centered average. At each cell, a finite-difference approximation for the derivatives in the three-dimensional flow equation yields an algebraic equation. For a model with N cells, a set of N simultaneous equations in N unknowns is generated. The simulation program solves this set of equations simultaneously, subject to prescribed initial and boundary conditions. Refer to Trescott (1975) and Trescott and Larson (1976) for details of the solution algorithm. The computer program used for this study (Posson and others, 1980) evolved from that of Trescott (1975) but does not differ in the strongly implicit solution algorithm.

Model Grid

The nonuniform grid network used in modeling the Albuquerque-Belen Basin consists of 43 rows and 67 columns for a total of 2,881 grid cells per model layer (fig. 12). In anticipation of transient simulations, the grid size was varied to allow a smaller cell size near the area of major stress (Albuquerque) and larger cells in areas remote from the stress. The grid size varied from 0.5 mile by 0.5 mile to 3 by 6 miles. For numerical stability and accuracy, a rate of change of grid spacing not greater than 1.5 times the adjacent grid spacing was used.

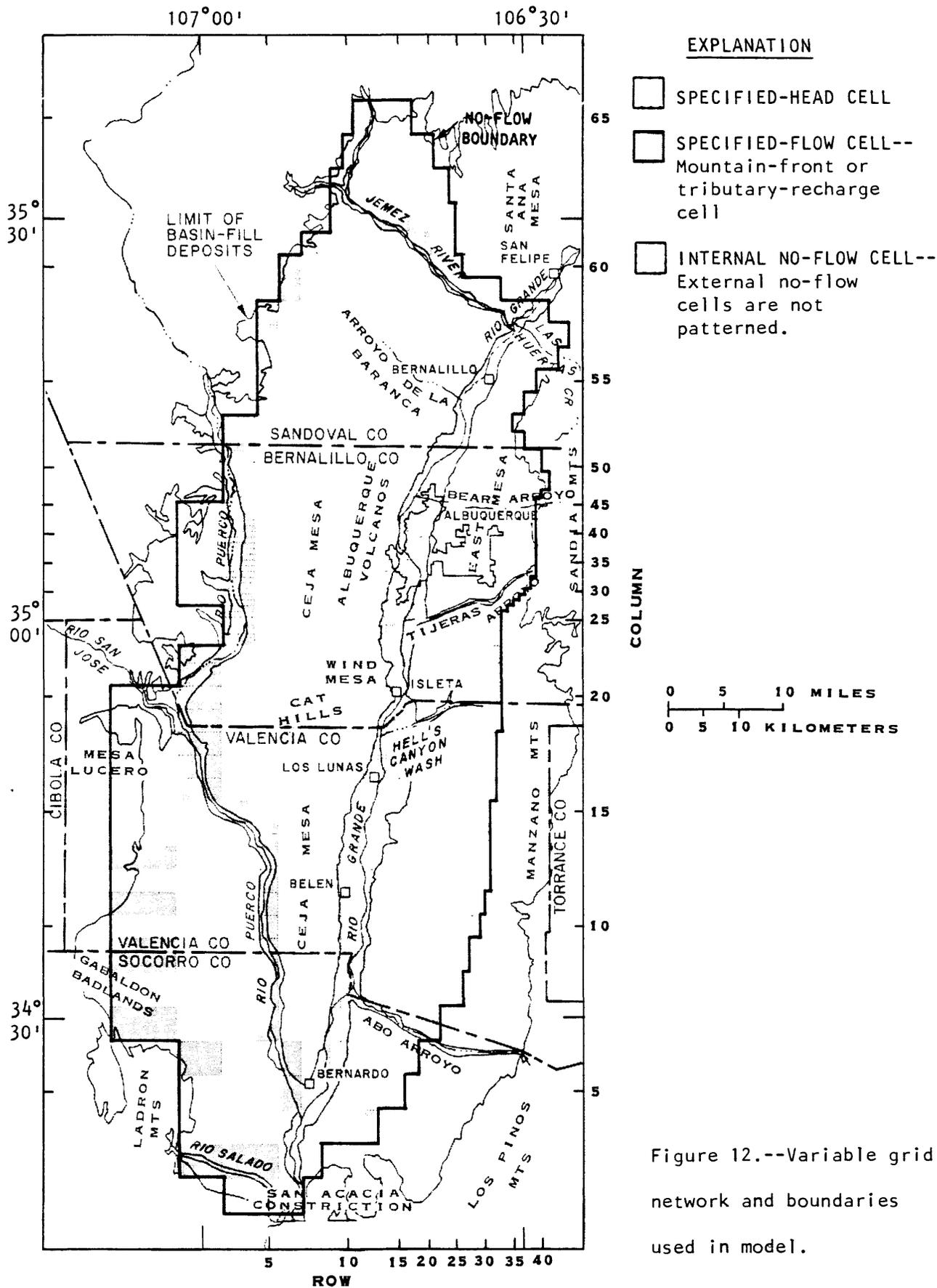


Figure 12.--Variable grid network and boundaries used in model.

The aquifer system was modeled as a six-layer system. The upper layer (layer 6) was defined as being 300 feet thick but a 200-foot saturated thickness was assumed when calculating transmissivity. The top layer represents both the Santa Fe Group outside of the flood plain and the saturated alluvium of the flood plain. The thickness for each of the remaining five model layers was determined by multiplying the thickness of the layer above by a factor of about 1.5. These lower five layers represented the Santa Fe Group as a single unit. The layers, which do not represent regional stratigraphic units, were needed to simulate the depth and vertical flow components of the aquifer system.

The configuration of the boundaries of each layer was determined from contours in figure 7, which was compiled from the interpretation of gravity anomalies for the basin, with supplemental information from oil tests, cross sections (Kelley, 1977, fig. 20), and from seismic interpretations (Brown and others, 1980). Because thicknesses of the Santa Fe Group greater than 2.0 kilometers occur over less than 10 percent of the study area, depths greater than this were excluded from the model. This convention allowed the elimination of the layers that would represent these depths and thus afforded a saving in computer time and data-storage requirements. Therefore, an arbitrary bottom of simulated basin fill was established at a depth of 6,175 feet from the top of layer 6. Flow below a depth of 6,175 feet was assumed to be small enough that no significant error would be introduced into the model if this flow were ignored.

Representation of Boundaries

The physical boundaries of the ground-water flow system need to be represented in the model by reproducing conditions that exist at these boundaries. The three ways, as explained by Hearne (1980, p. 24), that the computer program allows for boundaries to be represented are: specified flux (including no flow), specified hydraulic head, and hydraulic-head-dependent flux.

At specified-flux boundaries, water is recharged to or discharged from the aquifer system at a rate that is independent of the hydraulic head in the aquifer system. At specified hydraulic-head boundaries, the hydraulic head is maintained at the specified value throughout the simulation. As hydraulic heads in the aquifer system change adjacent to the specified hydraulic-head boundary, the rate of flow at the specified hydraulic-head boundary will change accordingly. At hydraulic-head-dependent flux boundaries, the flow to or from the boundary is proportional to the difference in hydraulic head between the aquifer and an external reference elevation. This type of boundary, which can be simulated with the computer model (Posson and others, 1980), was not employed in the model of the Albuquerque-Belen Basin.

STEADY-STATE MODEL

As discussed earlier in the report, ground-water levels in the Albuquerque-Belen Basin outside the flood plain remained virtually unchanged until after 1960, except in the vicinity of Albuquerque. Thus, the aquifer system was nearly in equilibrium, or at steady state, even though water was constantly being exchanged between areas of recharge and discharge. This equilibrium allowed the construction of a steady-state ground-water flow model of the basin based on hydrologic data reported prior to and including 1961.

The objectives of the steady-state model were to refine the estimates of hydraulic conductivities throughout the basin and to test the validity of the assumed boundary conditions. The 1960 ground-water levels were used as the basis for comparison with simulated heads during the process of calibration of the model.

Boundary Conditions

Other than no-flow boundaries, the boundaries represented in the steady-state model are either specified flux or specified head. These boundary types and locations are shown in figure 12.

