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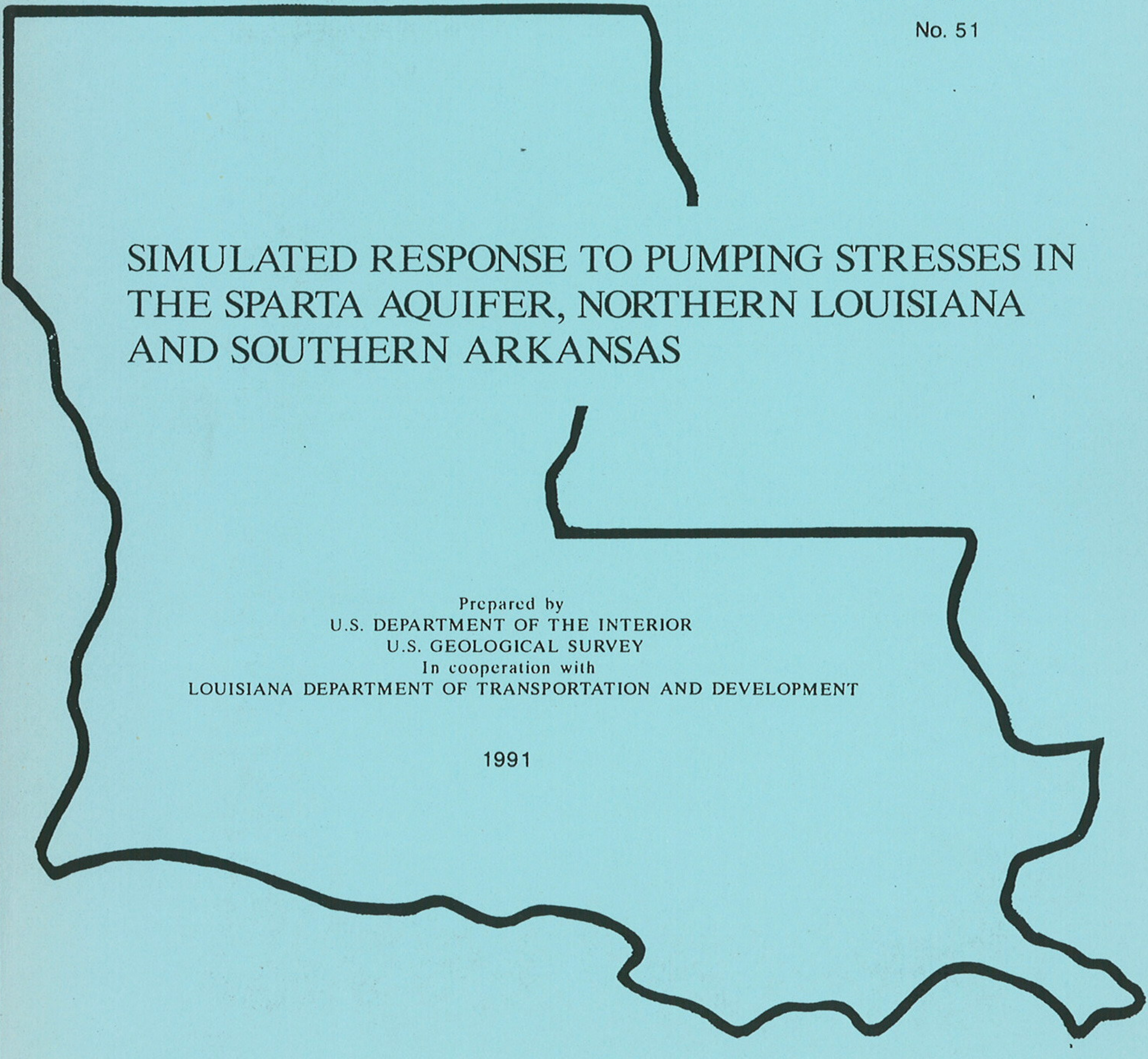
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

WATER RESOURCES
TECHNICAL REPORT
No. 51



SIMULATED RESPONSE TO PUMPING STRESSES IN THE SPARTA AQUIFER, NORTHERN LOUISIANA AND SOUTHERN ARKANSAS

Prepared by
U.S. DEPARTMENT OF THE INTERIOR
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1991

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
million cubic feet per day (Mft^3/d)	0.3278	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 X °C + 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 Sea Level Datum of 1929.

SIMULATED RESPONSE TO PUMPING STRESSES IN THE SPARTA AQUIFER, NORTHERN LOUISIANA AND SOUTHERN ARKANSAS

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ABSTRACT

A quasi-three-dimensional, finite-difference ground-water flow model was developed to evaluate the flow characteristics of recharge, discharge, and leakage and the effects of pumping stresses on water levels in the Sparta aquifer. In 1980, a total of 252 million gallons per day of water was withdrawn from the Sparta aquifer in northern Louisiana and in Arkansas. As a result of large withdrawals, water levels at El Dorado, Ark., and West Monroe, La., have declined more than 300 feet and 270 feet, respectively, since predevelopment (1898).

The aquifer system as modeled consisted of the Cockfield aquifer and hydraulically connected alluvial and terrace aquifers, the Cook Mountain confining unit, the Sparta aquifer, and the Cane River confining unit in northern Louisiana and southern Arkansas. Both steady state and transient (1898 to 1970 and 1970 to 1985) simulations were performed to calibrate the model. Simulated drawdowns exceeded 320 feet at El Dorado and Magnolia, Ark., and 280 feet at West Monroe, La. However, water levels were about 130 feet above the top of the producing aquifer sand beds at El Dorado, 120 feet at Magnolia, and 300 to 400 feet at West Monroe.

Pumpage, which accounted for 70 percent of outflow from the Sparta aquifer in 1985, has significantly changed regional flow patterns in the Sparta aquifer since predevelopment. The total amount of water flowing through the Sparta aquifer has increased from 20.4 million cubic feet per day prior to development to 38.6 million cubic feet per day in 1985. Effective recharge into the Sparta aquifer has increased by about four times. The direction of flow of water from the Sparta aquifer to overlying aquifers has reversed from a net rate of 7.20 million cubic feet per day to the overlying aquifers to 14.45 million cubic feet per day from the overlying aquifers.

Three pumping conditions were selected to simulate the effects of pumping stresses from 1985 to 2005. In the first simulation, in which pumping rates were held constant at the 1985 rate, water levels remained virtually unchanged.

In the second simulation, in which pumping rates in 2005 were about 25 percent greater than the 1985 rates, water levels declined an additional 85 feet at El Dorado, Ark., and West Monroe, La., and 100 feet at Magnolia, Ark. The projected drawdowns in this simulation were less than available drawdowns throughout the area.

In the third simulation, pumping rates in 2005 were assumed to be about 50 percent greater than the 1985 rate. In this simulation, water levels declined an additional 160 feet at El Dorado, Ark., and West Monroe, La., and 180 feet at Magnolia, Ark. The projected drawdowns exceeded the available drawdowns for El Dorado and Magnolia, but were less than the available drawdown for West Monroe.

The results from the simulations indicate that pumping rates 25 to 50 percent greater than 1985 pumping rates may cause water levels to decline below the tops of the producing sand in the Sparta aquifer beds in El Dorado and Magnolia, Ark. Most of the increases in ground-water flow resulting from projected increases in pumpage are attributed to vertical leakage from overlying aquifers into the Sparta aquifer.

INTRODUCTION

The Sparta aquifer is the most important source of ground water in northern Louisiana and southern Arkansas and is a major source in east-central Arkansas. It is a significant source of water for industrial and agricultural use and is the principal source for most municipal and domestic users. In 1980, approximately 72 Mgal/d were withdrawn from the Sparta aquifer in northern Louisiana (Walter, 1982, p. 8) and 180 Mgal/d were withdrawn from the aquifer in Arkansas (Holland and Ludwig, 1981).

The first wells penetrating the Sparta aquifer were developed in the late 19th century, but major pumping of water from the aquifer did not begin until the 1920's and 1930's when paper mills began operations in the region. Since then, intensive pumping has occurred at 12 major pumping centers and throughout the area underlain by the Sparta aquifer. Numerous cones of depression in the potentiometric surface have developed in the Sparta aquifer, and water levels generally have declined throughout much of the area.

State agencies in Louisiana and Arkansas share concern about future development of the Sparta aquifer. As part of the cooperative programs with the U.S. Geological Survey (Survey), the Louisiana Department of Transportation and Development, the Arkansas Soil and Water Conservation Commission, and the Arkansas Geological Commission initiated a study with the Survey in 1985 to evaluate the regional effects of increased pumpage on water levels in the Sparta aquifer. The objectives of the investigation were to: (1) Evaluate the geohydrologic characteristics of the Sparta aquifer, particularly the recharge, discharge, and leakage characteristics; and (2) assess the effects of past, present, and future pumping stresses on water levels in the Sparta aquifer.

Purpose and Scope

The purpose of this report, along with a report by Fitzpatrick and others (1990), is to present the results of a coordinated multistate investigation of the Sparta aquifer. This report describes the geohydrology of the Sparta aquifer and presents the results of simulation of the ground-water flow system in the aquifer in northern Louisiana and southern Arkansas (fig. 1). Discussions of these topics for the study area in east-central Arkansas and northwestern Mississippi are found in the report by Fitzpatrick and others (1990). Discussions of the conceptualization of the ground-water flow system in the modeled area (the combined study areas for both reports) are duplicated in each report.

The investigation described in this report began in 1985 and included field collection of water-level data to prepare a potentiometric surface map of the Sparta aquifer for 1985, collection of historical water-level and pumpage data, and development of a quasi-three-dimensional, finite-difference ground-water flow model to simulate ground-water flow. This information was used to evaluate the geohydrologic characteristics of the aquifer and the effects of pumping stresses on water levels.

Description of the Study Area

The Sparta aquifer extends areally throughout much of northern Louisiana, western and central Mississippi, southern and east-central Arkansas, and northward into parts of Tennessee and Missouri adjacent to the Mississippi River. The study area for this report is limited to northern Louisiana and southern Arkansas as shown in figure 1. Figure 1 also shows the study area for the parallel report of the Sparta aquifer in east-central Arkansas and northwestern Mississippi (Fitzpatrick and others, 1990).

Land-surface altitudes in the study area range from about 500 ft above sea level west of Ruston, La., to about 50 ft above sea level near the Mississippi River at the southernmost end of the study area. The relatively flat area between the Ouachita River and the Mississippi River includes part of the Mississippi River alluvial valley. The area to the west of West Monroe, La., includes part of the Gulf Coastal Plain and has a rolling terrain with low to moderate relief. The principal streams in the study area are the Mississippi, Saline, Ouachita, and Red Rivers; Saline, Black Lake, and Bodcau Bayous; and Bayou Dorcheat. These and most other streams generally flow in a southerly and southeasterly direction, in accord with the regional land-surface gradient.

The mean annual rainfall in the study area ranges from 48 to 56 in/yr. The mean annual temperature ranges from 14 °C in eastern Arkansas to 19 °C in central Louisiana (Cushing and others, 1970, p. A1).

Previous Investigations

Reports by Payne (1968; 1970; 1972; 1975), Hosman and others (1968), Ryals (1980a; 1980b; 1982; 1983; 1984), Rogers and others (1972), Boswell and others (1968), Cushing and others (1970), Reed (1972), and Trudeau and Buono (1985) were the principal literature reviewed for background information concerning the geology, geohydrologic characteristics of the aquifers, aquifer boundaries, potentiometric surfaces, stresses on the flow system, and natural flow conditions. These and other references are cited throughout this report.

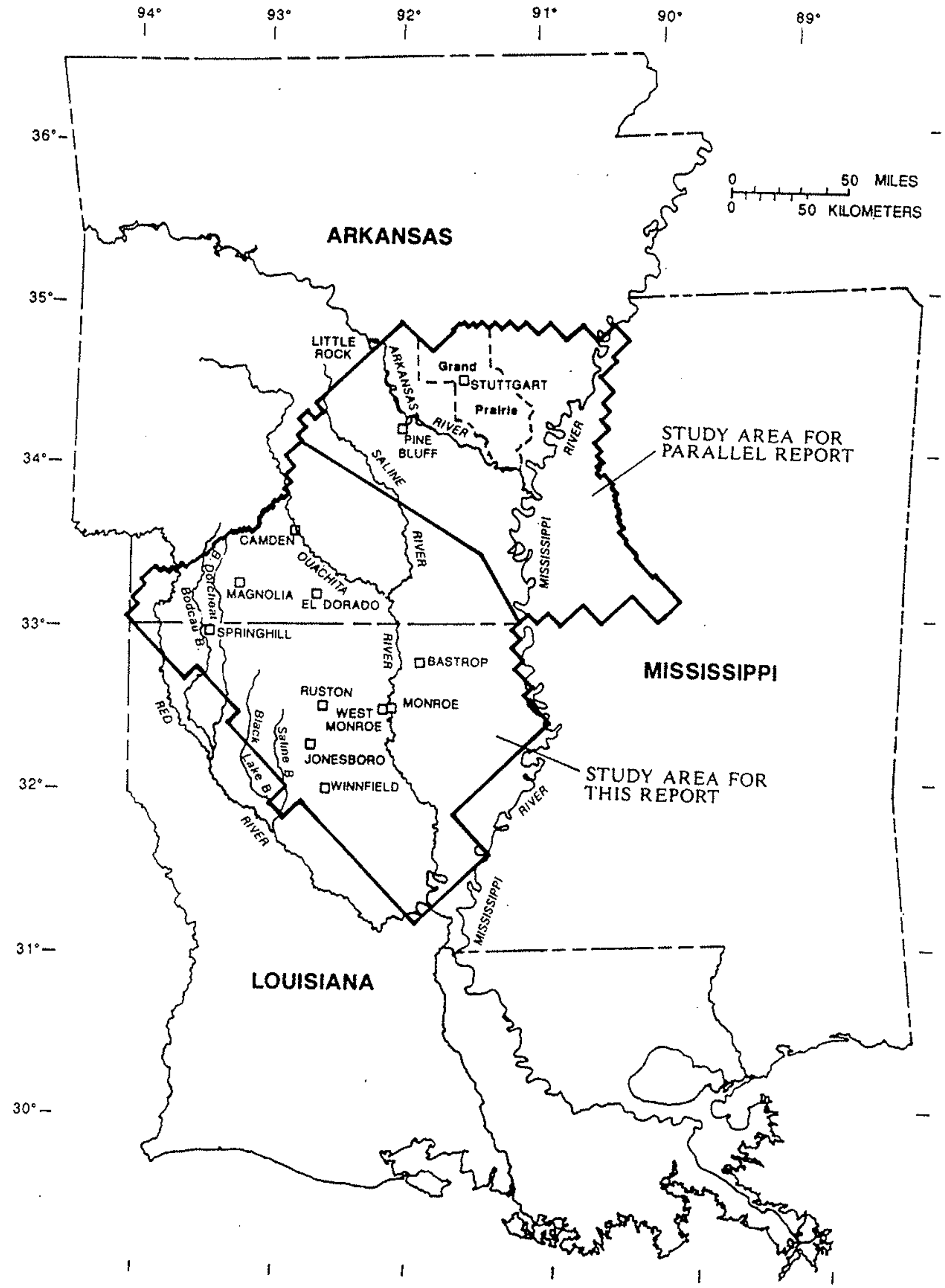


Figure 1.--Location of study area.

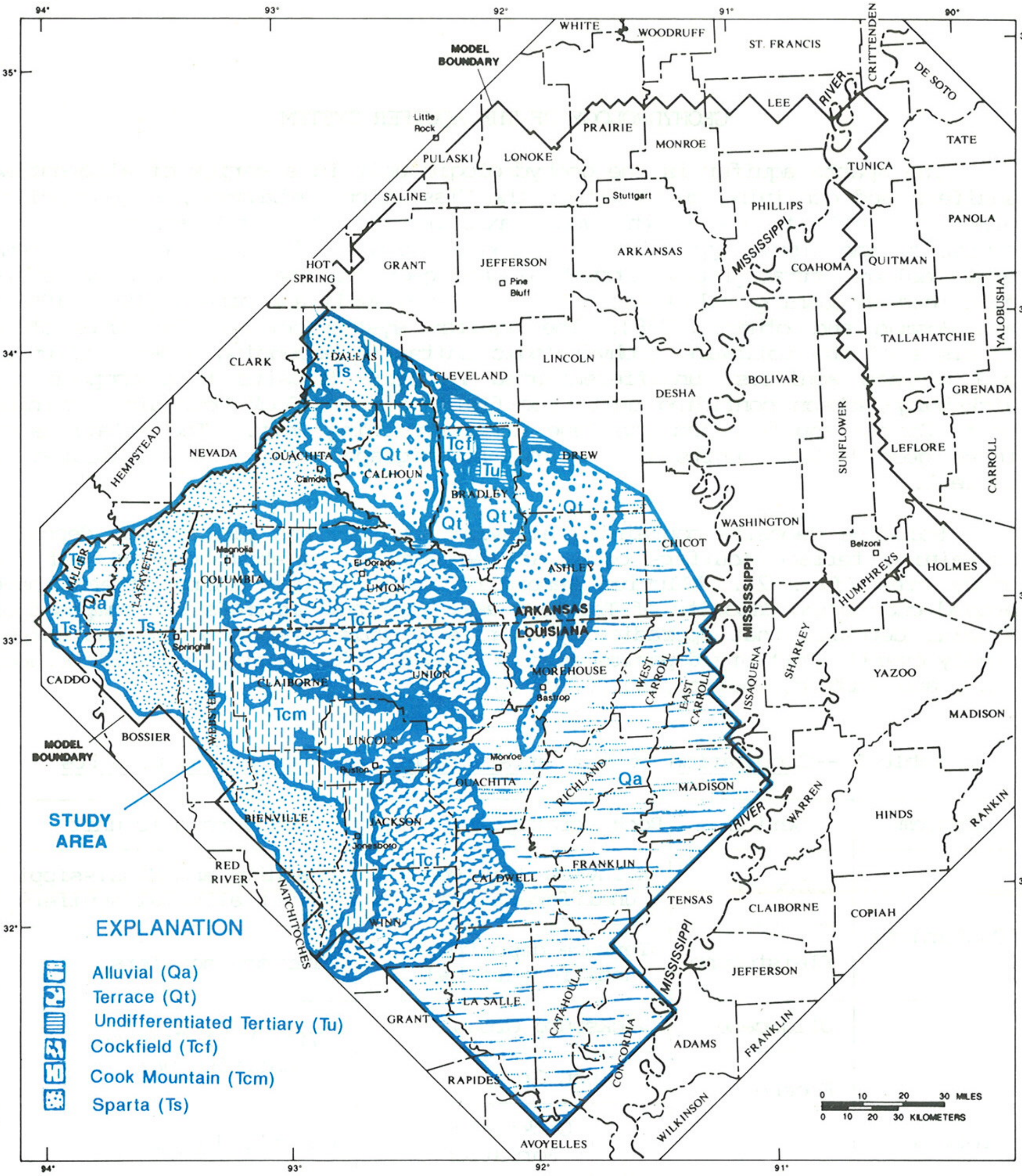
GEOHYDROLOGY OF THE AQUIFER SYSTEM

The Sparta aquifer is one geohydrologic unit in a series of alternating aquifers and confining units within the Mississippi embayment, a geosyncline plunging gently to the south, whose axis approximately follows the present course of the Mississippi River (Cushing and others, 1970, p. A1). The general geology, stratigraphy, structure, and geohydrology of the embayment are described in Cushing and others (1964; 1970); Boswell and others (1965; 1968); and Hosman and others (1968). The aquifer system defined for this study consists of the following geohydrologic units in descending order: alluvial and terrace aquifers, undifferentiated Tertiary deposits that compose the Vicksburg-Jackson confining unit, Cockfield aquifer, Cook Mountain confining unit, Sparta aquifer, and the Cane River confining unit. The relations of these geohydrologic units to the rock-stratigraphic units are indicated in table 1.

