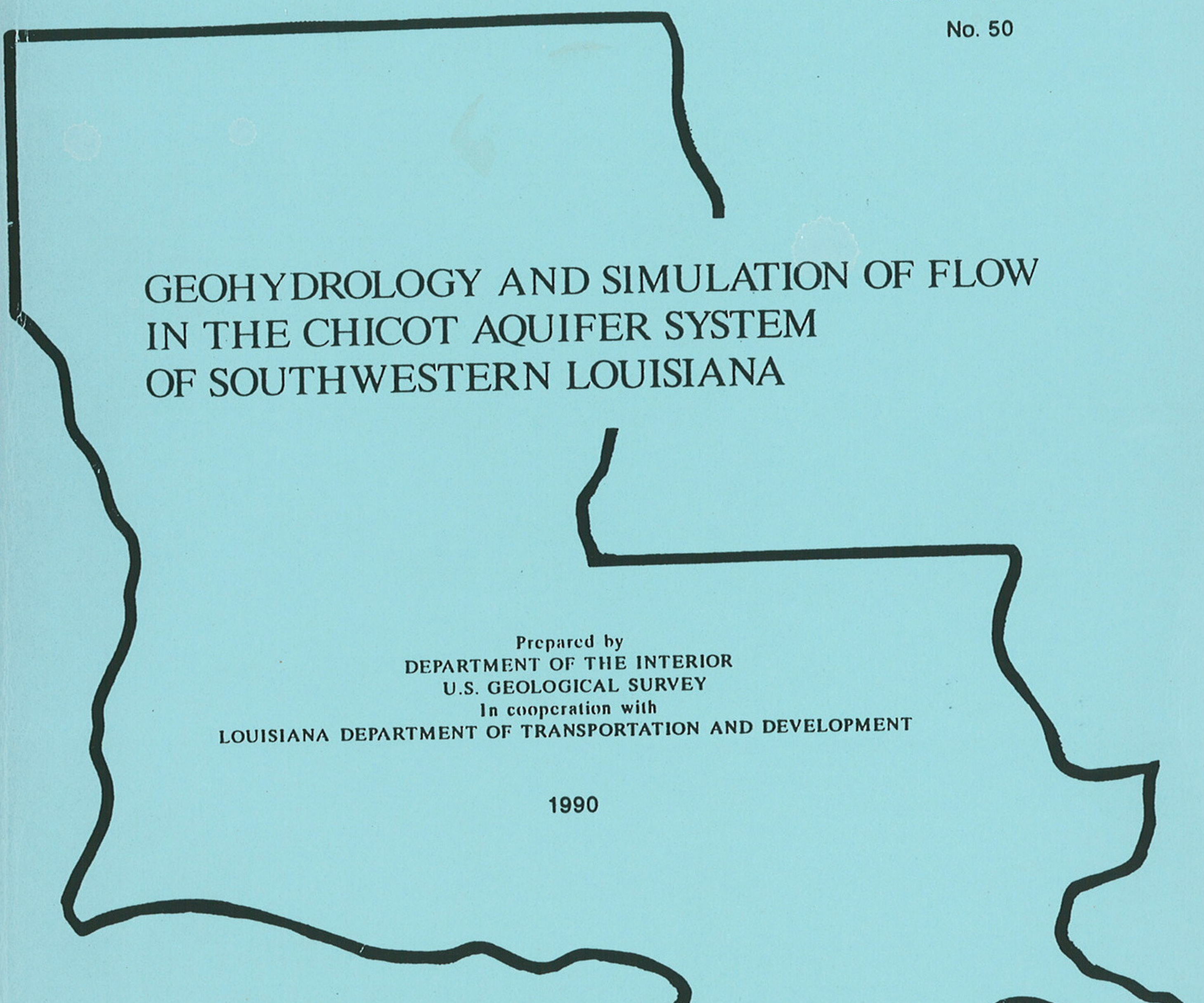
STATE OF LOUISIANA
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

WATER RESOURCES
TECHNICAL REPORT
No. 50



GEOHYDROLOGY AND SIMULATION OF FLOW IN THE CHICOT AQUIFER SYSTEM OF SOUTHWESTERN LOUISIANA

Prepared by
DEPARTMENT OF THE INTERIOR
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1990

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	43.81	cubic meter per second (m^3/s)

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."

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GEOHYDROLOGY AND SIMULATION OF FLOW IN THE CHICOT AQUIFER SYSTEM OF SOUTHWESTERN LOUISIANA

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ABSTRACT

Water was pumped at about 1 billion gallons per day from the Chicot aquifer system in 1980 by industry and rice growers in southwestern Louisiana. Records indicate that water levels in wells declined, on average, as much as 1 foot per year from 1900 to 1981 in the Lake Charles and rice-growing areas. Water levels rose, on average, 2 feet per year during the period 1982-85 because pumping rates during the period were reduced by 38 percent to 616 million gallons per day.

The Chicot aquifer system consists of a complex series of alternating beds of unconsolidated sand, gravel, silt, and clay. Under predevelopment conditions, ground-water flow was primarily from recharge areas where the aquifers outcrop in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes to discharge areas southward along the coast and eastward in the Atchafalaya River basin. As a result of development, flow throughout the aquifer system now converges to pumping centers in the rice-growing area and the Lake Charles area.

A digital ground-water flow model was developed to simulate flow in the Chicot aquifer system and to estimate the effects of pumping. In general, model-computed water levels compare closely with observed levels. Model results indicate that: (1) flow patterns in the Chicot aquifer system have been significantly altered downgradient from the area of outcrop since predevelopment; (2) approximately a fourfold increase (from 259 to 1,113 million gallons per day) in flow through the system has occurred since major development began; (3) water levels in and near the pumping centers declined, on average, 1 foot per year from predevelopment to 1981; (4) under 1981 conditions, vertical leakage was the largest component of recharge; and (5) water derived from aquifer storage is a relatively small part of flow in the entire system.

The model is least sensitive to changes in aquifer storage and most sensitive to changes in the vertical conductance of the confining units. Simulations indicate that, disregarding the possibility of saltwater encroachment in the aquifers along the coast, pumping rates 50 to 100 percent larger than the 1980 rate can be maintained indefinitely with the available recharge.

INTRODUCTION

The effects of the development of ground-water resources on the ground-water flow system in southwestern Louisiana paralleled the expansion of acreage devoted to the planting of rice. Rice was introduced into southwestern Louisiana during the 1800's. Initially, rice fields were irrigated using surface-water supplies such as streams, elevated canals, and tidal flow in the coastal marshes. Although irrigation wells were used at the turn of the century, they did not become widespread until after the "Great Depression" of the 1930's. Pumpage for industrial and municipal uses also began to increase rapidly in the late 1930's.

The average pumping rate from the Chicot aquifer system in Louisiana during 1980 was about 1 Bgal/d, which included about 850 Mgal/d for rice irrigation (Walter, 1982). Pumpage had declined by 38 percent to 616 Mgal/d by 1985 (Lurry, 1987, table 2) as a result of reduced pumpage for rice production and industrial use, and water levels rose, on average, 2 ft/yr from 1982 to 1985.

Today (1988) the Chicot aquifer system is the principle source of ground water for southwestern Louisiana and is the most heavily pumped aquifer system in the State. The present and future effects of pumpage on the aquifer system are of concern to State and local water-resources managers.

During the fall of 1984, the U.S. Geological Survey, in cooperation with the Louisiana Department of Transportation and Development, began a study to develop an understanding of the geohydrology of the Chicot aquifer system in southwestern Louisiana and to estimate the effects of pumping stress on the system.

Purpose and Scope

This report describes the geohydrologic setting of the Chicot aquifer system and the flow of water through the system, and provides estimates of the present and future effects of pumpage on the aquifer system. Previous studies of the Chicot aquifer system in Louisiana and Texas were used to establish the broad geologic and hydrologic framework of the study area. A digital flow model was used to simulate flow in the aquifer system under predevelopment and 1981 conditions and to estimate the effects of pumpage. Although southwestern Louisiana is the area of primary interest, the continuity of the ground-water flow system into Texas required that an area in southeastern Texas be included in some aspects of the investigation.

Description of Study Area

The study area (fig. 1) has been divided into four generalized regions for identification purposes in this report. These regions are: the Lake Charles area, the rice-growing area, the outcrop area, and the Atchafalaya River basin. Most of the study area consists of low-lying flatland at

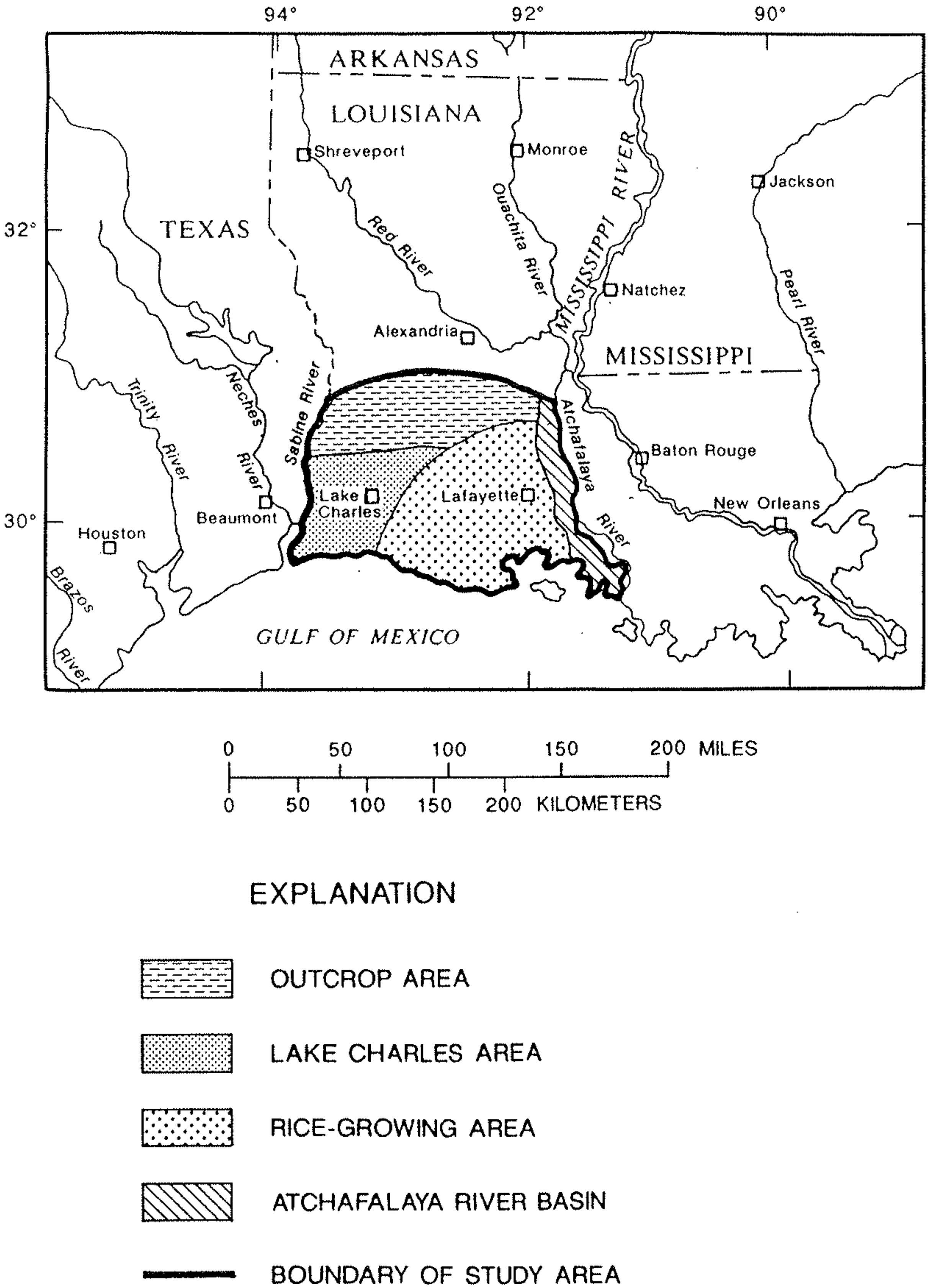


Figure 1.--Location of study area.

altitudes of less than 50 ft above sea level, but altitudes of 250 to 300 ft above sea level occur in the outcrop area.

Most of the study area is rural and used for growing rice. The proportion of land under cultivation decreases toward the coast because marshland extends from 30 to 50 mi inland from the shoreline. Lake Charles and Lafayette are the two largest cities within the study area. The Lake Charles industrial area lies within the Lake Charles area and covers about 60 mi^2 southwest of the city. Lake Charles supports a large petrochemical industry and commerce, whereas Lafayette is primarily a commercial center.

Climate of the region is warm and temperate with high humidity and frequent rains. The average annual temperature is 20 °C (U.S. Department of Commerce, 1984, p. 11). Temperatures range from highs of 38 °C in July and August to lows of -7 °C in December and January. The average annual rainfall is 59 in. and is relatively uniform from year to year (Jones and others, 1954, p. 15; Moody and others, 1986, p. 253). The region is primarily drained by the Sabine, Calcasieu, Vermilion, Mermentau, and Atchafalaya Rivers.

GEOHYDROLOGY

Geology

The Chicot aquifer system consists of a complex series of alternating beds of unconsolidated sand, gravel, silt, and clay. These beds are the result of two depositional environments. Sediments in the eastern part of the study area (the rice-growing area and the Atchafalaya River basin shown in fig. 1) were deposited by the ancestral Mississippi River that derived sediment and flow from the central part of the North American Continent. The sediments deposited in this environment are characterized by massive beds of coarse sand and gravel separated by relatively thin beds of clay (fig. 2).

Deposits in the western part of the study area (the Lake Charles area shown in fig. 1) were formed by rivers, such as the Calcasieu and Sabine, with smaller drainage areas and flow rates than the ancestral Mississippi River. The deposits formed by these rivers consist of thinner, finer grained beds of sand separated by relatively thick clays (figs. 3 and 4). Nyman (1984) describes the geohydrologic framework of the Chicot aquifer system within the study area in greater detail than presented in this report.

The Chicot aquifer system crops out in Louisiana in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes (fig. 5). The aquifer system thickens and dips to the south at a rate of about 30 ft/mi. Along the southern edge of the outcrop area water in the aquifer system becomes confined beneath surface clay that thickens to as much as 200 ft downdip. Clay within the aquifer system in the outcrop area generally is thin and discontinuous. Within parts of the outcrop and downgradient areas, the Chicot aquifer system consists of a single relatively massive sand.

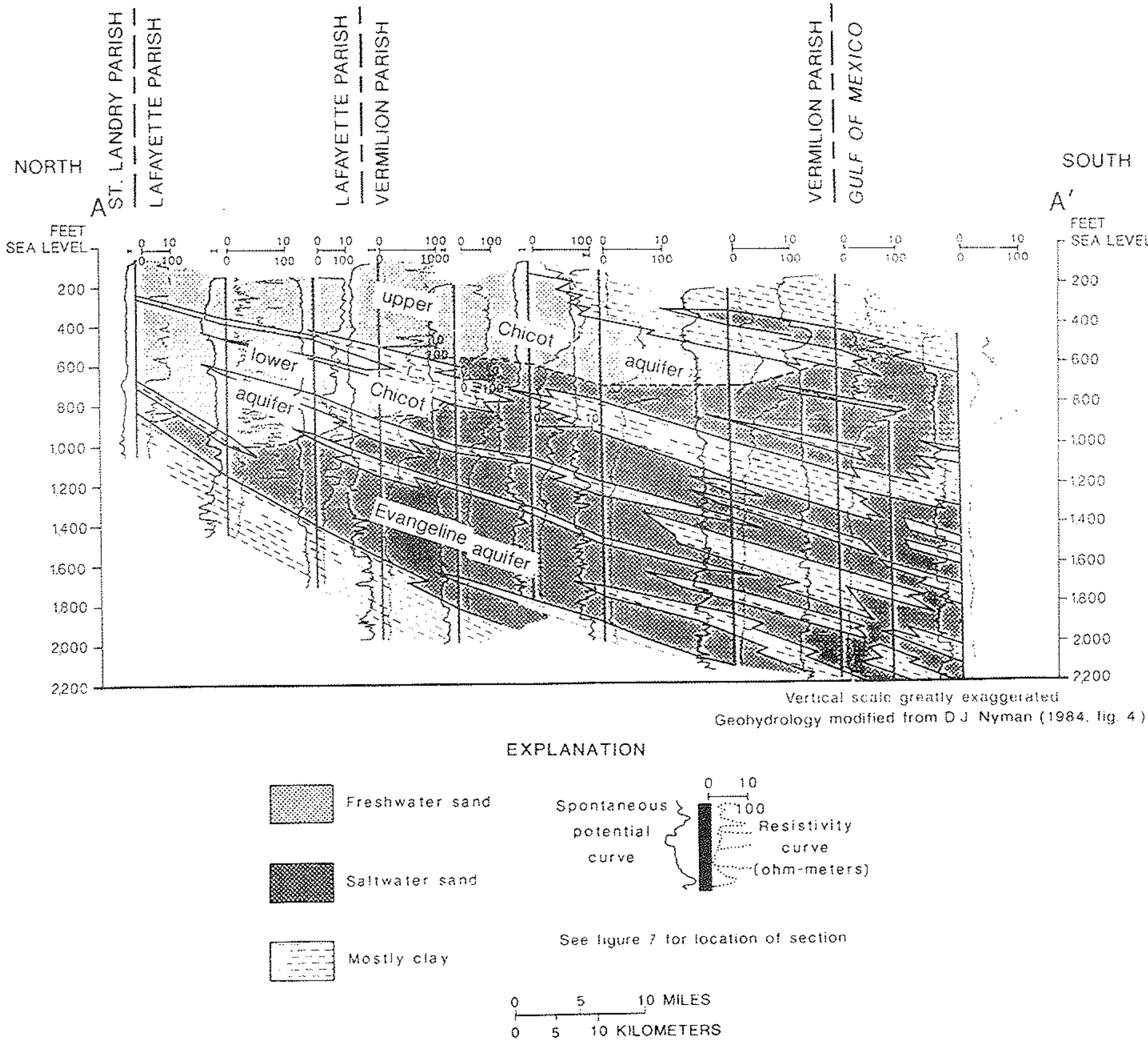


Figure 2.--Geohydrologic section in southwestern Louisiana, A-A'.

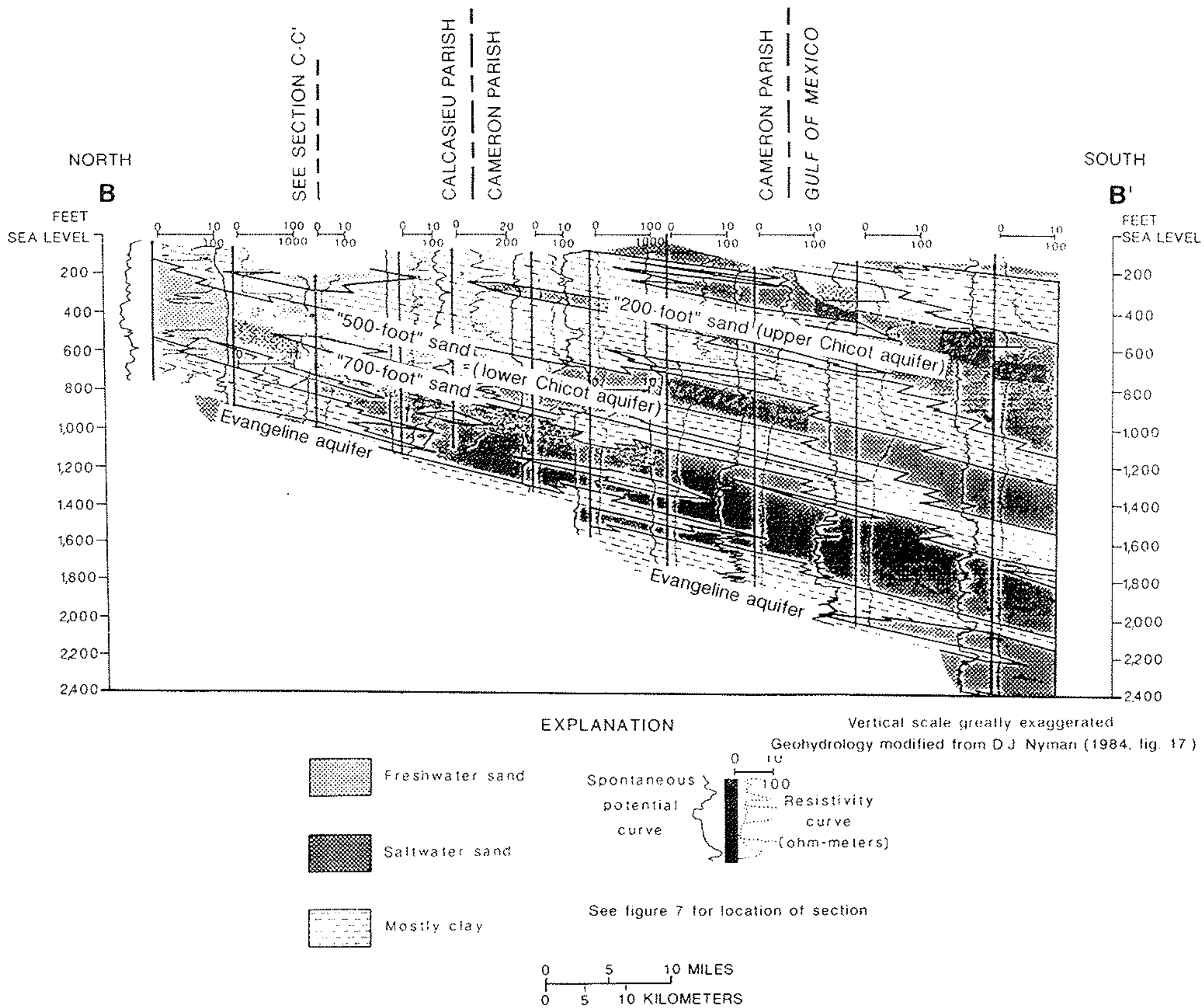


Figure 3.--Geohydrologic section in southwestern Louisiana, B-B'.

