SUMMARY OF THE SOUTHWEST ALLUVIAL BASINS REGIONAL AQUIFER-SYSTEM ANALYSIS IN PARTS OF COLORADO, NEW MEXICO, AND TEXAS

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. Department of the Interior
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PROFESSIONAL PAPER 1407–A

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Summary of the Southwest Alluvial Basins Regional Aquifer-System Analysis in Parts of Colorado, New Mexico, and Texas

By D.W. WILKINS

REGIONAL AQUIFER-SYSTEM ANALYSIS

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1407-A

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Thomas J. Casadevall

Thomas J. Casadevall
Acting Director

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Multiply	*By*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
foot per second	0.3048	meter per second
foot per mile	0.1894	meter per kilometer
mile	1.609	kilometer
acre	0.4047	square hectare
square mile	2.590	square kilometer
gallon	3.785	liter
gallon per minute	0.06309	liter per second
acre-foot	1,233	cubic meter
acre-foot per year per square mile	0.0004761	cubic hectometer per year per square kilometer

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

$$°F = 9/5\,(°C) + 32.$$

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

SUMMARY OF THE SOUTHWEST ALLUVIAL BASINS REGIONAL AQUIFER-SYSTEM ANALYSIS IN PARTS OF COLORADO, NEW MEXICO, AND TEXAS

By D.W. Wilkins

ABSTRACT

The Southwest Alluvial Basins study area consists of 70,000 square miles in parts of Colorado, New Mexico, and Texas, and includes 22 alluvial basins along and adjacent to the Rio Grande. Rocks of the region can be divided into four basic types: (1) basin-fill deposits--unconsolidated to poorly consolidated sand and gravel interbedded or intermixed with clay and silt; (2) volcanics--primarily basalt, including volcanic flow rocks, tuff, and small intrusive bodies; (3) consolidated sedimentary rocks--primarily shale and sandstone, including limestone, gypsum, and salt; and (4) crystalline rocks--intrusive igneous rocks and metamorphic rocks.

Structurally and hydrologically the 22 basins can be divided into two general types: open basins that have surface-water discharge and closed basins that have no surface-water discharge. The Rio Grande is the primary hydrologic connection among basins that have surface-water discharge. Recharge to the ground-water system is greater in the northern basins. About 3,580 cubic feet per second annually is recharged to the San Luis Basin. Recharge to the Mesilla Basin in southern New Mexico and western Texas annually is 6 cubic feet per second.

Basin-fill deposits, including fan deposits, river alluvium, and unconsolidated to consolidated sediments and some volcanics of the Santa Fe Group or Gila Conglomerate are hydraulically connected and form an aquifer system. Coarse-grained sediments were deposited by the relatively high energy ancestral Rio Grande; whereas, fine-grained lake or playa sediments were deposited in topographically closed basins.

Simulation of ground-water flow in the San Luis Basin indicates that of the 535 cubic feet per second of water that was withdrawn from the basin-fill aquifer system in 1980, 80 percent was from salvaged evapotranspiration, 14 percent was from aquifer storage, and 6 percent was from streamflow capture.

The total saturated thickness of sediments penetrated by wells in the Albuquerque-Belen Basin is made up of a mixture of clay, silt, and sand. Ground water in the southeastern part of the Albuquerque-Belen Basin contains calcium and sulfate as primary ions. Calcium generally is the dominant cation; bicarbonate is the dominant anion along the northeast side of the basin. Ground water in the flood plain of the Rio Grande generally is of a calcium sulfate type. A sodium chloride brine is found in the extreme southwestern part of the basin.

The ground-water flow model of the Albuquerque-Belen Basin shows that from 1976 to 1979 ground-water withdrawals outside the flood plain were composed of 36 percent intercepted ground-water discharge to the flood-plain system, 32 percent induced recharge from the flood plain; 25 percent aquifer storage; and 7 percent underflow from the Santo Domingo Basin, to the north.

Ground water east of the Rio Grande valley in the Socorro Basin contains large percentages of calcium, magnesium, and sulfate. Ground water in the southern part of the Rio Grande valley generally has a larger percentage of sodium and a smaller percentage of sulfate than ground water in the northern part of the valley. Water is a calcium bicarbonate type in the La Jencia Basin, in the principal recharge area to the east. The increase in the percent of sodium downgradient from the recharge area is significant.

The total saturated thickness of sediments penetrated by wells in the Mesilla Basin is made up of a mixture of clay, silt, and sand. Ground water is a sodium and sulfate type water along the northwest basin margin. Along the southwest basin margin one water type contains dominant ions of sodium and bicarbonate; another type contains dominant ions of sodium and chloride. West of Las Cruces chloride generally is the dominant anion in ground water.

Shallow ground water in the Rio Grande flood plain in the Mesilla Basin generally has a larger specific conductance than water deeper in the aquifer. Ground water associated with Mesozoic and Paleozoic rocks north and east of Las Cruces has a larger percentage of sulfate and chloride and greater specific conductance than water associated with volcanic rocks east of Las Cruces. The ground-water flow model shows that for nonirrigation ground-water withdrawals in the Mesilla Basin, 80 percent is from the surface-water system, including streamflow capture; 10 percent is from aquifer storage; and 10 percent is from salvaged evapotranspiration.

Ground-water movement in the study area is generally from west and east to the center of the valley and then southward. Through much of the study area the Rio Grande flood plain acts as a drain for the basin-fill aquifer system. Temperature of ground water from the San Luis Basin south to the northern end of the Albuquerque-Belen Basin generally ranges from 5 to 15 degrees Celsius. South of the northern end of the Albuquerque-Belen Basin the ground-water temperature generally ranges from 15.1 to 25 degrees Celsius. Ground water generally has a specific conductance less than 750 microsiemens per centimeter at 25 degrees Celsius, north of the Albuquerque-Belen Basin. East of the Rio Grande and south of the Albuquerque-Belen Basin the specific conductance of water is usually in the range of 751 to 2,250 microsiemens per centimeter at 25 degrees Celsius.

Chemical processes affecting ground-water quality are dissolution of calcite, dolomite, gypsum, and halite; precipitation of calcite and dolomite; exchange of calcium for sodium; and mixing of local recharge, geothermal, or inflowing ground water from adjacent basins with ground water in the area of study. Recharge water from the east and west, in basins north of the Albuquerque-Belen Basin, is a calcium bicarbonate type; the principal chemical process is dissolution of calcite. Chloride water is found in the Albuquerque-Belen Basin and basins to the south.

Recharge to basins is predominantly from uplifted areas east and west of the basins. Runoff from snowmelt and storms infiltrates the alluvial material near the contact of the alluvium and rocks of the uplifted areas. Recharge to the San Luis and Española Basins was estimated to be 0.984 and 0.175 cubic foot per second per square mile of alluvial area, respectively. Recharge rates in the Mesilla, Mimbres, and Lordsburg Basins, in the southern part of the study area, ranged from 0.004 to 0.003 cubic foot per second per square mile of alluvial area.

Irrigation is the primary use of surface water in open basins. In closed basins 93 percent of the irrigated acreage uses ground water as a source. In the Albuquerque-Belen Basin from 1975 to 1985, at least 90 percent of ground-water withdrawals were for uses other than agriculture. In the Mesilla Basin from 1975 to 1985, 32 to 45 percent of all ground water withdrawn was for nonagricultural uses.

INTRODUCTION

This report summarizes findings of the Southwest Alluvial Basins (SWAB) study, part of the Regional Aquifer-System Analysis (RASA) program of the U.S. Geological Survey in parts of southern Colorado, New Mexico, and west Texas. The main purposes of the SWAB study were to enhance the understanding of the regional hydrology of alluvial basins that serve as major ground-water reservoirs and to study the hydrologic effects of stresses on the system. Twenty-two alluvial basins are within the area. A planning report by Wilkins and others (1980) provides a more detailed description of the SWAB study.

The SWAB RASA is described in Professional Paper 1407, which will consist of two parts. Part A (this report) is a summary of the study. Part C (Frenzel and Kaehler, 1992) describes the geohydrology and ground-water quality of the Mesilla Basin. A summary of ground-water flow models planned as Part B of Professional Paper 1407 has been released as Open-Rile Report 90-361 (Kernodle, 1992) and is not included as a Professional Paper chapter.

PURPOSE AND SCOPE

This report summarizes studies of selected basins and discusses water quality, ground-water flow systems, and water use in the study area as a whole. Selected basins were studied in detail using various geohydrologic techniques. Geology, ground-water flow, ground-water geochemistry, ground-water recharge, and aquifer characteristics were studied. Digital flow models of the ground-water systems were developed for three basins. The techniques used and results of basin studies are presented in reports for the individual basins.

DESCRIPTION OF THE STUDY AREA

The study area includes parts of four physiographic provinces (fig. 1). The northern part of the study area is within the Southern Rocky Mountains province. The Basin and Range province includes most of the study area south of the Española Basin. The Colorado Plateau province includes small areas of the Albuquerque-Belen and San Agustin Basins. The Great Plains province lies along the east edge of the study area.

The study area is structurally and hydrologically divided into 22 basins of two general types: open basins that have surface-water discharge and closed basins that have no surface-water discharge. The Rio Grande is the primary hydrologic connection among basins that have surface-water discharge in southern Colorado, central New Mexico, and western Texas (fig. 2). Closed basins primarily are in southwestern and south-central New Mexico and western Texas. Of about 70,000 square miles in the study area, 7,500 square miles are in Colorado, 53,000 square miles are in New Mexico, and 9,500 square miles are in Texas.

GEOLOGIC AND HYDROLOGIC SETTING

The Rio Grande rift is a fault-bounded structural feature with uplifted blocks on the east and west and downdropped, alluvial-filled grabens in the middle. Rifting began about 26 million years ago (Chapin and Seager, 1975). Structural models and the observed fault patterns indicate that either regional extension caused by differential drift within the continental plate (Chapin, 1971; Kelley, 1977) or broad regional uplift (Baltz, 1978) resulted in downdropped basins (grabens) and tilted fault blocks that formed the Rio Grande depression. Woodward and others (1975, p. 239) placed the rift's southern limit at Socorro, New Mexico. Seager and Morgan (1979, p. 101) extended the rift into western Texas and northern Mexico, on the basis of shallow manifestations of the deep structure, such as "active faults and volcanoes, high heat flow, and exceptionally deep basins." The tectonic map by Woodward and others (1975) shows "generally thick, synorogenic sedimentary deposits in the Rio Grande rift; Miocene to Holocene" as far south as Presidio, Texas. Rifting took place along a general north-south structural grain, probably in response to east-west extension. The basins and bounding uplifts generally are arranged en echelon with each basin or uplift being offset slightly to the east of the one to its south. This pattern, together with gravity anomaly lineaments, indicates that the crust broke along north-northeast and north-northwest trends oblique to the main north-south structural grain (Ramberg and others, 1978). Uplifted blocks to the east of the basins generally rise several thousand feet above the valley floor. The basins are bounded on the north, east, and west mainly by Paleozoic and Mesozoic sedimentary rocks and Tertiary and Quaternary volcanics. The southern boundary of the study area is arbitrarily placed at the Mexico-United States international boundary. Detailed descriptions of bordering rocks and geologic features can be found in Chapin (1971), Hawley (1978), and Riecher (1979). Other geology-related publications are listed in bibliographies by Stone and Mizell (1979) and Wright (1978, 1979a, b).

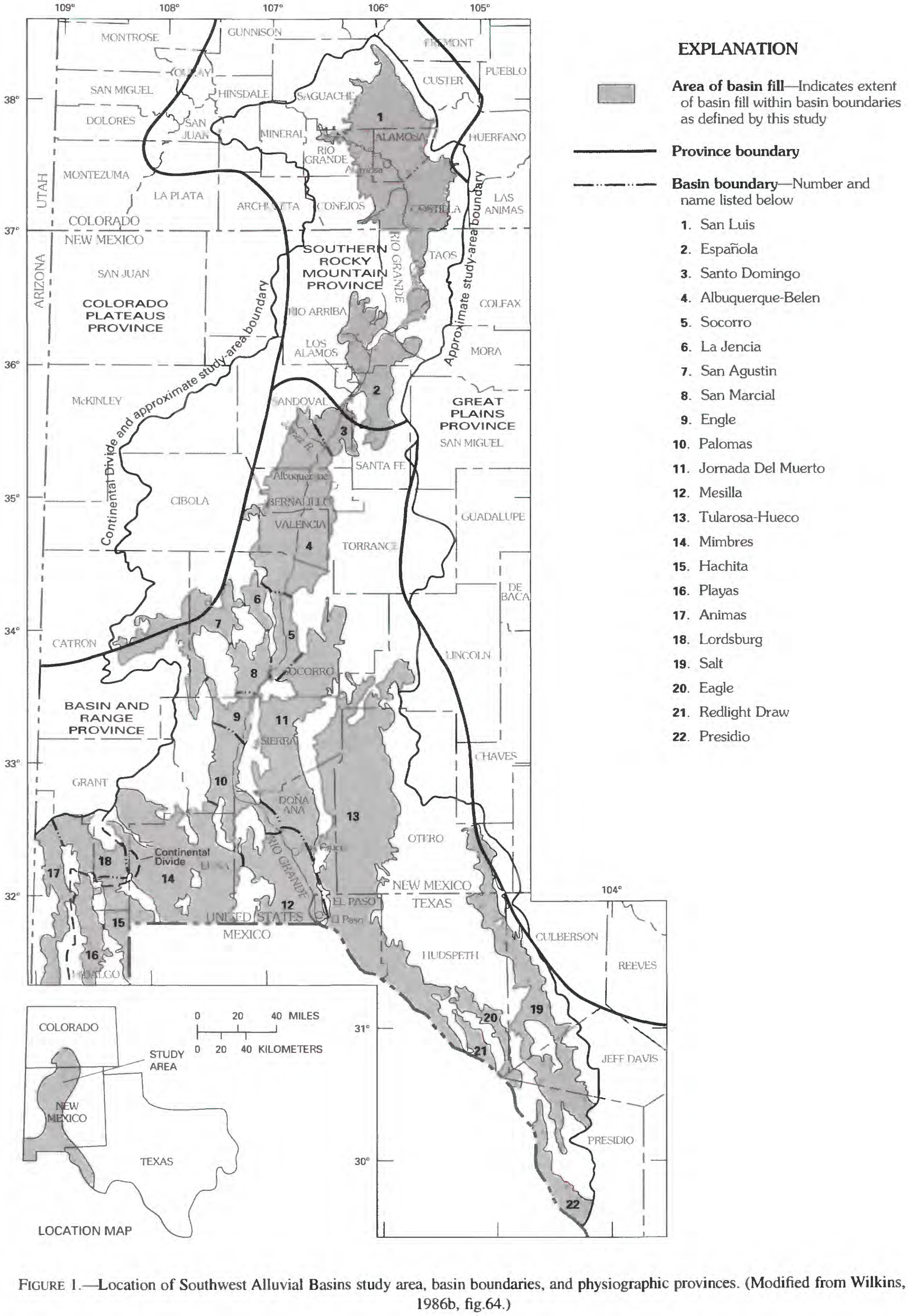


FIGURE 1.—Location of Southwest Alluvial Basins study area, basin boundaries, and physiographic provinces. (Modified from Wilkins, 1986b, fig.64.)

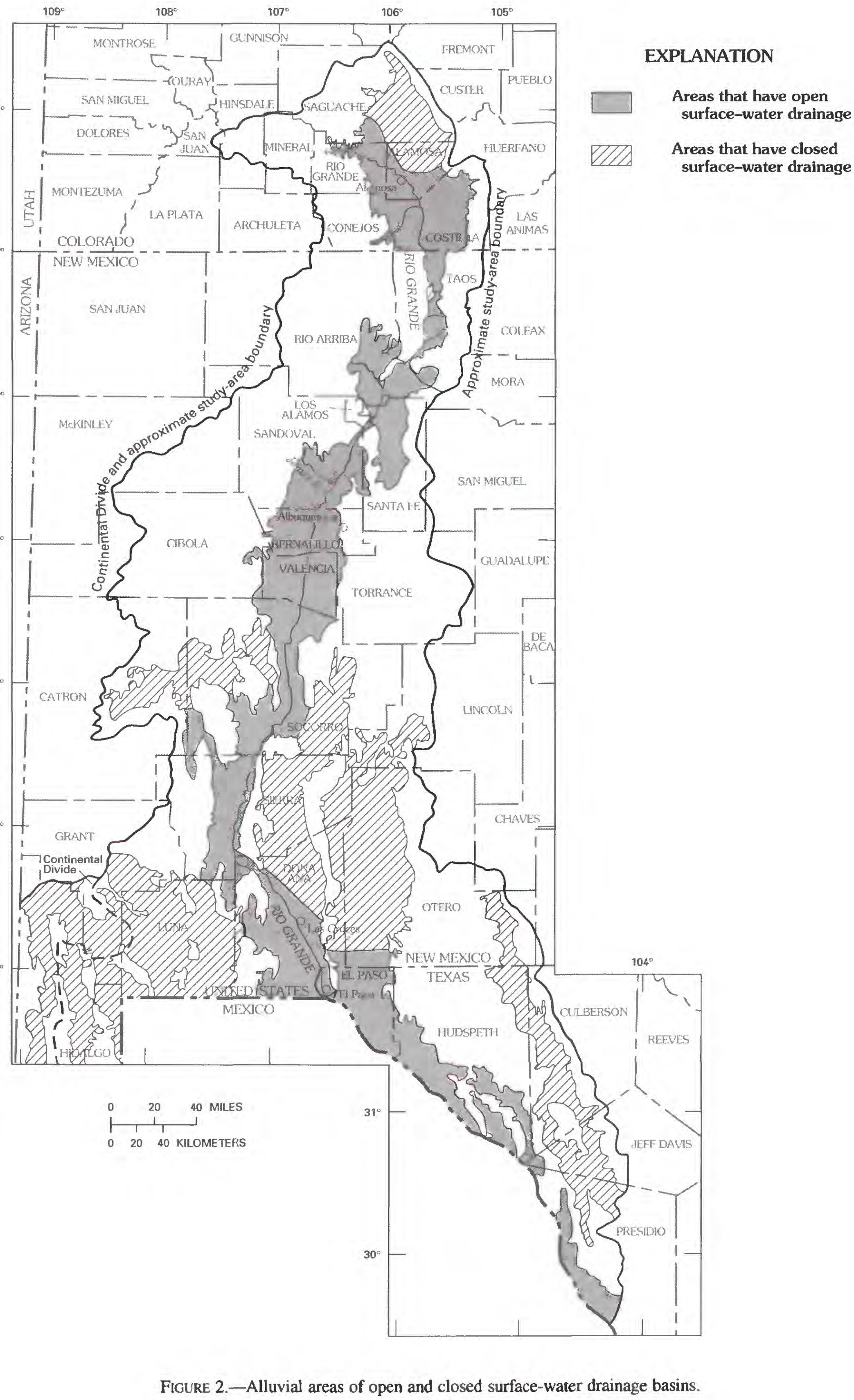


FIGURE 2.—Alluvial areas of open and closed surface-water drainage basins.

Basin boundaries are defined by the contact of alluvial fill and the toe of uplifted blocks. The hydrologic boundary for many basins, however, is a basin-bounding fault, usually buried by alluvial material. On the basin side of these faults, generally there is a substantial thickness of alluvial sediments. Structurally, several of the basins in the southern part of the study area extend into Mexico. Hydrologically, these areas are not considered significant because the basin aquifers receive small to negligible amounts of recharge from the south and are not stressed by ground-water withdrawals in Mexico.

West and Broadhurst (1975, p. 11-13) divided rocks of the region into four basic types: (l) basin-fill deposits--unconsolidated to poorly consolidated sand and gravel interbedded or intermixed with clay and silt; (2) volcanics--primarily basalt, including volcanic flow rocks, tuff, and small intrusive bodies; (3) consolidated sedimentary rocks--primarily shale and sandstone, including limestone, gypsum, and salt; and (4) crystalline rocks--intrusive igneous rocks and metamorphic rocks. For this study the first two types, consisting of Quaternary and Tertiary basin-fill deposits and volcanics, were considered to comprise the basin-fill aquifer system; the last two types, consisting primarily of Mesozoic through Precambrian rocks, were considered impermeable bedrock (fig. 3).

Quaternary deposits primarily consist of alluvial fans, colluvium, pediment gravels and sands (including dunes), playa muds and sands, river terraces, and inner river-valley flood-plain and channel deposits. With the exception of the flood-plain and channel deposits, Quaternary sediments are usually unsaturated.

The Tertiary and Quaternary Santa Fe Group, or Gila Conglomerate, is present throughout the study area. It consists of unconsolidated to moderately consolidated sedimentary deposits and some volcanic rocks. Bryan (1938, p. 205) used four criteria in defining the Santa Fe Formation:

> (1) All the beds are slightly cemented, and the fine-grained members have concretions of calcium carbonate; (2) all the deposits are deformed, mostly by normal faults, although in the centers of the basins the deformation is so slight as to pass unnoticed except under intensive search; (3) the beds within any one basin are of diverse lithologic types, ranging from coarse fanglomerate to fine silt and clay, and abrupt changes in the kind and size of the contained pebbles are characteristic; (4) and these markedly different materials attributed to one formation conform in their arrangement to a geographic pattern consistent with the laws of deposition in basins.

The base of the Santa Fe Group generally is placed above the middle Tertiary (Oligocene) volcanic and associated sedimentary rocks. Estimated thicknesses of sediments in closed basins range from about 2,400 feet in the Salt Basin to about 6,000 feet in the Jornada del Muerto Basin. Sediment thicknesses in open basins associated with the Rio Grande rift are as much as 20,000 feet in the San Luis Basin (Tweto, 1978, p. 27).

The basin-fill deposits, including fan deposits, alluvium within river valleys, and the Santa Fe Group or the Gila Conglomerate, form the hydraulically connected, anisotropic, and heterogeneous principal basin-fill aquifer system. Ground water within the first several hundred feet of saturated sediments generally is unconfined, but confined conditions may exist locally. Recharge, derived from precipitation in the surrounding mountain areas, occurs primarily near basin-bounding faults. Sediments, with sufficient saturated thickness to supply water to wells, are usually found on the basin side of these faults.

The Rio Grande is the major source of surface water in the study area. The Rio Grande originates along the eastern crest of the Continental Divide in southern Colorado, flows eastward into the San Luis Basin some 65 miles east of its headwaters, and then flows generally southward (fig. 1). Most surface water is diverted into canals south of the Santo Domingo Basin.

SUMMARY OF BASIN ANALYSES

Five of the 22 basins were studied in detail. These basins were selected on the basis of availability of data and ground-water development that lead to significant stress on the ground-water system in the basins. The following sections summarize results of the basin studies; additional information about the studies is available in the cited publications.

SAN LUIS BASIN

The San Luis Basin is in southern Colorado and northern New Mexico (fig. 1). It was selected for study because of a long history of ground-water withdrawals for irrigation in the San Luis Valley, north of the San Luis Hills.

GEOLOGY

Seismic-reflection data were collected east and west of the southern San Luis Hills near the Colorado-New Mexico State line as part of this project (Uitti, 1980, p. 10). Depth to the Precambrian basement rocks ranges from about 8,500 feet east of the Rio Grande to about 1,500 feet west of the river in the vicinity of the southern end of the San Luis Hills (Uitti, 1980, p. 42). East of the southern end of the San Luis Hills (fig. 4), the thickness of alluvial sediments, including the Santa Fe Group, is about 2,600 feet. A maximum thickness of 4,200 feet is indicated east of the hills in the vicinity of the Colorado-New Mexico State line. Alluvial sediments younger than the Santa Fe Group are about 1,300 feet thick west of the Rio Grande near the southern San Luis Hills where the Santa Fe Group is absent (Uitti, 1980, p. 38).