Holocene deposits containing alluvial aquifers and Pleistocene deposits containing terrace aquifers occur at the surface in about one-half of the study area (fig. 2). Alluvium generally fills valleys where streams have eroded underlying deposits of Tertiary age. Terrace aquifers are composed of fluvial deposits that sporadically overlie alluvial valley walls and extensively overlie Tertiary deposits east of Camden, Ark., northeast of El Dorado, Ark., and north of Bastrop, La. (fig. 2).

Table 1.--Correlation of rock-stratigraphic and geohydrologic units

System	Series	Rock-stratigraphic unit		Geohydrologic unit
Quaternary	Holocene	Alluvium deposits undifferentiated		Ouachita and Mississippi River alluvial aquifers
	Pleistocene	Terrace deposits undifferentiated		Terrace aquifers
Tertiary	Oligocene	Vicksburg Group		Vicksburg-Jackson confining unit
	Eocene	Jackson Group		
		Claiborne Group	Cockfield Formation	Cockfield aquifer
			Cook Mountain Formation	Cook Mountain confining unit
			Sparta Formation	Sparta aquifer
			Cane River Formation	Cane River confining unit



EXPLANATION

- ▤ Alluvial (Qa)
- ▨ Terrace (Qt)
- ▥ Undifferentiated Tertiary (Tu)
- ▧ Cockfield (Tcf)
- ▦ Cook Mountain (Tcm)
- ⁘ Sparta (Ts)

Figure 2.--Surface exposures of geohydrologic units.

The Cockfield aquifer, composed of sand beds in the Cockfield Formation, lies at or near the surface throughout much of the study area. The Cockfield generally is exposed at the surface in Louisiana from West Monroe westward to the updip limit of its extent (fig. 2). East of West Monroe, the Cockfield is overlain by the Ouachita and Mississippi River alluvial aquifers or terrace aquifers, which are in hydraulic connection with the Cockfield aquifer (Rogers and others, 1972, p. 41; Sanford, 1973a, p. 41). In south-central Arkansas, the Cockfield is either exposed at the surface or overlain by alluvial or terrace aquifers that are in hydraulic connection with the Cockfield aquifer (Broom and others, 1984, p. 34). In southeastern Arkansas, confining clay beds of the Jackson and Vicksburg Groups separate the Cockfield aquifer and the surficial terrace or alluvial aquifers.

The Cockfield aquifer consists of sands, silts, and shales, with minor amounts of interbedded lignite, bentonite, gypsum, and limestone. The sands are predominantly fine to medium in size (Payne, 1970, p. B2; Rogers and others, 1972, p. 40; Broom and others, 1984, p. 33).

In northeastern Louisiana the regional dip of the Cockfield aquifer is 15 to 50 ft/mi to the east and southeast (Payne, 1970, p. B2). Thickness of the Cockfield aquifer ranges from 100 ft near the updip limit to about 750 ft near the axis of the Mississippi embayment, just west of the Mississippi River (Hosman and others, 1968, p. D22; Payne, 1970, p. B3; Rogers and others, 1972, p. 40; Broom and others, 1984, p. 33).

The Cook Mountain confining unit underlies the Cockfield aquifer. The Cook Mountain confining unit is composed primarily of clay, but in and near the area of surface exposure it contains sand and is locally a source of water to shallow, domestic wells (Rogers and others, 1972, p. 34). The Cook Mountain confining unit ranges from less than 50 to more than 200 ft in thickness (pl. 1).

The Sparta aquifer underlies the Cook Mountain confining unit. The aquifer generally is confined, except in areas of surficial exposure where water-table conditions prevail. The Sparta aquifer generally exceeds 500 ft in thickness in southeastern Arkansas and northeastern Louisiana. In south-central and southwestern Arkansas and north-central and northwestern Louisiana the thickness ranges from less than 50 to 500 ft (pl. 2). The regional dip is 25 to 50 ft/mi to the east and southeast (Payne, 1968, p. A2).

The lithology of the Sparta aquifer is highly variable both laterally and vertically. The aquifer consists primarily of beds of fine to medium sand in the lower half and beds of sand, clay, and lignite in the upper half. Regionally, the sand content generally decreases to the south. Payne (1968, p. A3) attributes the existing pattern of well-developed lineations of sand concentrations in the aquifer to the depositional processes of a system of braiding, constantly shifting stream channels and interlacing lakes, marshes, and swamps of a large deltaic-fluvial plain. Payne (1968, p. A5) states that "although the Sparta is made up of several imperfectly connected sand bodies, any one of which may act locally and for short periods of time as a separate hydraulic unit, over longer periods of time and larger areas these units act as an integral part of the unified Sparta aquifer."

In some areas clay beds separate the Sparta aquifer into two or more geohydrologic units (Hosman and others, 1968, p. D18). In Union County, Ark., three distinct geohydrologic units within the Sparta aquifer have been identified by Broom and others (1984, p. 14). In this area, the lower part of the Sparta aquifer consists of 300 ft of thick-bedded sands with grains ranging from fine to coarse. This lower unit is known locally as the El Dorado aquifer. A 50- to 150-foot thick layer of clay and silt, termed the Middle confining unit by Broom and others (1984), lies between the lower and the upper part of the Sparta aquifer. The upper part of the Sparta aquifer consists of 200 ft of thin-bedded, very fine to fine sands and clays, and is known locally as the Greensand aquifer, due to the distinctively green color indicating the presence of glauconite.

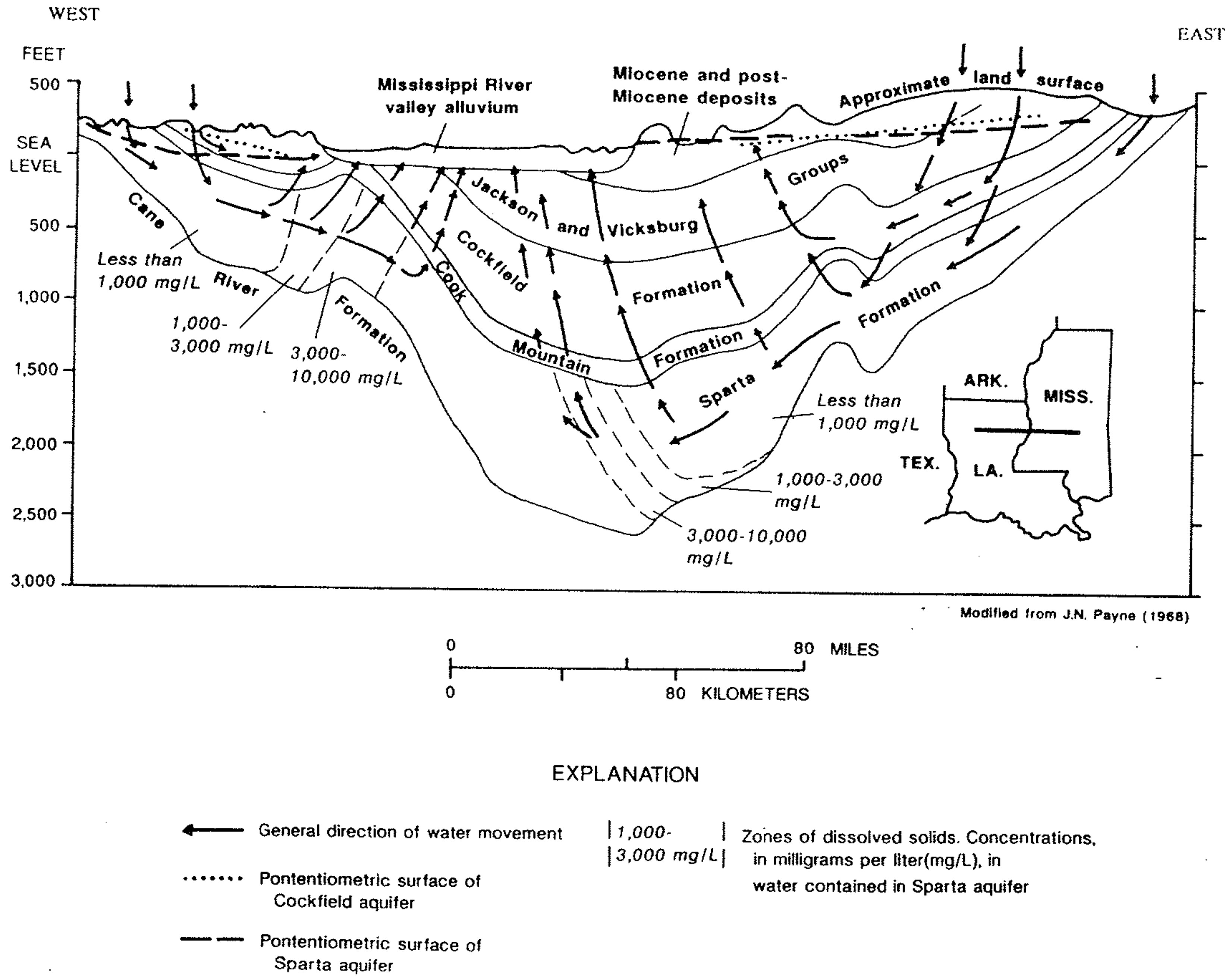
Sufficient evidence is presented by Broom and others (1984) to accept the concept that the Greensand aquifer functions hydrologically independent of the El Dorado aquifer. Although these distinct geohydrologic units are found throughout Union County, the lateral boundaries that separate the Greensand aquifer from the total Sparta aquifer are not known.

The Cane River confining unit underlies the Sparta aquifer. It consists of marine clays and shales with minor amounts of marls, silts, and marine sand. Some sand beds are present that are sources of water to domestic wells, where the Cane River confining unit is exposed at the surface in south-central and southwestern Arkansas. In the downdip areas, the confining unit has virtually no sand, is relatively uniform in lithology, and is relatively impermeable (Petersen and others, 1985). The thickness of the Cane River confining unit in the study area varies from 200 to more than 600 ft (Payne, 1972, p. C3; Hosman and others, 1968, p. D15).

Flow System

The direction of regional flow of water prior to development generally was controlled by the structural concavity of the Mississippi embayment (fig. 3). Rainwater infiltrated the geohydrologic units where they are exposed at the surface near the eastern and western edges of the embayment and either locally discharged to streams or flowed downdip toward the axis of the Mississippi embayment into the confined parts of the aquifers. In the downdip parts of the aquifers, flows converged from opposing directions, forcing water toward the surface into overlying confining units and aquifers (fig. 3). Major predevelopment discharge zones in the study area were the Ouachita River valley in Arkansas and the Mississippi River valley in Arkansas and Louisiana.

Concentrations of dissolved solids generally increase in the downdip direction (fig. 3). Dissolved-solids concentrations also increase laterally toward the center of the Mississippi River valley alluvium where regional ground-water flow discharges water with higher dissolved-solids concentrations to shallower aquifers. The lateral increase in dissolved-solids concentrations forms a density gradient that inhibits water movement.



Modified from J.N. Payne (1968)

Figure 3.--Generalized geohydrologic section of Mississippi embayment.

Land surface altitude is higher in the eastern part of the Mississippi embayment than in the western part. Therefore, hydraulic pressure is greater in the eastern-updip part of the embayment than in the western-updip part. This difference in hydraulic pressure causes the upward flow of water in the downdip parts of the embayment to be shifted to west of the axis (deepest extent) of embayment (fig. 3).

To conceptualize the ground-water flow system, two component flow systems, flow from the west and flow from the east, can be considered independent of each other. The flow system considered for the study area in this report extends from the western updip limit of the Sparta aquifer to about the midpoint of upward flow beneath the Mississippi River valley alluvium. Boundary conditions for the modeled flow system are discussed in the section Simulation of Ground-Water Flow.

Since development of the Sparta aquifer, the regional flow pattern has been substantially altered. Large cones of depression in the potentiometric surface have formed in areas centered around Bastrop and West Monroe, La., and El Dorado, Magnolia, and Camden, Ark. In the study area of Fitzpatrick and others (1990), a large cone of depression has formed in the Pine Bluff area of Arkansas (pl. 3). Water continues to flow from the updip, unconfined parts of the Sparta aquifer downdip toward the confined parts, but near heavily pumped areas water flows radially in all directions toward the centers of the cones of depression. In the Louisiana parishes of Richland, Morehouse, and eastern Ouachita and the Arkansas counties of Union and Ashley, regional flow has been reversed from an eastward direction toward the Mississippi River valley to a westward direction toward the centers of the large cones of depression. In unconfined areas, flow patterns in the Sparta aquifer have only locally been altered by pumping (pl. 3) and predominantly are controlled by topography and rainfall.

The Cockfield aquifer and the hydraulically connected alluvial and terrace aquifers range from unconfined to confined throughout the study area. Where the Cockfield is exposed at the surface the aquifer is unconfined. In the easternmost parts of the study area (Madison, Franklin, La Salle, and Catahoula Parishes in Louisiana and northeastern Ashley and Chicot Counties in Arkansas) the Cockfield aquifer is confined. The terrace aquifers generally are unconfined. The alluvial aquifers generally are unconfined but in places are semiconfined.

The flow patterns in the Cockfield aquifer and the hydraulically connected alluvial and terrace aquifers are controlled principally by topography and rainfall. Development of these aquifers has not substantially altered regional flow patterns. Prior to development of the Sparta aquifer, the Cockfield aquifer was a source of recharge (through the Cook Mountain confining unit) to the Sparta aquifer in the western part of the study area and an area of discharge (through the Cook Mountain confining unit) from the Sparta aquifer in the eastern part of the study area (fig. 3). Since predevelopment, water levels in the Sparta aquifer have been lowered below water levels in the Cockfield aquifer in the eastern part of the study area. The Cockfield aquifer is now a source of recharge to the Sparta aquifer in these areas (Sanford, 1973a, p. 41).

Ground-Water Withdrawals and Water-Level Trends

The earliest known pumpage of water from the Sparta aquifer began in the Pine Bluff area of east-central Arkansas in 1898 (Klein and others, 1950). By 1906, about a half dozen municipalities in southern Arkansas and northern Louisiana began developing the Sparta aquifer for public supplies; some development for industrial supply also began during this period (Veatch, 1906, p. 91). Based on available records, total pumpage in 1900 was about 189,000 ft^3/d or 1.4 Mgal/d. It was not until the 1920's that pumpage from the Sparta aquifer began increasing at significant rates as a result of industrial development. Pulp and paper mills began operations in Louisiana at Bastrop in 1921, West Monroe in 1930, Hodge in 1931, and Springhill in 1938. By 1940, total pumpage exceeded 9.3 Mft^3/d or 69.6 Mgal/d. Pumpage continued to increase until the late 1970's when total pumpage peaked at 33.7 Mft^3/d or 252 Mgal/d.

Records of pumpage from the Sparta aquifer are intermittent prior to 1960. Pumpage rates of the largest users (paper mills and larger towns) were documented about every decade up to 1960. From 1960 to present, water use was reported every 5 years. These data, plus additional water-use data collected more frequently from specific users, are maintained in water-use files of the Survey. Table 2 lists pumpage rates from the major pumping centers in the study area from 1920 to 1985. These data compare well with pumpage data reported in previous reports (Bieber and Forbes, 1966; Cardwell and Walter, 1979; Dial, 1970a; 1970b; Halberg, 1972; 1977; Halberg and Stephens, 1966; Stephens and Halberg, 1961; Walter, 1982; Trudeau and Buono, 1985; Sanford, 1973a; 1973b; Snider and Forbes, 1961; Snider and others, 1972; Ryals, 1982).

Table 2.--Pumpage from the Sparta aquifer at major pumping centers in northern Louisiana and southern Arkansas

[Pumpage in million gallons per day]

Year	Pumpage at indicated pumping center							
	Bastrop, La.	Hodge, La.	Monroe, La.	Ruston, La.	Springhill, La.	Camden, Ark.	El Dorado, La.	Magnolia, La.
1920	1.50	(a)	(a)	(a)	(a)	(a)	[b]0.20	[d]0.20
1930	(a)	10.00	10.20	(a)	(a)	(a)	2.50	.27
1940	(a)	10.00	10.40	0.50	20.00	(a)	4.60	.65
1947	(a)	(a)	(a)	(a)	(a)	(a)	10.60	(a)
1950	11.78	10.23	10.50	1.00	12.00	(a)	[c]17.58	2.75
1960	12.05	10.50	14.12	1.35	6.30	(a)	(a)	1.20
1965	11.99	13.00	13.95	2.00	6.30	0.17	17.95	2.29
1969	12.83	(a)	(a)	(a)	(a)	(a)	(a)	(a)
1970	11.28	13.00	9.68	2.38	5.60	.17	16.38	4.36
1975	11.12	13.60	11.72	3.47	4.23	.12	16.60	4.63
1980	10.66	12.87	13.48	4.50	.09	.17	14.80	4.60
1985	6.32	13.25	12.07	4.21	.00	.12	11.97	6.14

[a] No data available. [b] 1921. [c] 1952. [d] 1928.

Since predevelopment (1898), water levels in the Sparta aquifer have declined substantially in response to the long-term increases in pumpage with the greatest declines occurring at the major pumping centers. Broom and others (1984, p. 15) reported a total decline greater than 300 ft since 1921 at El Dorado, Ark., and Rogers and others (1972, pl. 4) reported a total decline of about 270 ft at West Monroe, La., from predevelopment to 1965.

Water levels in the Sparta aquifer have fluctuated in response to changes in the rate of withdrawals. Water-level fluctuation at the four major pumping centers in the study area are shown in figure 4. At Bastrop, La., water levels declined until about 1964, remained relatively constant until 1981, then began rising. Water levels at West Monroe, La., have fluctuated greatly, but the long-term trend has been downward. Water levels generally declined until 1965, recovered somewhat from 1965 to 1974, then trended downward again to 1980. Since 1980, water levels at West Monroe have fluctuated but no trend is evident. At El Dorado, Ark., water levels declined steadily until 1966 and have remained relatively constant since. At Magnolia, Ark., water levels have continued to decline, although at a slower rate.

Water levels in the Cockfield aquifer are related to topography throughout much of the study area (Rogers and others, 1972, p. 41; Snider and others, 1972, p. 28). There is no major pumping from the Cockfield aquifer (Sanford, 1973a, p. 39; Rogers and others, 1972, p. 41). Fluctuations in water levels are attributed primarily to seasonal changes in the amount of rainfall (Sanford, 1973a, p. 39; Snider and others, 1972, p. 28).