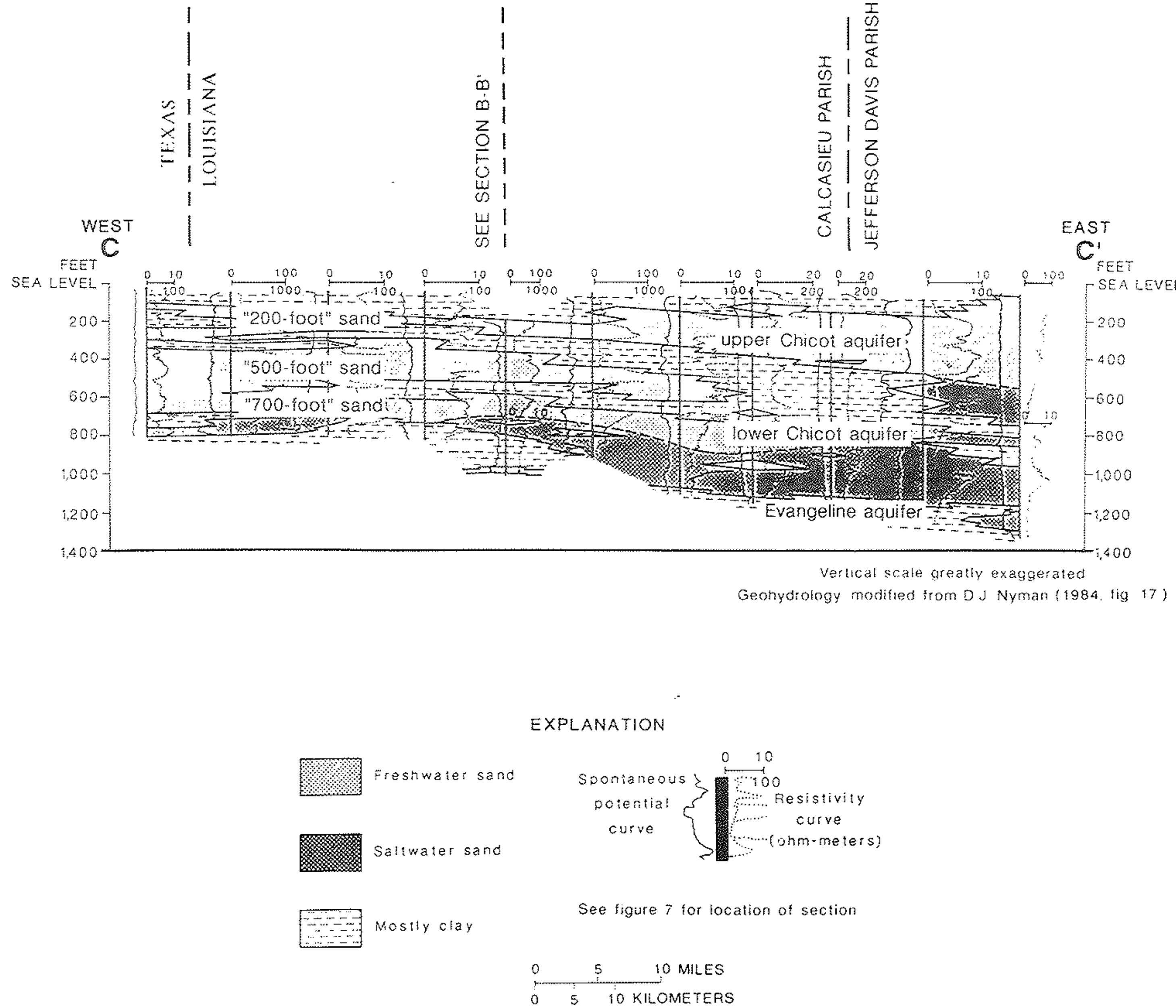
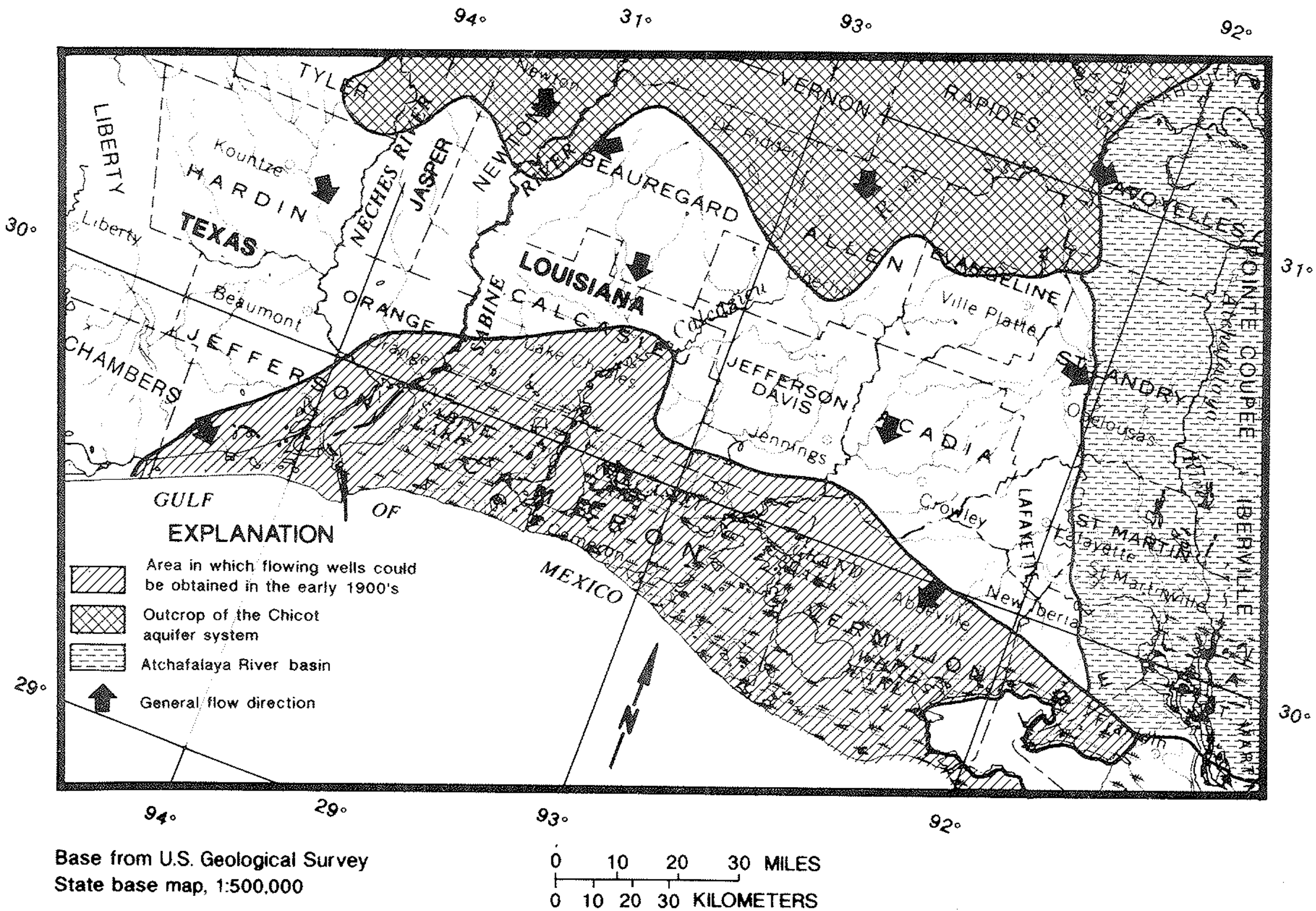


Figure 4.--Geohydrologic section in southwestern Louisiana, C-C'.



Base from U.S. Geological Survey
State base map, 1:500,000

Figure 5.--Generalized predevelopment flow paths of water in the Chicot aquifer system.

The range of thickness for the Chicot aquifer system within the study area is given in table 2. The southern limit of freshwater in the upper Chicot aquifer occurs near the coastline. This study includes that part of the Chicot aquifer system that contains water with dissolved-solids concentration up to 10,000 mg/L (milligrams per liter).

The lower Chicot aquifer is hydrologically similar to the upper Chicot aquifer, but the entire thickness of the lower Chicot aquifer contains saltwater south of the Calcasieu-Cameron Parish line. Nyman (1984) describes in detail the occurrence of saltwater in the Chicot aquifer system and presents illustrations showing the areal and vertical extent of freshwater in individual aquifers.

Previous investigators have divided the Chicot aquifer system in different ways. Table 1 shows the correlation between the aquifers and geologic units described in previous reports and the subdivisions currently used by the U.S. Geological Survey (Darwin Knochenmus, U.S. Geological Survey, written commun., 1988) which are used in this report. The Chicot aquifer system is divided into two aquifer units, the upper and lower Chicot aquifers. Further descriptions of these aquifers and their relation to units described by other investigators are given below.

In the rice-growing area and the Atchafalaya River basin (fig. 1) Harder and others (1967, p. 23) divided the Chicot aquifer system into two major units, the "upper sand unit" (upper Chicot aquifer in this report) and an undifferentiated lower unit (lower Chicot aquifer in this report). The upper Chicot aquifer contains mostly coarse sand grading to gravel near the base of individual beds. The sand beds generally are several hundred feet thick and are separated in places by thick discontinuous clays (figs. 2 and 4).

Jones (1950) divided the Chicot aquifer system in the Lake Charles industrial area into three major aquifers: the "200-foot" sand, "500-foot" sand, and "700-foot" sand. The names were based on the average depths of wells completed in these aquifers. The "200-foot" sand is considered part of the upper Chicot aquifer in this report, whereas the "500-foot" and "700-foot" sands are considered part of the lower Chicot aquifer.

The "500-foot" sand is the most important of the aquifers in the Lake Charles industrial area because it yields most of the water for the petrochemical industry and public supply. The "500-foot" sand ranges from 170 to 200 ft in thickness in the industrial area (Harder, 1960, p. 30). The aquifer is composed of fine sand at the top, grading to coarse sand and gravel near the base. The transition from freshwater to saltwater occurs in Cameron Parish near the Calcasieu-Cameron Parish line.

The "700-foot" sand contains saltwater in the southern two-thirds of Calcasieu Parish and is used less than the "500-foot" sand. The "700-foot" sand is pumped only in the northern part of the industrial area because saltwater occurs higher in the aquifer to the south and because of the risk of saltwater upconing to large-capacity wells. Lithology of the "700-foot" sand ranges from fine sand at the top to coarse sand at the bottom (Harder, 1960, p. 34). In the Lake Charles industrial area the aquifer is about 220 ft

Table 1.--Correlations between geohydrologic units and model layers used in this report and geologic and geohydrologic units described by previous investigators

<table>
<tr><th rowspan="2">System</th><th rowspan="2">Series</th><th rowspan="2">Wesselman (1971) south-eastern Texas</th><th rowspan="2">Jones (1950)[a]</th><th colspan="2">Harder (1960)[b]</th><th rowspan="2">Harder and others (1967)[c]</th><th colspan="3">Nyman (1984)</th><th colspan="3">This report</th></tr>
<tr><th>Forma-tion</th><th>Hydro-logic unit</th><th colspan="2">Lake Charles industrial area</th><th>East of Lake Charles</th><th colspan="2">Geo-hydrologic unit</th><th>Model layer</th></tr>
<tr><td rowspan="5">Quaternary</td><td>Holocene</td><td rowspan="2"></td><td rowspan="2"></td><td></td><td></td><td></td><td rowspan="5">Chicot aquifer system</td><td rowspan="2">Alluvium</td><td rowspan="2">Alluvium, Atchafalaya aquifer, and Abbeville unit</td><td rowspan="5">Chicot aquifer system</td><td rowspan="3">Upper Chicot aquifer</td><td rowspan="3">2</td></tr>
<tr><td rowspan="4">Pleistocene</td><td>Prairie</td><td>Chicot shallow</td><td>Shallow sand</td></tr>
<tr><td>Upper aquifer</td><td>"200-foot" sand</td><td>Montgomery</td><td>"200-foot" sand</td><td>"Upper sand unit"</td><td>"200-foot" sand</td><td>"Upper sand"</td></tr>
<tr><td rowspan="2">Lower aquifer</td><td>"500-foot" sand</td><td>Bentley</td><td>"500-foot" sand</td><td rowspan="2">Undifferentiated</td><td>"500-foot" sand</td><td rowspan="2">Undifferentiated "lower sand"</td><td rowspan="2">Lower Chicot aquifer</td><td>3</td></tr>
<tr><td>"700-foot" sand</td><td>Williana</td><td>"700-foot" sand</td><td>"700-foot" sand</td><td>4</td></tr>
<tr><td rowspan="3">Tertiary</td><td>Pliocene and Miocene</td><td>Evangeline aquifer</td><td rowspan="3"></td><td>Foley</td><td>Evangeline aquifer</td><td>Evangeline aquifer</td><td colspan="2">Evangeline aquifer</td><td>Evangeline aquifer</td><td colspan="2">Evangeline aquifer</td><td>5 (base of model)</td></tr>
<tr><td rowspan="2">Miocene</td><td>Burkeville aquiclude</td><td rowspan="2">Fleming</td><td rowspan="2"></td><td rowspan="2"></td><td colspan="2" rowspan="2">Jasper aquifer</td><td rowspan="2"></td><td colspan="2" rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Jasper aquifer</td></tr>
</table>

[a] Lake Charles industrial area.
[b] For Lake Charles area.
[c] For area east of Lake Charles (rice-growing area and Atchafalaya River basin).

thick. The Chicot aquifer system in Texas (adjoining the study area) is described by Wesselman (1967; 1971). Aquifer conditions there are similar to those in the Lake Charles area.

The upper Chicot aquifer is as much as 200 ft thick in parts of the study area but generally is less than 100 ft thick. According to Harder (1960, p. 27), this aquifer in Calcasieu Parish grades from a fine or medium sand at the top to coarse sand, often with gravel, at the base. The aquifer is discontinuous, varying greatly in thickness and texture. Saltwater occurs in the lower part of the upper Chicot aquifer near the Calcasieu-Cameron Parish line from Calcasieu Lake (fig. 3) westward into Texas and eastward to St. Martin Parish, Louisiana.

The Evangeline aquifer underlies the Chicot aquifer system throughout the study area. The Evangeline aquifer is included in this study because it is a source of water for the Chicot aquifer system. The Evangeline aquifer ranges from 400 to 900 ft in thickness beneath the study area and contains an alternating sequence of relatively thin sand and thick clay beds. Individual sand beds are thinner and finer grained than those of the Chicot aquifer system (Whitfield, 1975, p. 15; Turcan and others, 1966, p. D235). Sand in the Evangeline aquifer ranges from fine to coarse. The Evangeline aquifer contains freshwater in the northern third of the study area.

Clays that confine the Chicot aquifer system thicken consistently from the outcrop to the coastline and range from 1 to 200 ft in thickness. Clays between and within the aquifer units generally are thin from west to east, and clays are thin and discontinuous between Lake Charles and the Atchafalaya River. The clay beds consist primarily of mixed layer clay and smectites, but silt-sized quartz is commonly an important constituent.

Water Quality

Freshwater in the Chicot aquifer system is predominantly a calcium-bicarbonate type (Nyman, 1989). Fresh ground water generally is suitable for irrigation and industrial use, but locally high iron concentrations (greater than 0.3 mg/L) may require treatment for public supply (Moody and others, 1986, p. 276). Based on analyses of 653 samples of water from the Chicot aquifers throughout the study area, hardness ranges from 3 to 750 mg/L and averages about 130 mg/L (D.J. Tomaszewski, U.S. Geological Survey, written commun., 1989).

Ground-Water Flow System

Predevelopment Conditions

Before extensive ground-water development, the primary source of recharge to the Chicot aquifer system was precipitation on the outcrop areas. Most of this recharge was discharged locally to perennial streams and rivers or by evapotranspiration. Water that was not discharged locally entered the aquifer system as recharge. This water moved downgradient toward discharge areas in the Atchafalaya, Sabine, and lower Vermilion River basins and the coastal marshes. Recharge rates are relatively high in the outcrop area because surface clay is thin or absent. According to Jones and others (1956, p. 228), a study from 1946 to 1951 of the Bundick and Whiskey Chitto Creeks in the outcrop areas in Allen and Beauregard Parishes indicated a recharge rate of about 0.8 in/yr in an area where little ground-water development had taken place.

Under predevelopment conditions, water in the confined downgradient parts of the aquifer system discharged upward to shallower aquifers or the surface because hydraulic head generally increased with depth. Head increased with depth because each successively deeper aquifer in the system crops out farther north at a higher altitude. Figure 5 shows highly generalized lateral flow paths in the Chicot aquifer system under predevelopment conditions. Upward flow was greatest through sandy interconnections where confining clays between the aquifers are thin or missing. Natural ground-water discharge occurred in the coastal wetland areas and along the Atchafalaya, Mermentau, lower Vermilion, and Sabine Rivers, where water moved upward from the aquifer through the surface clays. Discharge was most concentrated where the Atchafalaya and lower Vermilion Rivers have breached the surface clays confining the Chicot aquifer system. The part of the coastal area that received natural ground-water discharge was defined approximately by Harris and others (1905) as the part of coastal Louisiana and Texas where wells flowed in the early 1900's. (See fig. 5.)

Pumpage

The pumpage of water for irrigation, municipal, and industrial purposes is the largest source of stress on the Chicot aquifer system and the Evangeline aquifer in southwestern Louisiana. Rice irrigation utilizes most of the water pumped. Annual rates of pumping for all purposes from the Chicot aquifer system and the upper Evangeline aquifer are shown in figure 6 for the period 1946-85. The total ground-water pumpage for 1985 is shown but was not used in the development of the digital flow model because detailed pumpage data were not available.

Irrigation

During 1980 nearly 90 percent of the ground water pumped in southwestern Louisiana was used for rice irrigation. About 500,000 acres of rice were planted in 1980. Of this acreage, 60 percent was irrigated with ground water and the remainder with surface water (Hill and others, 1981). Almost all ground water used for irrigation comes from the upper Chicot aquifer. Both ground water and surface water are used in some areas and estimation of the ground-water pumpage is difficult. Irrigation pumpage data from 1900 to 1960 used in this report were originally compiled for an analog model for southwestern Louisiana and eastern Texas (A.L. Zack and A.N. Turcan, U.S. Geological Survey, written commun., 1975).

Annual agricultural reports (Fielder and Parker, 1963; Fielder and Guy, 1978; Fielder and Nelson, 1983) supplied the acreage irrigated from 1960

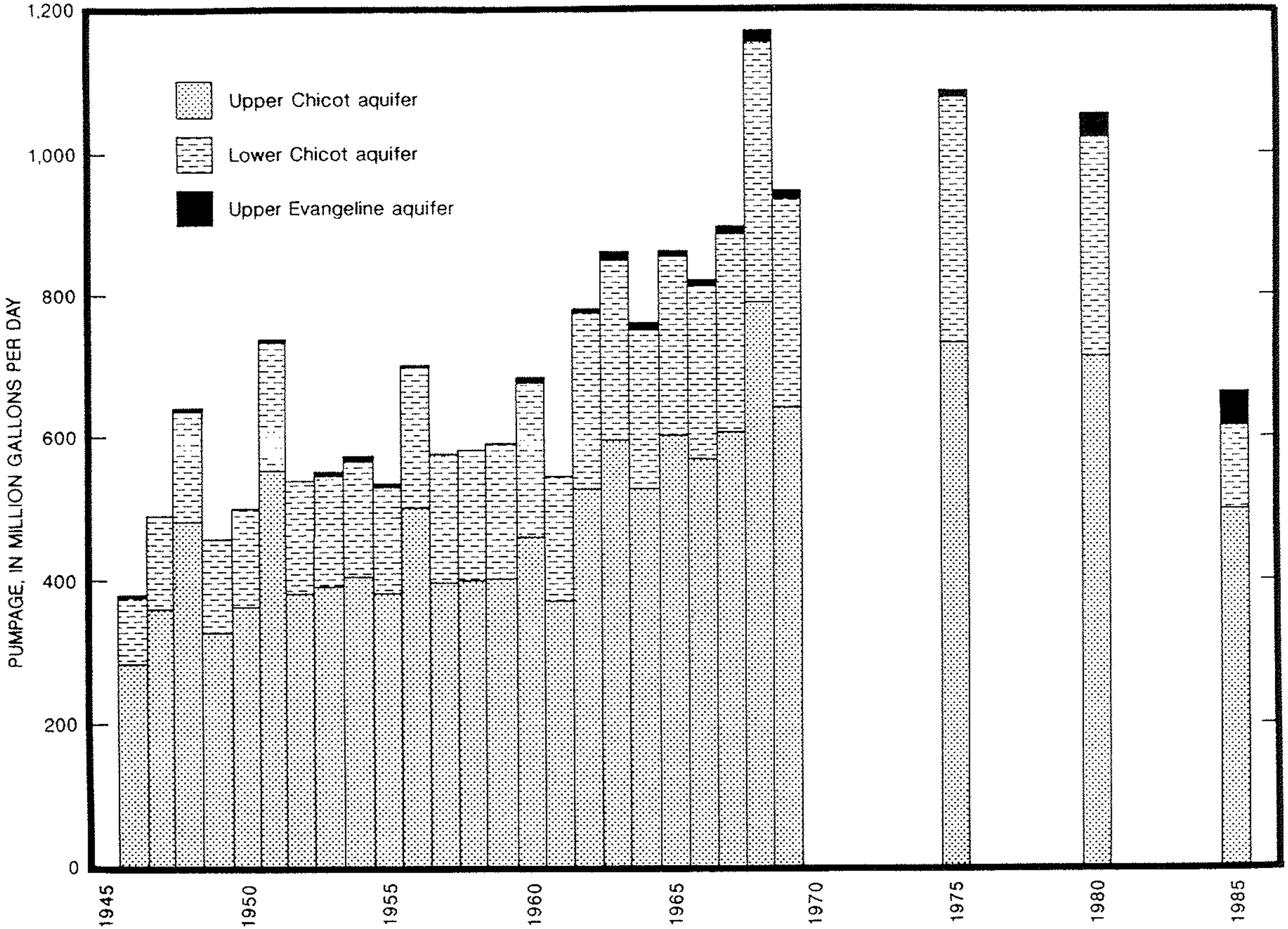


Figure 6.--Total pumpage from the Chicot aquifer system and the upper Evangeline aquifer within the study area.

to 1980. Remote-sensing techniques, established by Neal (1980), differentiated the acreage irrigated by ground water from that irrigated by surface water. Acreage estimates used to compute irrigation withdrawals were made from a photograph taken April 28, 1978, from the Landsat satellite (Eversull, 1986). By relating the distribution of acreage irrigated by ground water in 1978 to the annual rice acreage planted, an estimate of ground-water irrigated acreage was made for each year. The estimated acreage times the application rate (the average quantity of water applied per acre per irrigation season) provided the annual irrigation usage from 1960 to 1980. The application rate was estimated using a relation between rainfall and ground-water application rate developed by Zack (1971, fig. 2).

Industrial and Municipal

Industrial and municipal pumpage data have been collected in Louisiana at 5-year intervals in connection with State and national water-use surveys. These data are collected individually for each user, so pumpage can be assigned to a specific location.

About 70 percent of the industrial pumpage in southwestern Louisiana is from the "500-foot" sand for use by the petrochemical industry in the Lake Charles industrial area. The 5-year interval pumpage records for the Lake Charles area indicate that industrial and municipal pumpage averaged 75 Mgal/d in 1965, 100 Mgal/d in 1970, and 85 Mgal/d in 1975 and 1980.

Effects of Development

The first potentiometric map documenting the effect of pumpage of the Chicot aquifer system was based on data collected in 1944 (Jones and others, 1956, pl. 16). This map (fig. 7) shows a broad trough in the potentiometric surface in the rice-growing area caused by pumping for irrigation and a cone of depression in the potentiometric surface at Lake Charles caused by pumping for the petrochemical industry. Records indicate that water levels in wells declined, on average, about 1 ft/yr from 1900 to 1981 in the Lake Charles and rice-growing areas.

As water levels declined, less water was discharged locally and flow increased southward toward the pumping centers. Also, as water levels declined beneath the coastal marshes, wells ceased flowing and the former discharge areas became recharge areas. Movement of water through the surface clays reversed, and water began moving downward from the marshes to recharge the aquifer system. The Atchafalaya River also became a source of recharge for the Chicot aquifer system, particularly where the surface clays had been breached and where the river is in direct contact with the upper Chicot aquifer (Jones and others, 1956).

