POSSIBLE CHANGES IN GROUND-WATER FLOW TO THE PECOS RIVER CAUSED BY SANTA ROSA LAKE, GUADALUPE COUNTY, NEW MEXICO

By Dennis W. Risser

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CONVERSION FACTORS

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

Multiply inch-pound units	By	To obtain metric units
foot	0.3048	meter
foot per day	0.3048	meter per day
foot per mile	0.1894	meter per kilometer
foot per year	0.3048	meter per year
square foot	0.0929	square meter
foot squared per day	0.0929	meter squared per day
cubic foot	0.02832	cubic meter
cubic foot per second	0.02832	cubic meter per second
gallon	3.785	liter
gallon per minute	0.06308	liter per second
inch	25.40	millimeter
mile	1.609	kilometer
acre	0.4047	hectare
acre-foot	0.001233	cubic hectometer

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows:

$$°C = 5/9\ (°F - 32)$$

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

POSSIBLE CHANGES IN GROUND-WATER FLOW TO THE PECOS RIVER CAUSED BY SANTA ROSA LAKE, GUADALUPE COUNTY, NEW MEXICO

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ABSTRACT

In 1980 Santa Rosa Dam began impounding water on the Pecos River about 7 miles north of Santa Rosa, New Mexico, to provide flood control, sediment control, and storage for irrigation. Santa Rosa Lake has caused changes in the ground-water-flow system, which may cause changes in the streamflow of the Pecos River that cannot be detected at the present streamflow-gaging stations. Data collected at these stations are used to measure the amount of water available for downstream users.

A three-dimensional ground-water-flow model for a 950-square-mile area between Anton Chico and Puerto de Luna was used to simulate the effects of Santa Rosa Lake on ground-water flow to a gaining reach of the Pecos River for lake levels of 4,675, 4,715, 4,725, 4,750, 4,776, and 4,797 feet above sea level and durations of impoundment of 30, 90, 182, and 365 days for all levels except 4,797 feet. These simulations indicated that streamflow in the Pecos River could increase by as much as 2 cubic feet per second between the dam and Puerto de Luna if the lake level were maintained at 4,797 feet for 90 days or 4,776 feet for 1 year. About 90 percent of this increased streamflow would occur less than 0.5 mile downstream from the dam, some of which would be measured at the streamflow-gaging station located 0.2 mile downstream from the dam.

Simulations also indicated that the lake will affect ground-water flow such that inflow to the study area may be decreased by as much as 1.9 cubic feet per second. This water may leave the Pecos River drainage basin or be diverted back to the Pecos River downstream from the gaging station near Puerto de Luna. In either case, this quantity represents a net loss of water upstream from Puerto de Luna. Most simulations indicated that the decrease in ground-water flow into the study area would be of about the same quantity as the simulated increase in streamflow downstream from the dam. Therefore, the net effect of the lake on the flow of the Pecos River in the study area appears to be negligible.

Analyses of water-level fluctuations, water budget of the lake, and base flow of the Pecos River did not indicate any change in ground-water flow to the Pecos River caused by the lake during 1980 to 1983. Model simulations indicated that the effect of lake levels below 4,750 feet on water levels in observation wells completed in the San Andres Limestone could not be distinguished from the effects of other hydrologic stresses.

INTRODUCTION

Background, Purpose, and Scope

The Flood Control Act of 1954 authorized construction of Los Esteros Dam on the Pecos River about 7 miles north of Santa Rosa, New Mexico (fig. 1). Operation of the dam began in April 1980, and in October 1980 the name of the dam and reservoir were officially changed to Santa Rosa Dam and Lake. The reservoir was constructed to provide flood control, sediment control, and irrigation storage on the Pecos River.

Construction of Santa Rosa Dam has raised questions concerning proper measurement of Pecos River water for downstream irrigation districts. The Fort Sumner Irrigation District is entitled to the base flow of the Pecos River in amounts as great as 100 cubic feet per second. During periods when there is no natural inflow to the river downstream from the streamflow-gaging station near Puerto de Luna, the Fort Sumner right is administered on the basis of flow at this station. However, the Fort Sumner Irrigation District is not entitled to any unmeasured seepage from the lake that may reappear in the Pecos River downstream from the dam. Seepage from the lake that returns to the Pecos River downstream from the streamflow-gaging station below Santa Rosa Dam might not be measured until it is gaged near Puerto de Luna. At that point, the returned seepage cannot be distinguished from the natural base flow of the Pecos River to which the Fort Sumner Irrigation District is entitled.

The purpose of this study was to investigate the possible effects of Santa Rosa Lake on ground-water flow to the Pecos River. Specifically, the study focused on changes in flow of the river upstream from the gaging station near Puerto de Luna. Two major mechanisms were recognized and studied that could alter the volume of ground-water flow to the Pecos River: (1) Direct seepage of water through the lake bed that could return to the Pecos River between the streamflow-gaging stations below the dam and near Puerto de Luna; and (2) changes in the local ground-water-flow system caused by filling Santa Rosa Lake such that natural ground-water flow to the Pecos River is altered.

The scope of the study included surface and ground water in an area of about 950 square miles in the vicinity of the lake (fig. 1). The large study area was necessary because at high lake levels changes in the existing hydrologic system could extend several miles from the lake. Empirical methods and a mathematical model were used to investigate effects of the lake on the hydrologic system. The scope of this study was limited to estimating the change in ground-water flow to the Pecos River upstream from the streamflow-gaging station near Puerto de Luna. The effects on streamflow in the Pecos River caused by evaporation from the lake or by regulation of stormflows were not directly studied. Because the lake has held water for only a few years, the hydrologic data needed to estimate its effect on ground-water flow to the Pecos River are sparse; therefore, the effects of the lake mainly were estimated using the mathematical model.

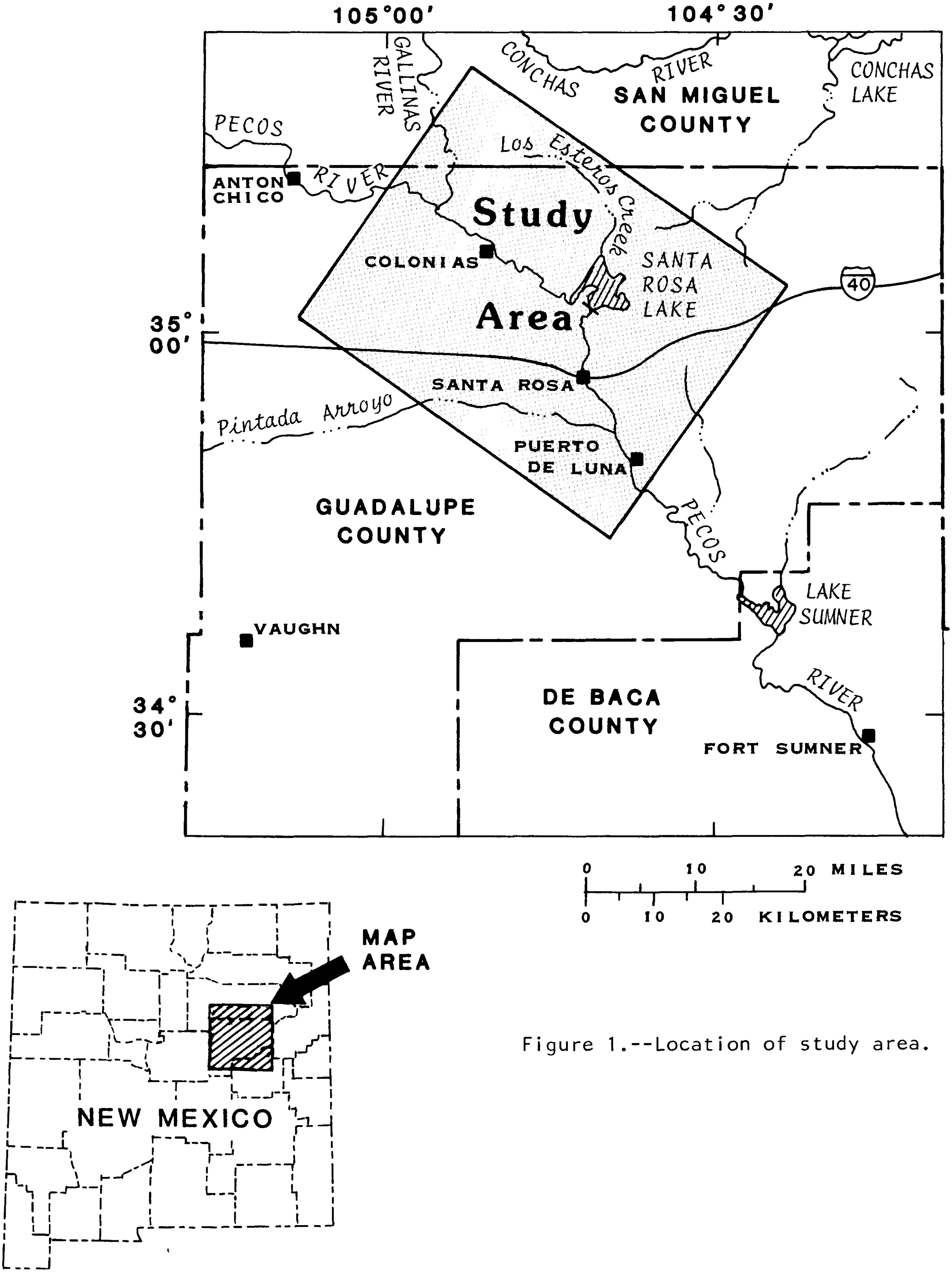


Figure 1.--Location of study area.

Location and Geographic Setting

Santa Rosa Dam is located on the Pecos River at river mile 766, about 7 miles north of the city of Santa Rosa (fig. 1). At its spillway capacity of 447,000 acre-feet, the lake will have a surface area of about 11,000 acres and have 80,000 acre-feet available for sediment storage, 200,000 acre-feet for irrigation storage, and 167,000 acre-feet for storage of floodwater (Hernandez, 1971, p. 11).

The study area includes about 950 square miles in the vicinity of the lake, extending from near Anton Chico to Puerto de Luna (fig. 1). The study area is part of the Pecos Valley section of the Great Plains physiographic province, characterized by rolling plains, rocky canyons, and karst topography (Fenneman, 1931, p. 274). Maximum relief in the study area is about 1,100 feet. The Pecos River is the major stream in the area, and it flows to the southeast at an average gradient of about 9 feet per mile. Major tributaries of the Pecos River include Gallinas River, Los Esteros Creek, and Pintada Arroyo.

The climate of the area can be classified as semiarid (Longwell and others, 1969, p. 288). Annual precipitation recorded at Santa Rosa during 1941 to 1970 averaged 14.0 inches, of which 70 percent occurred during May to September. Annual temperature at Santa Rosa for the same period averaged 57.0 °Fahrenheit. July had the highest average temperature of 77.4 °Fahrenheit during 1941 to 1970 and January had the lowest average of 38.8 °Fahrenheit during this period (U.S. Department of Commerce, 1979-80).

Santa Rosa has a population of 2,469 and is the major city in the study area (U.S. Department of Commerce, 1981, p. 4). The city is located on Interstate 40, the principal highway in east-central New Mexico. Additional small towns include Colonias, on the Pecos River northwest of Santa Rosa, and Puerto de Luna, on the river about 8 miles south of Santa Rosa.

Previous Investigations

A number of previous studies have been made of the hydrology in the vicinity of Santa Rosa Dam and Lake. The National Resources Planning Board (1942) published an investigation of the Pecos River that includes a description of surface- and ground-water relations, miscellaneous water-quality and streamflow measurements, and a historical account of water use in the upper basin. A detailed investigation pertaining to the design of Santa Rosa Dam and Lake was conducted by the U.S. Army Corps of Engineers (1959, 1960, and 1970). The reports contain interpretations of the hydrology and geology near the dam site based on data obtained by core drilling, water-quality sampling, and stream gaging. Hernandez (1971) reported on various methods to manage water resources of the Pecos Basin. He discussed, in general terms, the possibility of seepage from Santa Rosa Lake and the effects of that seepage on the quality of streamflow in the Pecos River. The possibility of large volumes of water seeping from Santa Rosa Lake also was briefly discussed by Spiegel (1972). The water resources of Guadalupe County were investigated by Dinwiddie and Clebsch (1973). Their study includes a geologic survey of the county, inventory of wells and springs, and measurements of streamflow gains and losses in the Pecos River between Anton Chico and Puerto de Luna.

Methods of Investigation

To monitor potential effects of Santa Rosa Lake on ground water, eight observation wells numbered E1 through E8 were drilled in 1975 and completed in the Bernal Formation, San Andres Limestone, and Glorieta Sandstone (figs. 2-3 and table 1). The wells were located mainly between River Ranch and Santa Rosa along a likely path of seepage that might occur when the lake covers small outcrops of San Andres Limestone near River Ranch. Six of these wells and one well located in the city of Santa Rosa well field were instrumented with continuous recorders to monitor water-level changes. Water-level changes in the remaining two E-series wells (E3 and E4) were measured periodically using a steel tape. Although these wells were drilled to monitor water-level changes caused by impoundment of water in the lake, it became apparent that many cycles of rising and falling lake levels would be needed to estimate seepage directly using these wells.

The New Mexico State Engineer decided in 1980 that estimates of the effects of the lake on base flow in the Pecos River could not be delayed until many cycles of lake-level fluctuations were recorded. Because of this decision, a three-dimensional ground-water-flow model was used to estimate the potential effects of the lake on ground-water flow to the Pecos River at various pool elevations and durations of impoundment. To aid in development of the model, several shallow wells completed in the Santa Rosa Sandstone and core holes with piezometers completed in the San Andres Limestone were added to the ground-water-monitoring network (fig. 2).

An analysis of base flow in the Pecos River and a water budget of the lake also were used to investigate the effect of the lake on streamflow since the beginning of reservoir operation in 1980. Calculations were based mainly on streamflow records at gaging stations within and near the study area (fig. 2).

This report contains a description of the geohydrology of the study area as it existed prior to impoundment of water in Santa Rosa Lake. Also, the measured and potential effects of the lake on ground-water levels and ground-water flow to the Pecos River are evaluated.

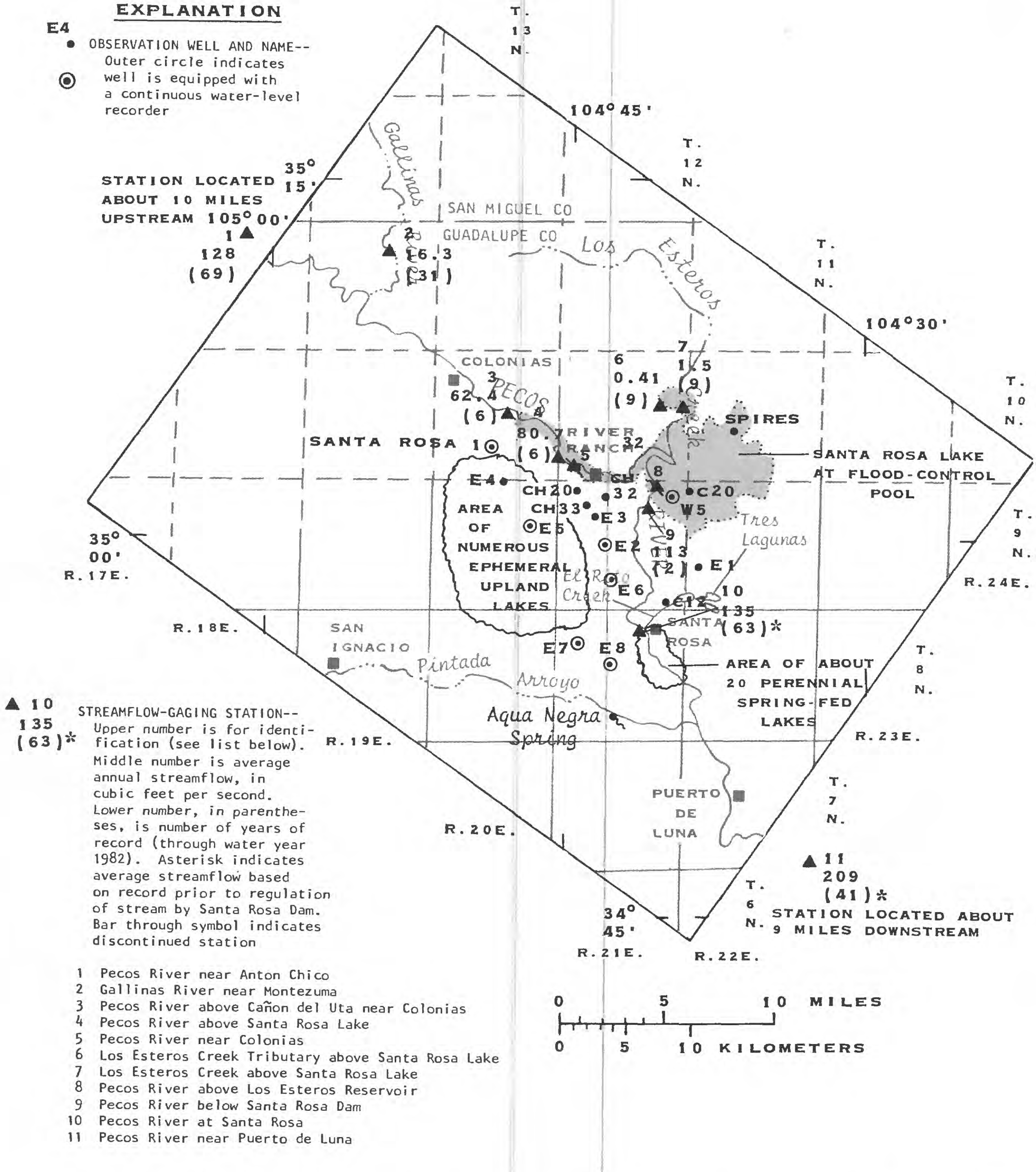


Figure 2.--Location of observation wells and surface-water gaging stations.

SYSTEM	FORMATION	LITHOLOGY	ESTIMATED THICKNESS	DESCRIPTION AND LOCATION	MODEL LAYER
QUATERNARY AND TERTIARY	Alluvium and caliche		0 to 250	Surficial deposits of sand and gravel capped by caliche in places. On upland areas, gravels are outliers of the Ogallala Formation. Alluvium in collapse depression around Santa Rosa is as much as 250 feet thick.	
TRIASSIC	Chinle Formation		About 800	Reddish-brown shale and siltstone with gray, brown, and purple sandstone layers. Also contains thin layers of limestone and conglomerate. Exposed in study area on uplands east of Pecos River and west of Colonias.	1
	Santa Rosa Sandstone		250 to 350	Upper member is fine-grained, gray to brown sandstone. Shale member of red to gray shale is as much as 50 feet thick. Middle sandstone is medium to coarse grained. Lower purplish-red sandstone is fine grained. Santa Rosa Sandstone is present beneath most of study area. Exposed in west and north part of area.	
PERMIAN	Bernal Formation		50 to 300	Mostly red and gray siltstone, shale and fine-grained sandstone. Also contains seams of anhydrite and limestone. Formation is present beneath entire area except near Esterito Dome. Crops out mainly along Pecos River and Pintada Arroyo.	2
	San Andres Limestone		90 to 300	Consists of dense gray limestone and anhydrite. Dolomite and gray shale are common in thin layers. Evidence of solution and collapse in western and southern parts of study area. Exposed on Esteritos Dome and along Pecos River near Colonias and River Ranch.	3
	Glorieta Sandstone		400 to 500	Light-gray to tan, massive, well-cemented quartzose sandstone. Present beneath entire study area. Exposed on Esteritos Dome (fig. 5).	

EXPLANATION

CALICHE — SHALE — SILTSTONE — LIMESTONE

SAND AND GRAVEL — SANDSTONE — ANHYDRITE — DOLOMITE

Figure 3.--Generalized stratigraphic section and designated model layers of exposed geologic units.

Table 1. Completion and water-level data for selected observation wells

Well name	Latitude	Longitude	Altitude above sea level (feet)	Depth to water: Feet below land surface	Depth to water: Date	Possible water-bearing units[1/]	Depth cased (feet)	Total depth (feet)	Comments
E7	35°56'13"	104°44'47"	4,750	146.0	11-30-81	₹s, Pb, Psa	455	472	Open hole 455-472 feet
E8	35°55'18"	104°43'07"	4,773	170.7	11-30-81	₹s, Pb, Psa	320	341	Open hole 320-341 feet
E5	35°00'57"	104°47'06"	5,188	506.3	11-30-81	Pb, Psa, Pg	386	815	Open hole 386-815 feet
C20	35°02'18"	104°39'32"	4,715	33.9	6-23-81	₹s	--	75	--
W5	35°01'27"	104°40'08"	4,734	37.5	12-01-81	₹s	--	103	--
CH20	35°02'24"	104°44'52"	5,127	271.6	6-24-82	Pb(?), Psa	379	379	1¼-inch-diameter piezometer
CH32	35°02'04"	104°43'37"	5,014	148.0	12-01-81	₹s(?), Pb(?), Psa	391	391	1¼-inch-diameter piezometer
CH33	35°01'48"	104°44'22"	5,093	149.0	6-24-82	₹s(?), Pb(?), Psa	474	474	1¼-inch-diameter piezometer
E3	35°01'25"	104°44'02"	4,142	545.5	11-30-81	Psa, Pg	591	837	Open hole 591-837 feet
E2	35°00'07"	104°43'33"	5,001	371.1	11-30-81	Pb, Psa, Pg	311	785	Open hole 311-785 feet
E6	34°58'21"	104°43'17"	4,997	368.8	11-30-81	Pb, Psa, Pg	391	837	Open hole 391-837 feet
E1	34°59'16"	104°39'07"	4,918	315.6	11-30-81	Pb, Psa, Pg	402	843	Open hole 402-843 feet
Santa Rosa 1	35°04'11"	104°49'01"	5,163	357.3	11-29-81	Psa	575	575	Casing perforated 515-575 feet
E4	35°02'33"	104°48'28"	5,157	362.5	11-30-81	Psa, Pg	590	597	Open hole 590-597 feet
Spires	35°04'43"	104°37'13"	4,794	68.31	1-12-81	₹s	--	185	--

1/ Possible water-bearing units include all rocks in which the well is completed. They are:

₹s, Santa Rosa Sandstone;
Pb, Bernal Formation;
Psa, San Andres Limestone;
Pg, Glorieta Sandstone.

GEOLOGY

The flow of ground water is controlled, in part, by the relative stratigraphic position and structure of geologic units that have differing hydrologic properties. The following sections describe the rocks that crop out in the study area.

Generalized Stratigraphy

Geologic units exposed in the study area range in age from Permian to Quaternary, the oldest of which is the Glorieta Sandstone (fig. 3). The Glorieta Sandstone is a grayish, well-cemented, quartz sandstone where it crops out along the Pecos River northwest of Colonias (fig. 4). The thickness of the unit is estimated to be 400 to 500 feet (Gorman and Robeck, 1946) although few wells in the area penetrate the entire formation.

The San Andres Limestone, which conformably overlies the Glorieta Sandstone, mainly is composed of thick, massive units of anhydrite and dense, gray limestone. From outcrop areas near Colonias (fig. 4), the San Andres thickens to about 300 feet in the eastern part of the study area, mainly due to the addition of anhydrite. Extensive solutioning of the formation is noticeable on outcrops and is indicated by depressions in the land surface west of the river between Colonias and Puerto de Luna. Observation wells E7 and E8 located in the large depression around Santa Rosa indicate that the San Andres Limestone has been mostly removed by solution at that location. These wells penetrated as much as 100 feet of residual San Andres Limestone mixed with broken blocks of the Bernal Formation and Santa Rosa Sandstone. Conversely, in the vicinity of the dam, data obtained by test drilling, water-quality sampling, and water-level monitoring indicate the existence of a thick sequence of anhydrite, limestone, and dolomite, lacking any evidence of solutioning. East and north of the Pecos River, little is known about the character of the San Andres Limestone. However, in general, the unit thickens to the east and contains increasing amounts of evaporites (Dinwiddie and Clebsch, 1973, p. 6).

The Bernal Formation, mainly composed of shale and siltstone with lenses of sandstone and gypsum, conformably overlies the San Andres Limestone. The Bernal Formation is exposed along the Pecos River and Pintada Arroyo (fig. 4). Thickness of the formation varies from about 50 to 300 feet and probably is thickest in the eastern part of the study area. In areas where part of the San Andres Limestone has been removed by solution, the overlying Bernal Formation has collapsed and also has been affected by solution. Solution and collapse features are especially evident in the depression around Santa Rosa.

The Santa Rosa Sandstone unconformably overlies the Bernal Formation and is composed of as much as 350 feet of sandstone and shale. The upper one-third to one-half of the formation consists of fine-grained sandstone. In some parts of the study area, as much as 50 feet of shale is present beneath the upper sandstone. In other areas, the shale is absent and a fine-grained reddish sandstone is present in the lower part of the formation. The Santa Rosa Sandstone can be found throughout most of the study area except along certain parts of the Pecos River and Pintada Arroyo (fig. 4).

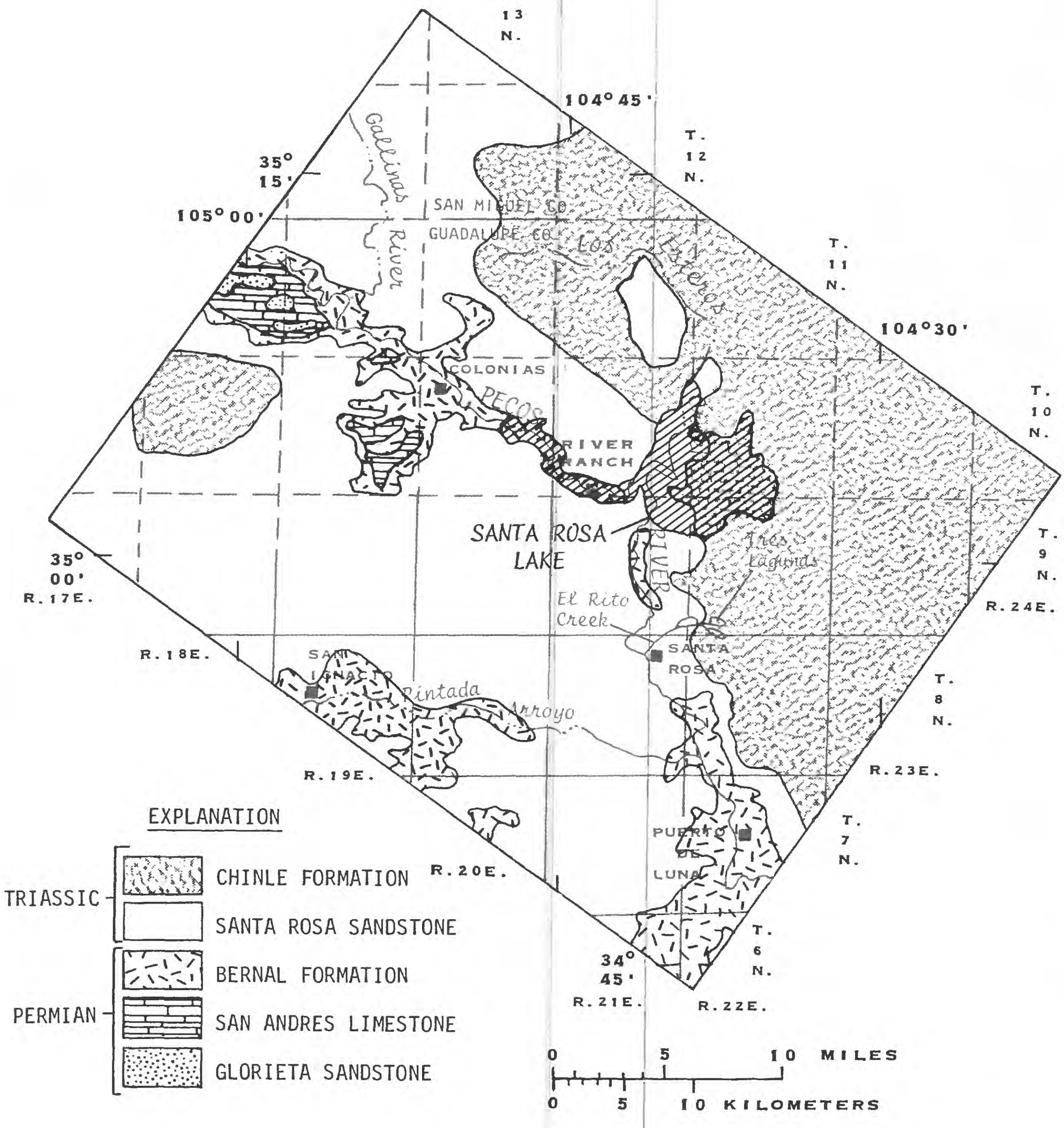


Figure 4.--Generalized geology.