The computer program requires a no-flow boundary on the perimeter of the modeled area; consequently, if no other boundary condition is specified, a no-flow boundary will automatically be assigned. Because ground-water inflow across the eastern and western perimeters of the basin is considered negligible, these perimeter boundaries are treated as no-flow boundaries in the lower five model layers. The bottom boundary is also treated as an impermeable, no-flow boundary.

A report by Frenzel and Lyford (1982) indicated a small ground-water discharge from the San Juan Basin into the northwestern part of the Albuquerque-Belen Basin. This flow was estimated to be about 1.8 cubic feet per second, based on the results of a steady-state ground-water flow model described in their report. The computed discharge from the San Juan model reported by Frenzel and Lyford (1982) was distributed along the northwest boundary of the Albuquerque-Belen Basin in the second layer from the top, which corresponds with a depth below the water table between 200 and 650 feet.

Other areas where ground-water inflow or outflow was assumed to occur from outside the basin were along the northern and southern boundaries in the area of the Rio Grande flood plain. To simulate the ground-water inflow and outflow across these boundaries, the cells in these areas were treated as specified-head boundaries. Cells in all six model layers along the northern boundary in and beneath the flood plain were designated as specified-head cells. Along the southern boundary only the top three layers (layers 4, 5 and 6) were included because the basin becomes more shallow in that area.

Boundary or mountain-front recharge, as defined previously, and seepage from major tributaries of the Rio Grande are treated in the model as specified-flux boundaries by designating recharging wells with the specified fluxes in the top layer at each appropriate boundary and tributary cell.

Mountain-front recharge along the base of the Sandia, Manzanita and Manzano Uplifts was assumed to enter the ground-water basin as distributed recharge along the Hubbell Springs and Sandia Faults, the eastern boundary of the model. The flux values assigned to the recharging wells are those determined by J.D. Dewey (U.S. Geological Survey, written commun., 1982).

The grid cells in the top layer that represent the saturated flood-plain alluvium were modeled as specified-head boundaries. These cells could either recharge or discharge the aquifer, depending on the head difference among adjacent cells.

The linear fissure flows of the Albuquerque and Cat Hills volcanic fields were modeled as being no-flow boundaries extending the full thickness of the model (over 6,000 feet). Very little actually is known about the configuration of the fissures at depth: they may narrow with depth to a pipe shape, which would have a negligible effect on the ground-water flow system, or they may expand to become part of a deep-seated regional fissure system. For this model, they are assumed to keep their surficial dimensions at all depths.

A pronounced variation in hydraulic conductivity can produce boundarylike effects on ground-water flow. Zones of low conductivity cause a restriction of flow and steepening of water-level gradients. Areas of very low conductivity may appear very similar to a no-flow boundary. Such a zone has been recognized by earlier investigators (Bjorklund and Maxwell, 1961) to occur as a bed of eastward-dipping, fine-grained material in the western part of the basin. This zone was represented in the model. Additional discussions of modeled hydraulic conductivity will follow.

Model Input Parameters

The physical properties of the aquifer are specified in the model by assigning parameter values to the cells. These values reflect transmissivity (computed from hydraulic conductivity and saturated thickness), storage coefficient, anisotropy ratio, and boundary and tributary recharge rates. Because the steady-state analysis dictates that no change in storage take place, the storage coefficient was set equal to zero. Ground-water withdrawals were not simulated.

Field-determined values of transmissivity were not available for the entire study area; therefore, the initial estimates were those determined by Reeder and others (1967, p. 11). These values, as mentioned in a previous section, are 26,700 feet squared per day for the Rio Grande flood-plain area and eastward, and 13,400 feet squared per day for west of the flood plain. To determine hydraulic conductivities, these transmissivity values were assumed to represent the top 650 feet of saturated thickness.

A uniform horizontal hydraulic conductivity of 40 feet per day was initially assigned to each layer for the flood-plain area and eastward, and a value of 20 feet per day for west of the flood plain. A hydraulic conductivity of 0.25 foot per day was assigned to the top model layer in an

area in and west of the Rio Puerco flood plain, and 2 feet per day in the second from the top layer from the Rio Puerco flood plain eastward to the Rio Grande flood plain. Transmissivities were then computed for each layer by multiplying model layer thickness by hydraulic conductivity.

The low hydraulic conductivity zone in the Rio Puerco area represents eastward-dipping playa deposits. This zone was noted by Bjorklund and Maxwell (1961, p. 25), by Reeder and others (1967, p. 6), and has been further delineated by recent test drilling (Wilkins, in press). The zone may extend the full length of the basin from the Jemez River valley on the north to the Gabaldon Badlands on the south.

Horizontal and vertical hydraulic conductivities are not necessarily identical. Because of horizontal interbedding of silt, clay, and sand lenses, the vertical conductivity of the aquifer is expected to be less than the horizontal conductivity. The only field data available on the vertical hydraulic conductivity of the Santa Fe Group indicate that the ratio of vertical to horizontal conductivities in the Albuquerque area is between 1:60 and 1:600 (Wilkins, in press). However, an estimate may also be made by computing a conductivity from the thickness-weighted harmonic mean of the conductances of the sand and clay lenses. This conductivity compares with the net horizontal conductivity computed as the weighted (by bed thickness) arithmetic mean of the conductivities of the sand and clay intervals. This method yields estimated vertical-to-horizontal conductivity ratios that range from 1:21 to 1:12,500 for materials and mixtures of materials commonly found in the basin.

However, because the minor clay lenses generally cannot be correlated over even small distances (less than a mile), ground water may simply flow around the clays rather than through them. If ground water flows around the lenses, then the apparent vertical conductivity is essentially the horizontal conductivity of the coarse material divided by the increased flow path of the water. For a horizontal lens with an areal extent of 1,000 feet and where the longest possible detour of flow is 500 feet, the apparent ratio of conductivities is less than 1:500 if the clay lenses are vertically separated by 1 foot or more of sand. In the Albuquerque-Belen Basin, flow around rather than through clay lenses is assumed to be the most probable vertical movement path of ground water. An initial estimate of 1:600 was selected for the ratio between vertical and horizontal hydraulic conductivities.

The initial hydraulic heads were estimated from the water-table contour map representing 1960 conditions (fig. 8) for the top 200 feet of saturated aquifer and from topographic maps showing altitudes of the Rio Grande and the system of drains in the flood plain. The head altitudes ranged from about 5,400 feet near the base of the Jemez caldera to about 4,660 feet in the flood plain near the outflow boundary. With the exception of heads in the flood plain, the initial heads were subject to change.

All of the mountain-front recharge and streamflow losses of the major tributaries to the Rio Grande were assumed to recharge the aquifer system. The flow rates for mountain-front recharge estimated by J.D. Dewey (U.S. Geological Survey, written commun., 1982) were proportioned over the perimeter

of the model boundary in the uppermost layer. Recharge along the eastern boundary (Sandia, Manzanita, and Manzano Uplifts) was distributed along the Sandia and Hubbell Springs Faults rather than at the topographic base of the mountains.

The infiltration rates for the major tributaries to the Rio Grande were also estimated by J.D. Dewey (U.S. Geological Survey, written commun., 1982). These estimates are specified as recharge in each representative tributary cell. The flow rates assigned as input to the model are shown in figure 5.

Either a negligible amount or no recharge occurs on the mesas outside of streams and arroyos and away from the mountain fronts. All of the direct precipitation probably is retained in the root zone and is evaporated or transpired without ever reaching the zone of saturation, which is more than 200 feet below land surface on the mesas.

Calibration Process

The process of model calibration consisted of adjusting modeled estimates of aquifer properties, including vertical and horizontal hydraulic conductivities, until the discrepancy between measured and computed heads was minimized.