Vertical leakage of water also increased through the lower confining clays. Similarities in water-level fluctuations in the upper and lower Chicot aquifers in the rice-growing area near Crowley, in Acadia Parish, Louisiana (fig. 8), demonstrate the good hydraulic connection between aquifers in the rice-growing area. In the vicinity of observation well

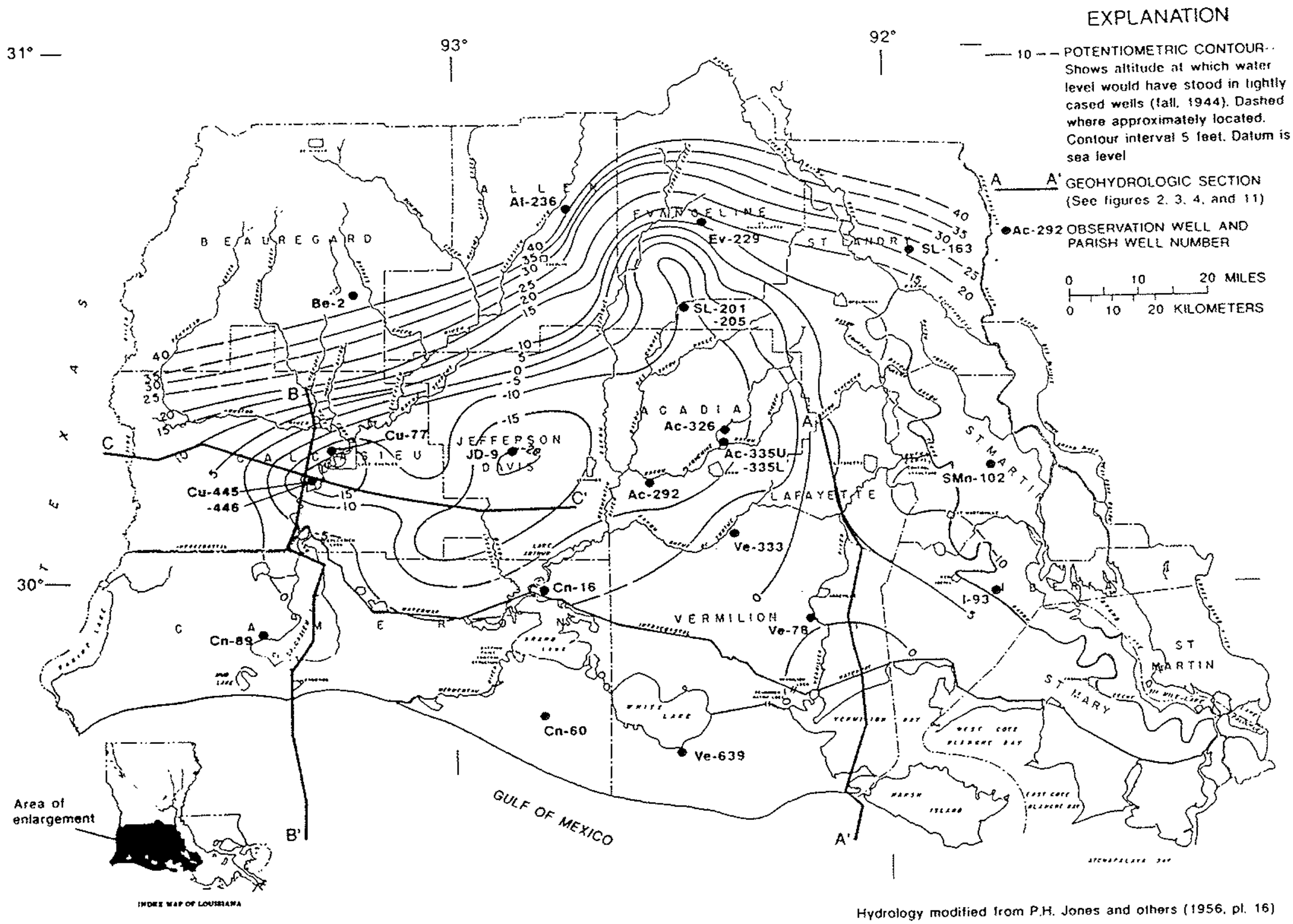
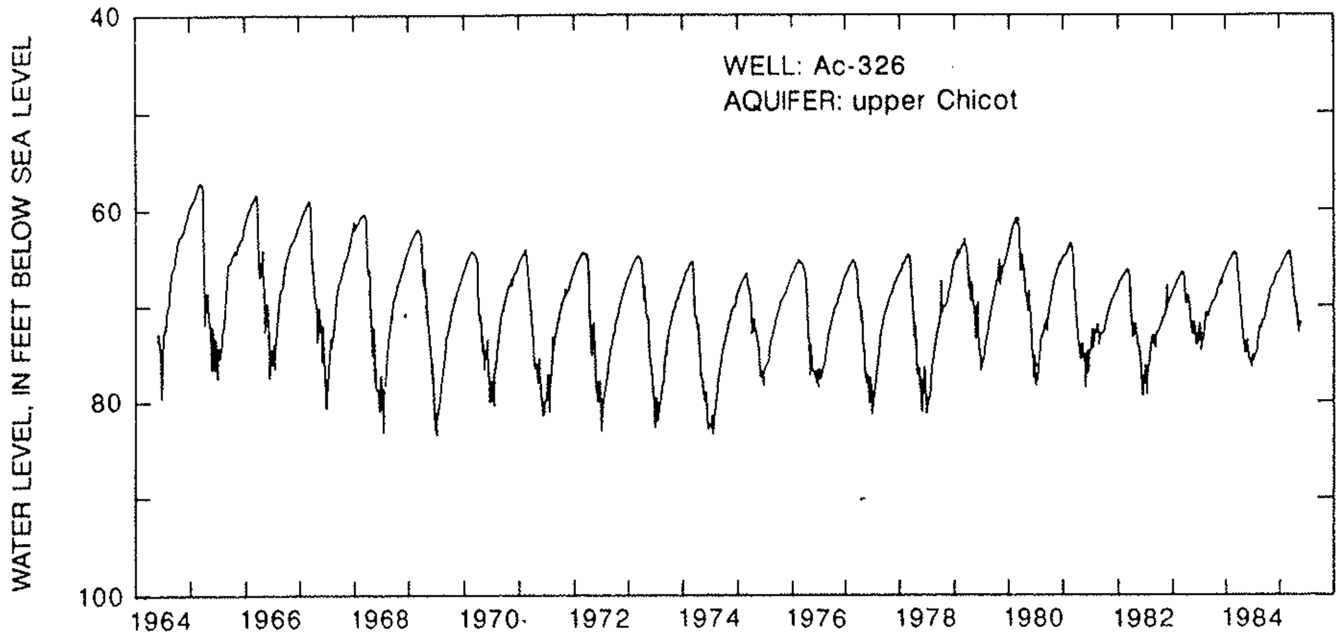


Figure 7.--The lowest water levels in the Chicot aquifer system during the fall of 1944.



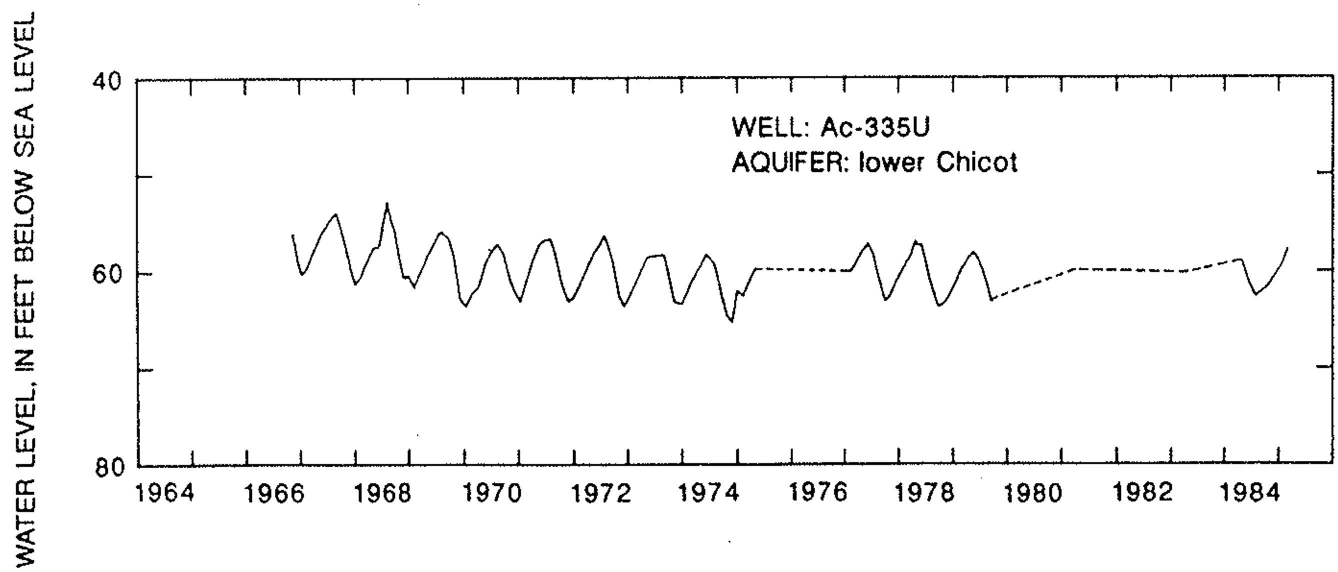


Figure 8.--Comparison of water levels in the upper and lower Chicot aquifers in Acadia Parish.

Ac-335U (fig. 7), there is no pumping for rice irrigation from the lower Chicot aquifer. However, seasonal water-level fluctuations caused by irrigation pumpage from the upper Chicot aquifer, reflected in the hydrograph of observation well Ac-326, are apparent in the hydrograph of well Ac-335U that was screened in the lower Chicot aquifer.

In the Lake Charles area, the "500-foot" sand is the most heavily pumped aquifer and has the lowest water levels in the Chicot aquifer system. Average pumpage from the "500-foot" sand is more than 10 times that from the "700-foot" sand and about 30 times greater than that from the "200-foot" sand. During 1980, pumpage from the "500-foot" sand was more than 40 Mgal/d in the vicinity of well Cu-445, whereas pumpage from the "700-foot" sand was less than 1.0 Mgal/d in the vicinity of well Cu-446 (fig. 7). A comparison of water levels and water-level fluctuations in these two wells in the "500-foot" and "700-foot" sands in the southern part of the industrial area (fig. 9) indicates a good hydraulic connection. Vertical leakage to the "500-foot" sand occurs from both the "200-foot" and "700-foot" sands.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

Description of Model

A finite-difference, digital ground-water flow model was developed to simulate flow in the Chicot aquifer system under predevelopment conditions and to estimate the effects of various simulated pumping stresses imposed on the system under current and future conditions. As previously discussed, the Chicot aquifer system is a composite of interbedded sands and clays where vertical flow components are as important as horizontal ones. Considering the nature of this system, a three-dimensional model was deemed necessary for an accurate simulation.

The U.S. Geological Survey's modular finite-difference model (McDonald and Harbaugh, 1988) was selected to simulate flow in the Chicot aquifer system. This model is well documented, has been tested on a wide range of problems, and has the features needed to simulate the Chicot aquifer system under both steady-state and transient-flow conditions.

The use of this finite-difference model, or any other, requires the discretization of the system into a series of blocks. This breakdown is done in layers, rows, and columns (fig. 10). The sizes of these blocks were based on the local stresses imposed on the system and the degree of resolution desired in the model. Relatively large blocks were used in this model because it was designed to describe a large regional system. This coarse discretization causes some discrepancies to occur between observed and calculated water levels in highly stressed areas where large, local water-level variations exist; however, use of smaller blocks would not have enhanced the understanding of the regional flow system.

Five layers were used in this model. Layer 1 is used to represent the boundary of the aquifer system as described in the section Boundary Conditions. Most of the Chicot aquifer system could be simulated by one layer

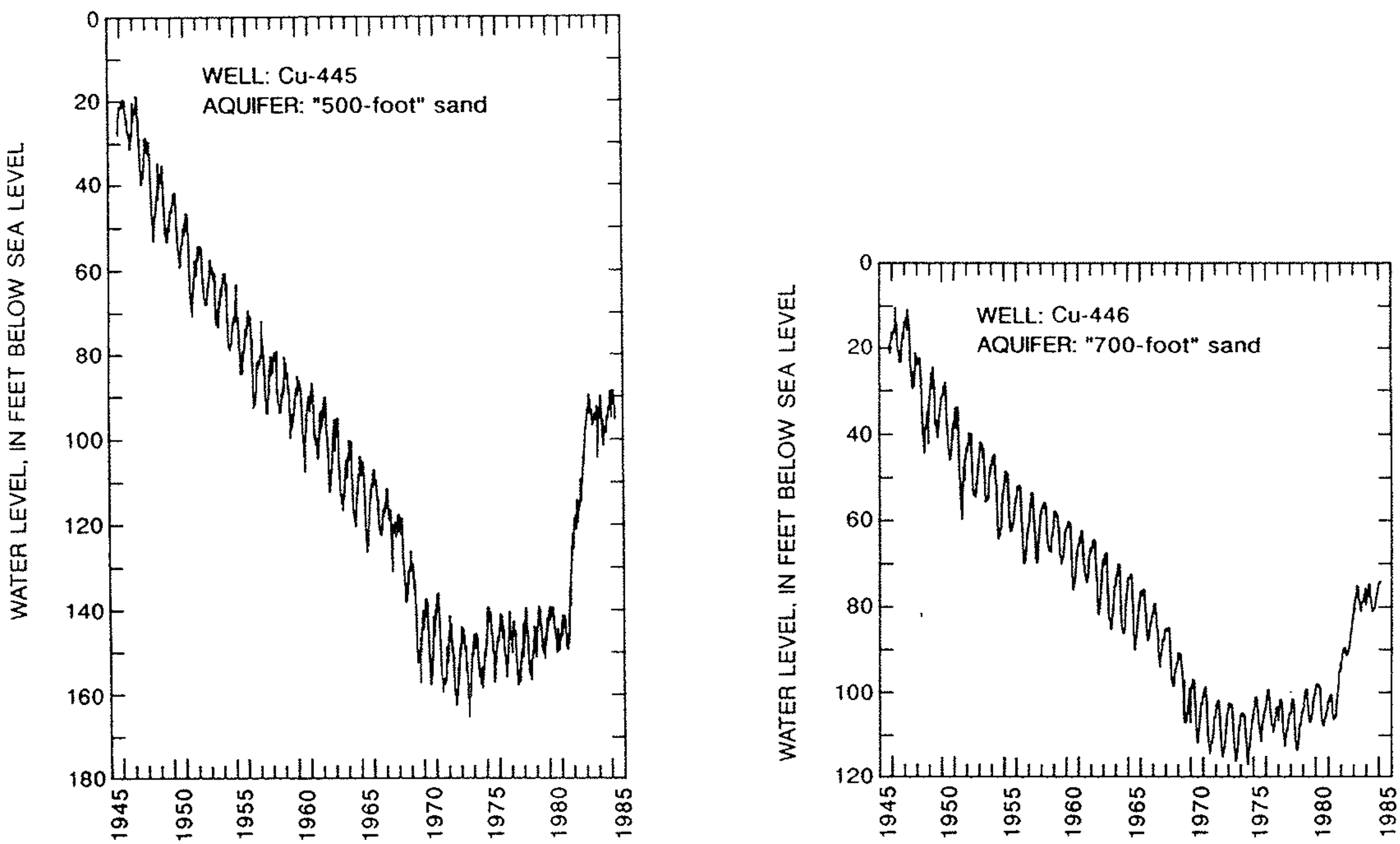


Figure 9.--Comparison of water levels in the "500-foot" and "700-foot" sands in the Lake Charles area, Calcasieu Parish.

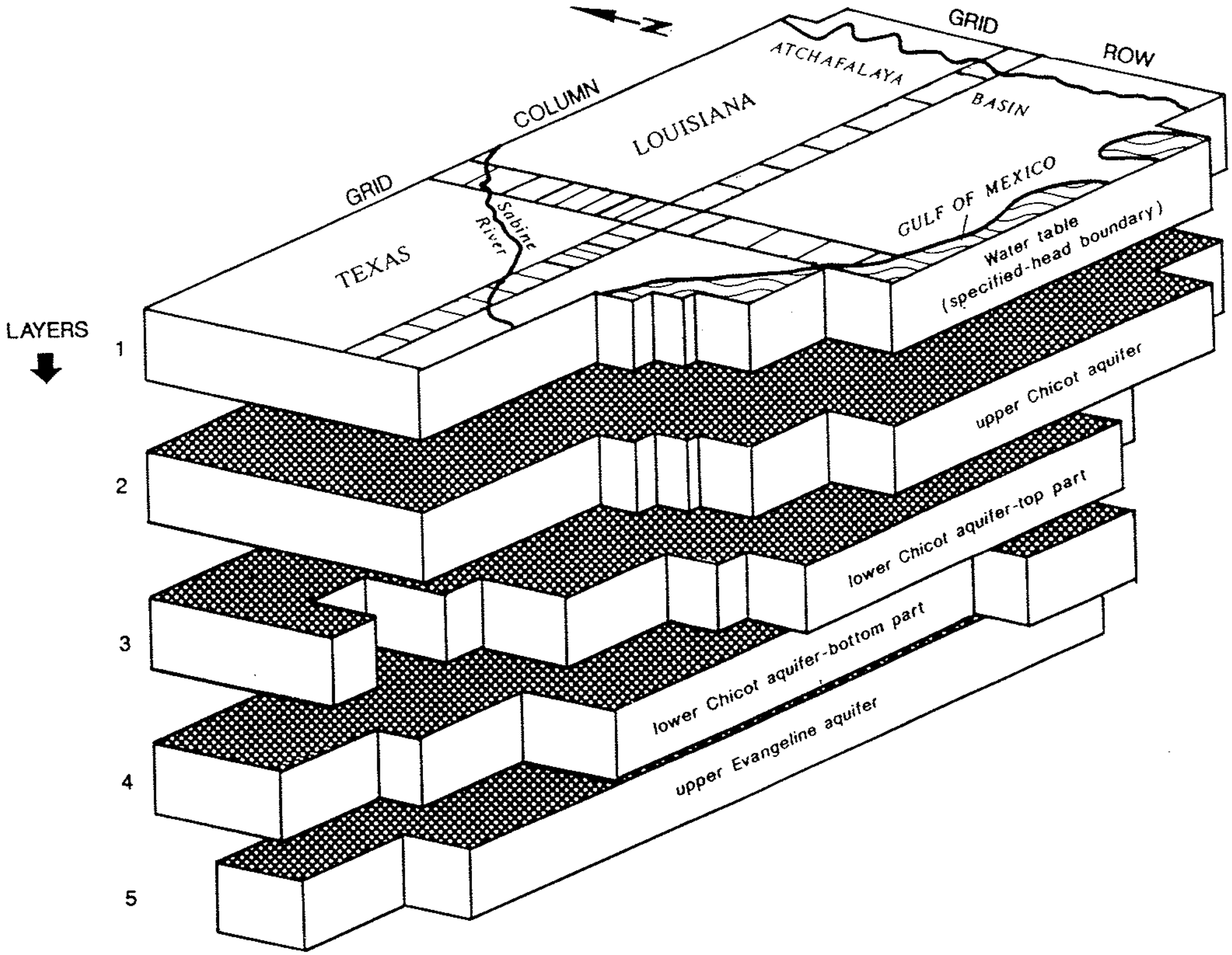


Figure 10.--Generalized schematic diagram of the digital model used to describe the Chicot aquifer system.

because large areas consist of a single massive sand. However, the aquifer system was simulated as three layers in this model because in the Lake Charles area the aquifer system consists of three distinct hydrologic units, the "200-, 500-, and 700-foot" sands which are separated by confining clay beds. In the model, layer 2 represents the upper Chicot aquifer which includes the "200-foot" sand in the Lake Charles area. Layer 3 represents the upper part of the lower Chicot aquifer and the "500-foot" sand. Layer 4 represents the lower part of the lower Chicot aquifer and the "700-foot" sand. Layer 5 represents the upper part of the Evangeline aquifer. Layer 5 is used in the model only as a water source or sink for the Chicot aquifer system, but lateral flow and potential are calculated in the layer. This study did not include a simulation of flow in the entire Evangeline aquifer. The relation of the model layers to geohydrologic units is shown in a north-south section through the Lake Charles area (fig. 11) and in table 1.

The confining units between sands are represented in the model by leakance values assigned between each model layer. Leakance is the vertical hydraulic conductivity of the clay bed divided by the thickness of the bed. The leakance values control the vertical flow of water between model layers.

The model grid has 14 rows of 21 columns and measures 197 mi east-west by 100 mi north-south (fig. 12). The grid is oriented parallel to the outcrop of the Chicot aquifers in Louisiana. Variably-spaced blocks were used to obtain more detail in highly stressed areas such as Lake Charles. The blocks range in size from 16 to 169 mi^2 with the largest blocks being located at the periphery of the model. The large blocks are acceptable because they are located in areas of little or no stress and beyond the main areas of interest. Values of aquifer hydraulic properties assigned to the center of each block, defined as the node, represent an average of the values within the block. Some of the blocks are inactive because they are in areas where the aquifer represented by its corresponding layer does not exist (fig. 12). Model layer 2, which represents the upper Chicot aquifer, is the most areally extensive layer, whereas model layer 5, which represents the upper Evangeline aquifer, is the least extensive (fig. 13).

Boundary Conditions

Proper representation of model boundaries is one of the most important aspects in the simulation of an aquifer system. Model boundaries must represent actual hydrologic boundaries that affect an aquifer system as accurately as possible or be far enough away from any simulated stresses to not significantly affect the simulation results.