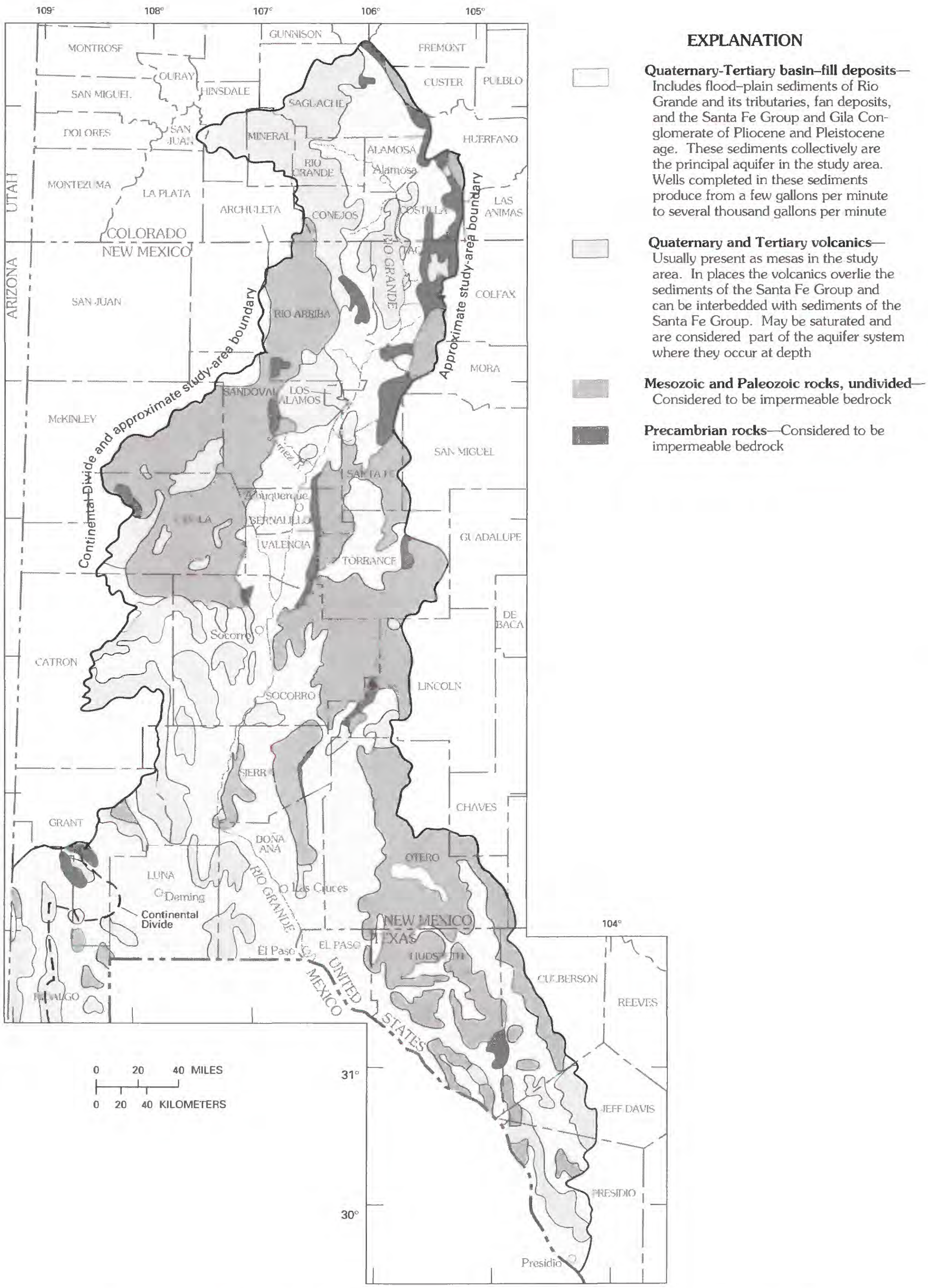


FIGURE 3.—Generalized geology of the Southwest Alluvial Basins study area. (From Wilkins, 1986b, fig. 66).

GROUND-WATER FLOW SYSTEM

The major components of the ground-water flow system in the San Luis Basin were analyzed to provide estimates of flow rates between these components. Additionally, the analyses were made to improve estimates of hydrologic changes in the ground-water flow system in response to management alternatives in the Alamosa Basin (Hearne and Dewey, 1988). Boundaries of the basin are the drainage divides in the Sangre de Cristo Mountains on the east and the San Juan Mountains on the west (fig. 4). The intermontane area is divided by the San Luis Hills into the Alamosa Basin to the north and the Costilla Plains and the Taos Plateau to the south. The Alamosa Basin is dissected by a low topographic divide, forming a closed basin north of the Rio Grande drainage basin.

The intermontane area contains several thousand feet of interbedded sedimentary and volcanic rocks that form complex aquifer systems. The San Luis Hills are a barrier to ground-water flow between the Alamosa Basin and the Taos Plateau or Costilla Plains.

The San Juan Mountains and the Sangre de Cristo Mountains are the source of most water for the Alamosa Basin, the Costilla Plains, and the Rio Grande. In the mountains, precipitation exceeds evapotranspiration, and excess water flows to the intermontane area. Water yield (surface flow and ground-water flow) from the San Juan Mountains is about 2,800 cubic feet per second (ft^3/s). Water yield from the Sangre de Cristo Mountains is about 780 ft^3/s (Hearne and Dewey, 1988, p. 110).

Hearne and Dewey (1988) calculated water budgets for the Costilla Plains and the Alamosa Basin. These water budgets represent average values for 1950-80. Two methods of estimating recharge were developed by Hearne and Dewey (1988). The mountain water-budget method was used in uplifted areas with significant secondary permeability. The method computes a volume of water that will infiltrate within and flow from the uplifted area. The mountain water-budget method is based on the following equation (Hearne and Dewey, 1988, p. 15, eq. 1).

$$Q = P - S - E \qquad (1)$$

where Q = sum of streamflow and ground-water flow to the alluvial basin (L^3/T),

P = precipitation (L^3/T),

S = sublimation (L^3/T), and

E = evapotranspiration (L^3/T).

Temperature was used to determine whether precipitation was added to storage in the snowpack or to the root zone and to calculate the volume of snowmelt to be moved from the snowpack to the root zone. Water in excess of the storage capacity of the root zone was assumed to flow to the alluvial basin either as streamflow or ground-water flow (Hearne and Dewey, 1988, p. 15).

The mountain water-yield method was used to compute water yield for uplifted areas in which secondary permeability is negligible and all discharge from the drainage basin is assumed to be in surface streams. Discharge of surface water into the alluvial basin was assumed to be by infiltration through streambed sediments on the basin side of basin-bounding faults and is called mountain-front recharge.

The mountain water-yield method uses a multiple-linear regression of mean annual water yield against mean winter precipitation and the area of drainage. The regression equation (Hearne and Dewey, 1988, p. 31, eq. 8) is

$$Q = 7.62 \times 10^{-5} A^{0.977} P^{3.596} \qquad (2)$$

where Q = mean annual water yield, in cubic feet per second (L^3/T);

A = area of the drainage basin, in square miles (L^2); and

P = mean winter precipitation, in inches (L).

Estimates of recharge using one of these methods were made for all basins in the study area.

For the Costilla Plains water budget (table 1), the change in the volume of water stored beneath the Costilla Plains was assumed to be negligible. Precipitation was estimated to average 1.0 foot per year. Precipitation on the 430,000 acres of the Costilla Plains was calculated to be 590 ft^3/s. Evapotranspiration from the Costilla Plains was assumed to depend on depth to water and land use. Three categories were considered: (1) water-course and riparian areas; (2) nonirrigated areas; and (3) irrigated areas.

Water-course and riparian areas include those along the Rio Grande from the San Luis Hills to Embudo, New Mexico, irrigation canals, stock ponds, reservoirs, and streams on the Costilla Plains. For these areas, water is at or near the land surface. For the 4,000 acres (estimated from U.S. Geological Survey topographic maps) of water-course and riparian areas in the Costilla Plains, evapotranspiration was assumed to be 4.5 feet per year. The resulting loss to the atmosphere was calculated to be 25 ft^3/s.

For other nonirrigated areas, evapotranspiration was assumed to be limited by precipitation. Precipitation from each storm event was assumed to be stored as soil moisture and returned to the atmosphere by evapotranspiration. Precipitation was estimated from isohyetal maps (National Oceanic and Atmospheric Administration, 1980) to average about 1.0 foot per year. Therefore, evapotranspiration from the estimated 340,000 acres of nonirrigated land in the Costilla Plains was calculated to be 470 ft^3/s.

For irrigated areas, evapotranspiration was estimated from irrigated acreage, average depletion, and precipitation. Total irrigated acreage of the Costilla Plains was estimated to be 84,000 acres. Precipitation on irrigated and nonirrigated acreage was estimated to be 1.0 foot per year. Therefore, precipitation on the 84,000 acres of irrigated land was calculated to be 120 ft^3/s.

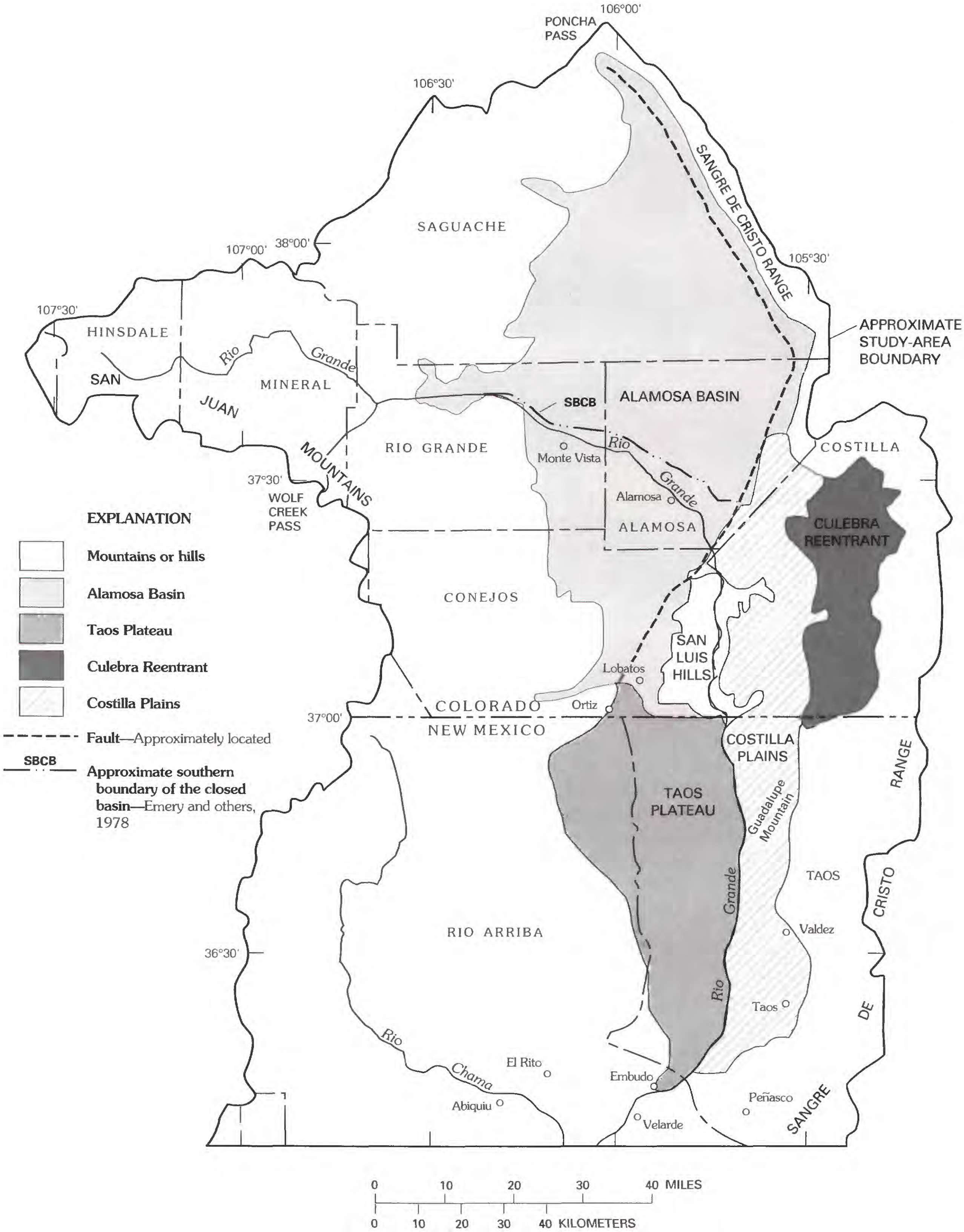


FIGURE 4.—Physiographic subdivisions and geographic features of the San Luis Basin. (Modified from Hearne and Dewey, 1988, fig. 2.)

TABLE 1.—Water budget for the Costilla Plains (1950-80) of the San Luis Basin.
[From Hearne and Dewey, 1988, table 13. All estimates are in cubic feet per second]

Flow source	Estimated flow
Inflow	
Sangre de Cristo Mountains	440
Taos Plateau	28
Precipitation on the Costilla Plains	590
Rio Grande, near Lobatos, Colorado	350
Ground-water flow past the San Luis Hills	([1])
Total inflow	1,408
Outflow	
Evapotranspiration from the Costilla Plains (Nonirrigated areas--490 (rounded). Irrigated areas--250).	740
Rio Grande, near Embudo, New Mexico	680
Total outflow	1,420

[1]Not estimated.

In addition to precipitation, irrigation withdrawals were made from surface and ground-water sources for application to irrigated areas. Irrigation depletion is the amount of water from surface-water and ground-water withdrawals that is consumed by crops or lost to the atmosphere during irrigation. A depletion rate of 1.14 feet per year was used to calculate a depletion of 130 ft^3/s for the 84,000 irrigated acres in the Costilla Plains (Hearne and Dewey, 1988, p. 40-41). Ground-water discharge at Embudo, New Mexico, is assumed to be negligible.

On the Taos Plateau for 1950-80, precipitation is estimated to exceed evapotranspiration by 28 ft^3/s. About 28 ft^3/s is estimated to flow through fractured volcanic rocks and discharge as spring flow or seepage flow to the Rio Grande.

Ground-water inflow to the Costilla Plains through and around the San Luis Hills cannot be measured directly. Inadequate definition of the transmissivity of the volcanic rocks of the San Luis Hills precludes an independent estimate of inflow using the hydraulic gradient (Hearne and Dewey, 1988, p. 40-41). "To balance the water budget, inflow should equal outflow. Ground-water inflow was calculated as the residual of the water budget to be about 10 cubic feet per second by subtracting other estimated inflows from estimated outflow. Because the flow is small relative to other items in the budget, this estimate is not accurate and was not included in table 13" [table 1 in this report] (Hearne and Dewey, 1988, p. 41).

The water budget for the Alamosa Basin (table 2) shows the estimated rates of inflow, outflow, and change in storage for 1950-80. Irrigation development is extensive only in the Alamosa Basin. Surface-water irrigation has been extensive since about 1890. Significant ground-water irrigation began about 1950. Recharge was estimated using the previously described methods. Precipitation was estimated to be 0.64 foot per year. Evapotranspiration was assumed to depend on land use and depth to water. Evapotranspiration consumes water from both precipitation and ground water. For nonirrigated areas, calculated evapotranspiration was dependent on depth to water. For nonirrigated areas, evaporation was assumed to consume ground water to meet part of the vegetation demand. Evapotranspiration from ground water in water-course and riparian areas along the Rio Grande and Conejos River was assumed to be 4.5 feet per year. Evapotranspiration from ground water in other areas where the

TABLE 2.—Water budget for the Alamosa Basin (1950-80) of the San Luis Basin.
[From Hearne and Dewey, 1988, table 17. All estimates are in cubic feet per second]

Flow source	Estimated flow
Inflow	
Sangre de Cristo Mountains	340
San Juan Mountains	2,800
Precipitation on the Alamosa Basin	1,500
Total inflow	4,640
Decrease of storage in the aquifer Alamosa Basin	87
Outflow	
Evapotranspiration from the Alamosa Basin (Nonirrigated areas--2,000. Irrigated areas--1,900)	3,900
Rio Grande, near Lobatos, Colorado	350
Ground-water flow past the San Luis Hills	([1])
Total outflow	4,250

[1]Not estimated.

depth to water was less than 2 feet was assumed to be 3.1 feet per year (69 percent of that from water courses). Similarly, evapotranspiration from ground water (table 3) was estimated for other depth-to-water zones (Hearne and Dewey, 1988, p. 43-46).

Within the irrigated areas, calculated evapotranspiration was dependent on crop type and an assumed depth to water. Evapotranspiration includes consumptive use required by the crop. Of the 710,000 acres irrigated in the Alamosa Basin, 320,000 acres were harvested; 210,000 acres (30 percent) were assumed to be nonirrigated pasture; and the remaining 180,000 acres were assumed to be irrigated pasture. Consumptive use for four major crops--alfalfa, grass, spring grains, and potatoes--was estimated. The consumptive use for each crop was assumed to be supplied by a combination of irrigation, shallow ground water, and precipitation. Table 4 shows the crop types, area of each crop, consumptive use, and evapotranspiration for irrigated lands. All precipitation on irrigated areas was assumed to be returned to the atmosphere by evapotranspiration.

The Rio Grande flows through the Alamosa Basin from Del Norte, Colorado, to the gap in the San Luis Hills. Flow in the Rio Grande near Del Norte, Colorado, is included in the estimated inflow from the San Juan Mountains. Average outflow in the Rio Grande near Lobatos, Colorado, averaged 350 ft^3/s for 1950-80.

The decrease in the volume of water stored beneath the Alamosa Basin from 1950 through 1969, estimated from an analog model simulation, was 730,000 acre-feet; 70 percent was from the unconfined aquifer, and 30 percent was from the confined aquifer (Emery and others, 1975, table 5). From 1970 to 1980, the decrease in storage in the unconfined aquifer, estimated from change in hydraulic heads, was 860,000 acre-feet (Crouch, 1985). The storage decrease in the unconfined aquifer was assumed to be 70 percent of the total. Total storage decrease for both the unconfined and confined aquifers was about 1,200,000 acre-feet. From 1950 to 1980, storage was estimated to decrease about 1,900,000 acre-feet based on the estimates presented previously (Hearne and Dewey, 1988, p. 50).

TABLE 3.—Calculated evapotranspiration for nonirrigated areas in the Alamosa Basin.

[From Hearne and Dewey, 1988, p. 45. ft/yr, feet per year; ft³/s, cubic feet per second]

Depth-to-water zone	Area (acres)	Evapotranspiration from ground water (ft/yr)	Evapotranspiration from ground water (percent)[1]	Evapotranspiration from precipitation (percent)[2]	Evapotranspiration from precipitation (ft/yr)	Total evapotranspiration (ft/yr)	Total evapotranspiration (ft^3/s)
Water course and riparian	30,000	4.5	100	0	0.0	4.5	190
Less than 2 feet	150,000	3.1	69	31	.20	3.3	680
2 to 4 feet	85,000	1.9	42	58	.37	2.3	270
4 to 6 feet	82,000	1.2	27	73	.47	1.7	190
6 to 12 feet	100,000	.40	9	91	.58	.98	140
Greater than 12 feet	590,000	.0	0	100	.64	.64	520
Total (rounded)	1,000,000						2,000

[1]Percent of water-course evapotranspiration.
[2]Percent of precipitation.

The approximate areal extent of water-level changes from December 1969 to January 1980 in the unconfined valley-fill aquifer system of the San Luis Basin is shown in a water-level-change map (fig. 5). According to Crouch (1985, sheet 1), "There are several factors that may have contributed to the general water-level decline in the San Luis Valley during the 1970's. These include an increase in ground-water withdrawals from the unconfined aquifer for irrigation of an expanded acreage and a decrease in surface-water diversion with a resultant decrease in ground-water recharge."

Annual ground-water withdrawals for 1940-79 vary from 3,000 acre-feet (less than 1 percent) of total irrigation water used in 1941 to greater than 981,000 acre-feet (66 percent) in 1977, an atypical year for surface-water diversions. Ground-water withdrawals and surface-water diversions for 1940-79 are shown in figure 6.

A preliminary analysis of the Alamosa Basin using a two-dimensional cross-sectional model concluded that (1) a seven-layer model, representing 3,200 feet of saturated thickness, could accurately simulate the behavior of the flow system, and (2) the 1950 condition was approximately stable and would be a satisfactory initial condition. Subsequently, a seven-layer, three-dimensional areal model was constructed to represent the aquifer system in the Alamosa Basin (Hearne and Dewey, 1988). Values of aquifer characteristics were assumed or estimated from the work of previous investigators. Recharge and discharge were defined to represent the changes since 1950 in ground-water withdrawals, return flow, salvaged evapotranspiration, and streamflow capture. Hydrologically consistent modifications to ground-water withdrawals resulted in simulated head changes approximating the measured data--water-level declines within 6 feet or less for 1950-69 and water-level declines within about 5 feet of measured values for 1970-79. The sources of the 535 ft^3/s of water withdrawn from the aquifer system in 1980 were 80 percent from salvaged evapotranspiration, 14 percent from storage in the aquifer, and 6 percent from streamflow capture (Hearne and Dewey, 1988, p. 111).

Sensitivity tests on the three-dimensional model indicated that simulated 1970-79 hydraulic-head declines were most sensitive to ground-water withdrawals. However, for most of the simulations, salvaged evapotranspiration was the major source (69 to 82 percent) of ground-water withdrawals. The simulations implied that evapotranspiration of ground water does occur in irrigated areas and that evapotranspiration has decreased as hydraulic head has declined (Hearne and Dewey, 1988, p. 111).

ALBUQUERQUE-BELEN BASIN

The Albuquerque-Belen Basin in central New Mexico (fig. 7) contains the city of Albuquerque and surrounding metropolitan area. This basin was selected for detailed study because water use has increased significantly, primary land use has changed from agricultural to urban, and wells are being drilled deeper and farther from the Rio Grande as the metropolitan area expands.

TABLE 4.—Crop type, consumptive use, and evapotranspiration for irrigated areas in the Alamosa Basin.
[From Hearne and Dewey, 1988, p. 48. ft/yr, feet per year; ft^3/s, cubic feet per second]

Crop type	Area (acres)	Consumptive use (ft/yr)	Evapotranspiration (ft/yr)	Evapotranspiration (ft^3/s)
Alfalfa	99,000	2.2	2.4	330
Other hay	91,000	1.8	2.0	250
Grain	96,000	1.2	1.6	210
Potatoes	34,000	1.4	1.8	85
Irrigated pasture	180,000	1.8	2.0	500
Nonirrigated pasture	210,000	([1])	1.7	490
Total (rounded)	710,000			1,900

[1]Not estimated separately.

GEOLOGY

The description of the structure and geology of the Albuquerque-Belen Basin is excerpted from Kernodle and others (1987, p. 12, 17). The structural basin is 35 to 40 miles in width and about 100 miles in length. The basin is bounded on the east and west sides by faults. Total fault displacement along the east side of the Rio Grande rift is 5,000 to 6,000 feet greater than that along the west side. Sandia and Hubbell Springs faults (fig. 7) separate the basin from the Sandia, Manzanita, and Manzano Uplifts on the east; whereas, numerous faults with less displacement separate the basin from Sierra Lucero, the Ladron Mountains, and the San Juan Basin on the west. These faults, having elevated benches of pre-Santa Fe Group bedrock near or at the present-day land surface, mark the east and west boundaries of the regional ground-water system in the Albuquerque-Belen Basin. The southern end of the basin is terminated by converging faults and bedrock highs at the San Acacia constriction. Flood-plain alluvium and a thin layer of Santa Fe Group deposits are present within the constriction, allowing some ground-water outflow southward to the Socorro Basin. The northern end of the Albuquerque-Belen Basin, as defined in this investigation, is at the southern and southeastern edge of the Jemez volcanic complex and along the southern and southwestern edge of Santa Ana Mesa. The central part of the Albuquerque-Belen Basin has been downfaulted in relation to the bordering highlands. Material derived by erosion of the highlands and sediment transported into the basin by the Rio Grande and other streams have filled the graben to a thickness locally in excess of 18,000 feet.