The accuracy of the steady-state simulation must be evaluated based on the amount and reliability of data available for comparison with the simulation results. Ground-water levels and flow paths that existed in 1960 (assumed to represent an approximate steady-state condition) were used as the basis of comparison. Water-level contour maps for 1960 were prepared using reported and measured water levels in approximately 150 wells. From these wells 31 were selected for statistical comparison of computed and reported or measured ground-water levels. The selection criteria were the reliability of well-completion data, method of determining depth to water and altitude of the measuring point, and uniformity in areal coverage of data. These 31 wells, and 3 other wells drilled after 1960, are distributed throughout the basin and are thought to provide an acceptable representation of available ground-water levels in the basin prior to appreciable development. Thirty-seven water-level observations are available from the 34 wells.

Although there was some development of ground water in the basin prior to 1960, withdrawal from municipal and other wells installed east of the flood plain near Albuquerque during the late fifties was not incorporated into the steady-state model. By 1960, withdrawal from these wells had caused local water-level declines of about 20 feet. Computed heads in this area of decline are expected to be higher than the measured heads and are acceptable within this range of difference.

The steady-state simulation not only serves as the initial condition for subsequent transient simulations but also permits refinement of the conceptual model and modeled hydrologic properties. The steady-state model was considered to be completed when the difference between measured and computed water levels was reduced to an acceptable amount.

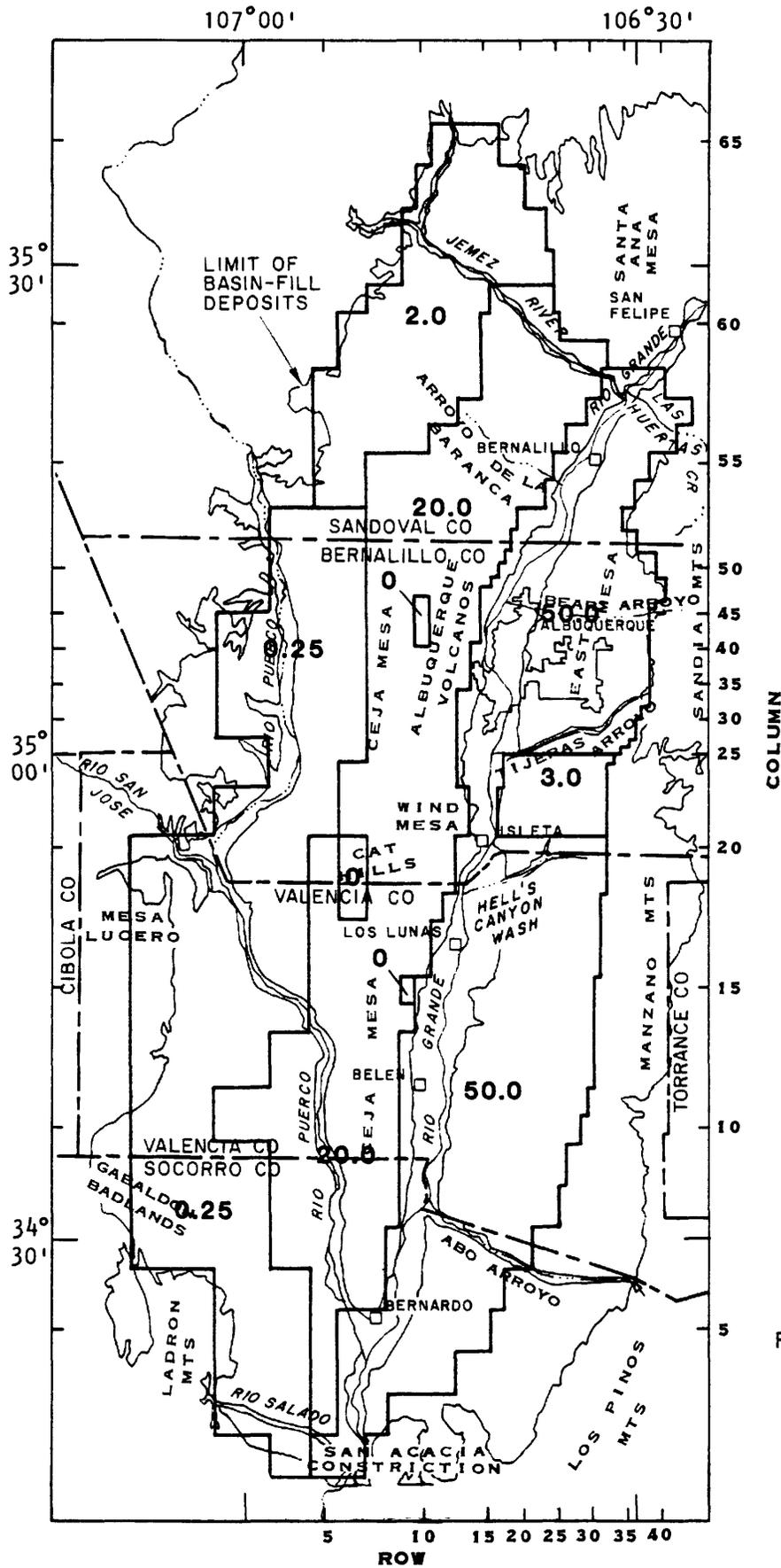
The method used to finalize the steady-state model was adjustment of modeled hydraulic conductivity values (resulting in new transmissivities) within acceptable limits until a best fit of computed and reported or measured heads at 34 control wells was achieved. The control wells are fairly evenly distributed over the basin, with a denser distribution in the vicinity of Albuquerque due to the availability of reliable well data (fig. 10) and in anticipation of the need for more calibration points in the Albuquerque area during subsequent transient simulations.

Initially, the modeled area was divided into four subareas that represented areas presumably having uniform hydraulic conductivities. Each represented an area potentially having a different conductivity on the basis of known or plausible hydrologic variations. However, the final model required six subareas within the basin.

Most of the area east of and including the flood plain of the Rio Grande was modeled as having a hydraulic conductivity of 50 feet per day. Most of the area west of the flood plain was modeled as having a hydraulic conductivity of 20 feet per day. This general distribution of hydraulic conductivities has as its basis the occurrence of coarser basin-fill deposits and fluviually reworked sediments on the eastern side of the basin. Among the exceptions is an area of reduced hydraulic conductivity just south of the city of Albuquerque mentioned by Bjorklund and Maxwell (1961). The hydraulic conductivity in this area was modeled as being 3 feet per day. Also, a 952-foot geologic section in the northern part of the basin was described by Kelley (1977, table 5) as containing a total of 764 feet of mudstone or mudstone and sandstone. This area was modeled as having a hydraulic conductivity of 2 feet per day. The final two subareas represent the eastward-dipping tight zone described by Bjorklund and Maxwell (1961) and further delineated by Wilkins (in press). Because the thicknesses of the top two model layers do not strictly correspond to the thickness of the tight zone, two hydraulic conductivities were needed to maintain approximately equal vertical harmonic leakances as the tight zone passed from the top to the next lower model layer. These hydraulic conductivities were 0.25 foot per day for the tight zone in the top layer (layer 6) and 2 feet per day for the tight zone in the modeled layer beneath the top (layer 5).

Adjustments to simulated hydraulic conductivity values resulted in final values that ranged from 0.25 to 50 feet per day. The ratio of vertical to horizontal hydraulic conductivities was 1:500 in the final model. The configuration of the model boundaries and hydraulic conductivity subareas in the six model layers are shown in figures 13a through 13f.

Due to the lack of data on the variations in hydraulic conductivity at depth, the value assigned to each block was assumed to be constant with depth, with the exception of the previously mentioned eastward-dipping low-conductivity zone. Selected sections showing the vertical geometry of the model are shown in figures 14-16.