SIMULATION OF GROUND-WATER FLOW

Three-dimensional ground-water flow in an anisotropic, heterogeneous aquifer is described by a partial differential equation in which the partial derivatives represent the movement of water (hydraulic conductance) in three dimensions. The equation, along with associated boundary conditions and initial conditions, is solved numerically by converting it to a finite-difference form. The aquifer is subdivided into a set of discrete points in space. These points (nodes) represent blocks (cells) of porous material within which the hydraulic properties are constant (discretizing). The flow through each cell is described by a finite-difference equation. The resulting set of equations is solved simultaneously by an appropriate numerical technique. The strongly implicit procedure (SIP) was used as the numerical solution technique in this study. The Survey's modular quasi-three-dimensional, finite-difference ground-water model developed by McDonald and Harbaugh (1986) was used to simulate the flow system.

Layering and Discretization

The flow system described in this report and in the parallel report (Fitzpatrick and others, 1990) was modeled with a two-layer variably-spaced, grid with 113 rows representing 267 mi and 95 columns representing 218 mi. Out of a total of 10,735 nodes, 8,996 were active. The active model area boundary (pl. 4) coincides with the perimeter of the two study areas (fig. 1).

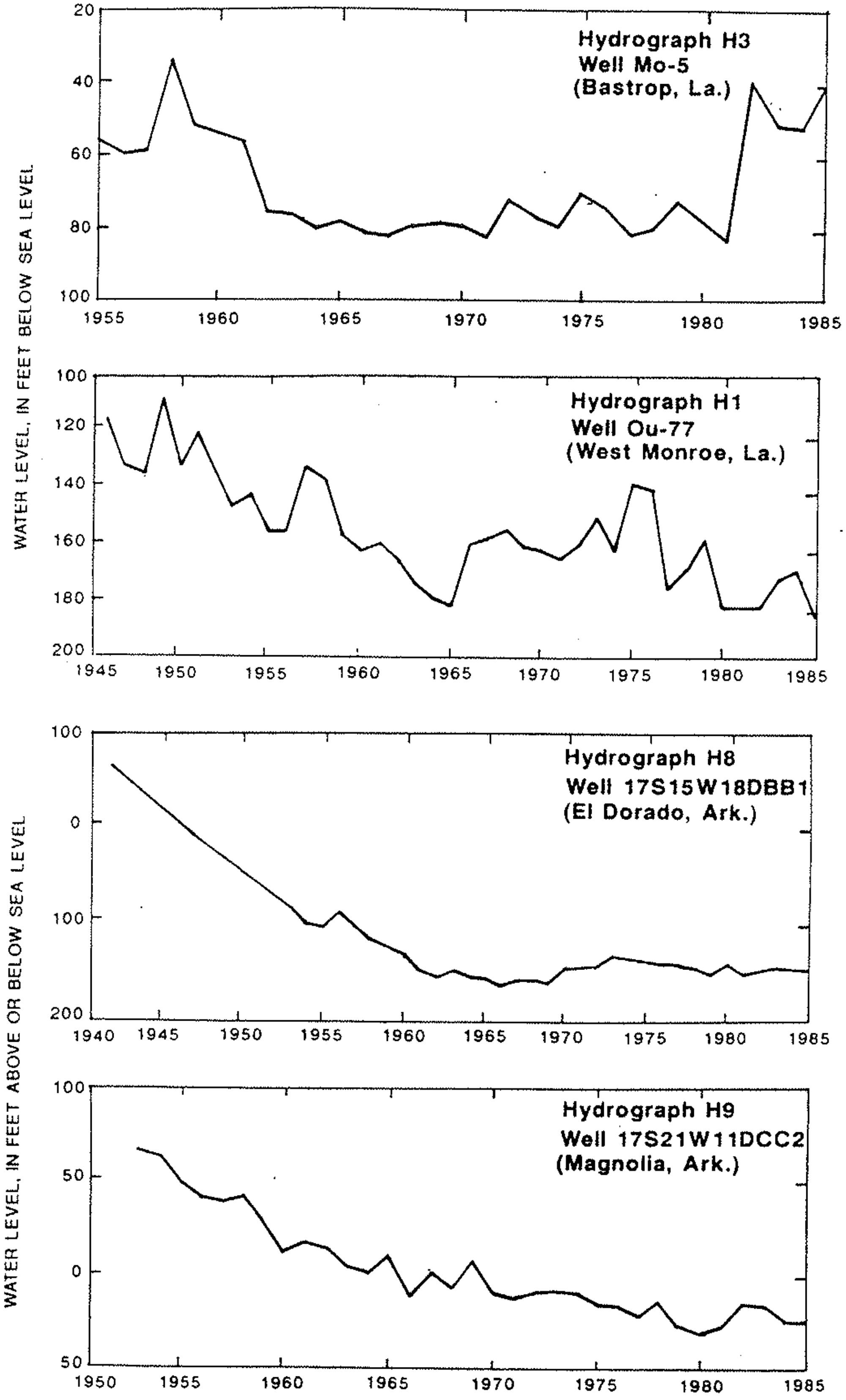


Figure 4.--Water levels in selected wells in the Sparta aquifer in or near major pumping centers.

Layer 1 represented the Cockfield, alluvial, and terrace aquifers. Layer 2 represented the Sparta aquifer. Active nodes in layer 1 correspond to active nodes in layer 2, except where the Sparta aquifer is unconfined (pl. 4), and the aquifers represented by layer 1 do not exist. In this area, nodes in layer 1 were inactive. The Cook Mountain confining unit, which separates the Sparta aquifer from the Cockfield aquifer, was represented in the flow equation by a vertical conductance term. Conditions defining the horizontal and vertical boundaries of the model are discussed in the following section.

To provide adequate resolution around major pumping centers, a 1 mi^2 cell size was used within a 3-mile radius of the centers. Grid cell dimensions were increased with distance from the centers to a maximum of 10 mi by 23 mi at the edge of the modeled area where relatively fine resolution is not needed. To reduce the potential for numerical instability during model simulation, cell dimensions along both axes increase by no more than 1.5 times the dimensions of an adjacent cell.

Based on the results of previous investigations (Payne, 1968, p. A8), it was assumed that no significant regional anisotropy of transmissivity in the Sparta aquifer exists. Therefore, the grid axes were oriented northeast and southeast to minimize the inactive cells within the grid. An inset map (pl. 4) shows the location and orientation of the variably-spaced grid.

Boundary Conditions

Boundary conditions were chosen to represent hydrologic conditions in the flow system. The boundary conditions utilized were either no flow, constant head, or specified head. An explanation of these boundary condition types and their applications in model simulations is discussed in detail by Franke and others (1987).

The upper model boundary, layer 1, was represented by a constant-head surface. The constant-head values primarily represented water levels in the Cockfield aquifer, but where the Cockfield aquifer is absent, they represented water levels in the surficial units, either the alluvial and terrace aquifers or the Cook Mountain confining unit. As discussed in the section Geohydrology of the Aquifer System, these units are hydraulically connected to the Cockfield aquifer. Where the Sparta aquifer is unconfined, layer 2 represented the upper model boundary as a no-flow (free-surface) boundary.

The constant-head values assigned to layer 1 were discretized from a water-level map (pl. 5) based on a potentiometric-surface map of the Cockfield aquifer published by Ackerman (1987), unpublished water-table maps prepared as part of a regional ground-water investigation (J.K. Arthur, U.S. Geological Survey, written commun., 1987) and supplemental water-level data in the files of the Survey.

Water levels in the Cockfield aquifer in localized areas have declined through time (Ackerman, 1987), but hydrographs of most wells in the Cockfield aquifer within major areas of interest generally indicate no appreciable change in water levels during the simulation period. In addition, the Cockfield aquifer is in direct connection with rivers and streams in much of the model area, particularly the southern part (Trudeau and Buono, 1985, p. 8). Consequently, representation of the Cockfield aquifer as a constant-head source is considered an appropriate boundary condition.

The Cane River confining unit, which lies directly beneath the Sparta aquifer, is relatively impervious (Petersen and others, 1985). Trudeau and Buono (1985, p. 31), reporting on an investigation of the Sparta aquifer in an area that approximately corresponds to the study area in this report, indicated that, under stressed conditions, only about 5 percent of the total inflow to the Sparta aquifer and less than two-tenths of 1 percent of the total outflow was through the Cane River confining unit. Consequently, the top of the Cane River confining unit was modeled as a no-flow boundary throughout the entire model area.

The western boundary of the model represented the updip limit of the Sparta aquifer in Arkansas and Louisiana and was modeled as a no-flow boundary (pl. 4). The eastern limit in Louisiana was also modeled as a no-flow boundary. This boundary generally underlies the Mississippi River where the Sparta aquifer is beyond the radius of influence of the cones of depression, and generally corresponds to the area where regional flow is upward to the Mississippi River alluvium (fig. 3).

The northern boundary of the model in Arkansas, the eastern and southern boundaries in Mississippi, and part of the southern boundary in Louisiana, were designated as specified head (pl. 4). The northern boundary approximates the location of the Cane River lithofacies change, where the Sparta Formation becomes the upper part of the Memphis Sand. The eastern boundary in Mississippi represents the downdip edge of the Sparta outcrop. The southern boundary in Mississippi, while not totally beyond the radius of influence of significant pumping to the south, was positioned to minimize pumping effects on water levels at the boundary. The southern boundary in Louisiana is beyond the radius of influence of any significant cone of depression.

The specified-head nodes are not directly responsive to pumping center withdrawals, but long-term declines in water levels since predevelopment was evident at selected nodes. A comparison of the predevelopment potentiometric surface map (Reed, 1972) and a 1985 potentiometric surface map (pl. 3) indicates water-level declines at the specified-head nodes ranged from about 20 to 80 ft. The average decline was about 39 ft. Maximum declines occurred at nodes on the southern boundary in Mississippi. Minimum declines occurred at the southern model boundary in Louisiana and the eastern boundary in Mississippi.

To account for changes in water levels at these boundaries over time, specified-head values assigned to the boundary nodes were adjusted during the transient simulation. The 25 stress periods were divided into four simulation intervals, with revised specified-head values at the start of each interval. The simulation intervals were selected so the rates of water-level change during the intervals were approximately equal (table 3). The specified-head values, based on potentiometric surface maps and unpublished data, represented the average water levels for the representative years.

Table 3.--Simulation intervals and corresponding stress periods used in model calibration

Simulation interval	Stress periods	Time frame
1	1- 8	1898-1942
2	9-16	1943-1962
3	17-22	1963-1977
4	23-25	1978-1985

Aquifer and Confining Unit Characteristics

The geohydrologic characteristics significant to ground-water flow in the model area are the transmissivity and storativity of the Sparta aquifer, represented in layer 2, and vertical conductance of the Cook Mountain confining unit, represented as leakance between layers 1 and 2.

Transmissivity

Transmissivity was determined by multiplying the total sand thickness by the horizontal hydraulic conductivity of the sand. Sand thickness values were discretized from the sand thickness map (pl. 2) prepared from the well-log data base of the Gulf Coast Regional Aquifer-System Analysis (GC RASA) program (Wilson and Hosman, 1988), which reported total sand thickness of geohydrologic units such as the Sparta aquifer.

Initial calibration efforts indicated that transmissivity values in the El Dorado and Magnolia areas were too large to achieve a reasonable simulation of the observed potentiometric surface. As discussed previously, the Sparta aquifer in Union County, Ark., is composed of two distinct subunits and most of the pumping is from the lower subunit. The GC RASA data base did not differentiate sand thicknesses within these subunits.

In addition, the area where the Sparta aquifer is exposed at the surface to the west of Magnolia, Ark., is faulted (Hosman, 1982). The observed potentiometric surface around Magnolia indicates that this faulting retards ground-water movement from the updip limit of the Sparta aquifer to the center of the cone of depression at Magnolia as evident by the extremely steep gradient between the faulted area and Magnolia (pl. 3).

The transmissivity of the Sparta aquifer was adjusted during the calibration process by varying hydraulic conductivity. Nine zones of hydraulic conductivity were delineated in the Sparta aquifer (fig. 5). Information on the areal extent of the subunits of the Sparta aquifer was limited; consequently, delineating the conductivity zones was somewhat arbitrary; however, the zone around El Dorado was delineated based on information reported by Broom and others (1984) and results obtained during model calibration. The faulted zone west of Magnolia was delineated based on fault traces mapped by Hosman (1982).

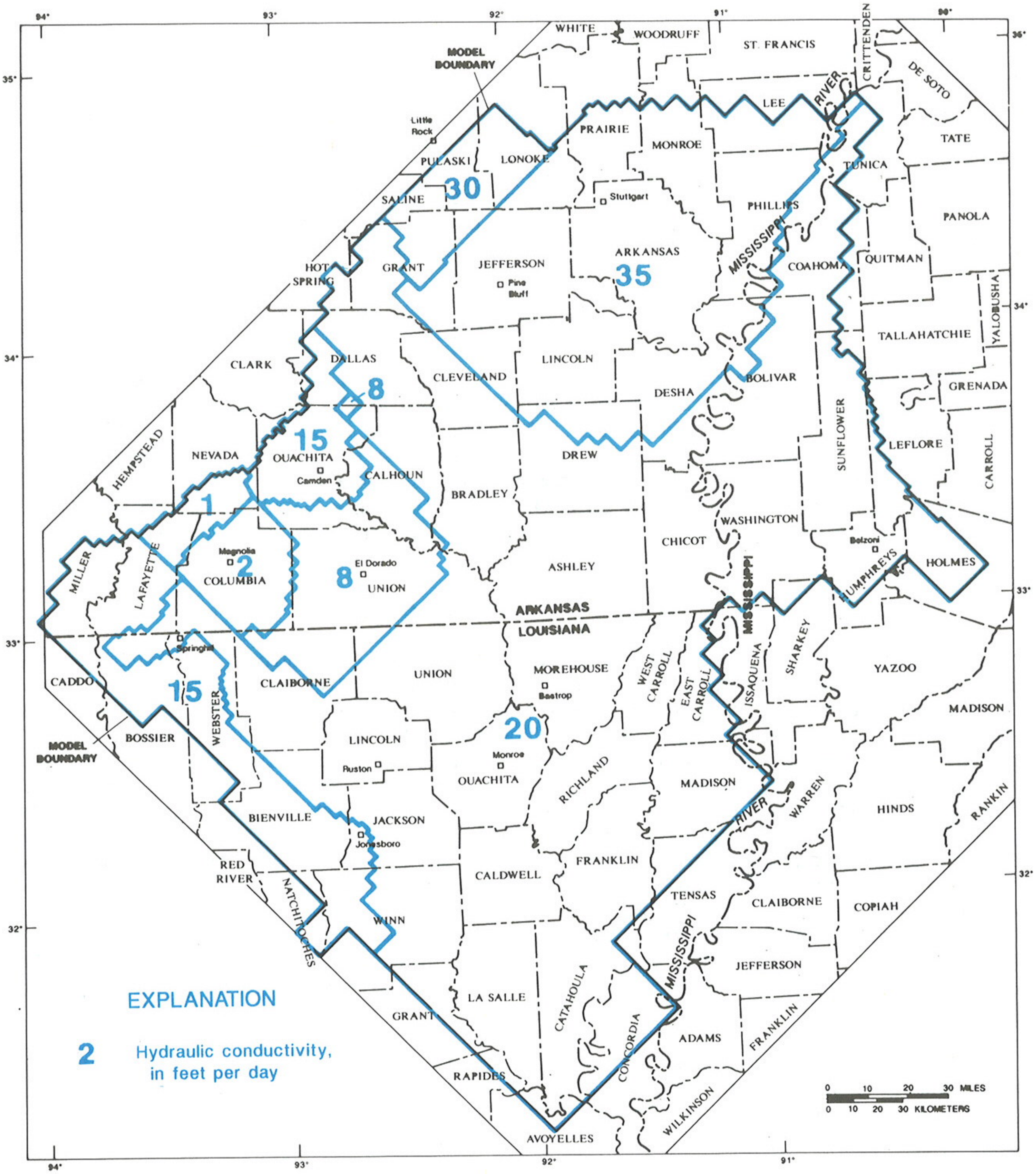


Figure 5.--Zones of horizontal hydraulic conductivity of the Sparta aquifer.

The final transmissivity values used in the calibrated model (pl. 6) were found to be on the order of 60 to 70 percent of the estimates reported by Payne (1968, pl. 7). Trudeau and Buono (1985, p. 22) showed similar results with an average of 65 percent of the values reported by Payne (1968, pl. 7). These values also fall within the range of transmissivity values determined for the Sparta aquifer in the GC RASA studies (Arthur and Taylor, 1990).

Storativity

The calibrated value for storage coefficient in the confined part of the Sparta aquifer was 0.0001. This value agreed with values determined from aquifer tests in the study area. Although data were limited, calibration indicated that model results were very insensitive to changes in storage; consequently, this average value was considered suitable for modeling purposes. Specific yield varied uniformly from 0.01 in the unconfined areas to 0.0001 in the areas where the aquifer changes from unconfined to confined (fig. 6).

Vertical Conductance

Vertical conductance for each grid cell was determined by dividing the vertical hydraulic conductivity of the Cook Mountain confining unit by the thickness of the confining unit times the area of the cell. Universal kriging was used to estimate the thickness of the Cook Mountain confining unit (pl. 1) in the study area. A detailed description of the kriging process and data analysis is given by Hebert (1986) and Nelson and Hebert (1986). Thickness data used in the estimation process were obtained from 161 well logs from the GC RASA data base (Wilson and Hosman, 1988). The process resulted in a well-behaved semivariogram that was fitted with an exponential model. Cook Mountain confining unit thickness values for the model area within the study area of the parallel report (Fitzpatrick and others, 1990) were obtained from thickness maps developed by Kilpatrick (1987). These thickness values were considered to be accurate and were not adjusted during calibration. The calibrated vertical-conductance values were determined by varying the vertical hydraulic conductivity.

Three zones of vertical hydraulic conductivity were delineated (fig. 7). These values ranged from 9×10^{-6} to 3×10^{-4} ft/d and are considered appropriate for marine clay (Freeze and Cherry, 1979).

Pumpage

In addition to transmissivity, storativity, and vertical conductance, other factors influencing flow in the Sparta aquifer are pumpage, river leakage, and recharge from rainfall infiltrating the unconfined part of the aquifer. Pumpage from the Sparta aquifer (layer 2) was specified in 25 stress periods for the model simulations. Pumpage from the Cockfield, alluvial and terrace aquifers (layer 1) was not specified because those aquifers were simulated as a constant-head boundary.