The upper boundary of the model consists of a specified-head layer (layer 1) overlying the 4 layers representing the Chicot aquifer system and the upper Evangeline aquifer. The water level assigned at each node in layer 1 is the long-term average altitude of the water table at the node. Layer 1 acts as a source or sink for all water entering or leaving the flow system, except for flow across other boundaries and water removed by pumpage. Use of a specified-head upper boundary is acceptable because there has been no

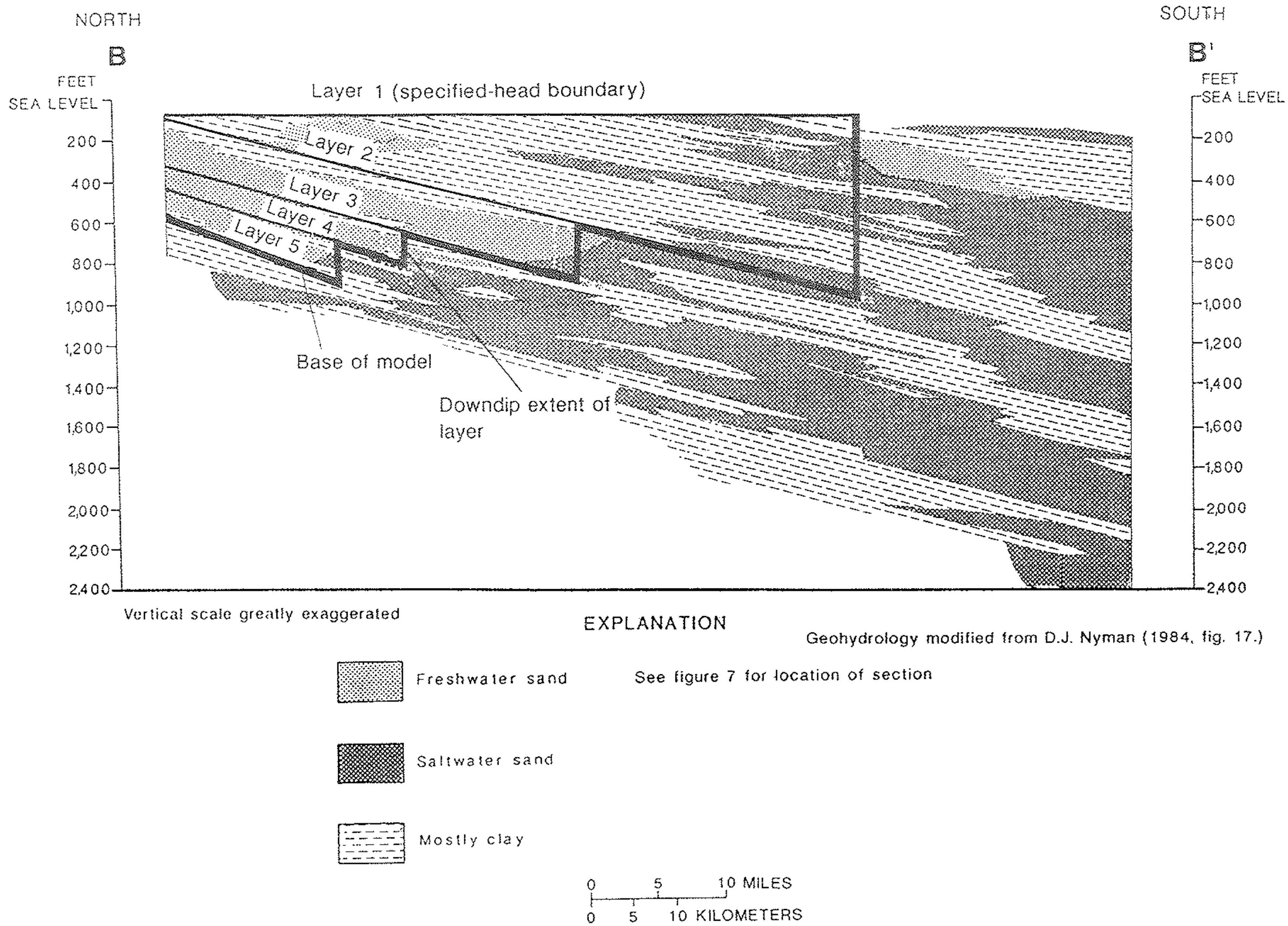


Figure 11.--Geohydrologic section B-B' in southwestern Louisiana showing layering scheme used in modeling the Chicot aquifer system.

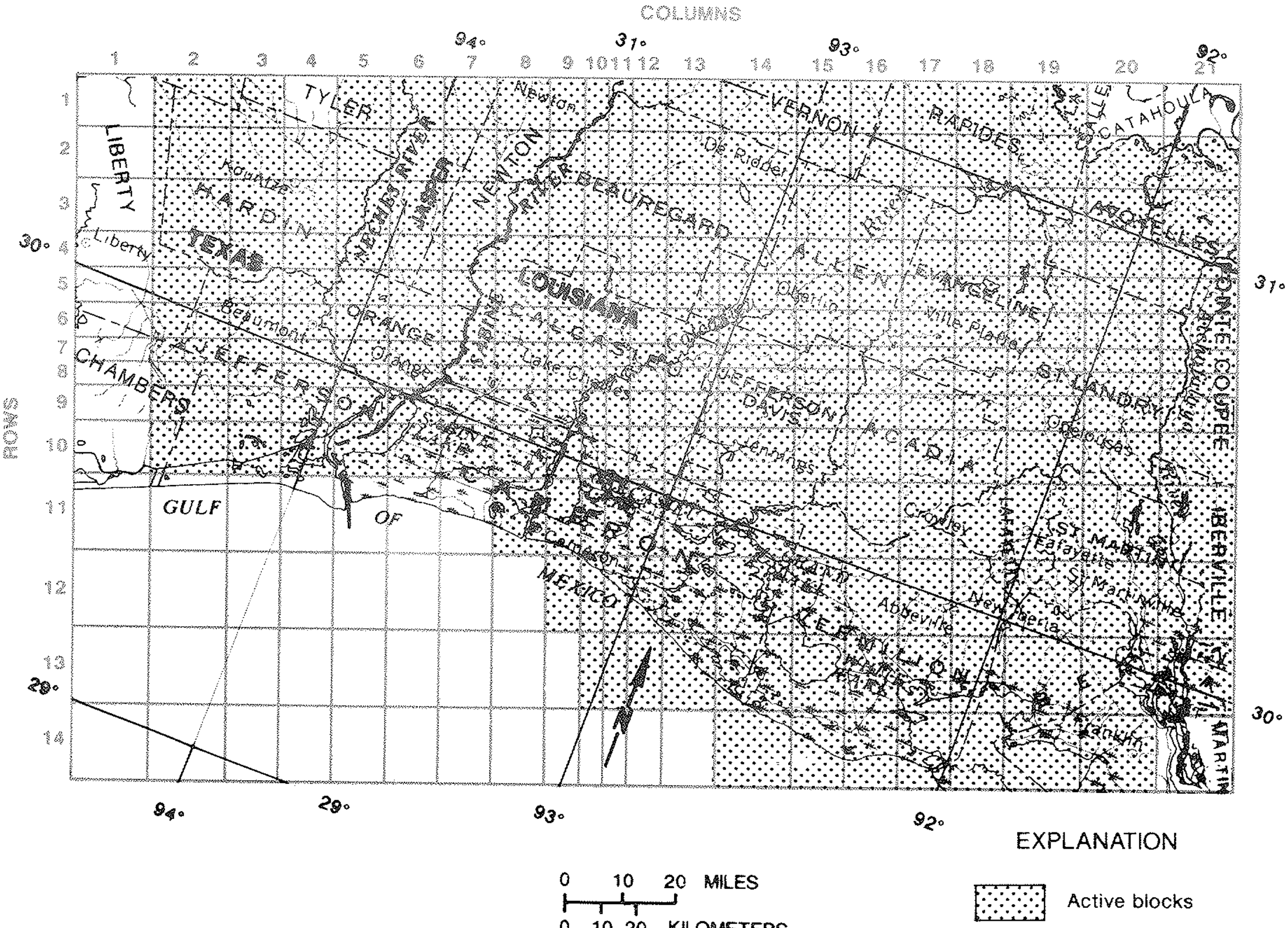


Figure 12.--Grid and areal extent of the model.

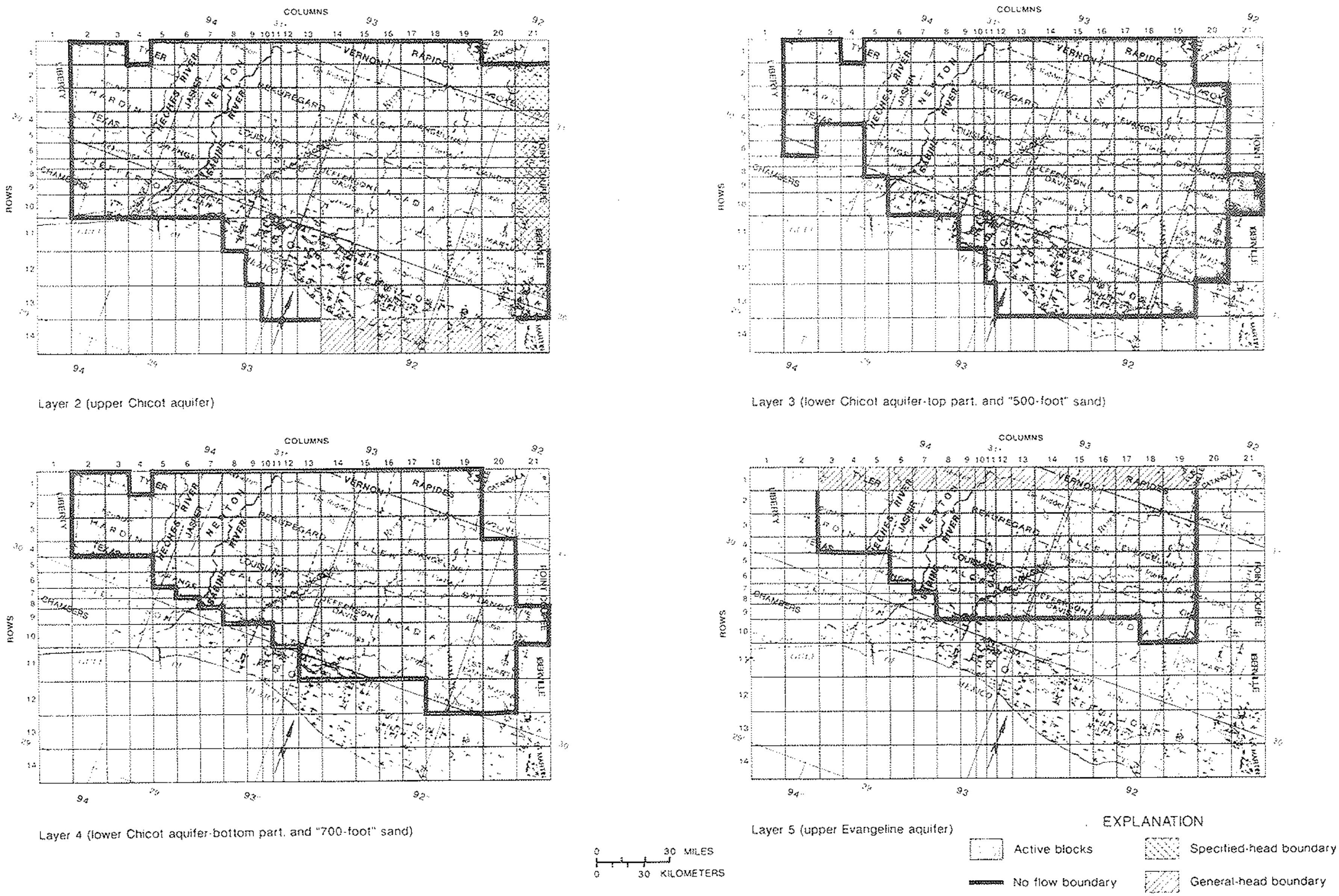


Figure 13.--Boundary conditions and extent of model for layers 2 through 5.

significant decline in water-table altitudes as a result of pumping through 1981. Streams draining the recharge areas have high base flows, indicating that recharge is being rejected by the Chicot aquifer system under 1981 conditions.

The northern and eastern boundaries of the model coincide with hydrologic boundaries of the Chicot aquifer system (fig. 13). The northern boundary is no flow because it is the northern limit of the Chicot aquifer system. The eastern boundary of the model coincides with the Atchafalaya River, which is well connected to the upper Chicot aquifer. The river acted as a drain for the aquifer under predevelopment conditions but under current conditions is primarily a source due to flow induced by pumpage. In either instance, the long-term mean stage of the river can be treated as a constant despite seasonal variations that are unimportant to the relatively long time scale used in the model simulation. Results are calculated for the average response of the Chicot aquifer system. Pumping from the Chicot aquifer system has negligible effects on the river stages, as the greatest pumping rates for the entire Chicot aquifer system are less than 1 percent of the mean flow rate of the Atchafalaya River at Simmesport, Louisiana (Carlson and others, 1985, p. 305). The effects of the Atchafalaya River are simulated in the model by making the eastern boundary a specified-head boundary in the upper Chicot aquifer with the head at each node specified as the average stage of the river in that node. Each of the deeper aquifers is simulated as having a no-flow boundary along its eastern side. The eastern boundaries of deeper layers are treated as no flow because little or no water crosses the axis of the river and future ground-water development near the river is not expected.

The southern boundary of the flow system is located, for modeling purposes, where the total dissolved-solids concentration of water in an aquifer is equal to or greater than 10,000 mg/L. Parts of the aquifer system containing water with a dissolved-solids concentration of 10,000 mg/L and greater are treated as stagnant relative to the time scale of the model and are represented as no-flow zones. Thus, the southern boundary of each aquifer is simulated as no flow at the freshwater-saltwater interface in that aquifer.

The southeastern part of the model in layer 2 is an exception to the southern no-flow boundary. Here the aquifer contains freshwater to the edge of the model area. Water levels have declined and are expected to continue declining. Neither a no-flow nor a specified-head boundary is appropriate. To better approximate the conditions that occur in this region, a general-head boundary was used.

The general-head boundary allows water to flow to or from an external source. The working assumption of the general-head boundary is that the external flow into or out of the model is one dimensional between an external source and the adjacent model block (McDonald and Harbaugh, 1988, p. 11-1). The flow is controlled by a conductance value which is based on the distance from the external source to the model block and the conductivity of the intervening material and by the difference between the head at the external source and the head in the model block.

The bottom of layer 5 is a no-flow boundary. The Evangeline aquifer crops out farther north than the Chicot aquifer system, and a general-head boundary is used along the northern edge of layer 5 to allow water to enter the model from the outcrop area of the Evangeline aquifer.

The western model boundary lies along a ground-water divide between cones of depression at Beaumont and Houston, Texas (Carr and others, 1985). Water flows along the divide primarily from north to south with little flow to the east or west. This boundary is treated as no flow in all of the modeled aquifers. Under the stresses imposed during the calibration period (1900-1981), this is a satisfactory approximation. If large stresses are imposed or the existing pumpage patterns are varied greatly in the western model area, this boundary condition may not properly simulate actual conditions. In either instance, careful consideration should be given to whether boundary-induced errors related to this boundary are acceptable. One possible alternative would be to change the western no-flow boundary to a general-head boundary.

Hydraulic Properties

Initial estimates of values for lateral hydraulic conductivity and storage used in the model were based on previous studies (Carr and others, 1985; Harder and others, 1967; Harder, 1960; Jones and others, 1956; Whitfield, 1975) and results of aquifer tests conducted within the study area (Martin and Early, 1987). The range of transmissivity and storage coefficient for aquifers in the study area is given in table 2. Final calibrated values of transmissivity and storage coefficients are different than those calculated from aquifer tests because of variations in sand thickness and heterogeneities of the aquifers.

No aquifer tests have been performed in the study area that permit calculation of leakance or the vertical hydraulic conductivity of the confining units. Laboratory studies of clay cores from the Lake Charles industrial area (F.S. Riley, U.S. Geological Survey, written commun., 1973) indicate that clay below the "200-foot" sand had a vertical hydraulic conductivity of 7.6×10^{-6} ft/d under a confining pressure equivalent to a 400 ft depth of burial and 1.5×10^{-3} ft/d at atmospheric pressure. Clay cores from below the "500-foot" sand had vertical hydraulic conductivities averaging 3.8×10^{-6} ft/d under a confining pressure equivalent to a 600 ft depth of burial and 8.9×10^{-4} ft/d at atmospheric pressure. Vertical hydraulic conductivity of confining units determined from other flow models of the Chicot aquifer system in Texas ranged from 3.2×10^{-5} to 4.6×10^{-3} ft/d (Carr and others, 1985, p. 45). These values were used as initial estimates in this model.

Model Calibration

The model was calibrated to historical water levels and water budgets by adjusting transmissivities, vertical leakances, and storages to minimize differences between simulated and observed values. The root-mean-square error

Table 2.--Range of thickness, transmissivity, and storage coefficient for aquifers in southwestern Louisiana and southeastern Texas

Aquifer	Thickness (feet)	Transmissivity (feet squared per day)	Storage coefficient (dimensionless)	References
Rice-growing area and Atchafalaya River basin, southwestern Louisiana				
Chicot aquifer (undifferentiated).	100-600	10,000-135,000	0.0004-0.003	Jones, and others (1956, p. 221) Harder, and others (1967, p. 7)
Upper Evangeline aquifer.	(a)	1,000- 12,000	.0002	Whitfield (1975, p. 14-20)
Lake Charles industrial area, southwestern Louisiana				
"200-foot" sand.........	116-123	10,000- 16,000	(b)	Harder (1960, p. 16-17)
"500-foot" sand.........	125-230	17,000- 37,000	.00011- .0011	
"700-foot" sand.........	140	20,000- 25,000	.00028- .0017	
Southeastern Texas				
Chicot aquifer (undifferentiated).	(a)	3,000- 50,000	.0004 - .0005	Carr, and others (1985, p. 25)

[a] Thickness not determined.
[b] No data available.

(RMSE) between observed and computed water levels provides a quantitative measure of the effect of changes made in the model between simulations. The RMSE is defined by:

$$\sqrt{\frac{\sum_{i=1}^{N} (h_i^o - h_i^c)^2}{N}},$$

where h^o is the observed water level; h^c is the model-computed water level; and N is the total number of water-level comparisons.

In addition to trial-and-error calibration, a statistical optimization program was applied to the model (Hugh Mitten and Alex Williamson, U.S. Geological Survey, written commun., 1987). This program automatically runs the model many times, changing the value of a single parameter for each run. Changes may be made in a parameter for the entire model, for individual model layers, or for subareas within a layer. After each run, the program statistically compares the results of that run with the results of an initial base run and with observed conditions in the aquifer system and computes a new value of the parameter that should improve the match of the model output to observed conditions in the aquifer system. This iterative process is continued until model errors are reduced to a specified level or until a specified number of iterations have been made (Durbin, 1983).

Observed base flow data are not available, so model-computed discharges to streams could not be directly evaluated. Computed flows were examined during calibration, however, to insure that results were reasonable. Model calibration was accomplished in two phases. The first phase involved steady-state calibration to match 1981 water levels. The second phase involved transient calibration to match observed changes in the aquifer system that occurred between 1900 and 1981.

Steady-State Simulation

Steady-state conditions were assumed to exist in the aquifer system in 1981. This assumes that water levels were not changing with respect to time. Although this assumption was not totally correct for the entire model area, it allowed initial calibration of transmissivities and leakances in an efficient manner. Pumpage data for 1975 were used for calibration because very little change occurred between 1970 and 1981. Using this relatively highly stressed period for calibration accentuated the effects of the boundaries and of changes of transmissivities and leakances on model-computed water levels.

The ranges of uncertainty for transmissivity and leakance differ. Transmissivity values are known with a higher degree of certainty because many aquifer tests are available to determine lateral hydraulic conductivity and many well logs are available to determine aquifer thickness. Although thicknesses of confining units can be determined from the well logs, good estimates of the vertical hydraulic conductivities of the clays were not available. Thus, initial estimates of vertical leakance were subject to a broad range of uncertainty and were allowed to vary over a broad range during calibration.

Calibrated transmissivity values generally are highest in the eastern part of the model area in all layers. Values average about 80,000 ft^2/d in the rice-growing area in model layers 2 and 3. Transmissivity averages 20,000 ft^2/d in model layer 3 in the Lake Charles area.

Calibrated leakance values range from 10^{-3} to 10^{-7} inverse day (day^{-1}) throughout the model area. Leakances generally decrease from upper to lower model layers. Leakances between layers 2 and 3 are about 10 times greater in the rice-growing area than in the Lake Charles area.

Overall, water levels simulated in the model were slightly lower than measured water levels. Comparison of the RMSE results for the calibrated steady-state model (table 3) indicates that model layer 2 is better calibrated than other layers and that calibration based on RMSE's becomes less accurate with deeper layers. Direct comparison of RMSE's between model layers is not entirely valid because the number of observations differs for each model layer. The greater number of wells in the upper Chicot aquifer permits more observations and, therefore, more comparisons for model layer 2.

Model calibration also is generally more reliable in model layers and in areas having significant stress, such as layer 2 in this model. The amount of stress, in terms of ground-water pumpage, decreases in the lower model layers. Calculation of RMSE's is not essential for model calibration but makes calibration less subjective.

Table 3.--Root-mean-square error of the calibrated steady-state model

Layer	Root-mean-square error (feet)	Number of observations
2	6.0	20
3	7.6	10
4	10.6	9
5	17.8	6
All	9.7	45

Transient Simulation

The transient effects of storage in the Chicot aquifer system appear to be relatively small as shown by the rapid response of water levels to changes in pumping rates (fig. 8). The relatively large seasonal water-level fluctuations are due to pumpage for rice irrigation. Varying the pumping rate causes water levels within the system to change. If pumpage increases, water levels decline. This generates greater gradients that allow the system to take in more water at a rate matching the new pumpage. For this system, a new quasi-steady-state condition is quickly reached after each stress change.

Stress periods were selected for transient simulation so that an assumption of constant pumping rates within a period would be valid. The pumpage from 1900 to 1981 was divided into 11 stress periods: 1900-12, 1913-22, 1923-33, 1934-44, 1945-50, 1951-56, 1957-62, 1963-66, 1967-70, 1971-76, and 1977-81. The calibration period ended in 1981 because 1982 marked the beginning of a significant decrease in pumpage for irrigation across southwestern Louisiana and an accompanying rise in average water levels (fig. 14). Water-level rises also occurred in the Lake Charles area after 1981 as a result of a reduction in industrial withdrawals from the "500-foot" and "700-foot" sands as some industries converted to surface-water sources. The period from 1971 to 1981 was a time of relatively stable water levels throughout southwestern Louisiana (figs. 8, 9, and 14). Pumpage data for 1980 were used in stress period 11, 1977-81.

Transmissivity, leakance, and storage were varied during transient calibration. Steady-state calibrated transmissivities and leakance were used in the initial simulation and were not significantly changed as a result of the transient calibration. Calibrated storage values ranged from 5×10^{-3} in layer 2 in the rice-growing area to 5×10^{-4} in layer 4 along the coast.