The areal distribution of lithologic sediment types for the total saturated depth analyzed is 20 to 50 percent clay, silt, mudstone, shale, or caliche in a band north to south throughout the central part of the basin (Kaehler, 1990) (fig. 8). Sediments containing more than 50 percent sand, gravel, cobbles, or boulders are more prevalent in the Albuquerque area and to the north. Sediments containing more than 50 percent clay, silt, mudstone, shale, and caliche are found along the western side of the basin adjacent to Albuquerque.

The areal distribution of saturated lithologic types for 100-foot-thick intervals to a depth of about 600 feet is basically the same as that for the total depth. In the interval from 600 to 900 feet below the water table, the coarse-grained sediments are found around Albuquerque and areas to the west and north; fine-grained sediments are found in the southern part of the basin. Generally, coarse-grained sediment is the predominant type to a depth of 600 feet below the water table. Below 600 feet, fine-grained sediments, or occasionally fine-grained mixed sediments, are predominant (Kaehler, 1990).

Analyses of borehole-geophysical logs suggest that the basin fill consists of sand lenses alternating with clay or silt lenses. The layering appears to be random; individual lenses cannot be traced from well to well. The clay lenses have a maximum thickness of 45 feet and are more common on the eastern side of the basin.

Analyses of gravity data (Birch 1980a, p. 19) show that the Albuquerque-Belen Basin is separated from the Santo Domingo Basin to the north by Neogene sediments less than 3,300 feet thick, defined by Birch (1980a, p. 5) as the upper Tertiary Santa Fe Group and Quaternary sediments. In most of the Albuquerque-Belen Basin the Neogene-sediment thickness is about 4,900 feet. A north-trending zone of Neogene sediments with a thickness of 6,500 to 8,200 feet (Birch, 1980a, p. 19) is present on the east side of the basin. In the southern Albuquerque-Belen Basin, the depth to Precambrian rocks decreases from 9,800 feet to near land surface north of the constriction between the Albuquerque-Belen and Socorro Basins (Birch, 1980a, fig. 22).

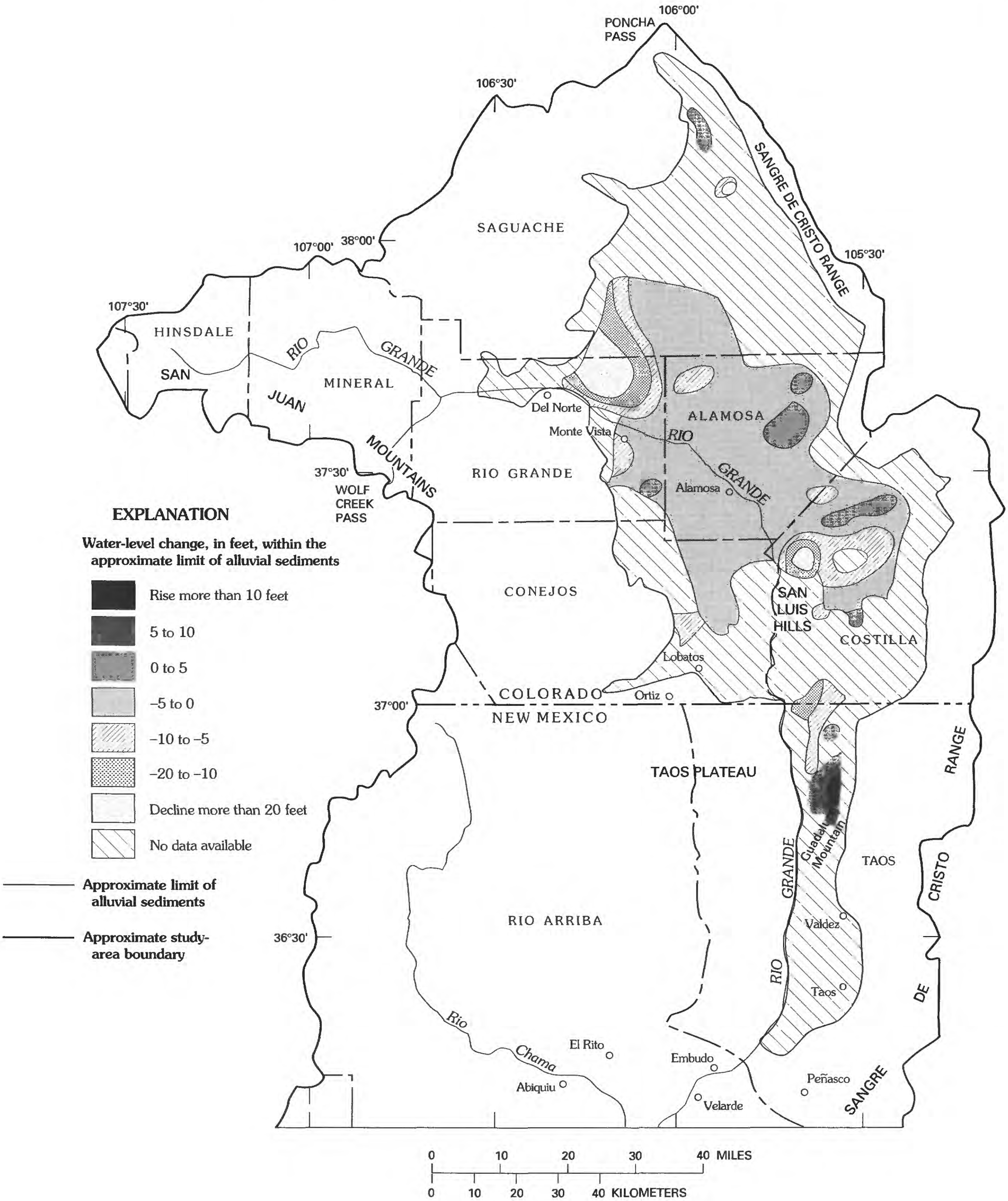


FIGURE 5.—Ground-water-level changes in the unconsolidated, unconfined valley-fill aquifer system from December 1969 to January 1980, San Luis Basin. (Modified from Crouch, 1985.)

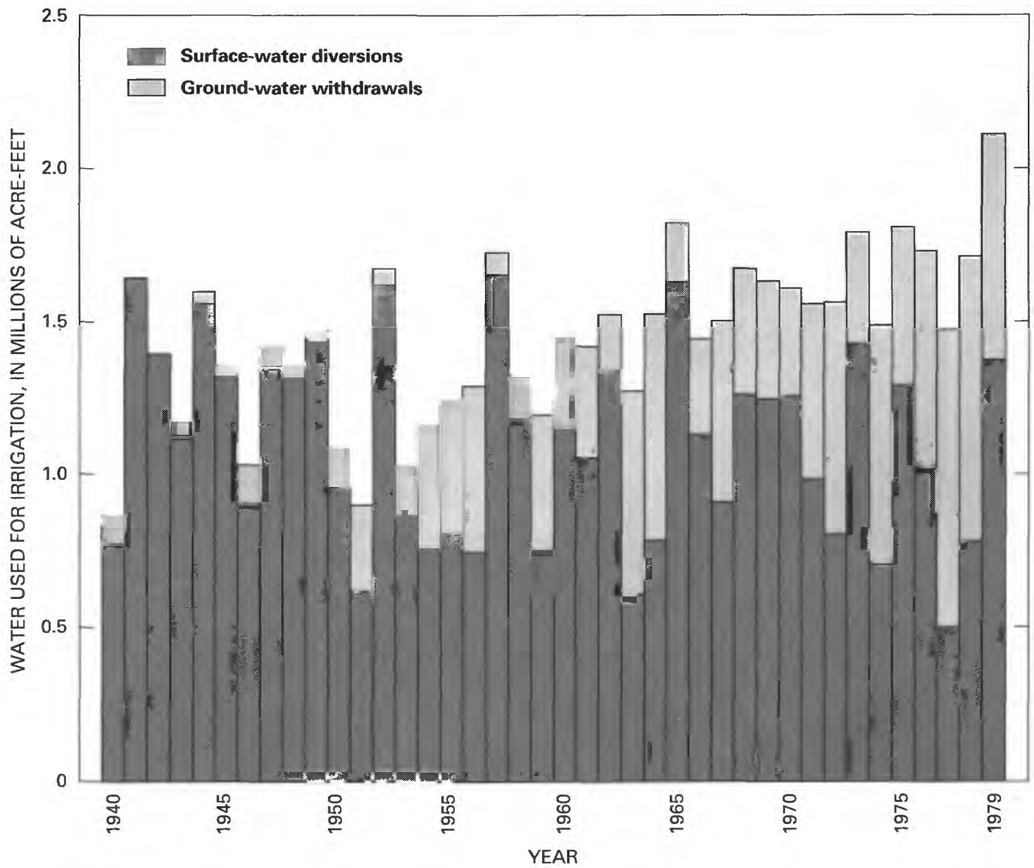


FIGURE 6.—Ground-water withdrawals and surface-water diversions for irrigation in the San Luis Basin. (From Hearne and Dewey, 1988, fig. 23.)

Analyses of surface-resistivity data resulting from surveys west of the volcanoes that are west of Albuquerque produced estimates of porosity ranging from 11 to 22 percent at a depth of 9,500 feet (Jiracek, 1982, p. 46). Porosity above this depth was not estimated because of lack of confidence in values of in situ resistivity of the formation water.

Southwest of the volcanoes west of Albuquerque (fig. 7) and just north of Interstate 40, bipole-dipole mapping indicated a northwest- to southeast-oriented ridge of high resistivity. Dipole-dipole mapping indicated a highly resistive zone, possibly overlain by a less resistive zone (Jiracek, 1982, p. 54). Conductive saline waters may move over Cretaceous basement rock due to the eastward hydraulic gradient or upward movement of deep saline water along faults. Depth to the top of this horstlike feature is from 660 to 820 feet. A zone of increased temperature gradients corresponds to the suspected horst (Jiracek, 1982, p. 66). The presence of increased temperature gradients in the area supports the possibility that deep geothermal water could be flowing over an uplifted bedrock mass.

A surface-resistivity survey was conducted at the southern end of the Albuquerque-Belen Basin. The survey indicated that the water table is at a depth of 38 feet, ground water has an equivalent sodium chloride concentration of 1,500 milligrams per liter, and the aquifer matrix has a porosity of 28 to 43 percent to a depth of about 154 feet. Between 154 and 200 feet below land surface, the porosity of the aquifer matrix is less than that estimated for the overlying sediments, and ground water is estimated to contain 5,000 milligrams per liter as equivalent sodium chloride. From 200 to about 1,300 feet below land surface, porosity probably is less than that of overlying sediments, and the salinity of ground water, expressed as sodium chloride, is about 8,000 milligrams per liter. Basement rock, possibly Paleozoic in age, is below 1,300 feet (Jiracek, 1982, p. 84-85).

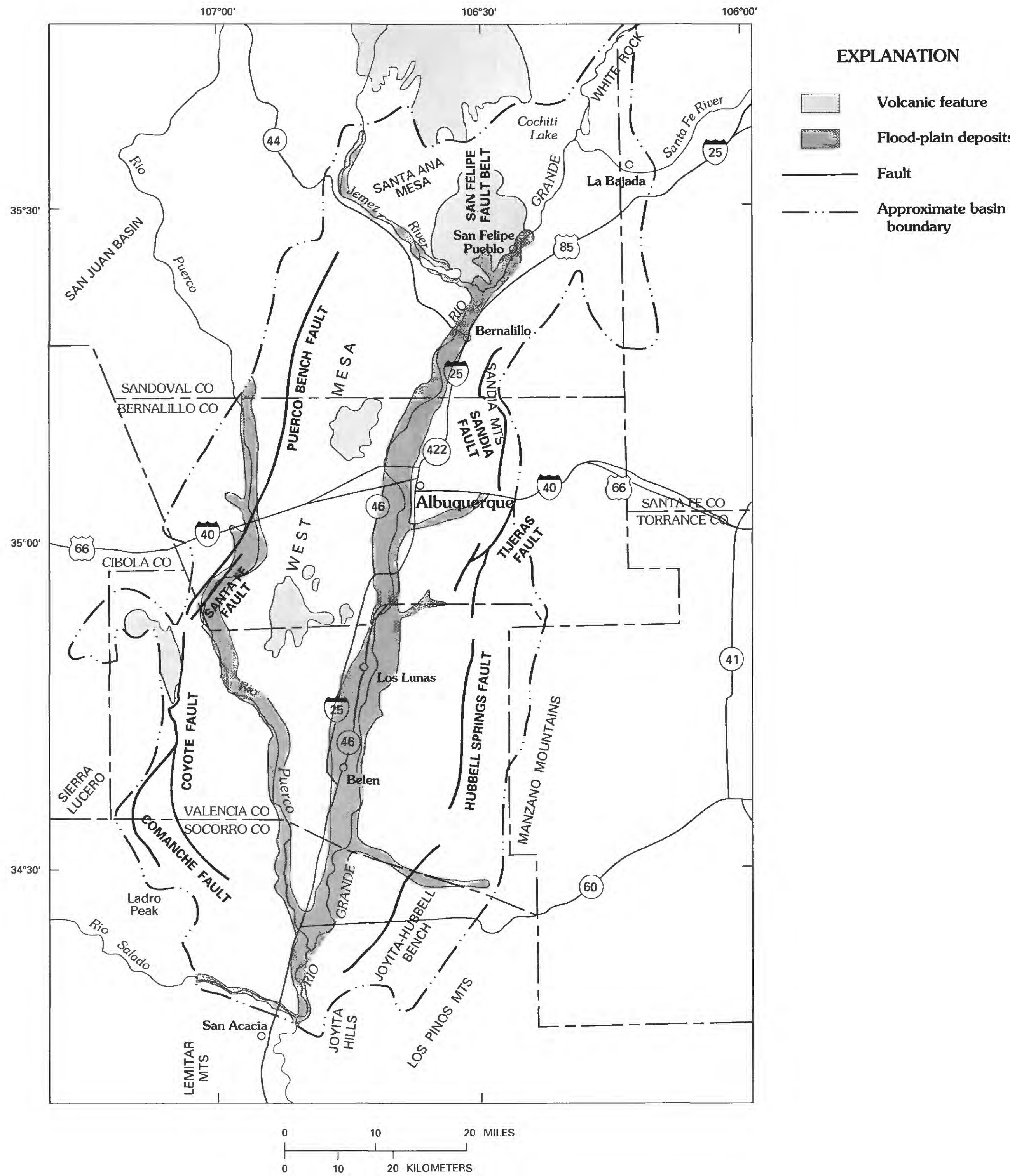


FIGURE 7.—Principal geographic and geologic features of the Albuquerque-Belen Basin. (Modified from Kernodle and Scott, 1986, fig. 3.)

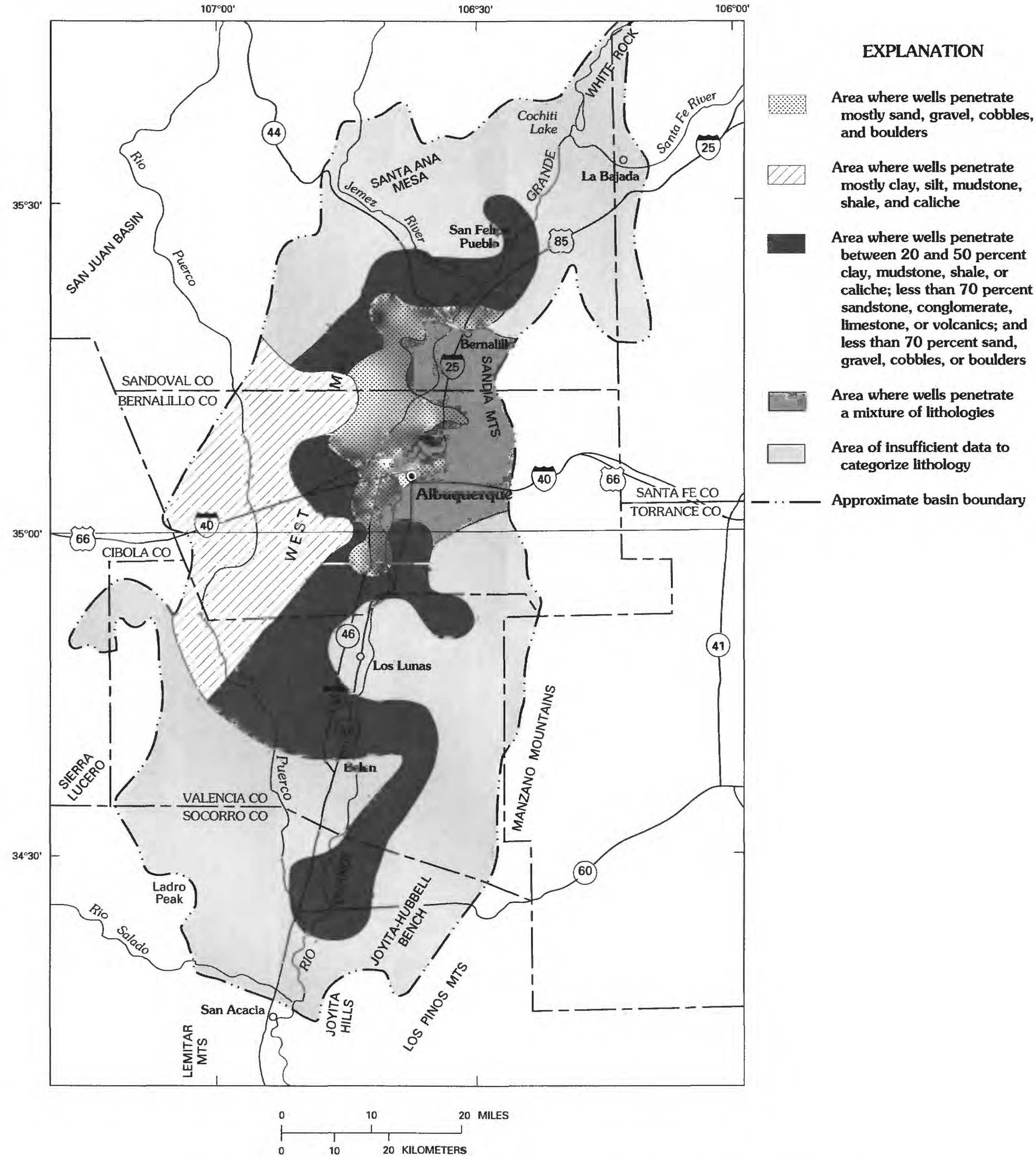


FIGURE 8.—Lithologic zones in the Albuquerque-Belen Basin. (Modified from Kaehler, 1990, fig. 5.)

GEOCHEMISTRY

Surface-water quality in the Albuquerque-Belen Basin is variable depending on the stream. Average specific conductance of water from September 1969 to August 1982 in the Jemez River was 1,283 microsiemens (microsiemens per centimeter at 25 degrees Celsius); in the Rio Puerco, near the confluence with the Rio Grande, it was 2,047 microsiemens; and in the Rio Salado, in the southwestern part of the basin, it was 1,670 microsiemens (Anderholm, 1988, p. 32). All of these streams empty into the Rio Grande within the Albuquerque-Belen Basin. For the same period, the specific conductance in the Rio Grande in the northern part of the basin was 358 microsiemens; whereas, downstream in the southern part of the basin it was 752 microsiemens. The downstream increase is attributed to solute concentration through evapotranspiration, tributary inflow, and return flow of excess irrigation water (Anderholm, 1988, p. 33).

Ground-water quality in the basin also is variable. The southeastern part of the basin contains water with calcium and sulfate as primary ions; specific conductance ranges from 1,000 to 1,200 microsiemens. Calcium is the dominant cation and bicarbonate generally is the dominant anion along the east side of the basin where ground-water quality is affected primarily by recharge of runoff from the high mountains. Ground water from the mountains to just east of the Rio Grande has a specific conductance of less than 400 microsiemens. Specific conductance of ground water in the flood plain of the Rio Grande south of Los Lunas ranges from 281 to 2,170 microsiemens (Anderholm, 1988, p. 59). The increased specific conductance probably is due to mixing of excess irrigation-return water with resident water in the aquifer system. Specific conductance of water west of the Rio Grande flood plain but east of the vicinity of the Rio Puerco ranges from about 500 to 900 microsiemens.

On the western side of the southern Albuquerque-Belen Basin, sodium chloride brine, containing specific conductance as large as 91,000 microsiemens, enters the basin-fill aquifer system. The brine then flows south and east, mixing with ground water in the basin. Specific conductance of the water in the general area of mixing varies from about 400 to 9,000 microsiemens because of different mixing ratios of the inflowing brine and existing ground water. In general, the specific conductance of the mixed water decreases as it moves eastward because of dilution of the brine with less saline recharge water from the east. The mixed water in this area dissolves gypsum as the water moves through the aquifer system, as indicated by a general increase in percentages of calcium and sulfate in the mixed water in comparison with percentages of calcium and sulfate in the brine. In the southwestern part of the basin, ground water has large chloride concentrations. These elevated chloride concentrations are probably due to upward movement of deep circulation water. The upward movement probably is caused by a constriction of ground-water flow in the extreme southern end of the basin (Anderholm, 1988, p. 77).

The overall ground-water quality in the northern part of the basin is a result of mixing of waters from the Jemez geothermal reservoir to the north and ground water in the basin-fill aquifer system (Anderholm, 1988, p. 101). Concentrations of chloride, as large as 1,300 milligrams per liter (mg/L), and of silica, as large as 91 mg/L, are found. These constituents generally are indicators of ground-water flow from the Jemez geothermal reservoir.

Sodium is the dominant cation in ground water west of Albuquerque. Ion exchange of calcium and magnesium for sodium is the dominant process affecting the ground water. Fine-grained sediments, indicated on drillers' and geophysical logs, provide the medium and constituents for the exchange process (Anderholm, 1988, p. 101).

GROUND-WATER FLOW SYSTEM

The main components in the water budget in the Albuquerque-Belen Basin are surface-water inflow and outflow in the Rio Grande. Inflow is derived from tributary streams, ground-water recharge from infiltrating tributary streams, mountain-front recharge to ground water, and ground-water inflow from the Santo Domingo Basin to the north. Outflow includes ground-water outflow to the Socorro Basin to the south, withdrawal of ground water from wells, ground-water and surface-water discharge to the flood plain of the Rio Grande, and evapotranspiration (Kernodle and others, 1987, p. 6). The surface-water system consists of the Rio Grande and its tributaries, irrigation canals, drainage ditches, and water that periodically flows in arroyos or washes, or is impounded in flood-retention reservoirs. The Rio Grande is a through-flowing river with an average steady-state inflow to the basin of 1,150 ft^3/s and an average outflow of 924 ft^3/s from 1948 to 1960. The difference of about 226 ft^3/s of water was only a part of the water the river lost in its passage through the basin. Also lost from the steady-state surface-water system were average tributary inflows of about 110 ft^3/s for the same period. The majority of this total net loss of 336 ft^3/s probably was caused by evapotranspiration in the flood plain (Kernodle and Scott, 1986, p. 11). However, since 1960 in the Albuquerque area an increasing proportion of evapotranspiration is being captured by the ground-water cone of depression associated with ground-water withdrawals (Kernodle and others, 1987, p. 6).

Evaporation accounts for a loss of about 5 feet per year in areas of exposed water. Evapotranspiration in the flood plain, whether from agricultural or riparian vegetation, is about 3 feet per year. About 0.5 foot of precipitation per year helps reduce evapotranspiration, but the net loss for the flood plain is estimated to be 428 to 539 ft^3/s (J.D. Dewey, Hydrologist, U.S. Geological Survey, written commun., 1983). The difference between the flood-plain loss and the surface-water loss (336 ft^3/s) is made up by loss from ground-water storage (Kernodle and others, 1987, p. 8).