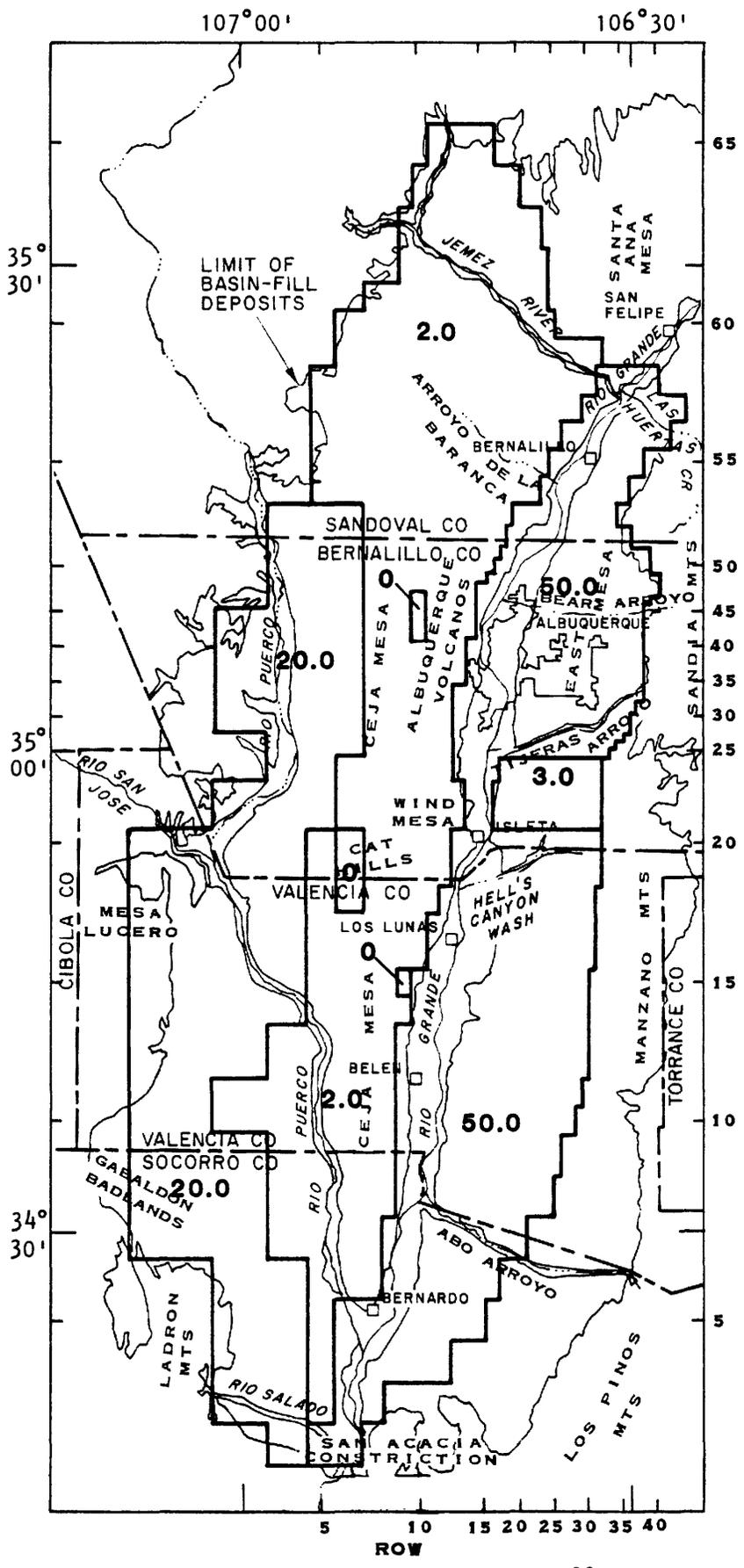


EXPLANATION

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



Figure 13a.--Simulated hydraulic conductivity in layer 6 (top layer) of the model.

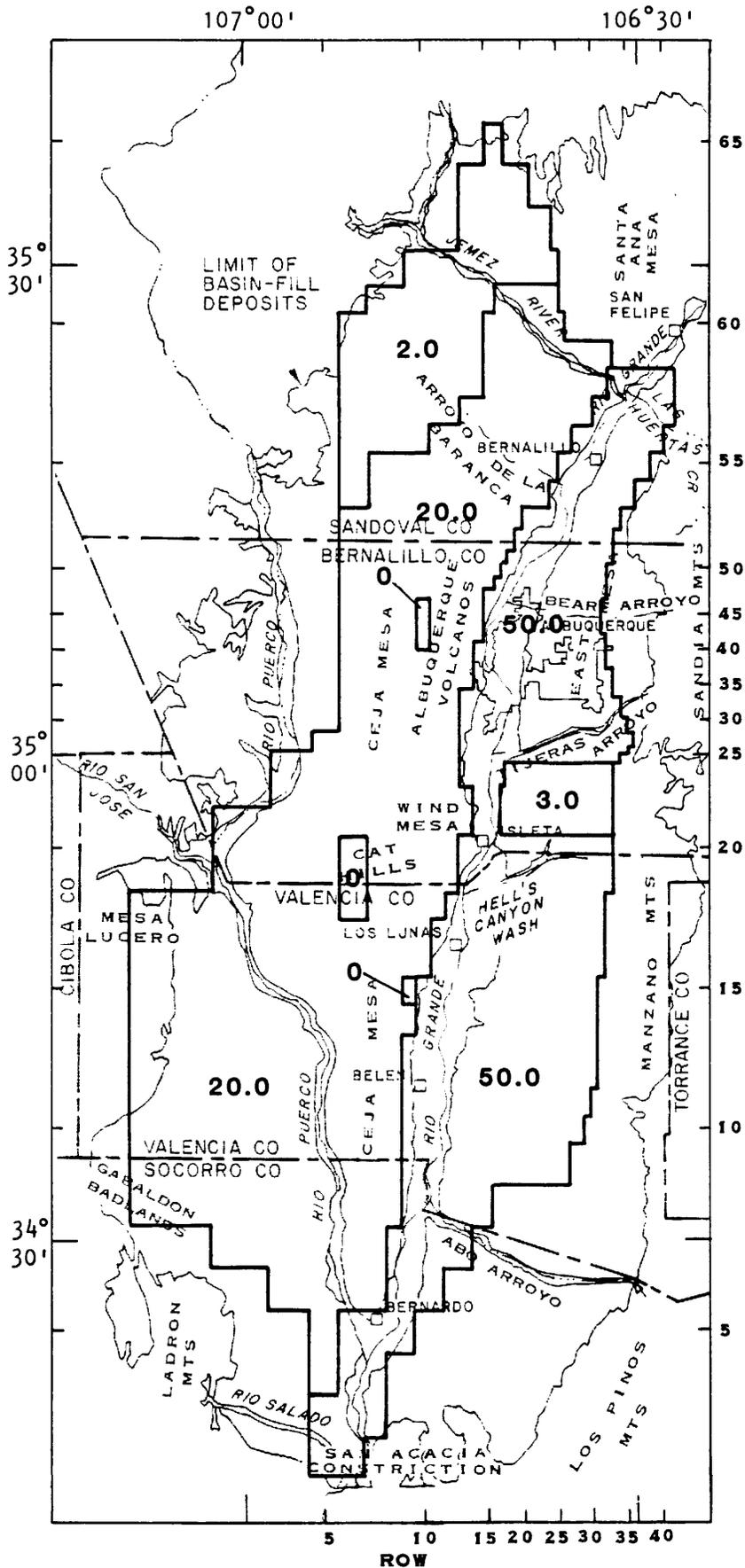


EXPLANATION

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



Figure 13b.--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 675 feet.