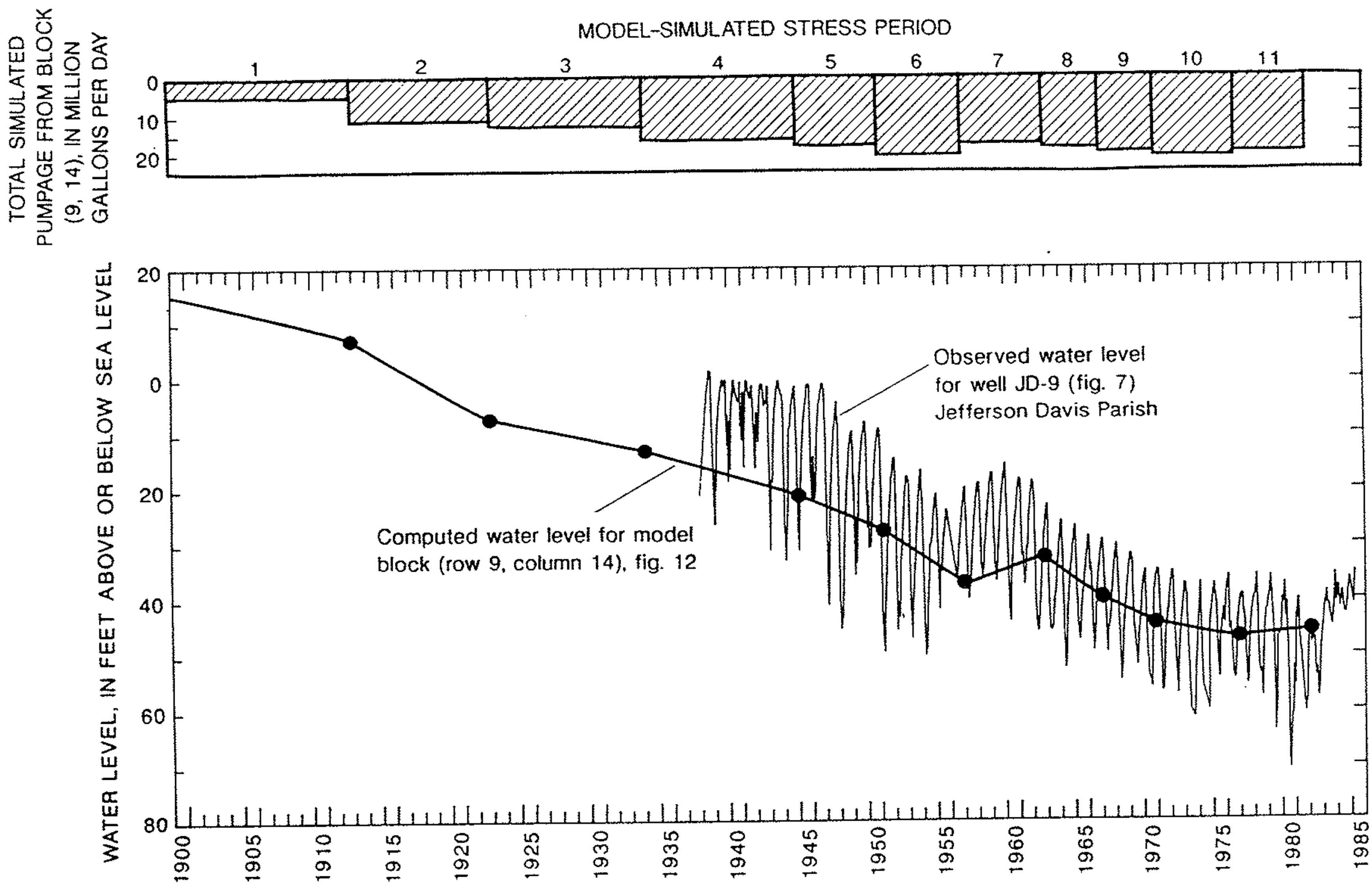


Figure 14.--Comparison of computed and observed water levels in model layer 2 (upper Chicot aquifer).

As in the steady-state calibration, RMSE's increase with deeper layers (table 4). The RMSE's from steady-state and transient simulations are not comparable because water levels from all stress periods are used for the transient comparisons. Water-level maps and vertical flows also were examined to ensure reasonable results.

Table 4.--Root-mean-square error of the calibrated transient model

Layer	Root-mean-square error (feet)	Number of observations
2	5.9	31
3	12.7	18
4	16.1	12
5	19.9	10
All	12.5	71

Computed water levels were compared to the average of the seasonal fluctuation in the hydrographs. This filtered out the large differences, as great as 40 ft, between spring and fall measurements in most rice-irrigation wells. Nineteen hydrographs were used in transient calibration: 12 in layer 2, 4 in layer 3, 1 in layer 4, and 2 in layer 5. Not every hydrograph matched well; but of the 19 compared, all model-computed hydrographs followed the trend of observed water-level rises and declines. The hydrograph of well JD-9 (fig. 14) corresponded well with the model results.

Hydrographs from the Lake Charles area proved to be the most difficult to match and showed the greatest discrepancies between observed and model-computed water levels. The high density of pumping wells in the "500-foot" sand (model layer 3) causes a significant amount of well interference that is superimposed on the average water-level decline. The discrepancy between observed and model-computed water levels is seen for well Cu-445 (fig. 15) which is in the "500-foot" sand. Well Cu-446 (fig. 16) in the "700-foot" sand (model layer 4) in the Lake Charles area showed the worst match of observed to model-computed results, but the computed water levels still follow the general trend of the measured water levels.

Model Results

After transient calibration, a steady-state simulation without pumpage was completed to represent predevelopment conditions. Simulated water levels were checked by comparison to water levels measured in the early 1900's (Harris and others, 1905). Results from the predevelopment simulation were compared with the 1981 transient-simulation results and show that:

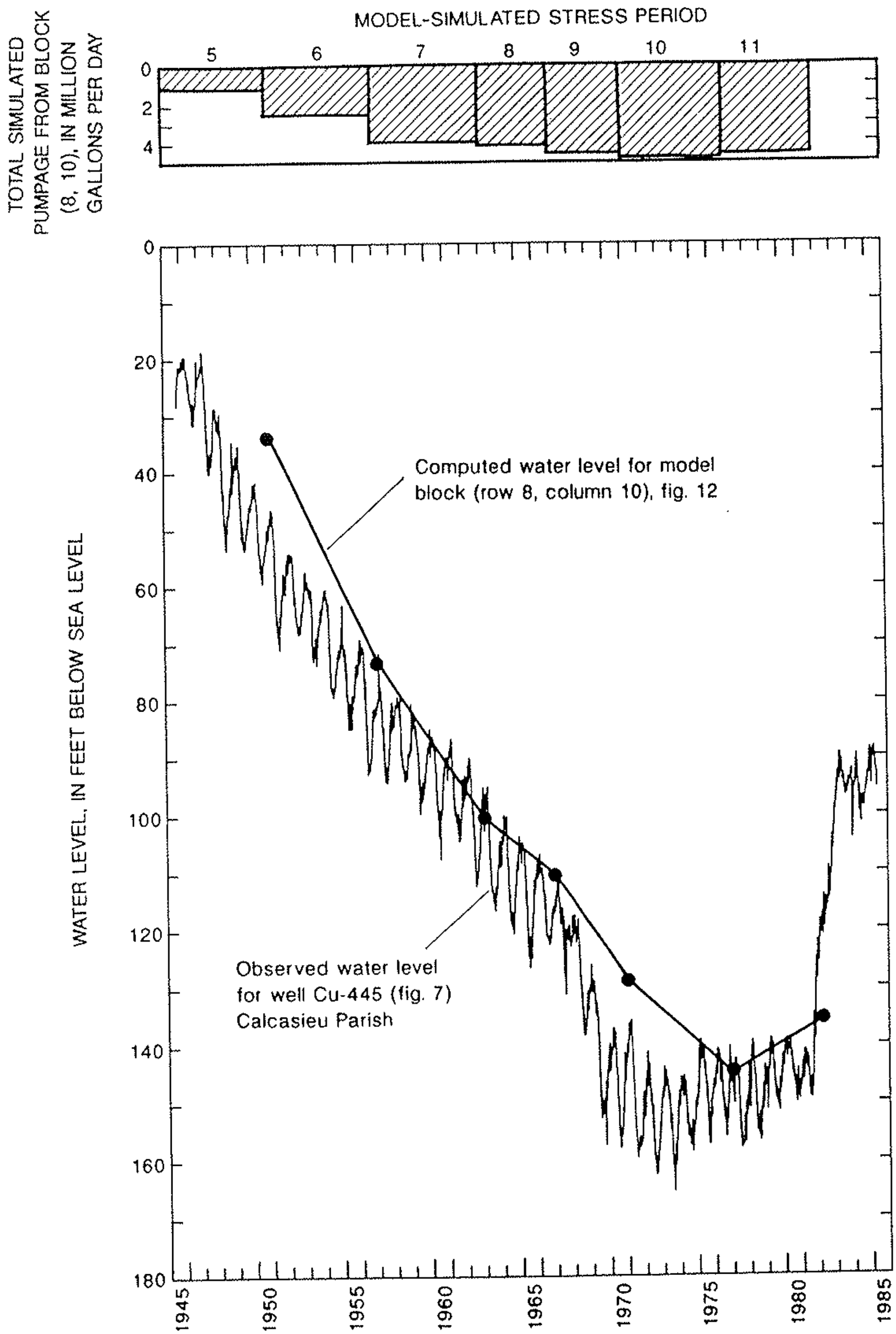


Figure 15.--Comparison of computed and observed water levels in model layer 3 ("500-foot" sand).

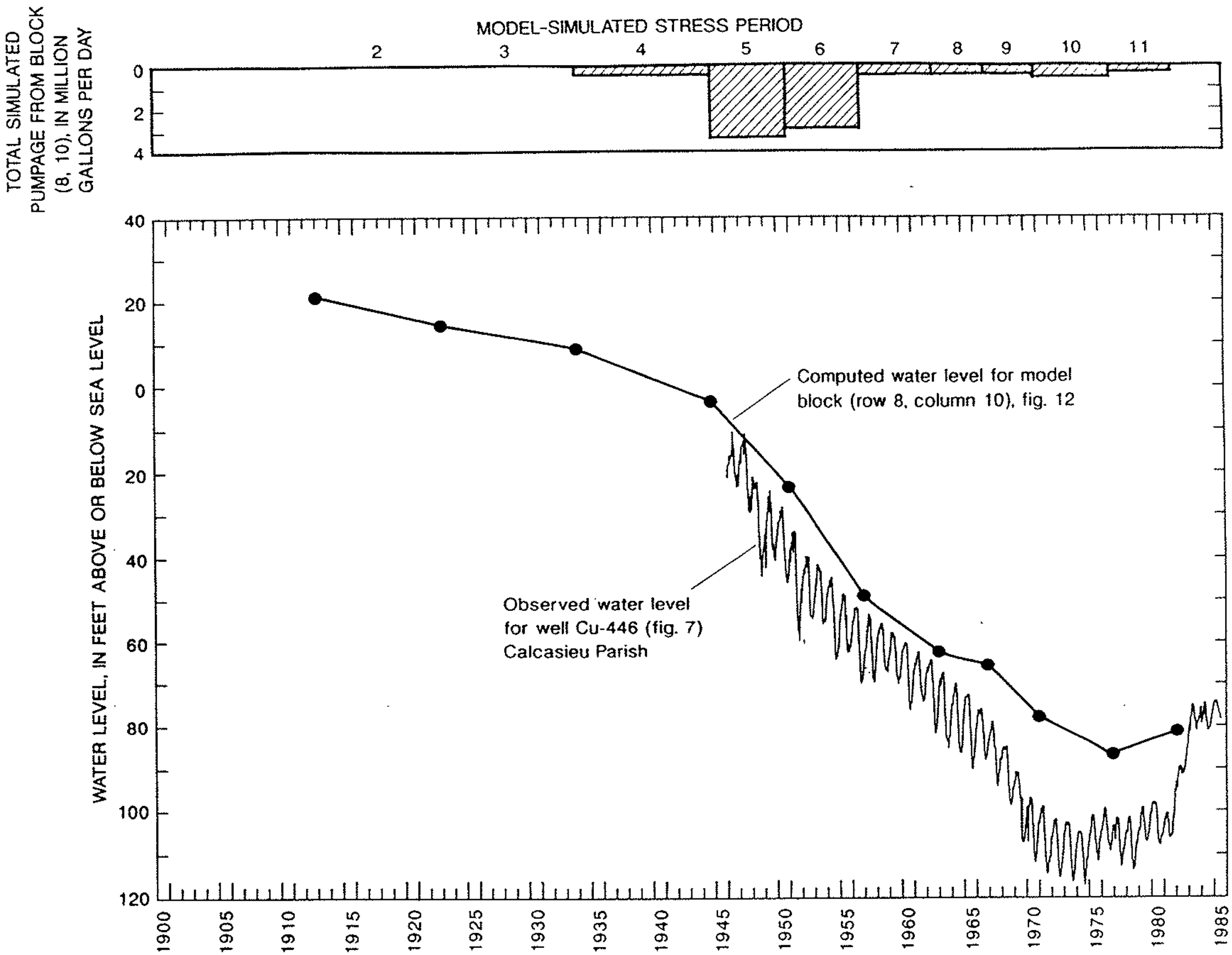
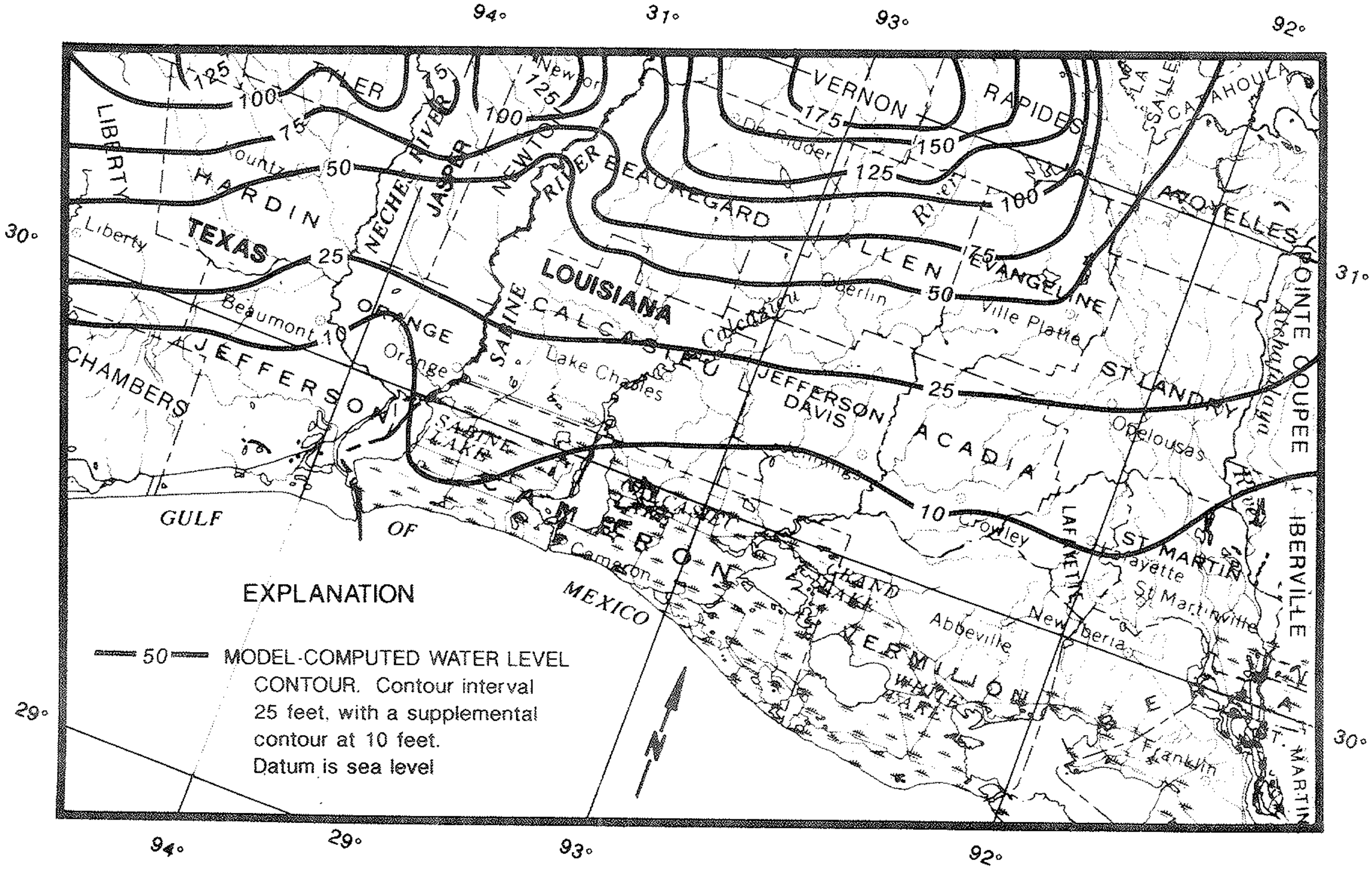


Figure 16.--Comparison of computed and observed water levels in model layer 4 ("700-foot" sand).

1. Flow patterns in the Chicot aquifer system have been significantly altered downgradient from the outcrop.
2. Total flow in the aquifer system has greatly increased (approximately fourfold).
3. Water levels have been lowered considerably in the Lake Charles and rice-growing areas.
4. Under 1981 conditions, vertical leakage is the largest component of recharge, and water derived from aquifer storage is a relatively small part of flow in the system.

Figure 17 shows the simulated potentiometric surface of layer 2 (upper Chicot aquifer) for predevelopment conditions. Ground-water flow directions can be inferred from the map because flow is perpendicular to the water-level contour lines. The map shows that ground water flows southward from the outcrop areas toward the coast, eastward toward the Atchafalaya River basin, and toward the Neches and Sabine Rivers. The distribution of vertical flow to and from the aquifer system under predevelopment conditions is shown in figure 18; positive values indicate flow from the surface is recharging the aquifer system. Negative values indicate discharge from the aquifer system to the surface. Ground-water discharges from the aquifer system to the large marshy areas along the coast at an average rate of about 0.5 in/yr, but the discharge rate may be more than 1 in/yr in localized areas. Approximately 259 Mgal/d of water flowed through the aquifer system prior to extensive development. A generalized schematic diagram (fig. 19) shows the quantities and directions of flow in the modeled aquifer system under predevelopment conditions. Of the total recharge (about 221 Mgal/d) to the upper Chicot aquifer (model layer 2), 46 percent (about 102 Mgal/d) circulates within layer 2 and the remaining 54 percent (about 119 Mgal/d) moves downward into the lower part of the aquifer system (layers 3, 4, and 5). Only 7 percent (15 Mgal/d) reaches the upper part of the Evangeline aquifer (layer 5).

Under 1981 conditions, ground-water flow in the Chicot aquifer system converges from all directions toward pumping centers in the rice-growing area and Lake Charles. Flow patterns have been significantly altered by development (figs. 17 and 20). In the rice-growing area water levels declined, on average, 1 ft/yr from 1900 to 1981. Comparison of the distribution of recharge to and discharge from the Chicot aquifer system under 1981 conditions (fig. 21) to the predevelopment distribution of recharge and discharge areas (fig. 18) shows that development has caused most of the discharge areas near pumping centers and along the coast to change to recharge areas. Up to 6 in/yr of water recharges the Chicot aquifer system at the major pumping centers (fig. 21). Approximately 1,113 Mgal/d of water enters the aquifer system under 1981 conditions (fig. 22). This is more than 4 times the circulation prior to development. Over 90 percent of this water entering the aquifer system is discharged as pumpage. Fifty-five percent (about 585 Mgal/d) of all water entering the upper Chicot aquifer (model layer 2) in 1981 was discharged to the surface or by pumpage without moving into the lower part of the aquifer system (fig. 22). Most of the increased flow under 1981 conditions caused by pumpage is supplied by recharge from the surface. In 1981, 65 percent of the water pumped from the rice-growing area was supplied by recharge from the surface. Less than 1 percent (about 9 Mgal/d) of the water entering the aquifer system came from storage.



Base from U.S. Geological Survey
State base map, 1:500,000

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0 10 20 30 KILOMETERS

Figure 17.--Simulated predevelopment potentiometric surface of model layer 2 (upper Chicot aquifer).

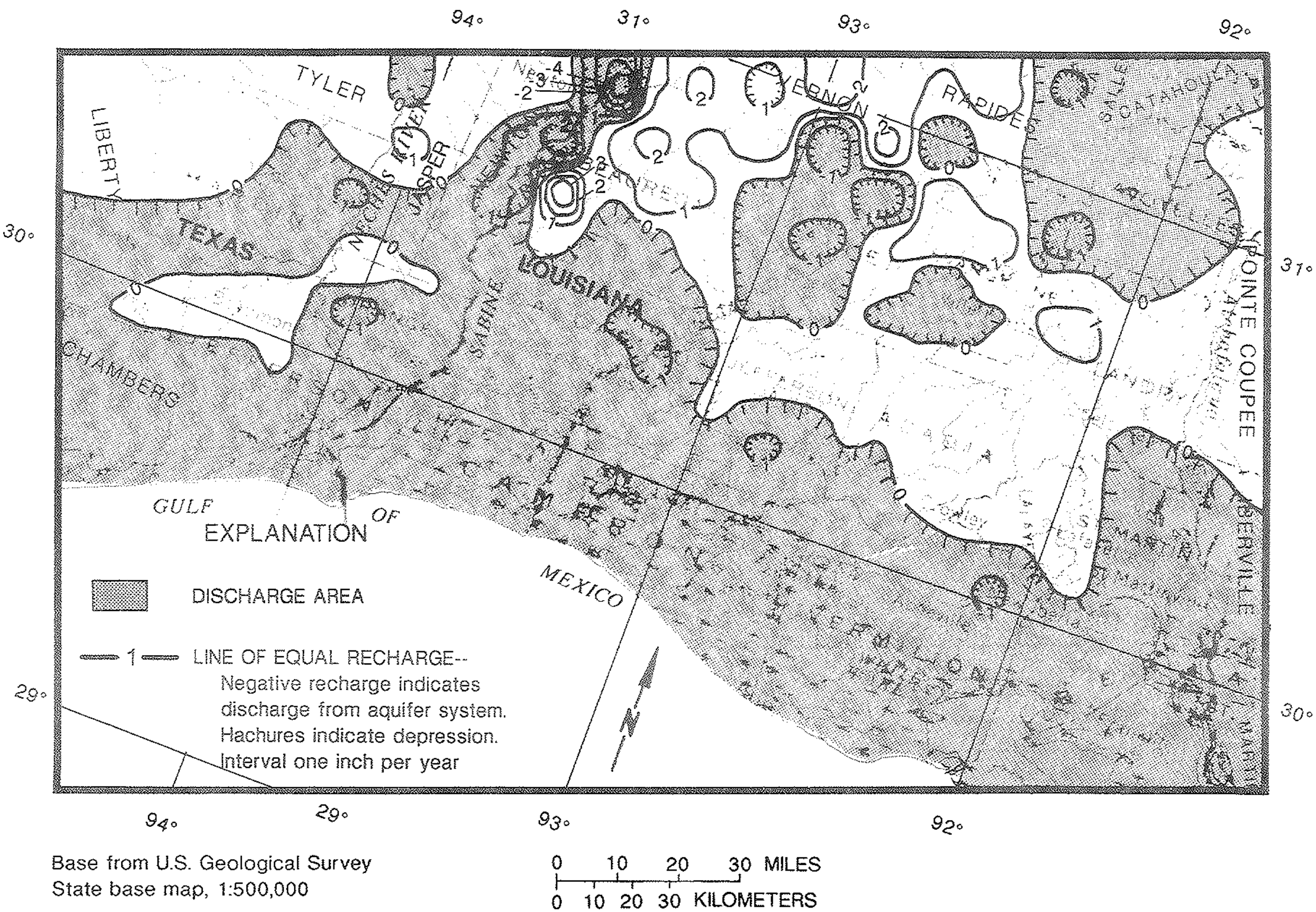

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Figure 18.--Computed rates of recharge to and discharge from the Chicot aquifer system under predevelopment conditions.