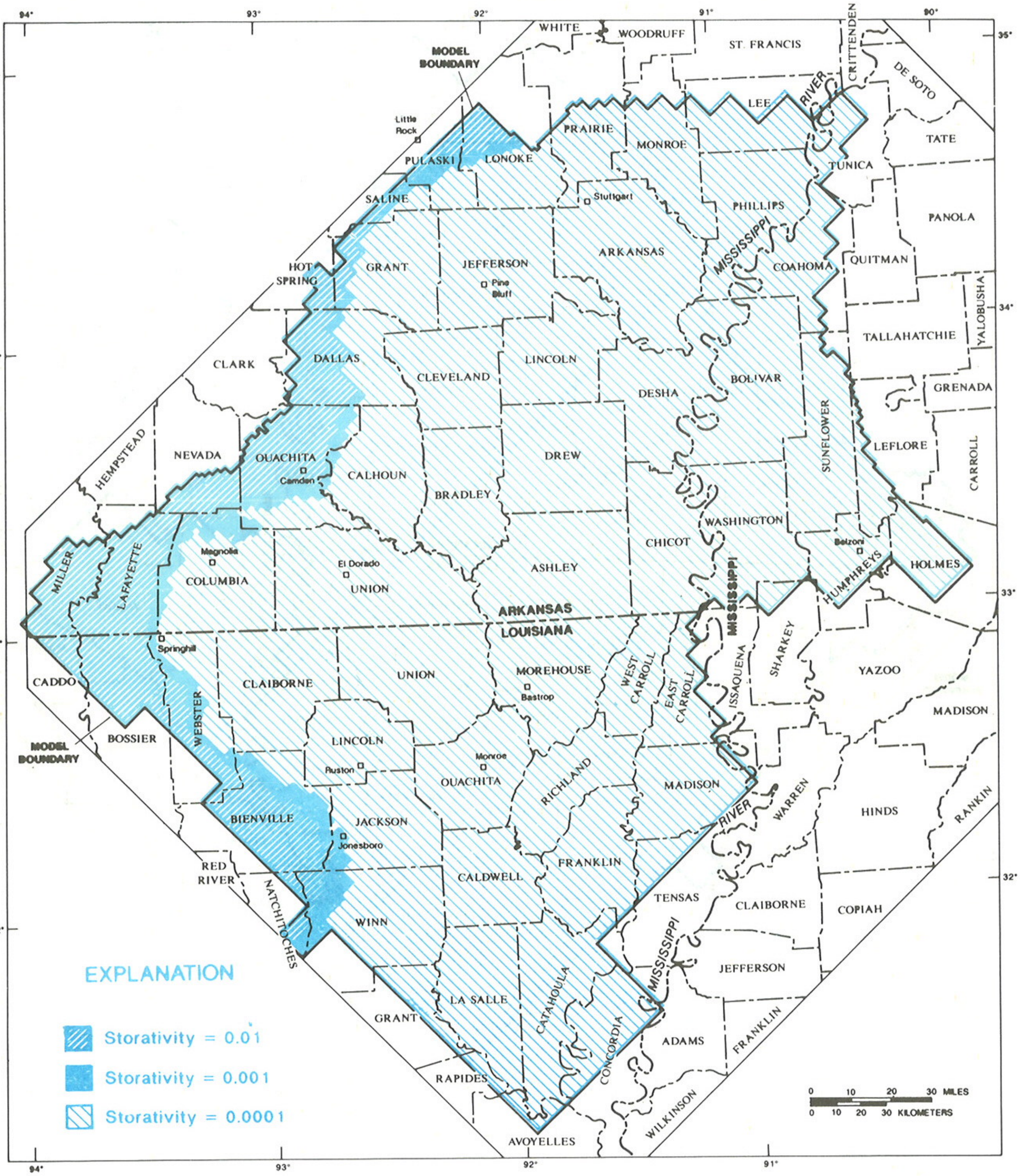


Figure 6.--Zones of storativity of the Sparta aquifer.

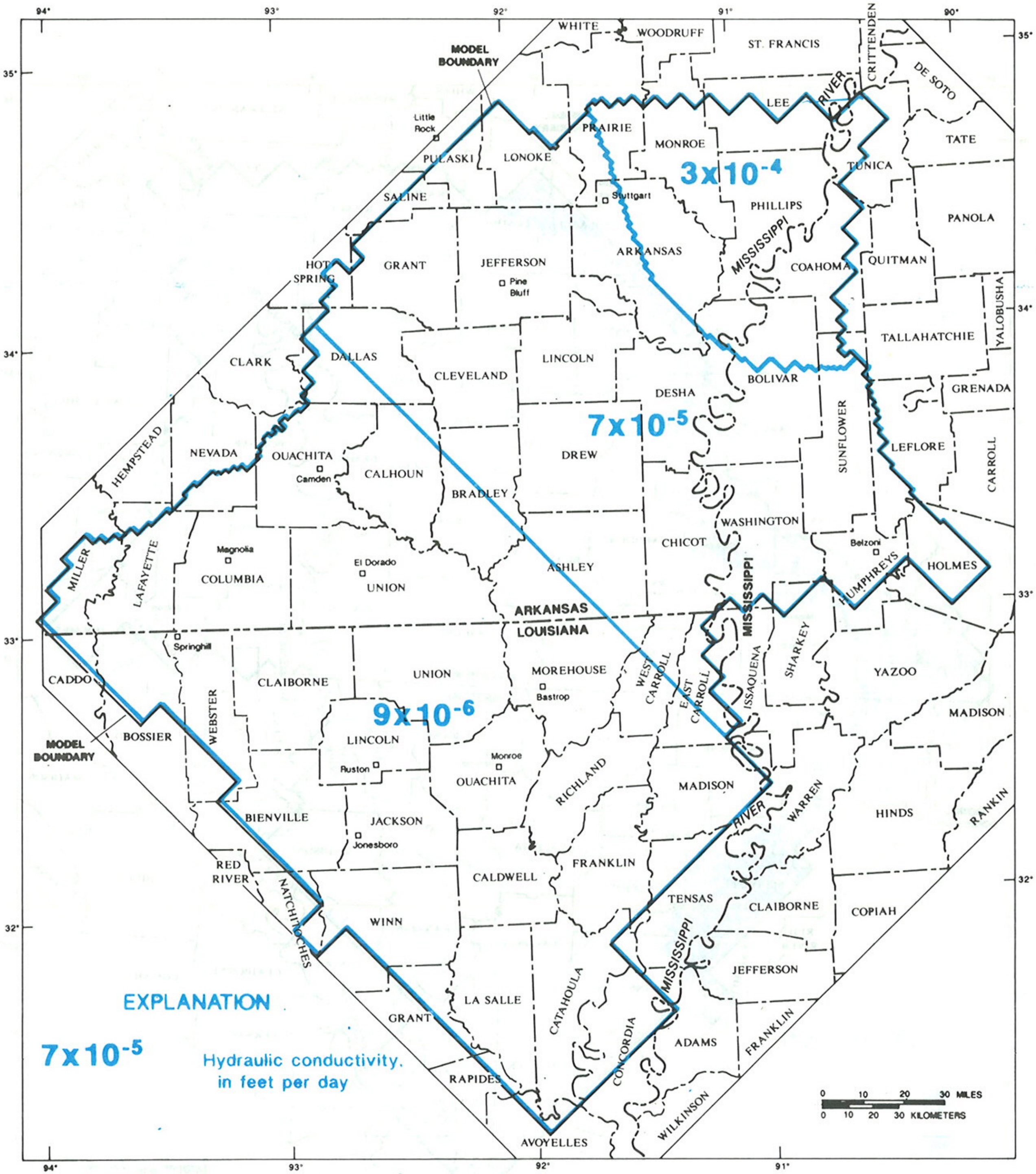


Figure 7.--Zones of vertical hydraulic conductivity of the Cook Mountain confining unit.

All known industrial and public-supply wells pumping from the Sparta aquifer with withdrawal rates of 20,000 ft^3/d (0.15 Mgal/d) or greater were tabulated and located on the model grid. Pumping rates from one or more wells located within a given grid cell were totaled and assigned to the corresponding node. Most of the large capacity wells were concentrated in small areas in or near the larger cities and in the Grand Prairie agricultural area (fig. 1). The pumpage from these wells usually was a fraction of the total pumpage recorded by county or parish. The remaining pumpage accounted for as much as half of the total reported pumpage in some parishes in Louisiana and was assumed to be from the numerous small public-supply, industrial, domestic or other wells with yields of less than 20,000 ft^3/d (0.15 Mgal/d) that are distributed throughout each county or parish. The distributed pumpage was added to the large capacity well pumping rates previously assigned to nodes within each county or parish.

Pumpage estimates for agricultural use prior to 1965 in the Grand Prairie region (Arkansas and Prairie Counties, Ark.) were based on rice acreage estimates similar to methods described in Engler and others (1945). In the Grand Prairie region, where most of the pumpage is for irrigation, only about 50 percent of the irrigation wells have been located. Pumping rates for located wells were assigned to the appropriate nodes. Unlocated irrigation wells were accounted for by assigning pumping rates to cell nodes where these wells were likely to be located. These unlocated wells were assumed to be in the same general area as the located wells. The pumping rates for the unlocated wells were determined by dividing total annual agricultural pumpage for each county by the total number of assigned well nodes in that county. Kilpatrick (1987) describes this method in detail.

The number of well nodes varied from 4 in stress period 1 to 329 in stress period 25. Plate 4 shows the distribution for the last stress period (1983-85).

Estimated pumping rates from wells screened in the Sparta aquifer were totaled by year for the period of simulation, 1898-1985 (fig. 8). Since 1960, water-use data have been reported every 5 years, but prior to 1960, water-use data were reported intermittently. For years with no reported data, pumping rates were linearly interpolated.

Pumpage data generally are reported as annual totals; therefore, the minimum stress period selected for simulation was 1 year. However, pumpage from wells is usually not constant over time but varies with the seasons. This is particularly true for irrigation pumpage in the Grand Prairie region where most of the pumpage occurs during the growing season from about May to September. Figure 9 shows the wide range of seasonal water-level fluctuations in the Sparta aquifer in response to the seasonal pumpage from 1980 to 1986. The model does not simulate this seasonal fluctuation but simulates an average annual water level in response to a constant pumping rate through each stress period.

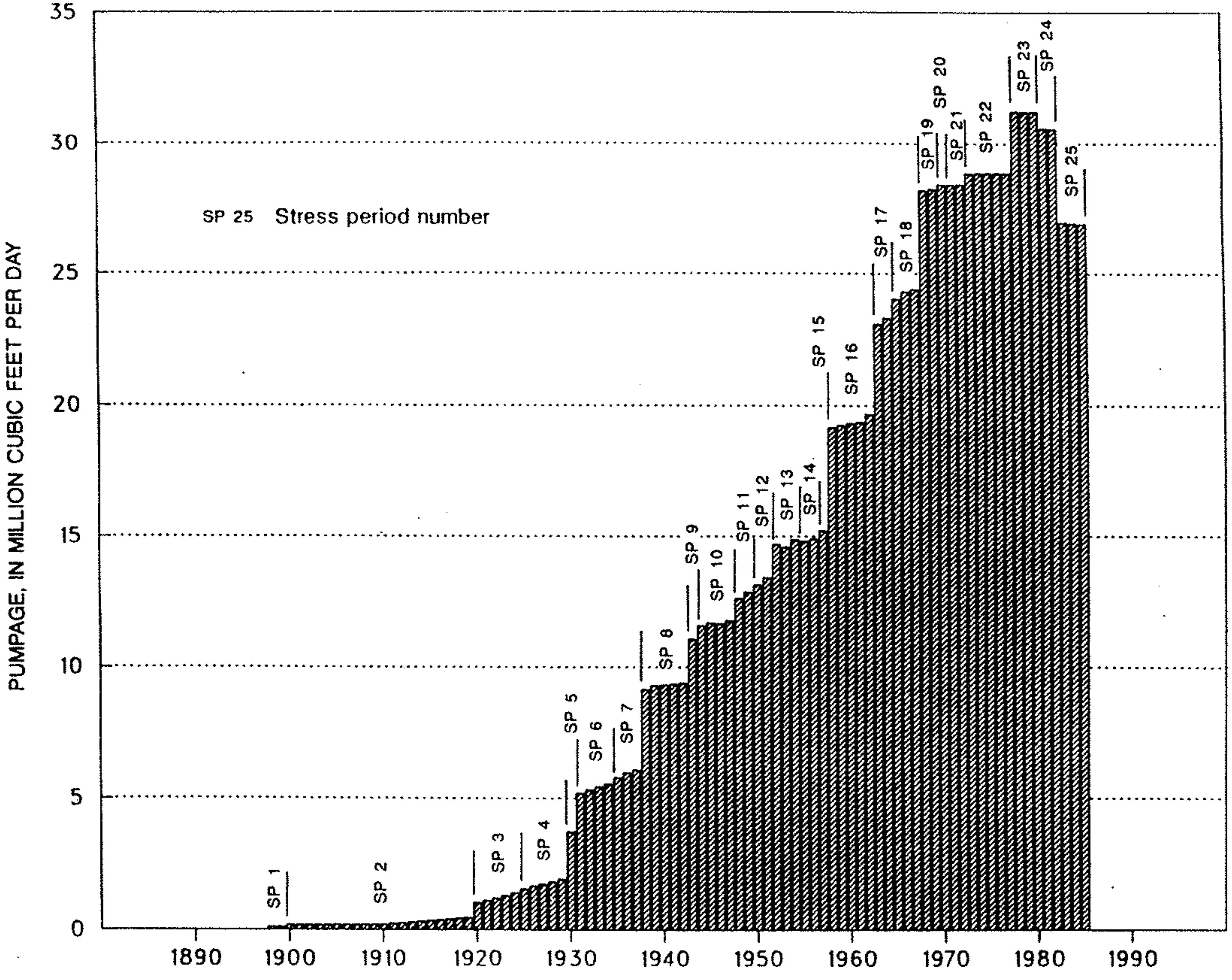


Figure 8.--Total pumpage from the Sparta aquifer, 1898-1985, and stress periods used in model calibration.

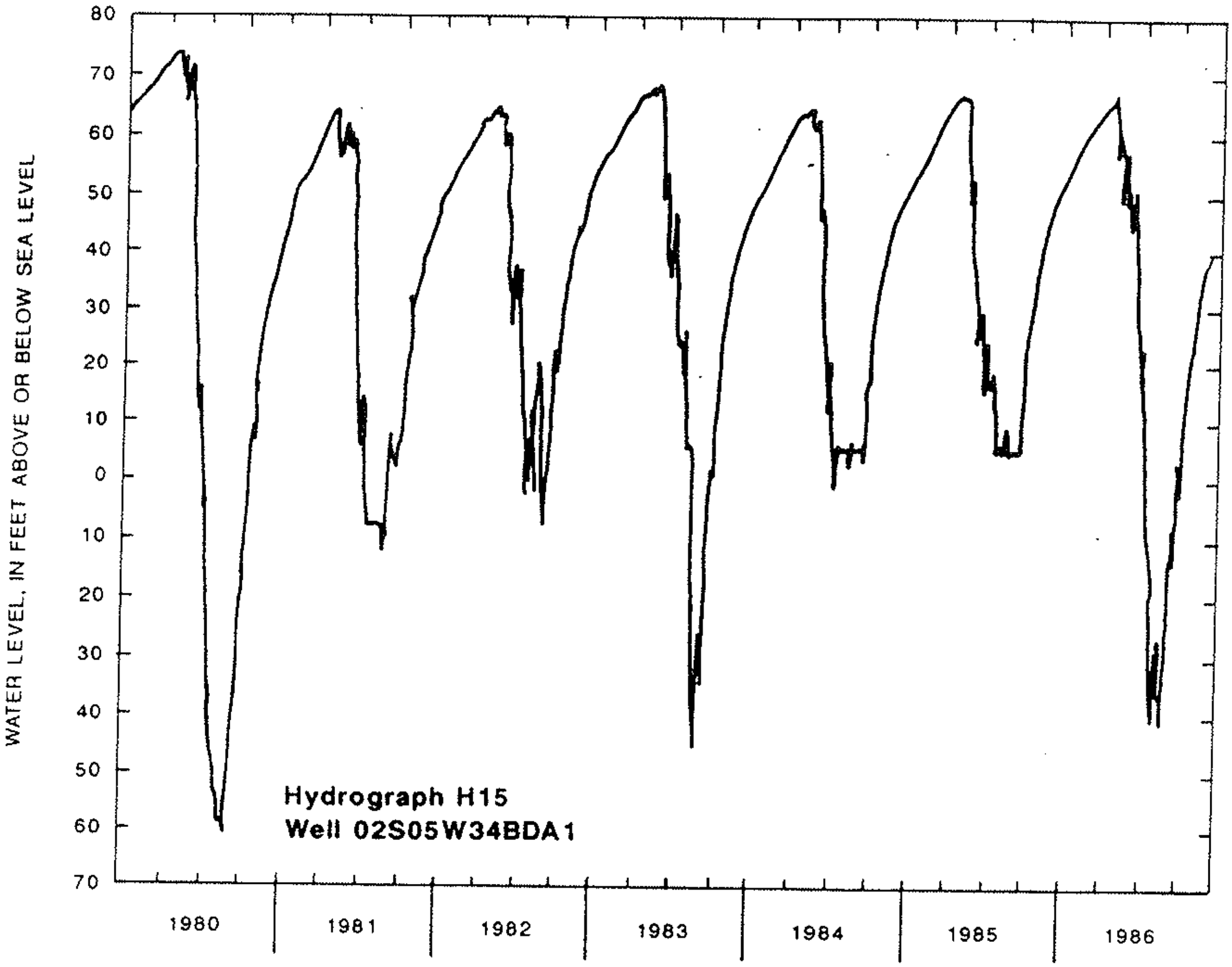


Figure 9.--Seasonal water-level fluctuations in the Grand Prairie area, Arkansas, 1980-86.

The 88-year period of simulation was divided into 25 stress periods (fig. 8) ranging from 1 to 21 years in length in which pumping rates were relatively constant. It should be noted that the greatest total annual pumpage compiled for this study was 31.2 Mft^3/d (233.6 Mgal/d) for 1978 (fig. 8). This is significantly different (7 percent) from the 72 Mgal/d withdrawn from the Sparta aquifer in Louisiana reported by Walter (1982) and the 180 Mgal/d withdrawn from the Sparta aquifer in Arkansas reported by Holland and Ludwig (1981) for the year 1980. All available written water-use records with locations known to be within the model area were carefully reviewed and compiled for this study. The reports by Walter (1982) and Holland and Ludwig (1981) present the data as total ground-water withdrawals by county and parish and total withdrawals by aquifer. Their pumpage data probably included pumpage outside the boundary of the study area.

River Leakage

The following streams were simulated for reaches flowing through the unconfined part of the Sparta aquifer (where nodes in layer 1 were inactive): Saline, Arkansas, Ouachita, and Red Rivers; Saline, Black Lake, and Bodcau Bayous; and Bayou Dorcheat, (fig. 1). Locations of the river nodes are shown on plate 4. Reaches of the streams within the boundaries of layer 1 were not simulated because layer 1 was designed to be a constant-head boundary. The stream bed and water-surface altitudes were determined from records of surface-water stations maintained by the Arkansas and Louisiana Districts of the Survey. Altitudes of stream beds and water surfaces for nodes between the gaging stations were linearly interpolated.

Stream bed vertical conductance for all river nodes was estimated to be 100,000 ft^2/d. This high value allowed good hydraulic interaction between the river and the aquifer.

Recharge

Only nodes actually contributing recharge to the Sparta aquifer (from rainfall infiltrating the unconfined part of the aquifer) were assigned recharge rates. Determination of recharge nodes and calculation of recharge rates (specified flux) were accomplished by assigning initial specified-head values to all nodes representing the unconfined part of the Sparta aquifer (where nodes in layer 1 were inactive). These nodes accounted for 13 percent of the active nodes in layer 2. Through a series of simulations of predevelopment conditions (steady state) specified-head nodes were changed to specified-flux nodes where these nodes were sources of water to layer 2. Specified-head nodes were changed to active nodes where these nodes were sources of discharge from layer 2. Plate 7 is a contour map of the recharge rates, converted to inches per year, to layer 2 derived from these simulations.