The Albuquerque-Belen Basin ground-water system can be divided into two subsystems. The first subsystem is in and near the area of the Rio Grande flood plain; the second is the basin ground-water subsystem adjacent to and under the Rio Grande flood-plain subsystem (Kernodle and others, 1987, p. 8). The first ground-water subsystem (fig. 9) consists of ground-water flow within the flood-plain alluvium of the river valley, which interconnects the Rio Grande, canals, drains, and evapotranspiration. In this subsystem, ground water flows because of hydraulic-head differences imposed by surface-water bodies, evapotranspiration, and recharge of excess irrigation water. Although a large volume of ground water moves through the flood-plain alluvium, the hydraulic heads and gradient remain unchanged from one year to the next, except in the vicinity of increasing ground-water withdrawals. Seasonal hydraulic-head changes seldom exceed 5 feet (Kernodle and others, 1987, p. 12).

The second basin ground-water subsystem (fig. 9) operates outside of, but is hydraulically connected to, the flood-plain alluvium. Two forms of ground-water recharge occur outside of the flood plain: (1) tributary recharge from streams as they traverse basin fill between the mountains and the river; and (2) mountain-front recharge from flows that infiltrate almost immediately after entering the basin from virtually impervious bedrock that encircles the basin-fill deposits. Tributary and mountain-front recharge totals about 180 ft^3/s and maintains high ground-water levels around most of the margin of the basin. Ground water then flows downgradient toward the axis of the basin, not necessarily toward the Rio Grande or its flood plain. As the flow approaches the axis of the basin, the flow paths curve and continue southward to the lower end of the basin (Kernodle and others, 1987, p. 12).

Ground water flows vertically as well as horizontally. In areas of recharge, some ground water moves into deeper parts of the aquifer system and follows a generally more direct route to the basin's ground-water discharge area. Although the shallow ground-water system includes and is substantially affected by the flood-plain alluvium of the Rio Grande, that effect decreases rapidly with depth (Kernodle and others, 1987, p. 12).

Diversion of surface water for irrigation was the earliest modification of the natural water system in the Albuquerque-Belen Basin. Irrigation continued, and the volume of diverted

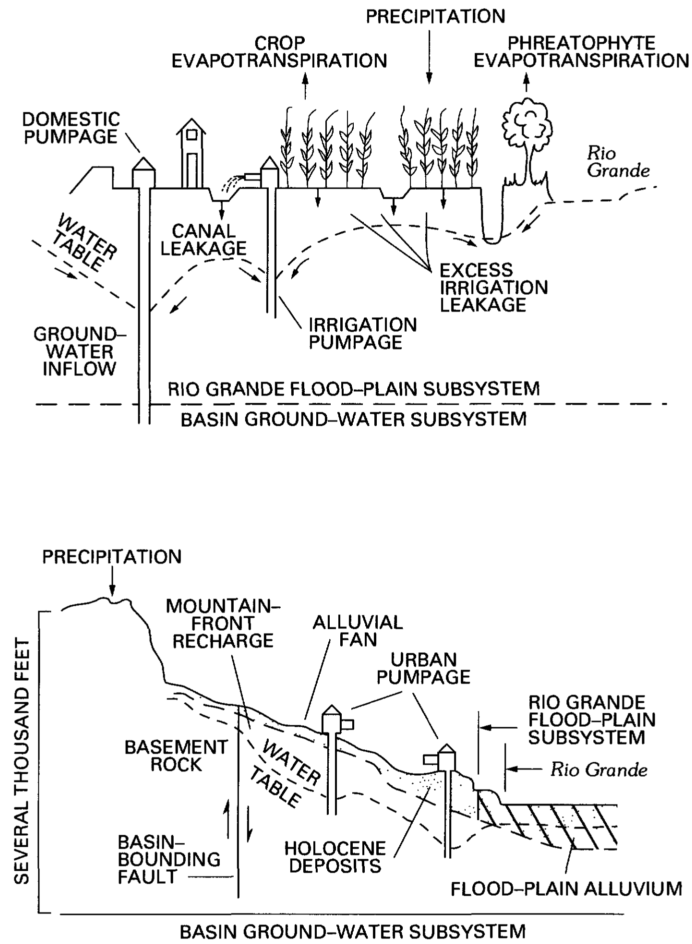


FIGURE 9.—Generalized ground-water subsystems in open basins.

water increased until drains to control waterlogging and salt accumulation in the soil became necessary in the 1930's (Kernodle and others, 1987, p. 19).

Until the mid-1940's Albuquerque's municipal water needs were met by ground-water withdrawals from wells completed in the flood-plain alluvium. The effect on the natural water system was insignificant in comparison to the effect of irrigation. Dry weather and decreased streamflow in the 1950's forced an increased dependence on ground water for irrigation. In addition, Albuquerque's population began to increase rapidly and municipal ground-water withdrawals increased. Legal regulations imposed in 1959 made construction of municipal wells outside of the flood plain increasingly attractive. The area of greatest ground-water stress began to shift away from the flood plain. In the area east of the flood plain, municipal withdrawals caused a decline in ground-water levels of about 20 feet by 1960 and an additional 60 to 80 feet by 1980. Since the 1980's, Albuquerque's municipal water needs have been met by ground-water withdrawals matched by the purchase and retirement of surface-water rights for water removed from the Rio Grande (Kernodle and others, 1987, p. 19-20).

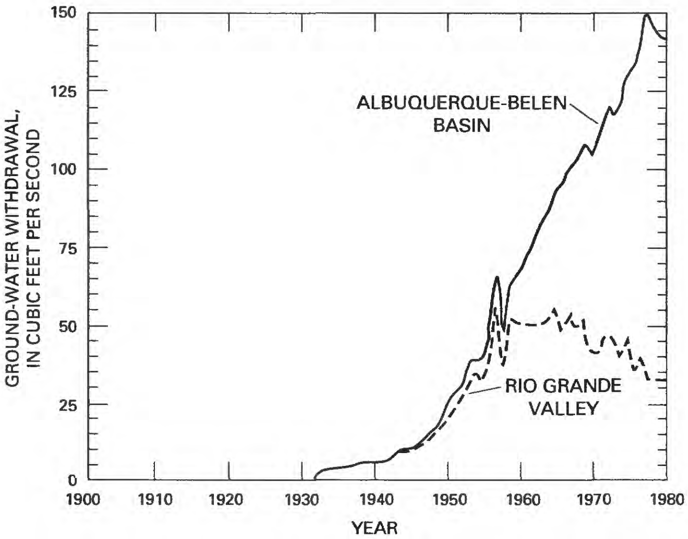


FIGURE 10.—Ground-water withdrawals in the Albuquerque-Belen Basin and in the Rio Grande valley, 1907-79. (From Kernodle and others, 1987, fig. 13.)

The trend of total ground-water withdrawals from 1907 to 1979 in the Albuquerque-Belen Basin and in the Rio Grande valley is shown in figure 10. The earliest documented ground-water withdrawal began in 1907 within the Rio Grande valley. Withdrawal remained at less than 0.17 ft^3/s until 1932, when the City of Albuquerque constructed the Main Plant well field, which supplied all of the city's water needs until 1948. The city's rapid population increase after the late 1940's necessitated the construction of five new well fields from 1948 to 1956. Ground-water withdrawal for all uses increased from about 17.3 ft^3/s during 1940 to 65.6 ft^3/s during 1956. Prior to 1956, ground water was produced mostly from wells in or near the Rio Grande flood plain (Kernodle and others, 1987, p. 20). After 1956, wells were constructed east of the Rio Grande valley in response to growing demand in that direction. Since about 1970, wells have been drilled west of the Rio Grande valley.

Ground-water withdrawal from the area east of the flood plain did not become significant until after 1959. The increase in ground-water withdrawal in the Albuquerque area for 1956-59 and 1976-79 is illustrated in figures 11 and 12, respectively.

A seven-layer, three-dimensional ground-water flow model was constructed to represent the basin geometry and flow system (Kernodle and others, 1987). The grid spacing was finer in the Albuquerque area to achieve greater resolution in the distribution of stress and observed head response. Six model layers represented the upper 6,000 feet of saturated basin-fill aquifer, where present. The top layer represented the upper 200 feet of saturated thickness. The surface-water system in the flood plain of the Rio Grande was assumed to maintain a constant hydraulic head in the immediately underlying alluvial deposits.

The initial phase of modeling (Kernodle and Scott, 1986) used estimated rates of mountain-front recharge and tributary channel losses for ground-water recharge. The process of calibration of the steady-state model was used to refine estimates of hydraulic conductivity and to test the validity of assumed boundary conditions (Kernodle and Scott, 1986, p. 33). The mean absolute difference between measured and simulated pre-1961 water levels was 14.6 feet. The second phase of the modeling process included the simulation of ground-water withdrawals from 1907 to 1979 (Kernodle and others, 1987). Because the hydraulic-head data were sparse for dates after 1961, the simulation to 1979 was considered to be a projection.

Ground-water declines for three simulated aquifer-system layers were the response to annual ground-water withdrawals in the Albuquerque-Belen Basin. Withdrawals increased from about 61.0 ft^3/s in 1959 to 106 ft^3/s in 1969. The total ground-water withdrawal has continued to increase at a nearly constant average rate since 1969 (Kernodle and others, 1987, p. 24). Simulated declines of as much as 60 feet are mainly east of and in the Rio Grande valley in the top 200 feet of the basin-fill aquifer system. In the area influenced by deeper wells drilled east of the Rio Grande valley and into the mesa west of the valley, in the layer simulating the aquifer from 200 to 600 feet below land surface, simulated declines are as much as 60 feet east of the river and 95 feet west of the river. Simulated hydraulic-head declines in the layer of the aquifer system from 650 to 1,325 feet below land surface are about 35 feet east of the river and 5 feet to the west. The magnitude of the drawdown is less because of fewer wells in this modeled layer, but the areal extent of the drawdown has expanded, perhaps reflecting a smaller storage value (Kernodle and others, 1987, p. 35).

One of the objectives of the model was to assess the effects of ground-water withdrawals on the combined ground-water and surface-water system in the Rio Grande flood plain (flood-plain system). At any selected time after 1950 about 25 percent of water withdrawn from the aquifer outside of the flood plain is derived from aquifer storage. The remaining 75 percent is obtained by depletion of flow in the Rio Grande or salvage of evapotranspiration loss, or is induced inflow from the Santo Domingo Basin (Kernodle and others, 1987, p. 59).

Water budgets for the Albuquerque-Belen Basin are presented in table 5 for 1960-61 and 1976-79. For 1976-79, 68 percent of all ground-water withdrawals from outside the flood plain are supplied by streamflow depletion or salvaged evapotranspiration in the flood plain; 25 percent are from aquifer storage; and 7 percent are induced ground-water underflow from the Santo Domingo Basin. Comparison of the two periods indicates an increase in the relative importance of induced flow from the flood-plain systems. Of lesser magnitude but also increasing significantly is the proportion of induced ground-water flow from the Santo Domingo Basin (Kernodle and others, 1987, p. 69).

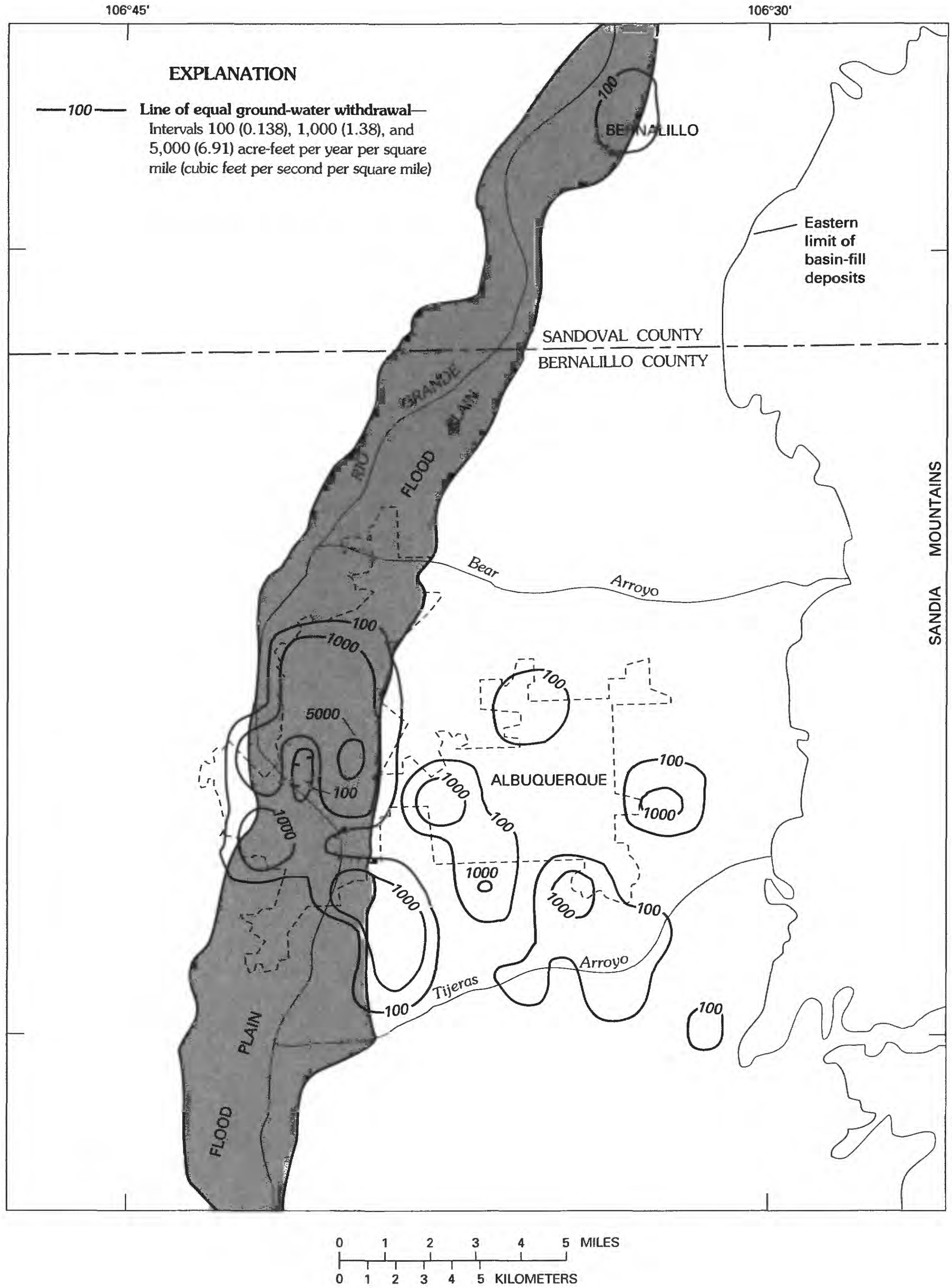


FIGURE 11.—Average ground-water withdrawal in the Albuquerque area, 1956-59. (From Kernodle and others, 1987, fig. 14.)

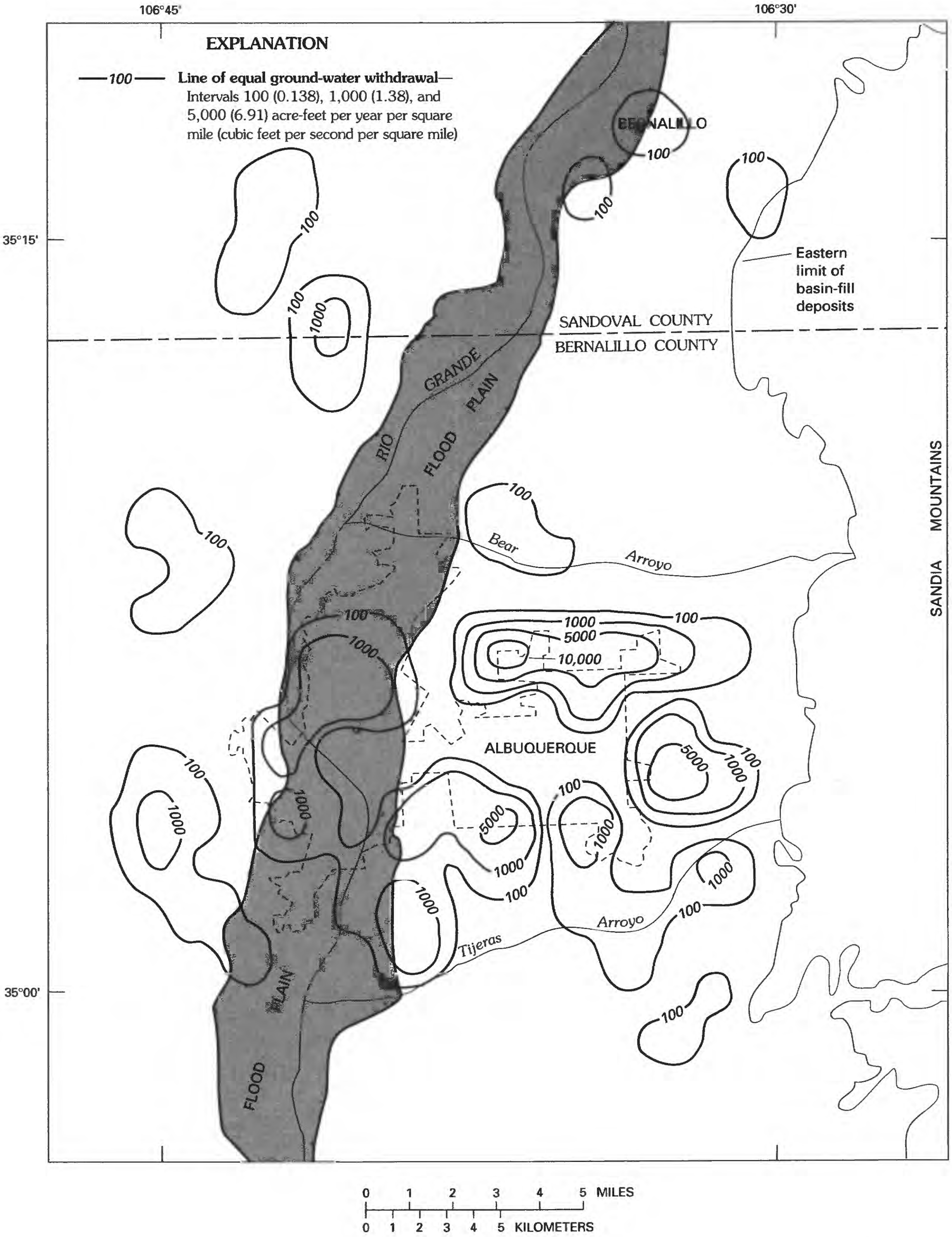


FIGURE 12.—Average ground-water withdrawal in the Albuquerque area, 1976-79. (From Kernodle and others, 1987, fig. 15.)

TABLE 5.—Water budget for the Albuquerque-Belen Basin, 1960-61 and 1976-79.

[Modified from Kernodle and others, 1987. All values are in cubic feet per second. Total ground-water withdrawal (64 cubic feet per second for 1960-61, 138 cubic feet per second for 1976-79) has been itemized as to source of withdrawn water. --, not applicable]

Budget component	1960-61 Inflow	1960-61 Outflow or loss	1976-79 Inflow	1976-79 Outflow or loss
Rio Grande main stem	1,152	924	1,222	1,040
Rio Grande tributaries (surface flow)	111	--	111	--
Ground water	80	18	86	18
Tributary and mountain-front recharge	178	--	178	--
Evapotranspiration	--	428-539	--	428-539
Ground-water withdrawal:				
Intercepted ground-water discharge to the flood-plain system	--	30	--	50
Induced recharge from the flood-plain system	--	15	--	44
Induced inflow from Santo Domingo Basin[1]	--	3	--	10
Depletion in aquifer storage[2]	--	15	--	34
Total	1,521	1,433-1,544	1,597	1,624-1,735

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

SOCORRO AND LA JENCIA BASINS

Anderholm (1987) studied the hydrogeology and geochemistry of the Socorro and La Jencia Basins (fig. 1). These basins were selected for study because geothermal resources in the Socorro Basin could have an influence on the ground-water flow system and on the chemistry of ground water in the basin. The La Jencia Basin is hydraulically connected to the Socorro Basin and offers a geohydrologic contrast to the Socorro Basin.

HYDROLOGY

Net Rio Grande streamflow depletion from San Acacia to San Marcial is about 98 ft^3/s annually for 1960-87. There is a loss in flow for the Rio Grande in this reach, but at the same time a gain in flow occurs in the adjacent conveyance channel (Anderholm, 1987, p. 46).

The principal aquifer system in the Socorro and La Jencia Basins (fig. 13) is composed of the Quaternary and Tertiary Santa Fe Group (Popotosa and Sierra Ladrones Formations)

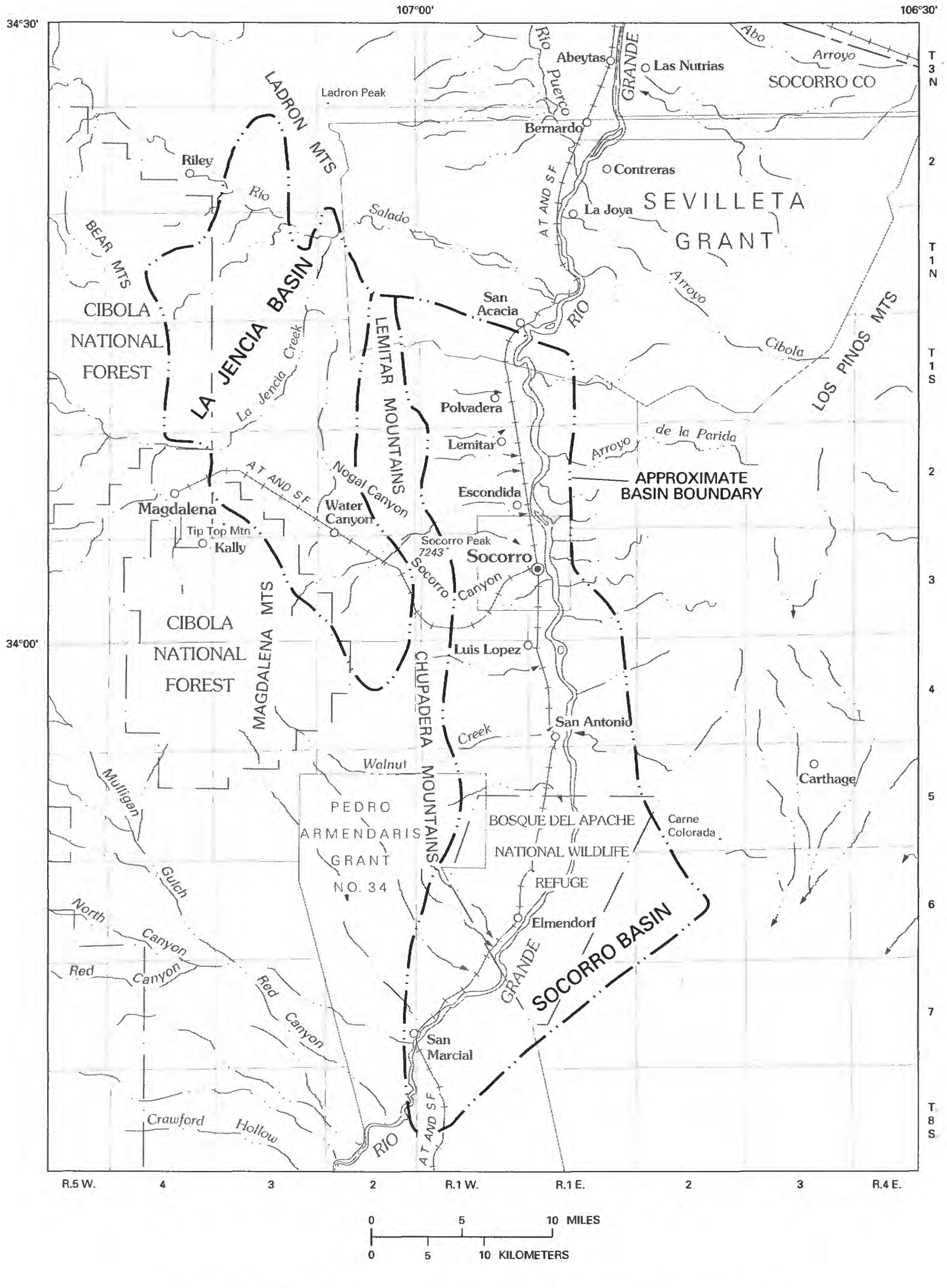


FIGURE 13.—Cultural and geographic features of the Socorro and La Jencia Basins.

and Quaternary deposits. Most wells in Socorro and La Jencia Basins derive water from the Sierra Ladrones Formation. The upper part of the Popotosa Formation is a confining unit consisting of playa deposits and mudstone. The remainder of the Popotosa Formation constitutes the lower part of the aquifer system (Anderholm, 1987, p. 18 and 20).