The Chinle Formation conformably overlies the Santa Rosa Sandstone and mainly consists of reddish-brown and purple shale, siltstone, and thin sandstone beds. The Chinle Formation crops out east of the Pecos River and in a small upland area about 8 miles west of Colonias (fig. 4). The thickness of the formation increases eastward to a maximum of about 800 feet.

Surficial deposits of sand, gravel, silt, and clay of Tertiary and Quaternary age mantle the bedrock units in many parts of the study area. Some upland areas are covered by sand and gravel of the Ogallala Formation that are capped by caliche. Along the river valleys, the alluvial fill is as much as 60 feet thick; in the collapse depression around Santa Rosa, the alluvium is as much as 250 feet thick.

Generalized Structure

The regional dip of geologic units in the study area is about 40 to 80 feet per mile to the east. However, several small structural features modify the regional dip locally as shown in figure 5. The most easily identified structures are the Esteritos Dome, Bar Y Dome, Guadalupe Anticline, River Ranch Anticline, and Santa Rosa Sink (Gorman and Robeck, 1946; U.S. Army Corps of Engineers, 1970, pl. 4; Kelley, 1972, p. 218). Faults with small displacements probably are associated with the uplifts and some are visible in the canyon of the Pecos River; however, there is no evidence of major faulting in the study area and faults probably do not significantly affect the regional flow of ground water. Fracture sets that trend northwest to southeast and northeast to southwest are clearly visible on aerial photographs and in sinkhole alignment.

The structure of rocks younger than the Glorieta Sandstone has been extensively modified west of the Pecos River by solution of anhydrite, gypsum, and limestone in the San Andres Limestone and by collapse of overlying formations. Most of the dissolution probably took place during Late Permian time, when the San Andres Limestone was exposed at or near land surface, but much of the collapse occurred after deposition of the Santa Rosa Sandstone of Triassic age and is continuing at the present time. The most obvious evidence of solution and collapse is the large depression about 6 miles in diameter, within which the city of Santa Rosa is located (fig. 5). Information from drilling wells E7 and E8 indicates that this structure, named the Santa Rosa Sink by Kelley (1972, p. 218), contains alluvium deposited by the Pecos River and the eroded remnants of Santa Rosa Sandstone, Bernal Formation, and San Andres Limestone. West of the Pecos River between Colonias and Santa Rosa, sinkholes and swales have developed at the land surface, which may indicate dissolution of the San Andres Limestone. However, some of the shallow swales on the upland area may be blowout features formed on thin outliers of the Ogallala Formation; they may not be related to solution and collapse of underlying formations. Near Santa Rosa Lake, and in general, east and north of the Pecos River, the surface expression of solution and collapse is absent. Either dissolution of the San Andres Limestone did not occur in these areas or the greater thickness of rocks overlying the formation has masked the effects of dissolution.

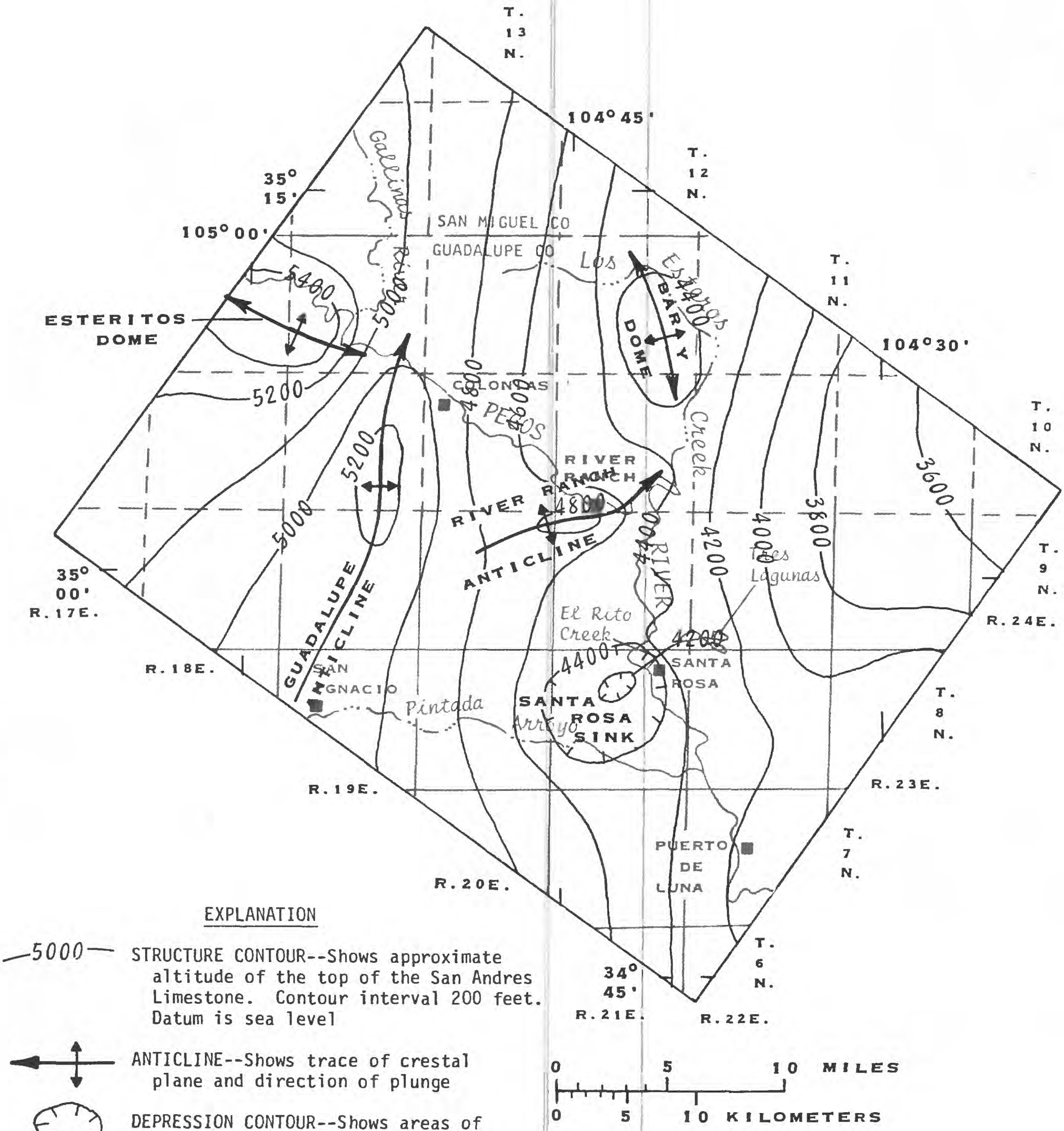


Figure 5.--Structure-contour map of the San Andres Limestone.

SURFACE WATER

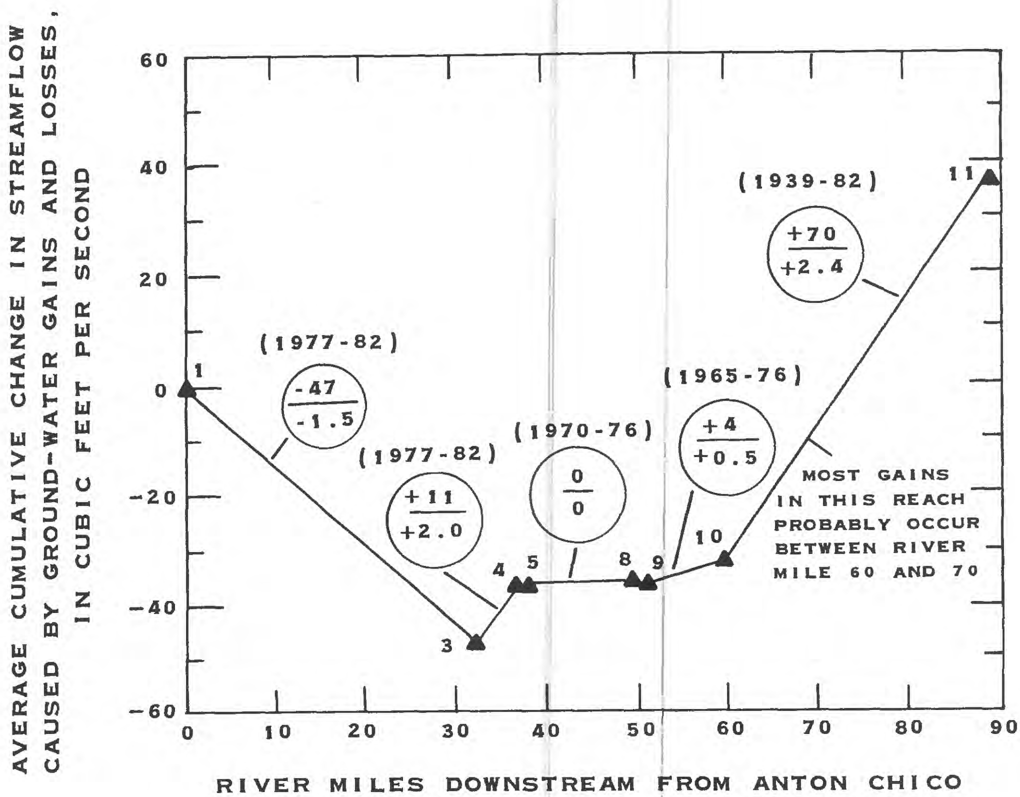
Surface and ground water are difficult to describe separately because interchange of water between the surface and subsurface occurs throughout the study area. For example, the base flow of the Pecos River near Anton Chico is from ground water. Some of this base flow returns to the ground-water system upstream from Colonias and probably then returns to the Pecos River downstream from Colonias and Santa Rosa. Also, the frequent rise and fall of water levels in Santa Rosa Lake cause water to move in and out of bank storage. Therefore, the ground-water and surface-water relations near the lake are dynamic, and what is ground water at one place and time later returns to the surface.

Pecos River

The Pecos River is the major stream in the study area and in east-central New Mexico. Streamflow in the Pecos is contributed by rainstorms, runoff from snowmelt, and base flow from ground water. The average annual streamflow of the Pecos River in the vicinity of the study area ranges from 62.4 to 209 cubic feet per second (fig. 2). The large range of streamflow is caused by inflow from tributaries and ground-water gains and losses. Several investigations have documented the gaining and losing reaches of the Pecos River between Anton Chico and Puerto de Luna (Dinwiddie and Clebsch, 1973, p. 11).

Streamflow-gaging stations installed in 1976 provide additional information on the average quantity of water gained or lost in various reaches. In the 32 stream miles between the streamflow-gaging stations near Anton Chico and above Cañon del Uta (fig. 6), an average of about 47 cubic feet per second of water was lost to seepage into the San Andres Limestone and Bernal Formation from 1977 to 1982. The loss is so large in this reach that in the fall and early winter months the Pecos River commonly is dry from about 6 miles upstream to about 3 miles downstream from Colonias. Downstream from the gaging station above Cañon del Uta, the streamflow of the Pecos River increases because of ground-water discharge. The largest increase (76 cubic feet per second) was measured between Santa Rosa and the gaging station near Puerto de Luna. The many large springs that discharge as much as 6.7 cubic feet per second (Dinwiddie and Clebsch, 1973, p. 39) provide most of the increase in streamflow between Santa Rosa and the point where Rio Agua Negra joins the Pecos River.

Although the years of record shown in figure 6 for determining streamflow gains and losses for various reaches are different, they are representative of long-term changes. For example, the long-term (1939-82) gain in streamflow between Santa Rosa and Puerto de Luna was 70 cubic feet per second (fig. 6). The gain was 66 cubic feet per second for 1970-76 and 67 cubic feet per second for 1977-82.



EXPLANATION

▲3 STREAMFLOW-GAGING STATION AND IDENTIFICATION NUMBER--Location of stations is shown in figure 2

(1939-82)—YEARS OF STREAMFLOW RECORD USED FOR CALCULATION

+70 — AVERAGE CHANGE IN STREAMFLOW BETWEEN STATIONS CAUSED BY GROUND-WATER GAIN OR LOSS

+2.4 — AVERAGE CHANGE IN STREAMFLOW PER RIVER MILE CAUSED BY GROUND-WATER GAIN OR LOSS

Figure 6.--Average change in streamflow in the Pecos River between Anton Chico and Puerto de Luna caused by ground-water gains and losses.

Tributaries of the Pecos River

The major tributaries of the Pecos River are the Gallinas River and Pintada Arroyo. Average annual streamflow of the Gallinas River at the gaging station near Colonias was 16.3 cubic feet per second, based on records for water years 1951-82 (fig. 2). However, the stream is not perennial where it joins the Pecos River and commonly is dry many days between June and October. Pintada Arroyo is ephemeral throughout most of its length, but about 4 miles upstream from where it joins the Pecos River, springs supply 10 to 15 cubic feet per second of water to the arroyo (U.S. Geological Survey, 1964, p. 599; U.S. Geological Survey, 1967, p. 572). Downstream from Agua Negra Spring, the stream is called Rio Agua Negra (fig. 2). Other tributaries to the Pecos River in the study area are ephemeral, flowing only for short periods after storms.

Lakes

Many perennial and ephemeral lakes have formed in sinkholes and in upland closed depressions that are common in the study area. About 20 perennial lakes are sustained by ground-water discharge in the Pecos Valley near Santa Rosa (fig. 2). In the upland areas west and northwest of Santa Rosa, numerous lakes, most of which are ephemeral, occupy broad depressions in the upland surface. Water in these lakes is supplied by surface drainage. Manmade lakes in the area include Tres Lagunas and Santa Rosa Lake. Tres Lagunas was constructed by the Rock Island Railway on El Rito Creek and was used for part of the water supply for Santa Rosa in the 1950's. Santa Rosa Dam, on the Pecos River about 7 miles north of Santa Rosa, first impounded water in 1980. Although the lake has a maximum capacity of 447,000 acre-feet, the maximum amount of water stored in the lake from April 1980 through September 1983 was 79,500 acre-feet.

GROUND WATER

The objective of this section is to describe the ground-water-flow system in the vicinity of Santa Rosa Lake. The analysis of ground-water movement, recharge rates, discharge rates, aquifer and confining-bed hydraulic properties, and water-level fluctuations will be used in estimating the possible change in ground-water flow to the Pecos River caused by Santa Rosa Lake.

Recharge, Movement, and Discharge

The average quantity of natural ground-water recharge in the entire Pecos River watershed can be approximated using base flow of the Pecos River. Because base flow is contributed from ground water, the quantity of base flow determined from streamflow-gaging records represents an approximate quantity of recharge to aquifers in the basin. Some ground water may be lost through evapotranspiration from the water table and as underflow to another ground-water basin; therefore, if these terms are large, they need to be added to base flow to provide the most accurate estimate of recharge.

Base flow at the streamflow-gaging station near Puerto de Luna averaged 88 cubic feet per second from 1939 to 1982. Base flow was separated by a method described by Welder (1973). Ground-water losses to evaporation from lakes and swamps near Santa Rosa may be about 5 cubic feet per second based on their surface area and an average annual evaporation rate of 65 inches per year (U.S. Department of Agriculture, 1972). Consumptive use of ground water by phreatophytes is not known. Underflow probably occurs to some extent in the San Andres Limestone and older aquifers, but the Pecos River is the major discharge area for the San Andres Limestone and younger rocks. The quantity of underflow probably is small because the San Andres Limestone is not very permeable east of the Pecos River.

Total ground-water recharge in the Pecos River basin was estimated from the sum of base flow plus estimated losses of ground water to evaporation. Base flow plus evaporation losses equal about 93 cubic feet per second, which corresponds to about 0.32 inch per year of recharge over the 3,970-square-mile drainage basin upstream from the streamflow-gaging station near Puerto de Luna. Because evapotranspiration and underflow are not known, 0.32 inch is a conservative estimate of the average ground-water recharge rate for the watershed as a whole. Recharge, movement, and discharge of ground water in each geologic unit are discussed in the following sections.

Chinle Formation

Ground water occurs in the Chinle Formation under water-table conditions mainly in areas east and north of the Pecos River where the formation crops out (fig. 4). The formation mostly is composed of shale; however, isolated sandstone units commonly contain perched water. These perched water supplies probably are recharged on outcrop areas by precipitation and ephemeral streamflow. The Chinle Formation does not receive water by leakage from adjacent aquifers because it occupies the highest topographic positions in the study area.

Available water-level data indicate that the horizontal component of ground-water flow in the Chinle Formation is toward the Pecos River (fig. 7) except in the easternmost part of the study area where the flow is toward the Canadian River basin. Although vertical hydraulic gradients have not been measured, the decrease in hydraulic head with depth probably is large because most of the formation is shale. Ground water in the Chinle Formation probably discharges mainly as leakage to the underlying Santa Rosa Sandstone or as minor amounts of seepage to small tributaries along the Pecos Valley.

Santa Rosa Sandstone

Ground water occurs in the Santa Rosa Sandstone under water-table conditions in the western two-thirds of the study area where the formation crops out (fig. 4). Recharge to the Santa Rosa Sandstone probably is provided mainly by precipitation and seepage from ephemeral streams and lakes. East of the Pecos River, ground water in the Santa Rosa Sandstone may be confined by the overlying Chinle Formation. Small quantities of recharge to the Santa Rosa Sandstone in this area probably are supplied by downward leakage from the Chinle Formation.

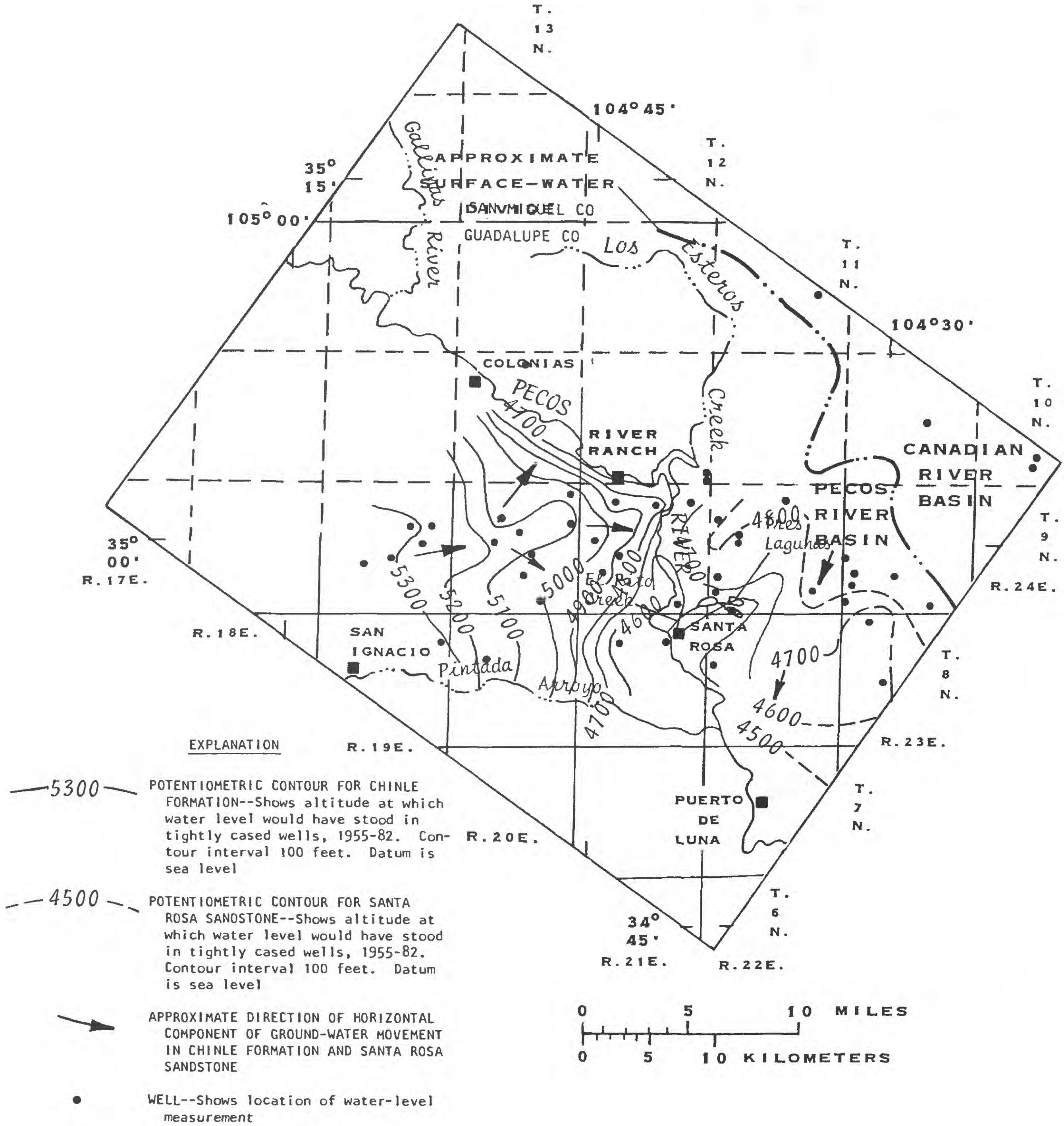


Figure 7.--Potentiometric surface of water in the Chinle Formation and Santa Rosa Sandstone.

The potentiometric surface and horizontal component of ground-water movement in the Santa Rosa Sandstone are shown for part of the study area in figure 7. On the basis of these data, ground water moves toward the Pecos River. Vertical gradients within the formation probably are downward in most areas because of the high topographic position of the formation. However, because the underlying Bernal Formation is much less permeable than the Santa Rosa Sandstone, most ground-water flow in the Santa Rosa Sandstone probably is horizontal. Throughout most of the study area, where the Pecos River has cut into the Santa Rosa Sandstone, ground water discharges from small springs that have formed along the river at the contact between the Santa Rosa Sandstone and Bernal Formation. Where the Pecos River flows on the Santa Rosa Sandstone, ground water probably discharges directly to the river.

The rate of flow in the Santa Rosa Sandstone can be approximated using a flow net constructed of "squares" and a modified form of Darcy's Law:

$$Q = \frac{T(\Delta h)n}{86{,}400}$$

where:

Q = estimated ground-water flow in the Santa Rosa Sandstone, in cubic feet per second;
T = average value of transmissivity, in feet squared per day;
Δh = change in hydraulic head between potentiometric contour lines, in feet; and
n = number of constructed "square" flow tubes (unitless).

The rate of ground-water flow in the Santa Rosa Sandstone between potentiometric contours of 5,200 and 5,300 feet (fig. 7) was estimated from a flow net constructed of seven "square" tubes and from an assumed transmissivity of 100 feet squared per day as shown below.

$$Q = \frac{(100 \text{ feet squared/day})\ (100 \text{ feet})\ (7)}{86{,}400 \text{ seconds per day}} = 0.8 \text{ cubic foot per second}$$

A similar calculation can be made to determine the quantity of flow through the same cross section between potentiometric contours of 4,800 and 4,900 feet assuming that the transmissivity remains constant. Because the 4,800-foot and 4,900-foot contour lines are closer together than the 5,200-foot and 5,300-foot lines, the number of square flow tubes required is proportionately greater.

$$Q = \frac{(100 \text{ feet squared/day})\ (100 \text{ feet})\ (24)}{86{,}400 \text{ seconds per day}} = 2.8 \text{ cubic feet per second}$$

The difference between the two estimates may represent ground-water accretion caused by recharge from precipitation and surface water. The accretion rate of 2.0 cubic feet per second, which takes place over an area of about 80 square miles, indicates a recharge rate of about 0.18 inch per year. The rate of 0.18 inch per year is about 1.3 percent of the 14 inches of mean annual precipitation recorded at Santa Rosa. The value is not exact because the saturated thickness (and hence, transmissivity) likely decreases between the upgradient and downgradient sections used to estimate ground-water flow. Also, no accounting is made for water that leaks downward to the Bernal Formation between the two sections. However, if these errors are small, then the calculated value may be useful as a rough estimate of the rate of recharge to the Santa Rosa Sandstone.

Bernal Formation

This formation acts as a confining unit in the study area. Because it is composed mainly of shale and siltstone, movement of water is impeded. However, numerous stock wells obtain small quantities of water from the Bernal Formation in the southern part of the study area. Some of these wells probably derive water from discontinuous sandstone lenses interbedded within the less permeable shale and siltstone. Most wells completed in the Bernal Formation are located in or near the Santa Rosa Sink, where the transmissivity has been increased due to dissolution of the underlying San Andres Limestone and collapse of the Bernal Formation.

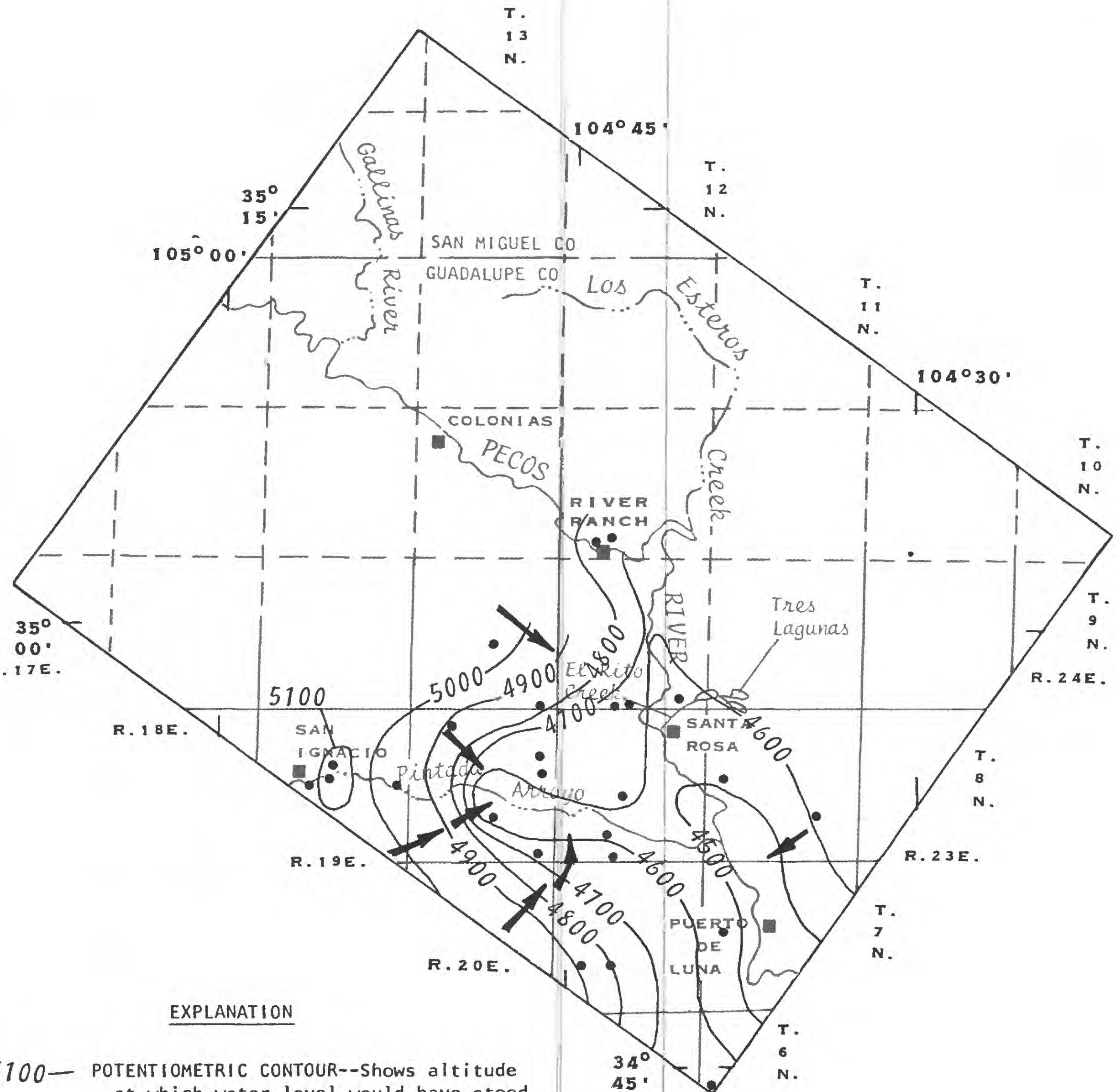
The horizontal component of ground-water movement in the Bernal Formation is toward Pintada Arroyo and the Pecos River (fig. 8). Part of the ground-water flow in the Bernal Formation probably discharges along Pintada Arroyo and the Pecos River as small springs and seeps. The large springs downstream from Santa Rosa probably discharge water from the San Andres Limestone that leaks upward through the Bernal Formation.