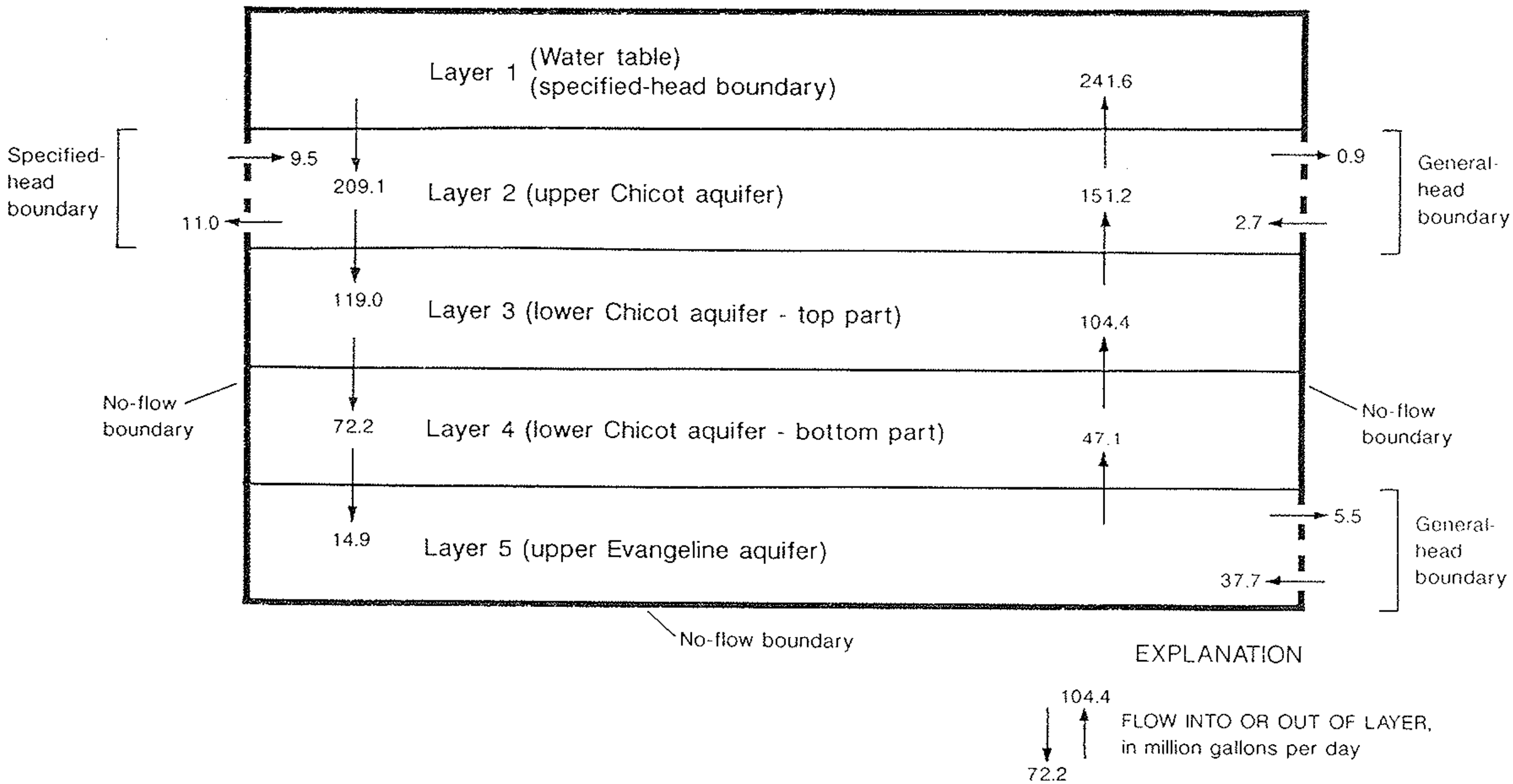


Figure 19.--The quantity and direction of simulated flow in the modeled aquifer system under predevelopment conditions.

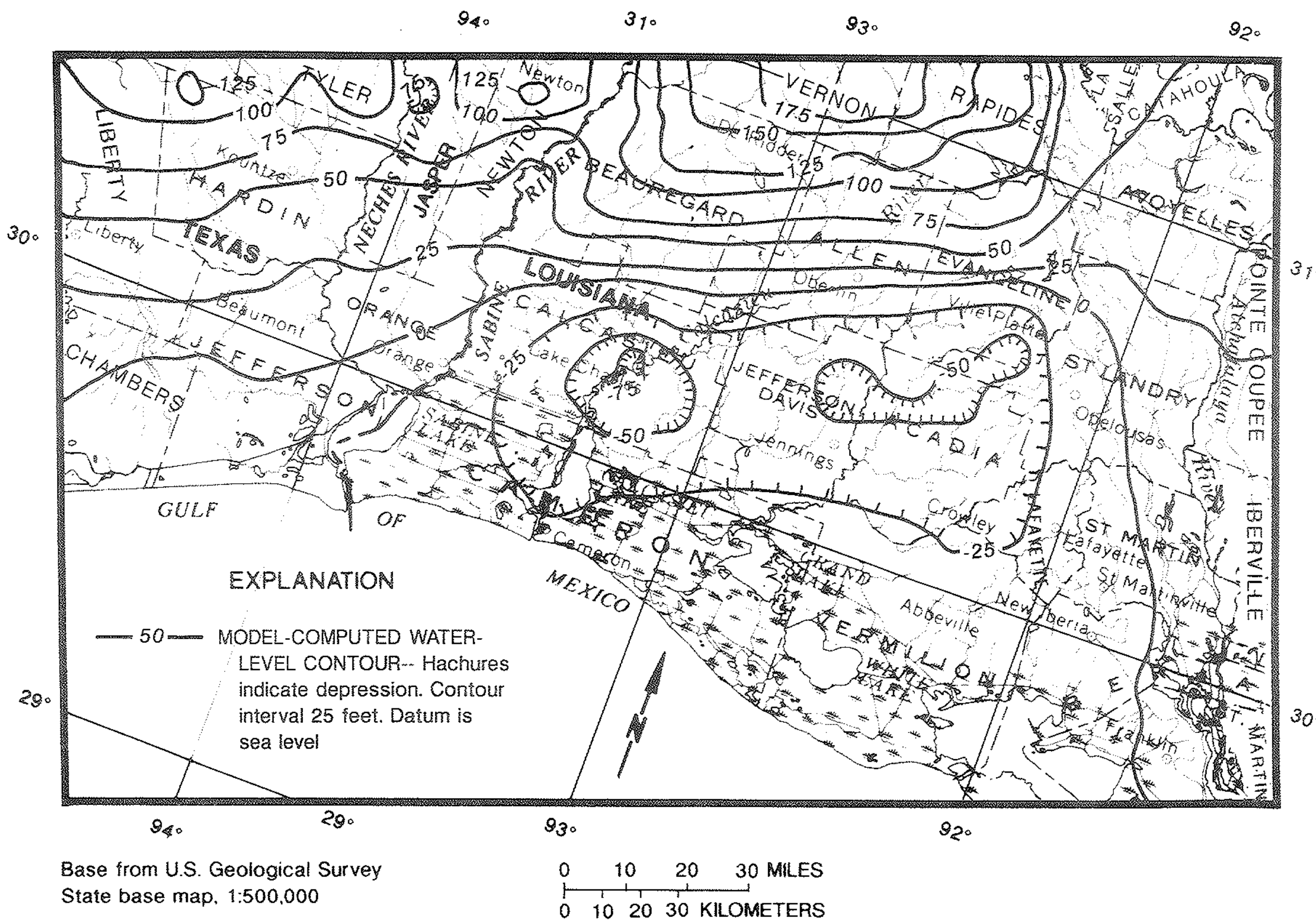
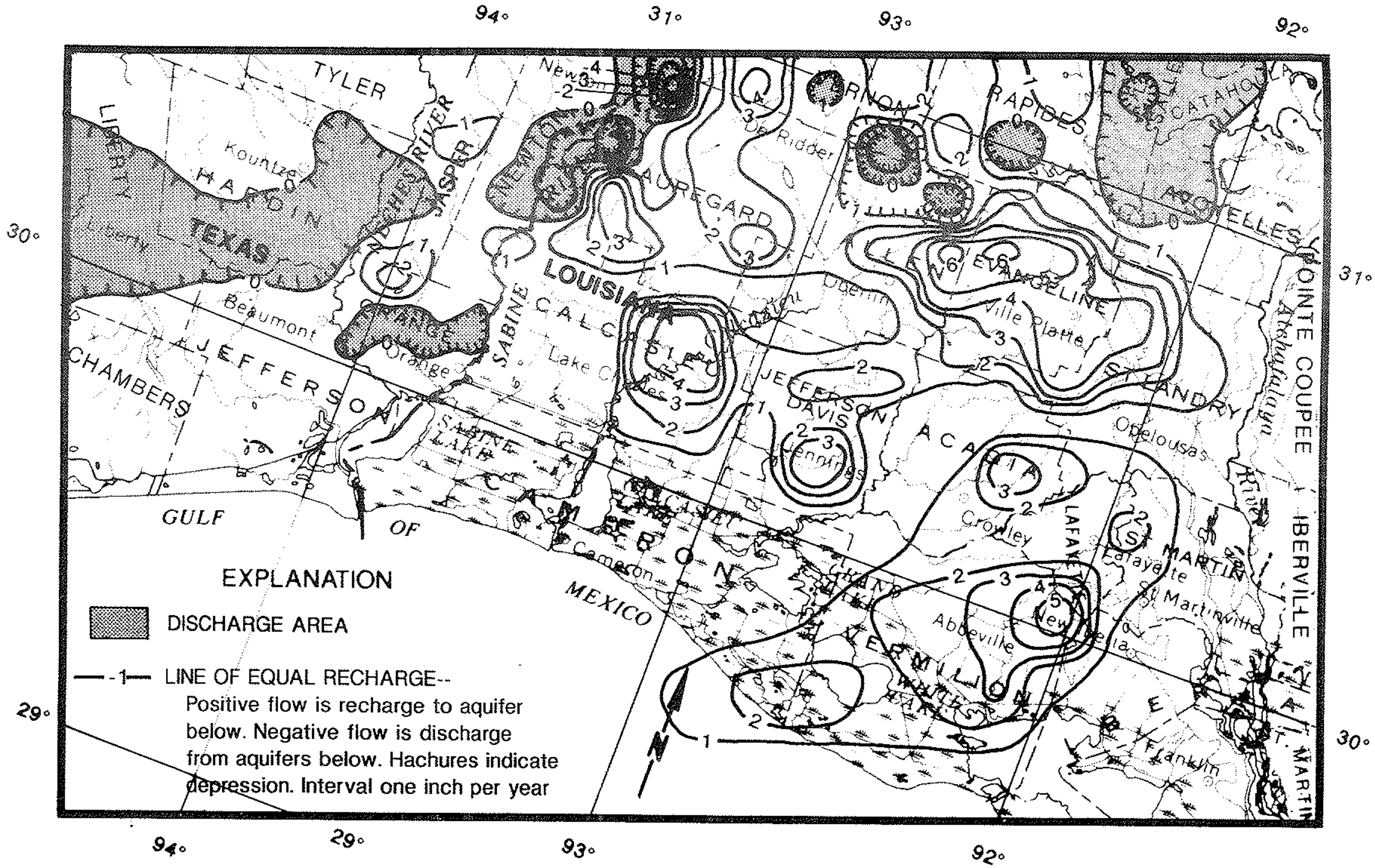


Figure 20.--Simulated potentiometric surface of model layer 2 (upper Chicot aquifer) for 1981.



Base from U.S. Geological Survey
State base map, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 21.--Computed rates of recharge to and discharge from the Chicot aquifer system for 1981.

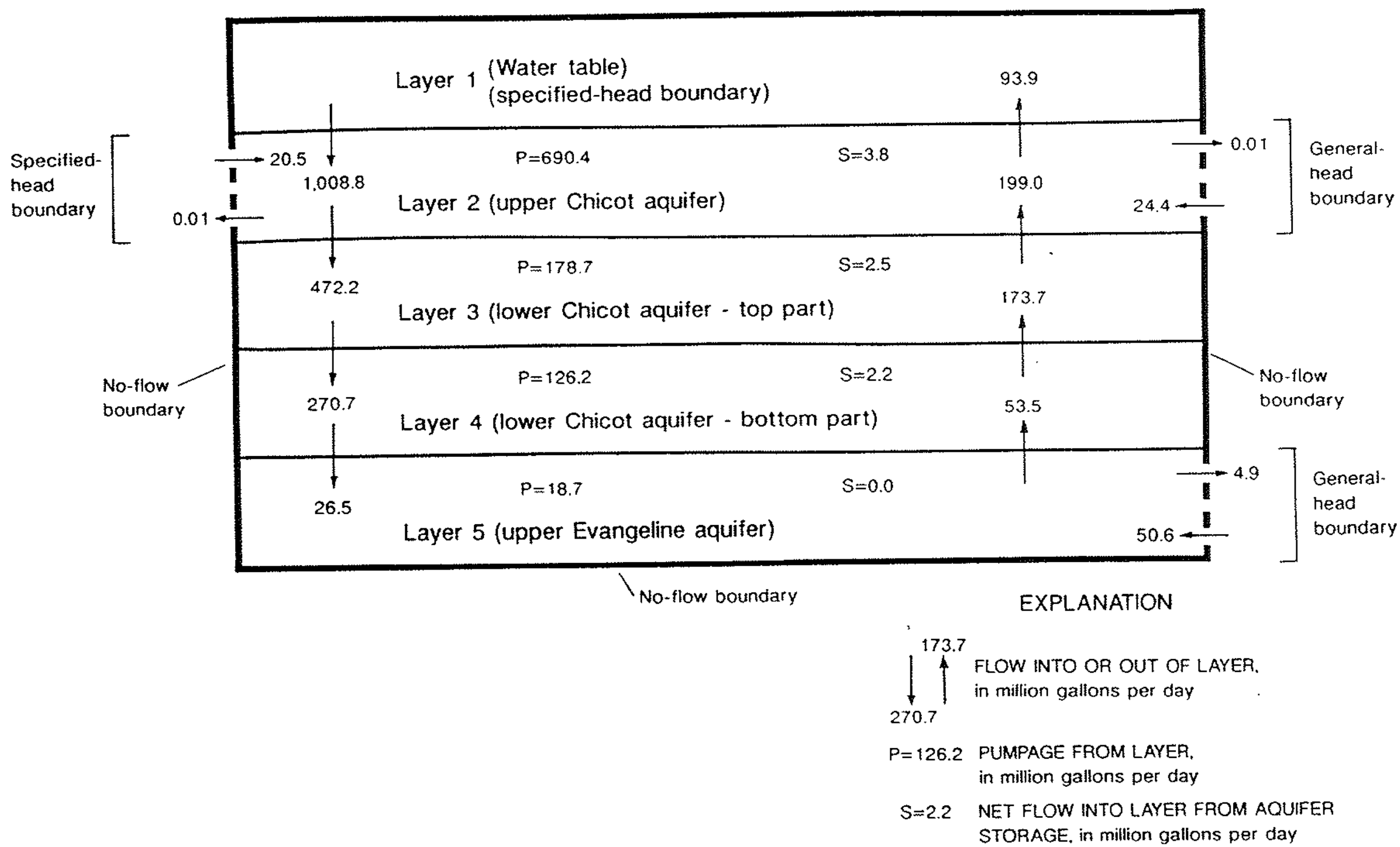


Figure 22.--The quantity and direction of simulated flow in the modeled aquifer system for 1981.

Sensitivity Analysis

Leakance, transmissivity, and storage were varied in model calibration because they were the hydraulic characteristics initially known with the least degree of certainty. To determine how each of these characteristics affected model simulation, the sensitivity of the model to adjustments in their values was examined. Model sensitivity was determined by comparing water-level RMSE results and water budgets from the calibrated model to the results of a simulation in which one of the characteristics had been changed. This process was repeated until each characteristic had been tested over a range of values. Boundary conditions and pumpage were not adjusted during calibration and were assumed to be correct, so sensitivity analysis was not performed on them.

Sensitivity of the model to adjustments in leakance between layers was examined for all model layers collectively, for layers 1 and 2 only, and for layers 2 through 5 collectively. In all instances, decreasing the leakance had a greater effect on the RMSE of water levels than an equivalent increase. Decreasing leakance between all layers by a factor of 10 produced a value of RMSE greater than 90 ft (fig. 23). The extreme sensitivity of the model to leakance reflects the strong influence of vertical recharge on the aquifer system and the predominance of pumping and points of comparison in the upper Chicot aquifer (layer 2). The model results are relatively insensitive to leakance between the lower layers. The sensitivity of the model to adjustments in all leakance values is almost identical to the sum of the two previous results.

Transmissivity, when varied for all layers, showed a symmetrical sensitivity curve (fig. 24). The minimum of this curve indicates lower transmissivity values would yield a slightly better calibration, but the slight improvement did not justify recalibrating the model. Within the range of uncertainty of the values of transmissivity, considered to be 0.5 to 2.0 times the calibrated values, the model is more sensitive to variations in transmissivity than to variations in leakance. At the lower end of the range of uncertainty associated with the values of leakance, considered to be 0.1 to 10.0 times the calibrated value, the model is more sensitive to changes in leakance than transmissivity.

Storage for all layers was varied collectively within a range of 0.01 to 5.0 times the calibrated value (fig. 25). This range was considered to be wider than the range of uncertainty. The model is sensitive to increases of storage coefficient greater than the calibrated value but is insensitive to decreases less than the calibrated value (fig. 25). The effects of storage are relatively insignificant in the Chicot aquifer system where transient conditions are of short duration. The hydrographs of rice-irrigation wells show sharp responses to pumpage changes (fig. 14). Changes in water level are directly related to changes in pumpage with little lag (fig. 26). This is because only a small part of the total flow is derived from storage.

Areally, the modeled system is more sensitive to parameter changes around Lake Charles and near the center of the rice-growing area, where pumpage is concentrated. Differences between water levels from the cali-

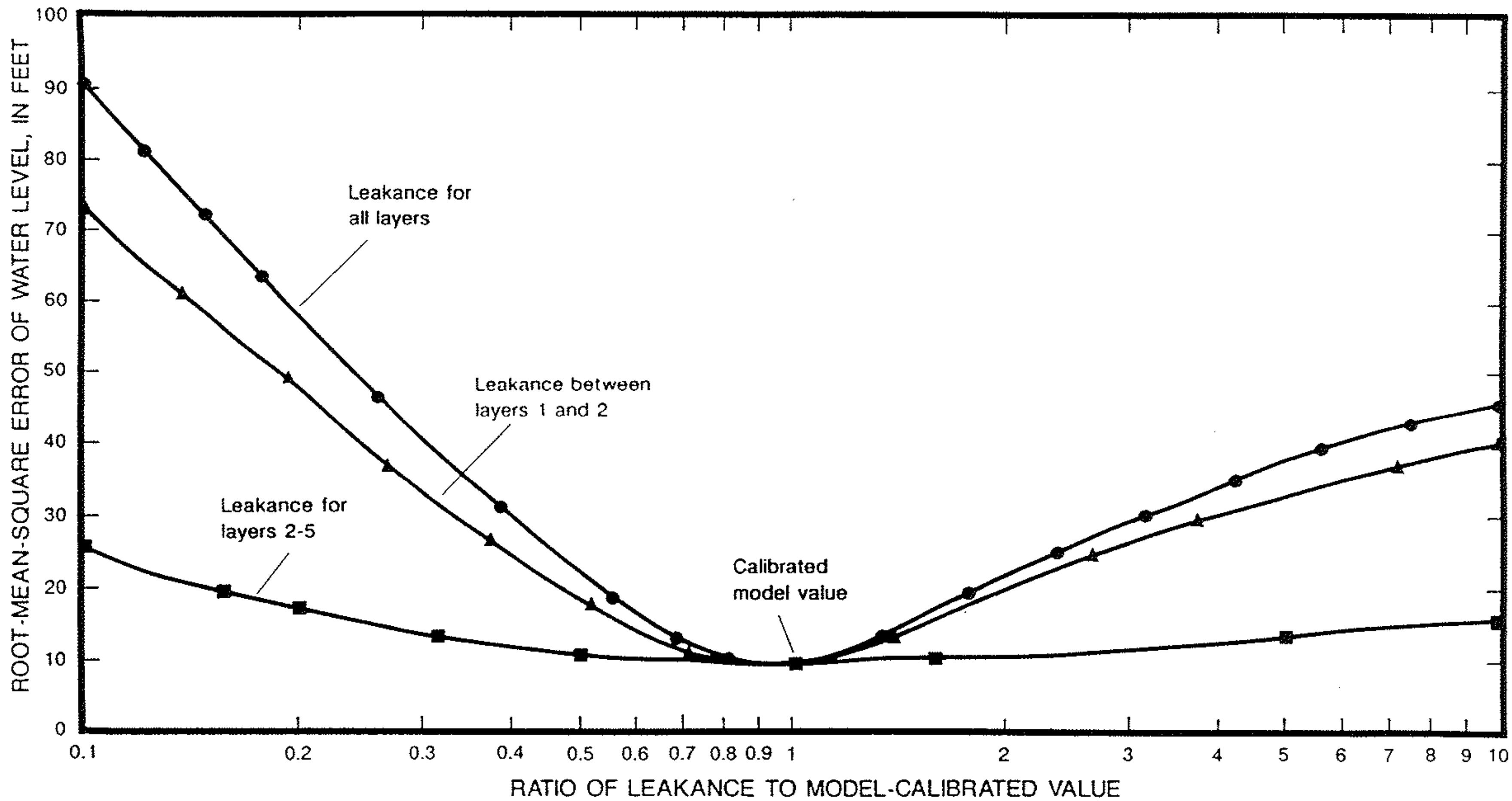


Figure 23.--Root-mean-square error of water level as a function of the ratio of adjusted leakance values to calibrated values.