Irrigation in the Rio Grande valley of the Socorro Basin was practiced before the 1600's (Yeo, 1928, p. 8). The capacity of the irrigation ditches in 1896 was 294 ft^3/s and the area irrigated was 5,700 acres. In 1928, the capacity of the ditches was 331 ft^3/s and the total irrigated acreage was 10,060 acres (Yeo, 1928, p. 9). By the early 1900's about 40,000 acres of the irrigable land had become waterlogged as a result of the infiltration of excess irrigation water (Bloodgood, 1930, p. 48-52). The rising water levels also resulted in the concentration of salts near the ground surface.

Ground-water inflow and outflow cannot be calculated because information about cross-sectional area, hydraulic gradient, and hydraulic conductivity are lacking (Anderholm, 1987, p. 46). Ground-water inflow occurs from the Albuquerque-Belen Basin north of the Socorro Basin near San Acacia, from La Jencia Basin along the west margin of the Socorro Basin, and from the Jornada del Muerto Basin along the southeast margin of the Socorro Basin. Anderholm (1987, p. 55) calculated a water budget for the Socorro Basin using ground-water inflow less ground-water outflow as the balancing factor in the budget. The budget shows that about 73 ft^3/s is the most probable value for net ground-water inflow less ground-water outflow.

Calculated mountain-front recharge for the east side of the Socorro Basin is about 2.21 ft^3/s using a method documented in Hearne and Dewey (1988). Mountain-front recharge for the Socorro Peak-Lemitar Mountains is 0.58 ft^3/s; one-half of this amount is assumed to recharge the Socorro Basin, and one-half the La Jencia Basin. Recharge from the Chupadera Mountains is about 0.51 ft^3/s; one-half is assumed to recharge the Socorro Basin and one-half the area between the Magdalena and Chupadera Mountains. Total recharge to the Socorro Basin is about 2.76 ft^3/s (Anderholm, 1987, p. 49). Ground water flows from La Jencia Basin into the Socorro Basin in the Socorro Canyon area. On the basis of tritium data, Gross and Wilcox (1981) indicated ground-water flows from La Jencia Basin through the Socorro Peak area. The volcanics and Mesozoic and Paleozoic aquifer systems are probably densely fractured near Socorro Peak; thus, ground-water flow between basins may be larger in this area than in other areas in the Socorro Peak-Lemitar Mountains (Anderholm, 1987, p. 25).

Consumptive use in the Socorro Basin includes vegetation (both natural and agricultural), evaporation from open water, use by rural homesites, and consumptive use by municipalities. Consumptive use in the basin is about 173.0 ft^3/s (Anderholm, 1987, p. 51 and table 9).

A water budget for the Socorro Basin was developed. Because of lack of confidence in the estimates, most probable values for each major factor in the water budget were presented. The water budget can be represented by the following equation:

$$\Delta S = (Q_{si} - Q_{so}) + (Q_{gi} - Q_{go}) - Q_{cu} + Q_r \qquad (3)$$

where ΔS = change in ground-water storage, in ft^3/s;
Q_{si} = surface-water inflow, in L^3/T;
Q_{so} = surface-water outflow, in L^3/T;
Q_{gi} = ground-water inflow, in L^3/T;
Q_{go} = ground-water outflow, in L^3/T;
Q_{cu} = consumptive use, in L^3/T; and
Q_r = recharge, in L^3/T.

Assuming no change in storage (ΔS = 0), equation 3 can be rearranged so that the ground-water inflow and outflow terms are isolated.

$$(Q_{gi} - Q_{go}) = Q_{cu} - (Q_{si} - Q_{so}) - Q_r \qquad (4)$$

and

(73 ft^3/s) = 173 ft^3/s - (97 ft^3/s) -3 ft^3/s (Anderholm, 1987, p. 54).

GEOCHEMISTRY

Ground-water quality in the Socorro Basin east of the Rio Grande valley is controlled by the mineralogy of the local Mesozoic and Paleozoic rocks. Dissolution of calcite, gypsum, and dolomite is reported to be the major factor controlling water chemistry. Ground water contains large percentages of calcium, magnesium, and sulfate (Anderholm, 1987, p. 56).

Three zones of differing water quality exist in the Rio Grande valley. In the northern part of the valley the water has chloride concentrations as great as 4,020 mg/L. The source of the chloride in the northern part of the basin probably is upward-flowing ground water entering from the southern Albuquerque-Belen Basin. Near Socorro, irrigation-return flow and inflow from basin margins probably control water quality. Chloride concentrations are 100 mg/L or less. South of Socorro, ground-water chloride concentrations are as great as 1,100 mg/L. These large concentrations could result from a constriction to upward-flowing deep-basin ground water with a large concentration of chloride, leakage of geothermal water upward along a lineament, or both (Anderholm, 1987, p. 56-57 and pl. 4).

In La Jencia Basin, ground water contains mostly calcium, sodium, and bicarbonate. In the principal recharge area, east of the basin, water is a calcium bicarbonate type. The increase of sodium, downgradient from the recharge area, probably is caused by exchange of calcium for sodium on clays in the aquifer system. Generally, ground water has a chloride concentration of less than 30 mg/L (Anderholm, 1987, pl. 4).

MESILLA BASIN

The Mesilla Basin is in south-central New Mexico and a small part of western Texas (north of El Paso), and Mexico (fig. 1). Only the part of the Mesilla Basin that lies within the United States will be discussed in this report. This basin was selected for detailed study because agriculture is a large user of surface water and ground water. A growing population in Las Cruces, New Mexico, and El Paso, Texas (fig. 14), requires increasing withdrawals of ground water. Sufficient data were available to simulate the surface-water/ground-water interaction in the flood plain of the Rio Grande by incorporating and routing flows in drains, canals, and the river into a ground-water flow model of the basin that will be described later.

GEOLOGY

The Mesilla Basin contains flood-plain alluvium along the Rio Grande and predominantly fluvial deposits of the Santa Fe Group outside and beneath the flood plain (Wilson and others, 1981). The flood-plain alluvium is 60 to 80 feet thick with a 30- to 40-foot basal layer of gravel overlain by sand, gravel, and clay.

The fluvial facies of the Santa Fe Group represent through-flowing Rio Grande deposition. The deposits are predominantly sand with layers of gravel, silt, clay, and sandy clay. A thick sequence of clay and sandy clay is reported on the east side of the valley from the Texas border north for about 15 miles (Wilson and others, 1981, p. 39). A zone indicative of an eolian depositional environment is found in a well field a few miles north of Cañutillo, Texas. These deposits are uniform, fine-grained brown sand with little or no clay in the interval from 600 to 1,100 feet below land surface.

Saturated basin-fill sediments with more than 50 percent sand, gravel, cobbles, and boulders are prevalent in the northern half of the Rio Grande valley within the Mesilla Basin, especially in the Las Cruces area and along the east side of the valley as far south as Vado (fig. 15). In the southern half of the basin, this lithology occurs in the Cañutillo area, which contains a sandy deep aquifer of possible eolian origin, also on the west side of the basin. Sediments that consist of more than 50 percent clay, silt, mudstone, shale, or caliche are most prevalent on the mesa west of the Rio Grande and south of the New Mexico-Texas State line.

Sand and gravel are most common to a depth of 400 feet below the water table. From 400 to 1,400 feet below the water table, sand and gravel sediments are most common; silt and clay are the second most common type. Sand and gravel in the Las Cruces area, possibly fluvial and alluvial-fan deposits, are present at greater depths.

The average thickness of Neogene sediments is about 2,400 feet (Birch, 1980b, p. 18). The sediments are less than 1,600 feet thick along the Mexican border (Birch, 1980b, p. 12). The greatest thickness of Neogene sediments is southwest of Las Cruces. The thickness of the Paleozoic and Mesozoic rocks is greater toward the southern end of the basin.

GEOCHEMISTRY

Anderholm (1992) described major factors controlling ground-water quality in the Mesilla Basin according to areas defined by Wilson and others (1981) that display common water-quality characteristics. Ground water flowing in from the northwest has a specific conductance of 1,400 to 2,310 microsiemens; sulfate and sodium are the predominant ions (Anderholm, 1992, p. C65). Along the southwest part of the basin margin, sodium bicarbonate type water has a specific conductance of less than 1,940 microsiemens, and a sodium chloride type water has a specific conductance of about 7,400 microsiemens (Anderholm, 1992, p. C65). The sodium chloride water may be either geothermal water or water that flows upward along a major fault on the southwest side of the basin. Sulfate is the dominant anion in ground water west of Las Cruces; specific conductance generally is less than 900 microsiemens. Ground-water chemistry in the Rio Grande flood plain varies vertically and horizontally. This variation is due to mixing of excess applied irrigation water from the river with water in the basin-fill aquifer system. Shallow ground water generally has greater specific conductance than deeper water because of greater dissolved-solids concentrations in irrigation-return flow. In the northeastern part of the basin, water associated with Mesozoic and Paleozoic rocks north and east of Las Cruces has a larger percentage of sulfate and chloride anions and a greater specific conductance than water associated with volcanic rocks east of Las Cruces.

Geothermal or upward-flowing deep-basin water results in water with large concentrations of dissolved solids in several parts of the basin. On the eastern side of the basin, geothermal water with large concentrations of chloride, silica, and potassium mixes with cooler, less mineralized water in the basin-fill aquifer system. Near Radium Springs, a Known Geothermal Resource Area, ground water containing a large concentration of chloride is found. In the southeastern corner of the basin, water containing large concentrations of chloride is attributed to upward flow of water from deep circulation within the basin.

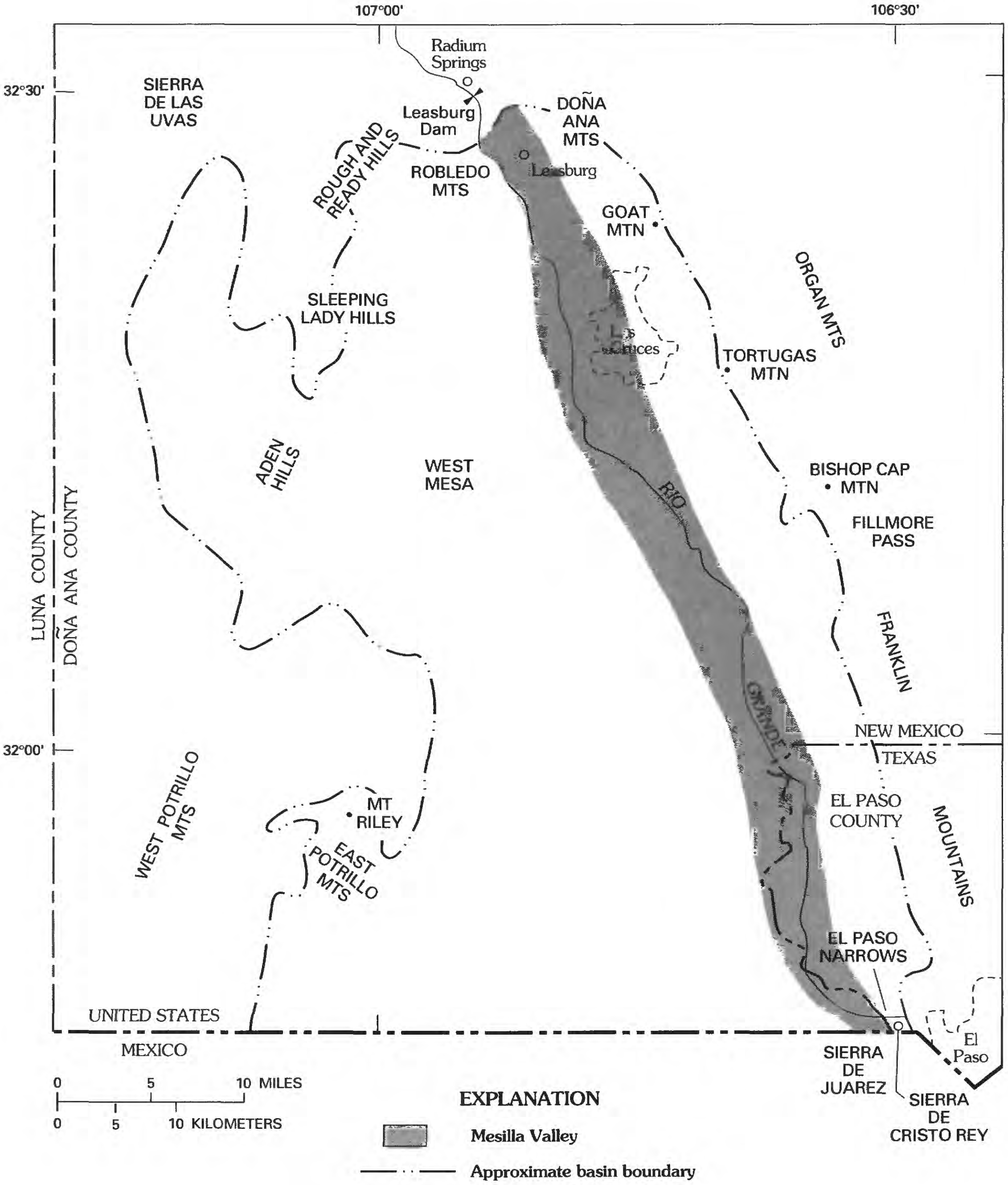


FIGURE 14.—Cultural and geographic features of the Mesilla Basin north of the United States-Mexico international boundary.

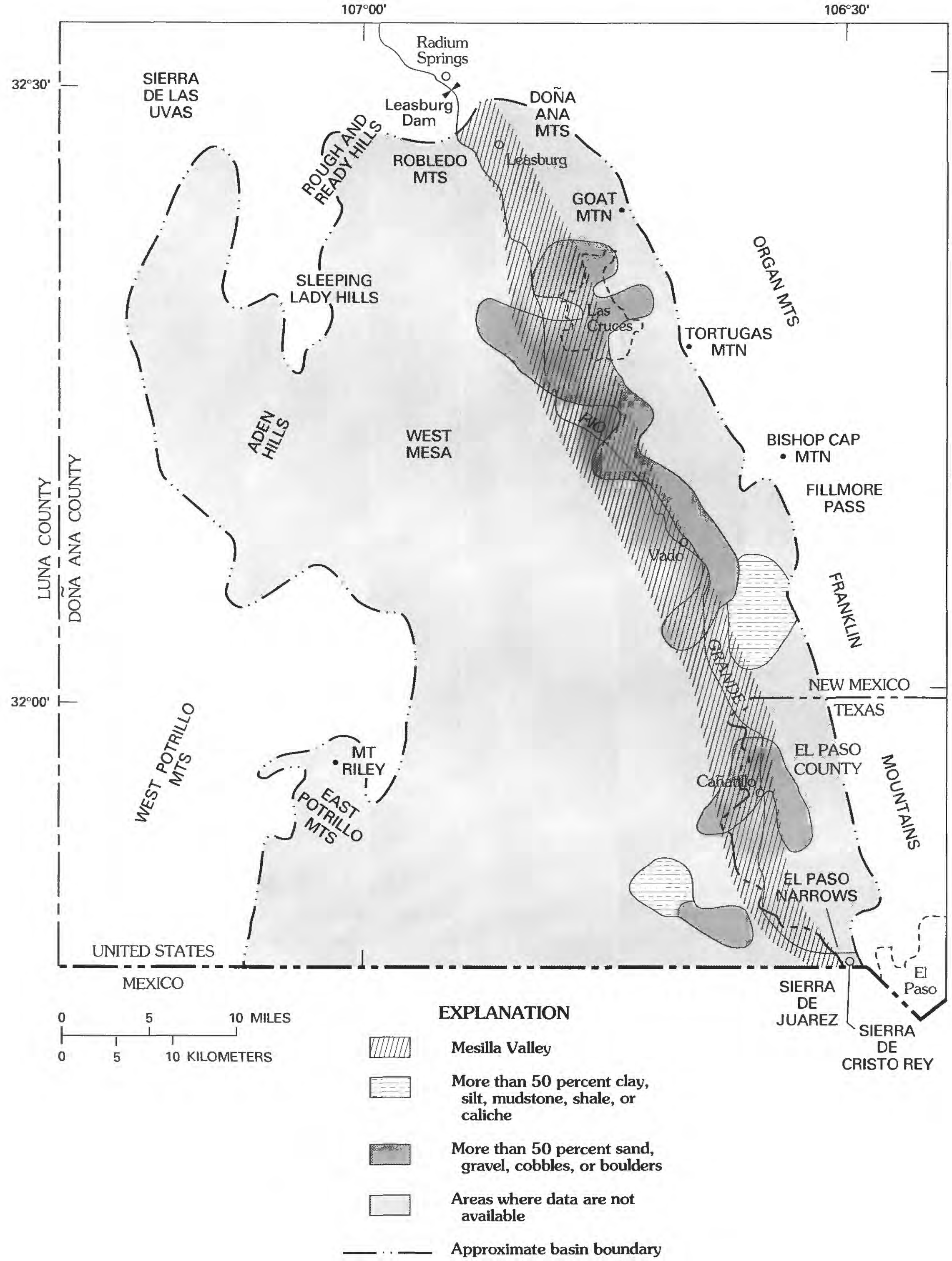


FIGURE 15.—Lithologic zones in the Mesilla Basin north of the United States-Mexico international boundary.

GROUND-WATER FLOW SYSTEM

Frenzel and Kaehler (1992) discussed the basin flow system. Figure 16 is a schematic diagram showing the following ground-water/surface-water interactions in the Mesilla Basin:

(1) (a) Net diversions (gross diversions less water returned directly from the irrigation system to the river or drains); (b) effective rainfall on both irrigated and nonirrigated lands (that part of rainfall that either recharges aquifers or reduces the volume of ground water that would be discharged); (c) evaporation from canal surfaces; and (d) evapotranspiration from irrigated lands, are summed to provide an overall flux for the valley area (fig. 17). This summation, termed "net irrigation flux," includes, by implication, (e) leakage from irrigation canals to ground water and that part of irrigation ground-water pumpage recirculated back to ground water.

(2) Seepage to and from the river and drains, including evapotranspiration from river and drains.

(3) Evapotranspiration from nonirrigated lands.

(4) Water pumped from wells for municipal, industrial, and domestic purposes. Also included in this group are septic-system return flows.

(5) Mountain-front recharge (drainage areas underlain by bedrock with incised ephemeral streams) and slope-front recharge (drainage areas underlain by basin fill).

(6) Underflow.

The discharge of the Rio Grande in the Mesilla Valley is regulated by releases of water from Caballo Reservoir that in turn are replaced by releases from Elephant Butte Reservoir north of the study area. Depletions (the flow passing Leasburg less the flow passing El Paso Narrows) averaged 305 ft^3/s during 1930-75 (Frenzel and Kaehler, 1992, p. C8-C9).

Drains have been constructed to keep the water table below the level of irrigated fields in the Mesilla Basin. By 1917 the need for drains arose because irrigated acreage had nearly doubled during the previous 10 years (Conover, 1954, p. 53-56). By the summer of 1919, about 75 miles of drains existed (Conover, 1954, pl. 6). The average drain discharge for 1923-50 was 1.4 ft^3/s per mile of drain. Drain discharges have been variable and intermittent since 1950, due to a lower water table (Frenzel and Kaehler, 1992, p. C9). Ground water is discharged to drains when ground-water levels rise above drain bottoms and drainwater eventually flows back to the Rio Grande. During periods of drought, the limited surface-water supply is supplemented by ground-water withdrawals and drain discharge is decreased (King and others, 1971, p. 57).

Evaporation from canal surfaces and drains was estimated to be 11.1 ft^3/s. Evaporation from the river channel was estimated to be 16.6 ft^3/s (Frenzel and Kaehler, 1992 p. C9).

Ground-water recharge occurs predominantly on the east side of the basin and along ephemeral stream channels. Recharge also takes place when excess irrigation water percolates through the flood-plain alluvium. Total recharge to the basin is about 15.3 ft^3/s (Frenzel and Kaehler, 1992, p. C23). After long periods of heavy pumping, ground-water levels rapidly recover when surface water is applied on agricultural lands (Taylor, 1967).

The general direction of ground-water flow in the Mesilla Basin is southeastward. Ground water probably moves southward away from the Mesilla Valley near Las Cruces and back toward the valley in the southern part of the basin. Ground water probably also moves vertically downward from the valley in the north. Upward movement of water in the southern part of the valley was indicated by increasing hydraulic head with depth (Leggat and others, 1962, p. 16).

The water-table gradient beneath the West Mesa averages about 4.5 feet per mile, approximately the same as in the Mesilla Valley. Near the margins of the Mesilla Basin, water flows into the basin from the surrounding highlands. The water-table gradient is steeper along the margins due to reduced aquifer transmissivity caused by less aquifer thickness and possibly smaller permeability (Frenzel and Kaehler, 1992, p. C18).

Ground-water withdrawals for municipal, domestic, and industrial uses increased from about 6 ft^3/s in 1950 to about 60 ft^3/s in the early 1970's. About one-half of this amount was withdrawn by the city of El Paso; about one-fourth was withdrawn by the city of Las Cruces. The remaining one-fourth was withdrawn by small towns, villages, and industries (Frenzel and Kaehler, 1992, p. C21). About 227,000 acre-feet of water has been removed from storage in the basin.

Most flow to and from the ground-water system in the valley fluctuates seasonally. Flow in the intermediate term, 1 to 5 years, fluctuates with the availability of surface water. Over the long term, flow to or from the ground-water body does not fluctuate much at all. Change in ground-water storage due to ground-water withdrawals for irrigation occurs only when net irrigation flux (fig. 17, line E) falls below zero, as occurred during the mid-1950's and early 1960's. When irrigation flux is above zero, drains maintain a constant water table in the central basin.

Frenzel and Kaehler (1992) completed a three-dimensional, finite-difference ground-water flow model of the Mesilla Basin. The model simulated the entire thickness (3,800 feet) of basin fill using five model layers; the uppermost layer of the model represented the top 200 feet of unconfined aquifer. The boundaries of the model were defined by the location of basin-bounding faults on the east and west and by shallow bedrock on the north and south. The model grid was constructed with the smallest cell size along the flood plain of the Rio Grande. Input hydraulic conductivity decreased with depth to simulate compaction of aquifer material. The simulated mass balance for the initial condition (pre-1915) and for the end of the simulated time (1975) is shown in table 6.