Water probably moves mostly in the vertical direction through the Bernal Formation. The difference in hydraulic head between the Santa Rosa Sandstone and San Andres Limestone about 10 miles west of Santa Rosa Dam is as great as 300 feet. The quantity of vertical flow of water can be estimated using Darcy's Law and making the following assumptions: (1) The difference in hydraulic head between the top and bottom of the Bernal Formation is 300 feet; (2) the thickness of the Bernal Formation is 300 feet; and (3) the range in vertical hydraulic conductivity of the Bernal is from 10^{-12} to 10^{-9} foot per second, based on studies of similar confining beds (Konikow, 1976; Frenzel and Lyford, 1982; Bredehoeft and others, 1983). The quantity of estimated vertical flow is:

$$Q = (dh/dl)\ K_z\ A$$

where:

Q = estimated rate of vertical ground-water flow, in cubic feet per second;
dh/dl = vertical hydraulic gradient;
K_z = vertical hydraulic conductivity, in feet per second; and
A = surface area over which leakage is being calculated, in square feet.



EXPLANATION

—5100— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, 1955-82. Contour interval 100 feet. Datum is sea level

APPROXIMATE DIRECTION OF HORIZONTAL COMPONENT OF GROUND-WATER MOVEMENT IN THE BERNAL FORMATION

• WELL--Shows location of water-level measurement

0 5 10 MILES

0 5 10 KILOMETERS

Figure 8.--Potentiometric surface of water in the Bernal Formation.

Therefore, over 1 square mile of surface area, the rate of vertical flow is:

$$Q = (300 \text{ feet}/300 \text{ feet}) \times (10^{-12} \text{ to } 10^{-9} \text{ foot per second}) \times (5{,}280 \text{ feet})^2$$
$$= 0.000028 \text{ to } 0.028 \text{ cubic foot per second.}$$

Although these rates are small, throughout the 950-square-mile study area, significant quantities of water may move through the Bernal Formation where large vertical hydraulic gradients exist.

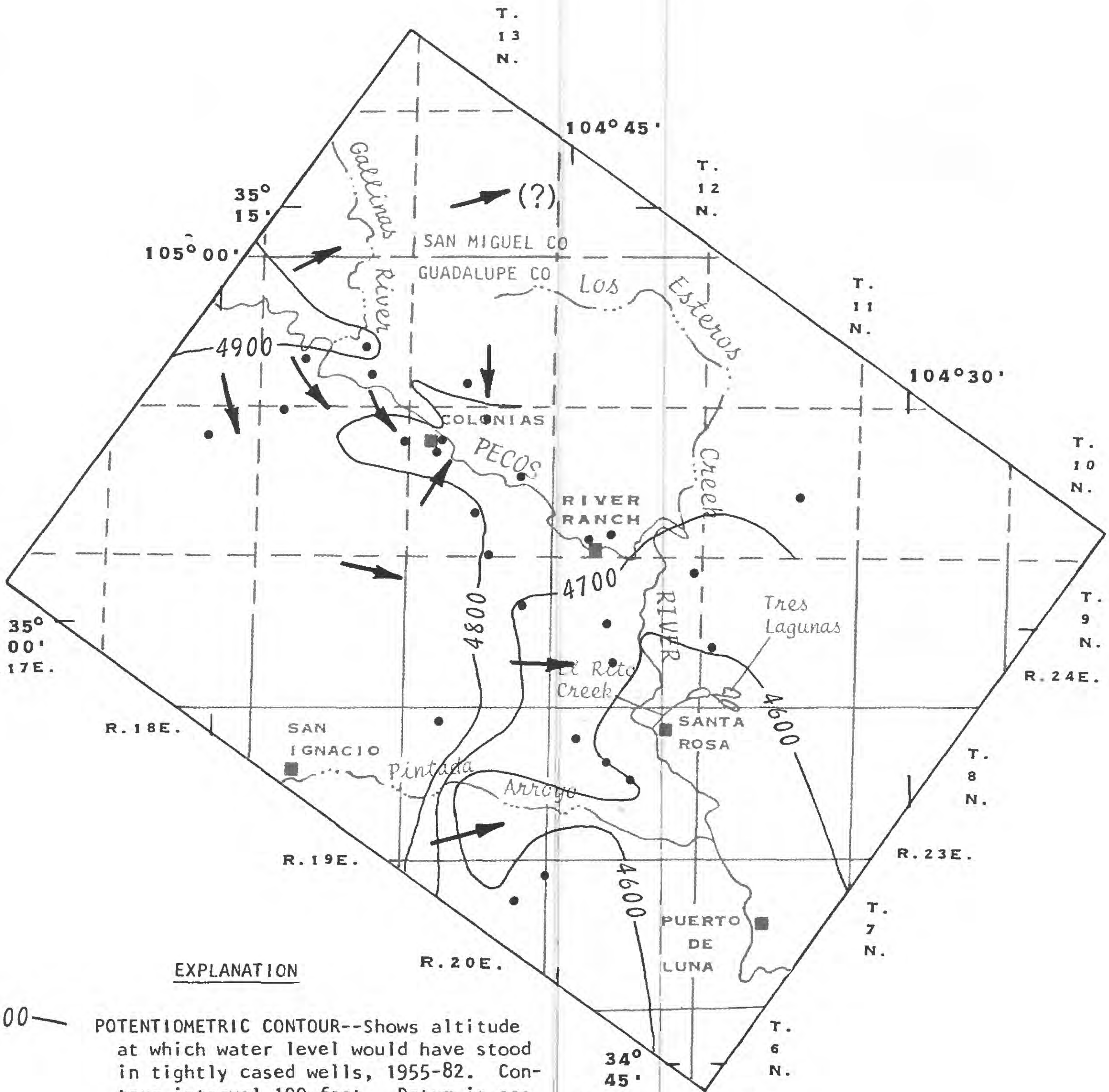
San Andres Limestone and Glorieta Sandstone

The San Andres Limestone and Glorieta Sandstone together represent the principal aquifer in the study area. Large quantities of ground water move through transmissive zones created by dissolution and collapse of the evaporite beds in the aquifer. For example, the city of Santa Rosa withdraws about 400 gallons per minute of water for public supply from two wells completed in the San Andres Limestone near Colonias (Joseph Pino, Santa Rosa Water Superintendent, oral commun., 1982).

Recharge to the San Andres-Glorieta aquifer takes place by seepage from the Pecos River, by precipitation on outcrop areas, and by leakage from adjacent formations. The approximate quantity of water recharged by seepage from the Pecos River is shown in figure 6. Between Anton Chico and Cañon del Uta an average of 47 cubic feet per second of streamflow recharges the San Andres Limestone and Glorieta Sandstone on outcrops around Esteritos Dome.

Seepage from the Pecos River upstream from Cañon del Uta probably moves southeastward in the San Andres-Glorieta aquifer toward Santa Rosa (fig. 9) through fractures in the formation, many of which have been enlarged by dissolution. Upland ephemeral lakes and depressions (fig. 2) may be evidence of solution and collapse along the ground-water-flow path between the river upstream from Colonias and Santa Rosa. Some ground water in the aquifer may move out of the study area to the northeast.

In the eastern part of the study area, the available data indicate that ground-water movement locally is toward the Pecos River (fig. 9). Water-level measurements are sparse east of the Pecos River, so the actual direction of ground-water flow is not certain. Some ground water may continue to move eastward beneath the Pecos River. Orr and Dutton (1983) showed regional ground-water movement in the San Andres Limestone toward Texas, based on a Kriging analysis of the few water-level measurements available in the area. Regardless of the direction of movement, the quantity of flow east of the river probably is small because the transmissivity of the San Andres Limestone is smaller there due to an increase of anhydrite.



EXPLANATION

4800 — POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells, 1955-82. Contour interval 100 feet. Datum is sea level

APPROXIMATE DIRECTION OF HORIZONTAL COMPONENT OF GROUND-WATER MOVEMENT IN THE SAN ANDRES-GLORIETA AQUIFER

• WELL--Shows location of water-level measurement

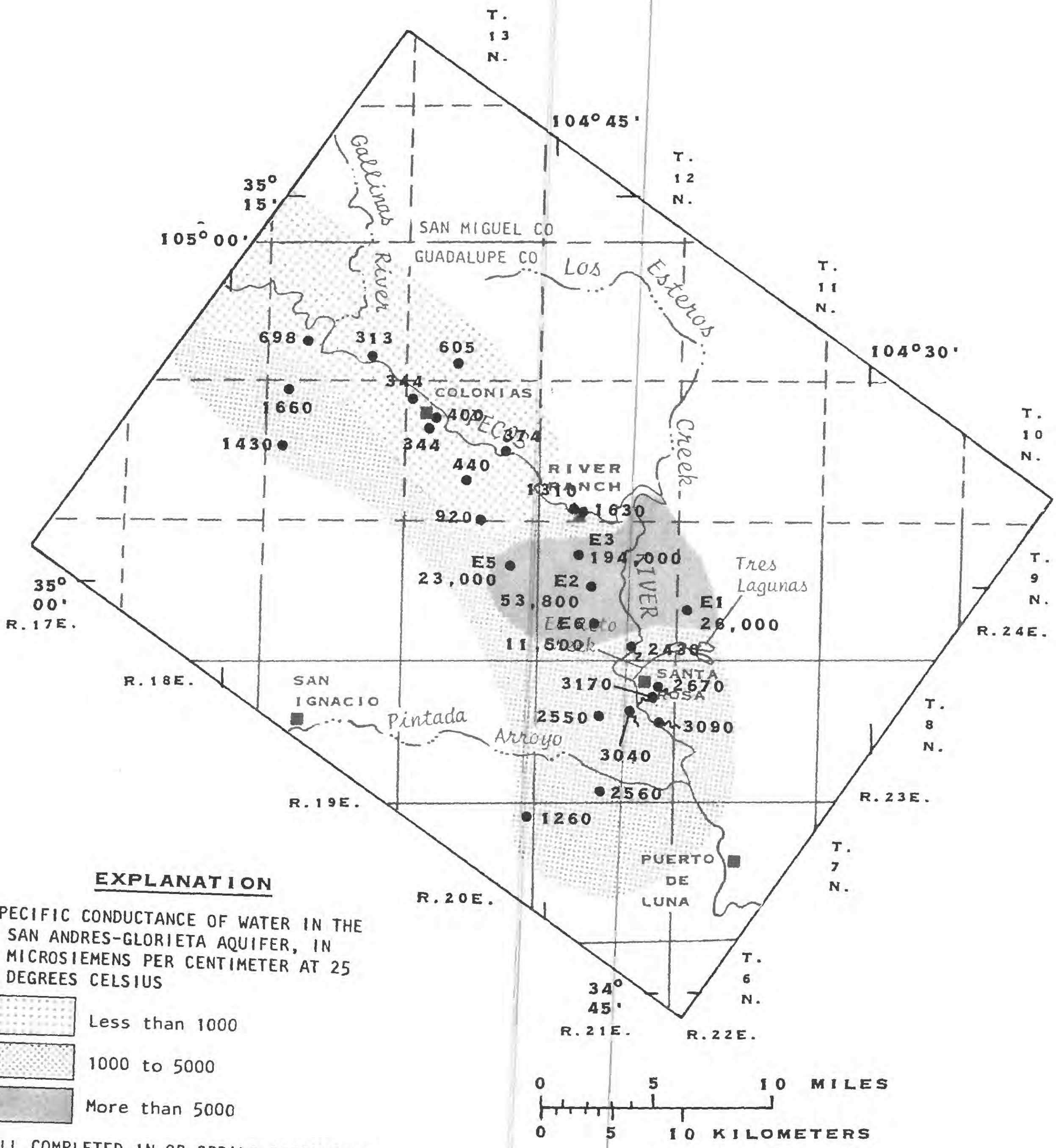
Figure 9.--Potentiometric surface of water in the San Andres-Glorieta aquifer.

The quantity of ground-water movement in the vicinity of observation wells E1, E2, E3, E5, and E6 (fig. 2) also is probably small. Aquifer tests conducted at these wells indicate that the San Andres-Glorieta aquifer is not very transmissive. In addition, the large dissolved-solids concentrations of water from these wells indicate that ground-water movement probably is slow. Specific conductance for water in the zone of small transmissivity ranges from 11,500 to 194,000 microsiemens per centimeter at 25 °C (fig. 10). Outside of this zone, specific conductance is generally less than 3,000 microsiemens. A change in the types of ions dissolved in the water also occurs. Throughout the study area, water in the San Andres-Glorieta aquifer contains calcium, bicarbonate, and sulfate as the major constituents. However, in the zone of low transmissivity, the water becomes enriched in sodium and chloride (fig. 11).

Water also was sampled from wells CH20, CH33, and CH32 (fig. 2), which reportedly are completed as piezometers in the San Andres Limestone. However, the hydraulic heads measured at these wells indicate that the reported completion zone may not be correct. The water levels are high and probably indicate a composite hydraulic head of the Bernal Formation, Santa Rosa Sandstone, and San Andres Limestone. The chemistry also does not indicate where the wells are completed. Water sampled from wells CH33 and CH22 has the same major ions as other water from the San Andres Limestone although the dissolved-solids concentration is much smaller.

Large quantities of ground water from the San Andres-Glorieta aquifer discharge to the Pecos River. In the reach between streamflow-gaging stations above Cañon del Uta and above Santa Rosa Lake, about 11 cubic feet per second of ground water discharges from the San Andres Limestone to the Pecos River (fig. 6). Stream gains in this reach correlate closely with the depth to water in nearby observation well Santa Rosa 1 (fig. 2) completed in the San Andres Limestone (fig. 12). Therefore, increases in streamflow in the river probably are contributed largely by ground-water flow from the San Andres Limestone because water levels in this reach are as much as 15 feet higher than the altitude of the Pecos River.

The quantity and specific conductance of streamflow between gaging stations above Cañon del Uta and above Santa Rosa Lake were investigated in detail on November 23, 1982 (fig. 13). On this date, the Pecos River was dry less than ½ mile upstream from the streamflow-gaging station above Cañon del Uta. In the first 2 miles downstream from the appearance of water, the river gained about 7 cubic feet per second, but the specific conductance remained nearly constant. This water probably traveled a short distance underground in the San Andres-Glorieta aquifer from the losing reach upstream from Cañon del Uta. Farther downstream, as ground-water discharge to the river increased, specific conductance also increased, indicating either that the water followed a longer path underground before returning to the surface or that the source of the water was different.



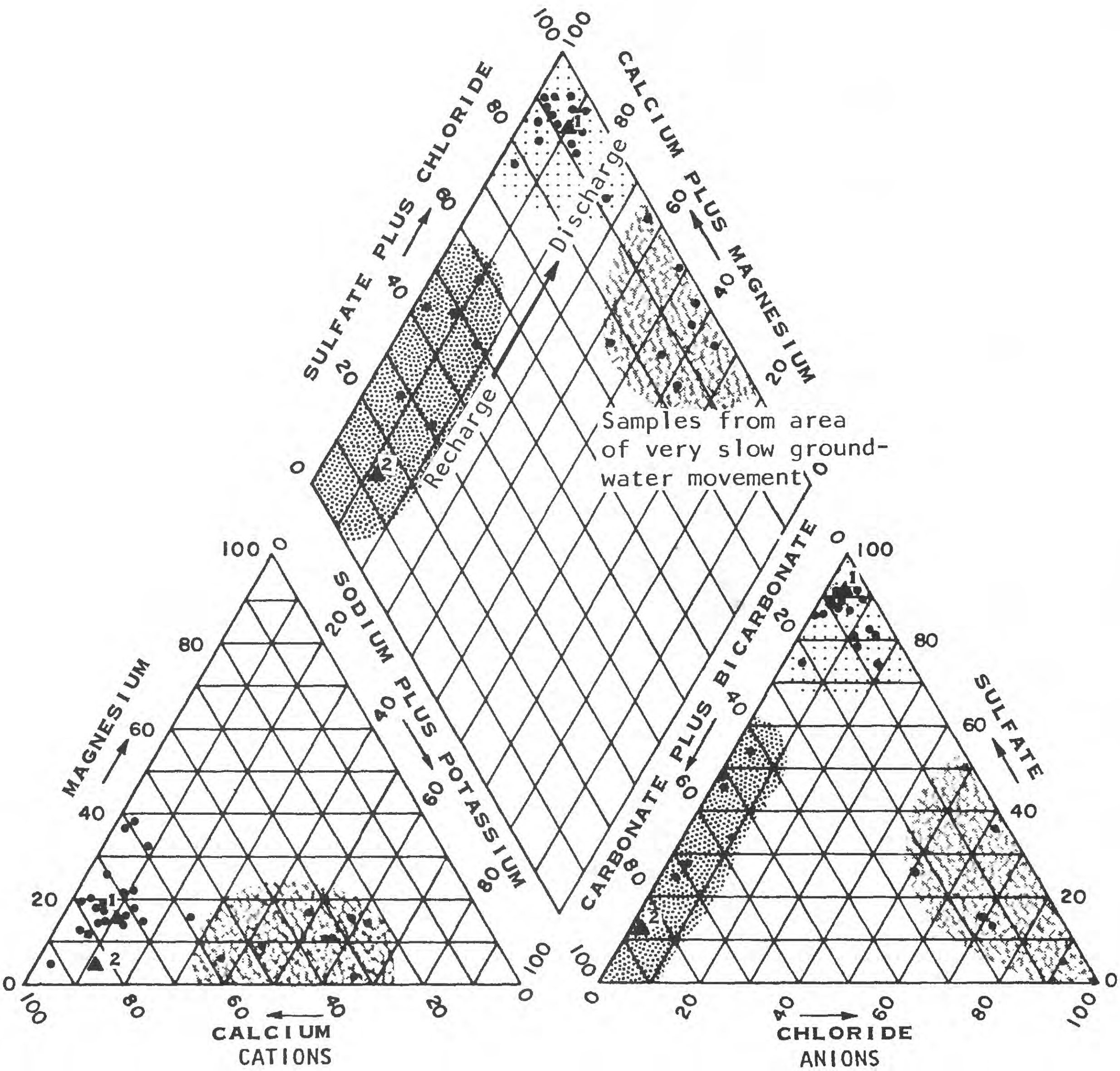
EXPLANATION

SPECIFIC CONDUCTANCE OF WATER IN THE SAN ANDRES-GLORIETA AQUIFER, IN MICROSIEMENS PER CENTIMETER AT 25 DEGREES CELSIUS

- Less than 1000
- 1000 to 5000
- More than 5000

1260 ● / 3090 — WELL COMPLETED IN OR SPRING DISCHARGING FROM THE SAN ANDRES-GLORIETA AQUIFER--Number is specific conductance of water, in microsiemens per centimeter at 25 degrees Celsius

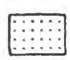
Figure 10.--Specific conductance of water in the San Andres-Glorieta aquifer.



EXPLANATION

WATER-QUALITY ZONES--


Samples from wells and Pecos River between Anton Chico and River Ranch (recharge area to San Andres-Glorieta aquifer)


Samples from wells and springs primarily near Santa Rosa and from the Pecos River near Puerto de Luna (ground-water discharge area)


Samples from wells in the area of large specific conductance near Santa Rosa Lake (wells E1, E2, E3, E5, E6, CH20, CH32, CH33)

• WELL OR SPRING--Obtains water primarily from the San Andres-Glorieta aquifer

▲1 PECOS RIVER--Sampled at streamflow-gaging station near Puerto de Luna

▲2 PECOS RIVER--Sampled at streamflow-gaging station near Anton Chico

Figure 11.--Piper diagram of water quality in the San Andres-Glorieta aquifer.

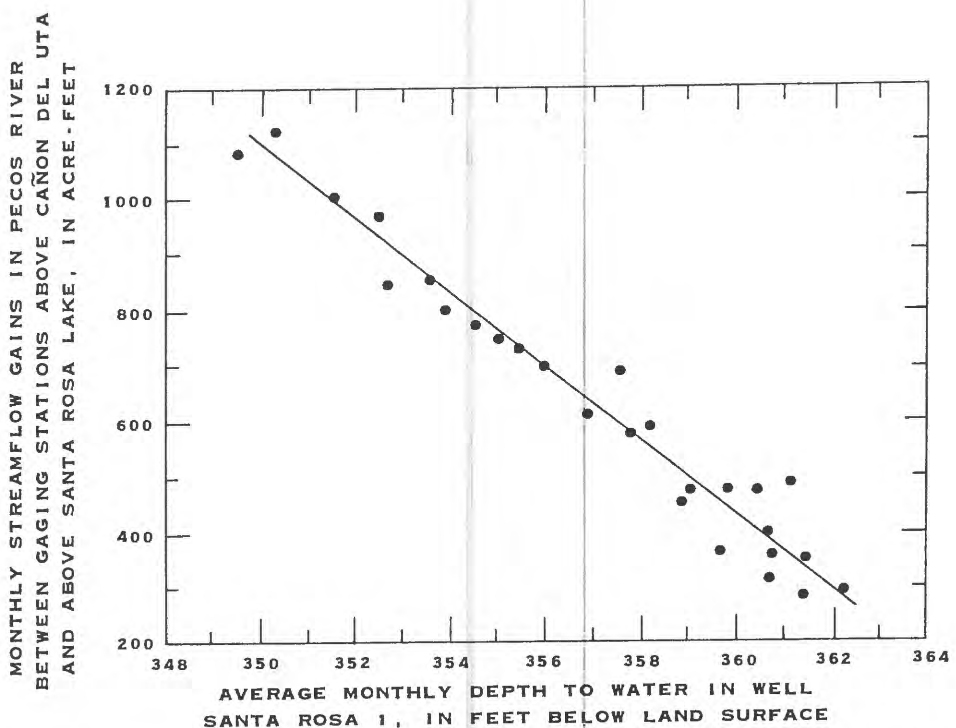


Figure 12.--Relation between depth to water in well Santa Rosa 1 and monthly streamflow gains in the Pecos River.

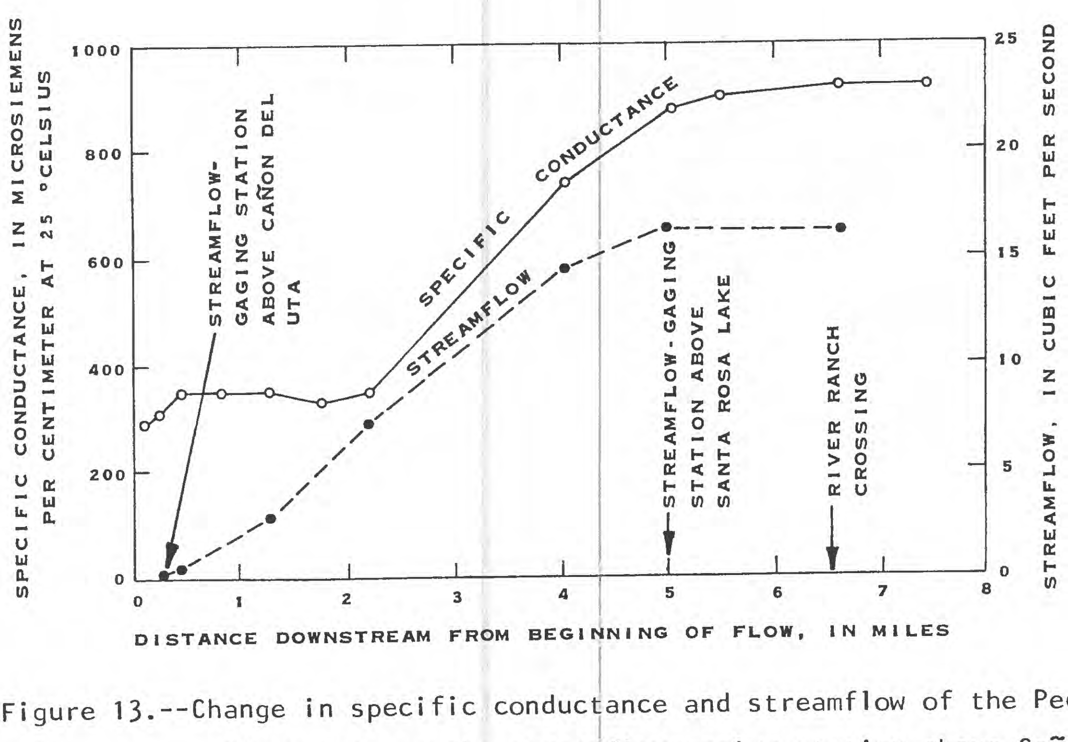


Figure 13.--Change in specific conductance and streamflow of the Pecos River between the streamflow-gaging station above Cañon del Uta and River Ranch crossing, November 23, 1982.

Streamflow gains between gaging stations upstream from Santa Rosa Lake and at Santa Rosa averaged about 4 cubic feet per second prior to construction of the lake (fig. 6). This increased flow probably was contributed by ground-water discharge from the San Andres-Glorieta aquifer, Bernal Formation, and Santa Rosa Sandstone. Most of these gains probably take place downstream from the dam (Dinwiddie and Clebsch, 1973, fig. 9).

The largest amount of ground-water discharge from the San Andres-Glorieta aquifer occurs between Santa Rosa and Puerto de Luna (fig. 6). In this reach, the average base-flow gain in the Pecos River from 1939 to 1982 was about 70 cubic feet per second, most of which probably occurred where the river flows across the Santa Rosa Sink between Santa Rosa and Rio Agua Negra (U.S. Geological Survey, 1964, p. 600). The increase in streamflow of about 85 cubic feet per second between Cañon del Uta and Puerto de Luna indicates that at least 38 cubic feet per second of water recharges the San Andres-Glorieta aquifer from a source other than seepage from the Pecos River above Cañon del Uta. Probably a large part of 38 cubic feet per second recharges the aquifer on outcrop areas between Vaughn and San Ignacio (figs. 1 and 2).

Aquifer Properties

The hydraulic properties of aquifers and confining units determine, in part, the magnitude and timing of seepage from Santa Rosa Lake. Transmissivity, diffusivity, horizontal and vertical hydraulic conductivity, storage coefficient, and specific yield for rocks in the vicinity of the lake are estimated in this section. Definitions of these properties are given in Lohman and others (1972).

Several analytical methods were used to estimate aquifer properties. Aquifer diffusivity, the quotient of transmissivity divided by storage coefficient, was estimated using a method described by Pinder, Bredehoeft, and Cooper (1969). Transmissivity values were estimated from aquifer tests by instantaneously injecting or removing a "slug" of water (Papadopulos and others, 1973). Other hydraulic properties, determined using various methods, are reported from published sources.

Chinle Formation

The hydraulic properties of the Chinle Formation are not known in the study area. However, because the formation is composed of shale and siltstone with minor sandstone lenses, the hydraulic conductivity probably is small. The horizontal hydraulic conductivity of the Chinle Formation is controlled by the permeability of the sandstone units. If sandstone units with a horizontal hydraulic conductivity of 0.5 foot per day are assumed to compose 10 percent of the formation thickness, then the average horizontal hydraulic conductivity of the Chinle Formation is about 0.05 foot per day.

The vertical hydraulic conductivity of the Chinle Formation is controlled by the least permeable shale units in the formation. Estimates of vertical hydraulic conductivity for shaley confining units determined by modeling studies range from 10^{-12} to 10^{-9} (Frenzel and Lyford, 1982; Bredehoeft and others, 1983).

The specific yield of the Chinle Formation probably also is very small because pore water is held tightly in clayey formations by surface tension and cohesive forces between water molecules. Johnson (1967, p. 53) reported specific yields of 3 percent or less for similar geologic materials.

Santa Rosa Sandstone

Aquifer properties of the Santa Rosa Sandstone are not well known; however, they probably vary greatly owing to different degrees of fracturing of the sandstone. At the northern rim of the Santa Rosa Sink, about 1 mile north of Santa Rosa, two aquifer tests were conducted on old municipal-supply wells to determine transmissivity of the Santa Rosa Sandstone (New Mexico State Engineer, 1957, p. 15C and 23C). Transmissivities estimated from these tests were 1,690 and 11,770 feet squared per day. These wells probably are in the most permeable area of Santa Rosa Sandstone.