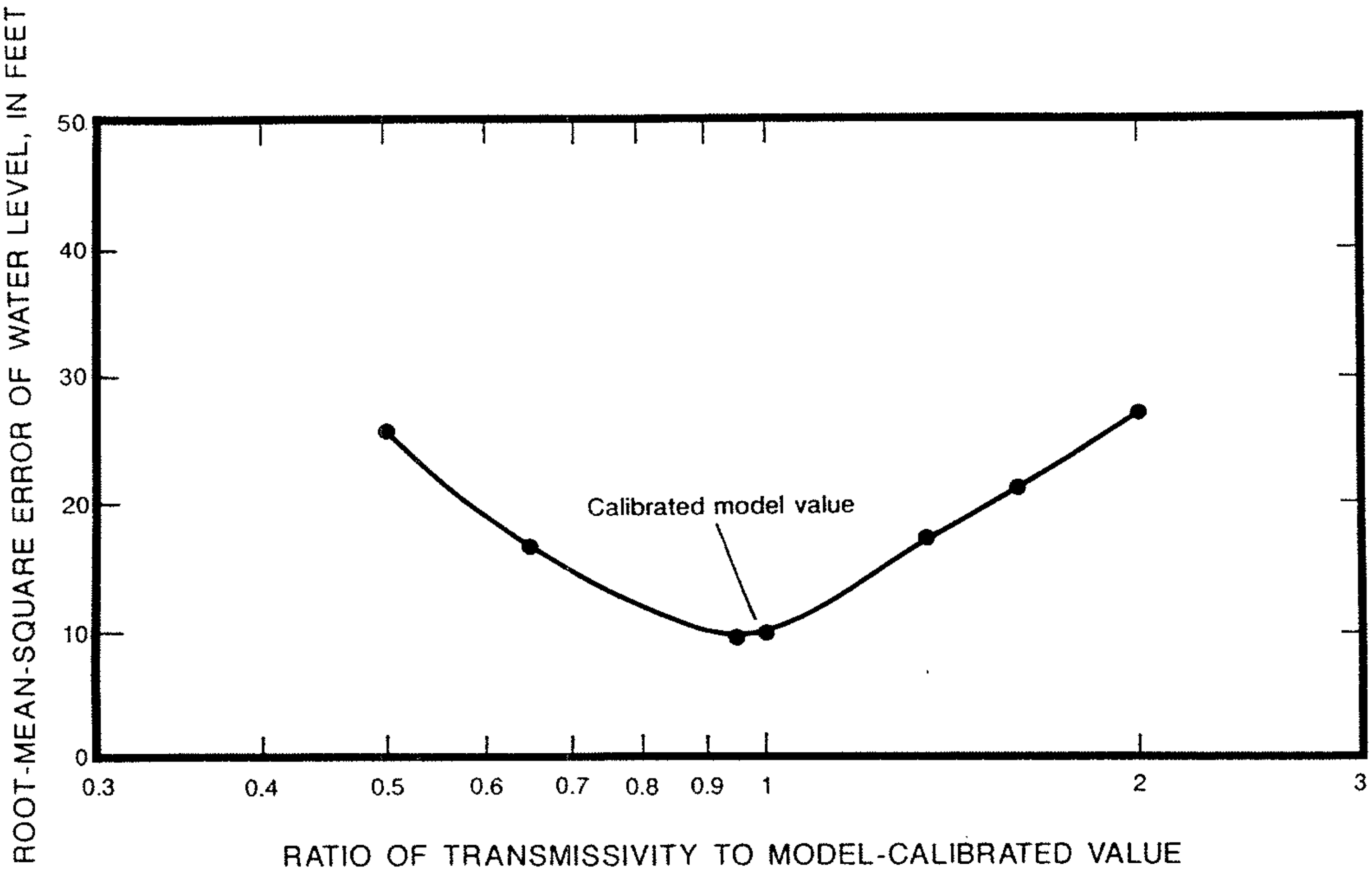


Figure 24.--Root-mean-square error of water level as a function of the ratio of adjusted transmissivity values to calibrated values.

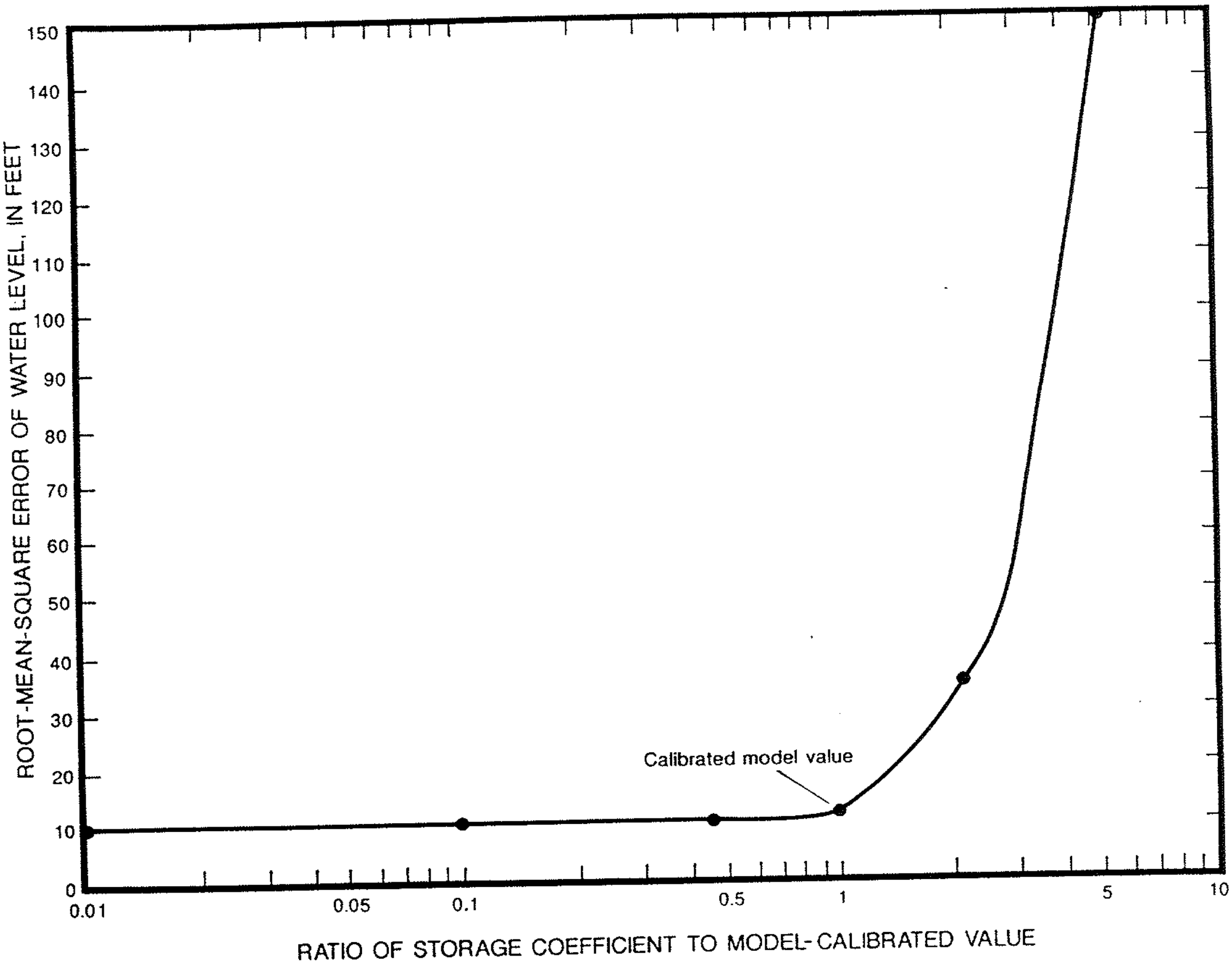


Figure 25.--Root-mean-square error of water level as a function of the ratio of adjusted storage-coefficient values to calibrated values.

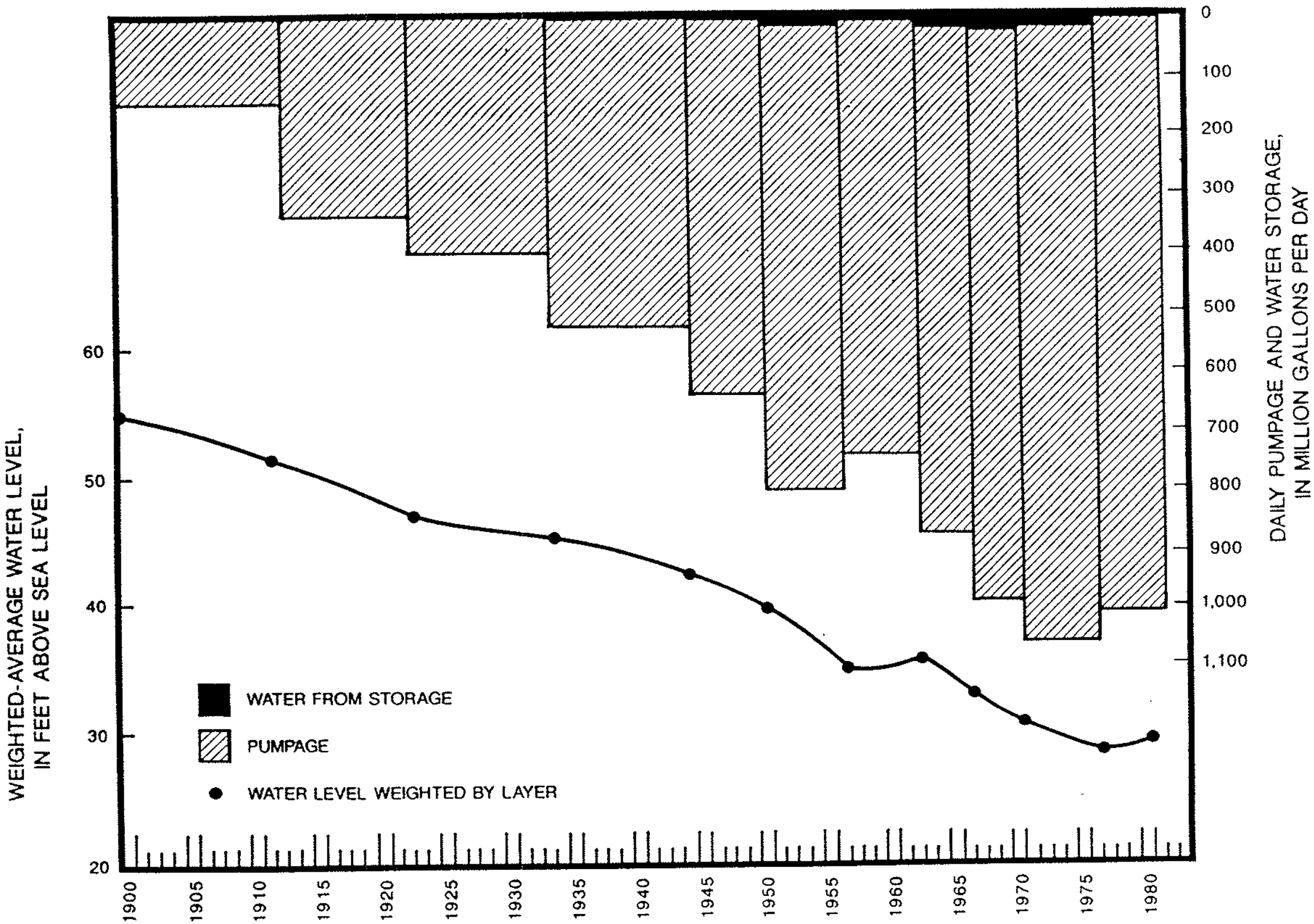


Figure 26.--Comparison of the fluctuations in weighted-average water level and pumpage as a function of time.

brated model and water levels from a simulation with a leakance one quarter of the calibrated value between layers 1 and 2 are shown in figure 27. Variations in transmissivity have their greatest effect in these same areas.

Because 90 percent of the water that enters the aquifer system under 1981 conditions leaves the system by pumpage at specified locations, variations in leakance, transmissivity, and storage did not significantly affect the total flow distribution simulated in the model. Ground-water gradients changed in inverse proportion to increases and decreases in leakance, transmissivity, and storage used in the sensitivity simulations.

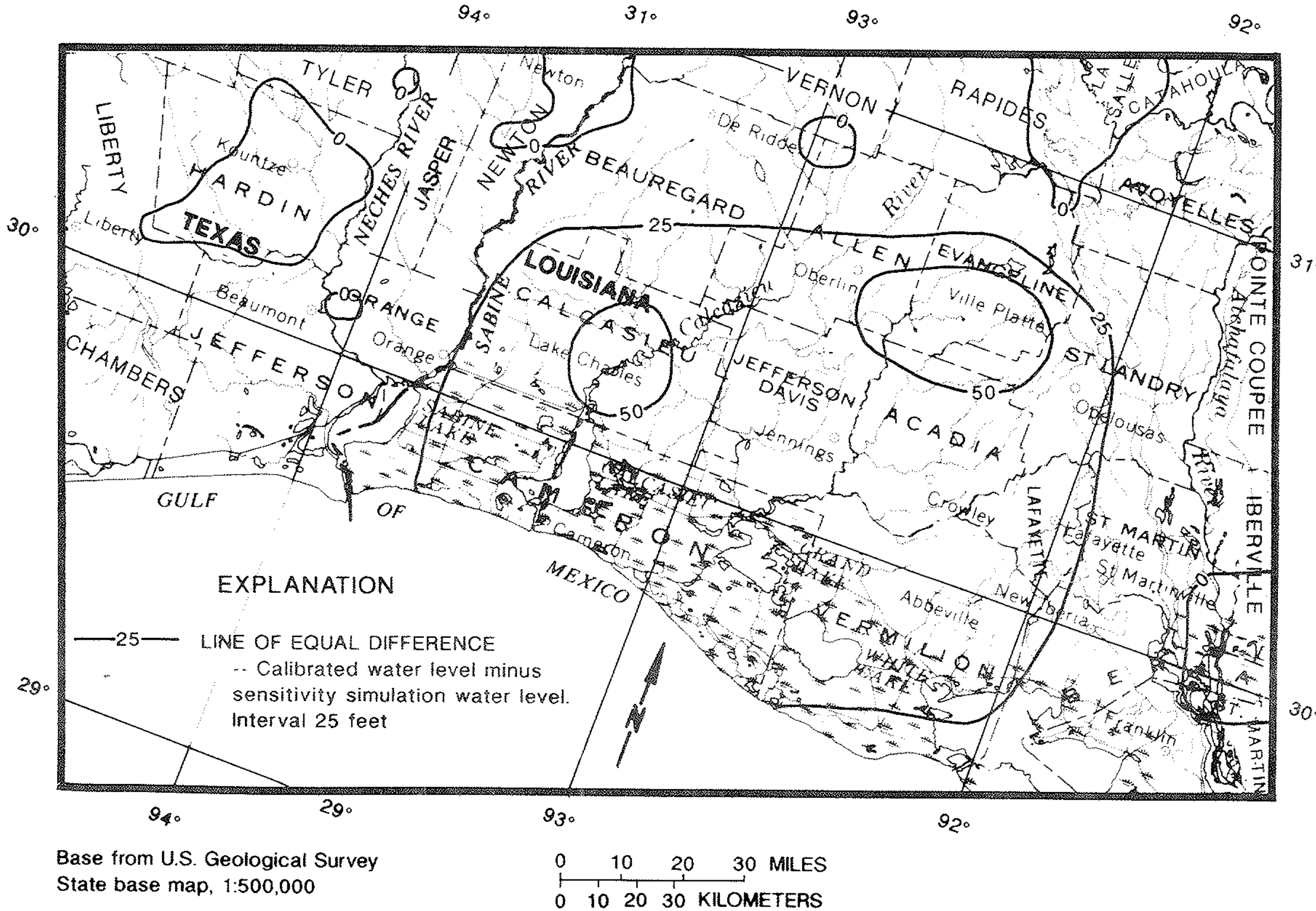
SIMULATED EFFECTS OF PUMPING

After the model was calibrated, a series of experiments were carried out to estimate the response of the aquifer system to changes in pumpage. The following conditions were simulated:

1. All pumpage was stopped after 1981, and the aquifer system was allowed to recover until the year 2064.
2. The pumpage was instantaneously increased by 50 percent at the beginning of 1982 and then held constant until the year 2064.
3. The pumpage was increased by 25 percent of the 1980 rate from 1982 to 2005 and by 50 percent of the 1980 rate from 2006 to 2040.
4. The pumpage was increased by 50 percent of the 1980 rate from 1982 to 2005 and by 100 percent of the 1980 rate from 2006 to 2040.
5. The pumpage was decreased by 25 percent of the 1980 rate from 1982 to 2005 and by 50 percent of the 1980 rate from 2006 to 2040.

The response of the system to the experiments is demonstrated by the weighted-average water level by layer in the aquifer system and water levels in specific blocks in highly stressed zones. Blocks (6,18) in layer 2 (upper Chicot aquifer in the rice-growing area) and (7,11) in layer 3 ("500-foot" sand in the Lake Charles industrial area) (fig. 12) are used to represent these highly stressed zones. The asymptotes in figures 28 through 31 represent the final steady-state water level after all transient effects have dissipated. In experiment 1, water levels recovered to approximately 80 percent of predevelopment levels 3 years after stopping all simulated pumpage (fig. 28). The system was within 3 percent of reaching steady-state conditions in approximately 15 to 25 years (1996-2006). In experiment 2, roughly 80 percent of the simulated decline in water levels occurred in the first 3 years of increased pumpage (fig. 29). Results of experiments 1 and 2 demonstrate the relatively rapid response of the aquifer system to changes in stress.

Experiments 3, 4, and 5 show transient response of the aquifer system to shorter periods of stress changes. The water-level response in block (7,11) in model layer 3 ("500-foot" sand) for each experiment (fig. 30) is typical of that of the aquifer system as a whole (fig. 31). In experiment 4, water levels would fall below the top of the upper Chicot aquifer and dewatering would begin in the Lake Charles and rice-growing areas 2 to 3 years after the second increase in pumping rates began in the year 2006. Although this model



Base from U.S. Geological Survey
State base map, 1:500,000

Figure 27.--Differences in water levels in model layer 2 (upper Chicot aquifer) due to a 75-percent decrease in the vertical hydraulic conductivity from calibrated values between layers 1 and 2.

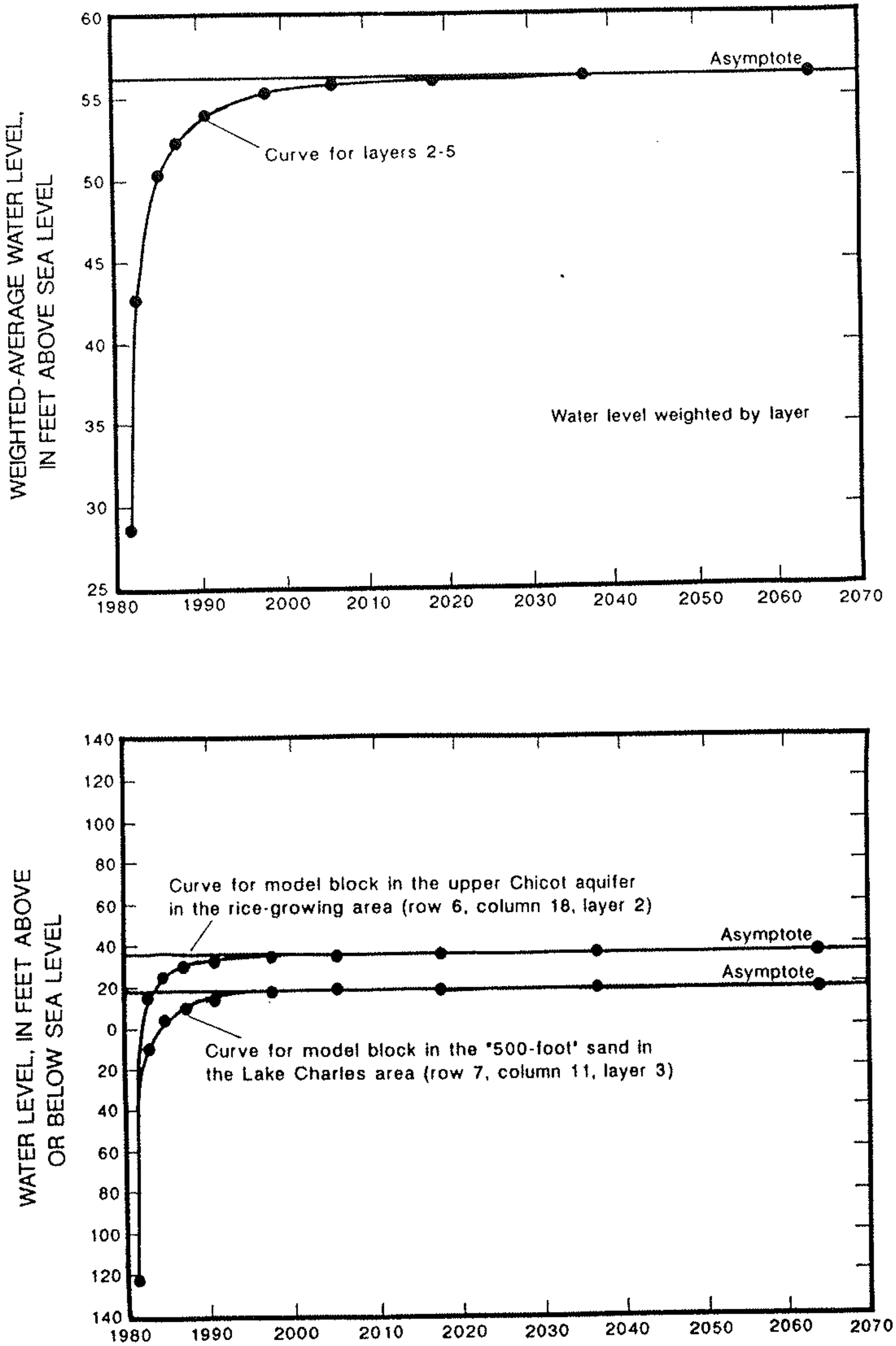


Figure 28.--Computed water levels resulting from experiment 1, stopping all simulated pumpage after 1981.

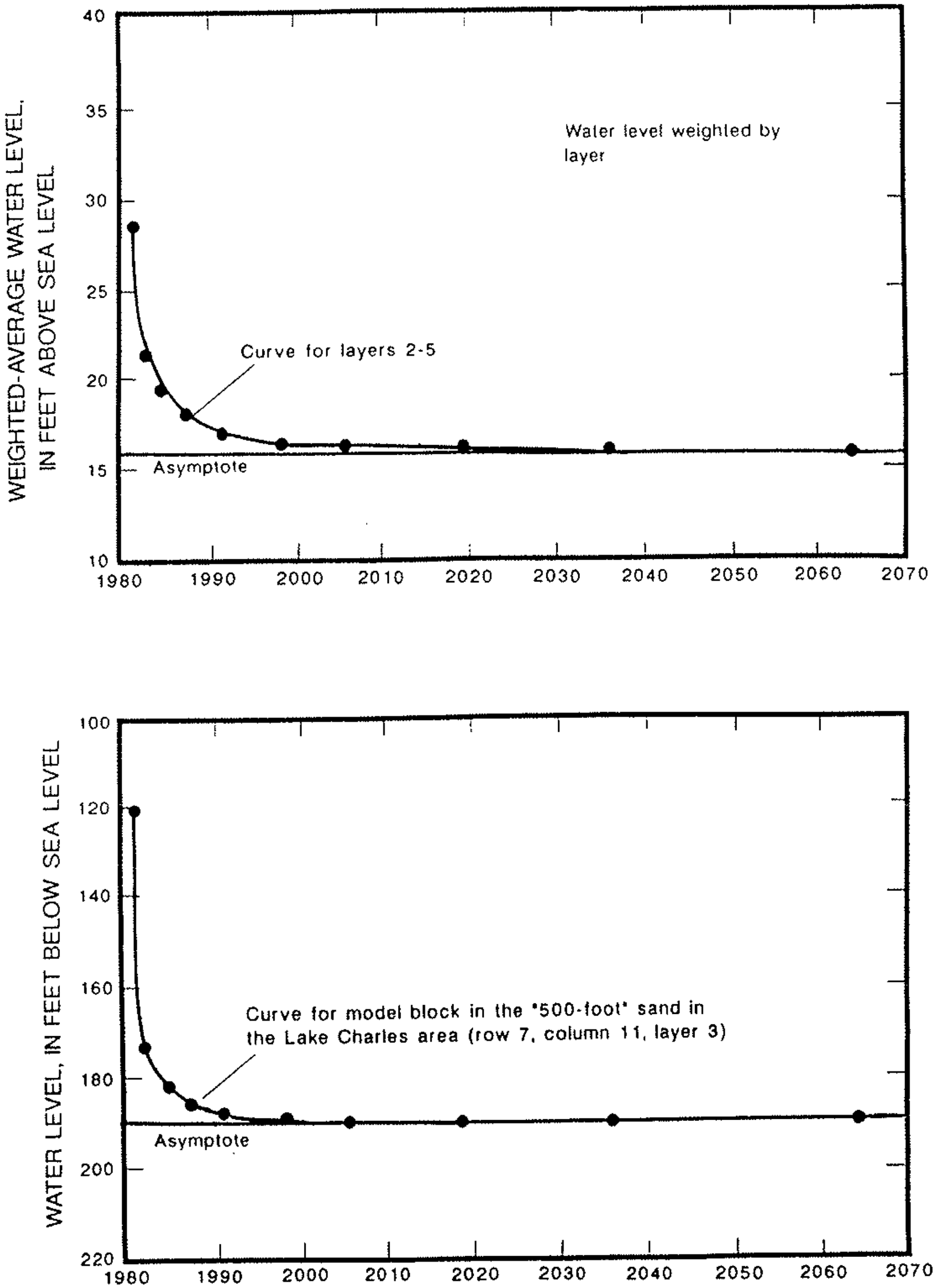


Figure 29.--Computed water levels resulting from experiment 2, simulating a pumping rate 50 percent larger than the 1980 pumping rate.