The initial specified-head values were determined from a predevelopment water-table map of the area where the Sparta aquifer is unconfined, prepared from water-level, stream-stage, and topographic data. The recharge rates calculated from the specified-head values assume no change in the water table of the Sparta aquifer over time. However, the water table has changed in some local areas, particularly in the Camden area, Ark., where a cone of depression has developed (pl. 3). The assumption of constant water-table altitudes was accepted to simplify the procedure for calculating recharge rates.

Pumpage causes an increase in the effective recharge to the confined part of the Sparta aquifer. An increase in either recharge rates, river leakage, or a combination of both would satisfy the increase in effective recharge. The effective recharge was simulated in the model by the combined net flow rates from recharge and river leakage. Because recharge rates were constant for transient simulations, the increase in effective recharge was satisfied by increased leakage of water from the streams into the Sparta aquifer.

MODEL CALIBRATION AND ACCEPTANCE TESTING

The model was calibrated by simulating the period between 1898 and 1970. The calibration procedure consisted of adjusting transmissivity and storativity in layer 2, and vertical conductance between layers 1 and 2, and comparing the resultant simulated water levels to observed 1970 water levels. All values were adjusted within the ranges that were considered reasonable as determined from previous reports (Payne, 1968; Sanford, 1973b; Trudeau and Buono, 1985) or other available data, such as aquifer-test results for transmissivity and storage coefficients.

As an additional check on the accuracy of the model, the period between 1970 and 1985 was simulated to test the acceptability (verification) of the calibrated model. Simulated water levels were compared against the observed 1985 water levels. The initial results of the acceptance test period were reasonable; however, they indicated the need for some additional adjustments to the model. Subsequent adjustments to the model variables and the delineations of the zones of horizontal hydraulic conductivity of the Sparta aquifer resulted in less error between the simulated and observed water levels for both the calibration and acceptance test periods.

Three criteria were used to determine how well the simulated water levels represented observed levels. The first criterion was a qualitative comparison between the simulated and observed potentiometric surfaces of the Sparta aquifer for 1970 and 1985. The simulated surfaces (pl. 9 for 1970 and pl. 10 for 1985) compared well with the observed surfaces (pl. 8 for 1970 and pl. 3 for 1985). The cones of depression on the simulated surfaces were of similar size and shape to the cones of depression on the observed surfaces. Generally, where the surfaces were flatter, the contours on the simulated potentiometric surface matched reasonably well with the contours on the observed potentiometric surface.

The second, more objective criterion was an error analysis of simulated and observed water levels at model nodes with observed data. The observed surfaces were based on 192 control points for 1970 (pl. 8), and on 233 control points for 1985 (pl. 3). Statistics were calculated, in particular, the root-mean-square error (RMSE) was used to judge the goodness of fit. The RMSE is given by

$$RMSE = [(h_s - h_o)^2/n]^{1/2}$$

where n = the number of water-level comparisons,
h_s = the simulated potentiometric head, in feet, and
h_o = the observed potentiometric head, in feet.

The error analyses for 1970 and 1985 are shown in table 4. Based on the observations in 1970, the mean error between the observed data points and simulated water levels at the corresponding nodes was 1.80 ft with a RMSE of 21.19 ft. The mean error for 1985 was 5.78 ft and the RMSE was 22.25 ft. The simulated values represent an average cell value while the observed values represent the potentiometric head at a particular point. In many areas, particularly where the gradient is steep or the cell is large, the potentiometric head across a given cell may vary 40 ft or more. Consequently, interpretation of the error analysis should not be the sole criterion in determining the goodness of fit.

Table 4.--Analysis of differences between observed and simulated water levels in the Sparta aquifer (model layer 2) for 1970 and 1985

Statistic	1970	1985
Number of water-level comparisons:	192	233
Mean error, feet	1.80	5.78
Mean absolute error, feet	16.34	17.07
Minimum absolute error, feet	.26	.00
Maximum absolute error, feet	70.59	78.19
Standard deviation of the differences, feet	13.45	14.22
Variance of the difference	180.84	202.30
Sum of absolute value of differences, feet	3,136.97	3,976.83
Sum of the square of the differences	85,793.44	114,809.56
Root-mean-square-error, feet	21.19	22.25

Maximum errors between observed and simulated water levels (table 4) occurred around the Magnolia area, Ark. Some information indicates that this area has a complex geologic structure controlled by faults, but specific data were not available to be incorporated into the model. The shape of the cone of depression around Magnolia (pl. 3) attests to this situation. Better results could be obtained in this area with a site-specific study using a finer discretized model, incorporating additional geologic and geohydrologic information.

The third criterion was a comparison between simulated and observed hydrographs over the calibration and verification periods. Nineteen wells with long-term hydrographs were available for comparison. Selected comparisons of simulated and observed hydrographs are shown in figures 10-16. The locations of these hydrographs are shown on plate 3 of the 1985 observed potentiometric surface. Results indicate an excellent comparison between simulated and observed hydrographs for most wells. Good fits were achieved at the major pumping centers of West Monroe and Bastrop, Louisiana, and El Dorado and Pine Bluff, Ark. Areas located away from major pumping centers also were simulated accurately. The most notable deviation between simulated and observed hydrographs occurred in the Magnolia area, Ark. (fig. 13), for reasons previously discussed. In addition, it is likely that not all of the pumpage has been reported and, thus, not simulated.

The two hydrographs for the Grand Prairie agricultural region in Arkansas show the correct water-level trend, but the simulated values are consistently lower than the observed values (fig. 16). Water levels in wells used for irrigation fluctuate seasonally in response to agricultural demand (fig. 9). The observed water levels used in the hydrographs in figure 16 were recorded in the spring, when levels are highest. The stress periods used in the model were multiples of whole years, so the simulated water levels are representative of average conditions. Therefore, it is reasonable to expect the simulated surface to be consistently lower than the observed surface.

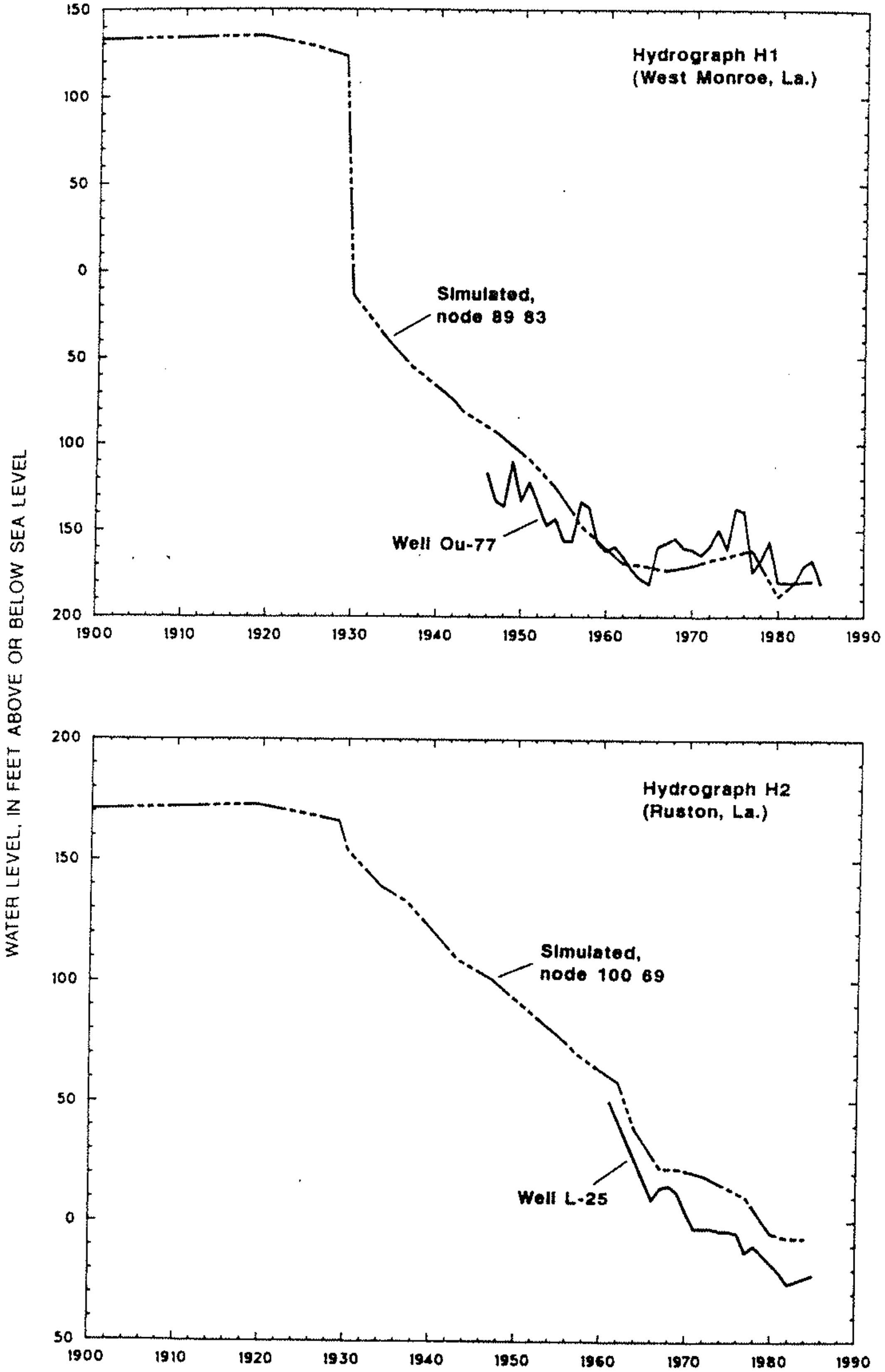


Figure 10.--Simulated and observed water levels, 1900-85, West Monroe and Ruston, Louisiana.

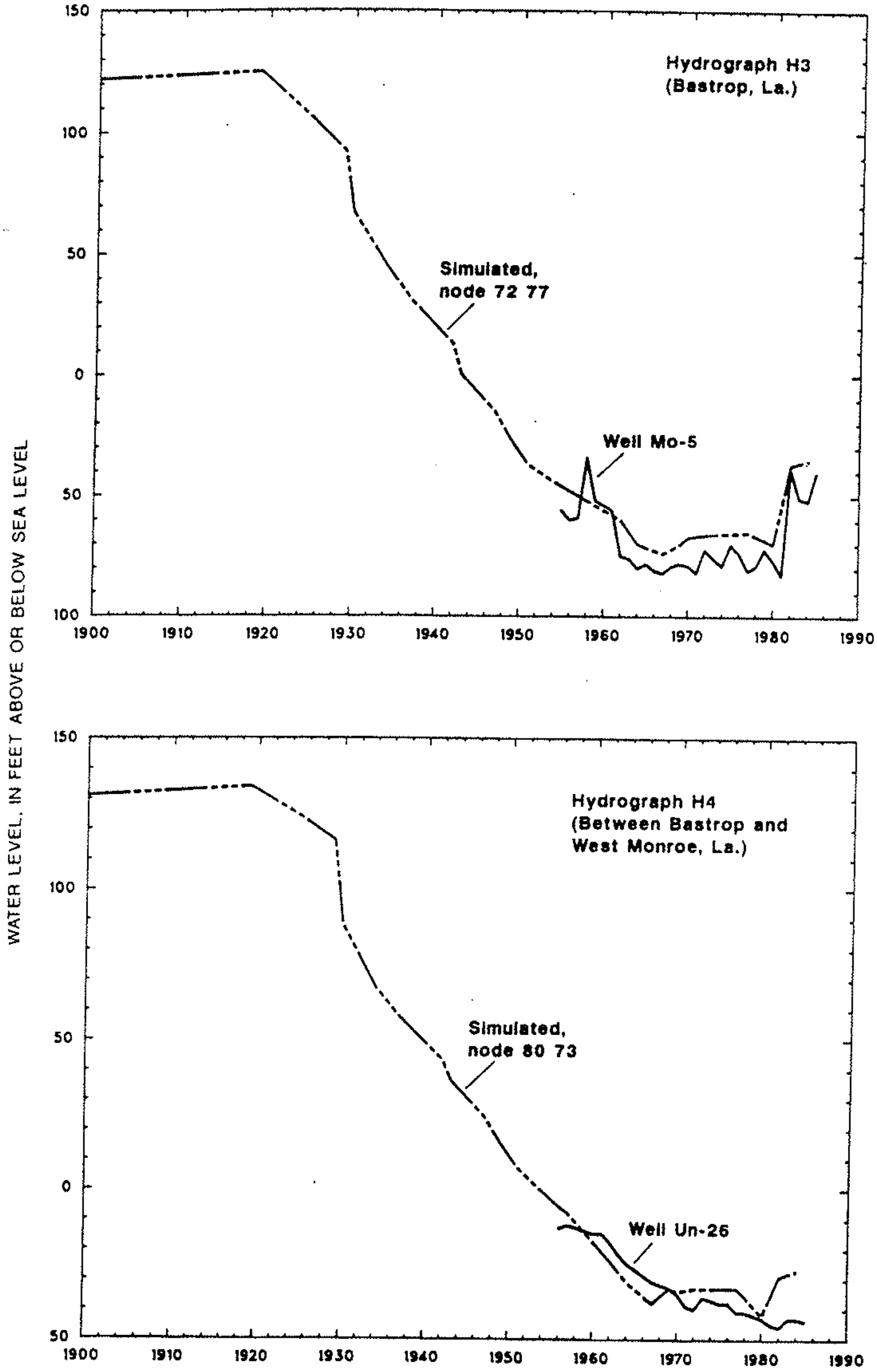


Figure 11.--Simulated and observed water levels, 1900-85, Bastrop and between Bastrop and West Monroe, Louisiana.

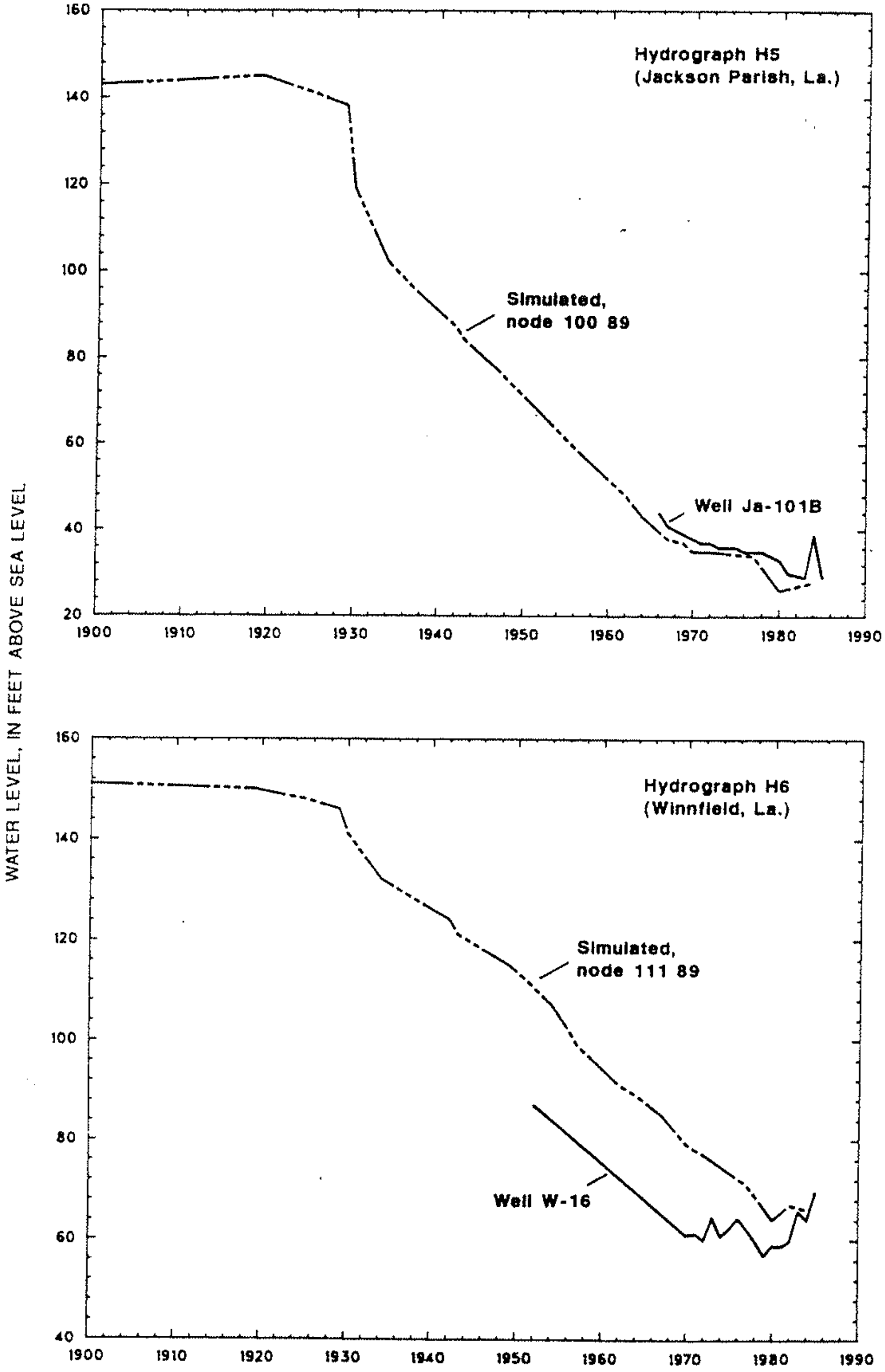


Figure 12.--Simulated and observed water levels, 1900-85, Jackson Parish and Winnfield, Louisiana.