Determinations of horizontal hydraulic conductivity of the Santa Rosa Sandstone were conducted at seven wells near the damsite using pressure tests (U.S. Army Corps of Engineers, 1970, pl. 19). The average horizontal hydraulic conductivity from 30 sandstone intervals was 0.52 foot per day, and the range was from 0 to 3.3 feet per day. The average horizontal hydraulic conductivity for six shale units in the Santa Rosa Sandstone was 0.13 foot per day. Gorman and Robeck (1946) also reported horizontal hydraulic conductivity of the Santa Rosa Sandstone ranging from about 0.04 to 0.87 foot per day. These values were determined in the laboratory. Budding (1980) reported the average range of horizontal hydraulic conductivity in the Santa Rosa area to be between 0.24 and 0.48 foot per day.

The storage properties of the Santa Rosa Sandstone are unknown, but where the unit is confined, an estimated value of 10^{-6} times the thickness is probably reasonable. Where the sandstone is unconfined on outcrop areas, a specific yield of about 0.05 may be a close estimate based on values published by Johnson (1967, p. D51) for similar units.

Bernal Formation

The hydraulic properties of the Bernal Formation are not known. The formation contains a large amount of shale and siltstone and acts as a confining bed for the San Andres Limestone. Confining bed groups having similar lithologies were assigned horizontal hydraulic conductivity from 10^{-8} to 10^{-7} foot per second in a study of ground-water flow in the San Juan Basin of New Mexico (Frenzel and Lyford, 1982). However, where the formation has significant permeability due to fracturing and solutioning, the hydraulic conductivity may be thousands of times greater. These conditions probably exist in the Santa Rosa Sink area and along the Pecos River upstream from and in the vicinity of Colonias.

Vertical hydraulic conductivity of confining bed groups in the San Juan Basin ranged from 10^{-12} to 10^{-9} foot per second (Frenzel and Lyford, 1982). Vertical hydraulic conductivity of confining beds reported by Neuzil (1980, table 1) ranged from 1.5×10^{-11} to 6×10^{-9} foot per second. In the Santa Rosa Sink area and along the Pecos River near Colonias, where the formation has been extensively fractured, vertical hydraulic conductivity may be much greater.

Storage properties of the Bernal Formation also are unknown. Estimates of 10^{-6} times the thickness of the aquifer probably are reasonable where the aquifer is confined. Where the unit crops out, a specific yield of about 0.03 or less is reasonable based on values reported for similar rocks by Johnson (1967, p. 53).

San Andres Limestone and Glorieta Sandstone

Evidence from water-level fluctuations and water quality in the San Andres-Glorieta aquifer indicates that hydraulic properties of the aquifer vary greatly throughout the study area because of changes in the number of interconnected fractures. Fractures trend northeast to southwest and northwest to southeast in an orthogonal pattern that is visible on aerial photographs and indicated by sinkhole alignment. Cavernous limestone outcrops near Colonias and sinks and closed depressions on the land surface between Colonias and Santa Rosa indicate the possibility of solution and collapse in the San Andres Limestone that may have created transmissive zones. Two wells completed in the San Andres Limestone in this probable transmissive zone provide water for the city of Santa Rosa. These wells are less than 1/4 mile west of observation well Santa Rosa 1 (fig. 2). A variable-discharge aquifer test was conducted on one of the city-supply wells in 1964. An estimated transmissivity of about 9,400 feet squared per day and a storage coefficient of about 1×10^{-4} were reported for this test (William Fowler, New Mexico State Engineer Office, written commun., 1964).

Slug-type aquifer tests (Papadopulos and others, 1973) were conducted at selected observation wells. The tests were performed at wells E5 and E8 (fig. 2) by rapidly lowering a barrel into the well to displace a known volume of water. The rapid rise and subsequent decline of water levels in the wells were measured using pressure transducers. From the tests, the estimated transmissivity at well E5 is 36 feet squared per day (fig. 14). In well E8, the water level returned to static so rapidly after the introduction of the barrel that a transmissivity could not be calculated. The rapid response, however, indicates that the aquifer is relatively transmissive near well E8.

At observation well E6, a slug-type test was conducted by bailing a known quantity of water to lower the water level in the well. The subsequent return of the water level to static is plotted in figure 14. Transmissivity is estimated to be about 0.13 foot squared per day.

Water-level recovery after drilling observation wells E1 and E3 provides an estimate of the transmissivity of the San Andres Limestone (fig. 14). Water levels recovered very slowly in these wells. In well E1, the water level returned to static nearly 2 years after drilling. The water level at well E3 probably has not reached static level 8 years after drilling. The transmissivity estimated from the slow recovery is 0.006 foot squared per day at well E1 and probably much less at well E3.

The slug-type aquifer tests and water-level recovery after drilling indicate that the transmissivity of the San Andres-Glorieta aquifer in the vicinity of wells E1, E3, E5, and E6 is very small. These results concur with geologic data collected from test drilling by the U.S. Army Corps of Engineers that indicated "tight" San Andres Limestone immediately west of Santa Rosa Lake (Norman Brown, U.S. Army Corps of Engineers, oral commun., 1980).

The diffusivity of the residual San Andres Limestone and younger rocks in the Santa Rosa Sink area between observation wells E6 and E7 was estimated using a method described by Pinder, Bredehoeft, and Cooper (1969). The analysis was based on the assumption that the rapid increases of water levels in wells E6 and E7 during July 1976, August and September 1977, and August 1980 (fig. 15) were caused by streamflow in Pintada Arroyo. The change in water level at well E6 was simulated for each of the three storms from water-level changes at well E7 using a diffusivity of 45,000,000 feet squared per day. A comparison of the measured and simulated water-level change in well E6 for the three periods is shown in figure 15. Assuming a storage coefficient of 0.0004, the average transmissivity between wells E7 and E6 is about 18,000 feet squared per day. Because it is known from slug-type aquifer tests that the transmissivity near E6 is about 0.13 foot squared per day, the value of 18,000 feet squared per day probably represents a very conservative estimate of the average transmissivity of the residual rocks in the Santa Rosa Sink.

The storage coefficient of the San Andres Limestone was tested at the Santa Rosa municipal-supply wells where a value of about 0.0001 was estimated (William Fowler, New Mexico State Engineer Office, written commun., 1964). Over the remainder of the study area where water in the San Andres occurs under confined conditions, the storage coefficient can be estimated as 10^{-6} times the thickness of the aquifer (Lohman and others, 1972, p. 8). In outcrop areas where the aquifer is unconfined, the specific yield of the unit applies. Although the specific yield of the San Andres-Glorieta aquifer is not known, reported values for typical Paleozoic limestone in Kentucky range from 0.18 to 0.87 percent (Walker, 1956).

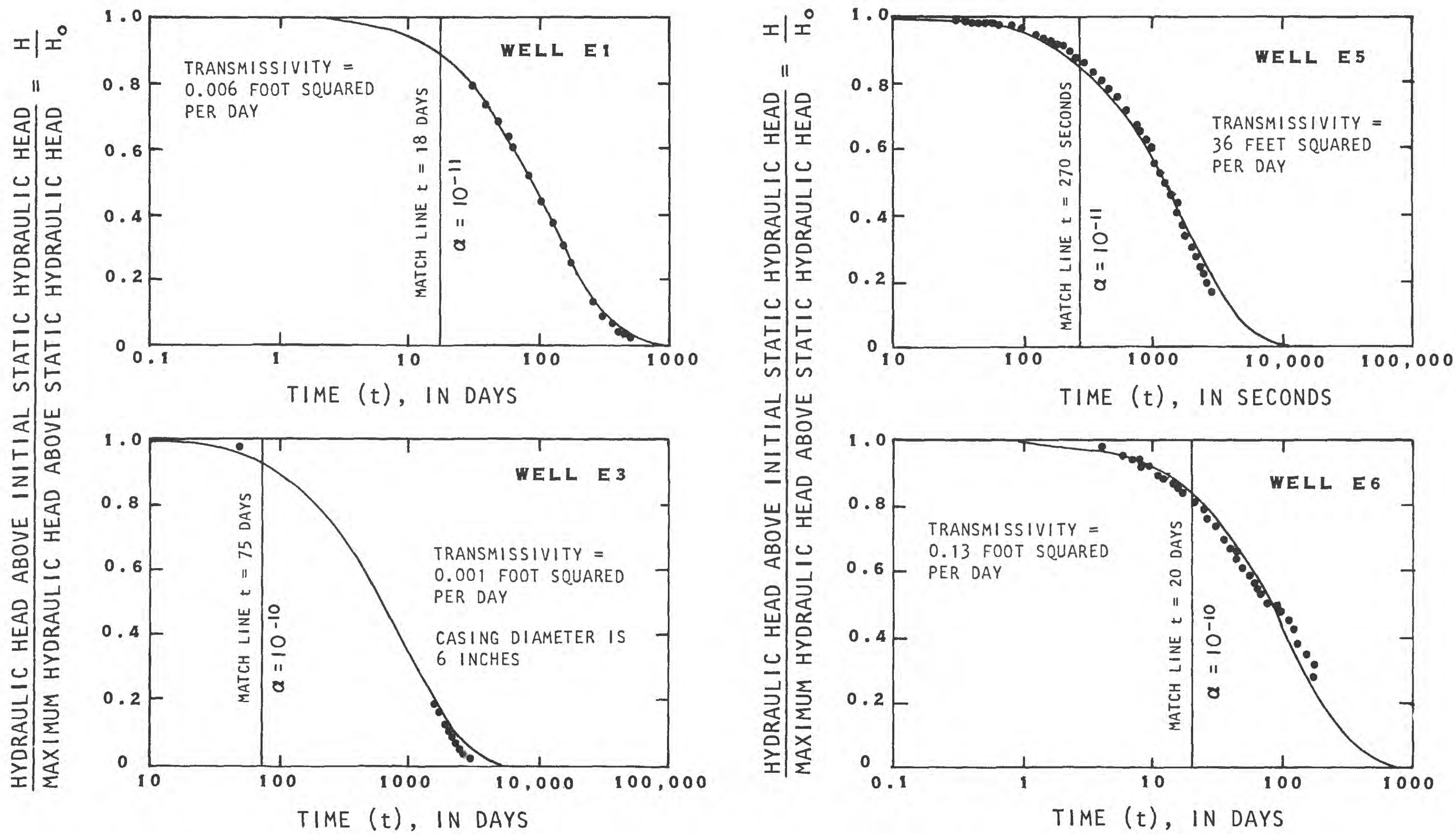


Figure 14.--Results of slug-type aquifer tests conducted at wells E1, E3, E5, and E6.

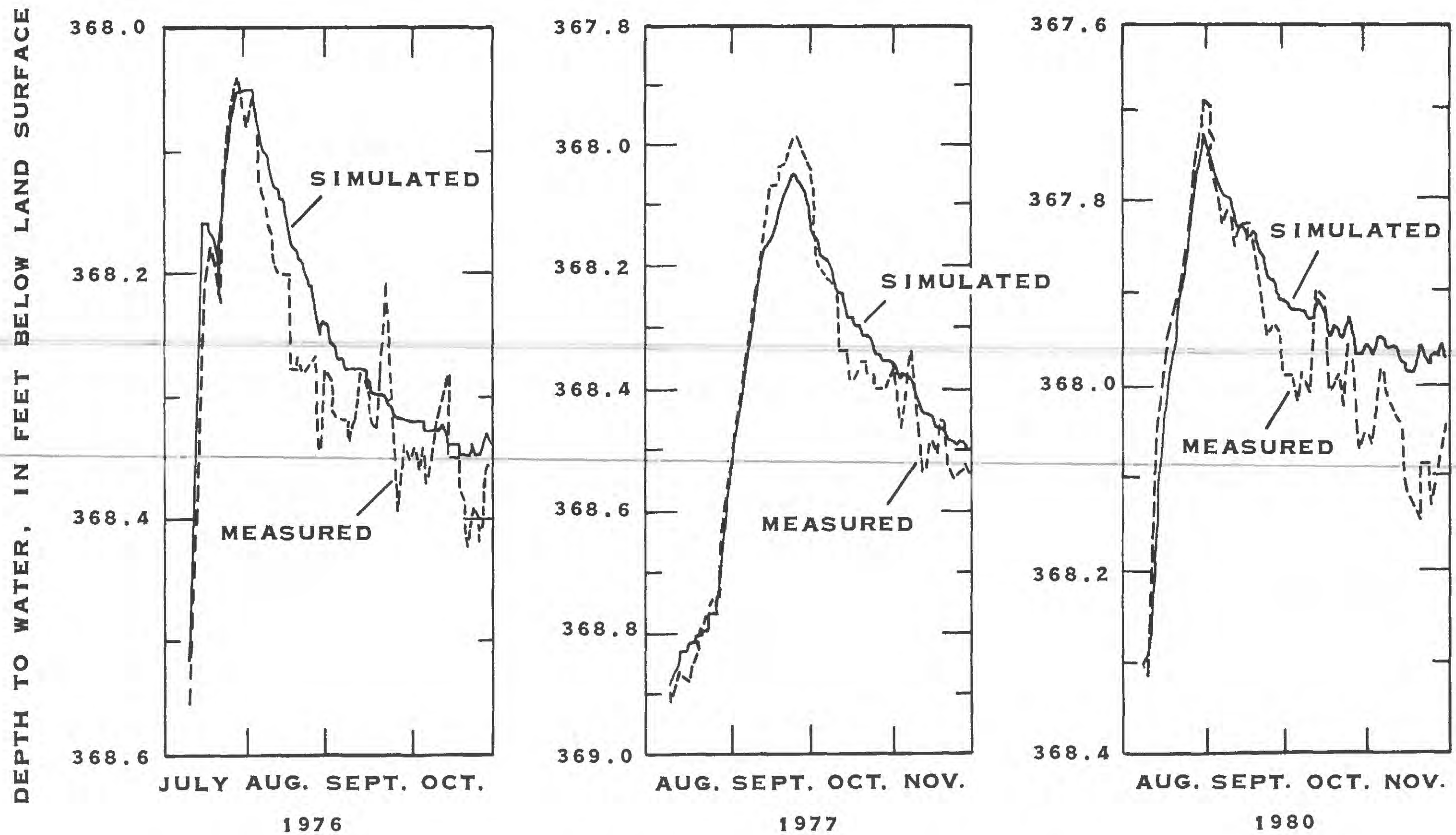


Figure 15.--Measured and simulated water levels in well E6 possibly caused by changes in stage of Pintada Arroyo.

Water-Level Fluctuations

Natural water-level fluctuations in wells in the vicinity of Santa Rosa Lake need to be understood before the effect of the lake can be estimated. For example, water levels in observation wells near the lake may fluctuate in response to changes in lake level, changes in streamflow in the Pecos River and Pintada Arroyo, seasonal variations in recharge and discharge rates, and ground-water withdrawals. If these effects are misunderstood, water-level fluctuations in observation wells may be misinterpreted and estimates of seepage volumes that are based on water-level measurements could contain large errors.

Natural Changes

Large water-level fluctuations in the San Andres Limestone are caused mainly by changes in the quantity of recharge to the aquifer from precipitation and the Pecos River. Between streamflow-gaging stations near Anton Chico and above Cañon del Uta, the Pecos River loses an average of 47 cubic feet per second of water to the Glorieta Sandstone, San Andres Limestone, and Bernal Formation (fig. 6). Water levels in the San Andres-Glorieta aquifer reflect the changes in streamflow of the Pecos River (fig. 16). In wet years, when streamflow was large, water levels rose as much as 13 feet; water levels declined during dry years. For example, from April through June 1979, large quantities of snowmelt provided large volumes of water to the Pecos River. In the reach between the streamflow-gaging stations near Anton Chico and above Cañon del Uta, the Pecos River lost at least 55,500 acre-feet of water during water year 1979. Water levels increased later that year in wells Santa Rosa 1, E4, E5, and E6. However, during water year 1977, only about 19,600 acre-feet of water was lost from the Pecos River, and ground-water levels gradually declined. The variability in streamflow losses in this reach of the Pecos River is shown below for the years of available discharge records.

Water year	Loss in streamflow between gaging stations near Anton Chico and above Cañon del Uta
1977	19,600
1978	29,600
1979	55,500
1980	24,000
1981	23,500
1982	52,800

The magnitude of the water-level fluctuations in wells depends on the quantity of recharge and on the distance from the recharge area. Water levels in wells Santa Rosa 1 and E4, nearest the losing reach of the Pecos River, are most sensitive to changes in streamflow (fig. 16). Water levels in observation wells E5 and E6, farther from the recharge area, respond to the change in streamflow with less sensitivity.

The time delay between changes in streamflow and water levels in a well also varies with distance from the recharge area. The highest water levels in well Santa Rosa 1 follow the major peaks of streamflow in the Pecos River near Anton Chico by about 60 days (fig. 16). The average delay between peaks of Pecos River flow and water-level peaks measured in wells Santa Rosa 1, E4, E5, and E6 is shown below.

Observation well	Santa Rosa 1	E4	E5	E6
Approximate time delay, in days from peak streamflow	60	100	115	145

Water-level fluctuations in wells E1, E2, and E3 are different in character from fluctuations measured at other locations, probably because of a marked decrease in transmissivity near these wells (fig. 17). Water levels in well E2 show a subdued response to recharge with a time delay from peaks in the Pecos River near Anton Chico of about 340 days. The small magnitude of fluctuations and large time delay indicate that transmissivity is small in the vicinity of this well. Distance from recharge area alone cannot account for the measured fluctuations. The reason for the steady downward trend shown on the hydrograph at well E2 is not known. Possibly this trend reflects regional changes in recharge averaged over several years rather than annual differences. Water levels in wells E1 and E3 also indicate that they are completed in a zone of small transmissivity. The water level in well E1 recovered about 2 years after drilling and has reached an apparent steady water level. However, the water level in well E3 still appears to be recovering after drilling in 1975 (fig. 17).

The rate of ground-water discharge varies throughout the year due to changes in the hydraulic-head gradients in the aquifers and to changes in the quantity of water lost to evapotranspiration. The decline of ground-water levels in summer months caused by increased evapotranspiration rates probably is most pronounced near the Pecos River where the greatest number of phreatophytes exist. Water-level declines in wells E6 and E7 during summer months possibly are caused by increased evapotranspiration (fig. 17).

Ground-water levels in the Santa Rosa Sink area probably are affected by natural changes in the ephemeral flow in Pintada Arroyo. These effects are most evident on records from observation wells E7 and E6 (fig. 17). The peaks in July 1976, August 1977, and August 1980 probably were caused by streamflow in Pintada Arroyo. The magnitude of the change was greater in well E7 than well E6, and the change occurred at well E7 first, which indicates that the source was nearer well E7. These water-level fluctuations probably were not caused by changes in streamflow of the Pecos River. The stage of the Pecos downstream from Santa Rosa Dam changed rapidly on July 7, 1980, May 29, 1981, and June 25 and September 1, 1982, due to release of water from the lake. No change in water levels in wells E6 and E7 was observed during these periods. Changes in discharge of the Pecos River upstream from the lake were indicated at well E6 as gradual increases in water level, but not as peaks. Changes in Pecos River flow affect the water levels in well E7 very little. For example, in 1979 the flow of the Pecos River upstream from the lake was large, and water levels rose in observation wells E5, Santa Rosa 1, E4, and E6. However, little change was detected in well E7.

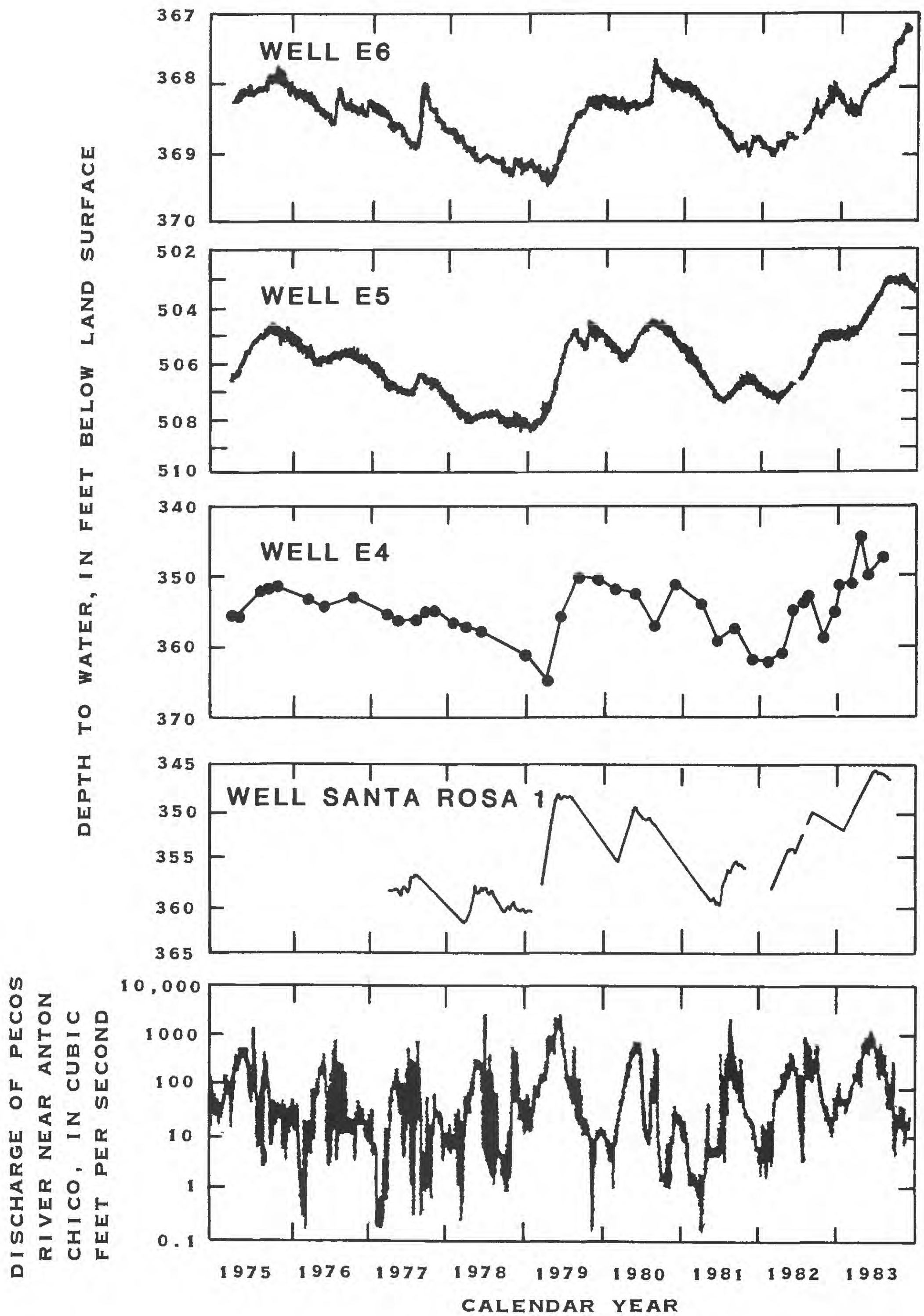


Figure 16.--Water levels in wells E6, E5, E4, and Santa Rosa 1, and discharge of the Pecos River.

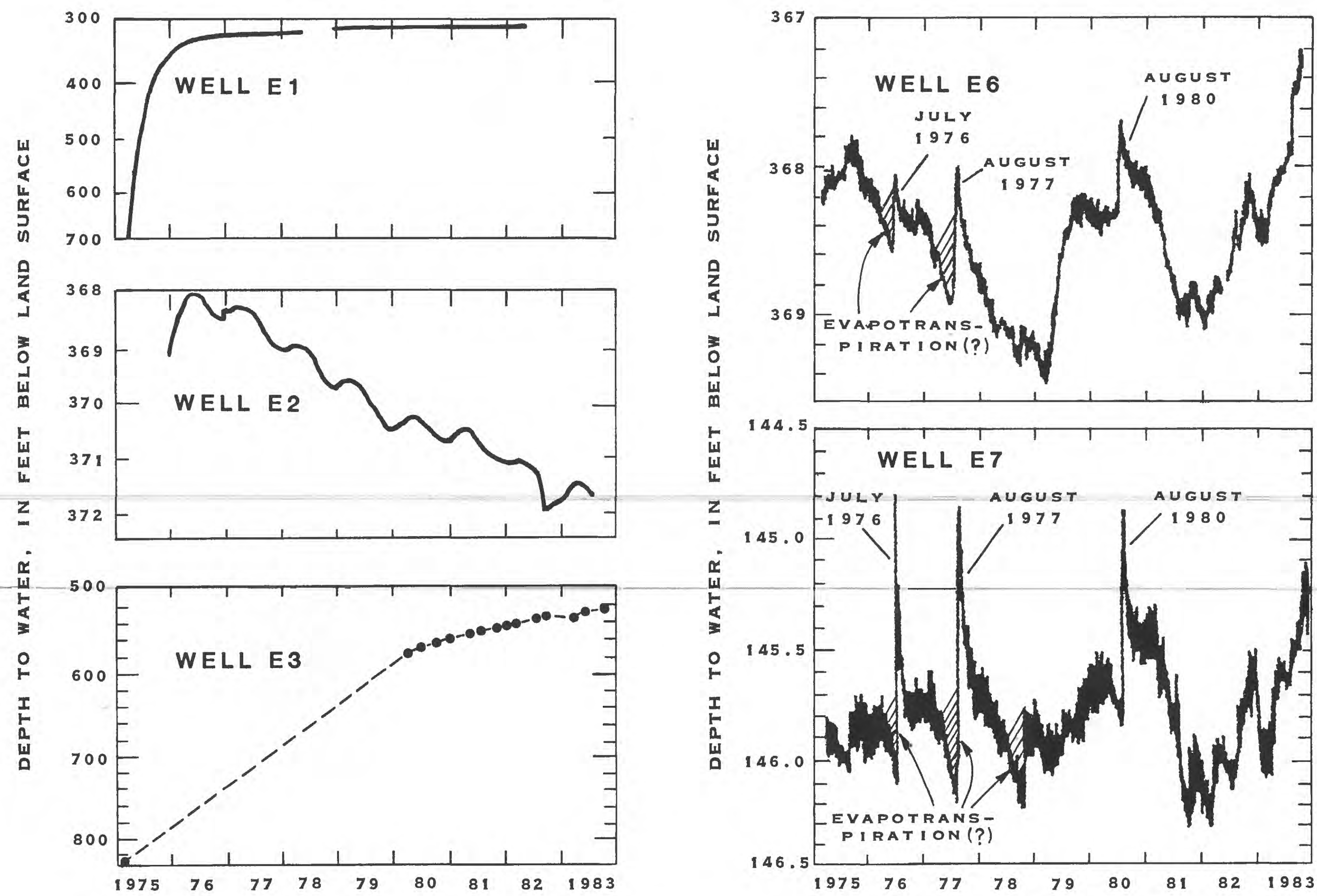


Figure 17.--Water levels in wells E1, E2, E3, E6, and E7.

A linear flood-pulse model (Pinder and others, 1969) was used to simulate water-level fluctuations in well E6 based on water levels at well E7. The model indicates that flow in Pintada Arroyo could cause all three sudden ground-water increases measured during summer months. Unfortunately, no streamflow-gaging station exists on Pintada Arroyo to verify that flow occurred on these dates.

Ground-Water Withdrawals

The largest draft of ground water in the study area is near Colonias where two wells completed in the San Andres Limestone are used to withdraw water for the city of Santa Rosa municipal supply. The wells are pumped at about 400 gallons per minute for varying durations each day. In 1981, a total of 156 million gallons of water was pumped from the San Andres Limestone (Joseph Pino, Santa Rosa Water Superintendent, oral commun., 1982). Pumping varied seasonally from 10 million gallons during February to 18 million during June.

The effects of the pumping were observed at well Santa Rosa 1, about 580 feet from the nearest supply well, and at well E5, 4 miles away. The magnitude of the water-level fluctuations was about 0.5 foot at well Santa Rosa 1 and about 0.1 foot at well E5. The magnitude of the fluctuations measured at the different wells can be used to help estimate aquifer properties, as discussed in a later section.

Change in Santa Rosa Lake Contents

When the contents of Santa Rosa Lake change, water-level fluctuations may be caused by the effects of loading on the aquifer and by seepage from the lake. Loading refers to the stress placed on the aquifer by the weight of the water in the lake. Because artesian aquifers are elastic, the load will compress the aquifer, increase hydrostatic pressure, and cause water levels to rise. An example of an idealized response of water levels in a confined aquifer is shown in figure 18. When the load is applied (fig. 18A, time 1), water levels rise rapidly and then slowly decline toward a static level as the aquifer adjusts to the stress. If the load is then removed by releasing water from the lake (fig. 18A, time 2), the aquifer will expand, causing water levels to decrease rapidly and then slowly rise to a static level as the aquifer adjusts.