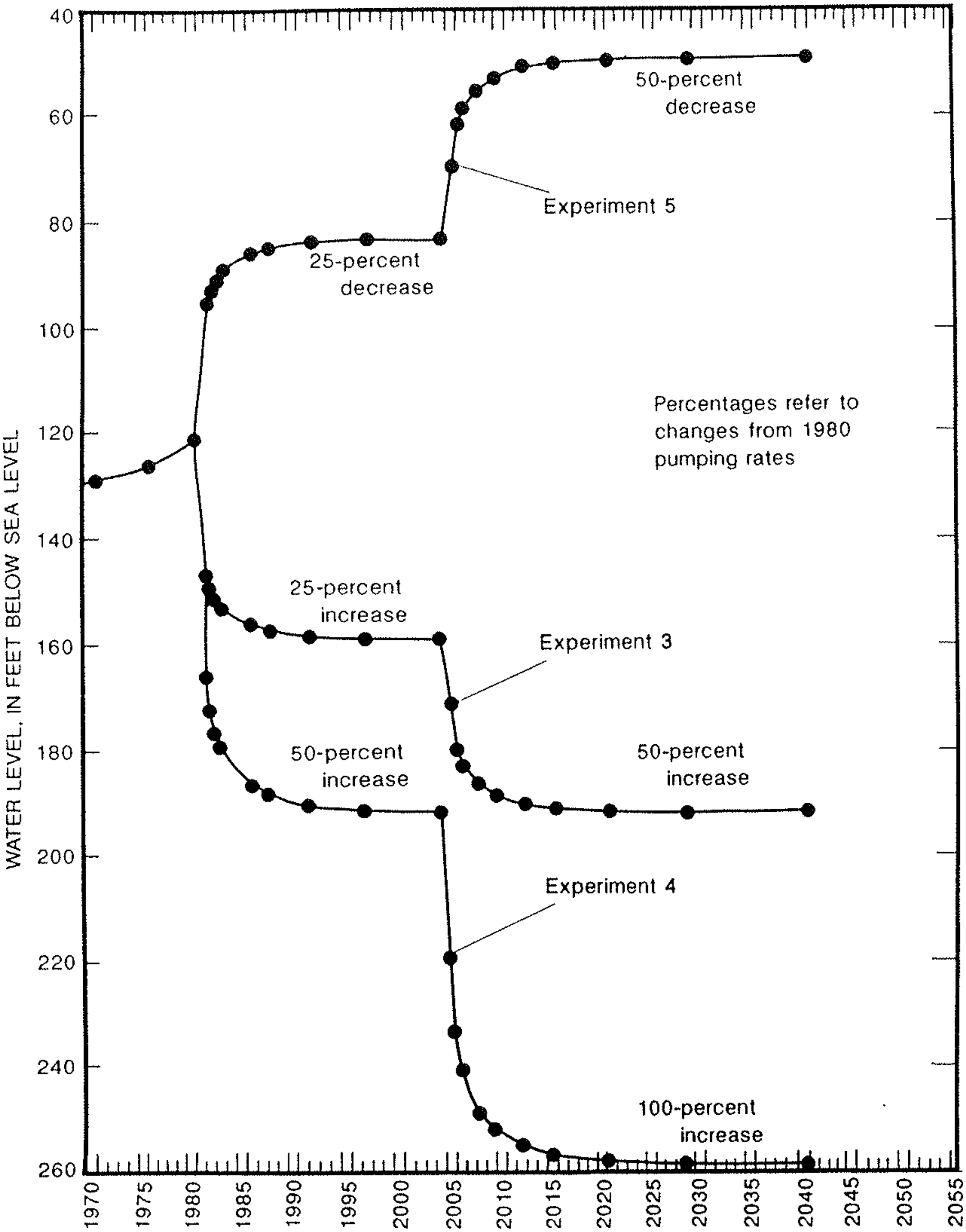


Figure 30.--Computed water levels in block (7,11) in the Lake Charles area in layer 3 resulting from changing pumping rates in experiments 3, 4, and 5.

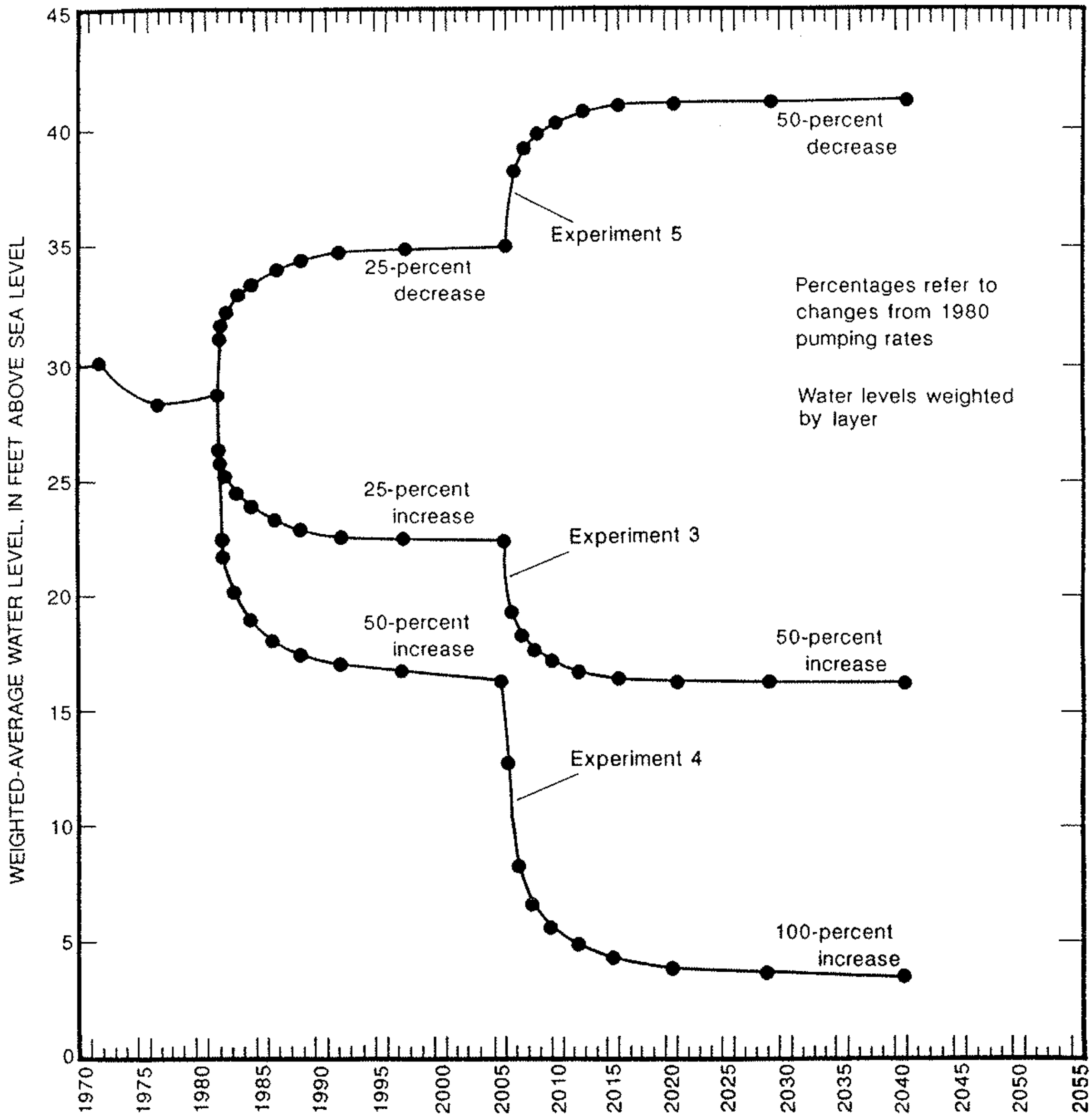


Figure 31.--Computed weighted-average water levels for layers 2 through 5 resulting from changing pumping rates in experiments 3, 4, and 5.

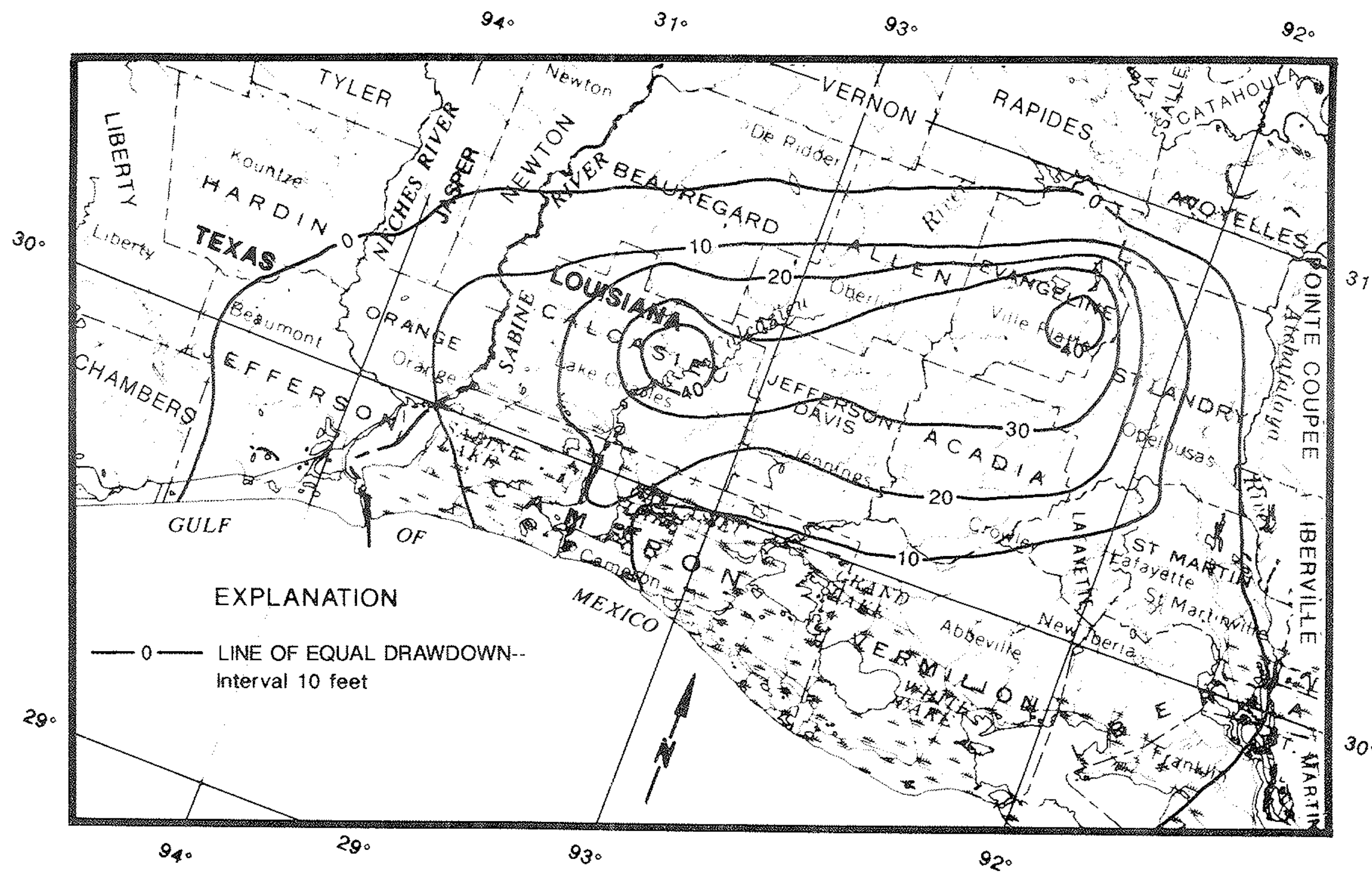
cannot be used to accurately determine the lateral and vertical extent of dewatering, indications are that only the Lake Charles industrial area would be significantly affected. Declines in water level are directly proportional to increases in pumpage for the areas tested in the aquifer system. The linear response of the system to pumpage can be used to interpolate drawdown for values of pumpage between those simulated in the two pumping experiments. This only applies to system-wide pumpage increases or decreases, not rate changes in individual wells.

Areally, the effects of uniformly increased pumpage are most pronounced from Lake Charles through the rice-growing area. Comparison of steady-state drawdowns from 1981 water levels for 50 percent (fig. 32) and 100 percent (fig. 33) increases in total pumpage indicates that the model-simulated drawdowns resulting from a 50-percent increase in pumpage are about half the drawdown resulting from a 100-percent increase. This comparison further illustrates the direct relation between pumpage and drawdown in the aquifer system.

Experiment 5 shows water-level recovery occurs rapidly for layers 2 through 5 as well as for individual blocks in response to decreases in pumpage (figs. 30 and 31). About 80 percent of the simulated recovery in water levels occurred in the first 3 years of decreased pumpage.

Water budgets are shown in table 5 for conditions ranging from predevelopment through pumpage at the highest rate simulated for the Chicot aquifer system. Most of the increases in flow in the aquifer system under developed conditions are attributable to vertical leakage in and near the pumping centers. Prior to development, more than 75 percent of the water entered the system in the outcrop area. Under 1981 conditions, recharge into the outcrop was 59 percent greater than the predevelopment recharge but only represented 28 percent of the water entering the Chicot aquifer system. Vertical leakage increased from 19 percent of flow in the aquifer system for predevelopment conditions to 67 percent for 1981 conditions. This trend would continue if pumping increases, as shown by the results with 50-percent and 100-percent increases in pumping rates.

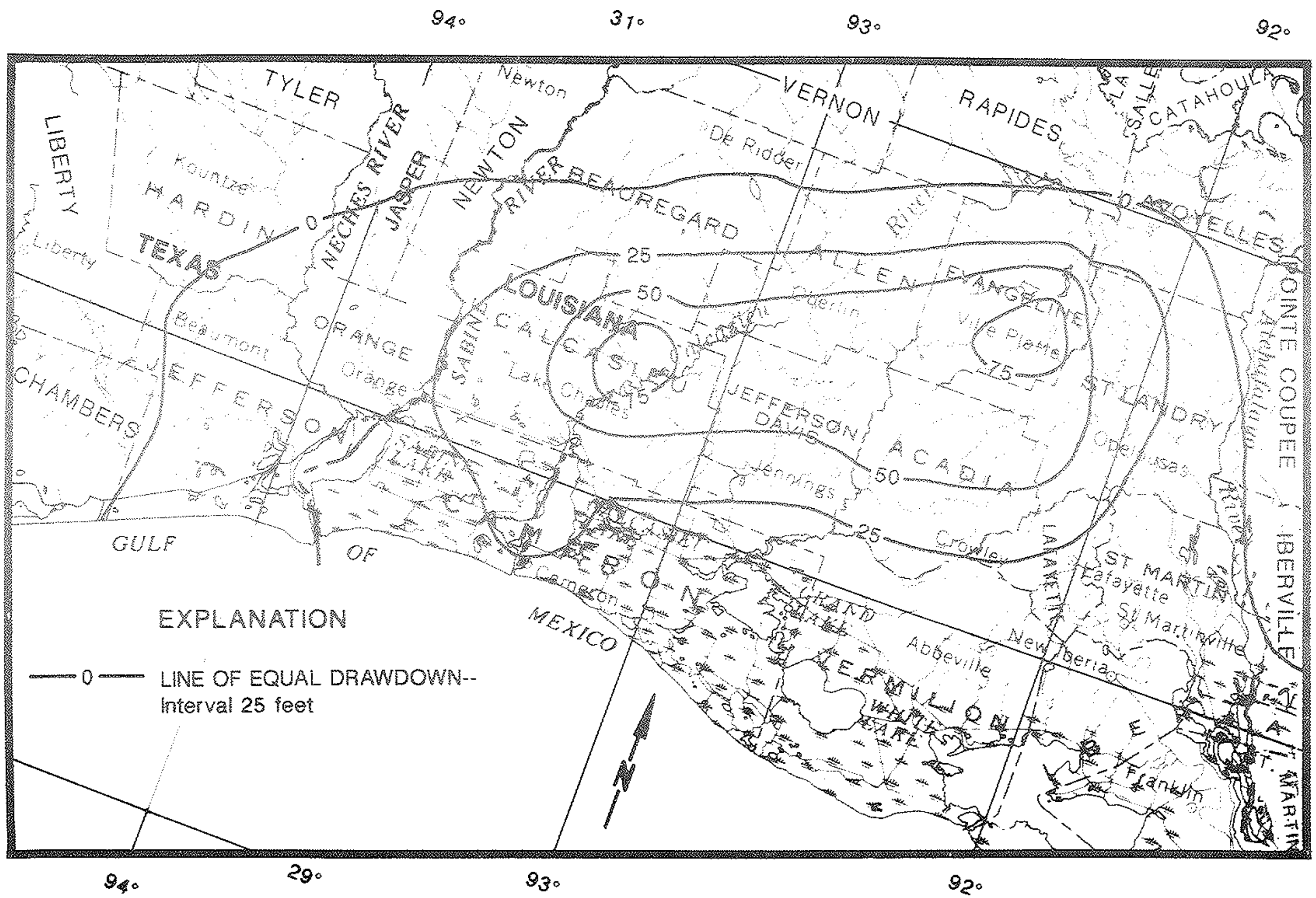
In all model experiments, pumping rates can be maintained indefinitely with the available recharge. This is without consideration of the possibility of saltwater encroachment in the aquifers along the coast. Although the effects of saltwater encroachment were not addressed in this study, these effects need to be considered in the coastal areas of southwestern Louisiana (Nyman, 1984). These simulations show that dewatering of the upper Chicot aquifer will occur in the Lake Charles and rice-growing areas when stresses of twice the 1980 magnitude are applied. Localized drawdowns in individual wells or well fields will be more severe than the average values predicted for blocks. Seasonal and annual variations in pumping for rice irrigation will produce lower water levels periodically than the averages computed by the model.



Base from U.S. Geological Survey
State base map, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 32.--Computed steady-state drawdowns from 1981 water levels in model layer 2 (upper Chicot aquifer) due to a simulated pumping rate 50 percent larger than the 1980 pumping rate.



Base from U.S. Geological Survey
State base map, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 33.--Computed steady-state drawdowns from 1981 water levels in model layer 2 (upper Chicot aquifer) due to a simulated pumping rate 100 percent larger than the 1980 pumping rate.

Table 5.--Changes in the water budget of the Chicot aquifer system for increasing pumping rates through time

[Units are in million gallons per day]

Water source	Simulation period							
	Predevelopment		1981		2005 (50 percent greater pumpage than 1981)		2040 (100 percent greater pumpage than 1981)	
	Quantity of water	Percent of total inflow	Quantity of water	Percent of total inflow	Quantity of water	Percent of total inflow	Quantity of water	Percent of total inflow
Outcrop..........	199	76	316	28	355	23	403	20
Vertical leakage.........	48	19	738	67	1,113	72	1,500	74
Atchafalaya River basin.....	10	4	20	2	15	1	28	1
General-head boundary in the upper Chicot aquifer (model layer 2)........	3	1	25	2	64	4	89	5
Storage..........	0	0	9	1	5	0	3	0
Sum of all sources.........	260	100	1,108	100	1,552	100	2,023	100
Pumpage..........	0		995		1,493		1,991	

SUMMARY

Aquifers of the Chicot aquifer system supplied about 1 Bgal/d of water in 1980 and are the most heavily pumped aquifers in Louisiana. Ninety-five percent of the water pumped from the Chicot aquifer system was used for rice irrigation and industry. Records indicate that water levels in wells declined, on average, 1 ft/yr from 1900 to 1981 in the Lake Charles and rice-growing areas. Water levels have risen, on average, 2 ft/yr during the period 1982-85 because pumping rates during the period decreased by 38 percent to 616 Mgal/d.

The Chicot aquifer system is a complex series of alternating beds of unconsolidated sand, gravel, silt, and clay. Generally, the sands are very coarse, permeable, and thick. The Chicot aquifer system crops out in Louisiana in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes. Confining clay beds within the aquifer system generally are thin and discontinuous in the outcrop area. Surface clay ranges from as little as 1 ft in thickness along the southern edge of the outcrop area where water in the aquifer system becomes confined to as much as 200 ft downdip.

Prior to ground-water development, water flowed from recharge areas where the aquifers outcrop in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes southward to discharge areas along the coast and eastward to the Atchafalaya River basin. Discharge took place upward through confining clay beds in the coastal-wetland areas and in the Atchafalaya River basin. Development has lowered water levels south of the outcrop and reversed the direction of flow in the aquifers south of Lake Charles and south and east of the rice-growing area.

A five-layer, finite-difference, digital ground-water flow model was developed to simulate flow in the Chicot aquifer system and to investigate the effects of present and future pumpage. Model calibration was completed in two phases. The first phase involved matching 1980 conditions treated as steady state. The second phase involved transient calibration to match conditions in the aquifer system from the start of development to 1981. Model-computed water levels generally compared closely with observed levels.

Results from the calibrated model show that development from the early 1900's to 1981 has significantly altered flow patterns and rates in the Chicot aquifer system. Approximately a fourfold increase (from 259 to 1,113 Mgal/d) in flow through the aquifer system has occurred. Vertical leakage is the largest component of recharge to the Chicot aquifer system under 1981 conditions. In 1981, 67 percent of the total flow in the aquifer system came from vertical leakage. Only 1 percent (about 9 Mgal/d) of the flow in the aquifer system came from storage.

The sensitivity of the model to simulated changes in vertical hydraulic conductivity, transmissivity, and storage varied. The effects of storage are relatively insignificant in the Chicot aquifer system, where transient effects are of short duration. For values of transmissivity and vertical leakance near the calibrated values, the model is most sensitive to changes in the values of transmissivity. Near the lower end of the range of uncertainty of these hydraulic characteristics, the model is most sensitive to changes in vertical leakance.

Analysis of simulations indicates that transient effects last for a relatively brief time in the aquifer system. High pumpages can be maintained indefinitely with the recharge available to the Chicot aquifer system. Salt-water encroachment along the coast is possible, but its effects were not addressed in this study. The upper Chicot aquifer would be dewatered in the Lake Charles and rice-growing areas if sustained withdrawal rates increase to more than 150 percent of the 1980 withdrawal rate. Model results indicate that only the Lake Charles industrial area would be significantly affected.

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