COLUMN

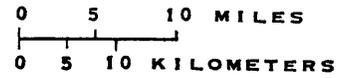
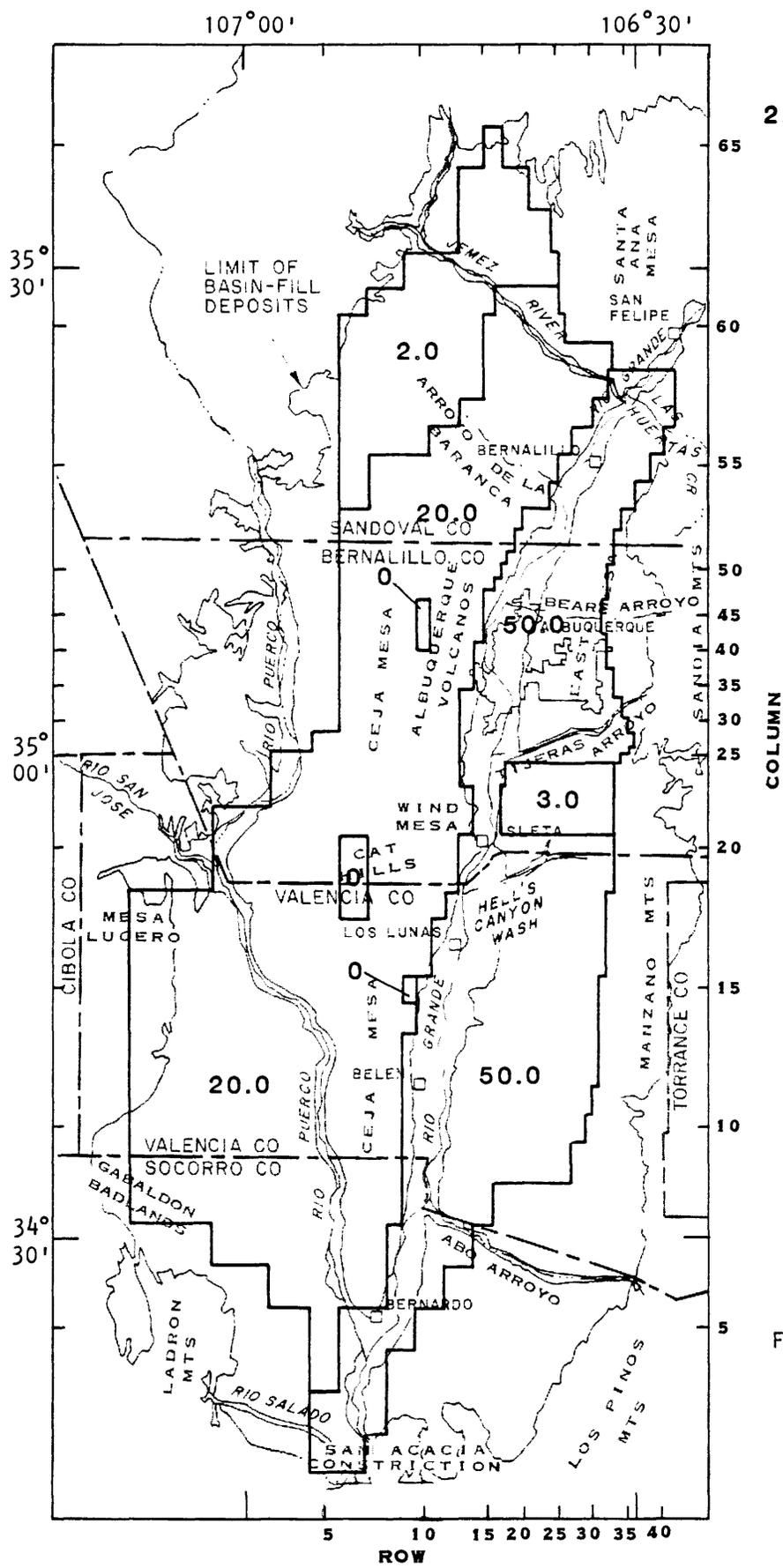


Figure 13c.--Simulated hydraulic conductivity in layer 4 of the model.

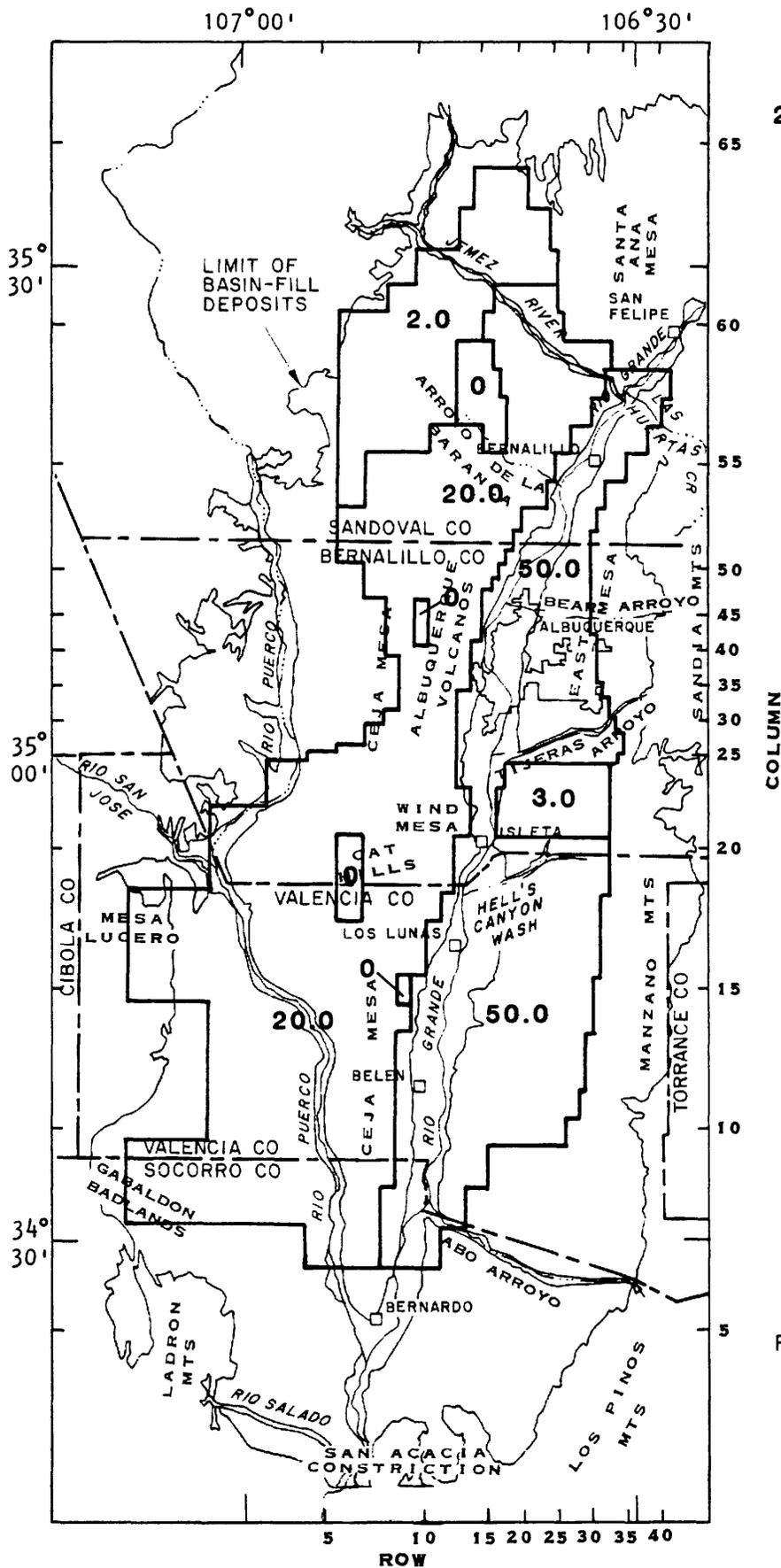


EXPLANATION

2.0 VALUE OF SIMULATED HYDRAULIC CONDUCTIVITY FOR DESIGNATED BLOCK, IN FEET PER DAY--Thickness of layer is 1000 feet.



Figure 13d.--Simulated hydraulic conductivity in layer 3 of the model.