Seepage of water from Santa Rosa Lake also can cause water-level fluctuations in wells; however, these effects can be distinguished from the effects caused by loading. When the lake contents increase (fig. 18B, time 1), seepage from the lake into adjacent aquifers will cause water levels to gradually increase until a new steady position is reached. When the lake contents decrease (fig. 18B, time 2), water levels will gradually decline to the original static level.

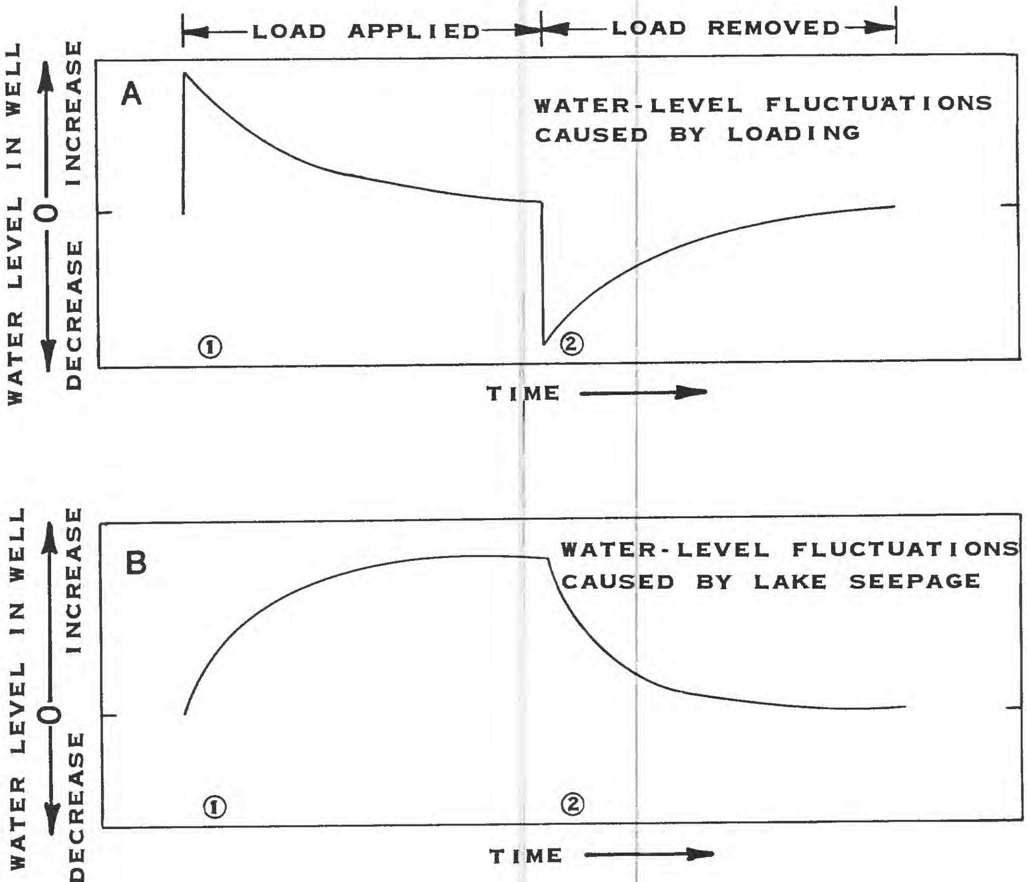


Figure 18.--Idealized water-level fluctuations caused by loading and lake seepage.

The ultimate effects of seepage from Santa Rosa Lake on water levels are schematically shown in figure 19. Before water is held in the lake, the static water table in the Santa Rosa Sandstone is maintained by a relatively constant source of recharge from the surface and by a base level of the Pecos River. When the lake contents increase, water seeps into bank storage and the water table rises as shown in figure 19, effect 1. If water in the lake is held for a sufficiently long time, water levels in the Santa Rosa Sandstone will increase across the ground-water divide and the position of the divide will shift toward the lake as the lake level increases (fig. 19, effects 2 and 3). These adjustments are necessary because the new ground-water gradients need to accommodate the same total amount of recharge. The increase in lake contents affects water levels at great distances from the lake and at elevations much higher than the elevation of the lake surface. When the lake is drained, water levels will decline and the ground-water divide will shift away from the lake.

Seepage of water from Santa Rosa Lake also may affect water levels in the San Andres-Glorieta aquifer. A change in lake contents will initially cause downward seepage (or a decrease in upward leakage) beneath the lake through confining beds of the Bernal Formation (fig. 19, effect 4). The volume and timing of the seepage depend upon the change in lake contents, duration that water is held in the lake, and hydraulic properties of the rocks. If the lake contents are held until water levels in the shallow Santa Rosa Sandstone aquifer increase across the ground-water divide, the vertical hydraulic gradient between the Santa Rosa Sandstone and San Andres-Glorieta aquifer throughout this entire area will be increased (fig. 19, effect 2). Therefore, throughout the area between the lake and the physical boundaries of the shallow aquifer, the net flux to the San Andres-Glorieta aquifer will increase. Water levels in the San Andres-Glorieta aquifer, therefore, may fluctuate throughout a large area due to changes in lake contents.

POSSIBLE CHANGES IN GROUND-WATER FLOW

Santa Rosa Lake will cause changes in hydraulic heads and ground-water flow, the magnitude and timing of which depend upon the hydrologic properties of rocks, location of physical boundaries, and amount and duration of the lake-level change. Five principal changes in the hydrologic system that could occur are summarized below:

1. Water in the lake will seep to bank storage in the Triassic rocks and change ground-water levels near the lake. If the lake level is lowered, most of the water held in bank storage will return to the lake because the water table slopes toward the lake (fig. 19).

2. If the lake impounds water for a sufficient time, the water table in the Triassic rocks will rise. The higher water table will increase the hydraulic gradient between the water table and water levels in the San Andres-Glorieta aquifer, thereby increasing leakage to and flow in the San Andres-Glorieta aquifer (fig. 19). Based on the potentiometric-surface map (fig. 9), a change in leakage to the San Andres-Glorieta aquifer probably will increase discharge to the Pecos River downstream from Santa Rosa or possibly increase ground-water flow eastward out of the drainage basin.

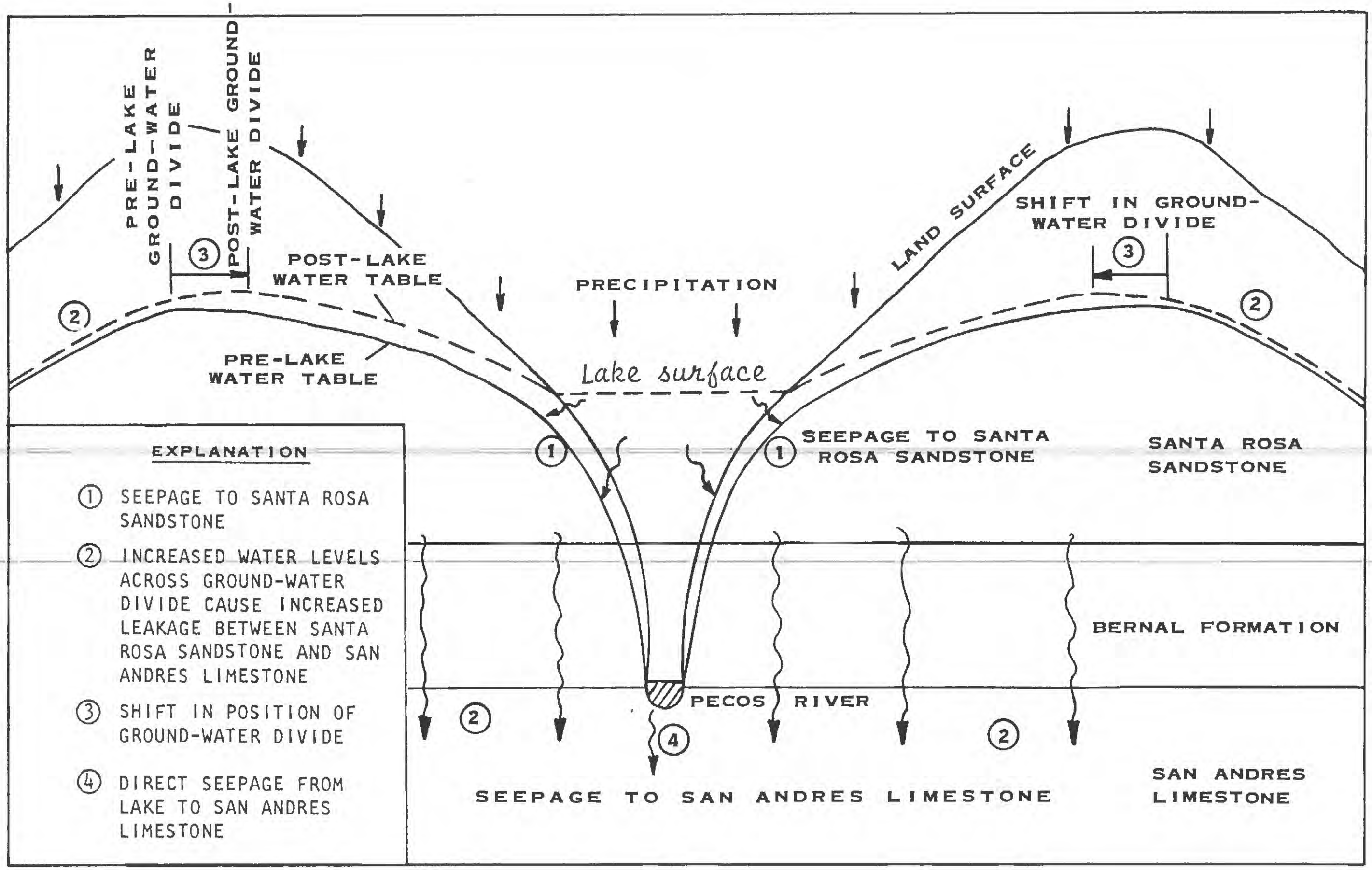


Figure 19.--Schematic diagram showing potential effects of Santa Rosa Lake levels on ground-water levels and movement.

3. A long duration of impoundment of water in the lake also will shift the position of the water-table divide toward the lake (fig. 19). The shift of the water-table divide will cause a maximum decrease in flow toward the lake by a quantity equal to the area over which the divide changes multiplied by the ground-water recharge rate in that area. This volume of water may flow to a different surface-water basin (and be completely lost to the Pecos River) or seep into the San Andres-Glorieta aquifer and return to the Pecos River downstream.

4. Increasing the water level in Santa Rosa Lake may decrease ground-water discharge to the lake where it covers previously gaining reaches of the Pecos River. The rejected flow may return to the Pecos River downstream from the lake or flow out of the drainage basin entirely.

5. Seepage directly from the lake to the outcrop of cavernous San Andres Limestone near River Ranch may occur at high lake levels. According to the potentiometric-surface map (fig. 9), this seepage could return to the Pecos River as base flow downstream from Santa Rosa or flow out of the basin to the northeast.

Prior to construction of Santa Rosa Dam, the Fort Sumner Irrigation District was entitled to as much as 100 cubic feet per second of Pecos River flow measured near Puerto de Luna. Changes in the hydrologic system caused by the lake could necessitate a change in measuring Fort Sumner allocation. If all possible effects of the lake could be measured, the changes to be considered are shown in figure 20.

Although terms Q(2b) and Q(4b) are changes caused by the lake (fig. 20), these terms, which represent base flow that Fort Sumner Irrigation District is entitled to, are measured at the gage near Puerto de Luna Q(PL). The significant terms not measured at streamflow-gaging stations are Q(2a), Q(3), and Q(4a), which represent possible loss of base flow to the Pecos River, and Q(5), which represents direct seepage of surface water from the lake to which the Fort Sumner Irrigation District is not entitled. The possible loss of base flow to the Pecos River (terms Q(2a), Q(3), Q(4a)) is water that will either return to the Pecos River downstream from the gaging station near Puerto de Luna or flow to another surface-water basin. In either case, the water is considered to be a loss of base flow to the river reach under consideration.

In the following sections, the effects of the lake that have already occurred during its operation from April 1980 to September 1983 will be described and estimates of future effects that may be caused by lake levels as yet unattained will be evaluated. Empirical methods used to evaluate lake effects that have already occurred include: water-level fluctuations, water balance for lake, base-flow changes, and water-quality changes. A quantitative analysis of potential future effects of the lake will be conducted using a mathematical model of the hydrologic system in the vicinity of the lake.

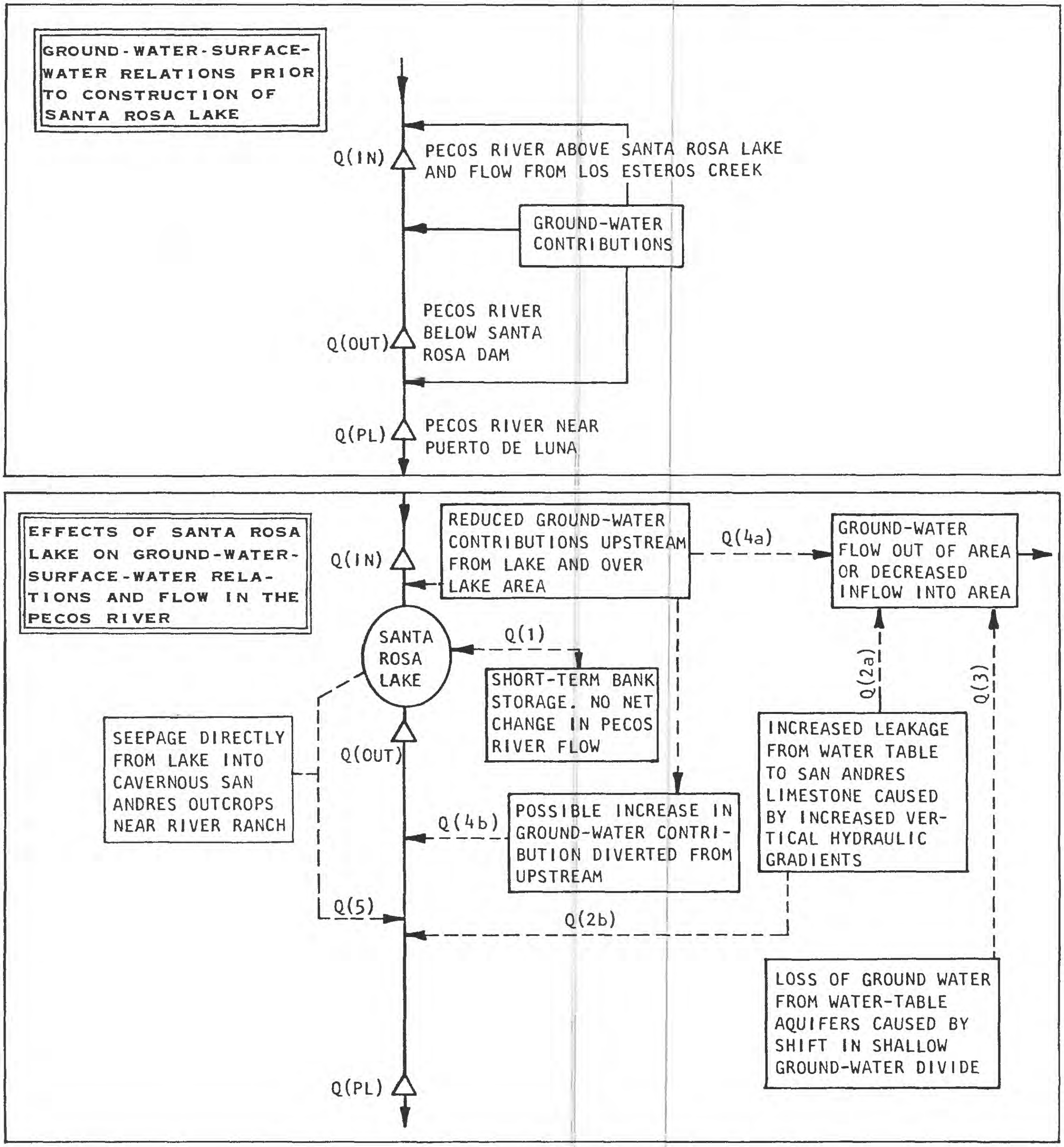


Figure 20.--Schematic diagram showing effects of Santa Rosa Lake on ground-water flow to the Pecos River.

Empirical Methods

Water-Level Fluctuations

Water-level fluctuations in observation wells W5 and Spires, which are completed in the Santa Rosa Sandstone, indicate that seepage to bank storage has occurred during operation of the lake from 1980 to 1983 (fig. 21). Most of the water in bank storage will return to the lake when lake levels are lowered unless downward seepage to the Bernal Formation and San Andres Limestone occurs. Water levels in observation wells completed in the Bernal Formation and San Andres Limestone do not indicate significant seepage from the lake (figs. 16 and 17). Water levels in well CH32 probably show the effects of seepage from the lake (fig. 21). However, it is not certain that the water levels represent the hydraulic head in the San Andres Limestone. Most probably, the water levels represent a composite head of the Santa Rosa Sandstone, Bernal Formation, and San Andres Limestone.

Continued monitoring of water levels in observation wells completed in the Bernal Formation and San Andres Limestone will help evaluate whether water is seeping to these formations and where it is moving. Quantification of seepage from water levels in observation wells may not be possible because some of the wells are completed in more than one formation.

Water Budget of Lake

The volume of water that seeped from the lake during April 1980 through June 1983 was evaluated using a water budget of the lake. Seepage was assumed to be the difference between inflow to and outflow from the lake. Inflows to the lake are: (1) streamflow of the Pecos River above Santa Rosa Dam, (2) streamflow of Los Esteros Creek and Los Esteros Creek tributary, and (3) precipitation on the lake surface. Outflows from the lake are streamflow of the Pecos River measured at the gaging station below Santa Rosa Dam and evaporation from the lake surface calculated from evaporation pans operated by the U.S. Army Corps of Engineers at the dam. The change in storage in the lake was evaluated from daily readings of lake level and stage-area-capacity curves for the lake.

The difference between inflow to the lake and outflow was calculated on a daily basis and plotted as a cumulative total in figure 22. The calculated volume of water that might represent seepage from the lake to the surrounding rocks is shown in this graph. Four cycles of fill and drawdown are illustrated in figure 22. The first two cycles are complete because the lake was empty at the beginning and end of the cycles. In the last two cycles, the lake was only partly drained before the next fill cycle began.

During the first fill cycle, inflow to the lake was about 35,400 acre-feet and the outflow was only about 24,500 acre-feet (fig. 22). About 10,900 acre-feet of water could not be accounted for and may have seeped into bank storage. Water-level fluctuations at observation wells W5 and CH32 (fig. 21) indicate that water did go into bank storage during this period.

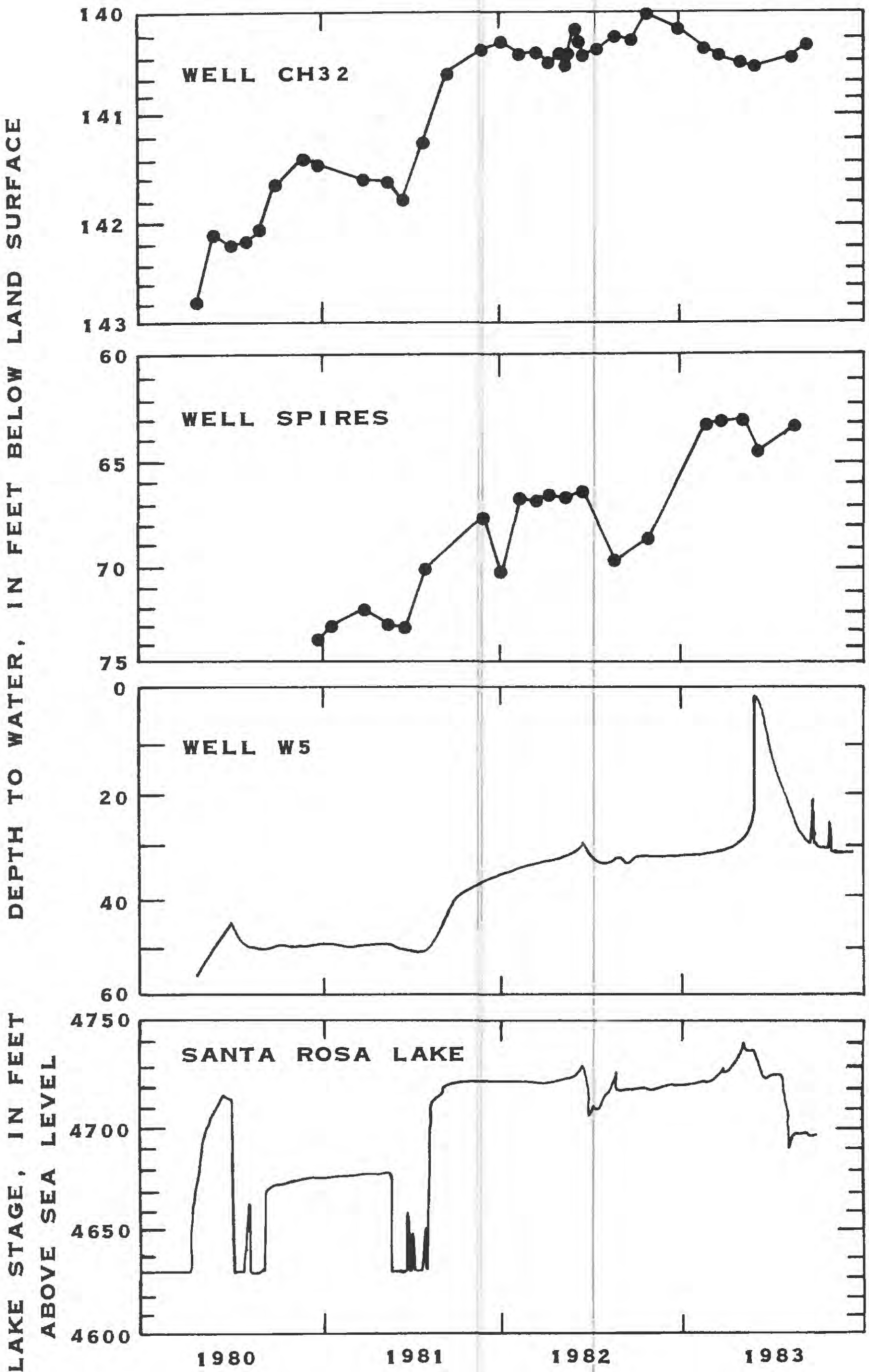
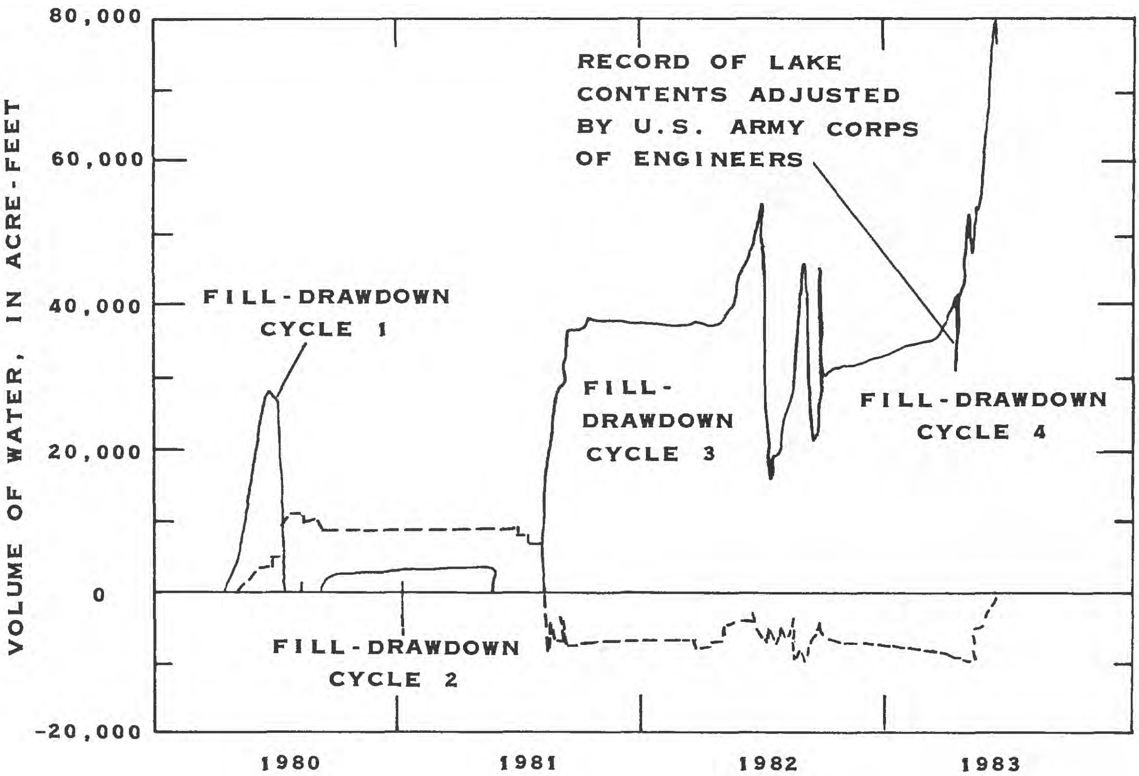


Figure 21.--Water levels in wells CH32, Spires, W5, and in Santa Rosa Lake.



EXPLANATION

CONTENTS OF SANTA ROSA LAKE

---- CUMULATIVE DIFFERENCE BETWEEN INFLOW TO AND OUTFLOW FROM SANTA ROSA LAKE--Positive values indicate cumulative inflow exceeds cumulative outflow

Figure 22.--Contents of Santa Rosa Lake and cumulative difference between inflow to and outflow from the lake.

A much smaller volume of water was stored in the reservoir during the second fill-drawdown cycle, September 1980 through May 1981, than during the first cycle. During this cycle, inflow was about 7,500 acre-feet and outflow was about 8,200 acre-feet, a net increase of about 700 acre-feet. During the period after the second fill cycle when the lake was empty, outflow continued to exceed inflow. The greater volume of outflow during this period may have been caused by return of bank storage from the previous fill cycle.

At the beginning of the third fill cycle, August 10-15, 1981, outflow exceeded inflow by about 12,200 acre-feet. This sudden change caused the estimated cumulative volume of water in bank storage to be less than zero (fig. 22). This sudden change probably was caused by inaccuracies in measuring the large volume of inflow, outflow, and change in lake storage during the 6-day period. For the remainder of the third and fourth fill cycles, inflow to the lake nearly balanced outflow. This result is difficult to explain because for the large volumes of water stored in the lake during cycles three and four, bank-storage volumes also need to be large. In fact, water levels in nearby observation wells indicate that bank storage did increase during fill cycles three and four. The only indication that inflow exceeded outflow during cycles 3 and 4 is shown at the very end of the record by the increase in cumulative difference between inflow and outflow in June 1983 (fig. 22).

Probably the accuracy of the inflow-outflow measurements is such that a detailed quantitative evaluation may not be possible. The greatest errors are made in measuring large releases of water from the lake and in estimating the lake storage term. Because the lake extends over a large area, small errors in topographic survey could cause large errors in calculation of storage. Also, the method used to estimate evaporation is approximate. The analysis does indicate, however, that large permanent losses from the lake probably have not occurred. If significant losses were occurring during cycles 3 and 4 when the storage in the lake was largest, inflow would have greatly exceeded outflow. The fact that the cumulative difference between measured inflow and outflow was nearly constant during these cycles (fig. 22) indicates that large losses probably are not occurring.

Change in Base Flow

The Pecos River gains a relatively constant amount of water between gaging stations at Santa Rosa and near Puerto de Luna. The gain between the two stations from November through April of each year is shown for water years 1939-82 in figure 23. These months were evaluated because diversions for irrigation and contributions from tributaries between the two gaging stations were small and gains mainly were from ground water. If seepage from the lake were to reappear in this reach at volumes of greater than 5,000 acre-feet during November through April, the increase in base flow could be identified. This volume corresponds to a seepage rate of about 14 cubic feet per second. Base-flow gains for water years 1980-1982, when Santa Rosa Lake contained water, do not indicate the addition of seepage at rates of 14 cubic feet per second or greater.