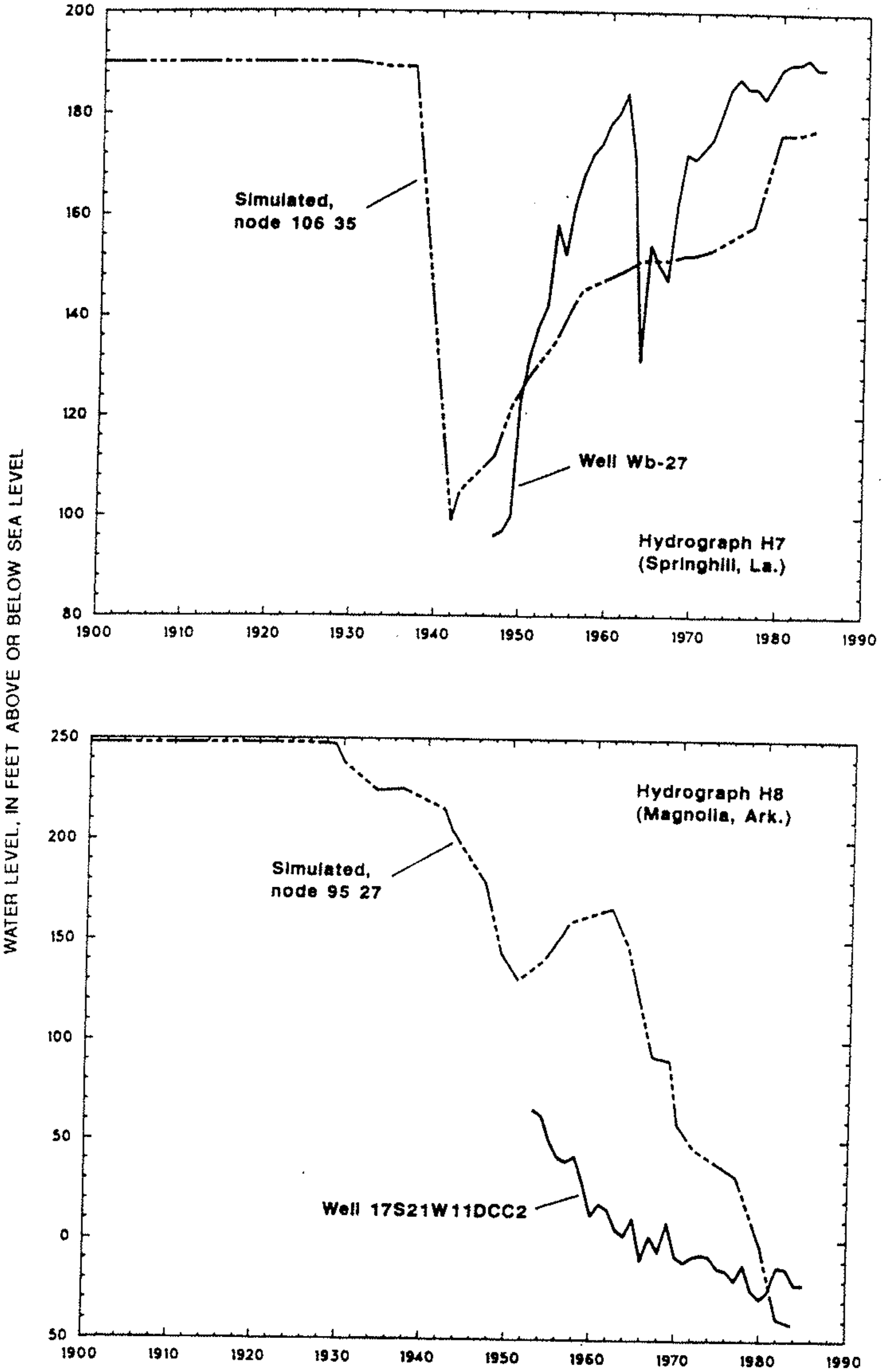
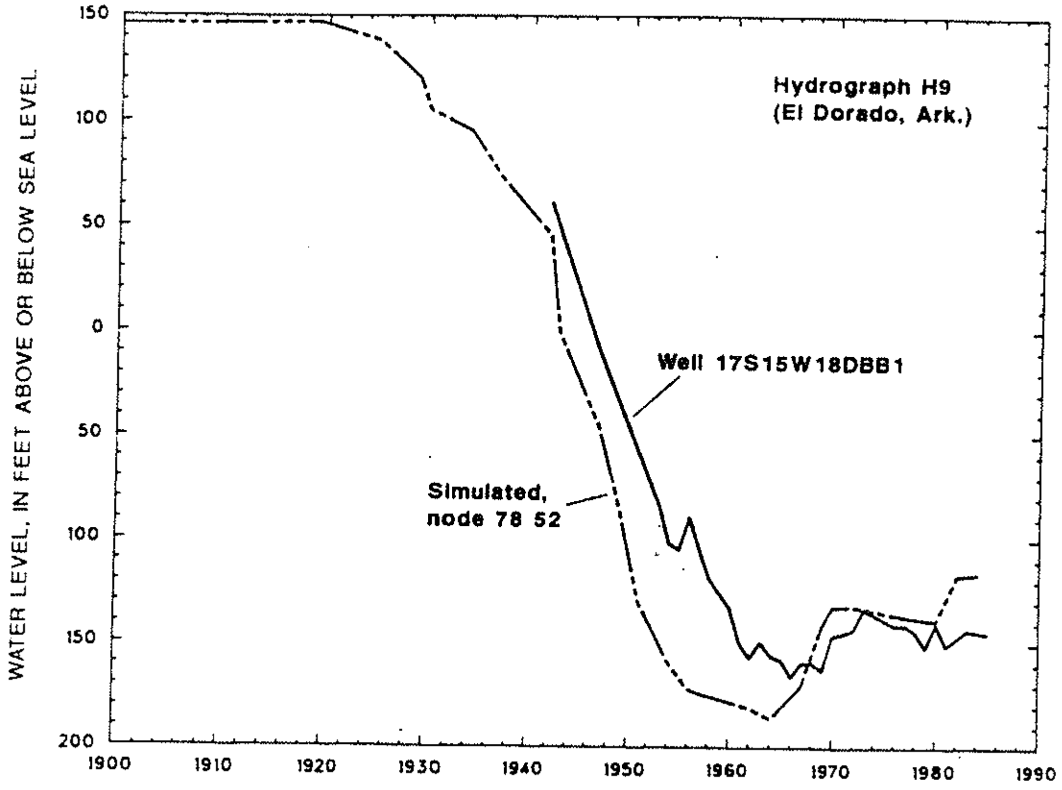


Figure 13.--Simulated and observed water levels, 1900-85, Springhill, Louisiana, and Magnolia, Arkansas.



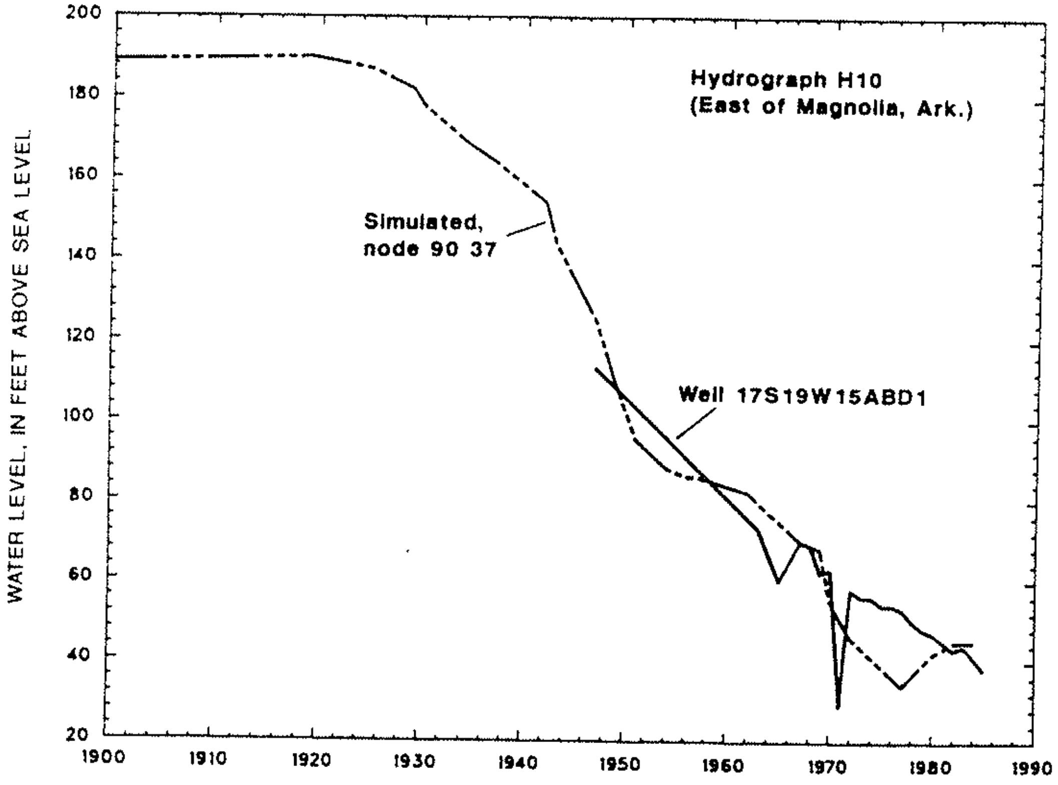
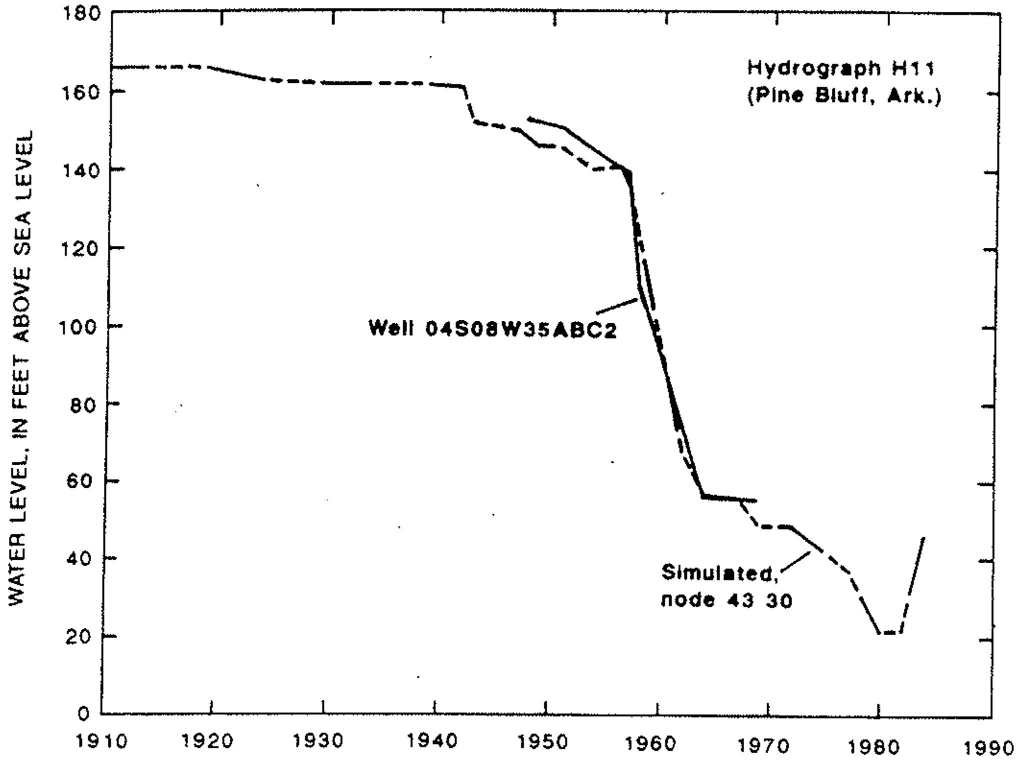


Figure 14.--Simulated and observed water levels, 1900-85, El Dorado, Arkansas, and east of Magnolia, Arkansas.



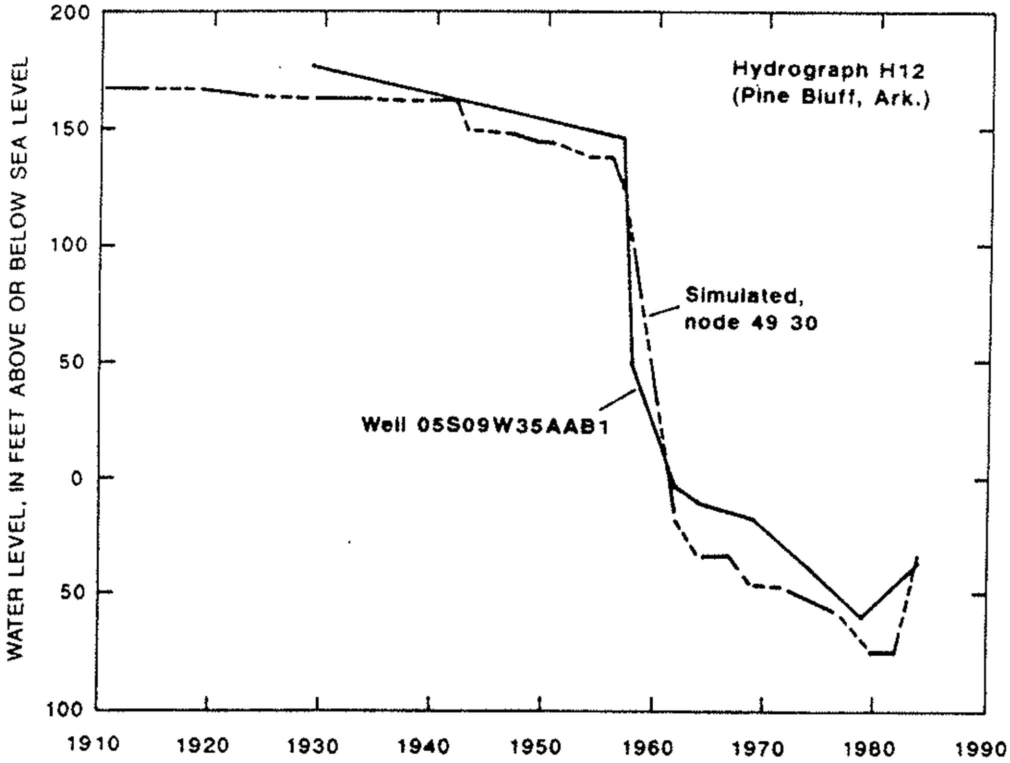


Figure 15.--Simulated and observed water levels, 1910-85, Pine Bluff, Arkansas.

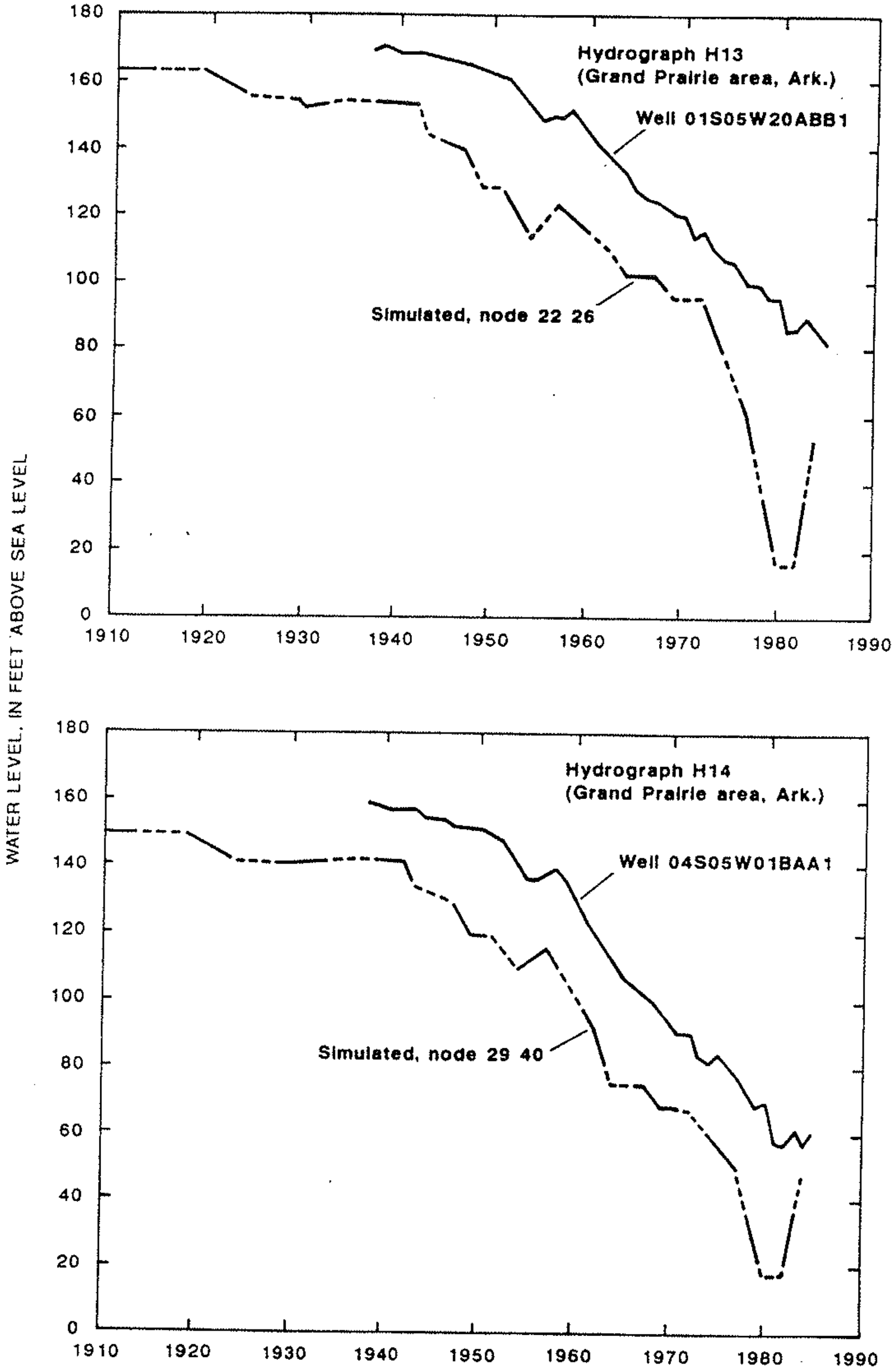


Figure 16.--Comparison of simulated and observed water levels, 1910-85, Grand Prairie area, Arkansas.

After adjustments to model variables were made during calibration of transient simulations, steady-state simulations were made to assure the solution was still valid for predevelopment conditions. Steady-state results were particularly sensitive to changes in the vertical hydraulic conductivity of the Cook Mountain confining unit whereas transient results were more sensitive to changes in transmissivity of the Sparta aquifer. Consequently, continually checking both steady-state and transient results helped to avoid nonunique solutions that might have been obtained otherwise.

The simulated steady-state potentiometric surface (fig. 17) agrees reasonably well with predevelopment surfaces proposed by Reed (1972) and Ryals (1980b). Considering the limited amount of data used to estimate the observed predevelopment surfaces and the results of the transient simulations, it is reasonable to assume that the model-simulated predevelopment potentiometric surface is as good an estimate of predevelopment conditions as previously published maps.