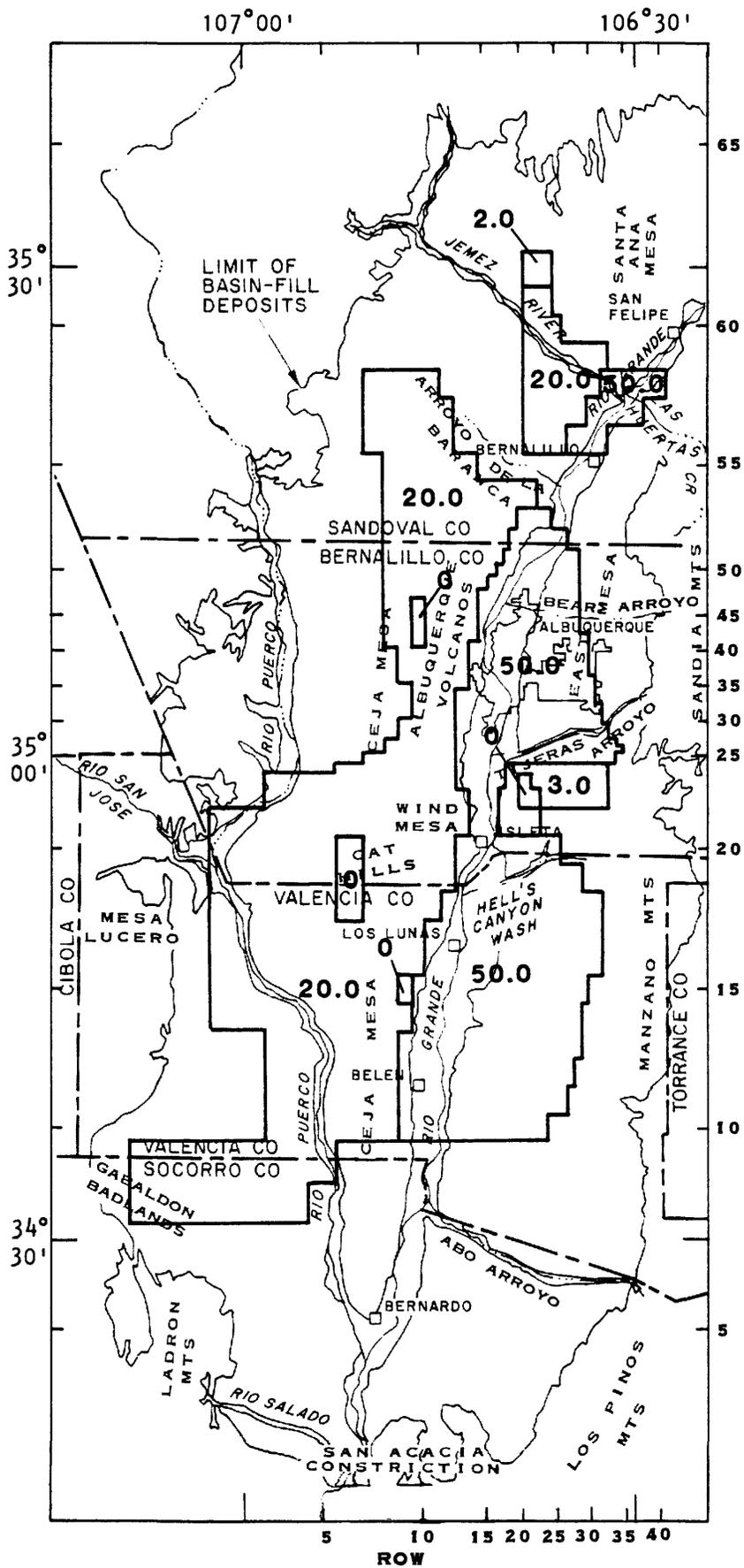
EXPLANATION

2.0 VALUE OF SIMULATED HYDRAULIC CONDUCTIVITY FOR DESIGNATED BLOCK, IN FEET PER DAY--Thickness of layer is 1500 feet.

COLUMN



Figure 13e.--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 2250 feet.



Figure 13f.--Simulated hydraulic conductivity in layer 1 of the model.

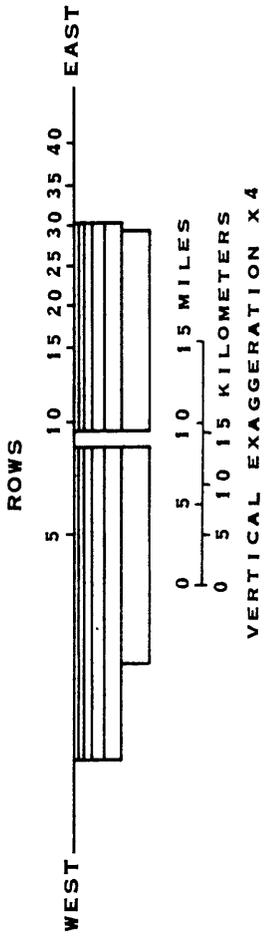


Figure 14.--Vertical geometry along column 15 of the model.

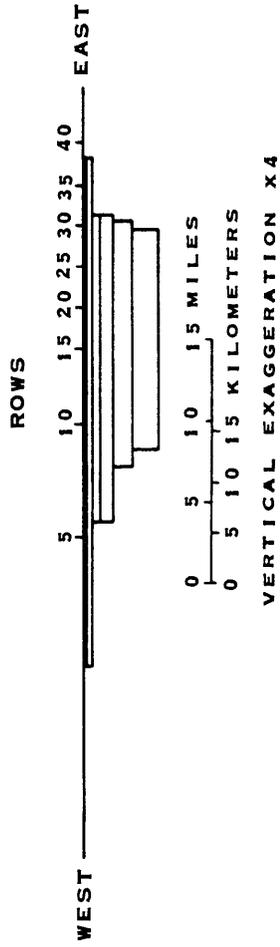


Figure 15.--Vertical geometry along column 40 of the model.

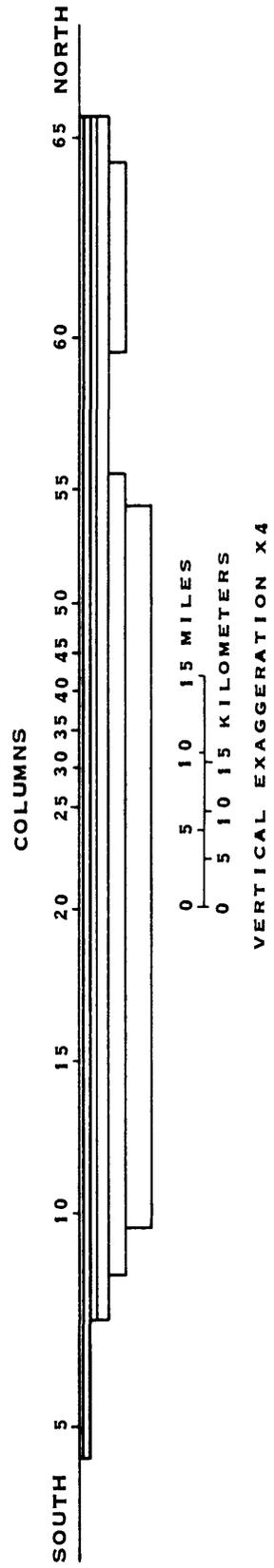


Figure 16.--Vertical geometry along row 15 of the model.

For this study, error was defined as the absolute difference between the water level computed at a given model cell and the measured water level at the approximate corresponding point in the aquifer. Because computed water levels are cell averages, large differences between computed and observed water levels can occur where gradients are steep or where cell dimensions are large. For the final simulation, 43 percent of the 37 computed water levels were in error 10 feet or less, 68 percent were in error less than 20 feet, and 89 percent were in error less than 30 feet. The median error was about 11 feet. The minimum error was 0.6 foot, the maximum error was 36 feet, and the mean absolute error was 14.6 feet. The computed and measured water levels for the 34 control wells (37 reported or measured water levels) are shown in table 2.