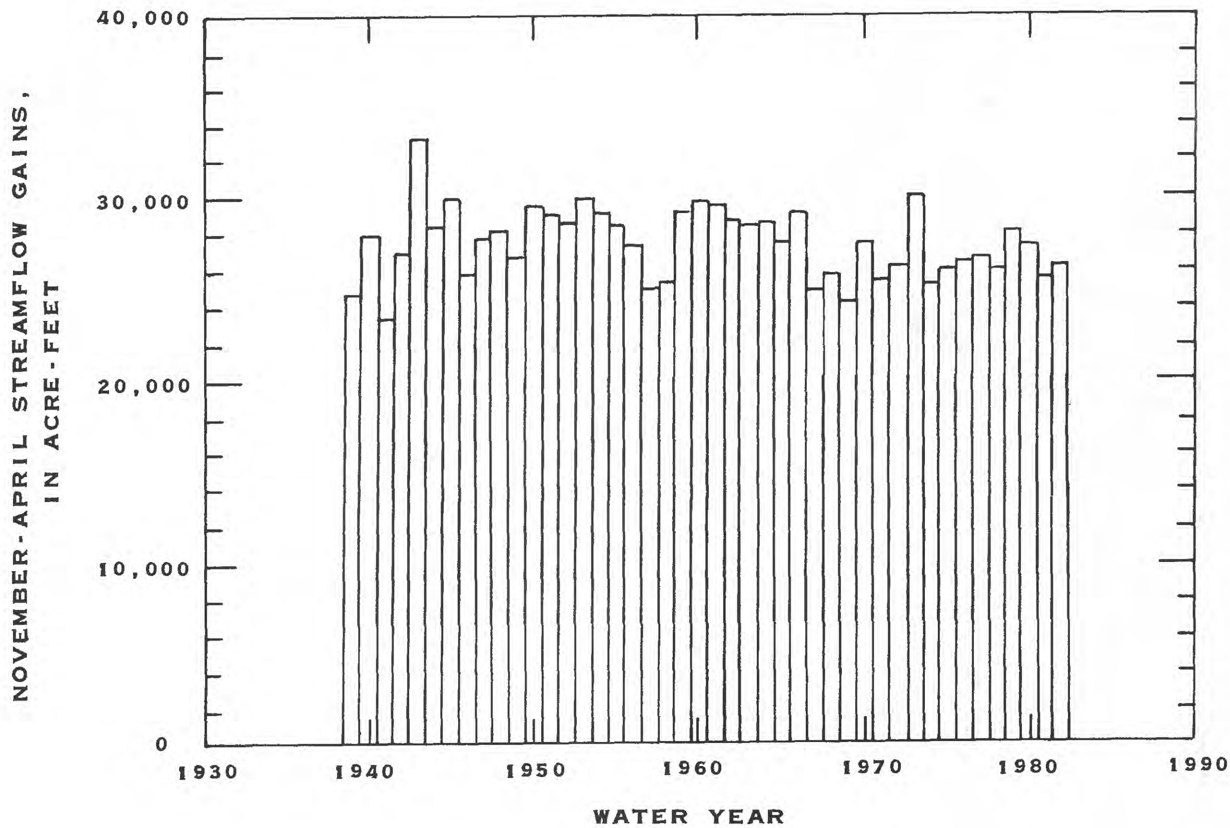


Figure 23.--November-through-April streamflow gains in the Pecos River between streamflow-gaging stations at Santa Rosa and near Puerto de Luna for water years 1939-82.

Water-Quality Changes

The specific conductance of water in the San Andres-Glorieta aquifer is quite large in the area immediately west of Santa Rosa Lake (fig. 10). Seepage to the San Andres-Glorieta aquifer in this area might flush this water toward discharge areas in the Pecos River between Santa Rosa and Puerto de Luna. Therefore, changes in the quality of water from observation wells and the Pecos River could be an indication of seepage from the lake. As of September 1983, no changes in water quality have been measured that could indicate significant seepage from the lake.

Mathematical Model

The previously discussed methods provide some techniques to qualitatively describe the effects of the lake. These methods, however, do not determine how much the lake will affect ground-water flow to the Pecos River between streamflow-gaging stations below the dam and near Puerto de Luna. Also, the methods are limited in that only the effects from lake levels and durations of impoundment already achieved can be analyzed. Estimates of seepage rates for higher lake levels and different durations of impoundment cannot be made. Furthermore, effects from the lake are difficult to separate into bank storage (which in large part will return to the lake), water lost from the study area, and water that may return as base flow in the Pecos River upstream of Puerto de Luna. Therefore, a mathematical model of the hydrologic system in the vicinity of Santa Rosa Lake was constructed to simulate potential effects of various lake levels and durations of impoundment on ground-water flow to the Pecos River.

Modeling Procedure

The mathematical model used to estimate the effects of Santa Rosa Lake on ground-water flow to the Pecos River is a simplified approximation of a complex hydrologic system. The simplicity of the model is due mainly to a lack of detailed knowledge about hydraulic properties and boundary conditions in the real hydrologic system. As stated by Konikow (1978, p. 87), "The numerical accuracy of the model is not commonly a factor limiting model reliability. Rather, the dominant cause of errors in model output is the presence of errors or uncertainty in the input data, which reflect our inability to accurately and quantitatively describe the aquifer properties, stresses, and boundaries." Because the model is a simplified representation of the real hydrologic system, questions may arise as to the validity of the predictions generated using the model. Unfortunately, ground-water-modeling techniques have not developed to the point where confidence bounds can be assigned to all predictions. However, some subjective measure of how closely the model can duplicate responses of the real hydrologic system can be gained by comparing simulated hydraulic heads and streamflow to measured values.

In this study, a model was first constructed to simulate steady-state values of hydraulic head and streamflow that were measured prior to construction of Santa Rosa Lake. The comparison of steady-state simulations to measured data improved the understanding of the real hydrologic system by allowing various working hypotheses to be tested and evaluated. The hypotheses-testing procedure continued in a trial-and-error manner until an acceptable match to the observed data was reached; however, an acceptable match to the observed data does not imply that a uniquely correct model has been constructed. Many "acceptable" models can be made using combinations of hydraulic properties and boundary conditions that are not physically possible. Therefore, during the trial-and-error adjustment of the steady-state model, the working hypotheses were restricted to those that used reasonable values for all physical parameters. Because the exact physical properties of the hydrologic system are not well known, the definition of reasonable values rests to a great extent on the experience and judgment of the modeler.

A subjective measure of confidence in the ability of a model to mimic the real system can be gained by comparing the measured response to a stress in the real hydrologic system to the model-generated response to an identical stress. This type of analysis was made by using historical changes in streamflow of the Pecos River and the level of Santa Rosa Lake. These transient changes were programmed into the model, then changes in water levels and streamflow were simulated and compared to the measured response of the real hydrologic system.

Model Used

The model used to simulate ground-water flow is a three-dimensional, finite-difference, mathematical model documented by McDonald and Harbaugh (1983). The differential equations of ground-water flow are approximated in the model by a series of finite-difference equations. For use in the model, the study area was divided into a grid with nodal points at the center of each cell. The finite-difference equations were then solved at each cell on a digital computer using the strongly implicit procedure.

Model Construction

Construction of the model involves dividing the area into a finite-difference grid, setting the boundary conditions that control the physical geometry and hydrologic flux of the model, and assigning hydrologic properties to each cell. The considerations that went into constructing the model are described in this section.

Finite-difference grid

The study area was divided into a finite-difference grid consisting of 1,152 variable-sized cells in each of three layers (figs. 24-26). The layers correspond to the following geologic units: layer 1 - Chinle Formation and Santa Rosa Sandstone, layer 2 - Bernal Formation, and layer 3 - San Andres Formation and Glorieta Sandstone (fig. 3). The grid is arranged in 32 rows and 36 columns (fig. 24). The nodal position at the center of each cell is designated by layer, row, and column. For example, node (3-20-15) is located in layer 3, row 20, and column 15. The orientation of the grid is arranged so that columns are aligned northwest to southeast. This orientation was chosen to follow the major fracture pattern and sinkhole alignment that probably controls the anisotropy with respect to hydraulic conductivity in the area. The horizontal dimensions of the cells were varied so that nodes would be closely spaced ($\frac{1}{2}$ mile on each side) near the lake and along the Pecos River where the largest effects of the lake were expected. The size of the cells was increased away from the lake to save computational costs and place arbitrary boundaries at a larger distance from the lake.

Boundaries

The model boundaries define the physical extent and the flow of water into and out of the study area. Three types of boundaries are used in this model: specified flow, specified hydraulic head, and hydraulic-head-dependent flow. A discussion of the boundary types, modified slightly from Hearne (1980, p. 24) follows. At specified-flow boundaries, water is recharged to or discharged from the aquifer at a rate that is independent of the hydraulic head in the aquifer. An impermeable or no-flow boundary is a specified flow of zero. At specified hydraulic-head boundaries, the hydraulic head is maintained at the specified value. As hydraulic heads in the aquifer system change adjacent to the specified hydraulic-head boundary, the rate of flow at the specified hydraulic-head boundary will change. At a hydraulic-head-dependent flow boundary, the hydraulic head is allowed to change as the aquifer is stressed. The rate that water is recharged to or discharged from the aquifer is calculated as a function of the hydraulic head in the aquifer, the stage of the river, and hydraulic conductivity of the riverbed. These boundary conditions are used to simulate the physical geometry of aquifers within the study area, flow from aquifers outside of the study area, recharge from precipitation, and flow to and from rivers.

Physical geometry.--The physical geometry of geologic units is specified by inactive or active cells within each layer. If the geologic units represented in a layer do not exist, the appropriate cells are specified as inactive (figs. 24-26). No flow of water can take place in the model between active and inactive cells.

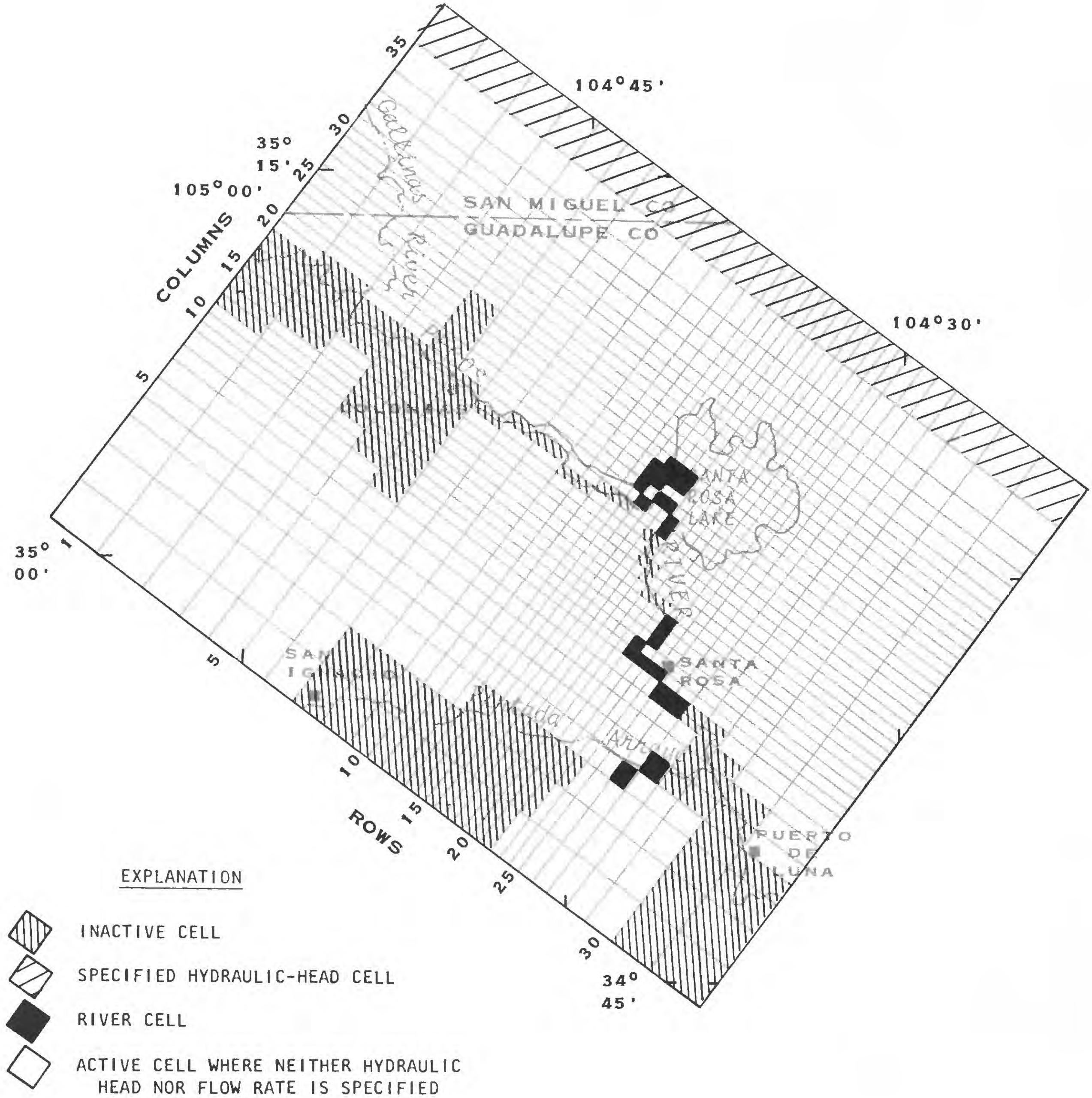


Figure 24.--Boundary conditions for the Chinle Formation and Santa Rosa Sandstone (layer 1).

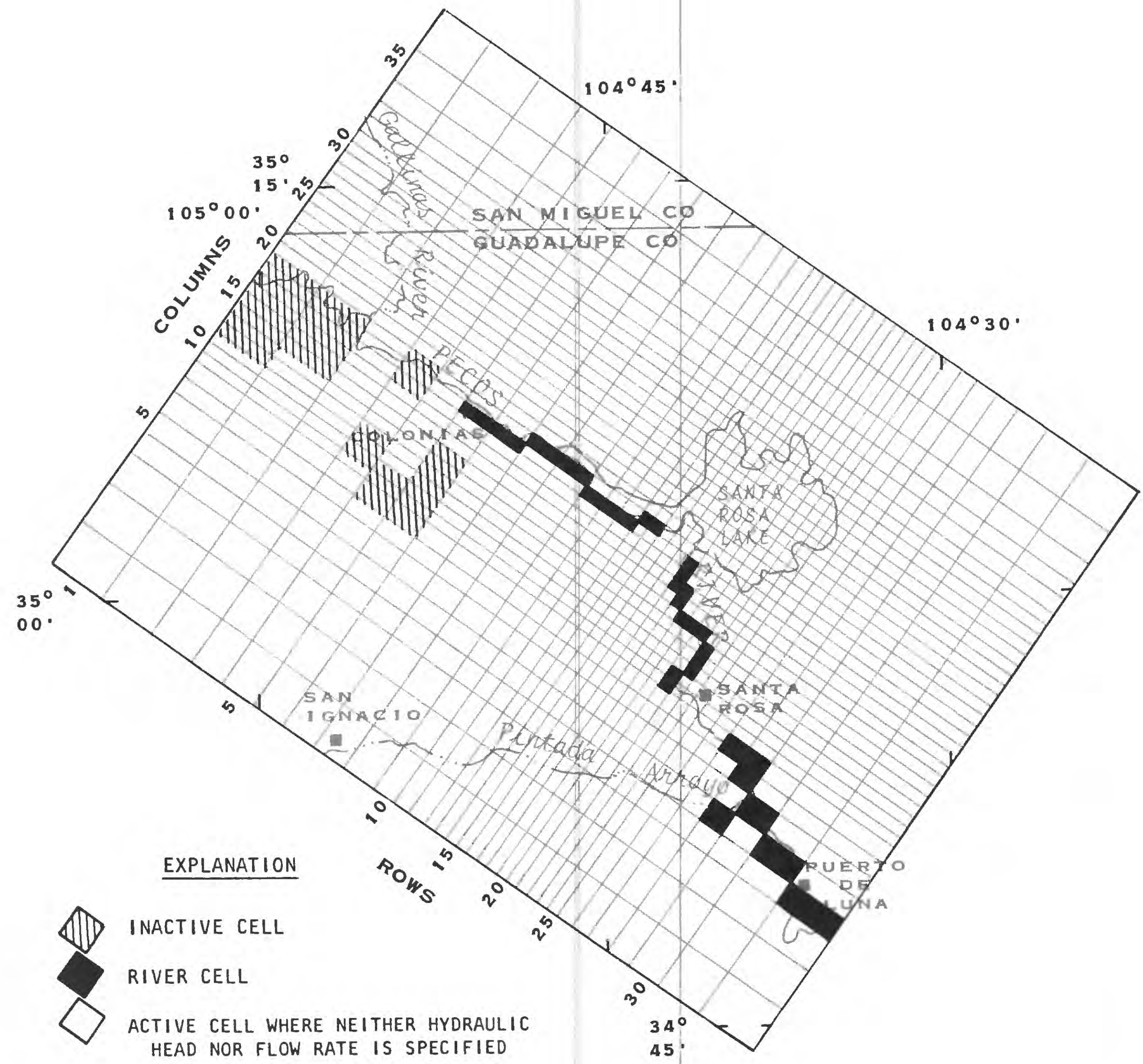


Figure 25.--Boundary conditions for the Bernal Formation (layer 2).

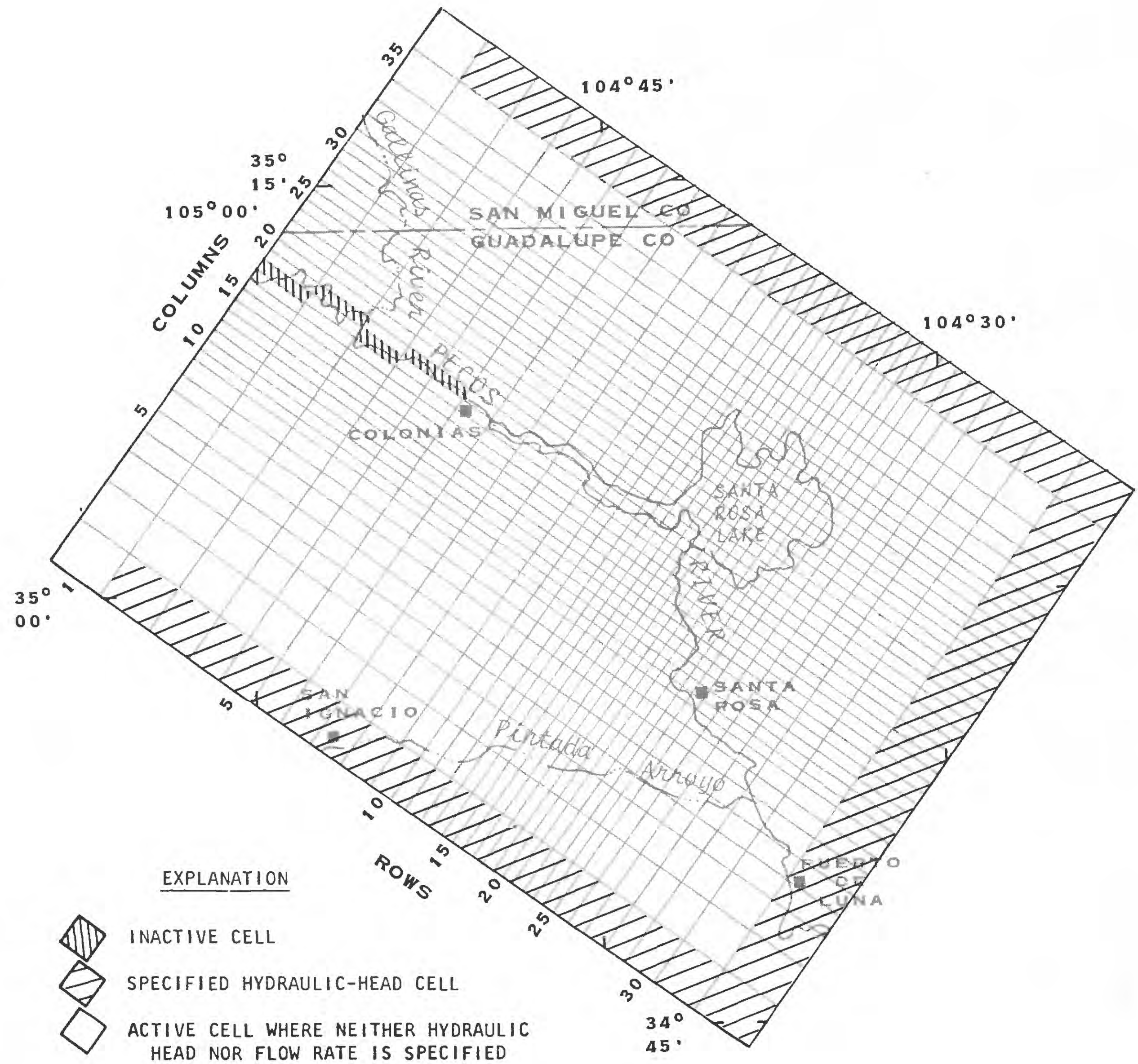


Figure 26.--Boundary conditions for the San Andres Limestone and Glorieta Sandstone (layer 3).

Aquifers outside of the study area.--Ideally, a model is constructed to extend to the real physical boundaries of all aquifers that are affected by Santa Rosa Lake. In this study area, the aquifers of interest extend for hundreds of miles from the lake. Therefore, a model of huge dimensions would be required to accurately simulate real physical boundaries. Where it is impractical to simulate the position of all real hydrologic boundaries, arbitrary boundaries may be placed at a sufficient distance from Santa Rosa Lake so that they will have a negligible effect upon the simulated ground-water flow to the Pecos River. The effect of the arbitrary boundaries on a simulation can be checked by changing the type of boundary and repeating the simulation (Trescott and others, 1976, p. 29).

Arbitrary lateral boundaries were placed around the perimeter of all layers as shown in figures 24-26. During the initial construction, some lateral boundaries of layers 1 and 3 were assigned specified values of hydraulic head that allowed the model to simulate flow passing through the study area. Specified hydraulic-head cells were used because the ground-water-flow rate into the study area was not well known; however, hydraulic heads at the boundaries could be approximated from water-level measurements in observation wells (figs. 7 and 9). No-flow boundaries were placed around layers 1 and 3 where ground-water flow was believed to be parallel to that edge of the study area. Around the perimeter of layer 2, a no-flow boundary also was specified because only very small quantities of water flow in a horizontal direction in this confining layer.

The base of the model was simulated using a no-flow boundary at the bottom of the San Andres-Glorieta aquifer. The no-flow boundary does not allow any water to enter or leave the model from geologic units older than the Glorieta Sandstone. Probably some movement does occur across this boundary, especially upward leakage from formations below the Glorieta Sandstone in the vicinity of the Pecos River. However, this volume of water probably is small because these subadjacent older formations are composed mainly of siltstone and shale.

Precipitation.--Recharge to the water table from precipitation directly on outcrop areas is represented by specified-flow cells in layer 1. Recharge from precipitation was estimated to range from 0.18 to 0.30 inch per year. The maximum rate was based on an estimate of the average recharge rate in the basin upstream from the gaging station near Puerto de Luna. This rate was used as a probable maximum rate because precipitation is much greater in the upper parts of the Pecos River drainage basin. The minimum rate of 0.18 inch per year was the value of ground-water accretion estimated for a small area of the Santa Rosa Sandstone.

Rivers.--In the model, the interaction between ground water and rivers was simulated by specified-flow and river cells (figs. 24-26). The river cell is a specialized type of hydraulic-head-dependent flow boundary. This type of boundary allows the simulated river to gain or lose water as a function of the difference between the specified head of water in the river, the head in the aquifer, and the conductance of the riverbed. The amount of flow from this cell is limited when the simulated head in the aquifer drops below the specified altitude of the riverbed. For all river cells, the riverbed altitude was determined from topographic maps; the stage of the river was assumed to be 2 feet above the riverbed; and the conductance of the sandy riverbed was calculated by measuring the stream length in each cell and assuming a riverbed thickness of 1 foot and a vertical hydraulic conductivity of 2 feet per day.

Upstream from Colonias, the Pecos River loses about 47 cubic feet per second to ground water. This stream reach was simulated with five specified-flux cells in layer 3 that together contributed 47 cubic feet per second to the San Andres-Glorieta aquifer (fig. 26). Throughout the remainder of the study area, the Pecos River is basically a gaining stream and was simulated as a partly penetrating stream in layers 2 and 3 using river cells (figs. 24 and 25).

The lower reach of Pintada Arroyo (Rio Agua Negra) is a perennial, gaining stream. It was simulated as a hydraulic-head-dependent flow boundary (figs. 24 and 25) using river cells.

Springs and seeps.--Throughout much of the study area, the Pecos River is entrenched completely through the Santa Rosa Sandstone. Some ground water in the Santa Rosa Sandstone moves toward the Pecos River and discharges as seeps and springs along the river at the contact with the underlying Bernal Formation. This discharge was simulated using drain cells in layer 1 along the river. The drain cells act as a special type of hydraulic-head-dependent flow boundary that only allows water to discharge from a layer. The altitude of each drain was specified as 20 feet above the Santa Rosa Sandstone-Bernal Formation contact.

The large springs along the Pecos River near Santa Rosa that discharge water from deeper units were not simulated using drains. These springs occur in the area covered by river cells that represent the Pecos River and Rio Agua Negra. Therefore, the springflow was simulated as part of this gaining reach of the Pecos River.

Hydraulic properties

During construction of the model, initial values of hydraulic properties for each layer were chosen recognizing that these numbers were trial values that would be adjusted. Initially, the hydraulic properties for all cells in a layer were identical. The values used for each layer are listed below.

Property	Layer 1 (Santa Rosa Sandstone)	Layer 2 (Bernal Formation)	Layer 3 (San Andres-Glorieta)
Horizontal hydraulic conductivity (feet per day)	0.52	0.04	-
Vertical hydraulic conductivity (feet per second)	6×10^{-5}	5×10^{-11}	1×10^{-6}
Transmissivity (feet squared per day)	-	-	10,000

Model Calibration

Calibration is a process in which model characteristics are adjusted until the model adequately simulates the known behavior of the real hydrologic system. The calibration process is not intended to establish with certainty the accuracy or precision of model predictions. Rather, the process is used to refine concepts and test hypotheses until an adjusted model is achieved that better mimics the real hydrologic system. The precision and accuracy of model simulations for a future event cannot be known until that event occurs.

The model was calibrated by matching as closely as possible the values of streamflow and hydraulic head measured in the real system. The calibration procedure consisted of two stages: (1) steady-state calibration, and (2) transient calibration.

Steady state

The model was calibrated against steady-state water levels and streamflow values measured prior to construction of Santa Rosa Dam. Aquifer characteristics were adjusted until simulated and measured water levels in layers 1 and 3 agreed within 50 feet at most locations and streamflow gains and losses agreed within about 10 percent. The greater degree of accuracy was placed on matching streamflow values because some water-level measurements probably represent composite hydraulic heads from wells completed in several aquifers.

Best-fit model.--A steady-state model was developed to match as closely as possible measured streamflow changes and ground-water levels. Boundary conditions for the best-fit model are shown in figures 24-26. The hydraulic properties for layers 1 and 3 are shown in figures 27 and 28, respectively. The transmissivity of layer 2 at each cell determined from calibration was 0.17 foot per day times the thickness of the aquifer. The layers were connected by a vertical hydraulic conductivity of 5×10^{-11} foot per second, except in the Santa Rosa Sink area and upstream from River Ranch where the value was increased to as much as 5×10^{-6} foot per second to simulate vertical fractures in the formations.

Comparison of simulated and measured steady-state water levels for layers 1 and 3 are shown in figures 29 and 30, respectively. Simulated and measured water levels in layer 2, the Bernal Formation, were not compared because the hydraulic-head change in the vertical direction of this confining unit probably is very large and could not be adequately simulated in one layer. The average absolute difference between simulated and measured steady-state water levels at 46 wells in layer 1 was 33 feet, with the largest absolute difference of 212 feet at row 7, column 5. The average absolute difference in layer 3 at 22 wells was 22 feet and the largest absolute difference was 53 feet at row 11, column 11.

Measured changes in streamflow in the Pecos River also were used to calibrate the steady-state model. The similarity between the measured streamflow and that simulated by the best-fit steady-state model is shown in figure 31. The change in streamflow needs to be compared only between 32 and 87 river miles downstream from Anton Chico (numbers 3 and 11 in fig. 31). The loss in streamflow in the first 32 miles downstream was simulated by specified-flow cells that were set to measured values of streamflow loss.