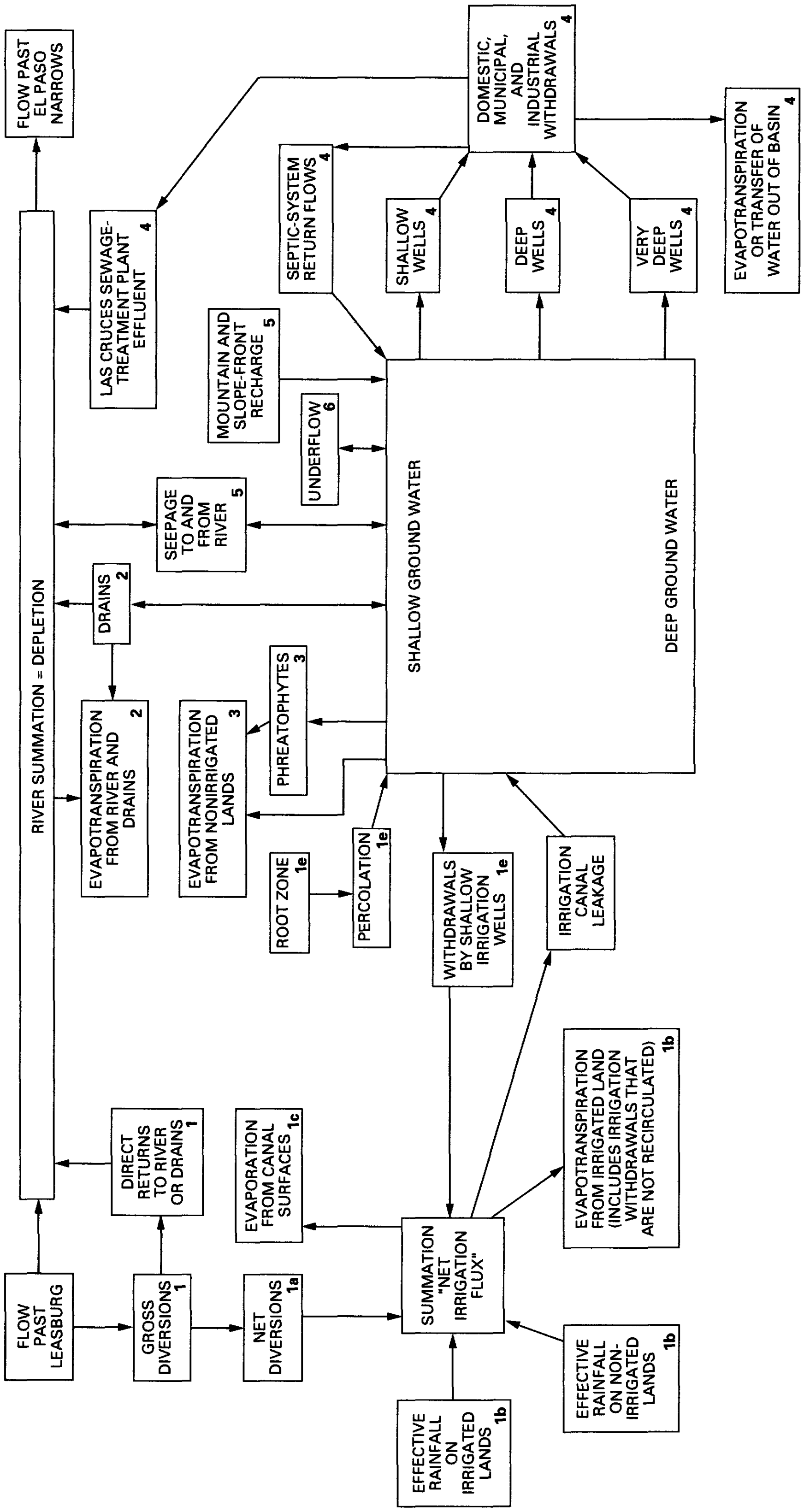


FIGURE 16.—Interactions between ground water and surface water in the Mesilla Basin. (Modified from Frenzel and Kaehler, 1992, fig. 15.)

From the simulation, about 80 percent of all ground water withdrawn for nonirrigation purposes was derived either from induced infiltration of surface water or capture of natural ground-water discharge to the surface-water system, 10 percent was from aquifer storage, and the remaining 10 percent was from salvaged evapotranspiration. These percentages remained essentially unchanged for a test of the model's response to a range of aquifer diffusivity (transmissivity divided by storage coefficient) from one-quarter to four times the diffusivity of the calibrated model. Ground-water withdrawals of 50 ft^3/s for 1941-75 first were simulated as a line of wells parallel to and just west of the flood plain and then as a line of wells parallel to but 12 to 14 miles west of the river. For the line of wells simulated near the flood plain, the sources of withdrawn water remained in the same proportion as for the historical simulation; 80 percent of withdrawals were from streamflow depletion, and changes in diffusivity had little effect. For the line of wells simulated 12 to 14 miles from the flood plain, streamflow depletion was 53 percent of the total withdrawal for the large diffusivity, 15 percent for the calibrated model, and 3 percent for the small diffusivity.

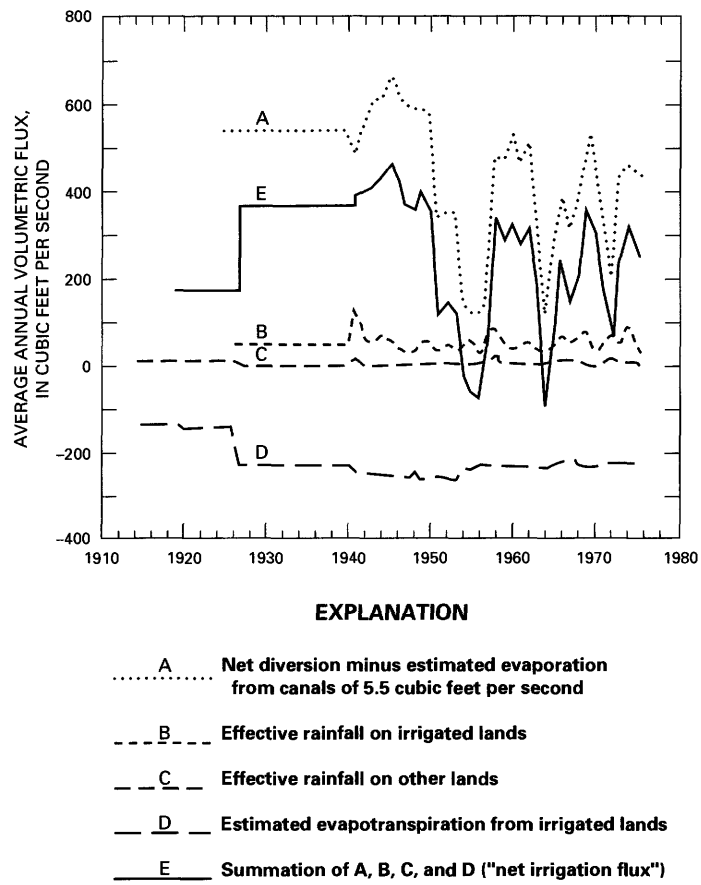


FIGURE 17.— Estimate of net irrigation flux in the Mesilla Valley, 1915-75. (From Frenzel and Kaehler, 1992, fig. 16.)

MIMBRES BASIN GEOLOGY

The Mimbres Basin in southwestern New Mexico (fig. 1) is a closed basin into which several intermittent streams flow. The Mimbres Basin was selected for a lithologic study because development of ground-water resources for irrigation made many drillers' logs available for the analysis.

Analyses of drillers' logs show that total saturated sediments penetrated by wells in the central part of the basin contain a mixture of sediment types. The extreme northwest corner of the basin contains sediments identified as conglomerate on drillers' logs (fig. 18). Areas of clay and silt are present principally near Deming, extending east and west, and in the Columbus area.

Wells primarily penetrate conglomerate in the first 200 feet of saturated sediments in the upper reaches of the Mimbres River and San Vicente Arroyo. The central part of the basin is composed predominantly of clay and silt. In the depth interval between 200 and 400 feet below the water table, conglomerate becomes more common than at shallower depths, except in the central part of the basin. Although data are sparse, the 400- to 1,000-foot depth interval in the northwest corner of the basin is composed of poorly sorted sediments; clay and silt predominate in the central part of the basin.

On the basis of gravity data, Birch (1980b, p. 12) concluded that the thinning of sediments along the international boundary is similar to that found in the Mesilla Basin. Average thickness of sediments in the Mimbres Basin is about 1,570 feet. The gap between the East and West Potrillo Mountains is estimated to be about 6 miles wide and 1,640 feet deep and may provide a hydraulic connection between the Mesilla and Mimbres Basins.

SUMMARY OF REGIONAL ANALYSES

Regional analyses also were conducted as part of the SWAB study. Aquifer characteristics, water chemistry, and various hydrologic topics are described for the complete study area in the remainder of this report.

LITHOLOGIC ANALYSES

Lithologic trends with depth in the Albuquerque-Belen, Mesilla, and Mimbres Basins are shown in table 7. The lithologic categories are defined by Kaehler (1990, fig. 4). For the Albuquerque-Belen and Mesilla Basins, the lithologic category for the total saturated thickness in each well for which a lithologic analysis was completed is most commonly a mixture of sand and gravel (category 5), particularly in the upper 600 feet. The second most common category for both basins is predominantly clay and silt (category 1). Generally, sand and gravel (category 5) are slightly more common than clay and silt at depths greater than 600 feet in the Mesilla Basin (table 7). In the Mimbres Basin, clay and silt (category 1) are common in most saturated depth intervals, except for

TABLE 6.—Simulated mass balance for the Mesilla Basin, pre-1915 and 1975.
[From Frenzel and Kaehler, 1990, p. 87. All values are in cubic feet per second]

Source	Initial condition	End of simulation (1975)
Inflow from:		
Net river seepage	320.9	76.58
Net irrigation flux	.00	258.83
Mountain- and slope-front recharge	14.95	15.89
Underflow in flood-plain alluvium	.16	.95
Outflow to:		
Net drain seepage	.00	-180.48
Net nonirrigation pumpage	.00	-56.73
Evapotranspiration from nonirrigated lands	-335.82	-112.28
Underflow in flood-plain alluvium	-.09	-.72
Net flow to storage	.00	-1.86
Difference	.12	.18
Percent difference	.04	.05

the 200- to 400-foot and 800- to 900-foot depth intervals in which conglomerate (category 3) is more common. The second most common category is a mixture of clay, silt, sand, and gravel sediments (category 2). The Mimbres Basin contains a significantly larger percentage of conglomerate (category 3) than the other two basins (table 7).

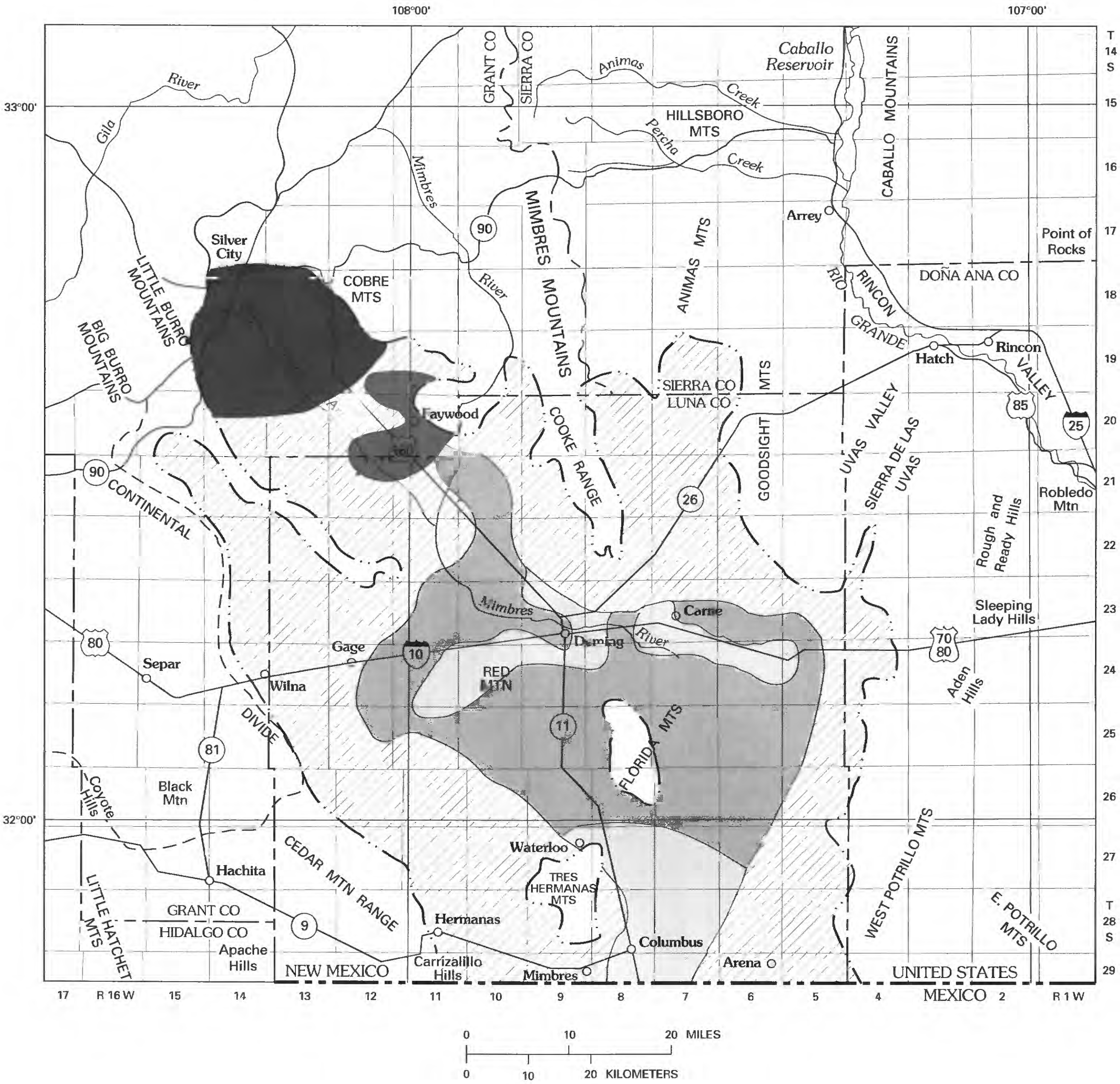
Similarities and differences in the lithologic data reflect the geologic setting and depositional history of the basins. Predominantly coarse grained sediments in approximately the upper 400 to 600 feet of saturated thickness in the Albuquerque-Belen and Mesilla Basins probably were deposited by the relatively high energy, ancestral Rio Grande. This depositional mechanism probably contributed to the general trend of coarse material near the northern end of each basin and fine-grained material toward the southern end.

The Mimbres Basin probably has remained a closed basin throughout its depositional history. Coarse, cemented older sediments common in the northern part of the Mimbres Basin were derived from local uplifts; these sediments currently are near the surface because of subsequent tectonic activity.

Lithologic data in the Albuquerque-Belen Basin and primarily in the southern parts of the Mesilla and Mimbres Basins indicate fine-grained sediments probably of lake or playa origin. All three basins were topographically closed during deposition of these older deposits. The ancestral Rio Grande probably emptied into a lake or playa in the southern part of the Mesilla and Mimbres Basins during much of this early depositional history.

POTENTIOMETRIC SURFACE

The potentiometric surface in the basin-fill aquifer system of the study area is shown in figure 19. The contours are based on water-level data resulting from measurements made in November through March during 1972-81. All wells used in the compilation of the map are completed in alluvial



EXPLANATION

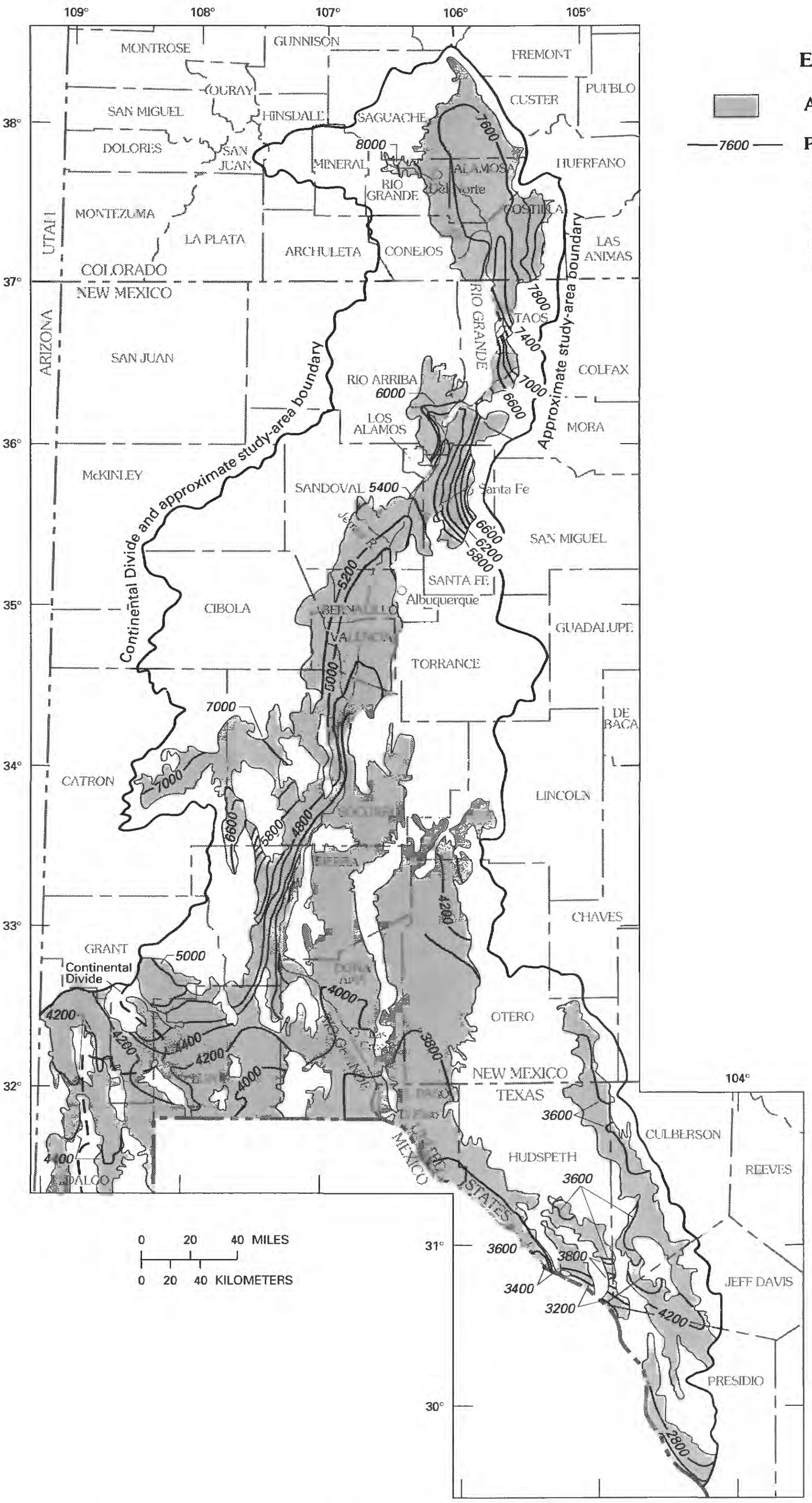
- More than 50 percent clay, silt, mudstone, shale, or caliche
- Between 20 and 50 percent clay, silt, mudstone, shale or caliche; less than 70 percent sand, gravel, cobbles or boulders; and less than 70 percent sandstone, conglomerate, limestone, or volcanics
- Less than 20 percent clay, silt, mudstone, shale, or caliche; less than 70 percent sandstone, conglomerate, limestone, or volcanics; and less than 70 percent sand, gravel, cobbles, or boulders
- Greater than 70 percent sandstone, conglomerate, limestone, or volcanics
- Areas where data are not available
- Approximate basin boundary

FIGURE 18.—Lithologic zones in the Mimbres Basin.

TABLE 7.—Percentage of wells in each lithologic category, by saturated interval, Albuquerque-Belen, Mesilla, and Mimbres Basins.

[Calculation of average percentage excludes total interval percentage. Percentages may not add to 100 percent due to rounding. Categories from Kaehler, 1990, fig. 4]

Saturated interval (feet)	Lithologic category 1 (More than 50 percent clay, silt, mudstone, shale, or caliche)			2 (Between 20 and 50 percent clay, mudstone, shale, or caliche; less than 70 percent sandstone, conglomerate, limestone, or volcanics; and less than 70 percent sand, gravel, cobbles, or boulders)			3 (More than 70 percent sandstone, conglomerate, limestone, or volcanics)			4 (Less than 20 percent clay, silt, mudstone, shale, or caliche; less than 70 percent sandstone, conglomerate, limestone, or volcanics; and less than 70 percent sand, gravel, cobbles, or boulders)			5 (More than 70 percent sand, gravel, cobbles, or boulders)		
	Albuquerque-Belen Basin	Mesilla Basin	Mimbres Basin	Albuquerque-Belen Basin	Mesilla Basin	Mimbres Basin	Albuquerque-Belen Basin	Mesilla Basin	Mimbres Basin	Albuquerque-Belen Basin	Mesilla Basin	Mimbres Basin	Albuquerque-Belen Basin	Mesilla Basin	Mimbres Basin
0-100	23.0	14.4	41.0	27.8	26.1	21.3	4.8	0.9	18.8	5.6	1.8	3.4	38.9	56.8	15.4
100-200	27.8	23.3	43.6	23.7	26.7	13.8	5.2	2.2	24.5	3.1	1.1	9.6	39.2	46.7	8.5
200-300	28.4	21.3	26.9	19.4	28.6	25.4	3.0	2.9	28.4	7.5	1.4	11.9	41.8	45.6	7.5
300-400	25.0	22.2	20.5	18.3	25.9	25.0	5.0	3.7	29.6	6.7	3.7	11.4	45.0	44.4	13.6
400-500	20.4	38.3	50.0	27.8	19.2	10.7	5.6	4.3	25.0	0.0	2.1	3.6	46.2	36.2	10.7
500-600	28.6	34.9	47.1	28.6	23.3	5.9	2.4	2.3	29.4	4.8	4.7	11.8	35.7	34.9	5.9
600-700	29.4	32.5	38.5	35.3	12.5	15.4	2.9	7.5	30.8	8.8	0.0	0.0	23.5	47.5	15.4
700-800	41.7	26.7	33.3	25.0	16.7	22.2	0.0	3.3	33.3	0.0	6.7	0.0	33.3	46.7	11.1
800-900	40.0	25.0	25.0	33.3	12.5	12.5	0.0	4.2	50.0	0.0	4.2	0.0	26.7	54.2	12.5
900-1,000	28.6	32.4	40.0	28.6	22.0	0.0	7.1	8.7	40.0	0.0	4.3	0.0	35.7	32.4	20.0
1,000-1,100	50.0	30.0	33.3	8.3	30.0	66.7	0.0	5.0	0.0	0.0	0.0	0.0	41.7	35.0	0.0
1,100-1,200	45.5	21.1	33.3	27.3	31.6	33.3	0.0	10.5	33.3	0.0	5.3	0.0	27.3	31.6	0.0
1,200-1,300	22.2	25.0	50.0	44.4	25.0	50.0	0.0	8.3	0.0	0.0	0.0	0.0	33.3	41.7	0.0
1,300-1,400	44.4	22.2	50.0	0.0	22.2	50.0	11.1	11.1	0.0	11.1	0.0	0.0	33.3	44.4	0.0
1,400-1,500	50.0	33.3	50.0	0.0	33.3	0.0	12.5	11.1	0.0	12.5	0.0	50.0	25.0	22.2	0.0
Total interval	20.5	14.3	39.3	39.4	42.0	28.2	1.6	0.9	18.8	8.7	2.7	9.4	29.9	40.2	4.3
Average percentage	33.7	26.8	38.8	23.2	23.7	23.5	4.0	5.7	22.9	4.0	2.3	6.8	35.1	41.3	8.0



EXPLANATION

Area of alluvial fill

—7600— Potentiometric contour—Shows altitude at which water level would have stood in tightly cased wells. 1972–81. Dashed where approximately located. Contour interval 200 feet. Datum is sea level

FIGURE 19.—Potentiometric surface in the basin-fill aquifer system, 1972-81. (Modified from Wilkins, 1986b, fig. 67.)

deposits. Water levels in the selected wells represent static head at many levels in the aquifer system. The sparse data on well depth and perforated interval prevented development of potentiometric-surface contours for specific depth intervals in the basin-fill aquifer system.