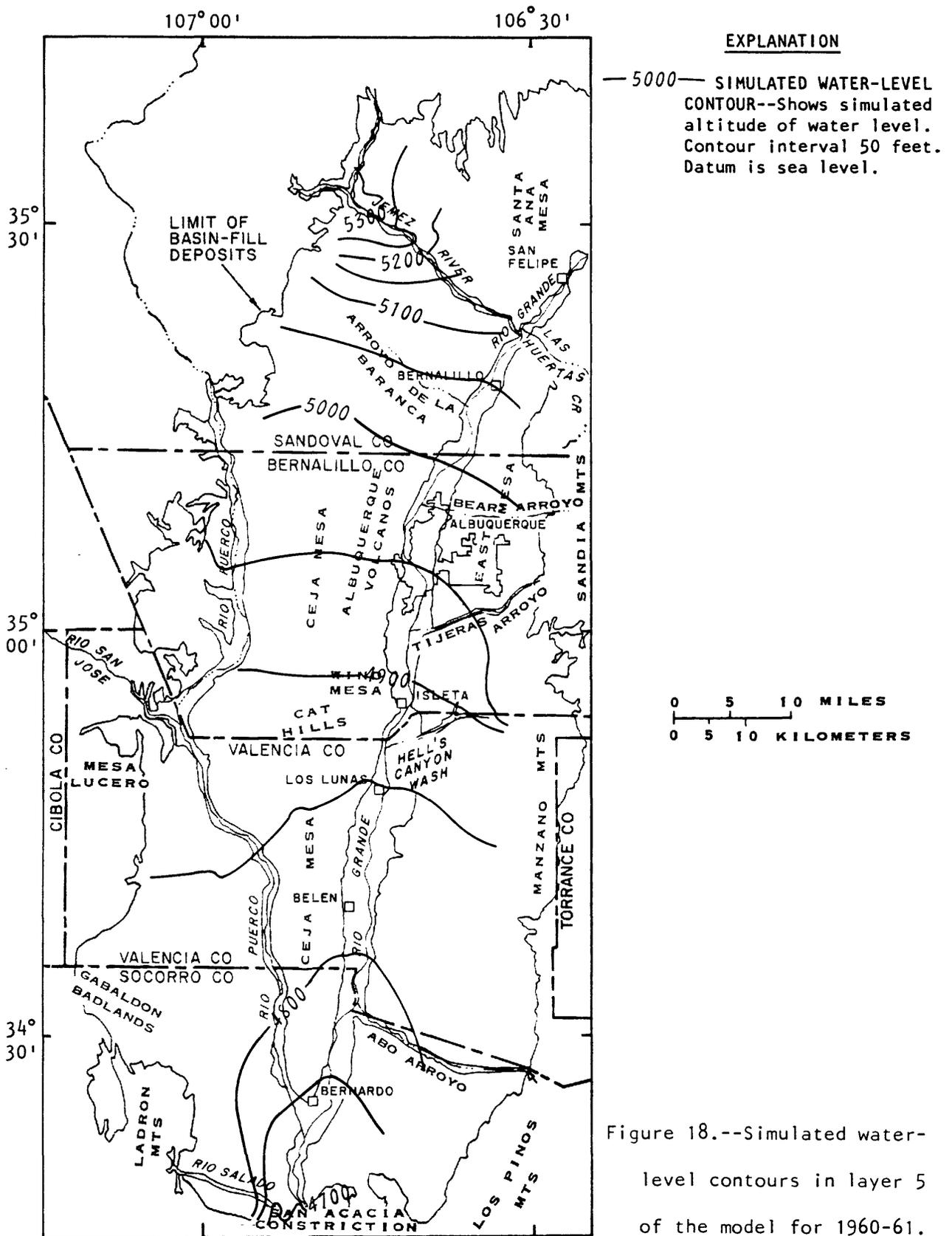
Over most of the modeled area the agreement between observed and computed water levels was good. In the area near Albuquerque, the match was usually within 20 feet. In the area west of Albuquerque where the ground-water trough was postulated by Bjorklund and Maxwell (1961), the computed water levels were generally 30 feet higher than the reported water levels. Hydrologic information is sparse in this area and needs to be defined in more detail in order to adequately assess the failure of the model to simulate a water-level trough of the same magnitude as observed. One possible explanation for the discrepancy between the computed and observed heads in this area is that there is an undetected zone or zones of high hydraulic conductivity deep in the central part of the basin. Such a zone would also cause a downward gradient as was noted by Wilkins (in press). Computed potentiometric heads for the top three model layers are shown in figures 17, 18, and 19.

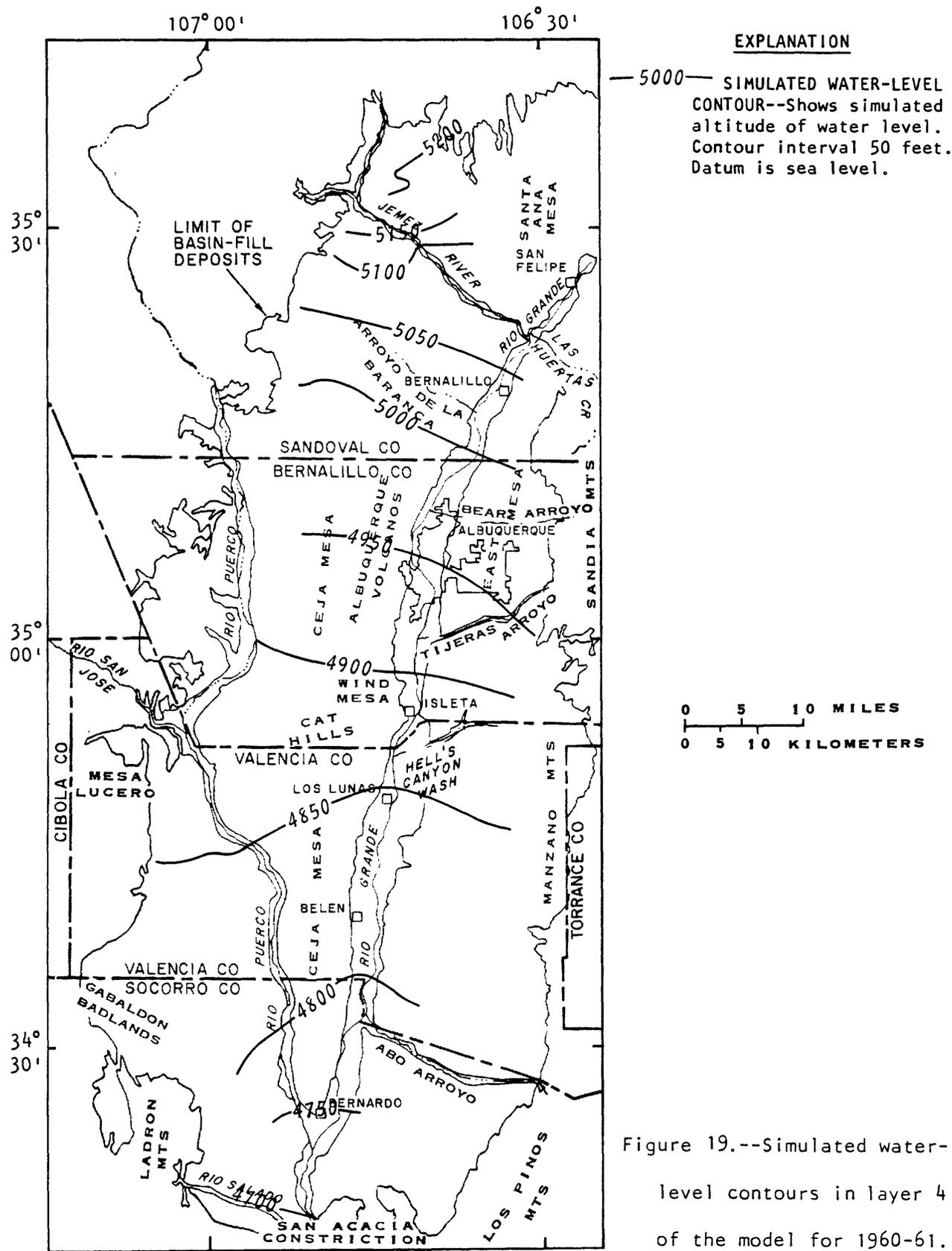
The subarea in the top layer (layer 6) representing the flood plain was modeled as a specified-head boundary. Ground-water flow to and from cells that represent this area was calculated by the model. The model calculated a net gain to the flood plain of 221 cubic feet per second (160,000 acre-feet per year). Because of the specified-head boundary designated for the flood plain, only the net gain or loss for the flood plain can be determined from the model, and a water budget for the flood plain, if needed, must be determined external to this model.