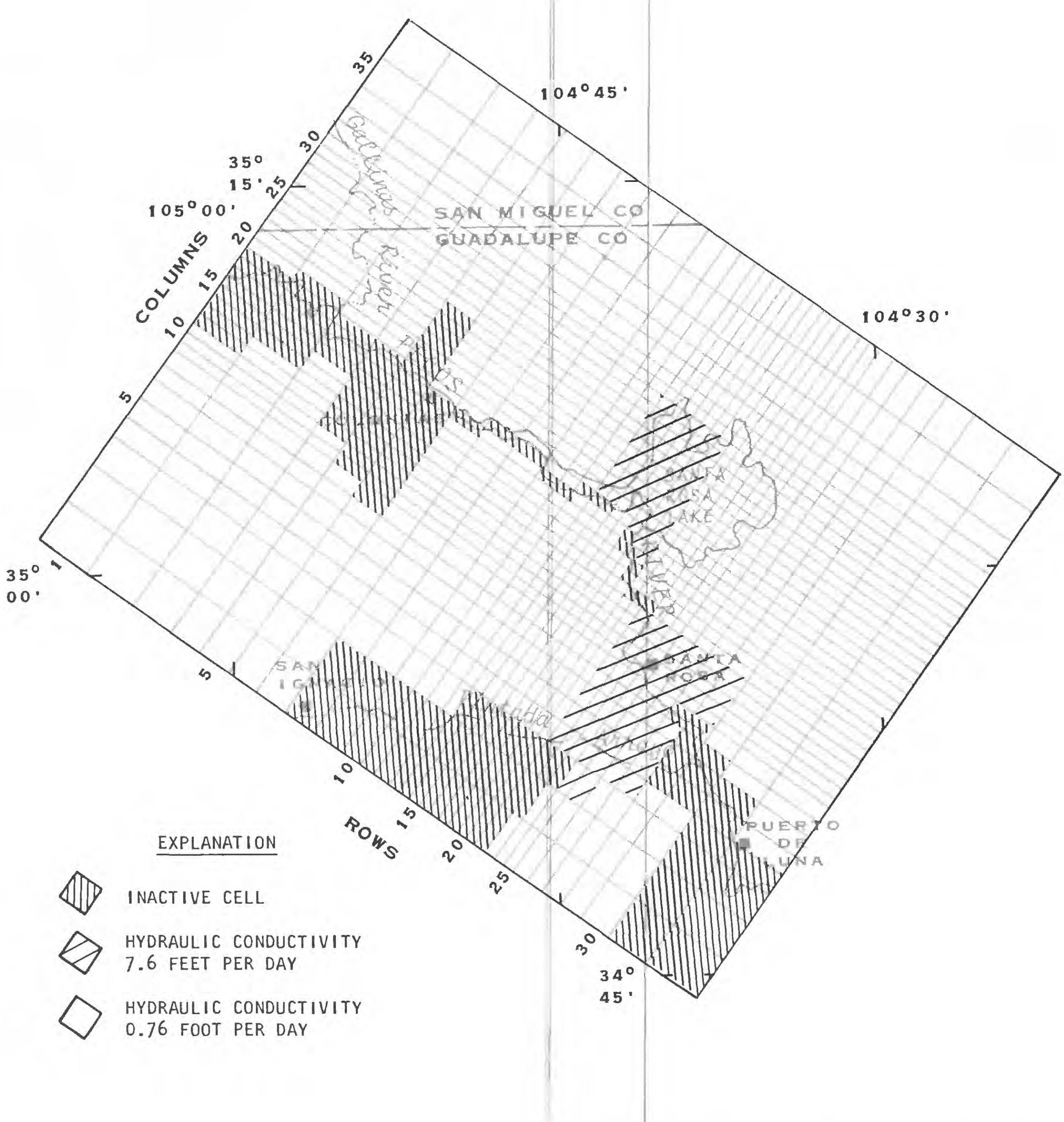


Figure 27.--Hydraulic conductivity of the Chinle Formation and Santa Rosa Sandstone (layer 1).

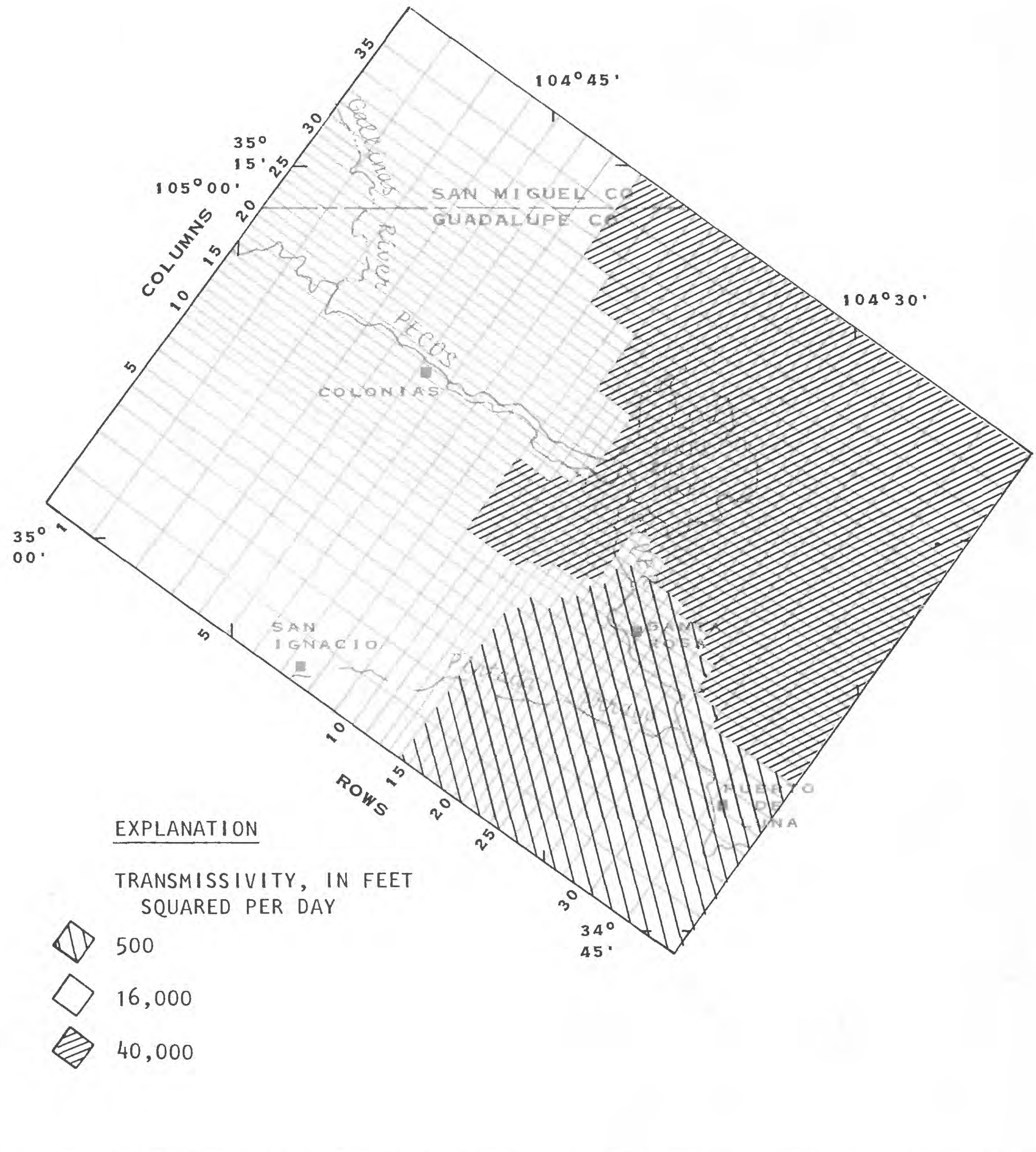


Figure 28.--Transmissivity of the San Andres Limestone and Glorieta Sandstone (layer 3).

A water budget was calculated for the best-fit steady-state model. Total flow is broken down into separate source and sink terms as shown below.

Inflow of ground water, in cubic feet per second	
From aquifers outside the study area (flow across perimeter boundaries)	= 78.8
Streamflow losses	= 49.5
Recharge from direct precipitation	= 17.2
TOTAL INFLOW	= 145.5

Outflow of ground water, in cubic feet per second	
To aquifers outside the study area (flow across perimeter boundaries)	= 38.8
Spring discharge from Santa Rosa Sandstone	= 4.6
Streamflow gains	= 101.9
TOTAL OUTFLOW	= 145.3

Model adjustments.--Before the best-fit steady-state model was finalized, several adjustments were made and hypotheses were tested about types of boundary conditions and values of hydraulic properties. The largest adjustments were made to layer 3 (San Andres Limestone and Glorieta Sandstone) primarily because few water-level measurements and values for hydraulic properties are known for rocks east and north of the Pecos River.

Initial simulations had values for specified-head cells on the northeastern boundary of layer 3 that simulated flow toward the Pecos River. Simulations with water moving toward the Pecos River upstream from Colonias caused the simulated hydraulic head to be several hundred feet higher than the measured hydraulic head. To lower the simulated hydraulic head, the transmissivity of layer 3 had to be increased to about 100,000 feet squared per day west and south of the Pecos River. This large transmissivity caused the simulated hydraulic head in layer 3 to be several hundred feet below the measured hydraulic head along the southeast edge of the model if a specified-flow boundary was used or unrealistic quantities of flow to move across the southeast boundary if specified-head boundary was used. A solution to the problem that was consistent with measured water levels, estimated water budget, and hydraulic properties was to decrease the specified heads along the northern edge boundary of the model. These new values result in ground-water outflow to the north (fig. 30). To allow enough outflow such that simulated water levels would be lower, the transmissivity was assumed to be the same on each side of the river near Colonias (fig. 28).

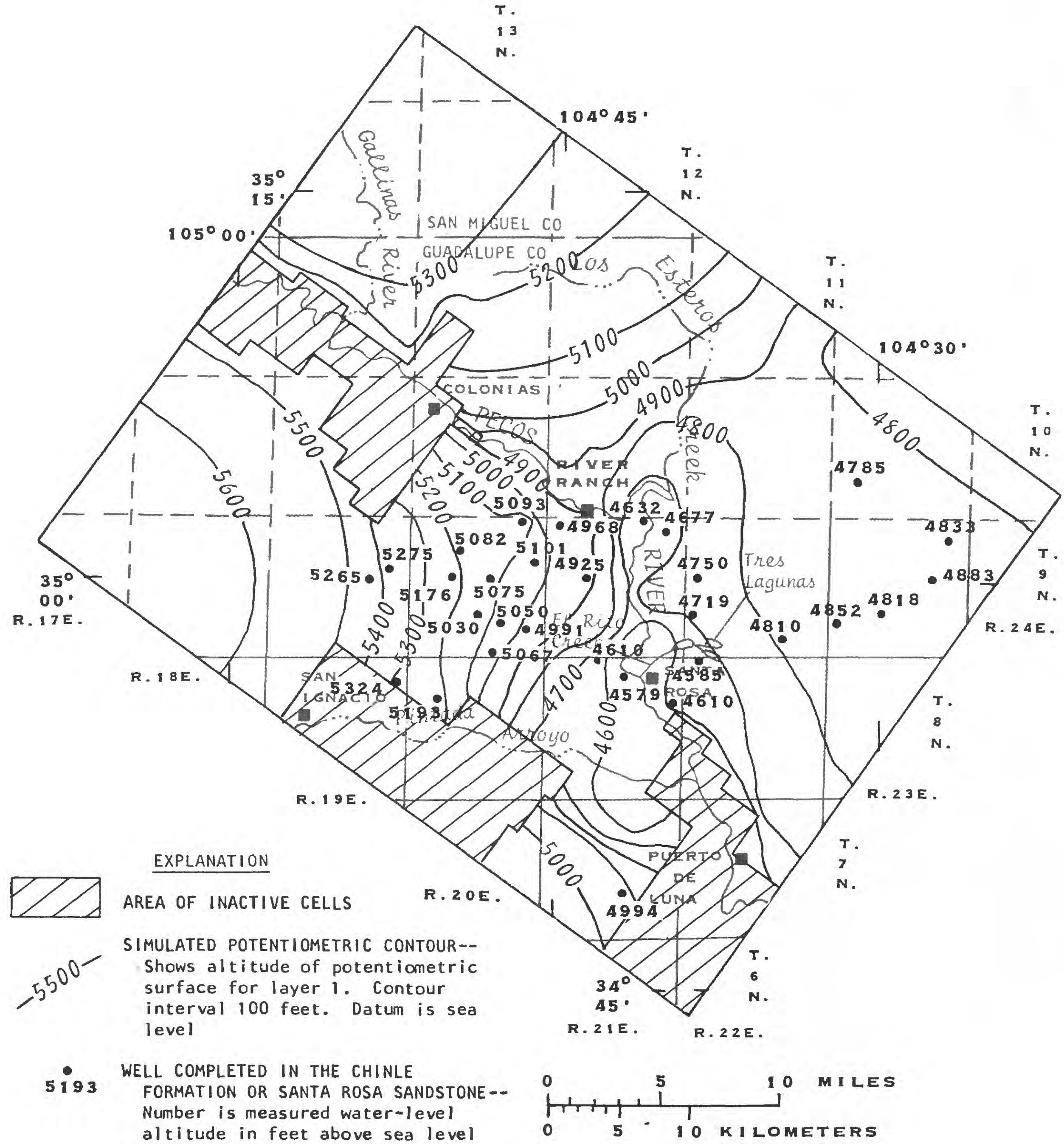


Figure 29.--Simulated steady-state potentiometric surface for the Chinle Formation and Santa Rosa Sandstone (layer 1).

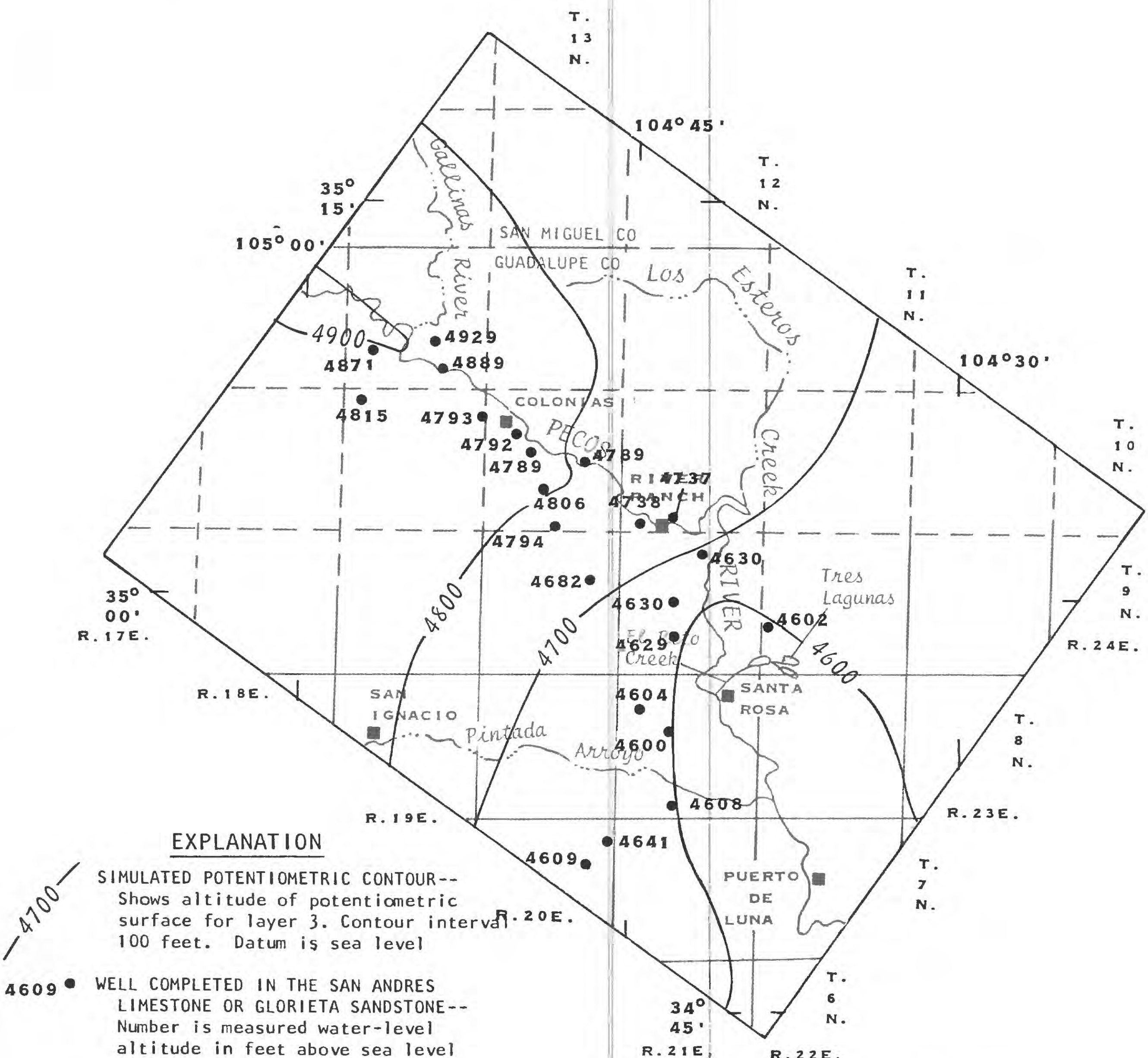


Figure 30.--Simulated steady-state potentiometric surface for the San Andres Limestone and Glorieta Sandstone (layer 3).

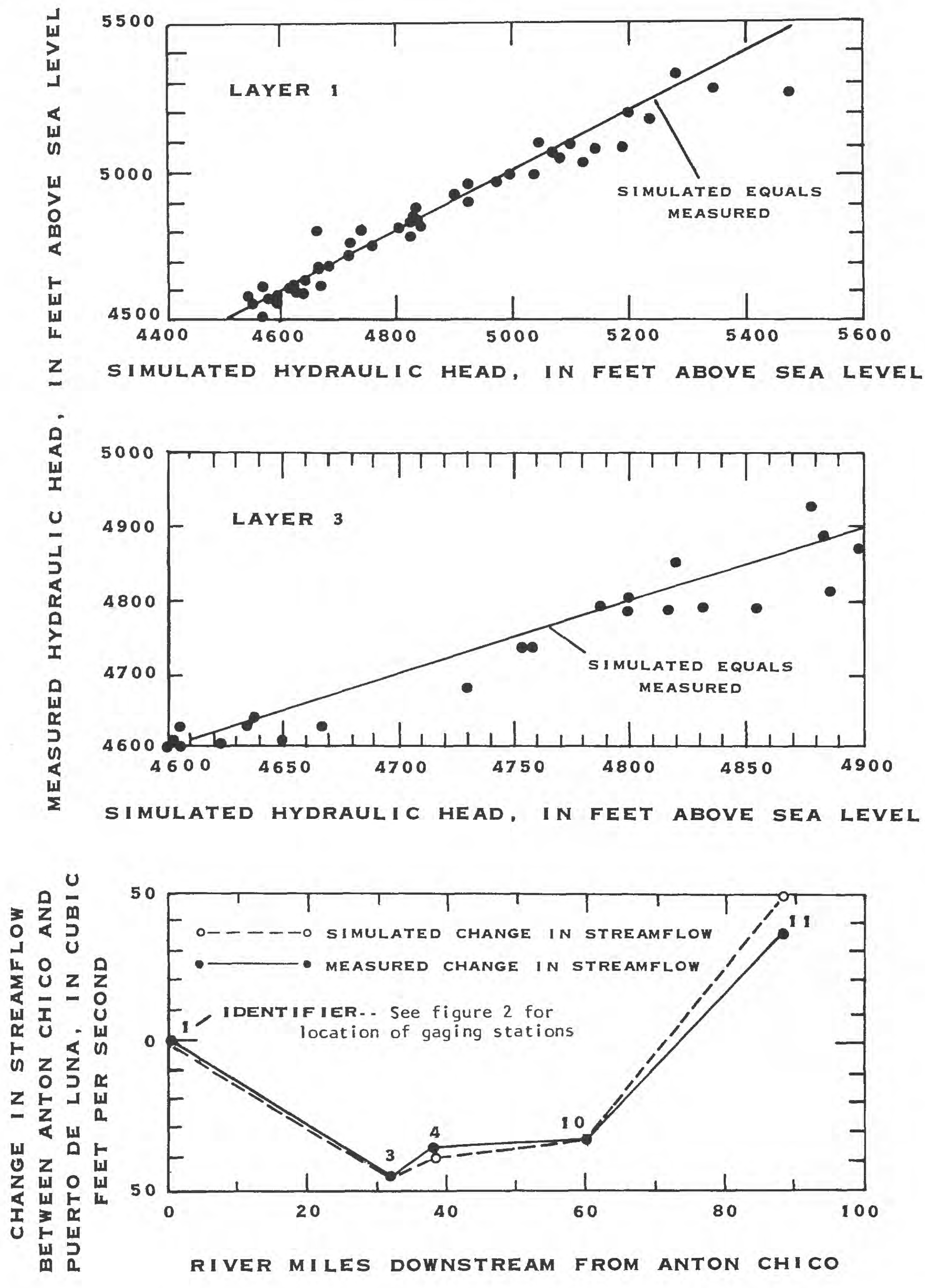


Figure 31.--Comparison between simulated and measured steady-state hydraulic head and streamflow change.

The range of transmissivity used in layer 3 varied from 500 to 40,000 feet squared per day (fig. 28). The zone of large transmissivity in the Santa Rosa Sink area was needed to simulate the highly fractured rock and small gradient of the potentiometric surface. The small transmissivity assigned to the eastern part of layer 3 was based on information from slug-type aquifer tests and water-quality data. A value of 500 feet squared per day was used primarily to represent the properties of the Glorieta Sandstone. The San Andres Limestone, which is mostly anhydrite in this area, was believed to have minimal permeability. Despite the few measurements of hydraulic head east of the Pecos River, the simulated potentiometric surface was judged to be acceptable.

Adjustments to the hydraulic conductivity of layer 1 were made along the Pecos River about 10 miles north of Santa Rosa and in the Santa Rosa Sink area (fig. 27). In these areas, the hydraulic conductivity was increased to 10 times that in the remainder of the layer. This increase was necessary to simulate the flat gradient caused by secondary permeability in these areas.

The sensitivity of simulated steady-state water levels and streamflow to changes in boundary conditions and hydraulic properties was noted during calibration. The steady-state problem is constrained mainly by the boundary conditions assigned to the model. Therefore, the greatest changes in water levels and streamflow rates throughout the study area could be achieved by changing the values of the arbitrary lateral boundaries or the source and sink terms such as rivers, drains, precipitation, and specified-flow and specified-head cells. Uniform changes in hydraulic conductivity throughout the study area produced changes of several hundred feet in the simulated water levels in layer 1. However, simulated water levels in layer 3 changed less than 20 feet when uniform changes in hydraulic conductivity were made. The simulated streamflow of the Pecos River and the total water budget of the model were highly sensitive to changes in all hydraulic properties except vertical hydraulic conductivity between layers. Doubling and halving the vertical hydraulic conductivity uniformly throughout the study area produced changes of only a few feet in simulated water levels. Changing a hydraulic property only in selected areas locally could produce a larger change in simulated water levels than a uniform change over the entire study area.

Transient

In addition to calibration to steady-state conditions, a measure of how well the model simulates the real hydrologic system can be gained by calibration to transient (nonsteady-state) conditions. During transient calibration, hydraulic properties and boundary conditions are not changed. The transient simulations are used to adjust the specific yield and storage coefficients of each layer. If, however, the model cannot adequately match the measured transient changes in water levels and streamflow using reasonable values for storage and specific yield, other hydraulic properties need to be reevaluated.

Changes in the amount of water lost from the Pecos River upstream from Colonias cause fluctuations of water levels in the San Andres-Glorieta aquifer (layer 3). The ability of the model to simulate changes in water levels in layer 3 at wells Santa Rosa 1, E5, E6, and E7 is shown in figure 32.

The values of storage coefficient and specific yield used in the transient simulation are shown below.

	Specific yield	Storage coefficient
Layer 1 (Santa Rosa Sandstone and Chinle Formation)	0.050	--
Layer 2 (Bernal Formation)	.015	0.0001
Layer 3 (San Andres Limestone and Glorieta Sandstone)	.015	.0001

The timing and magnitude of simulated water-level changes were found to be very sensitive to small changes in values of specific yield chosen for outcrops of the San Andres Limestone where the Pecos River loses water.

The model also was adjusted to transient conditions for 1980-83 by simulating the effect of Santa Rosa Lake on water levels in nearby observation wells W5 and C20 (fig. 2). The altitude of Santa Rosa Lake was simulated by adjusting the hydraulic head in each river cell 21 times. The bottom of each river cell used to simulate the lake was assigned the altitude of the land surface at the node of that cell. The hydraulic conductivity at each cell was set to 0.1 foot per day.

The match between measured and simulated water levels at wells C20 and W5 is shown in figure 33. Well C20 is in cell 1-19-22. Well W5 is in cell 1-19-21; however, because the starting head in this cell was about 16 feet lower than the measured prelake water level, the simulated response to lake-level changes was large. The adjacent cell (1-19-22) had a starting head closer to the measured prelake water level in well W5 and thus the change caused by the lake was closer to the measurements.

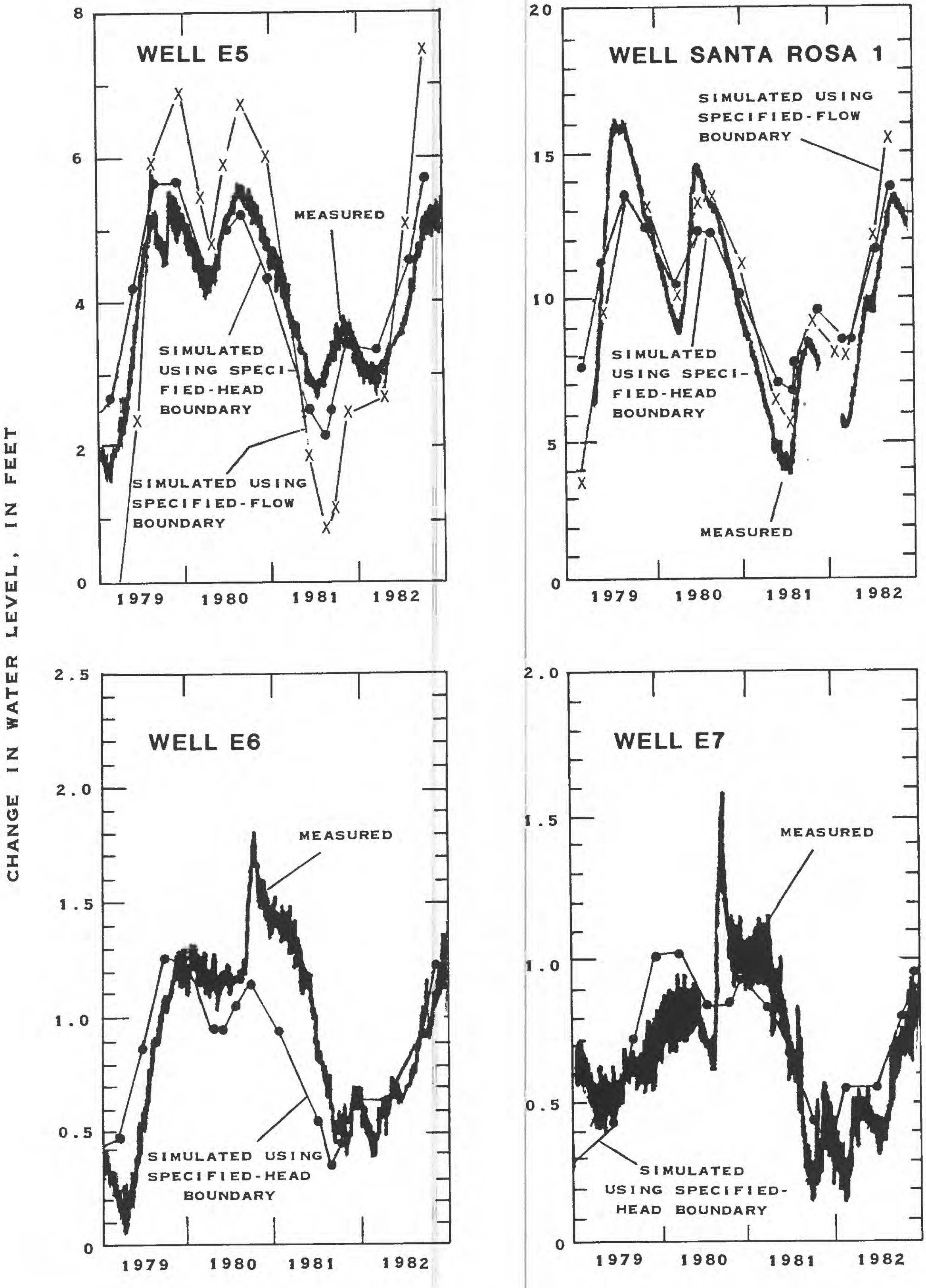


Figure 32.--Comparison between measured and simulated water levels in selected observation wells.