Potentiometric-surface contours were drawn on the basis of the assumption of hydraulic continuity between basin aquifers. This assumption appears to be justified from the continuity of measured water-level altitudes near some basin boundaries and the continuity of alluvial sediments between basins. Although the regional aquifer system can be considered unconfined, areas with confined conditions have been identified. Most notable of these areas of confinement are part of the San Luis Valley, Colorado, and an area around El Paso, Texas. There are also several small areas along the Rio Grande. The contours, as drawn, do not differentiate between confined and unconfined conditions.

Parts of the water table in the basin-fill aquifer system are not contoured. These areas lack sufficient data during the 1972-81 period to define the potentiometric surface. Additionally, contours have not been extended across areas where alluvium is missing. It is recognized that there are areas where sediments of the Santa Fe Group may be capped by volcanic rocks. In these places, there probably is hydraulic continuity between adjacent alluvial sediments and sediments underlying the volcanic-capped areas, but data generally are lacking to define the potentiometric surface. The area west of the Rio Grande between the Colorado-New Mexico State line and Embudo, New Mexico, and the mesa between Santa Fe and the Albuquerque-Belen Basin are two such areas. Contours within basins adjacent to the United States-Mexico boundary have not been extended into Mexico because of lack of data. It is recognized that these basins do not terminate at the boundary and that hydraulic continuity does exist.

Contours of the potentiometric surface indicate areas of ground-water recharge and discharge, direction of flow, and the gaining and losing reaches of streams. Throughout much of the study area, contours indicate that the Rio Grande flood plain gains water from the basin-fill aquifer system; the river acts as a drain. Locally, however, the river may supply water to the ground-water reservoir or may not be in hydraulic connection with the basin-fill aquifer system.

The topography in the Rio Grande rift relates to the graben structure where valleys are bounded by uplifted areas on the sides; potentiometric contours show that the aquifer is recharged from the highland areas where precipitation is greater. Closed surface-water basins in southwestern New Mexico display this same characteristic. In general, ground-water movement in the study area is from the west and east to the center of the valleys and then southward. However, ground-water movement in the Animas and Playas Basins in southwestern New Mexico is northward to the Gila River.

GROUND-WATER CHEMISTRY

Primary chemical processes that occur in ground water in the study area are dissolution of calcite, dolomite, gypsum, and halite; exchange of calcium for sodium; precipitation of calcite and dolomite; and mixing of water in the flow system. Dissolution, ion exchange, and precipitation largely are dependent on the presence of specific minerals and lithologies in the surrounding bedrock and basin-fill sediments. Mixing of water in the flow system depends on flow patterns that allow waters from different sources with different chemical compositions to combine.

The following descriptions of water temperature, specific conductance, and chemical water types provide an overview of the study area. Because the data are from wells completed at a variety of depths in the basin fill, the descriptions are generalized and may not apply to water at a specific depth interval. Wells generally are completed as shallow as possible and data usually represent the upper part of the basin-fill aquifer system.

TEMPERATURE

Ground-water temperature can be affected by recent volcanic activity, by faulting resulting in deep circulation of ground water, and by the local flow system. Generally, the temperature of ground water (fig. 20) from the San Luis Basin south to the northern end of the Albuquerque-Belen Basin ranges from 5 to 15 degrees Celsius. Farther south the temperature generally ranges from 15.1 to 25 degrees Celsius.

Small areas scattered throughout the study area have ground water with temperatures ranging from 25.1 to 35 degrees Celsius. These areas are associated with Quaternary and Tertiary volcanic rocks (fig. 3) that have retained heat associated with their formation and have transmitted the heat to the ground water. Another explanation for elevated ground-water temperatures is an increased temperature gradient associated with ground-water discharge sites (Freeze and Cherry, 1979, p. 509) within the Rio Grande flood plain. Faulting within the rift is common in the study area and is associated with warm water in the Socorro and Mesilla Basins (Anderholm, 1987, 1990).

SPECIFIC CONDUCTANCE

Specific conductance of ground water is related to geologic, hydrologic, topographic, and climatic factors. The type and occurrence of minerals in the bedrock and in sediments within the basin, through which ground water moves (in turn, dependent on the sequence and arrangement of geologic units), are important factors. Evapotranspiration rates, prior

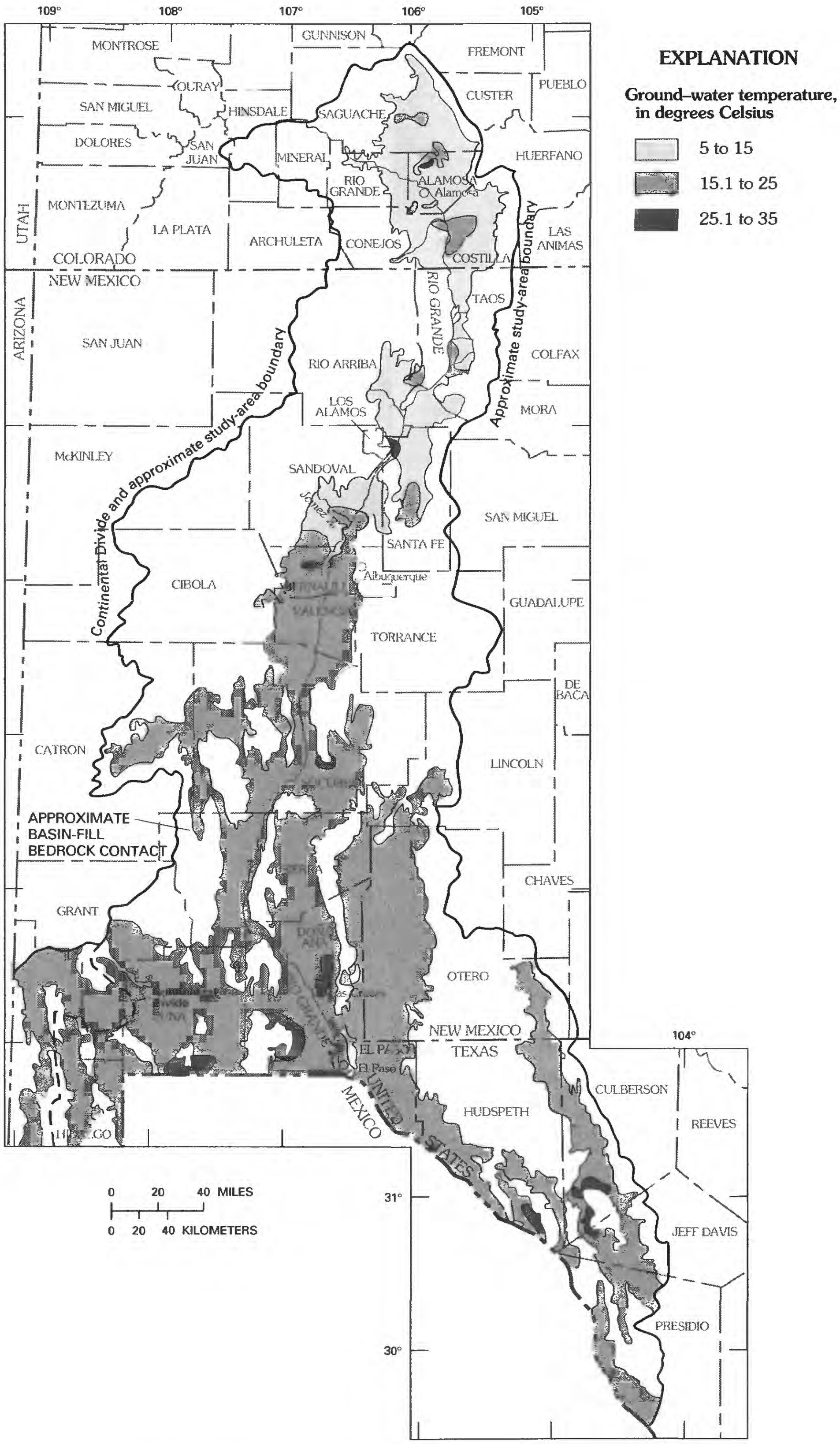


FIGURE 20.—Ground-water temperatures in the basin-fill aquifer system.

use of the water, location of the water in the flow system relative to recharge and discharge areas, and length of time the water has been resident in the flow system also are important. The distribution of various ranges of specific conductance of ground water in the basin-fill aquifer system is shown in figure 21. Four specific-conductance categories were selected on the basis of drinking water standards and crop tolerance to salinity. The category of 0 to 750 microsiemens is approximately equal to 0 to 500 mg/L dissolved solids and generally is recommended for human consumption (U.S. Environmental Protection Agency, 1986). The upper limit of the category, 751 to 2,250 microsiemens, is the upper limit of a high salinity hazard for irrigated crops. The category of 2,251 to 5,000 microsiemens corresponds to the very high salinity hazard (U.S. Salinity Laboratory Staff, 1954). The fourth category is specific conductance greater than 5,000 microsiemens.

In areas where specific-conductance data were not available, the predominant specific conductance in the surrounding area was assumed to exist. Small zones having a different specific conductance than the surrounding area were delineated only where data from more than one well and the scale of the map permitted delineation. Wells in these small areas may be producing water from different zones than wells in the adjacent larger area.

The San Luis and Española Basins and basins in southwestern New Mexico (fig. 1) generally have water with specific conductance in the range of 0 to 750 microsiemens. Basins south of the Española Basin along and east of the Rio Grande generally have water with specific conductance in the range of 751 to 2,250 microsiemens. Specific conductance of water in basins in west Texas is variable.

Within the closed-basin part of the San Luis Basin north of the Rio Grande (figs. 1, 2), there are areas where specific conductance of water ranges from 751 to 5,000 microsiemens (fig. 21). Depth to water in these areas is less than 20 feet (Crouch, 1985). Estimated evapotranspiration rates range from 0 to 4.5 acre-feet per year in the basin, depending, in part, on the depth to the water table (Hearne and Dewey, 1988, p. 40). Concentration of salts by evapotranspiration may account for the increased specific conductance. The areas with increased specific conductance north of the Rio Grande also correspond in a general way to areas with increased groundwater temperature (fig. 20). Higher temperature allows more solute to be dissolved in a given volume of water.

In the San Luis Basin south of the Rio Grande, the area in which ground water has specific conductance greater than 750 microsiemens corresponds to the area where water temperature ranges from 15.1 to 25 degrees Celsius (fig. 20). This area lies between major faults in the basin (Wilkins, 1986a, pl. 2). These faults may allow water with increased specific conductance and temperature to flow upward and mix with shallow ground water. The area also is a discharge area (Crouch, 1985).

The southern part of the Santo Domingo Basin and the northern part of the Albuquerque-Belen Basin have areas where water has specific conductance greater than 750 microsiemens. The area along and north of the Jemez River on the western side of the basins has water temperatures in the range of 15.1 to 25 degrees Celsius (fig. 20). The specific conductance of Jemez River water is more than 1,200 microsiemens and recharge to the basin fill from the Jemez River is reported to be 34.5 ft^3/s (Anderholm, 1988, p. 24). Mesozoic and Paleozoic rocks on the eastern basin boundary (fig. 3) are a source of soluble minerals that may cause increased specific conductance. Ground-water flow is from the north and east into the area of increased specific conductance. To the west, the Jemez Mountains consist of a volcanic complex and are a recharge area where increased ground-water temperatures and larger concentrations of dissolved constituents are found. Ground water in the Jemez geothermal reservoir in the Jemez Mountains contains dissolved-silica and dissolved-chloride concentrations of about 100 and 1,500 mg/L, respectively.

On the western side of the Albuquerque-Belen Basin south of the Jemez River, the specific conductance of water generally is greater than 750 microsiemens. Mesozoic rocks west of the alluvial material in the study area (fig. 3) are a source of soluble minerals as well as a recharge area for the basin. Anderholm (1988, p. 67) reported that specific conductance of water in the Mesozoic rocks is generally less than 10,000 microsiemens. As water moves downgradient from the Mesozoic rocks into the alluvial deposits, to the east, specific conductance decreases due to mixing of the large conductance water with water of lesser specific conductance. In the southwestern part of the basin, specific conductance is influenced by ground water flowing from volcanic rocks south and west of the basin and by inflow from La Jencia Basin. Ground water from La Jencia Basin has a specific conductance less than 750 microsiemens. In the south-central part of the Albuquerque-Belen Basin, specific conductance is in the range of 2,251 to 5,000 microsiemens, probably as a result of water with specific conductance greater than 5,000 microsiemens flowing from the north.

South of the Albuquerque-Belen Basin, the influence of geology on specific conductance is more apparent. West of the Rio Grande, Quaternary and Tertiary volcanics are the predominant rock type. Soluble minerals generally are absent in these volcanic rocks. Specific conductance west of the river, with the exception of the Mesilla Basin, generally is in the range of 0 to 750 microsiemens. Basins east of the Rio Grande generally have water with a specific conductance of 751 to 2,250 microsiemens (fig. 21). Paleozoic rocks make up most of the basin boundaries (fig. 3). In contrast, the

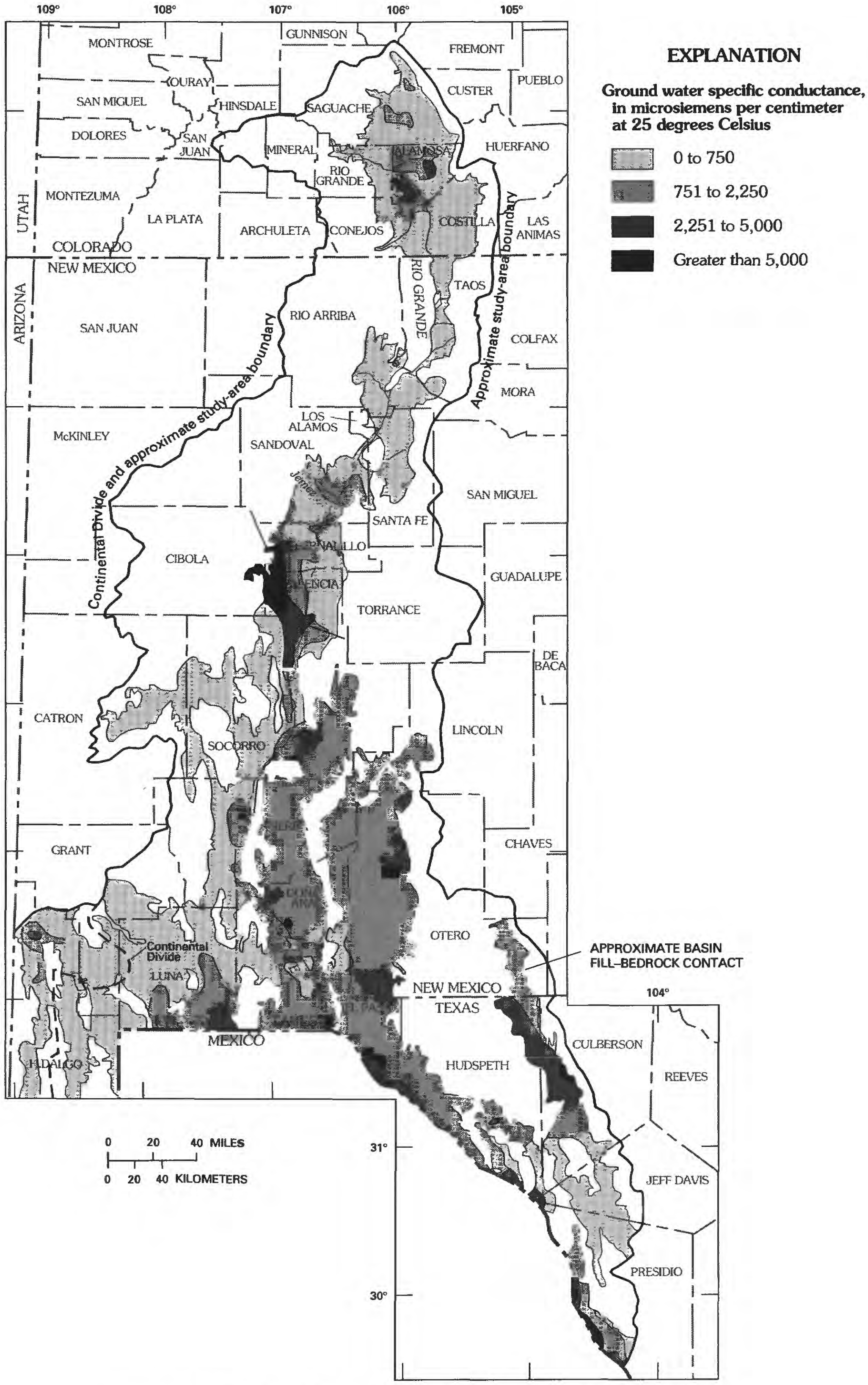


FIGURE 21.—Specific conductance of ground water in the basin-fill aquifer system.

southern part of the Salt and Eagle Basins and the eastern side of the Redlight Draw Basin in west Texas (fig. 1) have relatively large areas where water has a specific conductance less than 750 microsiemens; these areas correspond closely to the occurrence of volcanic rock along basin boundaries.

The ground water in the Mesilla Basin has a specific conductance in the range of 751 to 2,250 microsiemens that may result from geology, inflow, irrigation-return flow, or geothermal activity. Paleozoic rocks in the Robledo, Organ, and Franklin Mountains (fig. 14) comprise the recharge areas for the basin and may be a source of soluble minerals. Inflow of water from the Jornada del Muerto Basin (fig. 1) with a specific conductance of 751 to 2,250 microsiemens could be a source of the Mesilla Basin water. The Jornada del Muerto Basin is surrounded by Paleozoic rocks. Recharge from applied irrigation water concentrates solutes because of evapotranspiration and also increases specific conductance in the Rio Grande flood plain. Geothermal areas along the eastern side of the basin contribute water having increased specific conductance (Anderholm, 1992).

In the closed basins in southwestern New Mexico, the specific conductance of ground water generally is less than 750 microsiemens. Volcanic rocks in recharge areas of the basins contribute only small quantities of solutes. Areas of increased specific conductance in ground water correspond to the location of playas. Water recharged through playa sediments may have increased specific conductance because of evaporation during the time water is ponded in the playa.

WATER CHEMISTRY

Six water types are found in the study area, based on the occurrence of two major cations and three anions. If the sum of the calcium and magnesium equivalents per million was greater than 50 percent of the cations, the water was classified as calcium plus magnesium cation type. If sodium was greater than 50 percent of the cations, the water was classified as sodium cation type. Anion percentages were calculated on the basis of equivalents per million to determine the predominant anion in the water sample. The water was then classified as chloride, sulfate, or bicarbonate anion type.

Because of the division of chemical water types, the major-ion evolution method presented in Freeze and Cherry (1979) was a useful method to assist in the definition of basin flow systems. Freeze and Cherry (1979, p. 242) reported that younger water has a predominant bicarbonate anion and is low in dissolved solids. This is indicative of an upper zone of water in the aquifer system and active ground-water flushing through well-leached rocks. Sulfate is the predominant anion in the intermediate depth-to-water zone and is indicative of water that is usually older than the bicarbonate water. Water with a predominantly sulfate anion is usually greater in dissolved solids. Chloride anion predominance may be indicative of the oldest of ground waters, a lower zone of sluggish ground-water flow with large dissolved-solids concentration. Flow-system characteristics associated with anions were used to assist in the interpretation of water-quality data and to make inferences about regional and basin flow systems. Cation concentrations were used to indicate processes that might be active in the flow systems.

Figure 22 is a chemical water type map showing the dominant ions in ground water from the basin-fill aquifer system. Generally, calcium and magnesium are the predominant cations and bicarbonate the predominant anion in ground water along the Rio Grande and in the closed basins in southwestern New Mexico. East of the Rio Grande and south of the Socorro Basin, extending to the northern Mesilla and Tularosa-Hueco Basins and the northern Salt Basin in west Texas, calcium plus magnesium sulfate generally is the chemical water type. In the southern Tularosa-Hueco Basin, the water contains sodium chloride. Sodium sulfate water occurs on the west side of the Albuquerque-Belen Basin and along the flood plain of the Rio Grande in the southern part of the Albuquerque-Belen Basin into the La Jencia Basin. The basins in west Texas, with the exception of the northern part of the Salt Basin, have water types of calcium plus magnesium bicarbonate and sodium bicarbonate similar to closed basins in western New Mexico.

All six chemical water types occur in the study area. Each water type will be discussed in relation to processes that might be operating in the geochemical system. Only three small areas of calcium and magnesium chloride water occur in the study area: one in the Albuquerque-Belen Basin just south of the Jemez River, one just west of the Rio Grande in the Palomas Basin, and one in the west-central Tularosa-Hueco Basin. The geology of these three areas is similar to the surrounding area. The ground-water temperature and specific conductance are larger south of the Jemez River in the Albuquerque-Belen Basin (figs. 20 and 21), indicating the possibility of mixing geothermal water from the Jemez geothermal reservoir with water in the basin-fill aquifer system. Anderholm (1988, p. 89) reported large chloride concentrations in the Jemez geothermal reservoir, north of the Jemez River. Water moving from the geothermal reservoir and mixing with local recharge water may result in the calcium plus magnesium chloride water in the Albuquerque-Belen Basin. The calcium plus magnesium chloride water in the Palomas Basin is near known Geothermal Resource areas, which might be the source of this water type. The processes that produce this type of water in the Tularosa-Hueco Basin are not known due to lack of data in this area.

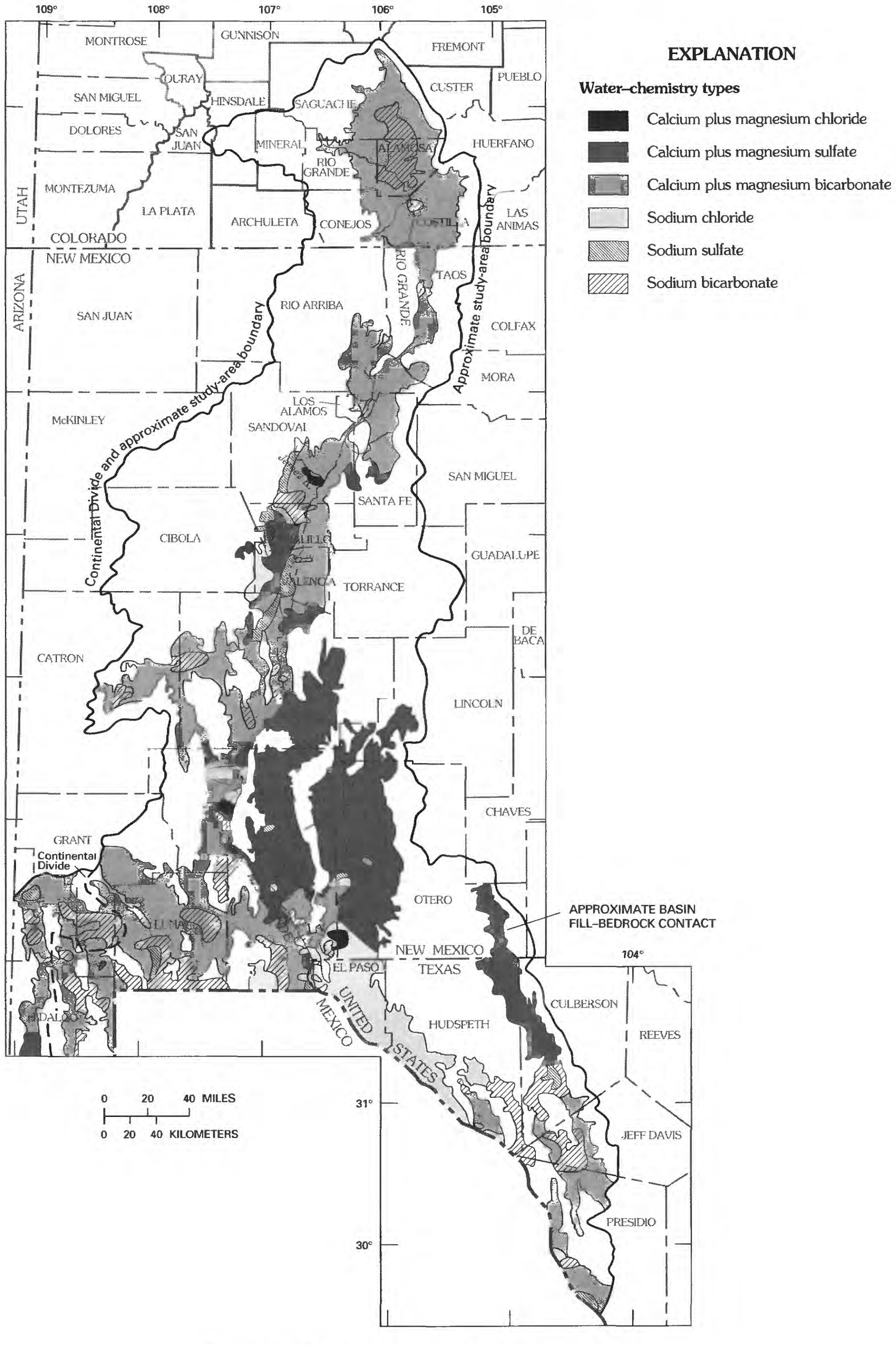


FIGURE 22.—Chemical water types in the basin-fill aquifer system.