Table 2. Computed and observed water levels at the 34 control-well sites

[Water levels are in feet above sea level. The error listed is the difference, in feet, between computed and observed water-level altitudes]

Well number	Node location (row, column)	Water-level altitude		Error (feet)
		Computed (feet)	Measured (feet)	
LAYER 6				
3N.1W.35.430	4, 6	4,791	4,765	26
4N.1E.09.324	6, 9	4,797	4,798	-0.6
6N.1E.05.412	6,16	4,846	4,832	14
10N.1E.22.322	7,38	4,940	4,907	33
12N.1E.22.222	7,54	4,990	4,955	35
10N.1E.26.343	8,36	4,935	4,899	36
11N.1E.26.424	8,48	4,964	4,942	22
8N.1E.01.342	9,22	4,893	4,888	5
9N.1E.25.241	9,25	4,907	4,871	36
11N.2E.18.313	9,50	4,972	4,962	10
11N.2E.22.441	13,49	4,975	4,967	8
3N.2E.26.330	14, 6	4,764	4,765	-1
5N.3E.19.212	18,12	4,823	4,798	25
14N.3E.06.423	18,62	5,291	5,298	-7
8N.3E.32.412	20,20	4,869	4,864	5
12N.3E.08.233	20,55	5,030	5,008	22
10N.3E.21.223	22,39	4,950	4,952	-2
10N.3E.03.412	24,44	4,965	4,969	-4
13N.3E.03.223	24,59	5,153	5,141	12
8N.3E.14.231	26,21	4,916	4,936	-20
10N.3E.01.114	27,45	4,974	4,956	18
9N.3E.36.211	29,24	4,959	4,944	15
12N.4E.32.242	33,53	5,016	4,987	29
9N.4E.15.311	35,28	4,966	4,964	2
LAYER 5				
11N.2E.18.313	9,50	4,970	4,946	24
11N.3E.18.411	17,50	4,978	4,967	11
10N.3E.27.243	24,36	4,951	4,945	6
14N.3E.03.434	24,61	5,150	5,145	5
10N.3E.35.111	25,35	4,951	4,954	-3
10N.3E.36.132	27,34	4,953	4,942	11
9N.3E.01.222	29,33	4,956	4,948	8
10N.4E.32.433	32,33	4,962	4,955	7
10N.4E.34.214	36,35	4,978	4,984	-6
10N.4E.05.122	36,45	4,990	4,965	25
LAYER 4				
11N.2E.18.313	9,50	4,969	4,946	23
11N.3E.18.411	17,50	4,977	4,960	17
10N.4E.20.111	31,39	4,960	4,954	6





The model used specified-head assignments along the boundaries of ground-water inflow and outflow. Ground-water inflow was computed to be about 46,000 acre-feet per year, and ground-water outflow was computed to be about 15,000 acre-feet per year (table 3). J.D. Dewey (U.S. Geological Survey, written commun., 1982) estimated that evapotranspiration losses in the flood plain were between 310,000 and 390,000 acre-feet per year depending on the amount of summer precipitation. This range compares favorably with the 325,000 acre-feet per year calculated as a residual in table 3.

Table 3. Water budget for the Albuquerque-Belen Basin

[Flow rates are in acre-feet per year]

	Inflow	Outflow	Source
Surface water	834,000	669,000	Published data
Ground water	46,000	15,000	Model simulation
Mountain-front and tributary recharge	129,000	--	Estimated and used as model input (J.D. Dewey, U.S. Geological Survey, written commun., 1982)
Evapotranspiration and other losses	--	325,000	Residual (total inflow-total outflow)

Simulated hydraulic conductivity values in the vicinity of Albuquerque are considered most reliable because of the density of control data points. Adjustments to simulated hydraulic conductivity that were made in the areas of few or no data control points (northwestern and western part of the basin) may be less reliable. The overall results of the model for the entire basin are compatible with the reliability of the hydrologic data used to construct the model.

The degree to which a model reliably represents the true aquifer system is in part a function of the accuracy, spatial distribution, and density of data regarding the physical properties and hydrologic responses of the system. Such information is used to determine the type and location of model boundaries, dimensioning of model cells, and the zoning of modeled hydraulic conductivity values. If and when additional data become available, or if existing data are refined, an existing model might be proven less reliable than earlier believed. Preferably, the existing model can then be altered to take advantage of the new data. Because of uncertainties in the available data and incomplete spatial coverage of information on the aquifer system, there cannot be an ultimate calibrated model. A model can undergo the process of calibration but is never truly calibrated.

Sensitivity Analysis

Several model simulations were performed to test the relative sensitivity of the model to changes in simulated hydraulic properties. The three properties that were tested are horizontal hydraulic conductivity, vertical hydraulic conductivity, and rate of mountain-front recharge. The method used to test sensitivity was to first increase, then decrease, the value of each property by 10 percent. The differences in mean absolute error between the final accepted model and sensitivity runs were compared. The difference in error was 0.66 foot for mountain-front recharge, 0.49 foot for vertical hydraulic conductivity, and 0.48 foot for horizontal hydraulic conductivity. A greater difference in error indicates a greater sensitivity. The multiplication factors (1.10 and 0.90) were applied uniformly over the modeled area to each tested property; no attempt was made to perform analyses on isolated subareas within the model. The model is slightly more sensitive to changes in mountain-front recharge than to changes in horizontal and vertical hydraulic conductivity.

The final sensitivity test for the model was to remove from active simulation the lowest layer, which has a thickness of 2,250 feet, or roughly one-third of the modeled aquifer thickness. The mean absolute error increased 1.5 feet for the steady-state model. Although this increase in error is large in comparison with the other sensitivity tests, it is remarkably small considering that over one-third of the modeled thickness was removed from simulation.

SUMMARY

The Albuquerque-Belen Basin, the largest basin of the Rio Grande Rift in New Mexico, is about 90 miles long and 25 to 40 miles wide. The basin is filled with poorly consolidated Tertiary- and Quaternary-age deposits whose constituents primarily were eroded from the bordering highlands or from upstream areas. The thickness of the basin fill, as interpreted from gravity anomalies, exceeds 8,000 feet in a north-south strip along the eastern side of the basin.

The Santa Fe Group, alluvial-fan deposits, and valley alluvium, collectively termed the basin fill, together constitute the principal aquifer in the basin. Flow of ground water in this aquifer system is three dimensional. It is assumed that rates of flow, together with the configuration of the water table as determined from the water-level measurements prior to 1960, represent a long-term, approximately steady-state flow system within the aquifer.

Assuming that a steady-state condition existed in 1960, a mathematical model of the ground-water flow system was constructed on the basis of a simplified conceptualization of this system. The calibration process for the steady-state model consisted of trial-and-error adjustments of simulated hydraulic conductivity values, within acceptable ranges, until a best fit of measured and computed heads at 34 control wells was achieved. Adjustments to simulated hydraulic conductivity values resulted in final values of 50 feet per day in the area east of the Rio Grande flood plain, 20 feet per day west of the flood plain, 3 feet per day in an area just south of Albuquerque, and 0.25 and 2 feet per day in an area of low conductivity in the western part of the basin. The ratio of simulated vertical to horizontal hydraulic conductivity was 1:500. The minimum error, defined as the absolute difference between the computed and the reported or measured water level at the approximately corresponding point in the aquifer system, was 0.6 foot, the maximum was 36 feet, and the mean absolute error was 14.6 feet for 37 water levels at the 34 control wells.

Mountain-front and tributary recharge was modeled as being about 129,000 acre-feet per year. Net gain for the flood plain was computed by the model to be 160,000 acre-feet per year. Ground-water inflow to the basin was computed to be about 46,000 acre-feet per year, and ground-water outflow was about 15,000 acre-feet per year. There is a net annual loss of about 325,000 acre-feet of water per year in the basin.

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