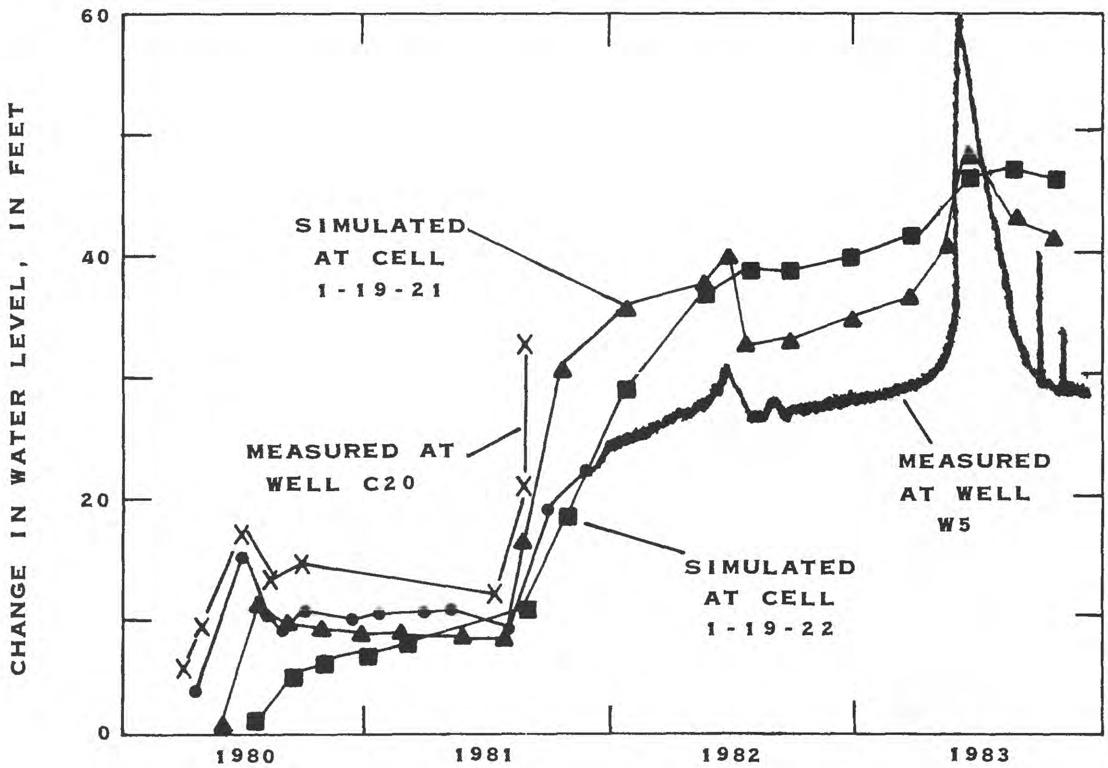


Figure 33.--Measured and simulated water levels at wells W5 and C20, 1980-83.

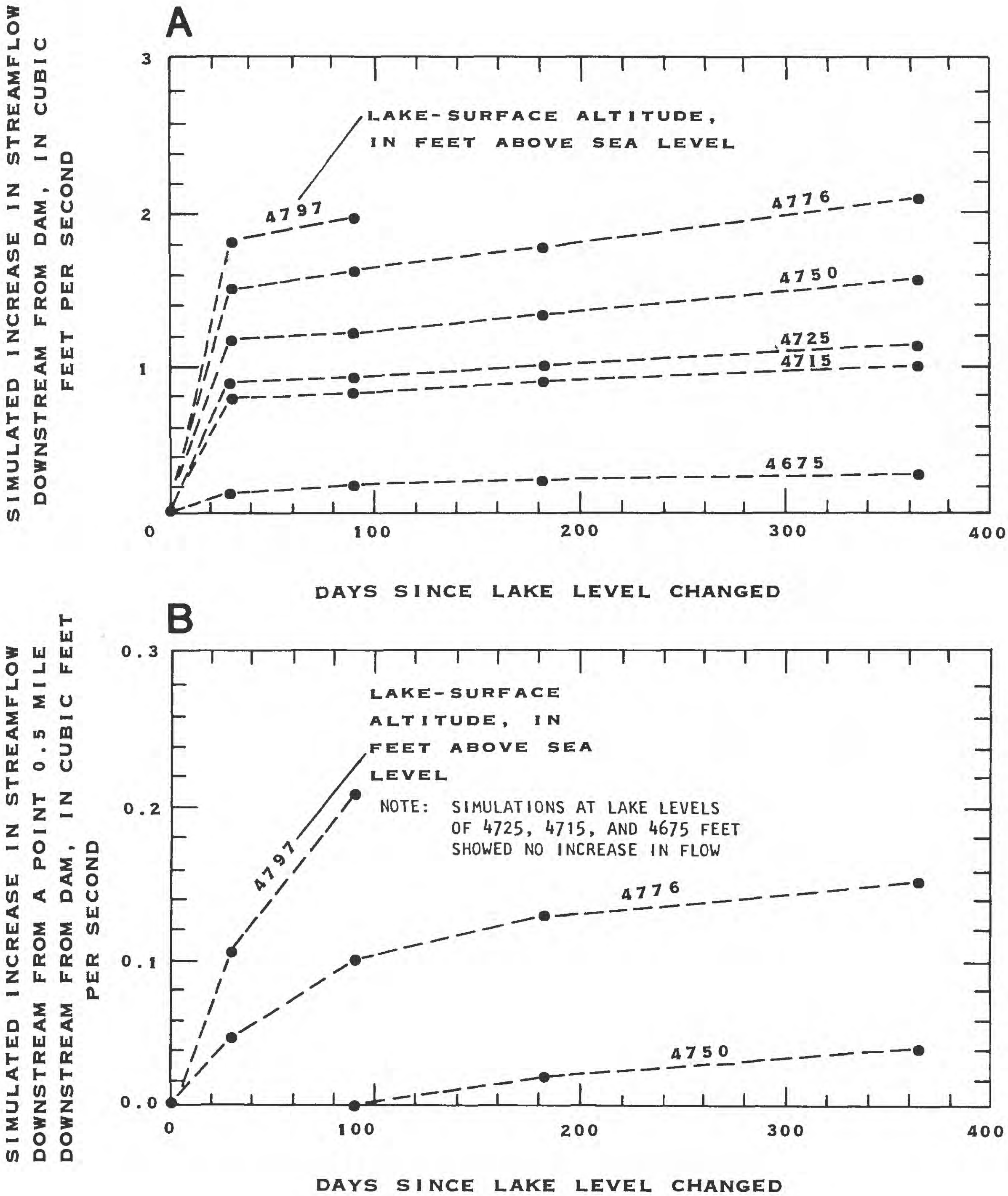
The specific yield of layer 1 used during these transient adjustments was 0.05. The timing and magnitude of simulated water-level fluctuations were very sensitive to changes in this value. A larger value resulted in simulated water-level changes of smaller magnitude and delayed response. The same effects also could be controlled by adjusting the hydraulic conductivity of the river cells that simulate the lake.

Model Results

The model was used to estimate the effect of Santa Rosa Lake on ground-water flow to the Pecos River. Hydraulic properties and boundary conditions used in the model for these predictions were determined from the steady-state and transient simulations. The effects of the lake were estimated at lake levels of: 4,797 (flood-control pool, top of spillway), 4,776 (maximum irrigation pool), 4,750, 4,725, 4,715, and 4,675 feet above sea level. For each lake level, except the flood-control pool, the effects were tested for durations of impoundment of 30 days, 90 days, 182 days, and 365 days. The flood-control pool level was simulated for a maximum duration of 90 days. Each simulation was made by instantaneously filling the lake to the specified altitude and holding that level for the specified duration.

Simulated changes caused by the lake are valid only for the conditions of "fill and hold" as stated above. The effects of the lake for any lake level and duration are dependent upon antecedent conditions that were assumed to be steady state for all simulations. In reality, the lake will not instantaneously change from empty to maximum pool as assumed for these simulations. Therefore, these simulations need to be viewed as examples of some extreme cases, not as a guide to the exact effect of the lake in all situations.

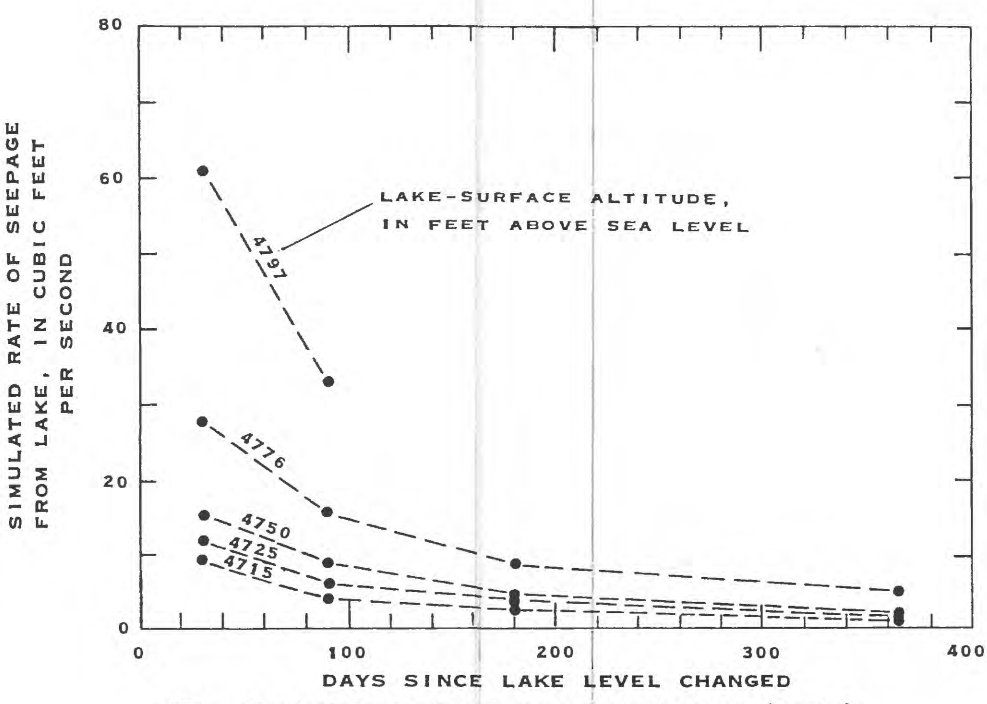
The simulated effects on streamflow in the Pecos River between the dam and Puerto de Luna caused by filling Santa Rosa Lake to various levels for various durations are shown in figure 34. The maximum simulated increase in streamflow is about 2 cubic feet per second after holding the water level in the lake at 4,797 feet for 90 days or 4,776 feet for 365 days (fig. 34A). The simulated increase in streamflow exclusive of the change that occurred in the first ½ mile below the dam is shown in figure 34B. These rates indicate that most of the simulated increase in streamflow occurred in the first ½ mile downstream from the dam for all lake levels and durations. For example, if the lake level was held at 4,797 feet for 90 days, the simulated flow of the Pecos River would increase about 1.8 cubic feet per second in the first ½ mile downstream from the dam, which is about 90 percent of the total simulated increase between the dam and Puerto de Luna. The difference in these rates is important because the streamflow-gaging station that measures outflow from the lake is located 0.2 mile downstream from the dam. Thus, part of the simulated increase in streamflow in the first ½ mile downstream from the dam will be measured at this gage. Only the part of the increased flow that bypasses the streamflow-gaging station is the unmeasured increase in streamflow caused by the lake.



NOTE: Simulations are based on an instantaneous change in lake level from empty to altitudes ranging from 4675 to 4797 feet above sea level

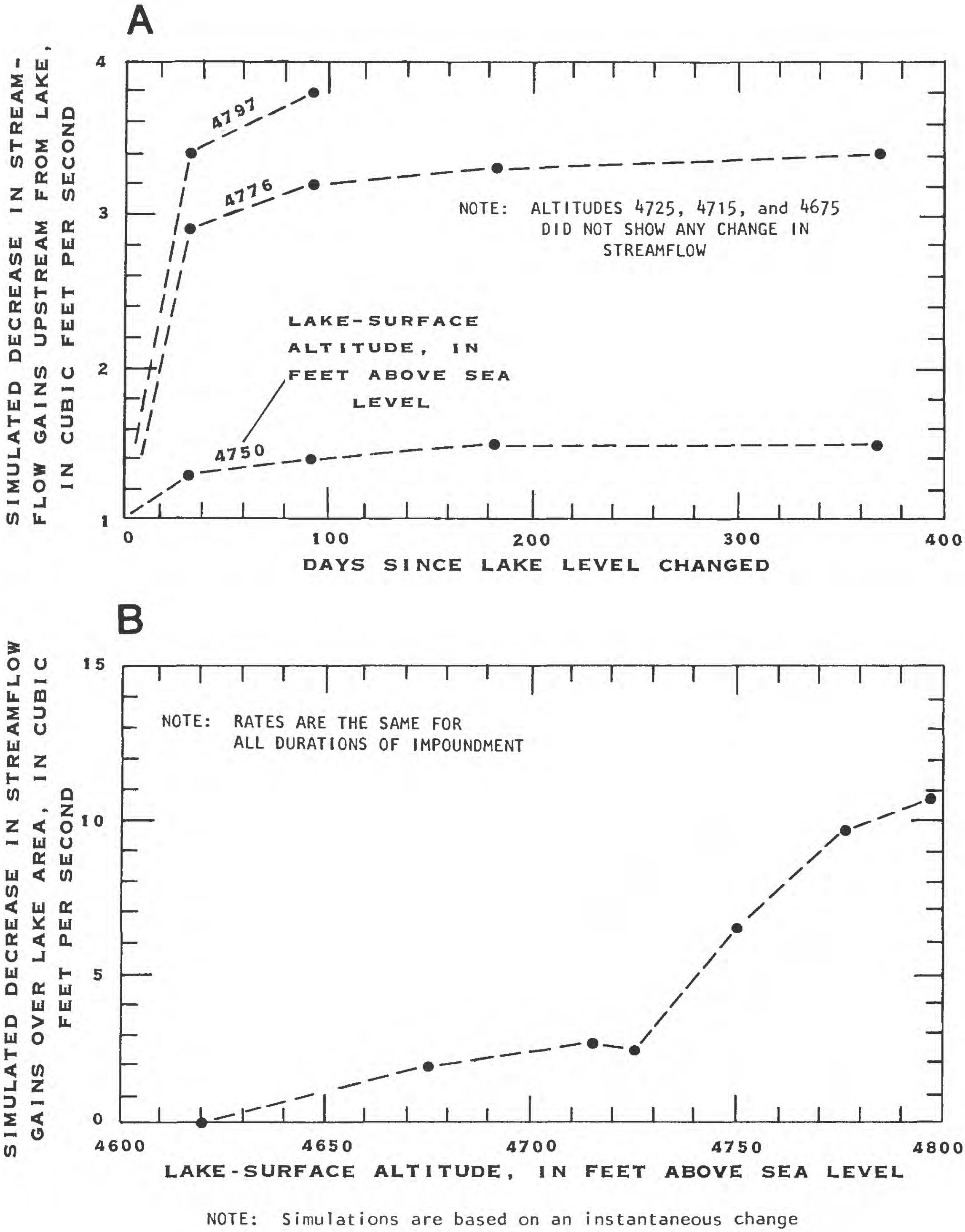
Figure 34.--Simulated increase in Pecos River streamflow downstream from Santa Rosa Dam at various lake levels and durations of impoundment.

Although the model simulates the quantity of streamflow increase downstream from the lake, the source of the water is uncertain. The simulated increase represents the sum of flow terms Q(5), Q(4b), and Q(2b) in figure 20. The simulated rates of direct seepage from the lake at various levels and durations of impoundment are shown in figure 35. This seepage could discharge to the Pecos River downstream (Q(5) in fig. 20). Probably most of the simulated increase in streamflow in the first 0.5 mile downstream from the dam is directly from lake seepage. This conclusion needs to be qualified, however, because local seepage around the dam can only be roughly simulated in a model with this grid size. In addition, storage in the lake could decrease ground-water discharge to the Pecos River at simulated rates of as much as 10.7 cubic feet per second over the area of the lake and 3.8 cubic feet per second upstream from the lake (fig. 36). Part of the ground water that discharged to the Pecos River before the lake existed may now discharge to the Pecos River downstream from the lake (Q(2b) and Q(4b) in fig. 20). Distinguishing between lake seepage (Q(5)) and other ground-water-discharge terms (Q(4b) and Q(2b)) was not attempted because the simulated sum of these terms (2 cubic feet per second) is so small that it would not be detected at the streamflow-gaging station near Puerto de Luna.



NOTE: Simulations are based on an instantaneous change in lake level from empty to altitudes ranging from 4715 to 4797 feet above sea level

Figure 35.--Simulated rate of seepage from Santa Rosa Lake at various lake levels and durations of impoundment.



NOTE: Simulations are based on an instantaneous change in lake level from empty to altitudes ranging from 4675 to 4797 feet above sea level.

Figure 36.--Simulated change in Pecos River flow over Santa Rosa Lake area and upstream from the lake.

Simulations also indicate that for lake levels of 4,750 feet above sea level and higher, the net ground-water flow into the model area from the San Andres-Glorieta aquifer may be decreased (fig. 37). Maintaining the lake at its flood-control pool (4,797 feet) for 90 days may decrease inflow by as much as 1.9 cubic feet per second. This simulated decrease in inflow represents the sum of terms Q(2a), Q(3), and Q(4a) shown in figure 20. The decrease in ground-water flow into the area will eventually reduce the natural base flow of the river by that amount. The decreased inflow will either be diverted to another drainage basin or returned to the Pecos River after bypassing the gaging station near Puerto de Luna. In either case, this quantity of water is lost to the basin upstream of Puerto de Luna and, therefore, needs to be added to any calculation of unregulated streamflow at Puerto de Luna. The simulated decrease of ground-water inflow to the basin (terms Q(2a) + Q(3) + Q(4a)) shown in figure 37 is of about the same magnitude as the simulated rates of increased streamflow (terms Q(5) + Q(4b) + Q(2b)) to the Pecos River shown in figure 34. From these simulations, it appears that the effects of the lake at certain levels and durations of impoundment nearly cancel out each other, and any adjustment to the flow of the Pecos River upstream from the gaging station near Puerto de Luna may not be necessary.

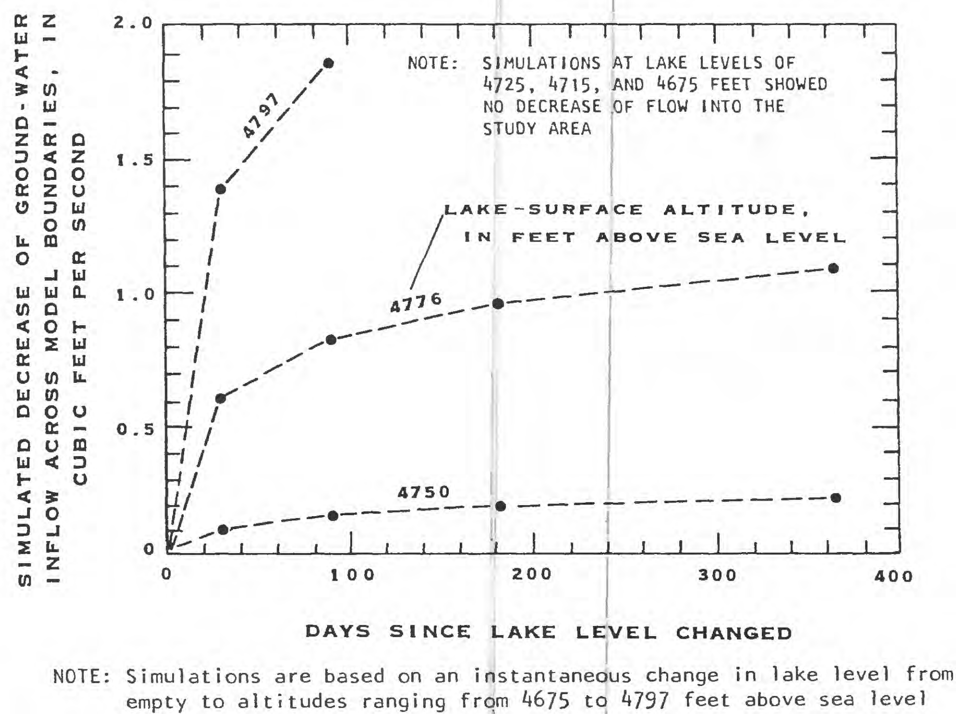


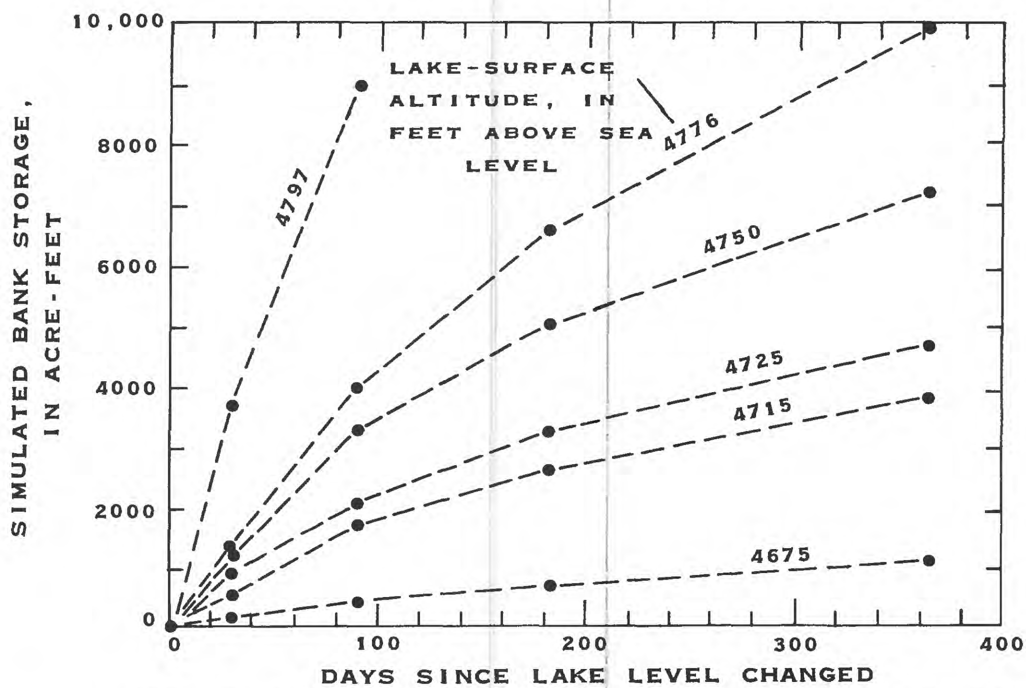
Figure 37.--Simulated net decrease of ground-water flow into the study area at various lake levels and durations of impoundment of Santa Rosa Lake.

The greatest change caused by filling Santa Rosa Lake is the increase in bank storage (fig. 38). The volume of water in bank storage increases over time mainly due to seepage from the lake and also because natural discharge to the Pecos River has been decreased at certain locations. Simulations indicate that maintaining the maximum irrigation pool for 1 year will put nearly 10,000 acre-feet of water into bank storage. This quantity is equivalent to about 4 percent of the water stored in the lake at that lake level.

The change in water levels in each model layer caused by the change in level of Santa Rosa Lake was noted for each simulation. For simulations with lake levels as high as about 4,750 feet, water-level fluctuations in the San Andres Limestone and Glorieta Sandstone (layer 3) generally are less than the natural water-level fluctuations measured prior to filling the lake. For higher lake levels, the simulated effect on water levels in layer 3 becomes more pronounced, as shown below for selected wells.

Lake level, in feet above sea level	Simulated water-level increase, in feet, caused by Santa Rosa Lake after 1 year		
	Well E4 (node 3-9-13)	Well E6 (node 3-18-12)	Well E1 (node 3-24-17)
4,797	8.00	2.63	2.16
4,776	2.98	1.46	1.22
4,750	.41	.37	.34
4,725	.01	.00	.01
4,715	.00	.00	.00
4,675	.00	.00	.00

The simulations indicate that the observation-well network, which is mainly completed in the San Andres Limestone and Glorieta Sandstone, may not clearly show any effects of the lake for lake levels lower than 4,750 feet above sea level and for durations of impoundment less than 1 year. Therefore, if continued monitoring of water levels is necessary to measure the effects of the lake at lower lake levels, observation wells need to be placed closer to the lake.



NOTE: Simulations are based on an instantaneous change in lake level from empty to altitudes ranging from 4675 to 4797 feet above sea level

Figure 38.--Simulated volume of water in bank storage at various lake levels and durations of impoundment of Santa Rosa Lake.

SUMMARY AND CONCLUSIONS

The effect of Santa Rosa Lake on ground-water flow to the Pecos River was investigated using several empirical methods and a three-dimensional ground-water-flow model. The following empirical relations were used in an attempt to estimate the actual effects caused by operation of the lake from 1980 to 1983.

1. The relation between lake-level changes and changes of water levels in nearby observation wells completed in the Santa Rosa Sandstone indicates that water seeps from the lake into bank storage. Water-level fluctuations in observation wells completed in the Bernal Formation, San Andres Limestone, and Glorieta Sandstone do not show any clear indication of lake seepage to these deeper formations.

2. A water budget of the lake was used to estimate the volume of seepage from the lake. During the first fill cycle of the lake, inflow apparently exceeded outflow by 10,900 acre-feet. However, subsequent fill cycles indicated that the measurement errors in the inflow and outflow terms probably are too large for significant results to be obtained by this method.

3. Base-flow gains between Santa Rosa and Puerto de Luna measured prior to lake construction indicate that a change in base flow of about 14 cubic feet per second or more could be distinguished from the natural variability in base flow. Base-flow gains occurring since Santa Rosa Lake has been impounding water do not indicate any increases in base flow of 14 cubic feet per second or more.

A three-dimensional, finite-difference, ground-water-flow model was used to estimate the effects of the lake on ground-water flow to the Pecos River for lake levels of 4,675, 4,715, 4,725, 4,750, 4,776, and 4,797 feet above sea level. Simulations were made assuming that each lake level except 4,797 was held for 30 days, 90 days, 182 days, and 365 days. The 4,797-foot level was held for a maximum of 90 days.

Simulated ground-water flow to the Pecos River between the dam and Puerto de Luna increased as much as 2 cubic feet per second after holding the lake at 4,797 feet above sea level (flood-control pool) for 90 days or at 4,776 feet (maximum irrigation pool) for 1 year. Because the simulated rate was within the measurement error of the streamflow gage near Puerto de Luna, no attempt was made to identify whether the source of water was direct seepage from the lake or water diverted from other parts of the area due to the changed hydrologic system.

Another effect of the lake was to decrease the natural streamflow gains to the Pecos River upstream from the lake and throughout the reach submerged by the lake. Simulations indicated that the streamflow gains could be decreased by 10.7 cubic feet per second over the lake area and 3.8 cubic feet per second upstream if the lake was held at 4,797 feet above sea level for 90 days.

The model also simulated a decrease of ground-water flow into the study area of as much as 1.9 cubic feet per second after holding the lake at 4,797 feet above sea level for 90 days. This flow probably was diverted to another basin or to the Pecos River downstream from the gaging station near Puerto de Luna. This simulated decrease in inflow to the study area is of about the same magnitude as the simulated increase in streamflow downstream from the lake. Therefore, these rates nearly cancel out each other so that the simulated net effect of the lake on ground-water flow to the river is nearly zero for the magnitudes and durations of impoundment tested.

According to model simulations, the observation wells completed in the San Andres Limestone and Glorieta Sandstone probably will not show any recognizable response to changes in the levels of Santa Rosa Lake until a level of 4,750 feet above sea level is held for about a year, or higher levels are held for shorter periods.

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