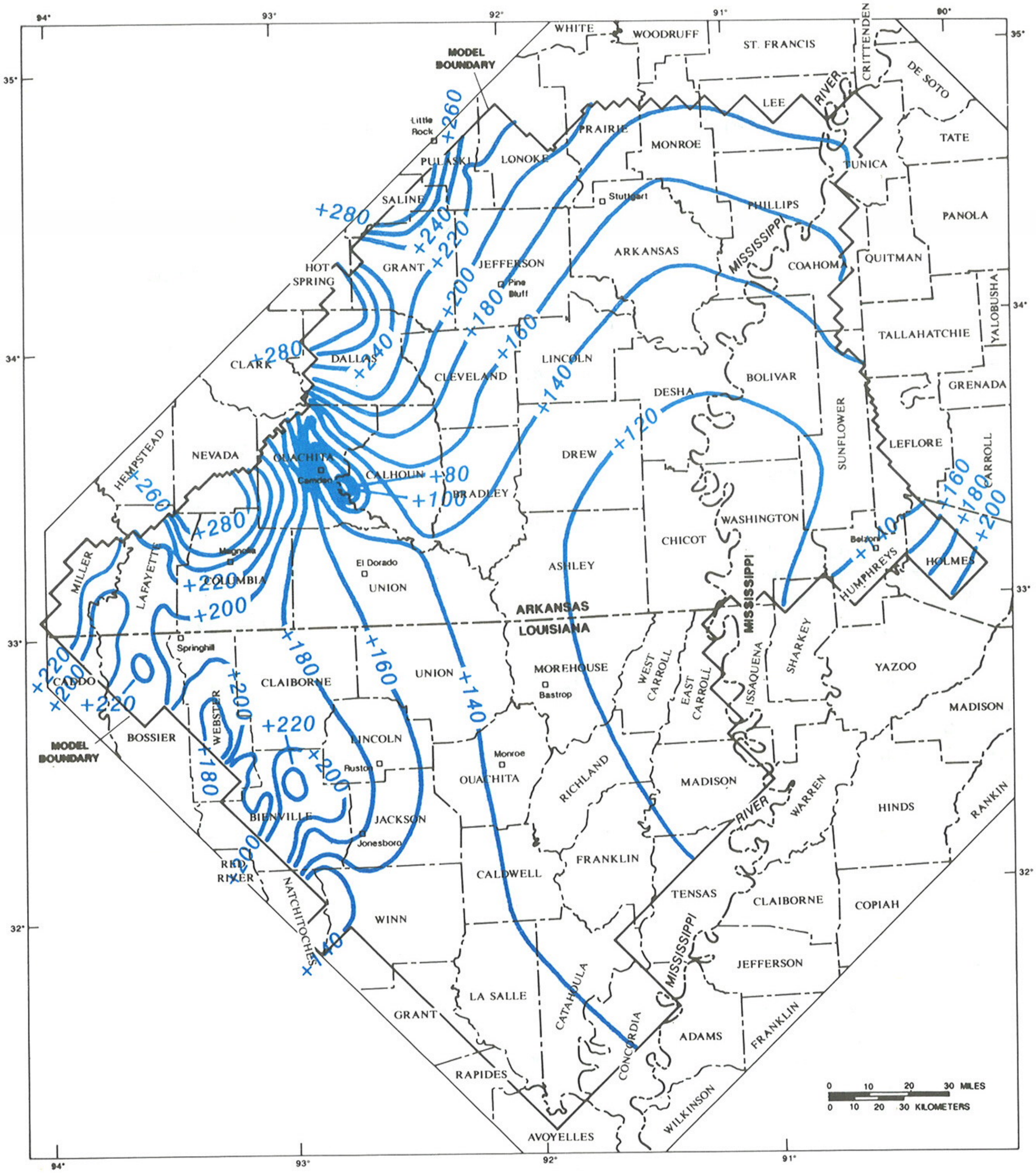
Flow rates calculated by the model were not directly comparable with actual flow rates, as these data are not precisely known; however, rates to rivers were randomly checked against streamflow data and generally were within base and average flow discharges. The flow percentages for 1985 (table 5) were compared with those by Trudeau and Buono (1985) and were found to be in agreement.

SENSITIVITY ANALYSIS

The responsiveness of the calibrated model to changes in model variables was examined through sensitivity analysis. Distributions of transmissivity and storativity of the Sparta aquifer (layer 2) and vertical conductance of the Cook Mountain confining unit were varied independently in transient simulations while the other variables were kept constant. No sensitivity analysis was performed for steady-state simulation because few reliable water-level data for the predevelopment potentiometric surface of the Sparta aquifer exist. The sensitivity of model results to these variations was determined by means of the RMSE comparison of simulated and observed water levels for 1970 and 1985.

The sensitivity of the model to areal changes in transmissivity was tested by varying the transmissivity by 0.25 to 50 times the calibrated distribution. The resultant RMSE's ranged between 22.28 and 182.80 ft for 1970, and 21.62 and 166.86 ft for 1985. The model was sensitive to changes in transmissivity; the RMSE's increased significantly as the transmissivities were increased or decreased (fig. 18).

The sensitivity of the model to areal changes in vertical conductance (vertical hydraulic conductivity divided by thickness of the Cook Mountain confining unit times the area of the cell) was tested. Because the area of the cell and the thickness of the Cook Mountain confining unit were constants in the vertical conductance equation, the vertical hydraulic conductivity was varied by 0.05 to 50 times the calibrated values. The resultant RMSE's ranged from 21.59 to 95.22 ft for 1970, and from 20.68 to 109.16 ft for 1985 (fig. 18). The model was much less sensitive to changes in vertical hydraulic conductivity than transmissivity, particularly for values less than 10 times the calibrated values. For vertical hydraulic conductivity values more than 10 times the calibrated values, the RMSE's for hydraulic conductivity approach the RMSE's for transmissivity.



EXPLANATION

—+140— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 20 feet. Datum is sea level

Figure 17.--Simulated steady-state potentiometric surface of the Sparta aquifer.

Table 5.--Water-budget analysis for the Sparta aquifer (model layer 2), predevelopment (1898) and 1985

[Rates are in cubic feet per day. Hyphens (--) mean not applicable]

Water budget element	Inflow		Outflow	
	Rate	Percent	Rate	Percent
Predevelopment				
River Leakage:				
Saline River, Ark	0		582,915	
Ouachita River, Ark	0		1,290,229	
Arkansas River, Ark	88,101		152,953	
Saline Bayou, La	110,125		3,223,245	
Black Lake Bayou, La	0		1,649,674	
Bayou Dorcheat, La	0		1,635,067	
Bodcau Bayou, La	0		2,098,472	
Red River, La	16,239		1,325,923	
Subtotal	214,465	1	11,958,478	59
Recharge	13,297,338	65	--	--
Layer 1 leakage	978,648	5	8,182,083	40
Specified head boundary	5,893,737	29	241,368	1
Total	20,384,188	100	20,381,929	100
1985				
River leakage:				
Saline River, Ark	35,974		302,713	
Ouachita River, Ark	82,082		670,414	
Arkansas River, Ark	237,970		6,406	
Saline Bayou, La	589,709		2,385,137	
Black Lake Bayou, La	263,138		1,365,181	
Bayou Dorcheat, La	476,324		914,934	
Bodcau Bayou, La	906		1,711,228	
Red River, La	16,259		1,321,115	
Subtotal	1,702,362	4	8,677,128	22
Recharge	13,297,338	35	--	--
Layer 1 leakage	15,004,858	39	554,511	1.5
Specified head boundary	4,759,267	12	2,126,513	6
Storage	3,872,927	10	149,416	.5
Wells	--	--	27,137,568	70
Total	38,636,752	100	38,645,136	100

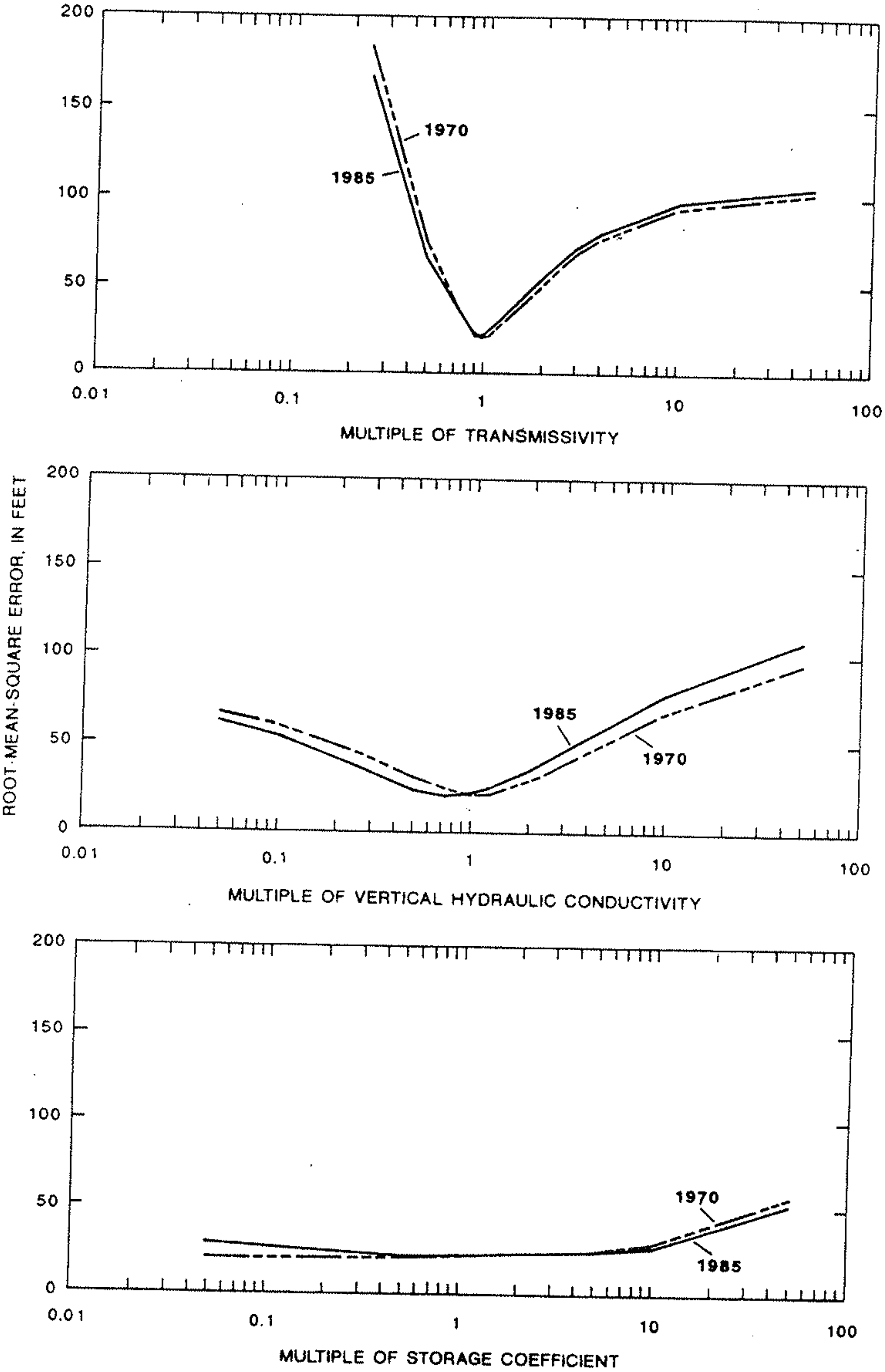


Figure 18.--Sensitivity of model to changes in transmissivity, vertical hydraulic conductivity, and storage coefficient.

The sensitivity of the model to changes in the storage was tested by varying the storativity by 0.05 to 50 times the calibrated distribution. The RMSE's ranged between 19.63 and 54.38 ft for 1970, and 22.45 and 51.82 ft for 1985. The model was relatively insensitive to changes in storage until storativity was increased by more than an order of magnitude (fig. 18).

The sensitivity analyses indicate the adequacy of the calibrated variables used in the model. The analyses do not indicate, however, that the values of the variables are optimal values. Since the solution to the ground-water equations is not unique, different combinations of values could yield similar results, although the potential for this was reduced by performing both steady-state and transient simulations. The model could be refined if better estimates of the areal distribution of the transmissivity of the Sparta aquifer and of the vertical hydraulic conductivity of the Cook Mountain confining unit were available.

SIMULATED RESPONSE TO PUMPING STRESSES

The calibrated ground-water flow model was used to evaluate the effects of pumping stresses on water levels and aquifer flow characteristics of recharge, discharge, and leakage. Drawdown from predevelopment water levels in the Sparta aquifer in response to pumping stresses is shown for 1985 on plate 11. A maximum drawdown in excess of 320 ft occurred at El Dorado, Ark., and drawdown in excess of 280 ft occurred at West Monroe, La. These simulated drawdowns are consistent with actual drawdowns reported in the literature. The model also simulated a drawdown in excess of 320 ft at Magnolia, Ark., but actual drawdown was only about 260 to 300 ft, based on available data.

Although these maximum drawdowns are quite large, water levels at the major pumping centers are adequate to allow significant additional drawdown. At El Dorado, Ark., the top of the El Dorado aquifer, the producing unit in the Sparta aquifer, is from 300 to 400 ft below sea level (Broom and others, 1984, pl. 8). The 1985 observed water level of 167 ft below sea level (the model simulated a minimum value of 175 ft below sea level) at the center of the cone of depression at El Dorado in 1985, allows at least 130 ft of additional drawdown before water levels approach the top of the aquifer.

Locating the true top of the Sparta aquifer, the geohydrologic boundary between the permeable aquifer material and the less permeable confining material, at West Monroe is difficult. The geologic determination for the base of the Cook Mountain Formation (top of the Sparta Formation) is about 100 ft below sea level at West Monroe (Ryals, 1984, pl. 7). The water level measured from a well screened in the lower part of the Sparta aquifer at the center of the cone of depression at West Monroe was 181 ft below sea level in 1985 (the model simulated a minimum value of 179 ft below sea level), which means that the potentiometric surface of the Sparta aquifer is below the top of the Sparta Formation. Most of the pumpage at West Monroe is from the lower part of the Sparta aquifer (Rogers and others, 1972, p. 21), which is from 500 to 800 ft below sea level. Some of the sand beds of the upper part of the Sparta aquifer, which are in poor hydraulic connection with sand beds in the lower part, have water levels higher than water levels in the sand beds in the lower part. This reversal of the normal hydraulic pressure differential indicates a lag in pressure adjustment to pumpage in the sand beds in the lower part of the Sparta aquifer (Rogers and others, 1972, p. 28). Clay and silt beds between the upper and the lower parts of the Sparta aquifer restrict flow and tend to partially confine the lower sand beds from the upper sand beds. In unconsolidated sediments, boundaries between geologic formations need not coincide with hydrologic boundaries. Therefore, even though water levels are below the top of the geologic boundary for the Sparta Formation, it may not be appropriate to conclude that the Sparta aquifer is dewatering at West Monroe. The conclusion is that confined conditions existed in the Sparta aquifer in 1985 (and continue to exist) at West Monroe and available drawdown from 1985 water levels to the heavily pumped zones in the aquifer ranges from 300 to 400 ft.

Similar geohydrologic conditions may exist at Magnolia, Ark. The top of the Sparta Formation is about 100 ft above sea level. Based on log data from a well near the center of the cone of depression a 60-foot thick clay separates an upper sand from a lower sand (top of the sand is 144 ft below sea level). Wells in the Magnolia area are pumping from the lower sand. The measured water levels in wells near the center of the cone of depression stood at about 20 to 27 ft below sea level in 1985 and simulated water levels for 1985 were about 80 to 115 ft below sea level. Therefore, about 120 ft of additional drawdown remain before water levels reach the top of the producing sand.

The delineation of a hydrologic boundary in a complex geologic environment to determine the potential for dewatering is scale dependent. The factors determining scale are the temporal and three-dimensional spatial distribution of pumping rates, the dimensions of the volumes of materials (aquifers and confining units) influenced by pumpage, and the hydraulic conductivities of those volumes. The data available for the design of this model cannot account for all these factors at a suitable scale. Therefore, this model is not designed to determine the potential for dewatering.

Reports by Sanford (1973a; 1973b) and Ryals (1982) discuss local dewatering of sands in the Sparta aquifer in the Ruston area and the Arcadia-Minden area, respectively. In areas where dewatering is occurring, results of this model will deviate from actual conditions. Specifically, actual water levels will be higher than those derived by the model. Drainage of the upper sands acts as a recharge source to the lower sands (Ryals, 1982); thus, the actual rate of water-level decline decreases. In addition, the confining units were not modeled as layers; therefore, the model does not compute changes in storage in the confining units.

Extensive, regional drawdown exceeding 80 ft occurred from predevelopment to 1985 in southern Arkansas, northern Louisiana, and in the Pine Bluff and Grand Prairie areas of east-central Arkansas. In the confined parts of the Sparta aquifer, drawdowns generally exceeded 40 ft, and in the unconfined parts, drawdowns were less than 20 ft.

Analysis of model-simulated flows indicated changes in the flow characteristics of the Sparta aquifer since predevelopment. Total flow through the Sparta aquifer increased from about 20.4 Mft^3/d before development to 38.6 Mft^3/d in 1985 (table 5).

Prior to development, about two-thirds of the water flowing into the Sparta aquifer came from rainfall (recharge) infiltrating the unconfined part of the aquifer (table 5). Most of this water (59 percent of total aquifer outflow) discharged locally to the rivers. All eight rivers simulated by the model received water from the aquifer. A net rate of about 1.55 Mft^3/d (table 5) of water was supplied to the confined part of the Sparta aquifer from the combined sources of recharge and net river leakage.

By 1985, the net rate of water supplied to the Sparta aquifer by the combined sources of recharge and river leakage increased approximately four times to about 6.32 Mft^3/d (table 5). Although the recharge rate applied to the Sparta aquifer was constant throughout the transient simulation, the increase in effective recharge to the confined part of the Sparta aquifer was the result of less water being discharged locally to the rivers. In 1985, only 22 percent of the total outflow discharged locally to rivers. The Arkansas River became a recharge source to the Sparta aquifer. The higher than normal river stages of a reservoir in the reach of the river simulated by the model may have induced additional recharge to the Sparta aquifer.

Prior to development, 40 percent of outflow from the Sparta aquifer went to overlying aquifers (layer 1 leakage), with a net flow rate of about 7.20 Mft^3/d (table 5). Due to pumpage, the net rate reversed and about 14.45 Mft^3/d (table 5) flowed from the overlying aquifers into the Sparta aquifer in 1985. The reversal in flow between aquifers in the system is shown spatially on plates 12 and 13. In most of the confined part of the Sparta aquifer the predevelopment flow is upward to overlying aquifers. Areally, in 1985, most of the flow is downward from the overlying aquifers into the Sparta aquifer. Conditions in 1985 were such that upward flow existed only locally.