Calcium plus magnesium sulfate water is most common in the south-central and southeast parts of the study area but also is found in most basins south of the San Luis Basin. This type of water can be associated with Mesozoic and Paleozoic rocks (fig. 3). The Mesozoic and Paleozoic rocks commonly are a source of sulfate.

Calcium plus magnesium bicarbonate water is the most common water type in the study area. This type of water is characteristic of recharge water and has low values of specific conductance (fig. 21).

Sodium chloride water is found in several basins south of the Española Basin. The presence of sodium chloride water probably is the result of different processes in each of the different basins. In the Albuquerque-Belen Basin, inflowing ground water from the San Juan Basin to the west is the source of the sodium chloride (Anderholm, 1988, p. 67). Inflowing ground water along fault zones west of the Albuquerque-Belen Basin is a sodium chloride brine; the specific conductance of water flowing into the basin is greater than 20,000 microsiemens. Small areas of sodium chloride water occur in the Engle and Palomas Basins and in the northern part of the Mesilla Basin. These areas are in or near Known Geothermal Resource Areas. Upwelling of water from a deep geothermal reservoir may be the source of this sodium chloride water.

Sodium chloride water also is found in the southern end of the Mesilla Basin, the southern end of the Tularosa-Hueco Basin, and the northern part of the Eagle Basin in west Texas. These areas are not associated with a known geothermal source or with inflow of water from adjacent basins with large sodium or chloride concentrations. Dane and Bachman (1965) and the Bureau of Economic Geology (1968) have mapped the Permian Hueco Limestone and Yeso Formation as the primary rock types in these areas. Dissolution of halite from the formations may be the process responsible for sodium chloride water in these basins.

Sodium sulfate and sodium bicarbonate water is found in discharge areas in most basins (fig. 22). In closed basins, sodium sulfate and sodium bicarbonate ground water is present in areas of playas. A clay-rich aquifer matrix can supply cation-exchange sites for exchanging calcium or magnesium for sodium.

RECHARGE

Recharge to the ground-water system was estimated for all basins in the study area using the "mountain water-budget" and the "mountain-yield" methods of Hearne and Dewey (1988). Total recharge and recharge from specific basin boundaries are listed in table 8. Recharge estimates from the western boundary of the San Luis Basin north of the San Luis Hills were determined using the mountain water-budget method. In the remainder of the study area, the volume of water that discharges to the alluvial aquifers was estimated using the mountain water-yield method. Precipitation on the basin surface was not included in the total recharge value because it is assumed to be lost by evapotranspiration while in the first few inches of the soil. Unit recharge is the annual estimated recharge, in cubic feet per second, divided by total alluvial area for a basin, in square miles. Unit recharge and recharge per length of basin boundary for each basin are given in table 9. Recharge from the eastern and western boundaries of each basin was computed by dividing recharge from the mountain front by mountain-front length. Recharge amount and general locations are shown in figure 23.

Recharge is greater in the northern basins than in the southern basins. Runoff from high mountains adjacent to the basins is the primary source of recharge. The San Luis Basin has the largest quantity of estimated unit recharge. Average annual estimated mountain water-budget and mountain-front recharge is about 3,580 ft^3/s, nearly 15 times the recharge to the Española Basin, the basin in the study area with the next largest recharge rate (table 8). The ratio of estimated recharge from the western boundary divided by the western mountain-front length of the San Luis Basin is more than 12 times the ratio for recharge from the western boundary of the Española Basin, to the south.

The Española Basin has the second largest unit recharge, followed by the Engle Basin (table 9). The large recharge is due to the adjacent high mountains that receive large amounts of precipitation. Recharge on the west side of the Engle Basin from the San Mateo Mountains and the small alluvial area of the basin contribute to the large unit recharge although there is no significant recharge from the east side of the basin. The Mesilla Basin has the smallest unit recharge along the Rio Grande. The absence of large, high mountain areas together with small amounts of precipitation accounts for the small unit recharge.

Estimated recharge to basins located partly in Mexico is greatest for the Tularosa-Hueco Basin. Runoff from the Sacramento Mountains to the east of the basin produces most of the recharge. Recharge from west of the basin also is greater than for the Eagle, Redlight Draw, and Presidio Basins (table 9).

Among closed basins (fig. 2), the San Agustin Basin has the largest unit recharge. This basin is surrounded by relatively large, high mountain areas. In contrast to most other basins in the study area, the San Agustin Basin also has a significant quantity of recharge from the northern and southern boundaries of the basin. The only other basins to receive recharge from the north or south are the Jornada del Muerto and Mimbres Basins.

TABLE 8.—Estimated recharge to alluvial basins.

[ft^3/s, cubic feet per second; mi^2, square miles; mi, miles; —, no data]

Basin	Total estimated recharge[1] (ft^3/s)	Alluvial area (mi^2)	Estimated recharge from eastern boundary (ft^3/s)	Eastern boundary length (mi)	Estimated recharge from western boundary (ft^3/s)	Western boundary length (mi)	Remarks
San Luis	3,580	3,640	780	201	2,800	292	
Espanola	246	1,410	129	139	117	156	
Albuquerque-Belen and Santo Domingo	114	3,150	104	147	10	195	
Socorro	8	346	2	28	6	36	
La Jencia	5	208	0	25	5	31	
San Agustin	49	1,260	4	30	5	15	16 ft^3/s, 139 mi north; 24 ft^3/s, 163 mi south
San Marcial	11	535	0	13	11	81	
Engle	26	455	0	21	26	63	
Palomas	33	766	5	38	28	105	
Jornada del Muerto	24	2,340	8	122	1	125	15 ft^3/s, 111 mi north
Mesilla	6	1,420	4	41	2	84	
Tularosa-Hueco	136	5,120	98	400	38	236	No data from Mexico
Mimbres	17	3,060	6	105	2	111	7 ft^3/s, 108 mi north; 2 ft^3/s, interior recharge
Hachita	3	491	0	28	3	55	
Playas	9	531	3	71	6	59	
Animas	2	201	2	40	0	27	No data from Mexico
Lordsburg	3	361	3	73	0	73	No data from Mexico
Salt	68	2,180	27	232	41	245	No data from Mexico
Eagle	2	618	2	35	0	34	
Redlight Draw	21	802	9	75	12	98	
Presidio	4	448	4	74	--	--	

[1]Does not include precipitation on the basin surface that is assumed to be lost to evapotranspiration.

TABLE 9.—Unit recharge (ratios of total estimated recharge to alluvial area) and estimated recharge from basin boundaries per boundary length.

[ft^3/s, cubic feet per second; mi^2, square miles; mi, miles; —, no data]

Basin	Total recharge[1] (ft^3/s) / Alluvial area (mi^2)	Eastern boundary recharge (ft^3/s) / Length (mi)	Western boundary recharge (ft^3/s) / Length (mi)	Northern boundary recharge (ft^3/s) / Length (mi)
San Luis	0.983	3.88	9.59	--
Española	.175	0.928	0.750	--
Albuquerque-Belen and Santo Domingo	.036	.707	.051	--
Socorro	.023	.071	.167	--
La Jencia	.024	.000	.161	--
San Agustin	.039	.133	.333	0.116
San Marcial	.021	.000	.136	--
Engle	.057	.000	.413	--
Palomas	.043	.132	.267	--
Jornada del Muerto	.010	.066	.008	.135
Mesilla	.004	.098	.024	--
Tularosa-Hueco	.030	.245	.161	--
Mimbres	.006	.057	.018	.065
Hachita	.006	.000	.055	--
Playas	.017	.042	.102	--
Animas	.010	.050	.000	--
Lordsburg	.008	.041	.000	--
Salt	.009	.054	--	--
Eagle	.003	.057	.000	--
Redlight Draw	.026	.120	.122	--
Presidio	.031	.116	.167	--

[1]Does not include precipitation on the basin surface that is assumed to be lost to evapotranspiration.

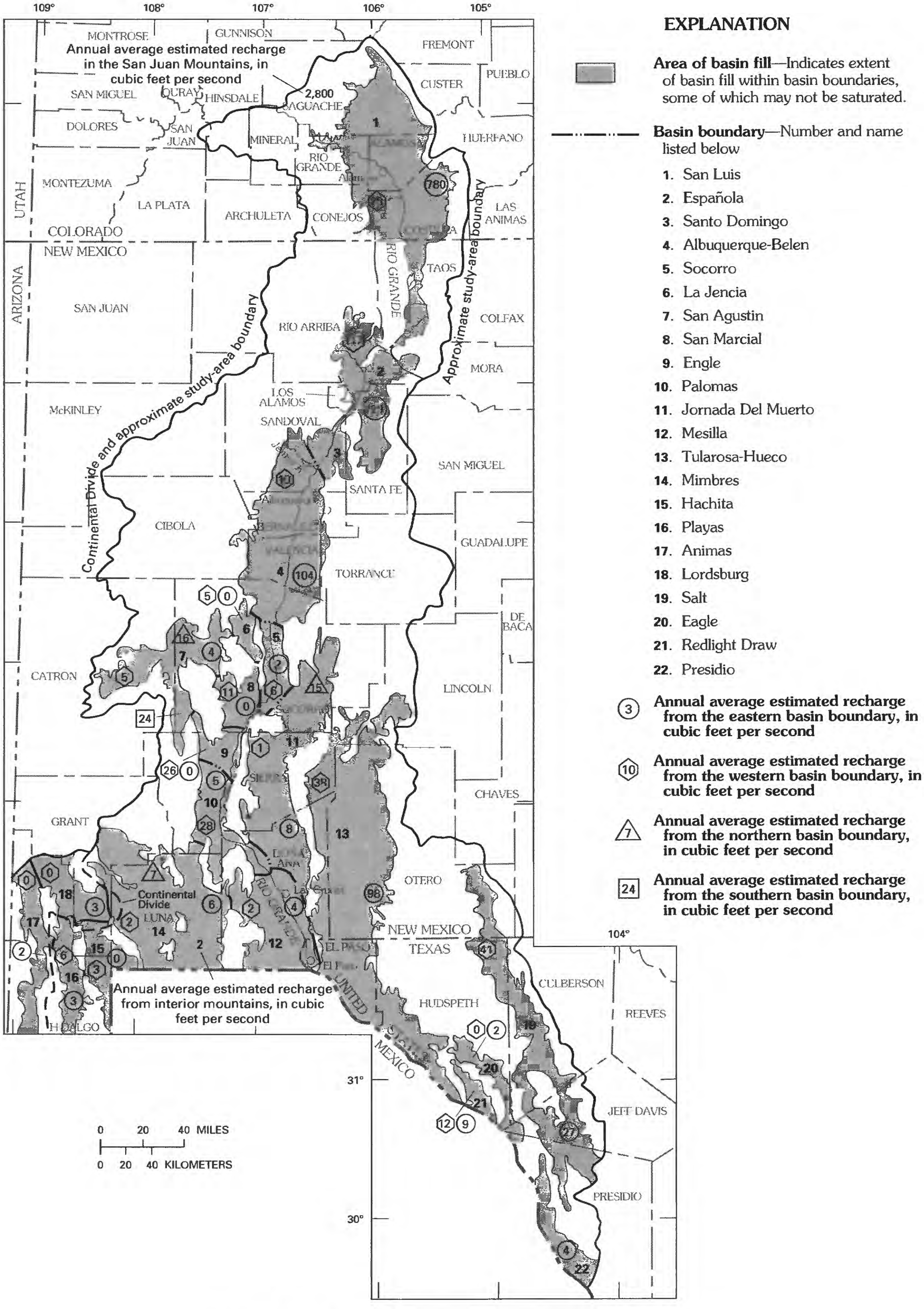


FIGURE 23.—Estimated recharge to the basin-fill aquifer system.

WATER USE

A comprehensive water-use study for the study area was not done due to the large number of basins, the complexities of determining the amount of water used from ground-water and surface-water sources for irrigation, and the lack of significant stress in many basins. The percentage of water from each source varies, depending on irrigation practices, the amount of surface water available, and the crop type. In basins other than the Albuquerque-Belen and Mesilla, municipal, domestic, and industrial uses are not a primary use of water; therefore, irrigated acreage was compiled as an indicator of water use. Water use in the study area was most accurately estimated in the San Luis (Hearne and Dewey, 1988), Albuquerque-Belen (Kernodle and others, 1987), Mesilla (Frenzel and Kaehler, 1992), and Animas Basins (O'Brien and Stone, 1983) during development of ground-water flow models. Detailed water-use information for the above mentioned basins may be found in the discussion of the particular basin and in the referenced reports.

Table 10 summarizes irrigated acreage by basin and source of water. The water used per acre is variable, depending on the quantity of precipitation, the source of the water (ground or surface), the efficiency of the farm operation, and the crop being irrigated.

Eighty-one percent of the irrigated acreage is in basins adjacent to the Rio Grande (fig. 24). With the exception of the San Luis Basin, where the percentage of the acreage irrigated by surface or ground water is not available, about 60 percent of the irrigated acreage is irrigated with both surface and ground water. In the open drainage basins, 24 percent of the irrigated acreage is irrigated by only surface water, 10 percent is irrigated by only ground water, and 66 percent is irrigated by both.

In closed basins ground water is the source of water for 93 percent of the irrigated acreage. Surface water is the source for 6 percent of the irrigated acreage from the Mimbres River in the Mimbres Basin. Mixed surface water and ground water are the source for 1 percent of the irrigated acreage.

In basins where the population is growing, ground-water withdrawals for uses other than agriculture are becoming greater. Percentages for other than agricultural use given below are calculated using data from Sorensen (1977 and 1982), Wilson (1986), and Don White (Hydrologist, U.S. Geological Survey, oral commun., 1987). In 1975, 1980, and 1985, ground-water withdrawals for uses other than agriculture in the Albuquerque-Belen Basin were 94, 90, and 95 percent, respectively, of the total ground-water withdrawal. Total withdrawals were 135,000, 161,000, and 152,000 acre-feet in each respective year. In the Mesilla Basin, which has a smaller population and less industrial development, nonagricultural ground-water withdrawals were 32, 41, and 45 percent of the total ground-water withdrawals in 1975, 1980, and 1985, respectively. Total withdrawals from the system were 108,000, 99,000, and 108,000 acre-feet in each respective year. Water use is predominantly for agriculture in the Socorro Basin. Only the town of Socorro has significant municipal withdrawals. Therefore, nonagricultural uses were 21, 13, and 29 percent of total ground-water withdrawals for 1975, 1980, and 1985, respectively. Total withdrawals were 40,000, 32,800, and 19,700 acre-feet in each respective year. No significant nonagricultural ground-water withdrawals were made in the Mimbres Basin. Therefore, only 3, 4, and 4 percent of the total ground-water withdrawals of 156,000, 122,000, and 112,000 acre-feet, respectively, were used for nonagricultural uses in 1975, 1980, and 1985.

REGIONAL SYNTHESIS

Structurally and hydrologically the 22 basins of the Southwest Alluvial Basins study area can be divided into two general types: open basins that have surface-water discharge and closed basins that have no surface-water discharge. The Rio Grande is the primary hydrologic connection among basins that have surface-water discharge.

Basin-fill deposits, including fan deposits, river alluvium, and unconsolidated to consolidated sediments and some volcanics associated with the Santa Fe Group or Gila Conglomerate, are hydraulically connected and form an aquifer system. Lithologies reflect the geologic setting and depositional history of the basins; predominantly coarse-grained sediments were deposited by the relatively high energy, ancestral Rio Grande; whereas, fine-grained lake or playa sediments were deposited in topographically closed basins.

Ground-water flow simulations show that aquifer storage supplies from 25 percent of ground water withdrawn in the Albuquerque-Belen Basin to 10 percent withdrawn in the Mesilla Basin. The remainder of the ground water withdrawn comes from surface water and capture of water that otherwise would have been lost to evapotranspiration.

A regional potentiometric-surface map of the basin-fill aquifer system indicates that ground-water movement is generally from west and east to the center of the valleys and then southward. Throughout most of the study area, the Rio Grande flood plain acts as a drain for the basin-fill aquifer system.

Generally, calcium and magnesium are the predominant cations and bicarbonate is the predominant anion in ground water in basins along the Rio Grande and in the closed basins in southwestern New Mexico and western Texas. South and east of the Socorro Basin, extending into western Texas, calcium plus magnesium sulfate generally is the chemical water type. In the southern Tularosa-Hueco Basin, the water contains sodium chloride.

TABLE 10.—Irrigated acreage in alluvial basins, 1978-80.

[NA, only irrigation total is available; —, no data]

Basin	Surface water	Ground water	Combined water	Total
San Luis	NA	NA	NA	796,500
Española	22,600	420	730	23,750
Santo Domingo	34,100	1,200	24,600	59,900
Albuquerque-Belen	5,500	--	130	5,630
Socorro	2,300	--	12,000	14,300
La Jencia	--	--	--	--
San Agustin	--	600	--	600
San Marcial	--	--	--	--
Engle	590	320	330	1,240
Palomas	70	14,200	22,700	36,970
Jornada del Muerto	--	440	--	440
Mesilla	--	5,700	69,300	75,000
Tularosa-Hueco	650	6,400	47,800	54,850
Mimbres	11,000	51,000	1,000	63,000
Hachita	--	--	--	--
Playas	--	12,000	--	12,000
Animas	--	--	--	--
Lordsburg	--	--	1,100	1,100
Salt	--	--	5,000	5,000
Eagle	--	9,100	--	9,100
Redlight Draw	--	14,000	--	14,000
Presidio	--	73,000	--	73,000
Totals	[1]76,810	[1]188,380	[1]184,690	1,246,380

[1]Totals do not include acreage in the San Luis Valley, Colorado.

Principal processes that influence the chemistry of ground water in the study area are varied. The mixing of water from adjacent ground-water systems, geothermal systems, and along faults modifies water chemistry in the basin-fill aquifer system. The presence of Mesozoic and Paleozoic rocks along ground-water flow paths causes increases in ions dissolved from the rock. Ion exchange in clay-rich aquifer matrix allows cation exchange of calcium or magnesium for sodium.

Recharge is greater in the northern basins than in the southern basins. Runoff from high mountains adjacent to the basins is the primary source of recharge. Average annual estimated recharge ranges from 3,580 ft^3/s in the San Luis Basin to 6 ft^3/s in the Mesilla Basin.

Water use in the study area is changing with time and varies from basin to basin. The percentage of ground water withdrawn for nonagricultural uses is increasing as urban

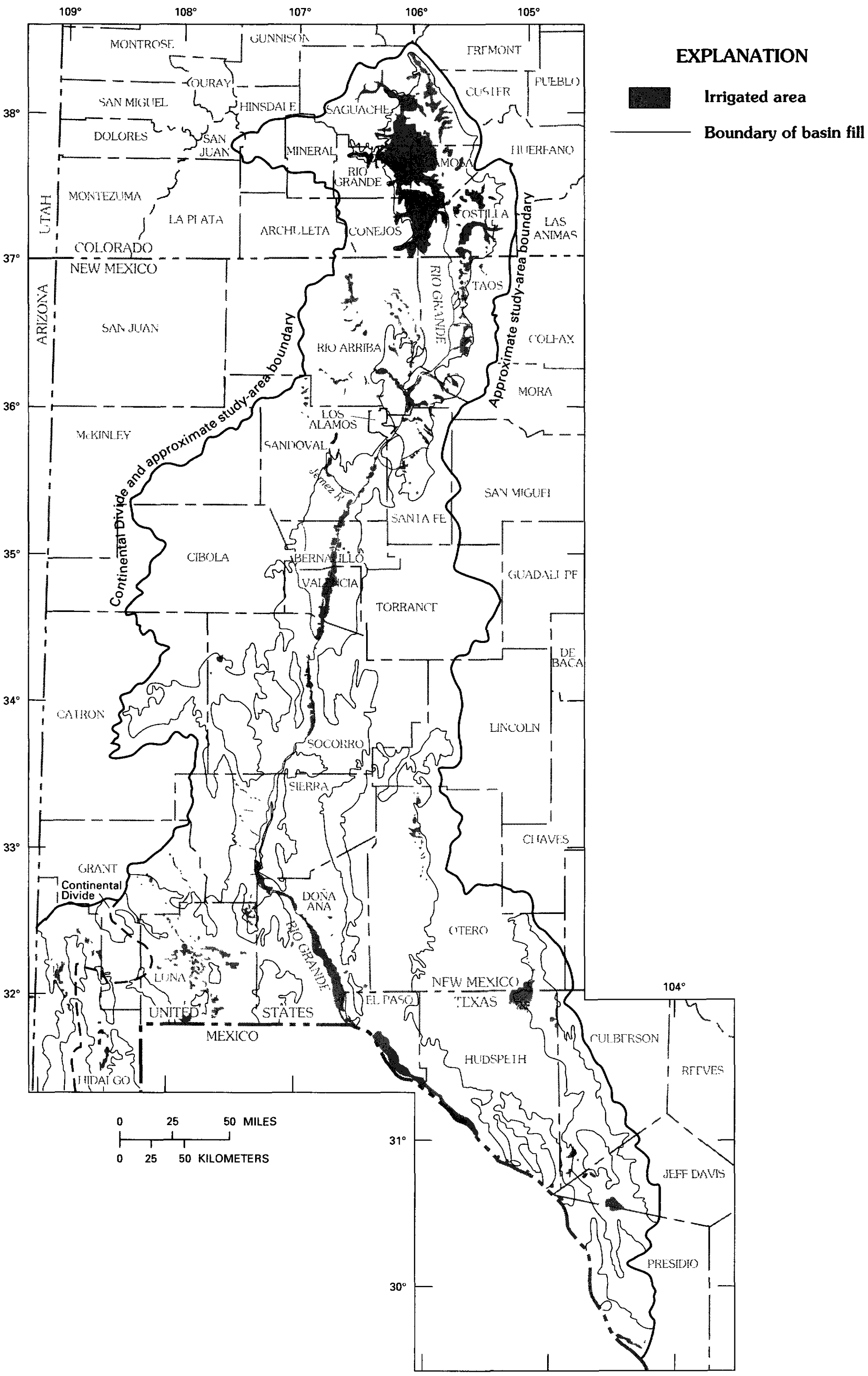


FIGURE 24.—Irrigated acreage, 1978-80.

areas and population in these areas increase. From 1975 to 1985 there was a 1-percent increase in nonagricultural ground-water withdrawals in the Albuquerque-Belen Basin, which represents an increase of more than 17,000 acre-feet. Similarly, there was a 1-percent increase in nonagricultural ground-water use in the Mimbres Basin relative to the total ground-water withdrawal. This actually amounts to a 200-acre-foot decrease in the amount of ground water withdrawn for nonagricultural use because of the overall decrease in total ground-water withdrawal from 1975 to 1985.

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