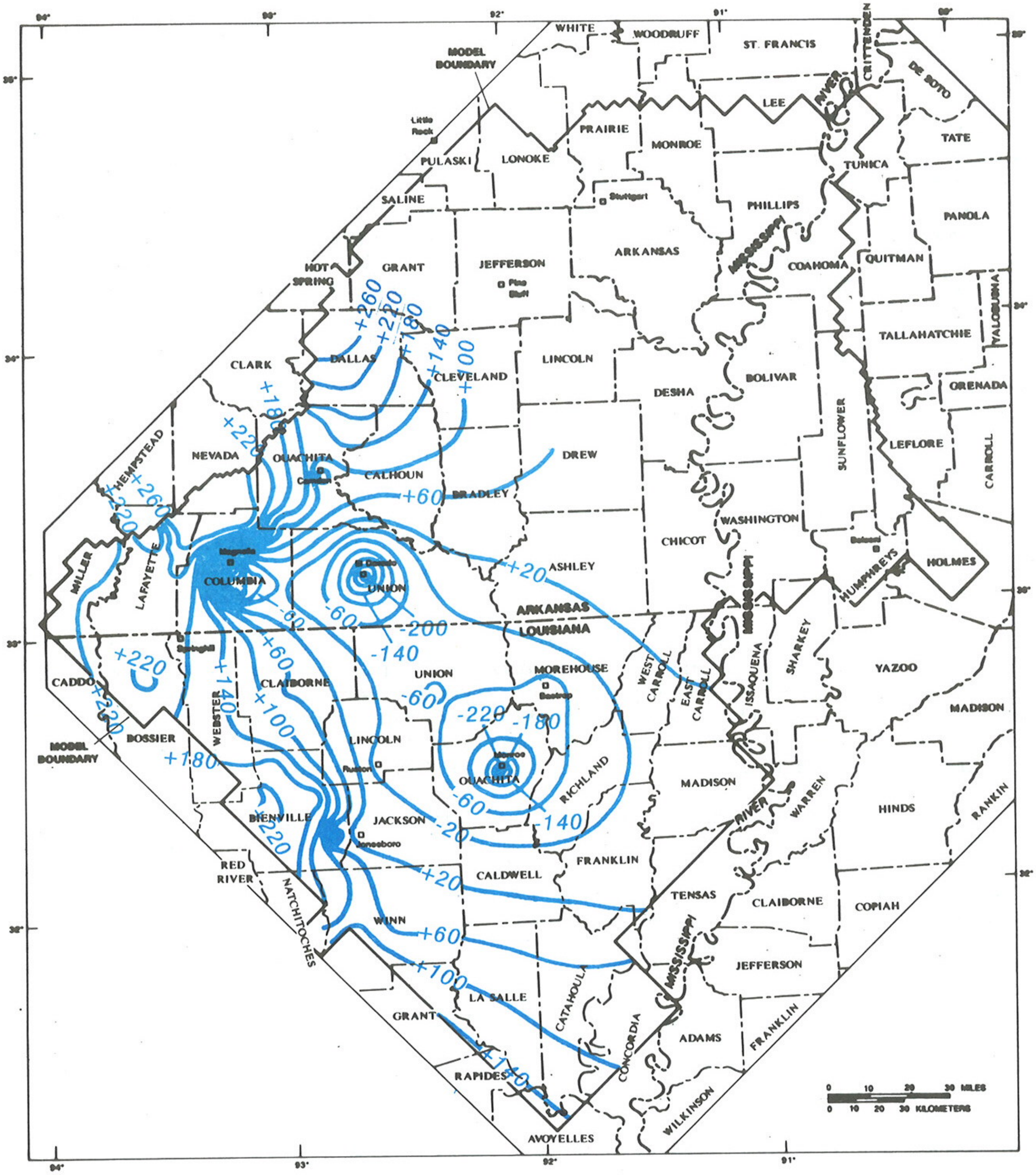
The most significant change in aquifer flow from predevelopment to 1985 was discharge to wells. Pumpage accounted for 70 percent of total outflow from the Sparta aquifer in 1985.

Results from a previous ground-water flow model that simulated transient flow through 1980 for a region of the Sparta aquifer encompassing the study area in this report are consistent with the results reported in table 5. Trudeau and Buono (1985, p. 32) reported inflows of 11 percent from storage, 40 percent from outcrop/subcrop recharge (constant-head leakage), and 44 percent from overlying aquifers (Cook Mountain confining unit leakage).

SIMULATED RESPONSE TO PROJECTED PUMPING STRESSES

The calibrated ground-water flow model was used to simulate response of the Sparta aquifer to projected pumpage from 1985 to 2005. Four 5-year stress periods were used to simulate conditions to 2005. Three pumping conditions were simulated: (1) Pumping rates were held constant at the 1985 rate, (2) pumping rates were projected to increase 25 percent over the 1985 rates, and (3) pumping rates were projected to increase 50 percent over the 1985 rates. Water levels remained virtually unchanged in the first simulation when pumping rates were held constant at the 1985 rate, indicating that by 1985 the Sparta aquifer was at steady-state condition.

The second simulation with pumping rates projected to increase 25 percent by 2005 (6.25 percent for each of the four stress periods from 1985 to 2005) resulted in the potentiometric surface shown in figure 19 (shown only for the study area of this report). In this simulation water levels at



EXPLANATION

-20 POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 40 feet. Datum is sea level

Figure 19.--Projected potentiometric surface of the Sparta aquifer in 2005 for simulated pumpage 25 percent greater than 1985 pumpage.

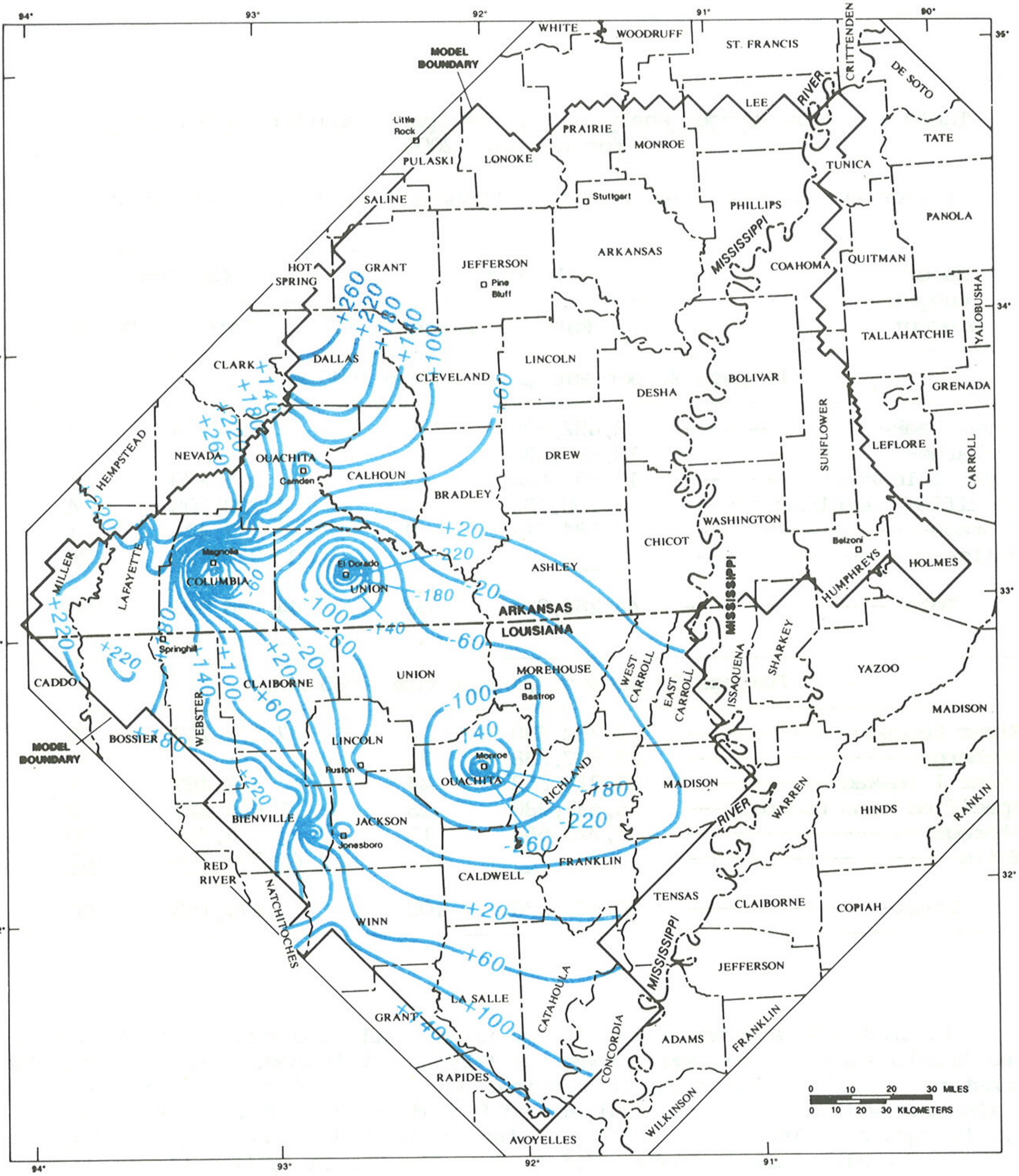
El Dorado, Ark., and West Monroe, La., declined to about 260 ft below sea level. This represents a drawdown of 85 ft from the simulated water levels in 1985. As previously discussed, the available drawdown was 130 ft for El Dorado and 300 to 400 ft for West Monroe. At Magnolia, Ark., water levels declined to about 215 ft below sea level. This represents a drawdown of 100 ft from the simulated water levels in 1985. The available drawdown for Magnolia was about 120 ft, and the projected drawdown would be near the top of the producing sand.

A third simulation with pumping rates projected to increase 50 percent by 2005 (12.5 percent for each of the four stress periods from 1985 to 2005) resulted in the potentiometric surface shown in figure 20 (shown only for the study area of this report). Water levels at El Dorado, Ark., and West Monroe, La., declined to about 335 ft below sea level. This represents a drawdown of 160 ft from the simulated water levels in 1985, which is still well within the range of available drawdown for West Monroe but exceeds the available drawdown at El Dorado. At Magnolia, Ark., water levels declined to about 290 ft below sea level. This represents a drawdown of 180 ft from the simulated water levels in 1985 and exceeds the available drawdown, as previously discussed.

These results suggest that pumping rates of 25 to 50 percent greater than 1985 pumping rates in the El Dorado and Magnolia areas may cause water levels to decline below the tops of the producing sand beds by 2005. Ground-water flow models with finer discretization and site-specific data could provide more precise and accurate information for the planning of increased ground-water withdrawals in the El Dorado and Magnolia areas.

As available drawdown decreases, well yields may decrease. For example, if the well drawdown exceeds the available drawdown and the water level is drawn down below the top of the aquifer, the saturated thickness of the producing aquifer will be decreased and well yields will be reduced. This could occur in the West Monroe area where municipal supply and domestic wells are screened in the upper sands and high capacity industrial wells are screened in the lower sands of the Sparta aquifer.

Flow rates in the Sparta aquifer (layer 2) for the increased pumpage simulations (25 and 50 percent) are listed for 2005 in table 6. These rates may be compared with the flow rates for the simulation to 1985 listed in table 5. The results of the projected simulations indicate that total flow in the Sparta aquifer increased with increased pumping. A 25-percent increase over 1985 pumping rates increased flow in the aquifer from 38 Mft^3/d in 1985 to 44 Mft^3/d in 2005, and a 50-percent increase over 1985 pumping rates increased the flow to 50 Mft^3/d in 2005. Most of the inflow increases resulting from increases in pumpage are attributed to vertical leakage from layer 1 (from overlying aquifers). In the 25-percent increase in pumpage simulation, inflow to the Sparta aquifer from layer 1 increased by almost 4 Mft^3/d over the inflow in 1985, while inflows from the other sources increased by less than 2 Mft^3/d over inflows in 1985. In the 50-percent increase in pumpage simulation, inflow to the Sparta aquifer from layer 1 increased by more than 7.2 Mft^3/d over the inflow in 1985, while inflows from the other sources increased by about 4.6 Mft^3/d over inflows in 1985. Leakage from layer 1 accounted for 39 percent of flow into the Sparta aquifer in 1985 (table 5), 43 percent in 2005 at the 25-percent increased pumpage simulation, and 44 percent in 2005 at the 50-percent increased pumpage simulation (table 6).



EXPLANATION

—— -20 —— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 40 feet. Datum is sea level

Figure 20.--Projected potentiometric surface of the Sparta aquifer in 2005 for simulated pumpage 50 percent greater than 1985 pumpage.

Table 6.--Water-budget analysis for the Sparta aquifer (model layer 2) for the year 2005

[Rates are in cubic feet per day. Hyphens (--) mean not applicable]

Water budget element	Inflow		Outflow	
	Rate	Percent	Rate	Percent
Pumpage 25 percent greater than 1985 rates				
River Leakage	2,452,825	5	7,752,974	18
Recharge	13,297,338	30	--	--
Layer 1 leakage	18,895,624	43	494,270	1
Specified head boundary	5,706,103	13	1,790,206	4
Storage	3,934,911	9	337,426	1
Wells	--	--	33,921,920	76
Total	44,286,801	100	44,296,796	100
Pumpage 50 percent greater than 1985 rates				
River Leakage	2,782,438	6	7,671,192	15
Recharge	13,297,338	26	--	--
Layer 1 leakage	22,214,852	44	469,487	1
Specified head boundary	6,437,980	13	1,616,427	3
Storage	5,725,668	11	6,756	0
Wells	--	--	40,706,296	81
Total	50,458,276	100	50,470,158	100

In areas where water levels in the upper sands actually reach the top of the Sparta aquifer, leakage across the Cook Mountain confining unit will be constant. Further increases in vertical leakage are derived from clays and silts from within the Sparta aquifer and from dewatering of upper sands in the Sparta aquifer. Therefore, the flow rates calculated by the model for layer 1 leakage may also include leakage internal to the Sparta aquifer (layer 2).

Increasing pumpage increases effective recharge to the Sparta aquifer. As constant recharge rates were used for all transient simulations, the increase in effective recharge was the result of decreased discharge to rivers (tables 5 and 6). As pumping rates increased from 1985 recharge to the Sparta aquifer from rivers increased and discharge from the aquifer to the rivers decreased for the year 2005 for both the 25- and 50-percent increased pumping conditions.

SUMMARY AND CONCLUSIONS

The Sparta aquifer is the most important source of ground water in northern Louisiana and southern Arkansas and a major source in east-central Arkansas. As a result of heavy pumpage (252 Mgal/d in 1980), numerous cones of depression and a general lowering of the water levels have occurred. A finite-difference ground-water flow model was developed to evaluate the flow characteristics of recharge, discharge, and leakage and the effects on water levels due to present and future pumping stresses within the Sparta aquifer.

The Sparta aquifer is one geohydrologic unit in a series of alternating aquifers and confining units. The Sparta aquifer is confined below by the Cane River confining unit and above by the Cook Mountain confining unit. The Cockfield aquifer and hydraulically connected alluvial and terrace aquifers overlie the Cook Mountain confining unit throughout much of the study area. The Cockfield, alluvial, and terrace aquifers are surficial units throughout most of the study area. In the southwestern and northwestern parts of the study area the Sparta aquifer is exposed at the surface.

Prior to development (1898) of the Sparta aquifer the direction of regional flow in the geohydrologic units was controlled by the structural concavity of the Mississippi embayment. Two components of the flow system, water from the eastern and western updip limits of the Sparta aquifer, move downdip to converge on the western side of the axis of the Mississippi embayment, then move upward from the downdip parts of the aquifer toward the surface through overlying geohydrologic units. Although the flow system in the Sparta aquifer has been altered by development, this flow pattern continues to dominate the regional flow system. The study area of this report is from the western updip limit of the Sparta aquifer in northern Louisiana and southern Arkansas to the approximate midpoint of upward flow beneath the Mississippi River valley alluvium. Prior to development, the major discharge zones in the study area were the Ouachita River valley in Arkansas and the Mississippi River valley in Arkansas and Louisiana.

Development of the Sparta aquifer has significantly altered the flow system. Large cones of depression have formed at Bastrop and West Monroe, La., and at El Dorado, Magnolia, and Camden, Ark. Water in the Sparta aquifer flows from all directions toward the centers of these cones. In eastern parts of the study area, water levels in the Sparta aquifer are below water levels in the Cockfield aquifer, resulting in downward flow from the Cockfield aquifer into the Sparta aquifer.

Significant development of the Sparta aquifer began in the 1920's and continued to the late 1970's when total pumpage peaked at 31.2 Mft^3/d. Water levels have declined about 300 ft at El Dorado, Ark., and 270 ft at West Monroe, La., in response to the pumpage.

The flow model consisted of a constant-head surface; layer 1, representing the Cockfield, alluvial, and terrace aquifers; and layer 2, representing the Sparta aquifer. The lower boundary is a no-flow boundary representing the Cane River confining unit. The Cook Mountain confining unit, which separates the Cockfield from the Sparta aquifer, is modeled as a vertical resistance to flow term. No-flow and specified-head nodes served as lateral model boundaries to the flow system.

Transmissivity and storativity values of the Sparta aquifer and vertical hydraulic conductivity values of the Cook Mountain confining unit were selected through calibration and acceptance testing of transient simulations from 1898 to 1970 and from 1970 to 1985, respectively, and through qualitative analysis of the steady-state simulation.

The transient simulation period 1898 to 1985 was divided into 25 stress periods. A total of 329 well nodes were used to simulate pumpage in the final stress period. Eight rivers in the recharge area (unconfined part) of the Sparta aquifer were simulated. Recharge rates, based on predevelopment water-table altitudes, were applied to nodes that were determined to be sources of recharge to the Sparta aquifer. Results of the sensitivity analysis indicate that the model was most sensitive to transmissivity and least sensitive to storativity (storage coefficient and specific yield).

The calibrated flow model simulated aquifer response to pumpage from predevelopment (1898) to 1985. Model results indicate drawdowns in excess of 320 ft occurred at El Dorado and Magnolia, Ark., although actual drawdown in the Magnolia area was about 260 to 300 ft. An additional 130 ft of drawdown at El Dorado and about 120 ft at Magnolia are available before water levels reach the top of the producing aquifer sand beds. At West Monroe, La., model results indicate drawdowns in excess of 280 ft from 1898 to 1985. An additional 300 to 400 ft of drawdown are available at West Monroe before water levels reach the top of the producing aquifer sand beds. Drawdowns in the Sparta aquifer from 1898 to 1985 exceeded 80 ft over most of the study area of this report.

Pumpage, accounting for 70 percent of outflow from the Sparta aquifer in 1985, has increased the amount of water flowing through the Sparta aquifer from about 20.4 Mft^3/d prior to development to 38.6 Mft^3/d in 1985. Prior to development, two-thirds of the flow of water into the Sparta aquifer was from recharge, but most of this was discharged to streams. As a result of development, effective recharge (recharge plus river leakage) increased by a factor of four. The increase in effective recharge to the Sparta aquifer was caused by a decrease in water discharging locally to streams.

Pumping has resulted in a reversal in the direction of flow of water between the Sparta aquifer and overlying aquifers in parts of the study area. Before development, water flowed from the Sparta aquifer into overlying aquifers (mostly beneath the Mississippi River valley and the Ouachita River valley) at a net rate of about 7.20 Mft^3/d. By 1985, 14.45 Mft^3/d of water flowed from overlying aquifers into the Sparta aquifer.

Three pumping conditions were chosen to simulate the effects of pumping stresses from 1985 to 2005. In the first projected simulation, pumping rates were held constant at the 1985 rate. Water levels in the year 2005 remained virtually unchanged.

In the second simulation, pumping rates were projected to increase about 25 percent over 1985 rates. By 2005 simulated water levels at El Dorado, Ark., and West Monroe, La., declined about 85 ft below simulated water levels in 1985. At Magnolia, Ark., water levels declined about 100 ft below simulated water levels in 1985. These projected drawdowns were less than the available drawdowns determined for each locality.

In the third simulation, pumping rates were projected to increase about 50 percent over 1985 rates. By 2005 simulated water levels at El Dorado, Ark., and West Monroe, La., declined about 160 ft below simulated water levels in 1985. At Magnolia, Ark., water levels declined about 180 ft below simulated water levels in 1985. These projected drawdowns exceeded the available drawdowns for El Dorado and Magnolia.

The results from the simulations suggest that pumping rates increase to 25 to 50 percent greater than 1985 pumping rates in the El Dorado and Magnolia, Ark., areas may cause water levels to decline below the tops of the producing sand beds. Ground-water flow models with finer discretization and site-specific data could provide more precise and accurate information for the planning of increased ground-water withdrawals in the El Dorado and Magnolia areas.

The simulations to 2005 with pumping rates projected to increase to 25 and 50 percent over 1985 pumping rates increased total flow in the Sparta aquifer to about 44 Mft^3/d and 50 Mft^3/d, respectively. Most of the flow increase in each simulation is attributed to increased flow of water (vertical leakage) into the Sparta aquifer from overlying aquifers.

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